USDA United States Department of Agriculture

Forest Ecosystem Vulnerability Assessment and Synthesis for Northern Wisconsin and Western Upper Michigan:

A Report from the Northwoods Climate Change Response Framework Project

Forest Service | Northern Research Station | General Technical Report NRS-136 | August 2014

ABSTRACT

Forest ecosystems across the Northwoods will face direct and indirect impacts from a changing climate over the 21st century. This assessment evaluates the vulnerability of forest ecosystems in the Laurentian Mixed Forest Province of northern Wisconsin and western Upper 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 the forests of this region 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 to 9 °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 future 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, quaking aspen, and paper birch may fare worse under future conditions, but other species may benefit from projected changes in climate. Published literature on climate impacts related to wildfire, invasive species, and forest pests and diseases also contributed to the overall determination of climate change vulnerability. We assessed vulnerability for nine forest communities in the assessment area. The assessment was conducted through a formal elicitation process of 19 science and management experts from across the area, who considered vulnerability in terms of the potential impacts and the adaptive capacity for an individual community. Upland spruce-fir, lowland conifers, aspen-birch, lowland-riparian hardwoods, and red pine forests were determined to be the most vulnerable ecosystems. White pine and oak forests 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-term natural resource planning.

Cover Photo

Lake of the Clouds in western Upper Michigan. Photo by Scott Pearson, used with permission.

Manuscript received for publication February 2014

Published by:

USDA FOREST SERVICE
11 CAMPUS BLVD., SUITE 200
NEWTOWN SQUARE, PA 19073-3294

August 2014

For additional copies, contact:

USDA Forest Service
Publications Distribution
359 Main Road
Delaware, OH 43015-8640
Fax: 740-368-0152

Visit our homepage at: **http://www.nrs.fs.fed.us/**

Forest Ecosystem Vulnerability Assessment and Synthesis for Northern Wisconsin and Western Upper Michigan:

A Report from the Northwoods Climate Change Response Framework Project

Maria K. Janowiak, Louis R. Iverson, David J. Mladenoff, Emily Peters, Kirk R. Wythers, Weimin Xi, Leslie A. Brandt, Patricia R. Butler, Stephen D. Handler, P. Danielle Shannon, Chris Swanston, Linda R. Parker, Amy J. Amman, Brian Bogaczyk, Christine Handler, Ellen Lesch, Peter B. Reich, Stephen Matthews, Matthew Peters, Anantha Prasad, Sami Khanal, Feng Liu, Tara Bal, Dustin Bronson, Andrew Burton, Jim Ferris, Jon Fosgitt, Shawn Hagan, Erin Johnston, Evan Kane, Colleen Matula, Ryan O'Connor, Dale Higgins, Matt St. Pierre, Jad Daley, Mae Davenport, Marla R. Emery, David Fehringer, Christopher L. Hoving, Gary Johnson, David Neitzel, Michael Notaro, Adena Rissman, Chadwick Rittenhouse, and Robert Ziel

AUTHORS

MARIA K. JANOWIAK is a climate change adaptation and carbon management scientist with the Northern Institute of Applied Climate Science, U.S. Forest Service, 410 MacInnes Drive, Houghton, MI 49931, mjanowiak02@fs.fed.us.

LOUIS R. IVERSON is a landscape ecologist with the U.S. Forest Service, Northern Research Station, 359 Main Road, Delaware, OH 43015, liverson@fs.fed.us.

DAVID J. MLADENOFF is a professor in the Forest Landscape Ecology lab at the University of Wisconsin, Department of Forest and Wildlife Ecology, 1630 Linden Drive, Madison, WI 53706, djmladen@wisc.edu.

EMILY PETERS is a data analyst with Minnesota Pollution Control Agency, 520 Lafayette Road N., St. Paul, MN 55155, Emily.Peters@state.mn.us.

KIRK R. WYTHERS is a research fellow at the University of Minnesota, 1530 Cleveland Avenue N., St. Paul, MN 55108, kwythers@umn.edu.

WEIMIN XI, formerly a research associate in the Forest Landscape Ecology lab at the University of Wisconsin – Madison, is an assistant professor at Texas A&M University – Kingsville, Department of Biological and Health Sciences, 700 University Boulevard, Kingsville, TX 78363, weimin.xi@tamuk.edu.

LESLIE A. BRANDT is a climate change specialist with the Northern Institute of Applied Climate Science, U.S. Forest Service, Northern Research Station, 1992 Folwell Avenue, St. Paul, MN 55108, lbrandt@fs.fed.us.

PATRICIA R. BUTLER is a climate change outreach specialist with the Northern Institute of Applied Climate Science, Michigan Technological University, U.J. Noblet Forestry Building, 1400 Townsend Drive, Houghton, MI 49931, prbutler@mtu.edu.

STEPHEN D. HANDLER is a climate change specialist with the Northern Institute of Applied Climate Science, U.S. Forest Service, 410 MacInnes Drive, Houghton, MI 49931, sdhandler@fs.fed.us.

P. DANIELLE SHANNON is a climate change outreach specialist with the Northern Institute of Applied Climate Science, Michigan Technological University, U.J. Noblet Forestry Building, 1400 Townsend Drive, Houghton, MI 49931, dshannon@mtu.edu.

CHRIS SWANSTON is a research ecologist with the U.S. Forest Service, Northern Research Station, and director of the Northern Institute of Applied Climate Science, 410 MacInnes Drive, Houghton, MI 49931, cswanston@fs.fed.us.

LINDA R. PARKER is a forest ecologist with the U.S. Forest Service, Chequamegon-Nicolet National Forest, 1170 4th Avenue S., Park Falls, WI 54552, lrparker@fs.fed.us.

AMY J. AMMAN is a soil scientist with the U.S. Forest Service, Ottawa National Forest, E6248 US 2, Ironwood, MI 49938, amyjor@fs.fed.us.

BRIAN BOGACZYK is a wildlife biologist with the U.S. Forest Service, Ottawa National Forest, E6248 US 2, Ironwood, MI 49938, bbogaczyk@fs.fed.us.

CHRISTINE HANDLER is a forest planner with the U.S. Forest Service, Ottawa National Forest, E6248 US 2, Ironwood, MI 49938, cahandler@fs.fed.us.

ELLEN LESCH is an aquatic ecologist/hydrologist with the U.S. Forest Service, Ottawa National Forest, E6248 US 2, Ironwood, MI 49938, elesch@fs.fed.us.

PETER B. REICH is a professor at the University of Minnesota, 1530 Cleveland Avenue N., St. Paul, MN 55108, preich@umn.edu.

STEPHEN MATTHEWS is a research assistant professor at Ohio State University, School of Environment and Natural Resources, and an ecologist with the U.S. Forest Service, Northern Research Station, 359 Main Road, Delaware, OH 43015, snmatthews@fs.fed.us.

MATTHEW PETERS is a geographic information systems technician with the U.S. Forest Service, Northern Research Station, 359 Main Road, Delaware, OH 43015, matthewpeters@fs.fed.us.

ANANTHA PRASAD is an ecologist with the U.S. Forest Service, Northern Research Station, 359 Main Road, Delaware, OH 43015, aprasad@fs.fed.us.

SAMI KHANAL is a postdoctoral research associate in the Forest Landscape Ecology lab at the University of Wisconsin – Madison, 1630 Linden Drive, Madison, WI 53706, skhanal2@wisc.edu.

FENG LIU, formerly a research associate in the Forest Landscape Ecology lab at the University of Wisconsin – Madison, is a research scientist in Wuhan Botanical Garden, Chinese Academy of Sciences, Wuhan China, liufeng@wbgcas.cn.

TARA BAL is a research assistant professor at Michigan Technological University, U.J. Noblet Forestry Building, 1400 Townsend Drive, Houghton, MI 49930, tlbal@mtu.edu.

DUSTIN BRONSON is a forest research ecologist with the Wisconsin Department of Natural Resources, 107 Sutliff Avenue, Rhinelander WI 54501, dustin.bronson@wisconsin.gov.

ANDREW BURTON is a professor at Michigan Technological University, U.J. Noblet Forestry Building, 1400 Townsend Drive, Houghton, MI 49931, ajburton@mtu.edu.

JIM FERRIS is a silviculturist with the Michigan Department of Natural Resources, 1990 U.S. Highway 41 South, Marquette, MI 49855, ferrisj@michigan.gov.

JON FOSGITT is a forest management specialist with Compass Land Consultants, 7750 U.S. Highway 51 South, P.O. Box 846, Minocqua, WI 54548, jon@compasslandconsultants.com.

SHAWN HAGAN is the Director-Forest Operations, The Forestland Group, LLC, 33687 Lake Gerald Road, Toivola, MI 49965, shawn@forestlandgroup.com.

ERIN JOHNSTON is the Lake Superior Program Coordinator for Keweenaw Bay Indian Community Natural Resources Department, 14359 Pequaming Road, L'Anse, MI 49946, ejohnston@kbic-nsn.gov.

EVAN KANE is an assistant professor at Michigan Technological University, U.J. Noblet Forestry Building, 1400 Townsend Drive, Houghton, MI 49931, eskane@mtu.edu.

COLLEEN MATULA is a forest ecologist/silviculturist with the Wisconsin Department of Natural Resources, P.O. Box 709, Mellen, WI 54546, colleen.matula@wisconsin.gov.

RYAN O'CONNOR is an ecologist & inventory coordinator at the Natural Heritage Conservation at the Wisconsin Department of Natural Resources, 101 S. Webster Street, Madison WI 53703, ryan.oconnor@wisconsin.gov.

DALE HIGGINS is a forest hydrologist with the U.S. Forest Service, Chequamegon-Nicolet National Forest, 500 Hanson Lake Road, Rhinelander, WI 54501, dhiggins@fs.fed.us.

MATT ST. PIERRE is a biologist with the U.S. Forest Service, Chequamegon-Nicolet National Forest, 500 Hanson Lake Road, Rhinelander, WI 54501, mstpierre@fs.fed.us.

JAD DALEY is a program director at the Trust for Public Land, 660 Pennsylvania Avenue SE., Suite 401, Washington, DC 20003, jad.daley@tpl.org.

MAE DAVENPORT is an associate professor at the University of Minnesota, 1530 Cleveland Avenue N., St. Paul, MN 55108, mdaven@umn.edu.

MARLA R. EMERY is a research geographer with the U.S. Forest Service, Northern Research Station, 81 Carrigan Drive, Burlington, VT 05405, memery@fs.fed.us.

DAVID FEHRINGER is the Great Lakes Assistant Regional Director with The Forestland Group, LLC, 33687 Lake Gerald Road, Toivola, MI 49965, dave@forestlandgroup.com.

CHRISTOPHER L. HOVING is an adaptation specialist with the Michigan Department of Natural Resources, P.O. Box 30028, Lansing, MI 48909, hovingc@michigan.gov.

GARY JOHNSON is an extension professor at the University of Minnesota, 1530 Cleveland Avenue N., St. Paul, MN 55108, johns054@umn.edu.

DAVID NEITZEL is an epidemiologist with the Minnesota Department of Health, 625 N. Robert Street, St. Paul, MN 55164, david.neitzel@state.mn.us.

MICHAEL NOTARO is an associate scientist and associate director of the Nelson Institute Center for Climatic Research, University of Wisconsin – Madison, 1225 West Dayton Street, Madison, WI 53706, mnotaro@wisc.edu.

ADENA RISSMAN is an assistant professor at the University of Wisconsin – Madison, 1630 Linden Drive, Madison, WI 53706, arrissman@wisc.edu.

CHADWICK RITTENHOUSE is an assistant research professor at the University of Connecticut, Wildlife and Fisheries Conservation Center, 1376 Storrs Road, Storrs, CT 06269, chadwick.rittenhouse@uconn.edu.

ROBERT ZIEL (retired) was the program coordinator for the Lake States Fire Science Consortium, 1680 Madison Avenue, Wooster, OH 44691. He can be reached at rhziel1@gmail.com.

Page intentionally left blank

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. Six Framework projects are currently underway, covering approximately 250 million acres in the northeastern and midwestern United States: Northwoods, Central Appalachians, Central Hardwoods, Mid-Atlantic, New England, and Urban Forests. Each 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 on the topic of climate change and forest ecosystems. Its primary goal is to inform forest managers in northern Wisconsin and western Upper 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. We acknowledge that 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. The overall document structure and much of the language was a coordinated effort among Leslie Brandt, Patricia Butler, Maria Janowiak, Stephen Handler, and Chris Swanston. Danielle Shannon conducted much of the data analysis and developed maps for Chapters 1, 3, and 4. Louis Iverson, Steve Matthews, Matthew Peters, and Anantha Prasad provided and interpreted Tree Atlas information for Chapter 5, and assisted with the data processing for the climate data presented in Chapter 4. David Mladenoff, Weimin Xi, and Sami Khanal provided results and interpretation of the LANDIS-II model. Emily Peters, Kirk Wythers, and Peter Reich provided results and interpretation of the PnET-CN model. All modeling teams coordinated their efforts impressively. Amy Amman, Brian Bogaczyk, Christine Handler, Ellen Lesch, and Linda Parker provided substantial input throughout the document.

Among the many others who made valuable contributions to the assessment, Scott Pearson furnished numerous photographs of the forests and wildlife present in the assessment area, and Keith Cherkauer (Purdue University) provided hydrologic data for Chapter 4. We also thank Jack Williams (University of Wisconsin – Madison), Eric Kruger (University of Wisconsin – Madison), and Christel Kern (U.S. Forest Service, Northern Research Station), who provided formal technical reviews of the assessment. Their thorough reviews greatly improved the quality of this assessment.

Page intentionally left blank

CONTENTS

Page intentionally left blank

EXECUTIVE SUMMARY

This assessment evaluates key ecosystem vulnerabilities for forest ecosystems in the Laurentian Mixed Forest Province in northern Wisconsin and western Upper 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 through this century. A final chapter summarizes the implications of these impacts and vulnerabilities for forest management across the region.

CHAPTER 1: THE CONTEMPORARY LANDSCAPE

This chapter describes the forests and related ecosystems across the Laurentian Mixed Forest Province in northern Wisconsin and western Upper Michigan and summarizes current threats and management trends. The information lays the foundation for understanding how shifts in climate may contribute to changes in forest ecosystems, and how climate may interact with other stressors on the landscape.

Main Points

- The assessment area of northern Wisconsin and western Upper Michigan contains approximately 16 million acres of forest land. Private individuals and organizations own more than 60 percent of forest land.
- Current major stressors and threats to forest ecosystems in the region include:
  - Fragmentation and land-use change
  - Fire regime shifts
  - Nonnative species invasion
  - Forest diseases and insect pests
  - Overbrowsing by deer
  - Extreme weather events
- Historical land use and past management practices tended to favor younger forests across the landscape and often reduced species diversity and structural complexity.
- The forest products industry is a major contributor to the region's economy, and much of the forest land in the assessment area is managed according to at least one sustainability certification standard.

CHAPTER 2: CLIMATE CHANGE SCIENCE AND MODELING

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 ecosystems. 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 over the past century.
- More than 95 percent of climate scientists attribute this increase in temperature to human activities.
- Major contributors to warming are greenhouse gases from fossil fuel burning, agriculture, and changes in land use.

CHAPTER 3: OBSERVED CLIMATE CHANGE

Many of the climatic changes that have been observed across the world over the past century are also evident in the assessment area. This chapter summarizes our current understanding of observed changes and current climate trends in the assessment area and across the Midwest region, with a focus on the last 50 to 100 years.

Main Points

- Mean, minimum, and maximum temperatures increased across all seasons over the past century, with winter temperatures warming the most rapidly.
- Precipitation patterns have changed across the region. The number of intense precipitation events has increased.
- Snowfall has generally decreased across the assessment area, although the severity of large winter storms may have 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 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 simulations of climate models. 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

- Temperatures are expected to continue to increase over the next century. A range of climate scenarios project warming in all seasons.
- Precipitation is projected to increase in winter and spring across a range of climate scenarios. Projections of summer and fall precipitation are more variable, and summer precipitation may decrease.
- Intense precipitation events are expected to continue to become more frequent.
- Snowfall is projected to continue to decline across the assessment area, 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

This chapter summarizes the potential impacts of climate change on forests in the Laurentian Mixed Forest Province in northern Wisconsin and western Upper Michigan, drawing on information from a coordinated series of model simulations and published research.

Main Points

- Boreal species such as black spruce, balsam fir, quaking aspen, paper birch, and white spruce are projected to have reductions in suitable habitat and biomass over the next century.
- Species with ranges that extend to the south such as American basswood, black cherry, northern red oak, and red maple may have increases in suitable habitat and biomass.
- Many species currently common in northern Wisconsin and western Upper Michigan are projected to decline under a hotter, drier future climate scenario.
- Forest productivity will be influenced by a combination of factors such as carbon dioxide (CO_2) fertilization, water and nutrient availability, and species migration.
- The model projections used in this assessment do not account for many other factors that may change under a changing climate. Scientific literature was used to provide additional information on these factors, including:
  - Altered precipitation and hydrology
  - Drought stress
  - Wildfire frequency and severity
  - Altered nutrient cycling
  - Changes in invasive species, insect pests, and forest diseases
  - Interactions among these factors

CHAPTER 6: FOREST ECOSYSTEM VULNERABILITIES

Forest ecosystems across the Northwoods will experience direct and indirect impacts from a changing climate over the 21st century. We assessed the vulnerability of major forest systems in the assessment area to climate change over the next 100 years, focusing on shifts in dominant species, system drivers, and stressors. The adaptive capacity of forest systems was also examined as a key component to overall vulnerability. Synthesis statements are provided to capture general trends. Detailed vulnerability determinations are also provided for nine major forest systems (Table 1).

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.
- **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.

Table 1.—Vulnerability determination summaries for the forest systems considered in this assessment

Forest system	Potential impacts	Adaptive capacity	Vulnerability	Evidence	Agreement
Aspen-birch	Moderate-Negative	Moderate	Moderate-High	Medium-High	Medium-High
Jack pine	Moderate-Negative	Moderate-High	Moderate	Medium	Medium-High
Lowland conifers	Negative	Moderate-Low	High	Medium	Medium-High
Lowland-riparian hardwoods	Moderate-Negative	Moderate	Moderate-High	Limited-Medium	Medium
Northern hardwoods	Moderate-Negative	Moderate-High	Moderate	Medium-High	Medium
Oak	Moderate	Moderate-High	Moderate-Low	Medium	Medium-High
Red pine	Moderate-Negative	Moderate-Low	Moderate-High	Medium-High	Medium-High
Upland spruce-fir	Negative	Moderate-Low	High	Medium-High	Medium-High
White pine	Moderate-Positive	High	Moderate-Low	Medium-High	Medium

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

Amnicon Falls in northern Wisconsin. Photo by Scott Pearson, used with permission.

- **Many nonnative species, insect pests, and pathogens will increase or become more damaging (limited evidence, high agreement).** Evidence indicates that an increase in temperature and greater ecosystem stress will 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).** Ecosystem 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 species.
- **Southern species will be favored by climate change (medium evidence, medium agreement).** Ecosystem models agree that many temperate species will gain suitable habitat and biomass across the assessment area, and that longer growing seasons and warmer temperatures will lead to productivity increases for temperate forest types.

- **Forest ecosystems will change across the landscape (medium evidence, high agreement).** Although few models have specifically examined how communities may change, model results from individual species and ecological principles suggest that species composition and recognized forest communities will change.
- **Forest productivity will increase across the assessment area (medium evidence, low agreement).** Some model projections and other evidence suggest forest productivity may increase in the assessment area, although there is uncertainty about the effects of and limitations to CO_2 fertilization. It is also anticipated 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 are more vulnerable 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 that are adapted to more frequent disturbance will be at lower risk.

CHAPTER 7: MANAGEMENT IMPLICATIONS

This chapter summarizes the implications of potential climate change to forest management and planning in northern Wisconsin and western Upper 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 by ecosystem, ownership, and management objective.

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.
- Climate change may present opportunities for the forest products industry, recreation, and other sectors if changing conditions are anticipated.

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 northern Wisconsin and western Upper Michigan and will serve as a companion for similar assessments completed in northern Minnesota and Michigan. Additionally, regional Framework projects are underway in several other regions: Central Appalachians, Central Hardwoods, Mid-Atlantic, New England, and Urban Forests.

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, 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
- 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 across northern Wisconsin and western Upper Michigan. Several independent efforts related to climate change, natural ecosystems, and human well-being are also occurring in this area. This assessment complements other assessments that have been created for the assessment area and for the broader Northwoods region. The Framework project will also work to integrate the results and outcomes from other projects related to climate change and natural resource management.

This assessment bears some similarity to other synthesis documents about climate change science, such as the National Climate Assessment (Melillo et al. 2014) and the Intergovernmental Panel on

Climate Change (IPCC) reports (e.g., IPCC 2007a, 2013). Where appropriate, we refer to these larger-scale documents when discussing national and global changes. However, this assessment differs from these reports in a number of ways. 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 Wisconsin and western Upper 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 Wisconsin and western Upper Michigan under a range of future climates, and determine the vulnerability of forest communities to these changes during the next century. Included is a synthesis of information about the current 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 about 16.0 million acres of forest land in northern Wisconsin and Michigan (Fig. 1). The assessment area boundaries are defined by the Laurentian Mixed Forest Province (Ecological Province 212) within northern Wisconsin and the western Upper Peninsula of Michigan (McNab and Avers 1994, McNab et al. 2007). The assessment area includes Ecological Sections VIII, IX, and X in Wisconsin and Ecological Section IX in Michigan of *Albert's Regional Landscape Ecosystems* (Albert 1995). In addition to these ecological boundaries, we used county-level information that most closely represented the assessment area when eco-regional data were not available, limiting our selections to the 41 counties that are most analogous to the assessment area.

The northern Wisconsin portion of the assessment area is substantially larger than the Michigan portion and covers 11.5 million acres. The western Upper Peninsula of Michigan contains 4.5 million acres of forest land. Land ownership is fairly similar across the two states. Overall, more than 60 percent of forest land in the assessment area is owned by private individuals and organizations. Approximately 12 percent of land is federally owned, with the Chequamegon-Nicolet and Ottawa National Forests making up the bulk of federal lands. State agencies own nearly 6 percent of forest land; and county, municipal, and local governments own 17 percent. This assessment synthesizes information covering all forest lands in the assessment area in recognition of the area's varied patterns of forest composition and land ownership.

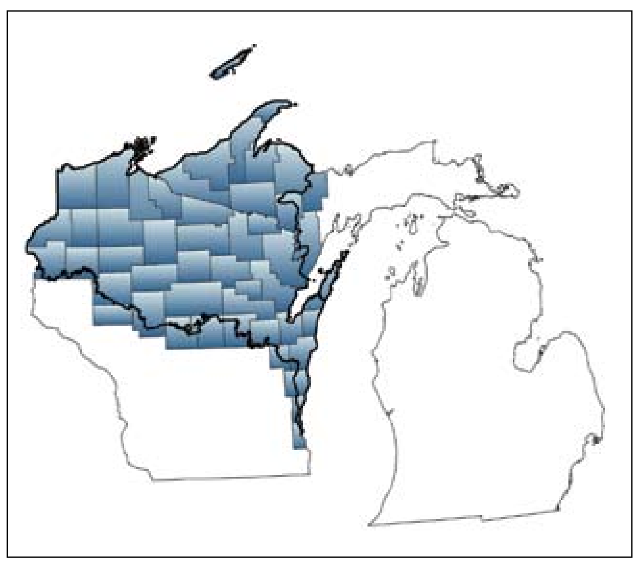


Figure 1.—The assessment area and the 41 counties used to approximate the Laurentian Mixed Forest Province when county-level data were required.

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 the assessment area.

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 Wisconsin and western Upper Michigan, summarized from the interactive ClimateWizard database and published literature. This chapter also summarizes some relevant ecological indicators of observed climate change.

Chapter 4: Projected Changes in Climate 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 the assessment area and the Midwest region.

Chapter 5: Future Climate Change Impacts on Forests summarizes ecosystem 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 literature review of 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 each major forested ecosystem.

Chapter 7: Management Implications draws connections from the forest ecosystem 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 northern Wisconsin and the western Upper Peninsula of Michigan results from numerous physical, ecological, economic, and social factors. This chapter includes a brief introduction to the complex variables that shape the northern forests in the assessment area and provides context for the modeling results and interpretations provided in later chapters.

LANDSCAPE SETTING

Northern Wisconsin and the western portion of the Upper Peninsula of Michigan are part of the Laurentian Mixed Forest system (Ecological Province 212), which covers much of the northern Great Lakes region (McNab and Avers 1994, McNab et al. 2007) (Fig. 2). Ecological provinces are broad geographic areas that share similar characteristics, such as climate, glacial history, and vegetation types. Albert (1995) characterized the region and outlined Ecological Sections based upon these factors, including a bedrock consisting of Precambrian granites, gneiss, and the Negaunee iron formation that underlies most of the assessment area. Below, we summarize the major physical and biological features of the assessment area.

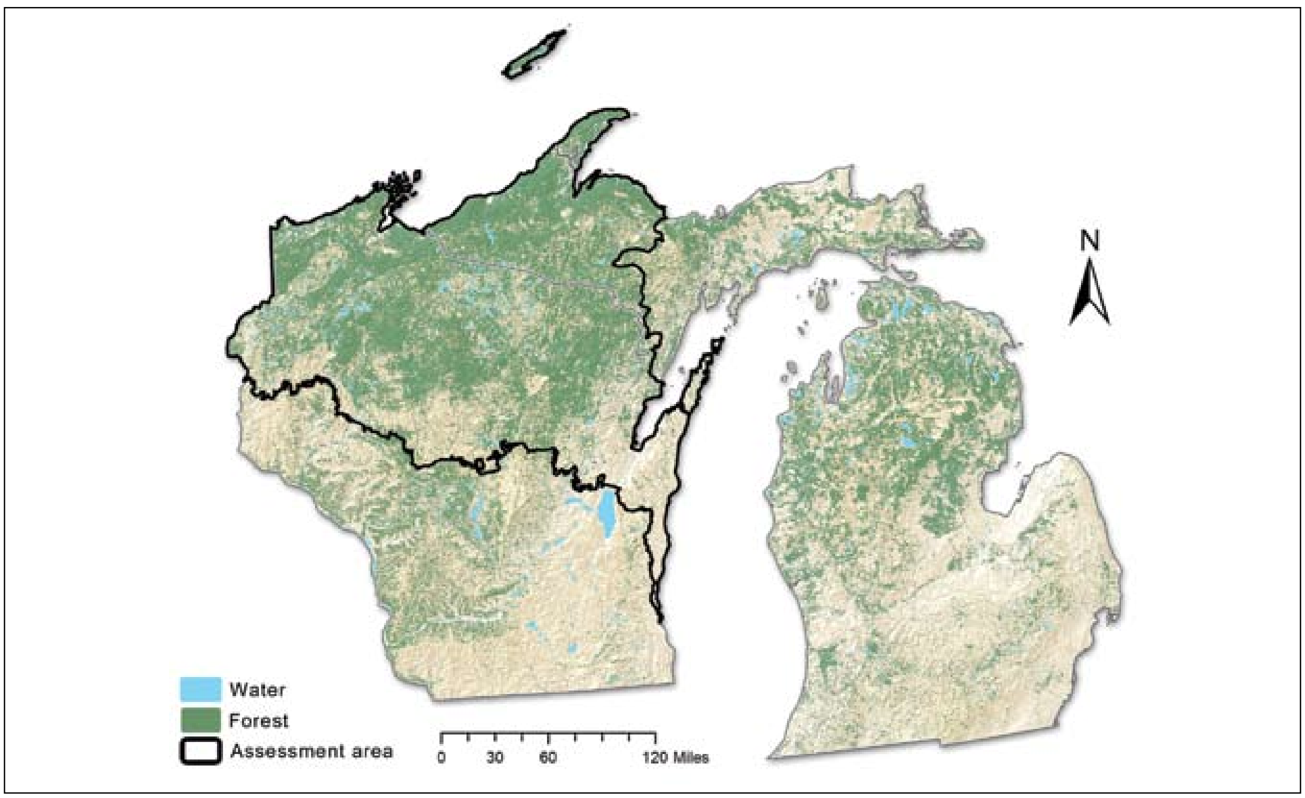


Figure 2.—The area used for this assessment includes the Laurentian Mixed Forest Ecological Province within northern Wisconsin and the western Upper Peninsula of Michigan (McNab and Avers 1994, McNab et al. 2007). The area covers Ecological Sections VIII, IX, and X in Wisconsin and Ecological Section IX in Michigan (Albert 1995).

Physical Environment

Climate

Located largely north of the 45th parallel (halfway between the equator and the North Pole), the assessment area is shaped by a convergence of several climatic systems (Eichenlaub 1979). Frequent polar air masses and a lower annual amount of solar energy typically keep this area colder than areas farther south (Sommers et al. 1984). Proximity to two Great Lakes—Superior and Michigan—creates a lake-effect zone across much of the assessment area that moderates temperatures throughout the year (Stearns 1997) (Box 1). The mean annual temperature for the assessment area from 1971 through 2000 was 41.5 °F (5.3 °C). July was the warmest month with an average temperature of 67.2 °F (19.7 °C) during this period, and January was the coldest month, with an average temperature of 11.6 °F (-11.3 °C) (ClimateWizard 2012). There are few days with temperatures above 90 °F (32.2 °C), and only four or fewer extremely hot days occur per year on average (Great Lakes Integrated Sciences and Assessments [GLISA] 2013, National Oceanic and Atmospheric Administration [NOAA] National Climatic Data Center 2006a). The growing season lasts for 100 to 140 frost-free days per year (Host et al. 1995, Michigan State University 2010), which has a strong influence on the type of vegetation that can be sustained. Winters in the assessment area are long and somewhat severe. Temperatures of -30 °F (-34.7 °C) are reported from northern Wisconsin weather stations almost every winter (NOAA 2006a). Many lakes and streams are covered in ice from late November to early April, and snow covers the ground all winter long in northern portions of the assessment area.

During 1971 through 2000, average annual precipitation across the assessment area totaled 32 inches, about two-thirds of which occurred during the growing season (ClimateWizard 2012, NOAA National Climatic Data Center 2006b). Seasonally, the most precipitation falls in summer (11.8 inches), followed by fall (8.8 inches), spring (7.5 inches), and winter (3.9 inches). August is the wettest month (4 inches) and February is the driest month (1 inch). An average of between 160 and 220 inches of snow falls in the assessment area every year (NOAA National Climatic Data Center 2006a), and snow cover and snowmelt play an important role in the hydrologic regime of the assessment area (Cherkauer and Sinha 2010). The climate of much of the assessment area is influenced by lake-effect weather patterns (Box 1), and the western Upper Peninsula

Box 1: What is Lake Effect?

A significant lake-effect zone along both Lake Superior and Lake Michigan produces temperatures that are warmer in winter and cooler in summer than inland areas at the same latitude (Eichenlaub 1970). The massive Great Lakes take much longer to adjust to temperature changes. They absorb heat in the summer and autumn and cool the land near the shore; in autumn and winter they release heat, thereby warming the land near shore (Stearns 1997). In the late fall and early winter, the air over the Great Lakes is generally warmer and moister than over land. As this air moves inland, the water condenses and enhanced cloud cover and precipitation (often in the form of snow) occur downwind of the lakes (NOAA National Climatic Data Center 2006a, Notaro et al. 2012). Higher, rougher terrain amplifies the lake-effect resulting in even more snowfall than many other locations in the United States (Albert et al. 1986, Eichenlaub 1979). In 2011, the Weather Channel ranked Hancock, Michigan, the third snowiest city in America based on 30-year average annual snowfall data; some unincorporated towns nearby were not included in the ranking, but annually receive even more snow than Hancock (Erdman 2011).

generally receives more precipitation than northern Wisconsin partly due to this phenomenon (NOAA 2010). Melting snow, combined with spring rains, contributes to a distinct hydrologic regime that can result in frequent and sometimes severe flooding in April.

Chapter 3 provides more details about current and historical climate trends, and Chapter 4 describes the projected future climate of the assessment area.

Geology, Landform, and Soils

The assessment area lies on the ancient rocks of the Precambrian Shield. Its geological foundation is composed of highly resistant igneous and metamorphic rock, lava flows, iron formations, granite and gneiss intrusions, conglomerates, limestone, and sandstone (Albert 1995). Exposed bedrock is found throughout the northern part of the assessment area, and the Porcupine and Huron Mountains in the western Upper Peninsula are remnants of some of the oldest mountains in the world (Sommers et al. 1984). Past glaciations are responsible for the area's surface geology. At the end of the Pleistocene epoch (2.6 million to 11,000 years ago), glaciers covered the assessment area with ice thousands of feet thick. As the glaciers advanced southward, and again as the ice age ended and the glaciers retreated, great volumes of soil and rock were moved substantial distances (Sommers et al. 1984). Glacial runoff cut channels throughout the assessment area. A massive deposit of glacial drift (more than 200 feet thick in some areas) and the subsequent melting of the glacial ice combined to create a diverse landscape of glacially scoured bedrock ridges and irregular glacial features including moraines, glacial lake beds, and outwash channels and clay plains (Albert 1995). Exposed bedrock knobs can be found in the northern portion of the assessment area; swamps, bogs, and other wetland areas are very common throughout (Jerome 2006).

Soils in the assessment area are relatively young, having developed since the retreat of the Wisconsin ice sheets at the end of the ice age approximately 10,000 years ago (Stearns 1997). Glacial deposits of coarse outwash sands, fine-textured clays, and tills serve as the parent material for the relatively infertile soils in this region (Hole 1968, Jerome 2006). Early logging practices and subsequent fires on newly exposed soils have destroyed the organic layer of many sandy loam forest soils, and tree-tipping during centuries of storms has resulted in occasional cradle-knoll formation (Hole 1976). Sandy barrens scattered across the north often have sands tens of feet deep with very little variation, and support vegetation adapted to low-productivity soils, in such ecosystems as pine barrens, aspen forests, and grasslands (Hole 1976). The depressions, or kettles, left by melting glacial ice masses are often filled by lakes or by peat bogs containing sphagnum moss. Fine-textured lacustrine deposits rich in silt and clay can be 2 to 3 feet deep in glacial lake plains. The poor drainage of these soils is limiting to agricultural production due to excess water in the spring and droughty conditions in late summer (Hole 1976). Red clay soils arising from pulverized iron redistributed by glacial lakes are found along the shorelines of Lake Superior and Lake Michigan (Hole 1976).

Hydrology

Water resources are abundant and diverse across the assessment area. The national forests alone (covering 15 percent of the assessment area) contain more than 4,000 miles of perennial streams and rivers, more than 1,000 lakes larger than 10 acres, and more than 550,000 acres of wetlands. Groundwater is generally abundant in unconfined sand and gravel aquifers that interact with surface water bodies to influence flow rates, water chemistry, and aquatic ecology. Inextricably linked with water supplies and cycling, forests play a critical role in protecting soil,

A small lake in Michigan's Upper Peninsula. Photo by Maria Janowiak, U.S. Forest Service.

moderating streamflow, sustaining water quality, and protecting sources of drinking water for human populations (Barnes et al. 2009).

Hydrology in the assessment area often follows a seasonal pattern. Climate is the primary driver of this seasonal pattern; the amount of runoff in a watershed results from a combination of snowfall, snowmelt, rainfall, and evapotranspiration. Stream flows are generally low in winter because most water is stored as snow or ice, which is followed by high stream flows in spring that result from snowmelt and increased precipitation. Flows often decline in summer as a result of greater evapotranspiration losses, with occasional runoff from rainstorms. Autumn is similar to summer but with higher flows due to reduced evapotranspiration and wetter conditions.

At a more local level, differences in watershed characteristics, such as landform, soil, geology, vegetation, and land use, have a greater influence on the hydrologic regime. In the assessment area, this response can be divided into three broad hydrologic regimes: surface, groundwater, and mixed. Surface runoff regimes are most responsive to rainfall and snowmelt events, particularly in watersheds where there is a limited capacity to absorb and store water from precipitation events, leading to more water in streams. Groundwater runoff regimes are least responsive to surface runoff from storms or snowmelt and have high, stable baseflows fed by a continuous supply of groundwater. Watersheds with groundwater runoff regimes generally have coarse-textured glacial outwash or till with high porosity that favors groundwater recharge. They also tend to have sufficient topographic change to produce a steady flow of groundwater from uplands to streams and fen-type wetlands. Mixed runoff watersheds typically have landform and soil characteristics that are intermediate between the surface and groundwater regimes. The predominant watershed type in the assessment area is mixed runoff. Groundwater runoff watersheds are least common.

Flood flows in the assessment area tend to be relatively low because of the area's high storage capacity in the form of wetlands and lakes, gentle relief, and soils with high infiltration capacity. There are some exceptions, however. For example, the clay plains along Lake Superior and Lake Michigan have a low infiltration capacity, less storage, and steep slopes in some locations. The Penokee-Gogebic Range contains shallow soils over bedrock, and its steeper slopes have a lower ability to absorb precipitation and runoff. Annual flood peaks in northern Wisconsin are caused by both snowmelt and rainfall runoff in about equal proportions; the western Upper Peninsula has a greater influence from snowmelt.

Ecosystem Composition

Land Cover

Although dominated by forest (50 percent of land cover), the assessment area also contains substantial components of wetlands (19.3 percent) and agricultural lands (19.2 percent). Developed or urban land (5.1 percent), water (3.7 percent), and other shrubland, herbaceous, or barren lands (2.8 percent) complete the landscape (U.S. Geological Survey 2011). The western Upper Peninsula of Michigan is generally less favorable for agriculture and urban development than northern Wisconsin, resulting in a greater percentage of forested land in the western Upper Peninsula compared to northern Wisconsin. A major vegetation change occurs along the tension zone (Fig. 3), where the more open landscape of southern Wisconsin (once prairie and oak savanna but now predominantly agricultural lands) transitions into the mixed deciduous-coniferous forests of the assessment area (Wisconsin Department of Natural Resources [WDNR] 2009a). The proximity of these ecosystems to the boreal forests that extend northward into Canada creates a complex and unique set of ecological conditions. Species that are at or near the southern extent of their range in the assessment area include jack pine, red pine, white pine, northern white-cedar, tamarack, balsam fir, yellow birch, paper birch, black spruce, and white spruce (Burns and Honkala 1990). American beech, absent in most of the western Upper Peninsula and limited to the Lake Michigan shoreline in Wisconsin, is at the western extent of its range. Eastern hemlock is close to the western edge of its range in the assessment area, and is rare in western Wisconsin. Tables 14 and 15 in Appendix 1 list common and scientific names of plant, fauna, and other species mentioned in this assessment.

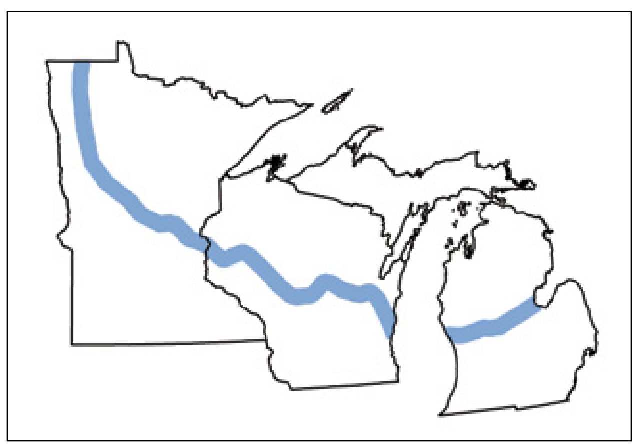


Figure 3.—Approximate location of the tension zone (blue line) in Minnesota, Wisconsin, and Michigan. Adapted from Andersen (2005), Curtis (1959), and Wisconsin Department of Natural Resources (1995).

Ecosystems Within the Assessment Area

In this assessment, we focus on forest ecosystems in the region. At the same time, it is important to recognize that although the assessment area is covered by extensive forest, many different types of ecosystems are present. Differences in landform, soils, and natural and human disturbances produce a great deal of ecological variation across the landscape. Within the forested areas, other ecosystems, including riparian and wetland systems, shrublands, and grasslands (described below), depend on, influence, or otherwise coexist with a variety of forested ecosystems. Great Lakes coastal systems and aquatic systems are also key components of the landscape, but are outside the scope of this assessment (Michigan Department of Natural Resources [MDNR] 2011b, WDNR 2009b). Here, we describe several of these regionally important ecosystems.

- Forests within the assessment area are influenced largely by differences in soil moisture and include northern hardwoods, lowland hardwoods, lowland conifers, aspen, and pine forest types. These forests vary in their association with understory plant communities, wildlife, and dominant species. Openings in the forest canopy may be composed of other ecosystem types, such as wetlands or grasslands (MDNR 2011b). These forested systems are described in greater detail later in this chapter.
- Wetlands are found in diverse forms throughout the assessment area and can include swamp (areas with peat or muck soils dominated by trees or shrubs), open bog (a carpet of living sphagnum moss over a layer of acid peat), shallow and deep marshes (areas of shallow seasonal or permanent water, supporting emergent aquatic plants such as cattails, bulrushes, wild rice, and arrowheads), and sedge meadows (peat or muck soils dominated by the sedge genus *Carex*, but also spike-rushes, bulrushes, and nut-grasses) (Eggers and Reed 1997, Shaw and Fredine 1971). Additionally, the assessment area contains many small (less than 1 acre) and isolated wetlands referred to as woodland ponds, vernal pools, or seasonal ponds that provide important habitat for salamanders, frogs, and many birds (MDNR 2011a). Forested swamps and bogs are the most common types of wetland (Box 2).
- Grassland systems include generally open lands (trees are absent or widely scattered) that are categorized as prairie, savanna, abandoned field, hayland, pasture, row crop, orchard, right-of-way, or fence row (MDNR 2011b). Many birds, including the sharp-tailed grouse, northern bobwhite, American woodcock, and red-headed woodpecker, require grassland habitat close to forests (MDNR 2011b).
- Shrublands are dominated by woody vegetation in seasonally or permanently saturated soils (lowland shrub) or moist to dry soils (upland shrub) (MDNR 2011b). Birds such as the American black duck, American bittern, and golden-winged warbler, and mammals such as the northern bat, bobcat, and snowshoe hare, depend on shrublands for habitat (MDNR 2011b).

SOCIOECONOMIC CONDITIONS

Approximately 1.6 million people live within the assessment area. Northern Wisconsin makes up the greater proportion of the assessment area by acreage and also has a higher population density. Almost 1.4 million people live in northern Wisconsin and the population has increased steadily since 1970 (Headwaters Economics 2011). In contrast, far fewer (172,774) people live in the western Upper Peninsula, and the population has decreased slightly during the same period.

Other socioeconomic conditions are very similar across the assessment area. Unemployment across the entire area was 9 percent in 2010 and more than doubled between 2000 and 2010 (Headwaters Economics 2011). Per capita income was $34,494

Box 2: Forested Wetlands

Forested bogs and swamps are common throughout the region (Eggers and Reed 1997). Differences in topography, soil characteristics, hydrology, vegetation, water chemistry, and other factors create a diversity of wetland types.

Inland wetlands occur primarily in low-lying areas where the groundwater is near the soil surface, or where precipitation saturates the soil above an impervious layer. Wetlands can be permanent or seasonal, becoming saturated for weeks or months each year. Wetlands are recognized for their water-filtering and recharging services, and their role in carbon storage. Forested wetlands can be broadly grouped into three main types:

- **Coniferous swamps** are dominated by northern white-cedar and tamarack, growing on peat or muck soils that are saturated during much of the growing season, and that may be temporarily inundated by as much as a foot of standing water. Balsam fir may be a component in some stands. Soils can vary from nutrient-poor and acidic to fertile and alkaline. Tamarack typically dominates on acidic soils, and northern white-cedar on alkaline soils (Eggers and Reed 1997). Northern white-cedar swamps are among the most fragile plant communities in the assessment area, containing many rare orchid species. Species relying on coniferous swamps include the wood turtle, spruce grouse, frogs, salamanders, great blue heron, and snowshoe hare (MDNR 2011b).
- **Coniferous bogs** are dominated by black spruce and tamarack, growing on a carpet of living sphagnum moss over a layer of acid peat. Sphagnum moss is the dominant ground layer species, but sedges, orchids, and pitcher plants are often present, along with shrubs in the heath family (Ericaceae) (Eggers and Reed 1997). Species that rely on coniferous bogs include dragonflies, Blanding's turtle, smooth green snake, American marten, and the southern bog lemming (MDNR 2011b).
- **Lowland hardwood swamps** are dominated by silver maple, black ash, red maple, and yellow birch growing on soils that are saturated during much of the growing season, and may be inundated by as much as a foot of standing water (Shaw and Fredine 1971). American elm and northern white-cedar can be a component in some stands. Bird species relying on lowland swamps include the green heron, great blue heron, and osprey; mammals include the arctic shrew, pygmy shrew, and snowshoe hare (MDNR 2011b).

and 5 percent of families were living below the poverty line during this time (Headwaters Economics 2011). As the assessment area has become a more popular retirement destination (especially in northern Wisconsin), the median population age has increased (Headwaters Economics 2011), along with the percentage of housing units used for seasonal, recreational, or occasional purposes. Across the assessment area, about 17 percent of all housing units are seasonal. In some Wisconsin counties (Vilas, Florence, Forest, Burnett, and Sawyer) and one Michigan county (Keweenaw), there are more seasonal than primary units (U.S. Census Bureau 2011).

Economic Sectors

Forest Products Industry

The forest products industry, much of which is supported by the heavily forested local land base rather than imports, is important throughout the assessment area, accounting for 5 percent of all jobs in 2009 (Headwaters Economics 2011). At the same time, recent economic conditions have resulted in reduced capacity or closings at many mills, leading to job losses. Within the assessment area, employment in the timber/forest products sector decreased by 36 percent between 1998 and 2009 (Headwaters Economics 2011). As fewer new residential homes are built or remodeling projects undertaken, the demand for solid wood panels and other building materials has plummeted (Smith and Guldin 2012). Across the northeastern United States alone, 505 sawmills have closed since 2005 (Smith and Guldin 2012). The number of active mills in Wisconsin has stayed fairly steady within the past decade, but the number of mills in Michigan decreased from 288 in 2004 to 201 in 2008 (Perry et al. 2012, Pugh et al. 2012).

Recreation

Many northern and rural counties depend on resource-based tourism (Stynes 1997), with 14.5 percent of the jobs in the assessment area being related to travel and tourism (Headwaters Economics 2011). Statewide in both Michigan and Wisconsin, popular recreational activities include walking and hiking, fishing, birdwatching, camping, boating, hunting, and swimming (MDNR 2012c). Many recreational opportunities are centered around water features (MDNR 2013, WDNR 2011). Participation in some recreational activities such as biking, cross-country skiing, and off-highway vehicle driving has increased over the past decade (MDNR 2013; WDNR 2006, 2011). Off-highway vehicle use, in particular, continues to grow rapidly in the assessment area. Snowmobiling remains popular, but demand for this recreational activity is declining due to fewer people taking up the activity and low snow levels in the past decade (WDNR 2006). Hunting is another important recreational activity in Michigan and Wisconsin. Although hunting participation has generally been decreasing regionally and nationally, due in part to land access and generational changes, there is some evidence that this decline may have recently slowed in Michigan (Cordell 2012, MDNR 2012c, WDNR 2011).

Agriculture

Agriculture is an important industry in Michigan and Wisconsin. The agricultural sector provided 33,740 on-farm jobs and more than $3 billion of farm business income to the assessment area in 2009 (Headwaters Economics 2011). Within the assessment area, 19.3 percent of the total land area is used for agriculture, with most of that acreage located at the southern portion of the assessment area (U.S. Geological Survey 2011, WDNR 1998a). Most of this acreage is dedicated to the production of hay and corn. Soybeans, wheat, oats, and barley are also common crops in the assessment area. Wisconsin is also the top producer of cranberries in the country, with 14,000 of the state's 17,700 acres of cranberry bogs located in the northern counties (National Agricultural Statistics Service 2009, WDNR 1998a).

FOREST ECOSYSTEMS

The assessment area is noted as a landscape of woods and water. Many forest communities, each with different characteristics, are represented in the area's 16 million acres of forest land (U.S. Forest Service 2013). Local factors, including landform, soils, climate, hydrology, and management history, result in a diversity of forest communities across the assessment area.

Forest Types Used in this Assessment

Different organizations describe forests using different classification systems. This assessment uses two classification systems (Table 2), which are useful 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.

Table 2.—Forest classification systems used in this assessment

FIA forest-type group	Forest type
Aspen/birch	Aspen-birch
Elm/ash/cottonwood	Jack pine
Exotic softwoods	Lowland conifer
Maple/beech/birch	Lowland hardwood
Oak/hickory	Northern hardwood
Oak/pine	Oak
Other eastern softwoods	Red pine
Other hardwoods	Upland spruce-fir
Spruce/fir	White pine
White/red/jack pine	

One system was created by the U.S. Forest Service, Forest Inventory and Analysis (FIA) program to characterize forests across the Nation. In this assessment, we describe acres, ownership category, and volume of timber using "forest-type groups" based upon the FIA classification system (Woudenberg et al. 2010). 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. In this assessment, FIA forest-type groups were used to provide quantitative data about forest conditions in the assessment area. Additionally, forest-type groups have been mapped for the assessment area and the Nation (Fig. 4).

Importantly, FIA forest-type groups are intentionally broad in order to characterize diverse forests across the country. For this reason, they are less useful to local natural resource managers and forest owners in describing the forests common in the assessment area. For example, the red/white/jack pine FIA forest-type group combines several unique forest communities that correspond to different site conditions, have different assemblages of tree species, and are subject to different types of natural disturbances and forest management activities; this grouping is too broad for use at a regional or local level. Throughout this assessment, we also used a classification of "forest systems" as the primary classification system whenever possible because these better describe the forest ecosystems present in the assessment area (Table 2). We developed this classification based upon the classification systems used by national forests, state agencies, and other forest management organizations in the assessment area. We also used these forest systems to assess forest vulnerability to climate change (Chapter 6).

Although these are different systems, there are many similarities. For example, the FIA maple/beech/birch forest-type group is largely synonymous with the northern hardwood forest system (though beech is present only on the far eastern extent of the assessment area), and the FIA elm/ash/cottonwood forest-type group includes forests comparable to the lowland hardwood forest system.

Forest Composition and Abundance

Several different kinds of forest are found across the 16 million acres of forest land in the assessment area (Fig. 4, Table 3). Maple/beech/birch (5.8 million acres) and aspen/birch (3.5 million acres) are the most abundant forest-type groups across the area (Table 3). More than half of the forest in the Upper Peninsula of Michigan is of the maple/beech/birch group, with aspen/birch and spruce/fir being the next most abundant. There is a more even distribution of forest-type groups across northern Wisconsin. Maple/beech/birch and aspen/birch forests each cover about a quarter of the forested land base in the Wisconsin portion of the assessment area. Elm/ash/cottonwood, oak/hickory, spruce/fir, and white/red/jack pine are also relatively common, with each making up about one-tenth of the forest land in northern Wisconsin. Differences between forest-type groups can influence the amount of carbon stored aboveground and belowground (Box 3).

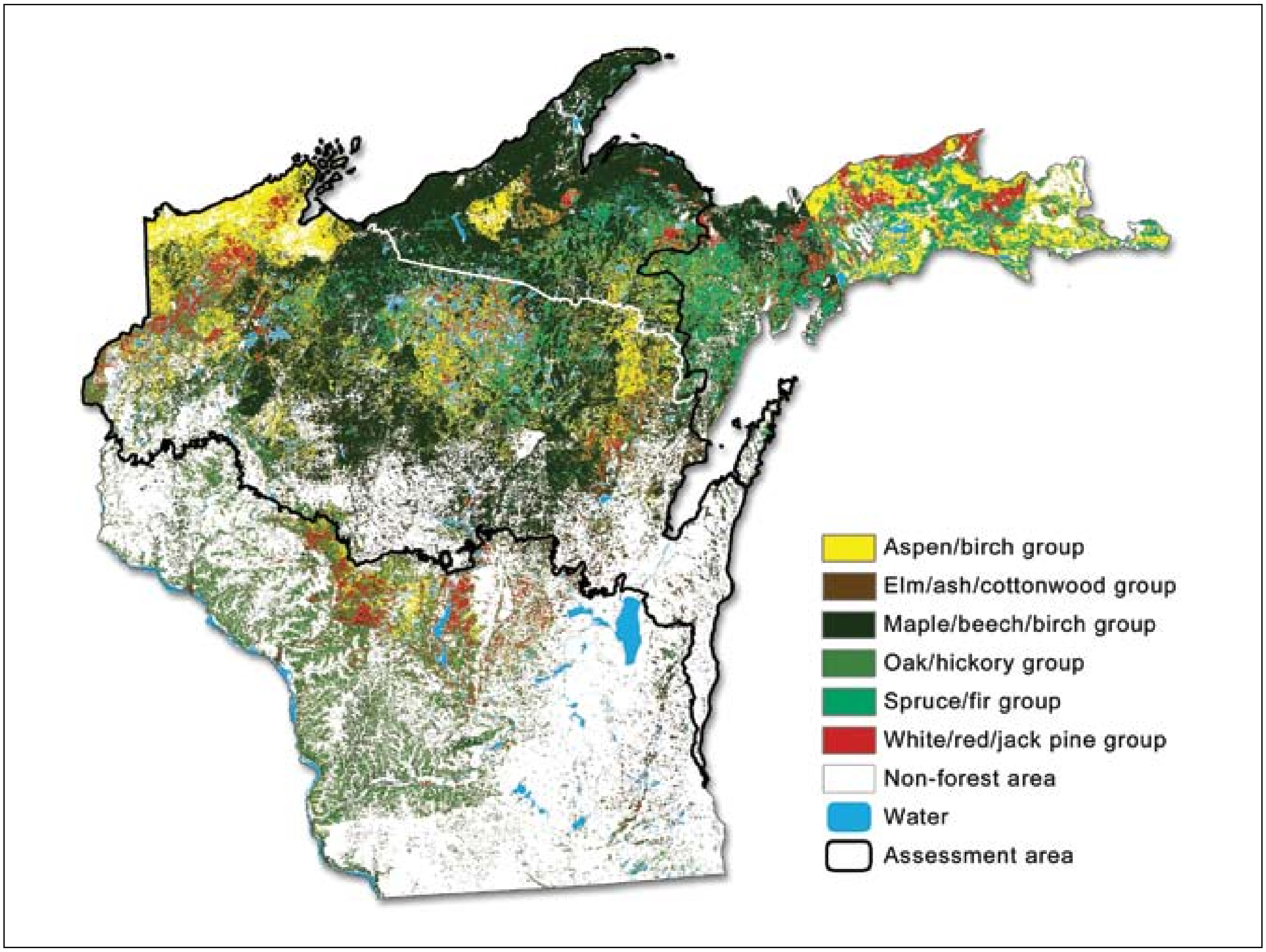


Figure 4.—Distribution of forest-type groups across the assessment area and surrounding region. Data source: U.S. Forest Service (2013).

Table 3.—Forest land (in acres and as a percentage of total forest land) in the assessment area by FIA forest-type groups (U.S. Forest Service 2013)

	Total assessment area		Assessment area (MI)		Assessment area (WI)	
FIA forest-type group[a]	Acres	Percent	Acres	Percent	Acres	Percent
Aspen/birch	3,473,558	21.7	761,823	16.9	2,711,735	23.5
Elm/ash/cottonwood	1,346,436	8.4	170,611	3.8	1,175,825	10.2
Exotic softwoods	25,644	0.2	11,797	0.3	13,847	0.1
Maple/beech/birch	5,826,887	36.3	2,525,778	56.0	3,301,109	28.6
Oak/hickory	1,571,067	9.8	68,701	1.5	1,502,366	13.0
Oak/pine	365,369	2.3	51,959	1.2	313,410	2.7
Other eastern softwoods	3,236	0.0	0	0.0	3,236	0.0
Other hardwoods	82,132	0.5	30,483	0.7	51,649	0.4
Spruce/fir	1,958,103	12.2	613,056	13.6	1,345,047	11.7
White/red/jack pine	1,267,350	7.9	272,116	6.0	995,234	8.6
Nonstocked	123,690	0.8	7,160	0.2	116,530	1.0
Total	16,043,474	100%	4,513,486	100%	11,529,988	100%

[a] Forest-type groups are used to present broad-scale information on forest trends based upon U.S. Forest Service, Forest Inventory and Analysis (FIA) data (Woudenberg et al. 2010). In this assessment, forest systems are often used to describe forest ecosystems as commonly grouped by local forest management organizations.

Box 3: Forest Carbon

Forest ecosystems around the world play a valuable role as carbon sinks. The accumulated terrestrial carbon pool within forest soils, belowground biomass, dead wood, aboveground live biomass, and litter represents an enormous store of carbon (Birdsey et al. 2006). Terrestrial carbon stocks in the region have generally been increasing for the past few decades (Rhemtulla et al. 2009), and there is increased attention on the potential to manage forests to maximize and maintain this carbon pool (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, climate variability, and forest stressors.

Forest lands within the assessment area are estimated to hold approximately 1.5 billion metric tons of carbon, or roughly 95 metric tons per acre. There is relatively little variation in carbon density across the different major forest ownership categories, ranging from 94 to 109 metric tons per acre across different land ownerships. Among different forest-type groups, however, there is greater variation in the amount of carbon stored per acre (Fig. 5). The spruce/fir forest-type group holds more carbon per acre than any other forest-type group, most of which is in the soil organic carbon pool. Maple/beech/birch forests tend to store the most aboveground carbon compared to other FIA forest-type groups.

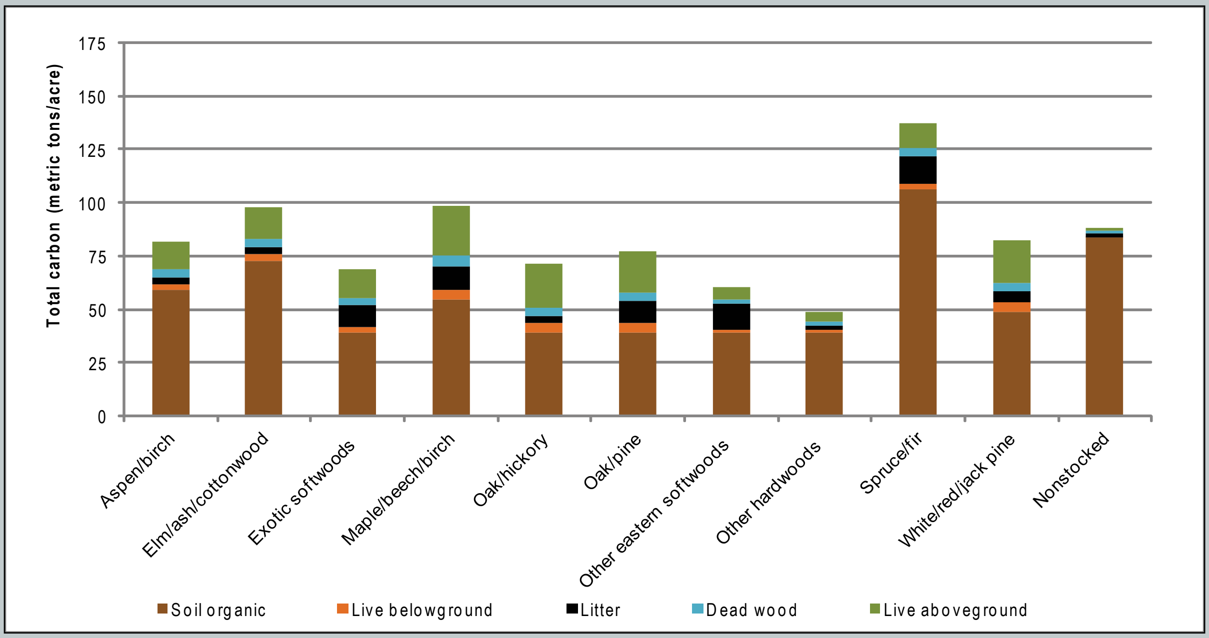


Figure 5.—Forest carbon density (metric tons per acre) by FIA forest-type group. Data source: U.S. Forest Service (2013).

Drivers of Change in Forest Ecosystems

Past Forest Ecosystem Change

Climatic changes occurring since the retreat of the glaciers about 10,000 years ago have influenced the migration and composition of the region's forests over time. During the early Holocene (about 10,000 years ago), regional forests underwent dynamic transformations, including species migration and forest succession, in response to climatic change and biological processes including species migration and forest succession. Most of the plant species present in the Lake States today had migrated into the region by 6,000 years ago, with hemlock and beech being among the most recent arrivals, about 2,000 to 3,000 years ago (Booth et al. 2012, Davis 1986). Beech is still slowly expanding westward (Bennett 1985, Burns and Honkala 1990) and other tree species distributions have continued to shift when measured at the scale of tens of thousands of acres. In addition to changes in distribution, the rate of succession and direction of compositional change have been influenced by glacial activity and the resulting landform and soil factors that influence moisture and nutrient availability (Host et al. 1987).

Before the 1850s, wind, fire, herbivory, insect infestation, and beaver activity were the primary natural drivers of change in the region's forests (Schulte and Mladenoff 2005). Intense wind events occurred more frequently than fires and affected a greater area than fires in all forest types across most of northern Wisconsin (Schulte and Mladenoff 2005). Fire events, both natural and human-caused, were most prevalent in fire-dependent forest types, such as jack, red, and white pine forests. Fire rotation periods estimated from Public Land Survey records suggest that a combination of frequent surface fire and less frequent stand-replacing fires constituted the natural fire regime (Schulte and Mladenoff 2005).

Profound changes occurred within the assessment area between the 1850s and the early 1930s, when Euro-American settlement and industrial logging began to greatly affect forests. Logging of eastern white pine began as early as the 1830s and peaked at the end of the 19th century. About the time pine logging was ending, removal of northern hardwoods began, followed by removal of hemlock for tannic acid, and cedar for fence posts and mine timbers. By the 1930s nearly all of the primary forest had been harvested or burned (Cleland et al. 2004). The amount and extent of slash left after logging fueled intense and catastrophic fires across most of the assessment area. Clearcutting, slash burning, and stream and river modifications during the logging era, combined with repeated cutting and intense wildfires, have resulted in long-term changes in the ecosystems within the assessment area. Long-lived conifers (e.g., hemlock, white pine, and northern white-cedar) have declined precipitously, often having been replaced by deciduous trees (Cleland et al. 2004). Pioneer tree species (e.g., aspen and cottonwood) represented no more than 5 percent of the northern hardwood forest before European settlement (Frelich and Lorimer 1991); in contrast, a single pioneer community, the aspen-birch forest-type group, currently occupies about 23 percent of the area (U.S. Forest Service 2013). Pine plantations have largely replaced pine barrens, and fire suppression has also allowed some successional advance of pine barrens to pine forests (WDNR 1995). Jack pine, aspen, oak, and maple forests have largely replaced white and red pine forests.

Natural Disturbance Regimes

Wind and fire events are still the primary natural disturbances influencing vegetation patterns in the assessment area, although anthropogenic disturbances are also major drivers of forest composition (Schulte and Mladenoff 2005, White and Mladenoff 1994). Wind and fire events can affect forest structure and composition on a broad spatial scale over time, although singular stand-replacing events are relatively rare (Canham and Loucks 1984). Logging that occurred from 1850 until the early 1900s was followed by frequent slash fires. Mature forests that were historically resistant to catastrophic fire or wind had many large trees and various size-class distributions. The second-growth forests that are managed today tend to remain young and even-aged. The return intervals of stand-replacing fires are approximately 6,500 years for sugar maple-basswood forests and 14,300 years for yellow birch-hardwood forests (Schulte and Mladenoff 2005). Fire-return intervals are about 10 times longer today than they were in pre-settlement times (Cleland et al. 2004).

Across most of the assessment area, small-scale blowdown events have been the primary natural disturbance agent. Windthrow events vary in extent and in the degree of tree mortality that they cause, in part because some tree species and age classes are more susceptible to windthrow (Rich et al. 2007). Return intervals for windthrow events vary geographically and have not been consistent over the past 40 years (Coniglio and Stensrud 2004).

Pests and Diseases

Insect and disease outbreaks have also influenced the vegetation of the assessment area (Pugh et al. 2012, WDNR 2007). Before European settlement, outbreaks were caused by native species. For example, outbreaks of jack pine budworm and spruce budworm have historically been an important agent of mortality for their host species (Bergeron and Leduc 1998, Fleming et al. 2002). More recently, insect and disease outbreaks have occurred at an increasing frequency as a consequence of introduction and establishment of nonnative insects and disease agents. For example, the emerald ash borer, a beetle that can cause nearly complete mortality of ash tree populations throughout the eastern United States, has been confirmed in the western Upper Peninsula and in northern Wisconsin near Green Bay. Outbreaks of the nonnative gypsy moth have caused widespread oak mortality, and fungal diseases such as oak wilt and butternut canker have resulted in tree mortality on smaller scales. Earthworm introduction has dramatically altered soil composition and structure and organic matter decay rates and processes, making seedbed and germination conditions less favorable for some native plants (Hale et al. 2006).

Nonnative Plant Species

Nonnative plant species have become an increasing concern across the assessment area because of their potential to outcompete native species and influence species interactions that are important to ecosystem function. Some nonnatives can establish more rapidly than native species, in part because native diseases or pests are not adapted to compete against them (Tu et al. 2001). Across the assessment area, numerous cooperative weed management areas have been established to control invasive plant species across political boundaries. Land management organizations in the assessment area have been actively combating the spread of nonnative, invasive plants (Table 4) with integrated pest management tools that include prescribed fire, mechanical treatments, and herbicide application.

Current Stressors and Threats

Each of the forest systems addressed in this assessment faces a particular suite of stressors and threats (Table 5). We define these as agents that tend to disrupt the natural functioning of forest ecosystems or impair forest health and productivity. This information is collected from published literature as well as from local forest managers. The impacts of particular stressors and threats are very dependent on local conditions and are not consistent across a landscape 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

Table 4.—Nonnative plant species that are present in the assessment area and being prioritized for control measures on National Forest lands

Woody shrubs	
	Asiatic honeysuckles
	Autumn olive
	Buckthorn
	Japanese barberry
	Oriental bittersweet vine**
	Siberian pea shrub**
Grasses	
	Common reed grass
	Reed canarygrass
Composites	
	Bull thistle
	Canada thistle
	European marsh thistle (swamp thistle)
	Spotted knapweed
Aquatic plants	
	Curly pondweed
	Eurasian water milfoil
Other herbaceous plants	
	Bishop's goutweed
	Brittle-stem hemp-nettle**
	Common mullein**
	Forget-me-not
	Garden (common) valerian*
	Garlic mustard
	Giant knotweed*
	Japanese knotweed
	Leafy spurge
	Purple loosestrife
	Tansy ragwort (stinking willie)*
	Wild chervil*
	Wild parsnip

*Species is a priority only on the Ottawa National Forest
**Species is a priority only on the Chequamegon-Nicolet National Forest

these landscape-level threats in isolation, because they have all interacted across the assessment area over 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 the region has been well documented, with the general outcomes being a transition to more early-succession forests with reduced structural, spatial, and species diversity (Dickmann and Leefers 2003). 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 forest ecosystems is 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 (Nowacki and Abrams 2008, Romano 2010).

Forest Wildlife

The assessment area is home to hundreds of native animal species, including more than 50 mammal species and approximately 250 bird species. A handful of mammal species have been extirpated from the assessment area, including woodland caribou, bison, and wolverine. Others have been reintroduced, or are returning by migration, including the moose, gray wolf, elk, fisher, and American marten.

The gray wolf population was eliminated from Wisconsin and decimated in Michigan through state bounty programs in the late 1950s and early 1960s. State and Federal protection as an endangered species has promoted a population rebound. From approximately 25 wolves in 1980, the population across the two states has grown to nearly 1,500 in the winter of 2011-12 (MDNR 2014, Wydeven et al. 2011), with the majority of packs located in the northernmost forests.

Table 5.—Current major stressors and threats for forest systems in the assessment area

Community	Major current stressors and impacts	Reference
Aspen-birch Stands are dominated by quaking aspen, bigtooth aspen, paper birch, or balsam poplar. Some stands may have co-dominant tree species such as balsam fir or white spruce.	**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 2011a; Pugh et al. 2009, 2012; Romano 2010; Wisconsin Department of Natural Resources 2012)
	Forest diseases such as hypoxylon canker, *Armillaria*, and white trunk rot lead to damage and mortality.	(Burns and Honkala 1990, Romano 2010, Weber et al. 2007, Wisconsin Department of Natural Resources 2013)
	Excessive drought causes reduced growth or mortality.	(Auclair et al. 2010, Cornett et al. 2000b, Hanson and Weltzin 2000, Nowacki and Abrams 2008, Wisconsin Department of Natural Resources 2005, Worrall et al. 2013)
	Deer herbivory results in reduced growth and mortality of seedlings and saplings of target browse species.	(Cornett et al. 2000a, Côté et al. 2004, Waller and Alverson 1997, Weber et al. 2006, Wisconsin Department of Natural Resources 2013)
Jack pine Stands are generally dominated by jack pine, with some composed primarily of mixed pine species or occasionally Scotch pine. Oak species may be co-dominant in some stands.	**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 2002a, Nowacki and Abrams 2008, Wisconsin Department of Natural Resources 2012)
	Insect pests such as jack pine budworm, white pine tip weevil, pine tussock moth, and bark beetles cause reduced growth or mortality of target species.	(Michigan Department of Natural Resources 2011a, Pugh et al. 2009, 2012; Wisconsin Department of Natural Resources 2013)
	Diseases such as *Armillaria* and scleroderris lead to damage and mortality.	(Burns and Honkala 1990)
	Limited ability to apply prescribed fire makes it difficult to simulate natural fire regimes.	(Cohen 2002a, Nowacki and Abrams 2008)
	Past management practices have led to reduced age class diversity across the landscape and a concentration of trees in young age classes.	(Wisconsin Department of Natural Resources 2012, 2013)

(Table 5 continued on next page)

Table 5 (continued).

Community	Major current stressors and impacts	Reference
Lowland conifers Stands are in low-lying sites and are dominated primarily by black spruce, northern white-cedar, tamarack, or a mixture of these species. Quaking aspen, paper birch, and other species may be co-dominant in some stands.	**Road or ditch building** leads to altered drainage patterns.	(Cohen 2006, Kost 2002, Swanson and Grigal 1991, Wisconsin Department of Natural Resources 2013)
	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)
	Insect pests such as tamarack sawfly, larch case bearer, eastern larch beetle, and spruce budworm cause reduced growth or mortality of target species.	(Cohen 2002b; Michigan Department of Natural Resources 2011a; Pugh et al. 2009, 2012; Kost 2002; Wisconsin Department of Natural Resources 2012)
	Diseases such as mistletoe lead to damage and mortality.	(Baker et al. 2012)
	Invasive plants such as reed canarygrass, 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; Wisconsin Department of Natural Resources 2012)
	Deer herbivory results in reduced growth and mortality of seedlings and saplings of target browse species.	(Cornett et al. 2000a, Côté et al. 2004, Rooney et al. 2002, Waller and Alverson 1997, Wisconsin Department of Natural Resources 2012)
	Past management practices removed coarse woody debris, reduced species diversity, or led to alder encroachment.	(Cohen 2006, Kost 2002)
	Excessive drought causes reduced growth or mortality.	(Cornett et al. 2000b, Hanson and Weltzin 2000, Kost 2002, Swanson and Grigal 1991, Wisconsin Department of Natural Resources 2005)
Lowland-riparian hardwoods Stands are in low-lying sites and are dominated primarily by black ash, red maple, American elm, or a mixture of these species.	**Altered hydrologic regimes** lead to excessively wet or dry soils 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, Wisconsin Department of Natural Resources 2013)
	Ash decline causes reduced growth, crown dieback, or mortality of ash species.	(Benedict and Frelich 2008, Palik et al. 2011, Weber et al. 2007, Tepley et al. 2004)
	Invasive plants such as reed canarygrass, Japanese barberry, 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 2011a; Pugh et al. 2009, 2012; Slaughter et al. 2007, Tepley et al. 2004; Weber et al. 2007)
	Diseases such as mistletoe lead to damage and mortality.	(Baker et al. 2012)
	Excessive drought causes reduced growth or mortality.	(Hanson and Weltzin 2000, Slaughter et al. 2007, Wisconsin Department of Natural Resources 2005)
	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, Wisconsin Department of Natural Resources 2013)

(Table 5 continued on next page)

Table 5 (continued).

Community	Major current stressors and impacts	Reference
Northern hardwoods Forests are composed largely of sugar and red maple. Eastern hemlock, yellow birch, basswood, red oak, and black cherry are common associates, found in varying amounts based upon site conditions.	**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, Pennsylvania sedge, Japanese barberry, 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; Wisconsin Department of Natural Resources 2004, 2010a)
	Insect pests such as emerald ash borer, forest tent caterpillar, gypsy moth, and white pine tip weevil cause reduced growth or mortality of target species.	(Michigan Department of Natural Resources 2011a; Pugh et al. 2009, 2012; Wisconsin Department of Natural Resources 2013)
	Diseases such as beech bark disease, white pine blister rust, and *Armillaria* lead to damage and mortality.	(Michigan Department of Natural Resources 2011a; 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; Wisconsin Department of Natural Resources 2012, 2013)
	Excessive drought dries ephemeral ponds and causes reduced growth or mortality.	(Auclair et al. 2010; Hanson and Weltzin 2000; Mladenoff and Stearns 1993; Rooney et al. 2000; Swanson and Grigal 1991; Wisconsin Department of Natural Resources 1995, 2005, 2013)
	Deer herbivory results in reduced growth and mortality of seedlings and saplings of browsed species.	(Cornett et al. 2000a, Côté et al. 2004, Powers and Nagel 2009, Rooney and Waller 2003, Waller and Alverson 1997)
	Past management practices removed coarse woody debris, reduced species diversity, simplified forest structure, or altered species composition.	(Cohen 2000, Crow et al. 2002, Powers and Nagel 2009, Wisconsin Department of Natural Resources 2013)

(Table 5 continued on next page)

Table 5 (continued).

Community	Major current stressors and impacts	Reference
Oak Stands are dominated by one or more oak species. Aspen, eastern white pine, and other species may be co-dominant in some stands.	**Suppression of natural fire regimes** has reduced structural and species diversity, allowed mesic hardwood encroachment on many sites, and limited suitable conditions for natural regeneration.	(Cleland et al. 2004, Cohen 2001, Courteau et al. 2006, Nowacki and Abrams 2008, Nowacki et al. 1990)
	Limited ability to apply prescribed fire makes it difficult to simulate natural fire regimes.	(Cohen 2001, Courteau et al. 2006, Nowacki and Abrams 2008)
	Diseases such as oak wilt, oak decline, gypsy moth, and two-lined chestnut borer cause reduced growth, crown dieback, or mortality of oak species.	(Courteau et al. 2006; Michigan Department of Natural Resources 2011a; Pugh et al. 2009, 2012; Wisconsin Department of Natural Resources 2013)
	Deer and rabbit herbivory results in reduced growth and mortality of seedling and saplings of target browse species.	(Alverson et al. 1988, Côté et al. 2004, Courteau et al. 2006, Waller and Alverson 1997)
	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, 2012b)
	Excessive drought causes regeneration failure or mortality.	(Radeloff et al. 1999; Wisconsin Department of Natural Resources 2005, 2012)
	Soil frost damages roots and new growth, and may cause crown dieback or widespread decline of oak species.	(Burns and Honkala 1990)
Red pine Stands are dominated by red pine. Some stands have an oak component in the understory and sometimes as a co-dominant.	**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 2002a, 2002b; Nowacki and Abrams 2008; Radeloff et al. 1999)
	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 insect pests.	(Michigan Department of Natural Resources 2011a; Munck et al. 2009; Pugh et al. 2009, 2012; Stanosz et al. 2001)
	Invasive plants such as spotted knapweed and Japanese barberry reduce suitable conditions for natural regeneration, facilitate other exotic species, and alter understory plant communities.	(Powers and Nagel 2009; Pugh et al. 2009, 2012; Wisconsin Department of Natural Resources 2004, 2013)
	Diseases such as white pine blister rust, red pine shoot blight, and *Armillaria* lead to damage and mortality.	(Burns and Honkala 1990)
	Excessive drought causes reduced growth or mortality.	(Hanson and Weltzin 2000; Rogers et al. 2008; Wisconsin Department of Natural Resources 2005, 2013)
	Deer herbivory results in reduced growth and mortality of seedlings and saplings of target browse species.	(Cohen 2002a, Côté et al. 2004, Waller and Alverson 1997)

(Table 5 continued on next page)

Table 5 (continued).

Community	Major current stressors and impacts	Reference
White pine Stands are dominated by eastern white pine. Some stands may include a component of eastern hemlock or northern red oak and white ash.	**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 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 insect pests.	(Michigan Department of Natural Resources 2011a; Munck et al. 2009; Pugh et al. 2009, 2012; Stanosz et al. 2001; Wisconsin Department of Natural Resources 2013)
	Diseases such as white pine blister rust, red pine shoot blight, and Armillaria lead to damage and mortality.	(Burns and Honkala 1990, Wisconsin Department of Natural Resources 2013)
	Deer herbivory results in reduced growth and mortality of seedlings and saplings of target browse species.	(Cohen 2002b, Côté et al. 2004, Waller and Alverson 1997)
Upland spruce-fir Stands are generally dominated by white spruce (occasionally black spruce or Norway spruce). Some stands may have co-dominant tree species such as balsam fir or quaking aspen.	**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 2011a; Pugh et al. 2009, 2012; Wisconsin Department of Natural Resources 2013)
	Excessive drought causes reduced growth or mortality.	(Cornett et al. 2000b; Hanson and Weltzin 2000; Wisconsin Department of Natural Resources 2005, 2013)
	Deer and moose herbivory results in reduced growth and mortality of seedlings and saplings of target browse species.	(Cohen 2007, Côté et al. 2004, Waller and Alverson 1997)

American marten in western Upper Michigan. Photo by Scott Pearson, used with permission.

Moose populations disappeared from the area by the 1890s, largely due to hunting pressure and habitat change following increased settlement of the area (Beyer et al. 2011). Moose were reintroduced to the western Upper Peninsula from Ontario in 1985 and 1987 and have successfully grown from 59 individuals to a population of about 430 in January 2011 (Beyer et al. 2011). A reintroduction of 25 elk in 1995 into the Clam Lake area of Wisconsin (Ashland County) has resulted in somewhat slower population growth; there were approximately 130 in the summer of 2009 (Stowell and McKay 2009). Vehicle collisions, accidental shooting by hunters, and predation by wolves are leading mortality factors for elk.

Fishers, one of the largest members of the weasel family, were extirpated from the assessment area in the early 1900s following widespread logging and over-trapping. After reintroduction in the 1950s and 1960s, the population expanded rapidly in the 1980s (Kohn et al. 1993), and the trapping of fisher across the assessment area resumed in the 1980s and continues today. American marten also were extirpated from the assessment area after the logging era, but reintroduction efforts have not been as successful. The species remains protected from trapping in Wisconsin despite population sizes sufficient to allow harvesting in neighboring Minnesota and Michigan (Skalski et al. 2011, Williams et al. 2007). The Michigan population has been slowly expanding its range and has supported a modest recreational trapping season since 2000 (Skalski et al. 2011).

White-tailed deer are perhaps the wildlife species of highest recreational interest across the assessment area. Deer hunting is a strong tradition throughout the region (Willging 2008). The 2010 post-hunt white-tailed deer population in the northern forest region of Wisconsin was an estimated 341,300 animals, 32 percent higher in 2010 than in 2009 and 12 percent above the goal in 2010 (Rolley 2010). The long-term goal is to maintain a population of 270,000 animals, which is 70 percent of the carrying capacity (WDNR 1998b). Across the western Upper Peninsula, deer density is generally lower than in northern Wisconsin, due in part to the deeper snowpack and less agriculture (MDNR 2010). Currently, white-tailed deer in the western Upper Peninsula are managed based on deer population trends, with current deer populations generally trending downward (C. Albright, MDNR, pers. commun.). Deer have been called a keystone species due to their profound effect on forest structure and composition through their browsing patterns (Côté et al. 2004, Waller and Alverson 1997). Chronically high deer populations can suppress the regeneration of some tree species and can result in lower diversity of the whole forest community (Rooney and Waller 2003, Waller 2007).

Populations of the snowshoe hare naturally fluctuate, peaking every 7 to 10 years (Shefferly 2007). It is an important herbivore and key prey species for many predators across the assessment area. Primarily a boreal species, it occurs at the southern edge of its range in the assessment area (Shefferly 2007). The reddish brown or gray fur of the snowshoe hare species molts to white during the winter (Kuvlesky and Keith 1983) and reduced snow cover may increase vulnerability to predation.

Ruffed grouse is a popular game bird across the assessment area. At the time of European settlement, it was thought to be common in most areas (Schorger 1945). After the logging era, regenerating forests in central and northern Wisconsin provided high-quality grouse habitat (Schorger 1945). The relationship between aspen acreage, particularly 7- to 25-year-old aspen, and grouse numbers (McCaffery et al. 1997) suggests that decreasing grouse populations may be the result of declines in aspen acreage (Perry et al. 2008).

Beaver were hunted and trapped heavily for their pelts during European settlement and their population was dramatically reduced by 1900. Restricted trapping and favorable habitat changes resulted in a rapidly growing beaver population, and from 1940 to 1960 the population (120,000 to 170,000 individuals in northern Wisconsin) may have exceeded the historical level (Knudsen 1963). Beaver populations peaked again in 1995 at 126,000, but are now on the decline throughout northern Wisconsin, with only 45,000 reported in 2008 (Rolley et al. 2008). Similar declining trends are evident in the western Upper Peninsula.

Brook trout is the only trout native to streams in the assessment area. The introduction of nonnative trout (e.g., brown and rainbow), habitat alteration by beaver and by humans, and heavy fishing pressure in some areas have caused declines in the distribution, numbers, and sizes of brook trout since European settlement (Becker 1983). Brook trout is often considered an indicator species for coldwater communities because of its sensitivity to water temperature.

Breeding bird surveys conducted over roughly 20 years across the national forests have recorded the presence of approximately 175 species on the Chequamegon-Nicolet National Forest and 140 species on the Ottawa National Forest (Etterson et al. 2007, Howe and Roberts 2005, Johnson 2004). Both positive and negative trends in abundance have been observed for some of those species. The declines in abundance observed for some species are often attributed to loss or fragmentation of mature forest (no such trend revealed with Ottawa National Forest data), loss of habitat in wintering areas, mortality during migration, and pesticide use on wintering grounds. For example, several species associated with early successional, wetland, and shrub habitats have declining populations, such as red-winged blackbird, common yellowthroat, mourning warbler, and brown thrasher.

Hermit thrush nest and eggs. Photo by Scott Pearson, used with permission.

FOREST OWNERSHIP AND USE

Ownership

There are numerous types of forest landowners within the assessment area (Fig. 6). About one-third of the forest land in the assessment area is publically owned, which includes Federal, State, and local ownership. The U.S. Forest Service owns approximately 2 million acres when the Chequamegon-Nicolet and Ottawa National Forests are combined. State ownership accounts for more than a million acres, with the part of the assessment area in Michigan having a somewhat greater proportion of state-owned forest land compared to Wisconsin (12 percent in Michigan vs. 7 percent in Wisconsin). County and municipal governments own more than 2 million acres, nearly all of which is held by Wisconsin county governments.

Most of the forest land, covering 10 million acres or about two-thirds of the assessment area, is privately held (Box 4). This category reflects a diversity of landowner types, including industrial and corporate entities, conservation organizations, families, individuals, and tribes. As a result, private ownership patterns are complex and change over time. For example, in recent decades a substantial amount of forest owned by the forest products industry has been sold to other corporate owners, largely through sales of company lands to real estate investment trusts (REITs) and timber investment management organizations (TIMOs) (Pugh et al. 2012, WDNR 2012). Across Wisconsin, the amount of land owned by forest product companies fell from 62 percent of private lands to 24 percent between 2002 and 2008 (WDNR 2012). A similar transition is taking place in the western Upper Peninsula; more than 1 million acres of industry-owned lands were sold to REITs or TIMOs in 2005 and 2006 alone (Froese et al. 2007).

Forest Harvest and Products

As mentioned above, forest industry is a major economic contributor in the region. In 2009, Michigan and Wisconsin produced 319 million and 261 million cubic feet of industrial roundwood, respectively, across the entire state (Perry et al. 2012, Pugh et al. 2012). This material includes saw logs, veneer logs, pulpwood, and other wood products used by wood processing mills within the region, and most of this wood is from hardwood species. In both states, more than half of this roundwood is in the form of pulpwood; this proportion is somewhat higher in Wisconsin (Perry et al. 2012, Pugh et al. 2012), reflecting the greater importance of the pulp

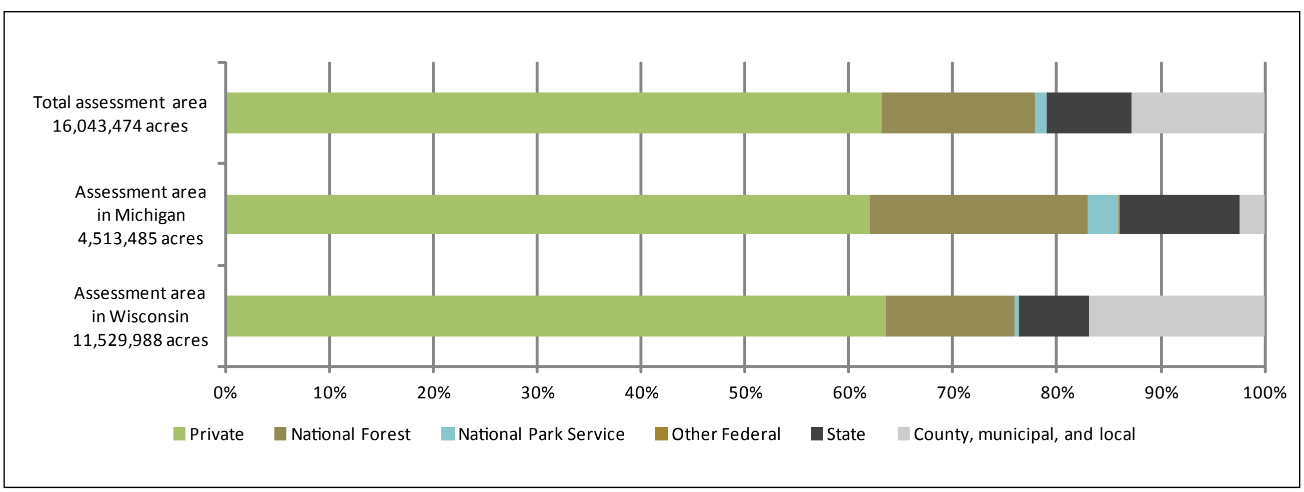


Figure 6.—Forest land ownership in the assessment area, as a proportion of total forest land. Data source: U.S. Forest Service (2013).

Box 4: Forest Management Takes Many Forms

Family forest owners were asked about their reasons for owning forest land as part of the National Woodland Owner Survey (Butler 2008). The top reasons that most families acquired or retained forest lands include: scenic quality, nature protection, privacy, family legacy, hunting or fishing, land investment, or other recreation activities (Butler 2008). Less than 8 percent of families owned forest for the primary purposes of firewood production, timber production, or the collection of nontimber forest products. Family owners can enroll their lands in conservation easements or forest certification programs such as the American Tree Farm System, which require forests to have written management plans. Engaged family forest owners often look to extension agents, Conservation Districts, and private consultants to provide technical assistance and other resources for managing forests.

Industrial forest land owners manage for timber products. Many industrial forest land owners voluntarily participate in third-party certification, but millions of acres of corporate land has been transferred to real estate investment trusts (REITs) and timberland investment management organizations (TIMOs) in the last decade (Froese et al. 2007). Considered private (nonindustrial) forest landowners, REITs and TIMOs have been acquiring much land and receiving substantial attention in the last 20 years. REITs own and operate income-producing real estate and timberland holdings, sometimes made public through trading of shares on a stock exchange. REITs are required to distribute at least 90 percent of taxable income to shareholders annually, which is an allowable deduction from corporate taxable income. TIMOs act as investment managers for institutional clients, who own the timberlands as investments or partnership shares (Fernholz et al. 2007) with the goal of maximizing growth of the timberland asset. In contrast with corporate holdings, the risk of large investment losses is spread out among investors, as are the frequency and rate at which capital gains are taxed. The purchase of timberland by REITs and TIMOs raises concerns about parcelization, development, and high-yield management practices (Fernholz et al. 2007).

Public (Federal, State, and county) agencies and tribal organizations own extensive tracts of forest in the assessment area. These lands are often managed to provide many benefits, often including wildlife habitat, water protection, nature preservation, timber production, recreation, cultural resources, and a variety of other uses (Pugh et al. 2012).

and paper industry in Wisconsin (Prentiss & Carlisle 2008, WDNR 2012). In both states, about one-third of the roundwood produced is saw log products.

The amount of wood harvested annually in Michigan and Wisconsin is less than the amount that is grown each year, suggesting that the harvest of timber products is biologically sustainable (Perry et al. 2012, Pugh et al. 2012). The net annual growth-to-removal ratio is based upon FIA data and provides a primary measure of sustainability. This ratio compares net growth (i.e., gross growth minus mortality) to removals from forest management for forested lands; values greater than 1.0 indicate that net annual growth is greater than annual removals and that the removal rate is sustainable (Perry et al. 2012). Across all ownership classes in the assessment area, the growth-to-removal ratio was 1.6 for the most recent inventory period (2008 through 2012), meaning that growth was more than 50 percent greater than removals (Table 6).

The FIA data also provide more information about the amount of wood removed from forests in the assessment area through timber harvest or conversion of forest to nonforest, with the vast majority of removals in this region being due to timber harvest. Among the major forest-type groups,

Table 6.—Net growth and removals and the growth-to-removal ratio for forest-type groups in the assessment area (U.S. Forest Service 2013)

Forest-type group	Annual net growth (cubic feet)	Annual removals (cubic feet)	Annual net growth : removals
Aspen/birch	86,496,227	62,698,908	1.4
Elm/ash/cottonwood	35,855,663	8,659,921	4.1
Exotic softwoods	2,309,062	0	n/a
Maple/beech/birch	173,827,074	122,088,446	1.4
Oak/hickory	44,475,288	39,294,233	1.1
Oak/pine	18,947,689	3,056,096	6.2
Other hardwoods	463,509	3,299,590	0.1
Spruce/fir	40,465,110	10,241,705	4.0
White/red/jack pine	79,064,680	34,794,979	2.3
Other*	433,437	9,923,185	0.0
Total	482,337,739	294,057,063	1.6

* “Other” represents estimated net growth and removals for lands converted from forest to nonforest.

oak/pine had the highest growth-to-removal ratio (6.2), and elm/ash/cottonwood, spruce/fir, and white/red/jack pine forests all had higher ratios than the assessment area average. The only forest-type group with a ratio less than 1.0 was the other hardwoods group, which represents only one-half of 1 percent of forest land in the assessment area. Removals from forest management and timber harvest in the assessment area were greatest in the most commercially important forest-type groups: maple/beech/birch (42 percent of total removals), aspen/birch (21 percent), oak/hickory (13 percent), and white/red/jack pine (12 percent).

Programs for Private Landowners

Both states offer incentives to private forest landowners, with the intent of maintaining larger parcels of privately owned forest and promoting sustainable production of forest products. The Commercial Forest (CF) program in Michigan provides a property tax reduction to private landowners as an incentive to keep and manage land as commercial forest land. There are currently almost 1.6 million acres enrolled in the CF program in the western Upper Peninsula, which accounts for more than half of the 2.2 million CF acres statewide (MDNR 2012a). Land enrolled in the CF program is required to be open to the public for hunting, trapping, and fishing. More recently, the Qualified Forest (QF) program was developed, which also provides tax benefits to private landowners without the requirement for public access.

In Wisconsin, two programs provide tax relief to qualified forest landowners. The Forest Crop Law program was enacted in 1927 as a means to promote private forestry. Enrollment closed in 1986, when the Managed Forest Law (MFL) program was started, and the last participant contracts will expire in 2034 (Wisconsin Department of Revenue 2009). Within the assessment area, 210,767 acres are enrolled in the Forest Crop Law program, which is approximately 80 percent of the total enrollment within the state (WDNR 2003, 2012). The Managed Forest Law is a property tax reduction program for landowners with 10 acres or more. Landowners are required to develop and implement comprehensive Forest Stewardship Plans which are a prerequisite for Federal cost-sharing assistance. There were 2,293,205 acres in the assessment area participating in the MFL program as of 2009, which represents nearly all of the acres enrolled statewide (P.E. Pingrey, Forest Stewardship Council, pers. commun.). In the last decade, the number of enrollments has more than doubled, which means that more management plans have been written for small parcels (WDNR 2012). Although public access is often allowed on enrolled lands, many newly enrolled owners do not permit public access (Wisconsin Council on Forestry 2006).

Forest Certification

Forest certification is a process designed to ensure that forest products originate from forests that are sustainably managed. In both Wisconsin and Michigan, forest lands are certified through several systems, including the Forest Stewardship Council (FSC), the Sustainable Forestry Initiative (SFI), and the American Tree Farm System (ATFS). Across the entire state, about 42 percent (7.0 million acres) of forest land is certified in Wisconsin and approximately 31 percent (6.1 million acres) of forest land is certified in Michigan (Table 7). In 2005, Wisconsin's Managed Forest Law program received third-party forest certification under ATFS, making it the largest group-certification program usable by private landowners in North America, with 2.2 million acres enrolled in northern Wisconsin (P.E. Pingrey, Forest Stewardship Council, pers. commun.; Wisconsin Council on Forestry 2006).

Table 7.—Forest land (in thousand acres) enrolled in forest certification programs (P. Pingrey and S. Robbins, pers. commun.)

	Forest land enrolled in certification program (thousand acres)				
	Forest Stewardship Council (FSC)	Sustainable Forestry Initiative (SFI)	American Tree Farm System (ATFS)	Dual-certified (FSC & SFI)	Dual-certified (ATFS & FSC)
Michigan					
State of Michigan	0	4,200	0	0	0
Industry/REIT/TIMO	584	1,125	0	0	0
Private/nongovernment	0	0	235	0	0
Wisconsin					
State of Wisconsin	0	57	0	1,541	0
County	166	724	0	1,465	0
Industry/REIT/TIMO	354	282	0	5	0
Private/nongovernment	0	0	194	0	2,239

CHAPTER 2: CLIMATE CHANGE SCIENCE AND MODELING

This chapter provides a brief background on climate change science, models that simulate climate, and models that project the effects of changes in climate on species and ecosystems. Throughout the chapter, boxes point to recent 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) reports (IPCC 2007a, 2013), the National Climate Assessment (Melillo et al. 2014), and the whitepaper contributions to the Midwest Chapter of the 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 (2007a: 30, 2013) defines climate change as "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." A key finding of the IPCC in its Fourth Assessment Report (2007a) 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. Additional assessments are underway internationally, nationally, and regionally to provide updated information regarding the potential effects of climate change. Selected global and national assessments are listed in Box 5.

The Warming Trend

The Earth is warming, and the rate of warming is increasing (IPCC 2007a, 2013). 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. 7) (IPCC 2007a), although annual and decadal fluctuations do occur (Box 6). The first 12 years in the 21st century rank among the warmest 14 years in the 133-year period of record of global temperature (NOAA National Climatic Data Center 2012). The average temperature across the entire United States has risen by 1 to 2 °F (0.6 to 1.1 °C) in the last 50 years (Karl et al. 2009). The year 2012 ranked as the warmest on record in the United States, 1.0 °F (0.6 °C) warmer than the previous record year of 1998 and 3.3 °F above the 20th-century average (NOAA National Climatic Data Center 2013).

Average temperature increases are simplifications of a more complex pattern of regional and seasonal climatic changes. For example, the frequency of cold days, cold nights, and frosts has decreased over many regions of the world while the frequency of hot days and nights has increased (IPCC 2007a). Within the United States, 356 all-time high

Box 5: Global and National Assessments

Intergovernmental Panel on Climate Change

The Intergovernmental Panel on Climate Change (IPCC; 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 The U.S. Global Change Research Program (USGCRP; www.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 a number of national synthesis reports on climate change in the United States, which are available for download at the Web addresses below.

National Climate Assessment

http://nca2014.globalchange.gov/downloads

Global Change Impacts on the United States

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

Synthesis and Assessment Products

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

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

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)

http://glisa.msu.edu/resources/nca

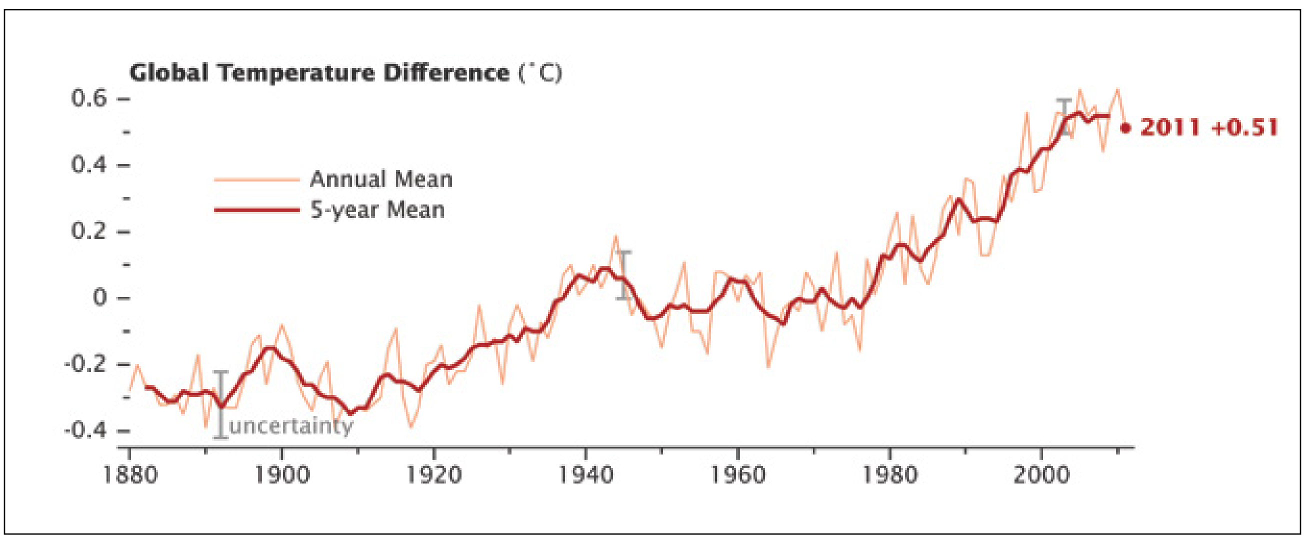


Figure 7.—Trends in global temperature compared to the 1951 through 1980 mean. Data source: NASA Goddard Institute for Space Studies. Image courtesy of NASA Earth Observatory, Robert Simmon; www.giss.nasa.gov/research/news/20120119/.

Box 6: Is the Climate Cooling?

Global temperature trends during the 2000s generated some discussion about climatic change in the popular media. Lines plotted through specific subsets of years during this period appear to have negative or flat slopes, leading some to conclude that warming has slowed, stopped, or reversed since 1998 (Easterling and Wehner 2009, Knight et al. 2009). Trends over such a short period should be interpreted with great caution, however, because meaningful global trends need to be calculated over a multi-decadal period in order to account for natural annual variation in the Earth's climate (Easterling and Wehner 2009, IPCC 2007b). Global mean temperature can increase or decrease from year to year because of volcanic eruptions, solar activity, and large-scale ocean circulation patterns like El Niño. Since 1880 there have been several 5- to 10-year periods during which trends appeared to be flat or even decreasing, including a long, level period from the 1940s to the 1970s. Nonetheless, the overall trend has been increasing over the last century, and recent decades are clearly warmer than preceding decades (Fig. 7). In fact, the NASA Goddard Institute for Space Studies (2010) ranked the decade from January 2000 to December 2009 as the warmest decade observed since recording began in 1880. Information from multiple years, data sets, and organizations provides no valid statistical evidence for long-term global cooling, and the weight of evidence still supports a long-term trend of global warming.

temperature records were broken in 2012, compared to only 4 all-time low temperature records (NOAA National Climatic Data Center 2013). There is also strong evidence that the frequency of heat waves and heavy precipitation events has increased over this period (IPCC 2012, 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 2007a).

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. The end of the last ice age, roughly 10,000 years ago, was triggered by a global warming on the order of 5.4 to 9 °F (3 to 5 °C) (Annan and Hargreaves 2013, Shakun and Carlson 2010, Shakun et al. 2012). Further, 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: 12). Temperature increases above 3.6 °F (2 °C) 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 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. 8). The greenhouse 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. Several naturally occurring gases in the atmosphere, including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and water vapor, contribute to the greenhouse effect. 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 emissions of CO_2, CH_4, and N_2O since the beginning of the industrial era (Fig. 9) and perhaps even earlier (Ruddiman 2003, 2013), leading to an enhanced greenhouse

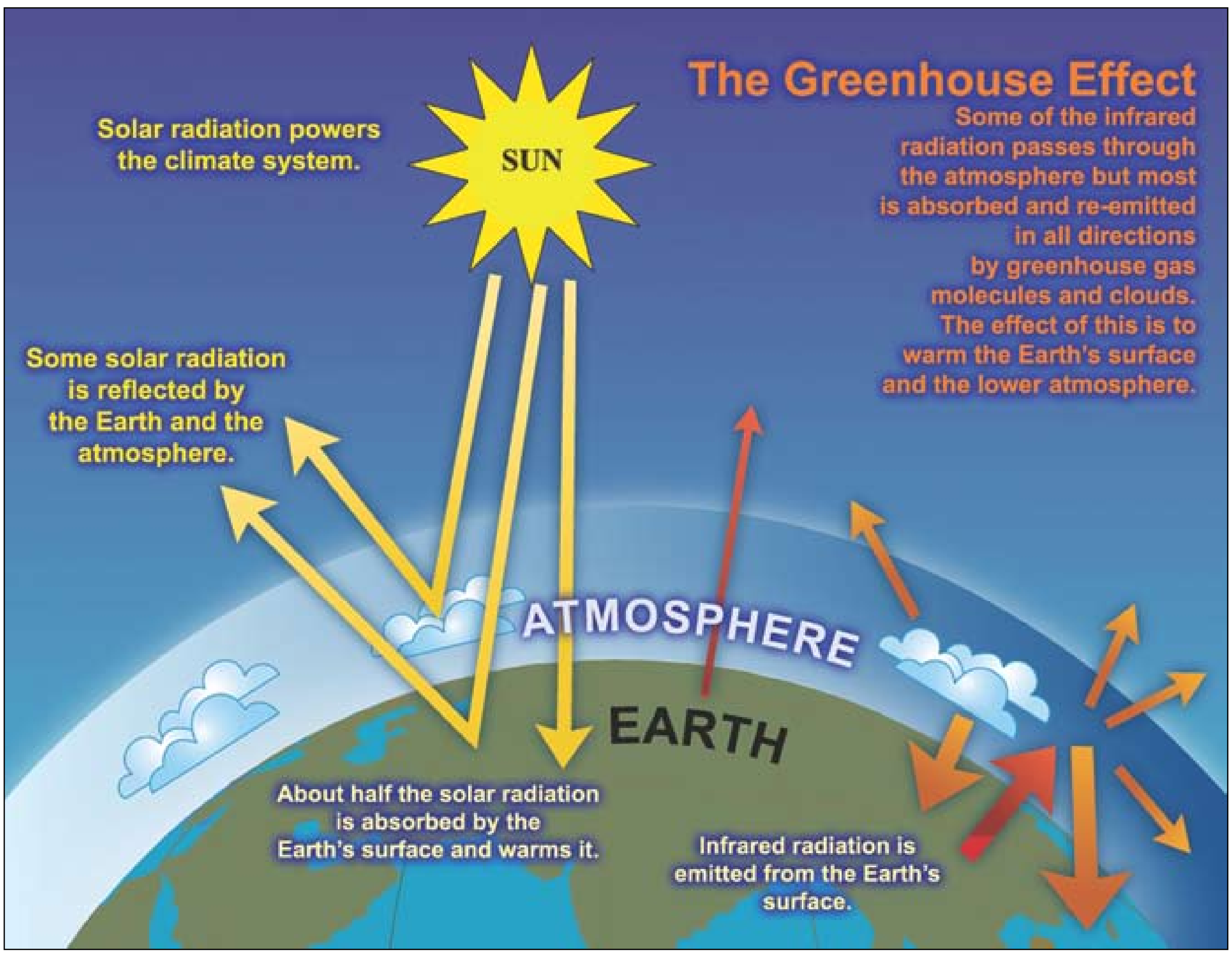


Figure 8.—Idealized model of the natural greenhouse effect. Figure courtesy of IPCC (2007).

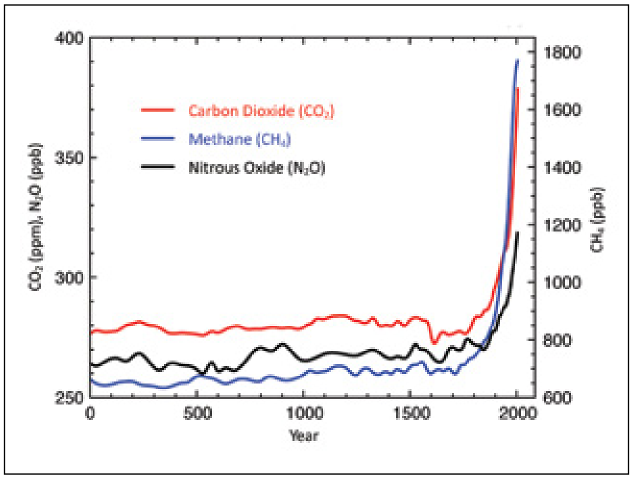


Figure 9.—Concentrations of greenhouse gases over the past 2005 years, showing increases in concentrations since 1750 attributable to human activities in the industrial era. Concentration units are parts per million (ppm) or parts per billion (ppb), indicating the number of molecules of the greenhouse gas per million or billion molecules of air. Figure courtesy of IPCC (2007).

effect. More CO_2 has been released by humans into the atmosphere than any other greenhouse gas. Carbon dioxide levels have been increasing at a rate of 1.4 parts per million (ppm) per year for the past 50 years (IPCC 2007a), 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 the greenhouse gas effect (IPCC 2007a). Concentrations of this gas have also been increasing as a result of human activities, including production of livestock and of rice. Livestock production contributes 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.

Nitrous oxide accounts for about 8 percent of the global greenhouse gas effect (IPCC 2007a). The primary human source of N_2O is agriculture. Using more fertilizer increases 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 ozone in the stratosphere 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 2007a).

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. They are used in short-term weather forecasting as well as long-term climate projections.

General Circulation Models

General circulation models simulate physical processes in the Earth's surface, oceans, and atmosphere through time 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 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 (although this is improving as computer power increases). Instead of simulating climate for every single point on Earth, modelers divide the land surface, ocean, and atmosphere into a three-dimensional grid (Fig. 10). Each cell within the grid is treated as an individual unit, and able to interact with adjacent cells. Although each model

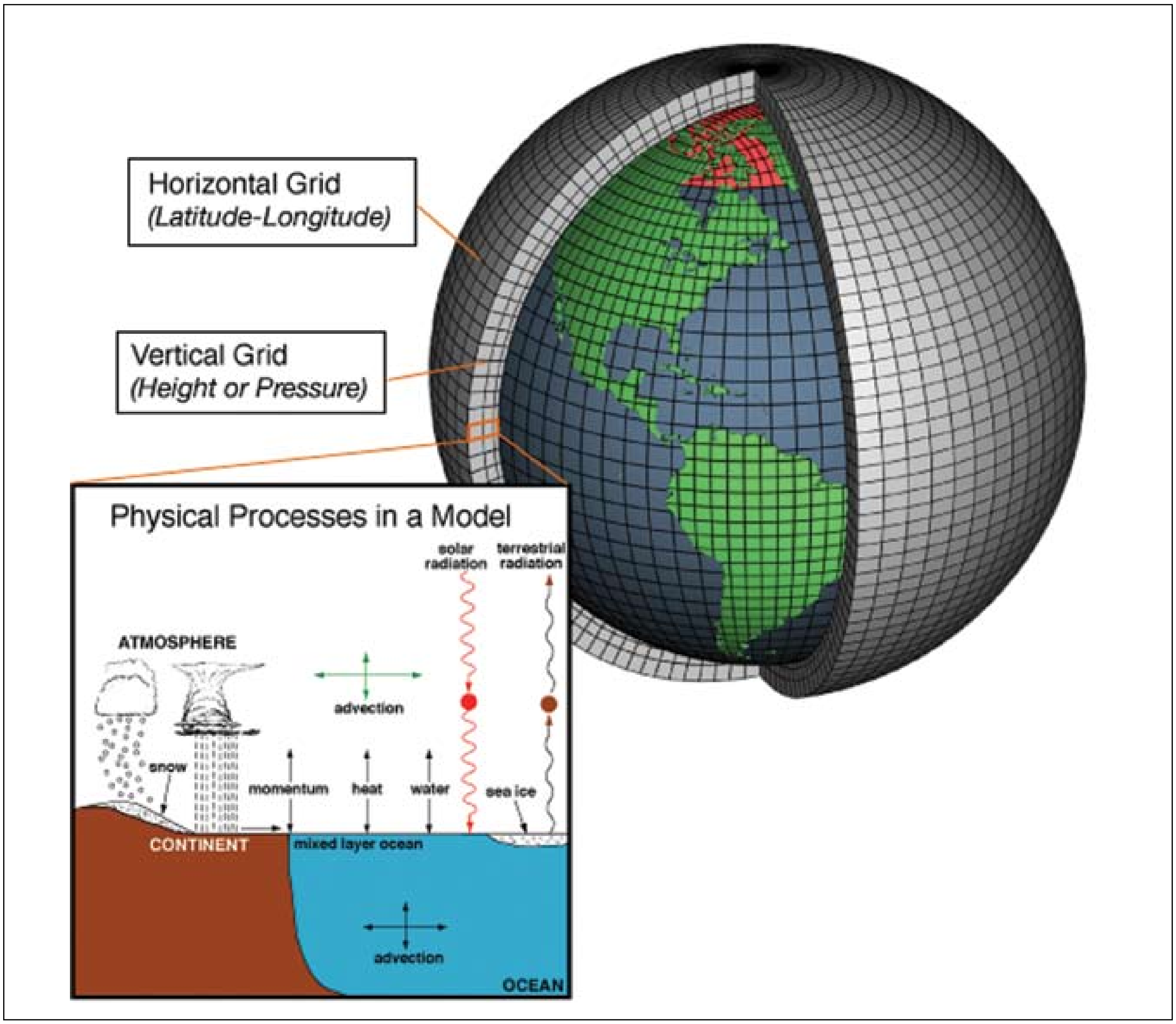


Figure 10.—Schematic describing climate models, which are systems of differential equations based on the basic laws of physics, fluid motion, and chemistry. The planet is divided into a three-dimensional grid that is used to apply basic equations and evaluate results. Atmospheric models calculate winds, heat transfer, radiation, relative humidity, and surface hydrology within each grid and evaluate interactions with neighboring points. Figure courtesy of NOAA (2008).

is slightly different, each square in the grid used in the IPCC (2007a) modeling is usually between 2 and 3° latitude and longitude, or for the middle latitudes, about the size of the assessment area. 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.

Several research groups from around the world have developed GCMs that have been used in climate projections for the IPCC reports and elsewhere (Box 7). 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 and CCSM; 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 8). In general, they are useful and reliable tools because they are based on well-understood physical processes and have been successful at projecting climate and weather conditions. Simulations of past climates by GCMs generally correspond well with proxy-based estimates of ancient climates and actual historical measurements of recent 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). Sources of error in model output include incomplete scientific understanding of some climate processes and the fact that some influential climate processes occur at spatial scales too small to be modeled with current computing power. Additionally, future climate projections regarding changes in precipitation and extreme events are particularly uncertain. Lastly,

Box 7: 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
http://glisa.msu.edu/resources/nca

future GCM projections are driven by future conditions that have never previously occurred, making it impossible to perfectly validate the models. Instead, partial analogs can be found in the geological record and used to test the ability of the models to recreate past climate conditions (IPCC 2013, Williams et al. 2013). Additional resources on climate models and emissions scenarios are listed in Box 7.

Technological advances in the computing industry along with scientific advances in our understanding of Earth's physical processes will lead to continued improvements in GCM projections. Future 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 8: Model Limitations and Uncertainty

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

Models are conceptual or mathematical representations of reality, so they will always depart from reality in some ways. Hence, 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 and to characterize the amount of uncertainty and limitations inherent in models.

Model results from both climate models and forest impact models 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 limitations on the numbers of inputs that a model can reliably handle. Precipitation projections usually have much more variability across future climate projections than do temperature projections. Regions with complex topography contain much more diversity in microclimates than many models can capture, even after downscaling. 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 subsequently integrated 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 distribution and 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 for existing forests, but does not model shifts in species or ecosystem distribution. 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.

In this assessment, we used an integrated approach drawing from multiple models and expert judgment. 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. The integration of model results and expert judgment to assess forest vulnerability to climate change is described in Chapter 6 and Appendix 6.

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 storylines about how the future may unfold and then calculate the potential greenhouse gas concentrations for each alternative storyline. The use of different emissions scenarios to run GCM simulations results in different climate projections. The IPCC's set of standard emissions scenarios is a widely accepted set of storylines that are used throughout this assessment (IPCC 2007a).

Emissions scenarios are a quantitative representation of alternative storylines given certain demographic, technological, or environmental developments. None of the current scenarios include any changes in national or international policies 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. 11).

The A1FI scenario is the most fossil-fuel intensive, and thus projects the highest future greenhouse gas concentrations; GCM simulations using the A1FI scenario project the highest future warming. On the other end of the spectrum, the B1 scenario represents a future where alternative energies and new technologies decrease our reliance on fossil fuels and greenhouse gas concentrations increase the least. GCM simulations using the B1 scenario project the lowest increase in global temperature. 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 the year 2000 have even exceeded the A1FI scenario values in some years (Raupach et al. 2007).

Downscaling

As mentioned previously, GCMs simulate climate conditions for relatively large areas. To examine the future climate of areas within the assessment area, a smaller grid scale is needed. One method of projecting climate on smaller spatial scales is statistical downscaling, a technique by which

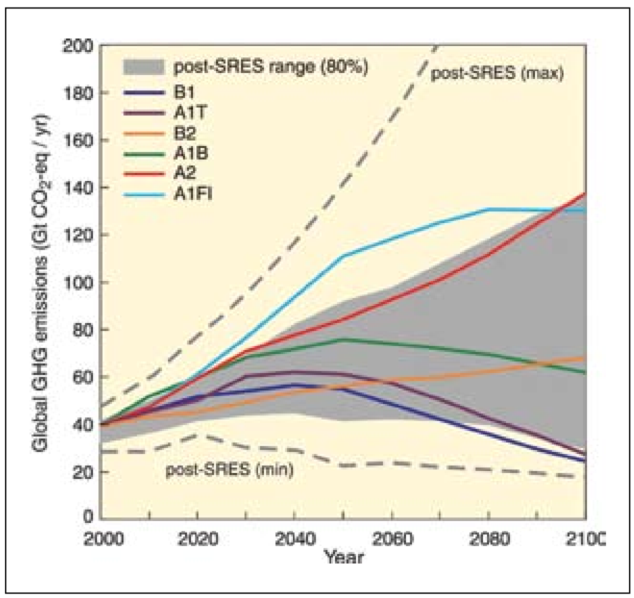


Figure 11.—Projected global greenhouse gas (GHG) emissions (in gigatons [Gt] of carbon dioxide equivalent per year) assuming no change in climate policies under six scenarios (B1, A1T, B2, A1B, A2, and A1FI) originally published in the Special Report on Emissions Scenarios (SRES) (IPCC 2000), and the 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 IPCC (2007).

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. The level of downscaling is limited by the resolution of the initial climate data set, with many data sets available at a resolution on the order of 6.2 miles.

Statistical downscaling has advantages and disadvantages (Daniels et al. 2012). It is a relatively simple and inexpensive way to produce smaller-scale projections from GCMs. However, statistical downscaling assumes that past relationships between modeled and observed temperature and precipitation will hold true under future change, which may or may not be true. Statistical downscaling also depends on local climate data. If there are no weather stations 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, lake-effect snow, topography, or particulate matter) also add to uncertainty when climate projections are downscaled.

Another approach, dynamical downscaling, uses a regional climate model (RCM) embedded within a GCM. 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 regional phenomena such as lake-effect snow and extreme weather events. However, like GCMs, RCMs require a lot of computer power. Therefore, dynamically downscaled data are usually available only for one or two GCMs or emissions scenarios and for limited geographic areas. Because dynamically downscaled data were unavailable for the assessment area at the time it was developed, we use statistically downscaled data in this assessment.

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 2007a). The latest version of the National Climate Assessment (Melillo et al. 2014) 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 roughly 20 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 (Melillo et al. 2014). 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 range of projected changes in climate and provides a set of alternative scenarios that can be used by managers in planning and decisionmaking.

The Geophysical Fluid Dynamics Laboratory's Climate Model (GFDL CM2) 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. The National Center for Atmospheric Research's Parallel Climate Model (PCM), by contrast, 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 much lower than the trajectory for greenhouse gas emissions over 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 is closer to current trends in greenhouse gas emissions (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 statistically downscaled data set is different from that 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 and provide the opportunity to examine questions related to growing season length, heavy precipitation events, and droughts. Fourth, the statistical technique used is more accurate at reproducing extreme values at daily time steps than simpler statistical downscaling methods (Hayhoe 2010b). Finally, the 7.5-mile resolution of the downscaled data is useful for informing land management decisions.

To show projected changes in temperature and precipitation, we calculated the average daily mean, maximum, and minimum temperature and mean precipitation for each month for three 30-year periods (2010 through 2039, 2040 through 2069, and 2070 through 2099). Using 30-year periods reduces the influence of natural year-to-year variation that may bias calculations of change. The use of 30-year periods also allows for more direct comparison with the 1971 through 2000 historical data, highlighting longer-term trends over annual fluctuations. Monthly averages were used to calculate seasonal and annual values. We then subtracted the corresponding 1971 through 2000 average from these values 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 and Appendix 2 contain more information about the observed climate data from ClimateWizard.

Importantly, this set of downscaled future climate projections was also used for all the forest impact models described below (Fig. 12). The complete data set containing daily mean, minimum, and maximum temperature and total daily precipitation data was provided to each modeling team and incorporated into the models. This consistency in future climate data allows for more effective comparison of results across different forest impact models.

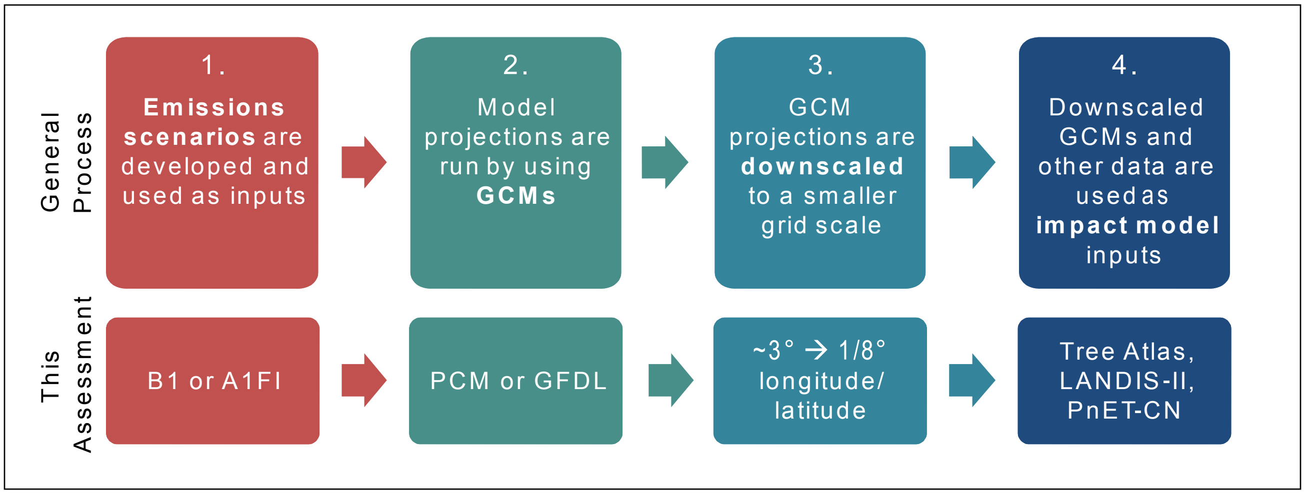


Figure 12.—Steps in the development of climate impact models using climate projections from general circulation models (GCMs) and the specific steps taken in this assessment.

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. In this assessment, we used forest impact models with GCM projections as inputs, as well as information about tree species, life-history traits of individual species, and soil types. Several 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. We used one species distribution model, the DISTRIB component of the Climate Change Tree Atlas (U.S. Forest Service 2014), 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.

Species distribution models establish a statistical relationship between the current distribution of a species or a community and climate, habitat, or other environmental variables. This relationship is used to model how the range of the species will shift as climate change affects those attributes. These models are less computationally expensive than process models, so they can typically provide projections for the suitable habitat of many species over a large 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 interactions with other species (e.g., predation, disease, and competition), limitations on dispersal, and the existence of suitable climates (Soberón 2007). A species' fundamental niche, in contrast, is the full set of habitats a species potentially could occupy. 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, this is an indication that they will be living farther outside their ideal range and will be exposed to more climate-related stress. Lastly, SDMs may have difficulty in accurately extrapolating into projected climates with no current analog (Fitzpatrick and Hargrove 2009, Williams et al. 2012).

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 the spatial and temporal dynamics of a variety of complex processes, they typically require more computer power than a species distribution model. Therefore, fewer species or forest types can be modeled compared to a SDM. Process models have several assumptions and uncertainties that should be taken into consideration when results are applied 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. The inputs to the forest impact models for current distribution of trees, site characteristics, and downscaled GCM projections are all based on estimates, each with its own 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 over the next century (Iverson et al. 2008, U.S. Forest Service 2013). 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

Union Bay in western Upper Michigan. Photo by Scott Pearson, used with permission.

importance values and suitable habitat for individual tree species by using the downscaled GCM data described above.

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 current pests and diseases that have been negatively affecting the species. This supplementary information indicates 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. Data are presented for three periods (2010 through 2039, 2040 through 2069, and 2070 through 2099) in Appendix 4, with analysis of the results for 2070 through 2099 discussed in Chapter 5. The GFDL A1FI and PCM B1 model-scenario combinations used for this assessment are those described earlier in this chapter, which differ slightly from the scenarios used in the online Tree Atlas. 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 for the assessment area.

LANDIS-II

The LANDIS-II model is a spatially explicit and dynamic model for simulating forest landscape changes that is process-driven and flexible for a variety of applications (Scheller et al. 2007). It simulates forest succession, natural disturbance (e.g., fire, wind, and insect outbreak), management (i.e., harvesting and planting), and other processes (e.g., climate change and drought, seed dispersal) in a grid-based framework that emphasizes spatial interactions across the landscape and among processes. Thus processes occur within a given grid cell, and also between cells. This model can run simulations over many decades and over large spatial extents (e.g., greater than 20 million acres in this study). Some processes are simulated to occur randomly based on probabilities and cell conditions, such as fire disturbance or seed dispersal (see www.landis-ii.org for further details).

Inputs to LANDIS-II include an initial forest conditions map with tree species assigned to age cohorts in all forested cells, an ecoregion map with similar ecological (i.e., climate, soils and topographical conditions), and other spatial data related to forest management. 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) using the PnET-II model at every time step. LANDIS-II calculates these parameters by using monthly maximum and minimum temperature, precipitation, and solar radiation under different climate change scenarios. Other inputs include species foliar nitrogen content, maximum foliar mass area, and ecoregion parameters such as soil water-holding capacity and actual evapotranspiration. LANDIS-II also requires modelers to specify timber harvest methods and rates of harvesting (Ravenscroft et al. 2010) and rotation periods and size information for fire and wind disturbances (Cleland et al. 2004, White and Host 2008). Projections of aboveground biomass are provided for individual species and for aggregated forest types as aboveground biomass provides a useful metric for comparing tree and forest growth over time.

For this assessment, two future climate scenarios, PCM B1 and GFDL A1FI, were used to simulate a range in potential future climate. The simulations used a landscape with 15-acre grid cells. A 300-year time horizon from 2000 to 2300 was simulated, and the results from 2000 through 2100 are discussed in this assessment (Chapter 5 and Appendix 5). Biomass values in three individual years (2040, 2070, and 2100) were compared to year 2000 biomass to make comparisons of change over time. The landscape modeled covered most counties in northern Wisconsin, the western Upper Peninsula of Michigan (Baraga, Gogebic, Houghton, Iron, and Ontonagon Counties), and Chisago County in eastern Minnesota, an area of more than 20 million acres of forest across much of the assessment area. LANDIS-II simulations included 27 tree species currently present within this landscape (Chapter 5). Forest management practices were described with a business-as-usual scenario using the current harvesting rates in the study area under different ownership types.

PnET-CN

The PnET-CN model is an ecosystem-level process model that simulates carbon, water, and nitrogen 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 carbon, water, and nitrogen cycles to interact with each other. This enables PnET-CN to simulate the effects of water and nitrogen 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, nitrogen 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 does not simulate 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 carbon, water, and nitrogen cycling, including key ecosystem processes such as net primary production, net ecosystem production, evapotranspiration, and nitrogen 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, the PnET-CN model simulations were run from 1960 through 2100 with a grid resolution of 0.6 miles (Chapter 5). Relative change in aboveground net primary productivity was calculated by subtracting the modeled values for the years 1971 through 2000 from the 2070 through 2099 period. 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 nitrogen deposition rates (data provided by the U.S. Environmental Protection Agency) were held constant into the future. Soil water-holding capacity was characterized by the Natural Resources Conservation Service's Soil Survey Geographic Database (Matthew Peters, U.S. Forest Service, pers. commun.). Current vegetation cover was defined by using a vegetation map based on FIA data and satellite imagery (Wilson et al. 2012), which included six forest types (maple/beech/birch, elm/ash/cottonwood, oak/hickory, aspen/birch, spruce/fir, and pine). Although PnET-CN can account for discrete disturbance events, for this assessment we did not include any disturbances related to harvest, fire, or wind.

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 GCMs. These large-scale climate models can be downscaled to finer resolution and incorporated into multiple different forest impact models that project changes in forest composition and ecosystem processes for use in informing management 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.

CHAPTER 3: OBSERVED CLIMATE CHANGE

Climate is one of the principal factors that have determined the composition and extent of forest ecosystems of this region over the past several thousand years. Many of the climatic changes that have been noted across the world over the past century are also evident in the assessment area. This chapter describes changes in climate that have been observed since 1900 in the assessment area. We also present a few case studies that illustrate the effects of climate change on ecological indicators such as growing season, lake ice, and bird migration.

CURRENT CLIMATE

Weather stations in Wisconsin and Michigan have recorded measurements of temperature and precipitation for more than 100 years, providing a rich set of information to evaluate changes in climate over time. The ClimateWizard Custom Analysis application was used to estimate the changes in temperature and precipitation across the assessment area (ClimateWizard 2012, Girvetz et al. 2009). This tool uses data from PRISM (Gibson et al. 2002), which converts measured point data from weather stations onto a continuous 2.5-mile grid over the entire United States. Temperature and precipitation data for the assessment area were used to derive annual, seasonal, and monthly values for the 30-year "climate normal" during 1971 through 2000 (Table 8), as well as long-term trends during 1901 through 2011. Additional information regarding confidence in trends, the PRISM data, and the ClimateWizard Custom Analysis application is available in Appendix 2.

Table 8.—Average temperature and precipitation for the assessment area, 1971 through 2000 (ClimateWizard 2012)

	Mean temperature (°F)	Minimum temperature (°F)	Maximum temperature (°F)	Mean precipitation (inches)
Winter	**15.4**	**5.6**	**25.1**	**3.9**
December	17.4	8.9	26.0	1.5
January	11.6	1.6	21.7	1.4
February	17.0	6.2	27.7	1.0
Spring	**40.9**	**29.2**	**52.6**	**7.5**
March	27.7	17.2	38.3	1.9
April	41.1	29.5	52.7	2.4
May	53.8	41.0	66.7	3.2
Summer	**65.0**	**53.1**	**76.8**	**11.8**
June	62.4	50.1	74.8	3.8
July	67.2	55.4	79.0	3.9
August	65.3	53.8	76.7	4.0
Fall	**44.2**	**34.3**	**54.1**	**8.8**
September	56.5	45.3	67.6	3.8
October	45.2	34.8	55.7	2.7
November	30.9	22.8	38.9	2.3
Annual	**41.3**	**30.5**	**52.2**	**32.0**

The regional climate is generally characterized by cold winters and relatively hot, humid summers (Albert 1995). Annual temperature and precipitation patterns are generally similar across the assessment area, with some notable exceptions in areas heavily influenced by Lake Superior and, to a lesser extent, Lake Michigan (see Chapter 1 and Box 1). Mean annual air temperature fluctuates by about 50 °F (27.8 °C) between winter and summer. July is the warmest month with a mean temperature of 67.2 °F (19.6 °C), and January is the coldest month with a mean temperature of 11.6 °F (-11.3 °C; Table 8, Fig. 13). Areas to the south and east of Lake Superior tend to be cooler and wetter during the summer months than areas farther inland (Fig. 13). Precipitation is greatest in summer and least in winter (Table 8, Fig. 14).

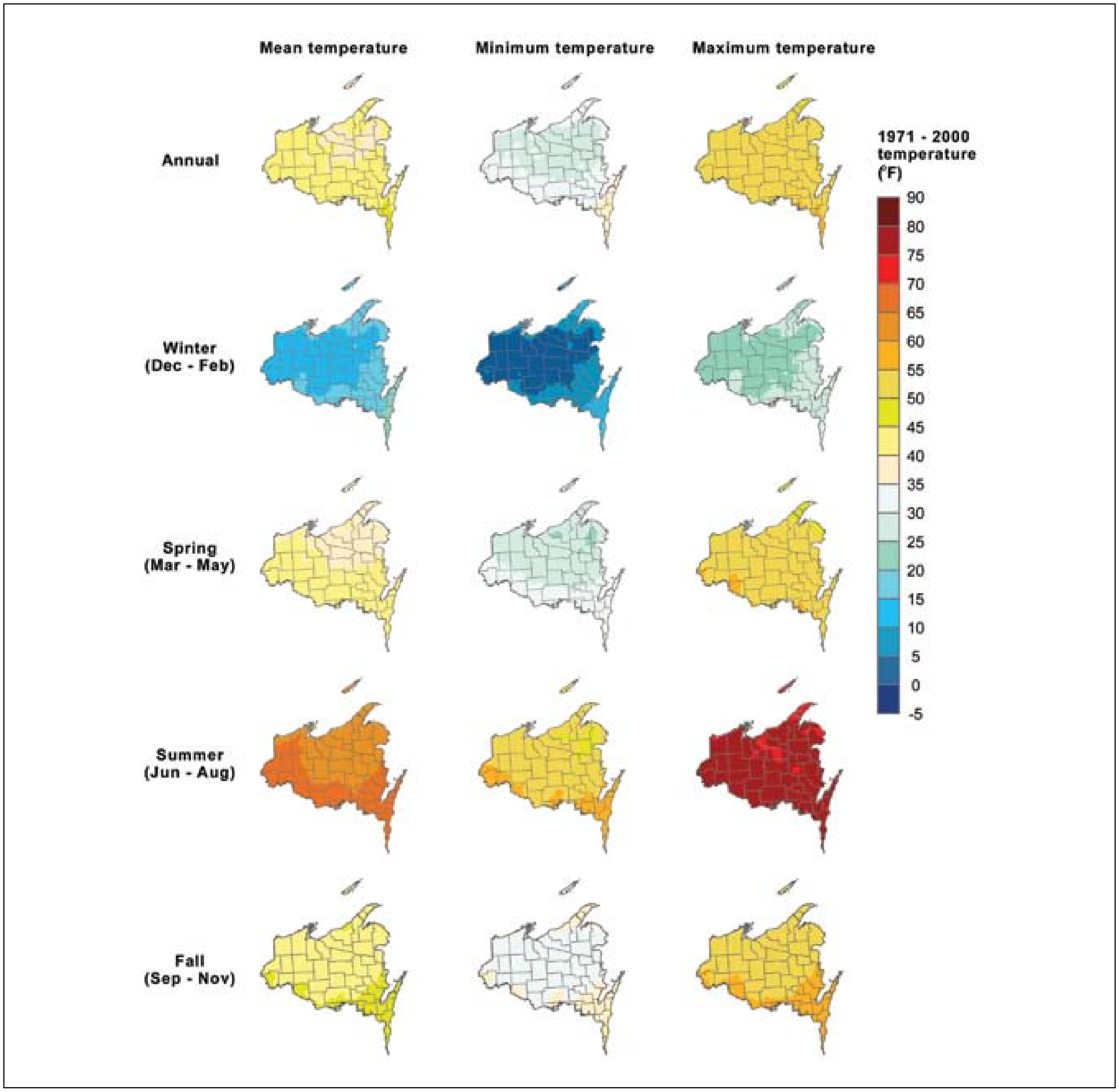


Figure 13.—Thirty-year annual and seasonal averages of mean, minimum, and maximum temperature across the assessment area from 1971 through 2000. Data source: ClimateWizard (2012).

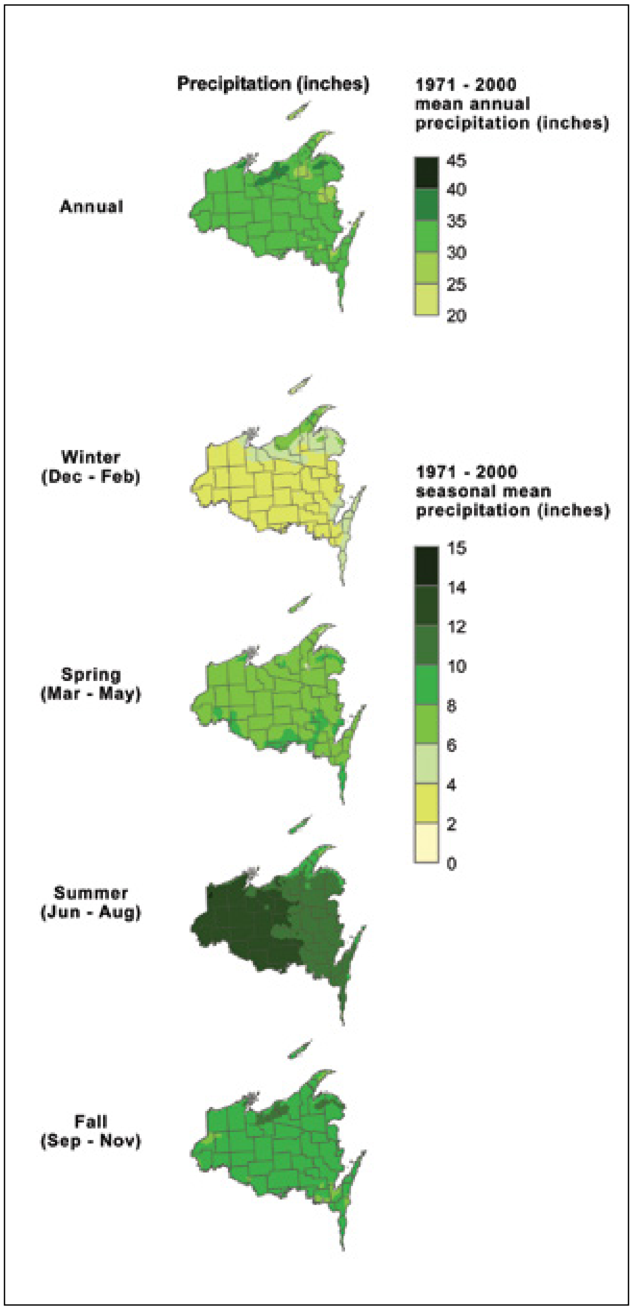


Figure 14.—Thirty-year averages of mean annual and seasonal precipitation across the assessment area from 1971 through 2000. Data source: ClimateWizard (2012).

TRENDS IN TEMPERATURE AND PRECIPITATION (1901-2011)

Temperature

The Midwest has experienced substantial changes in temperature and precipitation over the past 100 years, and the rate of change appears to be increasing (Andresen et al. 2012). In addition to the 30-year climate normal (1971 through 2000) data described above, the long-term climate record (1901 through 2011) was analyzed by using the ClimateWizard Custom Analysis tool to gain a better understanding of how the climate has changed over the last century (Appendix 2). Although there is variation in annual mean (average) temperature from year to year, there is a long-term warming trend (Fig. 15) that is consistent with changes observed at state, continental, and global scales (Andresen et al. 2012, IPCC 2007b, Kunkel et al. 2008, Wisconsin Initiative on Climate Change Impacts [WICCI] 2011b). Across the assessment area, the mean annual temperature increased by 1.4 °F (0.8 °C) between 1901 and 2011 (Fig. 15).

The greatest change in temperature during the 20th century was observed during winter, with an increase in mean temperature of 2.2 °F (1.2 °C) and an increase in minimum (low) temperature of 3.0 °F (1.6 °C). The greatest increases in mean, minimum, and maximum temperatures have all been observed during February (Fig. 16), with an increase in mean temperature of 4.6 °F (2.6 °C). Mean and minimum temperatures have increased over nearly all seasons and months, whereas changes in maximum temperature have been more variable (Fig. 16, Appendix 2).

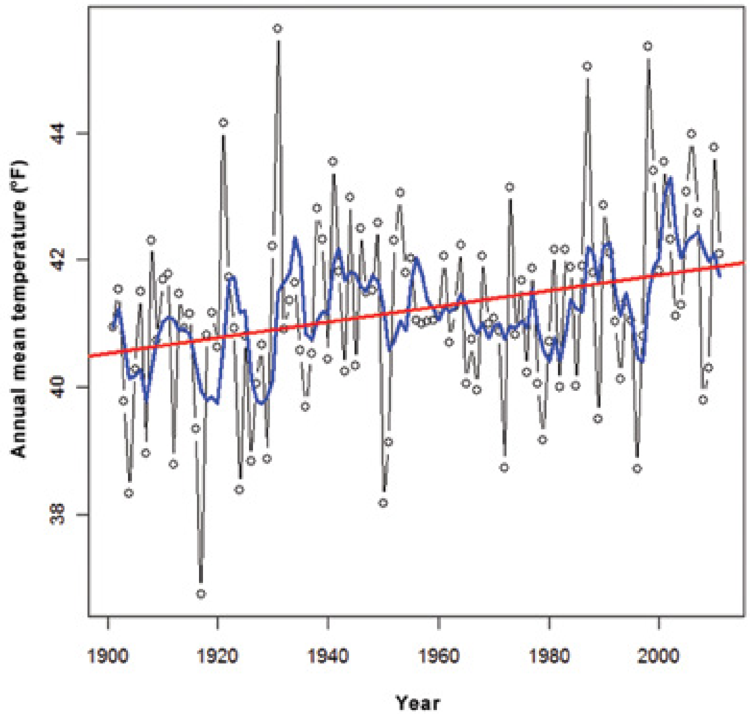


Figure 15.—Mean annual temperature across the assessment area from 1901 through 2011. The blue line represents the rolling 5-year mean. The red regression line shows the trend across the entire period (0.012 °F/year). Source: ClimateWizard (2012).

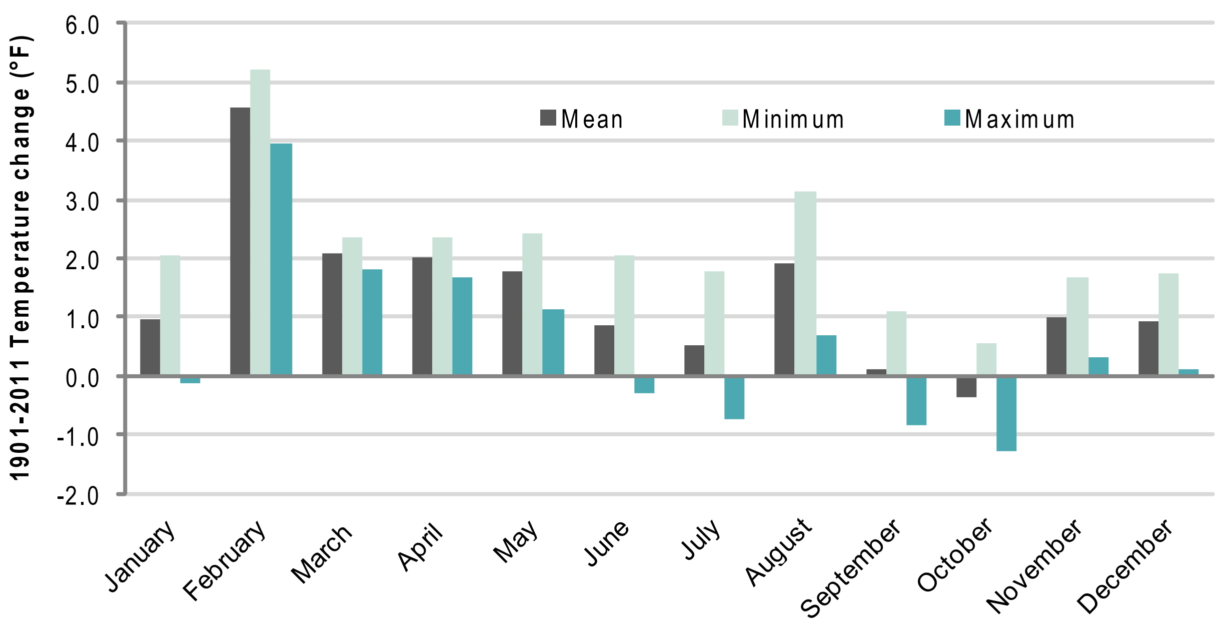


Figure 16.—Change in mean monthly temperatures across the assessment area from 1901 through 2011. Data source: ClimateWizard (2012). Numeric change values are provided in Appendix 2.

Within the assessment area, there are local differences in the magnitude and direction of temperature change observed over the last century. Mean annual temperature has increased by 2 to 3 °F (1.1 to 1.7 °C) in northwestern Wisconsin and much of the western Upper Peninsula. Parts of north-central and northeast Wisconsin have not changed as much or have even cooled slightly during some seasons (Fig. 17). Increases in minimum temperature have generally been the most widespread across the assessment area, although the magnitude varies. Minimum temperature increases during the 1900 to 2011 time period ranged from 2 °F (1.1 °C) in central Wisconsin to 6 °F (3.3 °C) in northwestern Wisconsin.

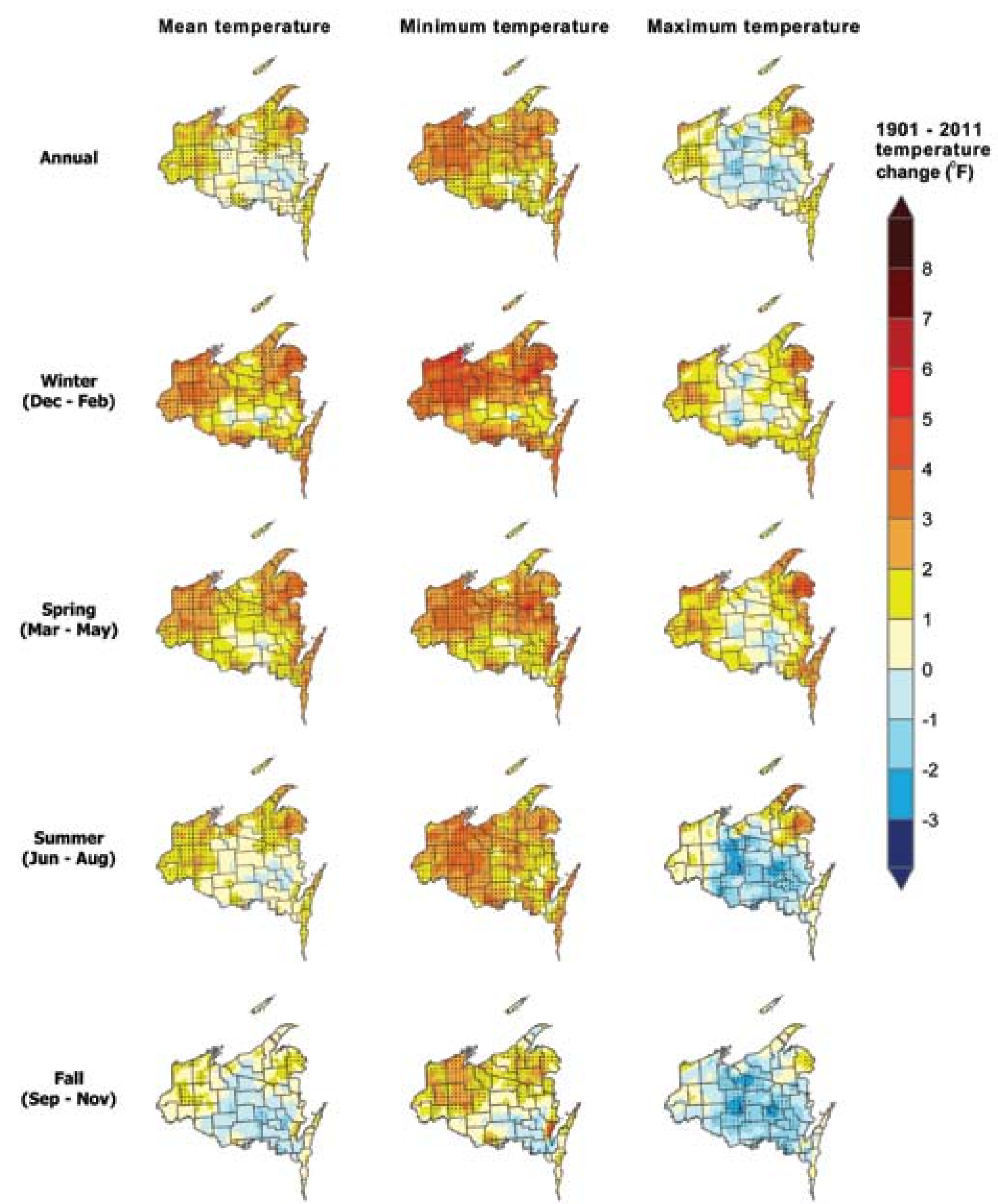


Figure 17.—Annual and seasonal change in mean, minimum, and maximum temperatures across the assessment area from 1901 through 2011. Stippling indicates there is less than 10-percent probability that the trend could have occurred by chance alone. Data source: ClimateWizard (2012). Additional information is available in Appendix 2.

The general trend toward increasing temperatures in the assessment area is similar to observations reported elsewhere. Much of the United States has warmed by 1 to 2 °F (0.6 to 1.1 °C) since the 1960s and 1970s (Karl et al. 2009), and annual average temperatures across the lower 48 states increased by 1.3 °F (0.7 °C) from 1901 to 2009 (U.S. Environmental Protection Agency 2013). Across the Midwest, temperatures rose an average of 0.1 °F (0.06 °C) per decade during 1900 through 2010, for a total increase of approximately 1.2 °F (0.6 °C) during that period (Andresen et al. 2012); further, this rate of warming has increased to more than 0.4 °F (0.2 °C) per decade during the past 40 years (Andresen et al. 2012).

These data are also similar to results from other regional studies. Measurements from Wisconsin weather stations between 1950 and 2006 show that minimum (low) temperatures have increased 1.1 to 4.0 °F (0.6 to 2.2 °C) across the state (Kucharik et al. 2010a). This is greater than the increase in maximum temperatures, which have risen 0.5 to 1.1 °F (0.3 to 0.6 °C) during the same time period. Similarly, data from 16 weather stations across the Upper Peninsula showed a 3.7 °F (2.1 °C) increase in minimum daily temperatures from 1970 to 2007, and the fastest rise was observed during winter (Myers et al. 2009).

These changes in temperature lead to other important changes in climate. For example, the length of the growing season increased by 12 days across Wisconsin between 1950 and 2006, with the greatest change in central and northwestern Wisconsin (Kucharik et al. 2010a). The date of the last spring freeze is occurring 5.6 days earlier on average, and the first autumn freeze is occurring 6.5 days later.

PRECIPITATION

Precipitation patterns have also changed over the past century (Figs. 18 and 19). Although annual mean precipitation varies widely from year to year, there is a slight trend toward greater annual precipitation in the assessment area. This trend is consistent with changes observed in statewide analyses of Michigan and Wisconsin (Andresen 2007, WICCI 2011b). Mean annual precipitation increased by 2.0 inches, or about 6.5 percent, across the assessment area from 1901 through 2011. Observed precipitation changes were variable across months and seasons (Figs. 18 through 20). Precipitation generally increased during the late fall and winter and decreased during May through June (Fig. 19).

There were also geographic differences in precipitation change. The greatest increase in precipitation was observed in northwestern Wisconsin, where annual precipitation increased by more than 6 inches from 1901 through 2011 (Fig. 20). The area near Iron County, Michigan, experienced the greatest decrease in precipitation with an annual decrease of as much as 8 inches. Seasonal changes also varied geographically, and were generally less pronounced (Fig. 20). Summer precipitation increased as much as 3 inches in some areas yet decreased by the same amount in parts of the Upper Peninsula and north-central Wisconsin. Winter precipitation increased slightly over much of the assessment area, with notable increases of 3 to 4 inches along parts of the Lake Superior shoreline. This change may be related to increases in lake-effect snowfall; long-term, upward trends in lake-effect snowfall were recorded in the Great Lakes region from 1931 to 2000 (Burnett et al. 2003).

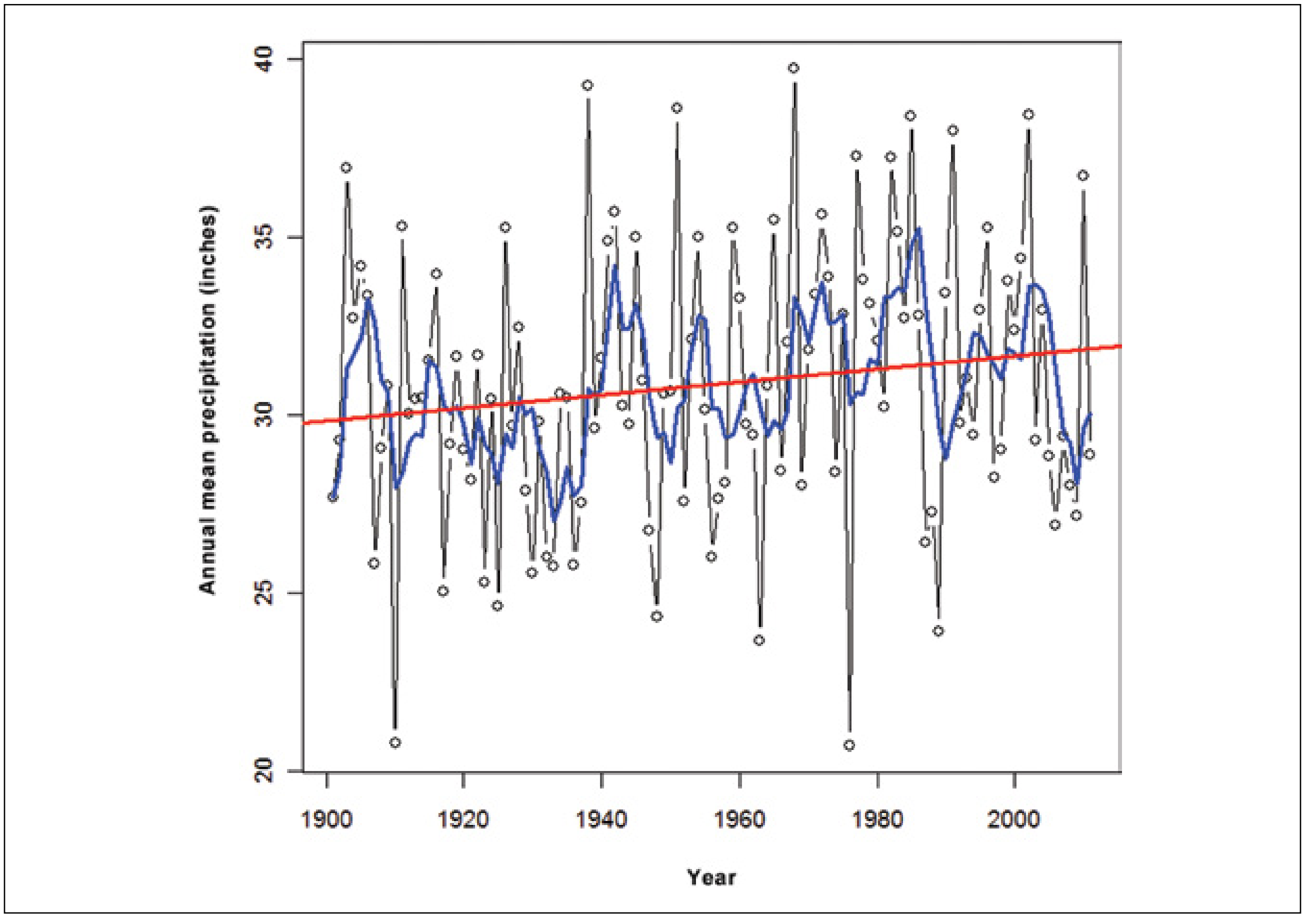


Figure 18.—Mean annual precipitation across the assessment area from 1901 through 2011. The blue line represents the rolling 5-year mean. The red regression line shows the trend across the entire time period (0.018 inches/year). Source: ClimateWizard (2012).

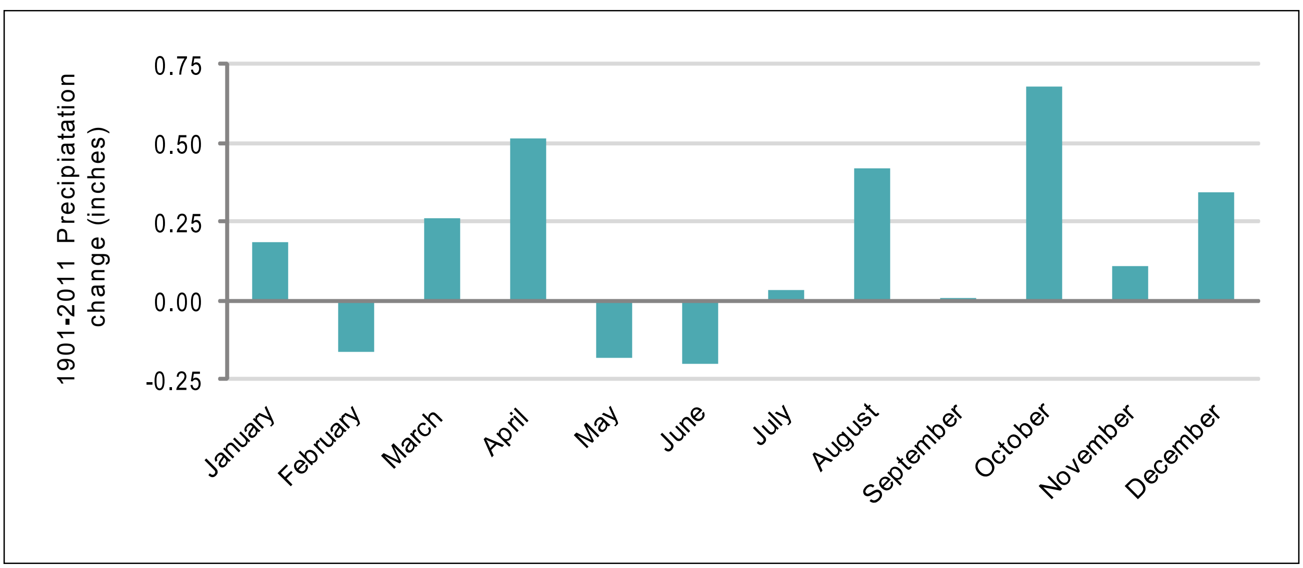


Figure 19.—Change in mean monthly precipitation across the assessment area from 1901 through 2011. Data source: ClimateWizard (2012). Numeric change values are provided in Appendix 2.

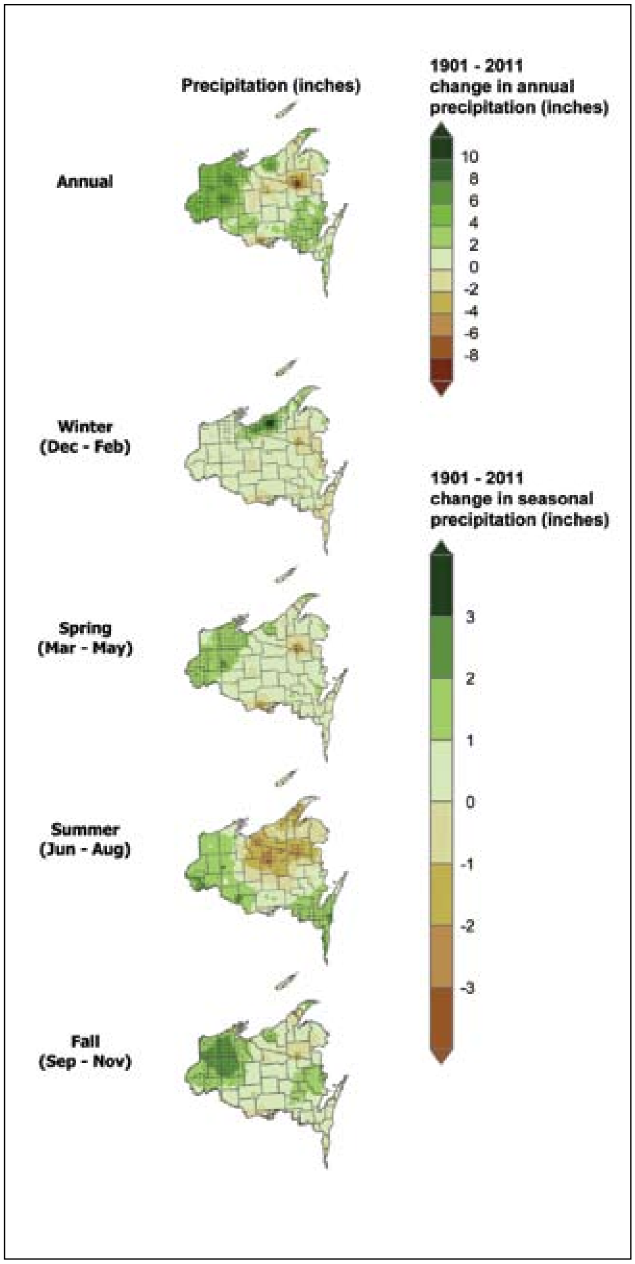


Figure 20.—Change in mean annual and seasonal precipitation across the assessment area from 1901 through 2011. Stippling indicates there is less than 10-percent probability that the trend could have occurred by chance alone. Data source: ClimateWizard (2012). Additional information is available in Appendix 2.

TRENDS IN EXTREME WEATHER EVENTS

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 forest ecosystems 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 (Climate Change Science Program [CCSP] 2008b). These events can trigger catastrophic disturbances in forest ecosystems, along with significant socioeconomic impacts. Evidence suggests that extreme events are becoming more frequent and severe across the United States and globally, and that global climate change is part of the explanation (Coumou and Rahmstorf 2012, IPCC 2012, Kunkel et al. 2008). At the same time, it is difficult to directly attribute the occurrence of a single event to climate change (Coumou and Rahmstorf 2012, Stott et al. 2010).

Many physical processes important for forest ecosystems are driven by climate and weather patterns. These factors, 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 the assessment area and throughout the Midwest.

Temperature Extremes

Warmer mean temperatures are often correlated with higher extreme temperatures (Kling et al 2003, Kunkel et al. 2008). For example, the number of heat waves has increased across the United States since 1960, driven largely by an increase in the frequency of extremely high nighttime temperatures (Kunkel et al. 2008). Multi-day heat waves have also become more common over the past 60 years in the

Midwest, and summer cool days have become less frequent over this same time period (Perera et al. 2012). These trends correspond to global patterns of increasing occurrence of extreme hot weather and decreasing occurrence of extreme cool weather (Hansen et al. 2012). There is less evidence for this trend in the assessment area. In Wisconsin, the number of hot days with a maximum temperature greater than 90 °F (32.2 °C) stayed relatively stable from 1950 through 2006 (Kucharik et al. 2011).

Additionally, the number of extremely cold weather events may be decreasing. Minimum temperatures have increased more than maximum temperatures in parts of the United States, including the Midwest (Peterson et al. 2008). Similarly, cold days with a minimum temperature below 0 °F (-17.8 °C) are becoming less frequent in Wisconsin. There were 9.5 fewer such days statewide and 20 fewer such days in the northwest portion of the state between 1950 and 2006 (Kucharik et al. 2010a). A study across the entire Midwest region found that intense cold waves (4-day durations of temperatures below a 1-in-5-year recurrence threshold) have been less frequent over the past 17 years, but there has not been a clear trend across the 20th century (Perera et al. 2012).

Intense Precipitation

Intense heavy precipitation events have become more frequent throughout North America, the Midwest, and the assessment area (Groisman et al. 2004, Karl et al. 2009, Saunders et al. 2012). Evidence of change across the United States includes a doubling of heavy downpours compared to a century ago and a 50-percent increase in the frequency of days with more than 4 inches of precipitation (Karl et al. 2009). Greater changes have been observed in the Midwest than other parts of the country (Kunkel et al. 1999, Saunders et al. 2012). The frequency of rainstorms of 3 inches or more between 1961 and 2011 increased by 203 percent in Wisconsin and 180 percent in Michigan (Saunders et al. 2012). At the same time, the number of light and average precipitation days (less than 1 inch) changed very little or even decreased (Groisman et al. 2004, 2005; Saunders et al. 2012). Events on the all-time record rainfall list are quickly being replaced by record rainfalls that have occurred in recent decades. In Wisconsin, 6 of the 10 heaviest downpours from 1961 through 2011 have occurred since 2000, resulting in 5 flooding disasters (Saunders et al. 2012). The Wisconsin record for the most rainfall ever recorded in a single day occurred in 2008. In Michigan, four of the heaviest downpours on record have occurred since 2000 (Saunders et al. 2012).

Extreme Storms and Wind

Strong thunderstorms occur most frequently in the summer in the assessment area, and these weather events can be particularly damaging if they also occur with tornadoes or severe wind or rain. Based on long-term data from 1896 through 1995, the assessment area averaged 25 to 35 thunderstorm days per year with fewer storms occurring in the Upper Peninsula (Changnon 2003). Damaging or dangerous storms are relatively infrequent in the assessment area and are more likely to occur in the southern parts of Wisconsin and Michigan and in states to the south and west (Changnon 2003, National Oceanic and Atmospheric Administration [NOAA] 2006a). From 1981 through 2010, there were 23 tornadoes per year in Wisconsin and 17 in Michigan, 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 few of these tornadoes occur within the assessment area, with the most tornadoes occurring in the southern portion (National Weather Service 2012).

In warm months of the year the assessment area occasionally experiences very powerful, convectively generated windstorms, or derechos. These events can result in substantial windthrow disturbances in forest ecosystems. 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 the assessment area, and these events are relatively rare in the assessment area (Coniglio and Stensrud 2004). The 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).

CHANGES IN WATER AND SOILS

Numerous studies have investigated hydrologic processes and have found that snow density and extent, snow and frost depth and duration, soil moisture and structure, and soil temperature are critical components of seasonal hydrology in the Great Lakes region. Trends in temperature and precipitation can influence hydrologic cycling, leading to changes in soil moisture, groundwater availability, and streamflow.

Lake Temperature and Ice Cover

The Great Lakes are drivers of the region's local climate, with water temperature and ice cover playing important roles. With increases in air temperatures, water temperatures also increase. From 1979 through 2006, Lake Superior water temperatures increased 2.5 °F (1.3 °C), an increase much greater than that observed in regional air temperatures. Lake Michigan showed a similar trend (Austin and Colman 2007).

The timing and extent of lake ice formation have been recorded for more than 150 years across the Great Lakes region. These records show that the duration of ice cover has decreased by 1 to 2 days per decade (U.S. Environmental Protection Agency 2010). This decrease is a result of later ice formation in the fall and earlier ice breakup in the spring. During a period of rapid warming from 1975 to 2004, average ice duration in the Great Lakes region decreased by more than 5 days per decade (Jensen et al. 2007). Lakes and bays in northern Wisconsin showed a similar rate of decrease in lake ice duration from 1850 through 2000 (Magnuson 2003). A long-term simulation of historical lake ice trends across Michigan, Minnesota, and Wisconsin 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). 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). Another study found an average decline of 71 percent in ice coverage on the Great Lakes between 1973 and 2010 (Wang et al. 2012). 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).

Warmer water temperatures and reduced ice cover often interact in a positive feedback cycle where warmer winter air and water temperatures reduce ice cover and increase the duration of open water conditions. The ensuing open water conditions allow the water to absorb more heat, further increasing water temperatures (Assel 2005, Austin and Colman 2007). Similarly, thermal stratification is another important process in many lakes where a layer of warm water is present on the surface of the lake and separated from colder, deeper water during warmer times of the year. Earlier onset of lake stratification (currently occurring about 2 weeks earlier) increases the period during which the lake is able to warm during the summer months and further reinforces the warming trend (Assel 2009, Lofgren et al. 2002). These changes can strongly influence near-shore climates and weather events, such as lake-effect snow.

The "ice road" from Bayfield to Madeline Island in Wisconsin. Photo by Maria Janowiak, U.S. Forest Service.

Snowfall

Cold and snowy winters are characteristic of the assessment area. There are clear patterns of winter precipitation across the assessment area, with areas near the Lake Superior shoreline having the highest amounts of winter precipitation (Fig. 14). These trends are dictated by the prevailing wind direction, topography, and lake-effect snow from Lake Superior and, to a much lesser extent, Lake Michigan.

During the 20th century, winter (December through February) precipitation increased slightly across the assessment area (0.3 inches), with the most substantial increases observed in the lake-effect zone along Lake Superior (Figs. 19 and 20). Long-term records from across the Great Lakes also indicate that lake-effect snow increased gradually across the region during the 20th century (Burnett et al. 2003, Kunkel et al. 2013). This increase is largely attributed to declining ice cover on the Great Lakes and greater evaporation from lakes; this moisture is then deposited over land as snowfall (see Box 1). Other regional studies of snow measurements also observed increased snowfall and snowfall frequency during the winter months (December through February) and decreases during the month of April (Burnett et al. 2003, Ellis and Johnson 2004, Groisman and Easterling 1994, Norton and Bolsenga 1993).

Regional trends indicate that snowfall amounts are quite variable from year to year, but fewer heavy snowfall years have occurred over the last 30 years (Kunkel et al. 2013). Individual snowfall events may have become more severe, however. During the 20th century, there was an increase in snowstorms of 6 inches or more across the upper Midwest (CCSP

2008b). Similarly, a four-state region including Michigan and Wisconsin had fewer extreme low-snow years over the 20th century (Kunkel et al. 2009).

As described above, there is substantial evidence that winter air temperature and precipitation have increased over the assessment area during the last century. Whether precipitation falls as rain or snow is strongly influenced by air temperature, and evidence suggests that the proportion of precipitation falling as snow has decreased in some parts of the assessment area (Feng and Hu 2007, Mishra and Cherkauer 2011).

Soil Temperature and Soil Frost

Soil frost dynamics are important for forest ecosystems because soil temperatures can impact water infiltration rates, nutrient cycling, and tree growth. Snowcover insulates the soil surface from changes in air temperature, thereby helping reduce both the number of freeze-thaw cycles and the depth to which frost penetrates the soil (Hardy et al. 2001, Isard et al. 2007, Sinha et al. 2009). Research has shown that deeper snow depth can result in shallower soil frost depth in northern forests, whereas thinner snowpack results in colder soil temperatures and deeper soil frost where temperatures are sufficiently cold (Hardy et al. 2001).

Observations of how soil temperature and soil frost have changed across the assessment area are complex and influenced by local factors including soil characteristics and lake effect. However, some general trends are notable. In the northeastern extent of the assessment area, winter soil temperatures have decreased (Isard et al. 2007) and the number of soil frost days increased (Sinha et al. 2010). This area often has greater snowfall and snowcover (and therefore, insulated soils) than other parts of the assessment area, so it is possible that warmer temperatures have resulted in more variable snowpack conditions and increased occurrence of soil frost.

Conversely, in northwestern Wisconsin where winter warming has generally been greatest (Fig. 17), soil temperatures increased since 1950 (Isard et al. 2007) and fewer frost days occurred in recent decades (Sinha et al. 2010). Weather stations from six locations across Wisconsin also point to a shorter duration of frozen ground, especially in the southern and western portions of the state (C. Rittenhouse, University of Connecticut, and A. Rissman, University of Wisconsin – Madison, unpublished data). For example, the greatest reduction in the number of days of frozen soil (4 inches deep) was observed in Eau Claire County, where days with frozen soil decreased 39 days since 1949 and winter soil temperature increased slightly.

Runoff, Streamflow, and Flooding

Long-term data on flooding are 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 Wisconsin, and there were 4 such years between 1983 and 2001 (Cartwright 2005). There are several

Amnicon Falls in northern Wisconsin. Photo by Scott Pearson, used with permission.

complicating factors in attributing this trend. In particular, human-caused 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). Even after these factors are accounted for, Midwestern watersheds still exhibited increased discharge over the past several decades and this trend has been attributed to climate change (Tomer and Schilling 2009). Data from streamflow stations in the Great Lakes show an earlier occurrence of spring peak flows, which are attributed to increased air temperature and earlier melting of snowpack (Hodgkins and Dudley 2006, Small et al. 2006).

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 United States, 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. 1996). Other studies of hydrologic trends in the United States over the last century also observed reduced duration and severity of droughts across the upper Midwest as a result of increased precipitation (Andreadis and Lettenmaier 2006, Peterson et al. 2013), although this observation was not as strong in the assessment area (Peterson et al. 2013).

Statewide data from Michigan and Wisconsin support this general pattern. Between 1895 and 2013, the Midwest trend has been toward slightly less common and less severe droughts during the growing season (June through September), with the years between 1920 and 1940 representing the most extreme droughts during the period of record (NOAA National Climatic Data Center 2013). This trend, however, has not been observed across the assessment area. The western Upper Peninsula in particular has been drier than average in recent decades, and moderate drought during the growing season has been recorded in nearly every year since 2000. North central Wisconsin has also experienced more frequent periods of drought than many other parts of the Midwest, although not to the same degree as the Upper Peninsula.

ECOLOGICAL INDICATORS OF CLIMATE CHANGE

Phenology is the timing of biological events, such as bird migration, wildlife breeding, and plant flowering and fruiting, or the study of these events. The timing of these events is determined by many variables, including seasonal temperature, food availability, and pollination mechanisms (Bradley et al. 1999). Increases in the growing season length and other climatic changes are causing noticeable changes in the timing of biological activities (Ellwood et al. 2013, Schwartz et al. 2006a, Walther et al. 2002), and changes in events such as plant flowering and bird migration have been observed across the region (Bradley et al. 1999, Notaro et al. 2010). The following case studies present some examples of early indications of climate change within the assessment area. These examples are by no means comprehensive, but they are intended to highlight a few of the ways that shifts in temperature, precipitation, and other factors may be influencing the environment and natural communities.

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. 21) (Burton et al. 1996). Annual growing season across the gradient of study sites differs by about 3 weeks, being longer in southern Michigan 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 between 1989 and 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. Growing season length 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. 22). Tree growth increased at each of the study sites in the Lower Peninsula, with an average 26-percent gain in aboveground biomass. The study site near Twin Lakes, 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 less able 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 illustrates that forest productivity may be limited by moisture availability, even as temperatures rise and growing seasons lengthen.

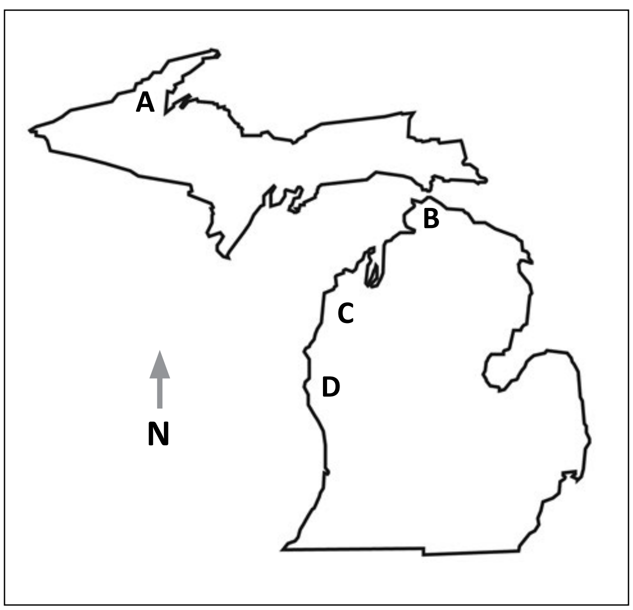


Figure 21.—Location of four long-term study sites (A, B, C, D) tracking phenology in hardwood forests in northern Michigan (Burton et al. 1996). © Canadian Science Publishing or its licensors.

Bird Populations and Range Shifts

Spring is coming earlier across the assessment area, and migratory birds are returning earlier, too. In the Upper Peninsula, a study shows that among the 47 bird species that migrate through the region, 20 species arrived an average 19 days earlier in 1994 than in 1965 (Price and Root 2000). Another study indicates that birds that winter in the southern United States have been arriving disproportionately earlier (13 days) than birds that winter in Central or South America (4 days), suggesting that short-distance migrants are better able to track changes in local conditions than are long-distance migrants (Butler 2003).

Nonmigratory species are also taking up new residency in northern locations. In the Upper Peninsula, a few bird species that historically migrated south for the winter have now become year-round residents (Price and Root 2000). The red-bellied woodpecker has expanded its winter range into northern Wisconsin and the western Upper Peninsula, possibly because the milder winters

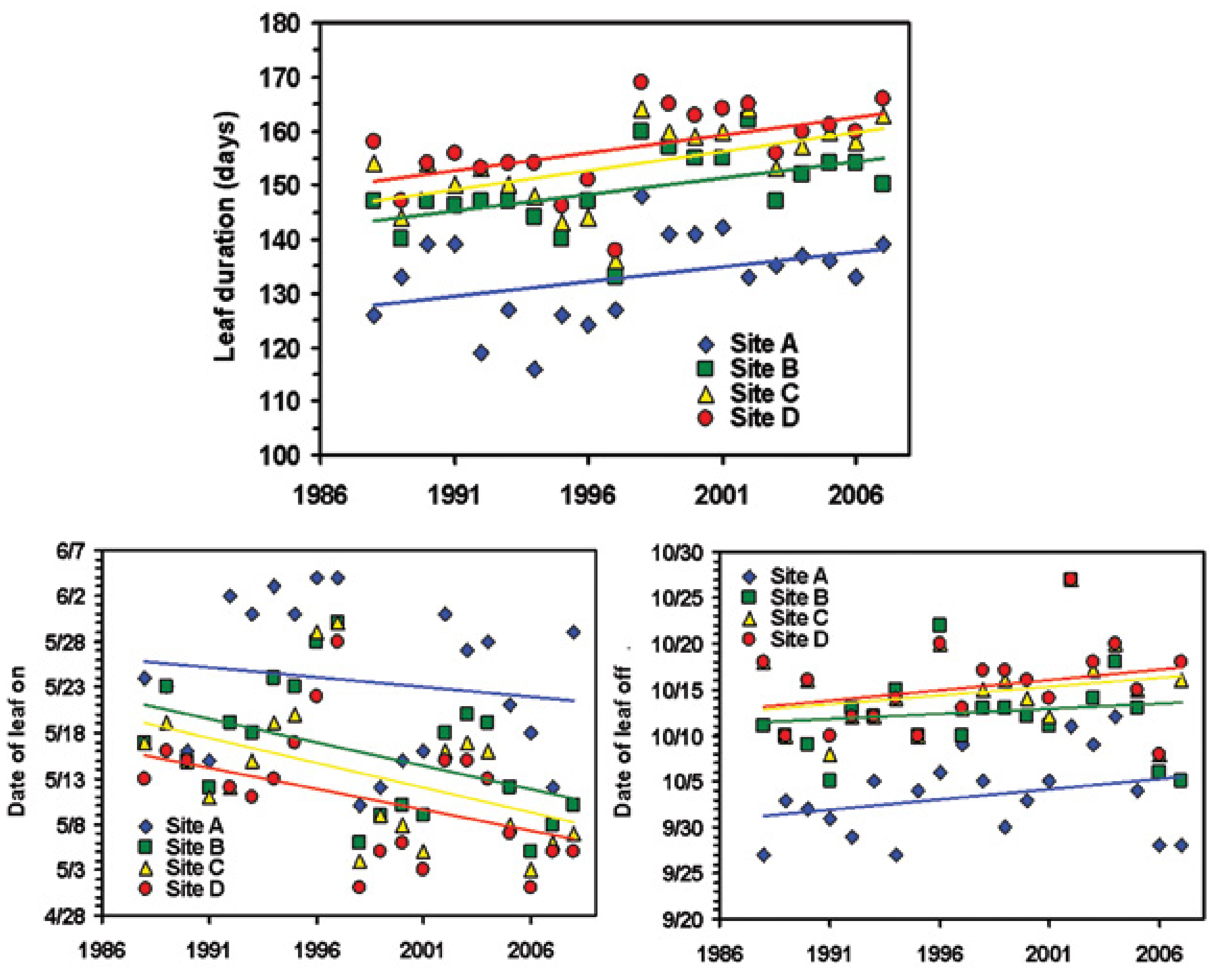


Figure 22.—Leaf phenology trends across four northern hardwood study sites in Michigan. Leaf duration is the number of days between leaf-out and leaf-drop (A.J. Burton, Michigan Technological University, unpublished data). All trends are consistent with and likely caused by rising temperatures in the region.

allow birds to survive farther north than previously (Adams and Wenger 2011).

Changes in the climate can affect the timing of events both for particular species and for the species they depend on. Migration dates are closely tied to availability of food and spring temperatures. If arrival dates are not aligned with similar phenological changes in food sources and other resources, reproductive success may decline (Both et al. 2004). Many species rely on day length rather than temperature for their phenological cues. Even though temperature is warming, the day length stays the same, which suggests the potential for a future mismatch with required resources, such as insect larvae for food. The complexities of phenological shifts may pose a greater challenge for conservationists and land managers in the future.

SUMMARY

The assessment area has observed several notable shifts in climate, climate-driven processes, and extreme weather events. In general, the assessment area is experiencing warmer weather across the year, particularly with respect to mean minimum temperatures and winter 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 appear to be 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.

A swan nesting in a wetland on the Ottawa National Forest. Photo by Maria Janowiak, U.S. Forest Service.

CHAPTER 4: PROJECTED CHANGES IN CLIMATE AND PHYSICAL PROCESSES

Climate across the Great Lakes region has changed over the past century, and it will continue to change in the future. 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 simulations of climate models. The models, data sources, and methods used to generate these downscaled projections, as well as the inherent uncertainty in making long-term projections, are described in greater detail in Chapter 2. In some cases, these downscaled data are then incorporated into hydrologic models to better understand impacts on such variables as soil moisture, evapotranspiration, and streamflow. Information related to future weather extremes and other impacts is drawn from published research.

PROJECTED CHANGES IN TEMPERATURE AND PRECIPITATION

Projections of future climate show the potential for dramatic changes over this century. Temperature and precipitation are projected to change, with important seasonal variations and associated changes in snow and ice cover, growing season length, soil moisture, lake levels, and streamflow.

In this chapter, we report downscaled climate projections for two combinations of global climate models and emissions scenarios: GFDL A1FI and PCM B1 (unless otherwise noted). The GFDL A1FI model-scenario combination projects greater increases in regional temperature than does the PCM B1 scenario (see Chapter 2). It is possible that actual emissions and temperature increases could be lower or higher than either of these projections. The GFDL A1FI scenario represents a projection of future greenhouse gas emissions and temperature increases that is closest to current trends (Raupach et al. 2007). The future will probably be different from any of the developed scenarios, and therefore we encourage readers to consider the range of possible climate conditions over the coming decades rather than one particular scenario.

Daily mean, minimum, and maximum temperature and total daily precipitation were downscaled to an approximately 7.5-mile grid across the United States (see Chapter 2). Projected values were determined for the average daily mean, minimum, and maximum temperature for each season and the entire year for three 30-year periods (2010 through 2039, 2040 through 2069, and 2070 through 2099). Daily precipitation values were summed by year and season, and 30-year means were calculated. We compared these means with the baseline historical data from 1971 through 2000, presented in Chapter 3, in order to determine the future change from current climate conditions.

Temperature

Scientists agree with greater than 90-percent certainty that the global climate will get warmer in the next 100 years (Intergovernmental Panel on Climate Change [IPCC] 2007a). This warming will translate into a wide-ranging set of changes to the climate system, globally as well as locally.

The assessment area is projected to experience substantial warming over the 21st century (Figs. 23 through 26; see also Appendix 3). Although projected temperature increases are fairly small from 2010 through 2039, the projections under the two future scenarios diverge mid-century, with the GFDL A1FI scenario projecting much larger temperature increases. Compared to the 1971 through 2000 baseline period, the mean annual temperature is projected to increase 2.6 °F (1.5 °C) under PCM B1 and 8.7 °F (4.8 °C) under GFDL A1FI by 2100 (Fig. 23).

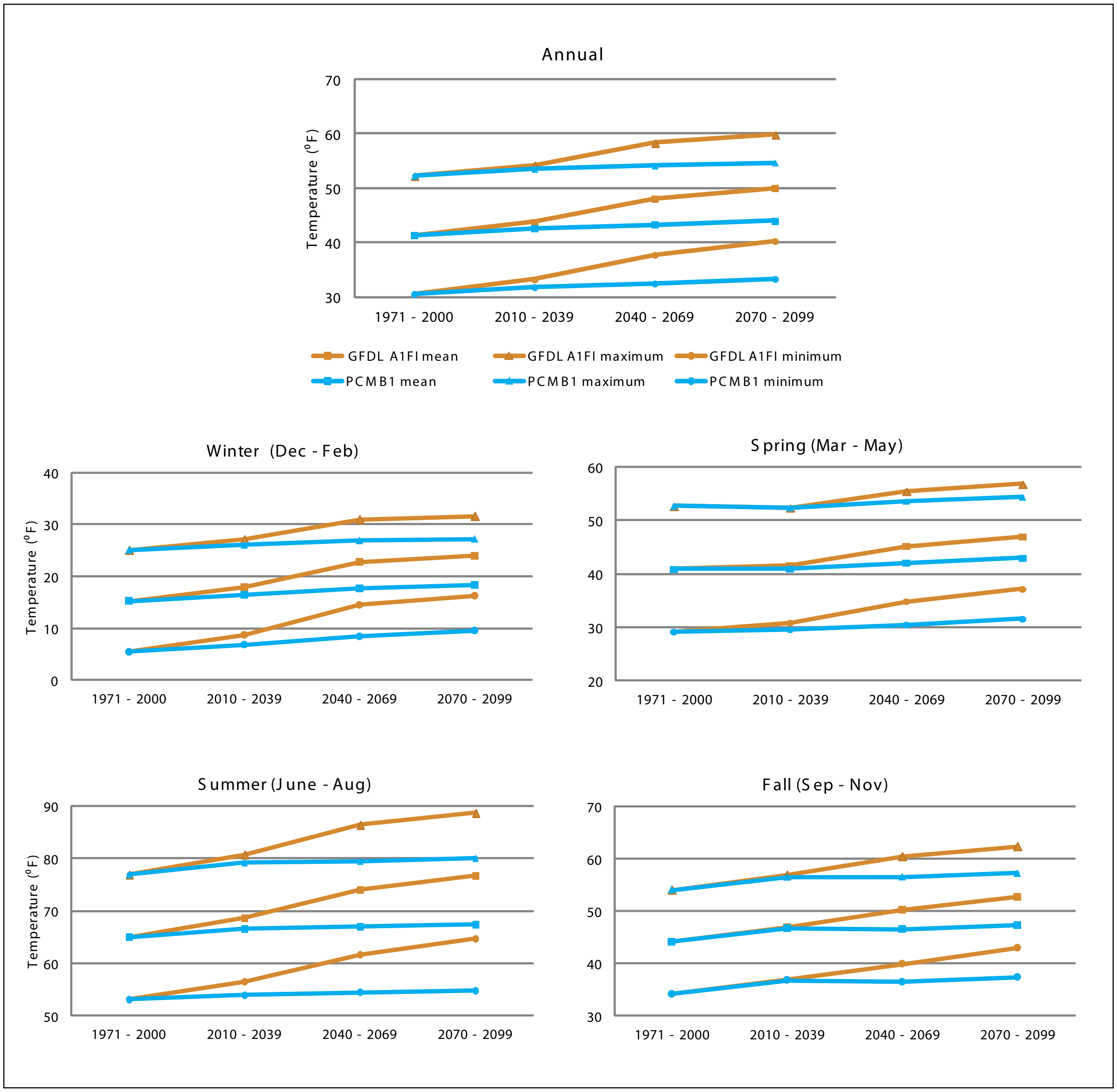


Figure 23.—Projected mean, maximum, and minimum temperatures in the assessment area averaged over 30-year periods for the entire year and by season. The 1971 to 2000 value is based on observed data from weather stations. Note that the panels have different Y-axis values. See Appendix 3 for values of projected change in the early century (2010 through 2039) and mid-century (2040 through 2069).

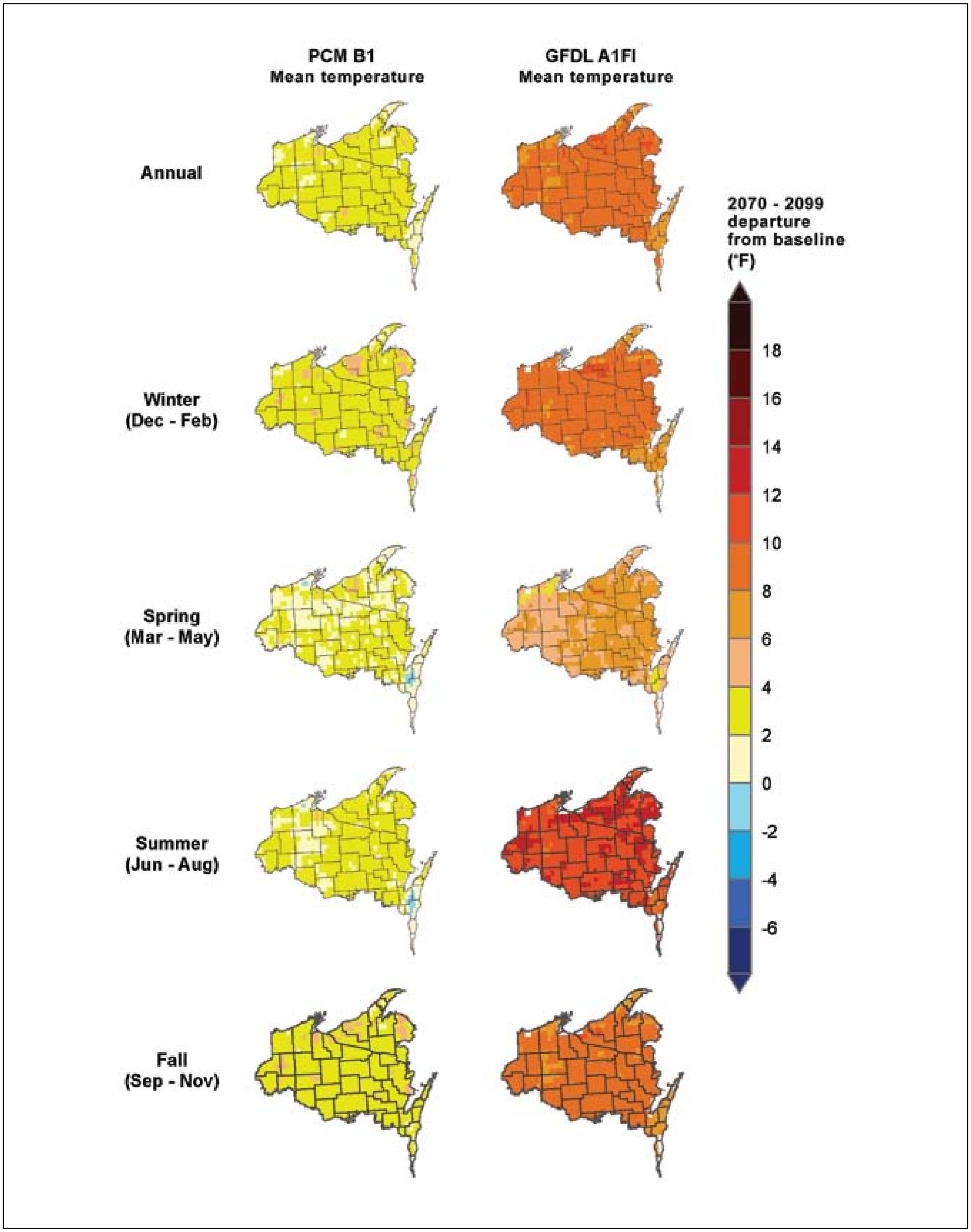


Figure 24.—Projected difference in mean daily temperature at the end of the century (2070 through 2099) compared to baseline (1971 through 2000) for two climate scenarios. Sufficient data were not available for Isle Royale, Michigan.

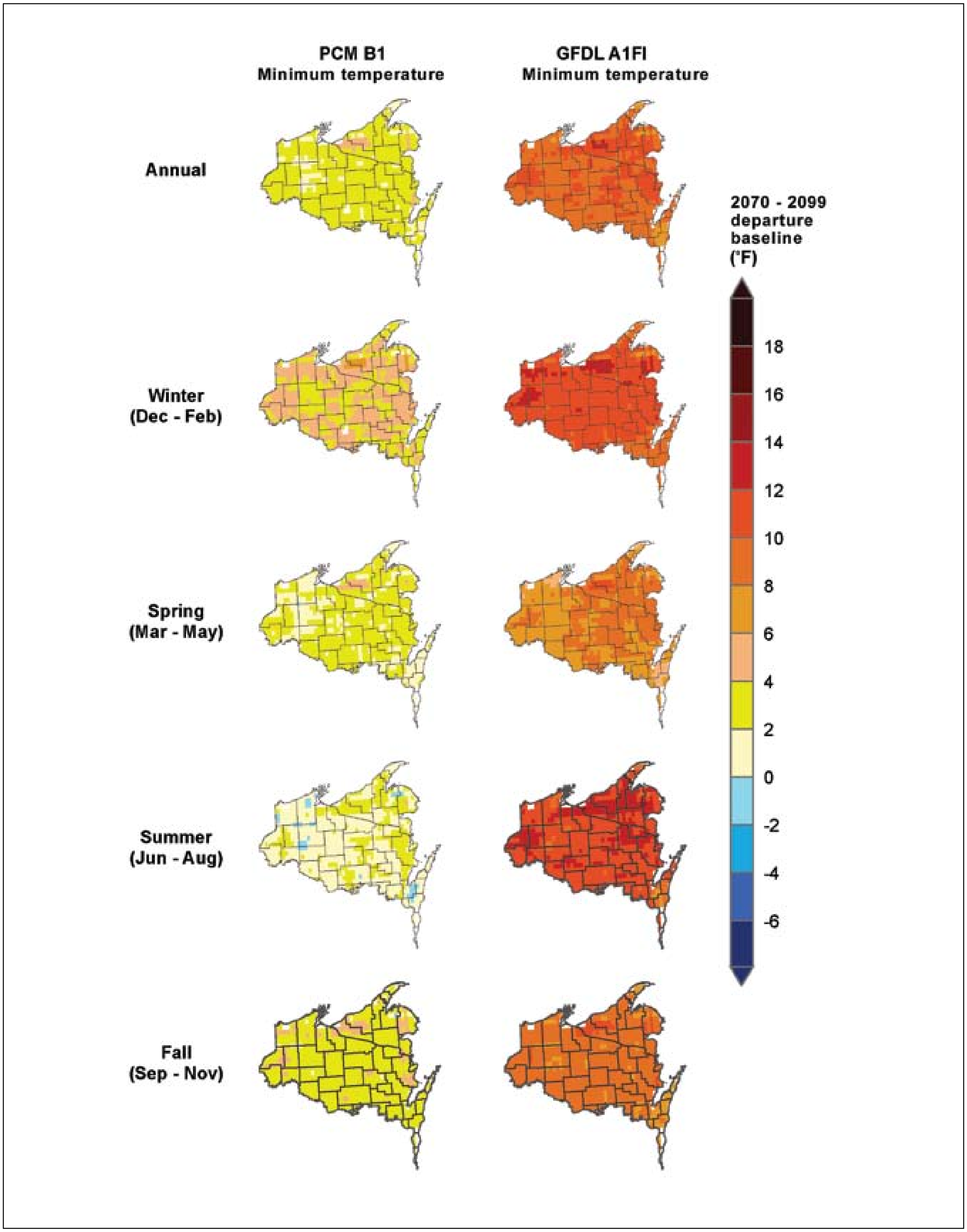


Figure 25.—Projected difference in minimum daily temperature at the end of the century (2070 through 2099) compared to baseline (1971 through 2000) for two climate scenarios. Sufficient data were not available for Isle Royale, Michigan.

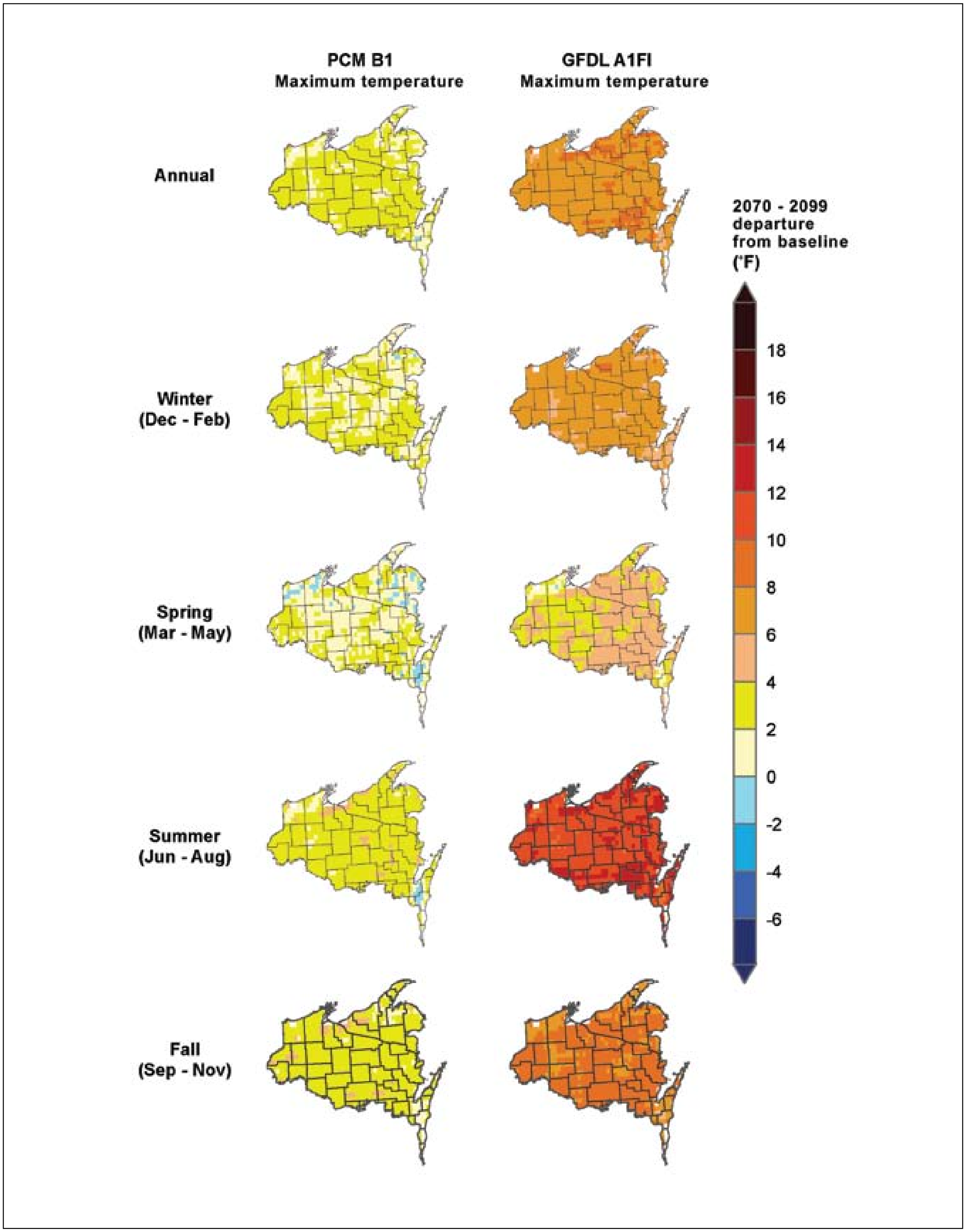


Figure 26.—Projected difference in maximum daily temperature at the end of the century (2070 through 2099) compared to baseline (1971 through 2000) for two climate scenarios. Sufficient data were not available for Isle Royale, Michigan.

The projected increase in mean temperature is not equal across all seasons. The PCM B1 scenario projects relatively similar warming throughout the year, with increases of 2.0 to 3.2 °F (1.1 to 1.8 °C) during each season. In contrast, the GFDL scenario projects mean temperature increases of 6.0 °F (3.3 °C) and greater in each season. Under this scenario, summer is projected to have the most substantial warming with an increase of 11.6 °F (6.5 °C). Appendix 3 contains numerical values and maps of projected temperature change in the early century (2010 through 2039) and mid-century (2040 through 2069).

Minimum annual temperature is projected to increase across the assessment area by 2.7 and 9.7 °F (1.5 and 5.4 °C) by the end of the century under the PCM B1 and GFDL A1FI scenarios, respectively (Fig. 25). Minimum temperature under the PCM B1 scenario is projected to increase the most in winter, warming 4.1 °F (2.3 °C) by the end of the century. Under GFDL A1FI, the projected increase in winter mean temperature is 10.9 °F (6.0 °C).

Minimum temperatures are generally projected to increase more than maximum temperatures under both scenarios during nearly all seasons. Maximum annual temperature is projected to increase by 2.4 to 7.5 °F (1.3 to 4.2 °C) under the two scenarios (Fig. 26). Summer is the only season where increases in maximum temperatures are expected to exceed increases in minimum temperatures. Summer maximum temperatures are projected to increase 3.0 °F (1.7 °C) by the end of the century under PCM B1 and 11.6 °F (6.5 °C) by the end of the century under GFDL A1FI.

Although the two climate scenarios project different amounts of warming, they are in agreement that mean, maximum, and minimum temperature will increase in the assessment area during all seasons. The PCM B1 scenario projects much less warming than the GFDL A1FI scenario for the end of the century. Under PCM B1, the mapped results show few areas that are projected to experience temperature changes more than 2.0 °F (1.1 °C; Figs. 24 through 26). Conversely, the GFDL A1F1 scenario generally indicates warming greater than 6.0 °F (3.3 °C) across much of the assessment area. This divergence is due in part to the two climate scenarios we chose for this assessment, which are intended to bracket the potential range of future temperature for the assessment area.

Precipitation

The two climate scenarios we chose for this assessment also describe two markedly different scenarios of future precipitation for the assessment area (Figs. 27 and 28). Substantial variation exists among future projections of precipitation across the Midwest (Center for Climatic Research 2013, Kunkel et al. 2013, Winkler et al. 2012). For this reason, it is important to keep in mind that other climate model and emissions scenario combinations vary widely in projected future precipitation. Other scenarios may project precipitation values outside of the range presented in this assessment.

For the assessment area, mean annual precipitation is projected to increase by 0.5 inches under the GFDL A1FI scenario by the end of the 21st century (Fig. 28; see also Appendix 3) compared to the 1971 through 2000 baseline. By contrast, annual precipitation is projected to increase more substantially under the PCM B1 scenario, by an average of 2.7 inches. Appendix 3 contains tables and maps of projected precipitation change in the early century (2010 through 2039) and mid-century (2040 through 2069).

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 1.5 inches more precipitation over the

21st century. Summer precipitation under this scenario is projected to increase by 1.1 inches by mid-century. The GFDL A1FI scenario projects a much sharper distinction between these seasons, with spring precipitation increasing 3.2 inches and summer precipitation declining by 4.8 inches. Those projections represent a 47-percent increase in spring precipitation, followed by a 41-percent decrease in summer precipitation. Winter precipitation is expected to increase slightly over time under both scenarios. Fall precipitation is expected to decline slightly by the end of the century under the PCM B1 scenario (-0.3 inches), and to increase 1.6 inches under GFDL A1FI.

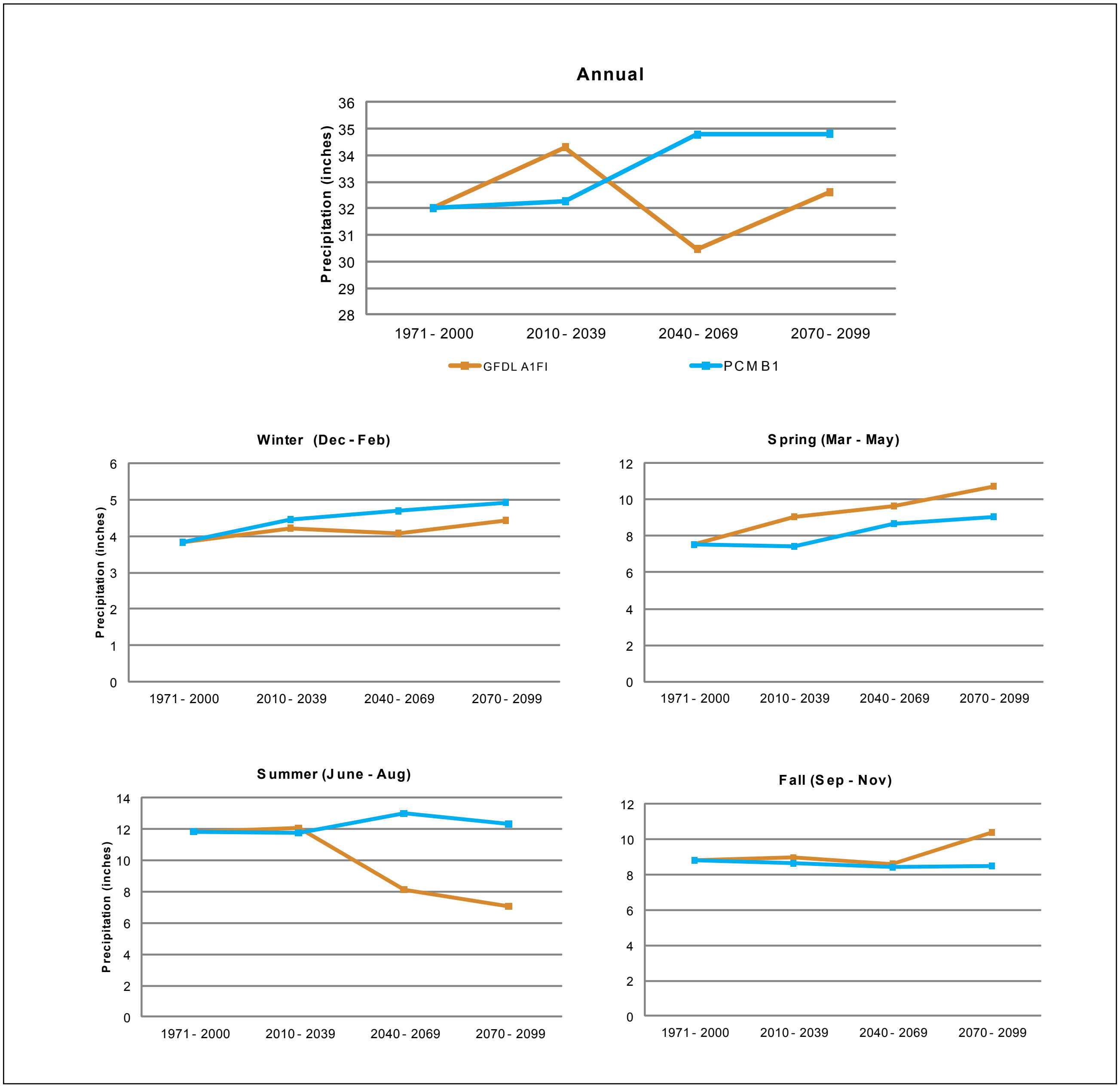


Figure 27.—Projected trends in average precipitation in the assessment area averaged over 30-year periods for the entire year and by season. The 1971 through 2000 value is based on observed data from weather stations. Note that the panels have different Y-axis values.

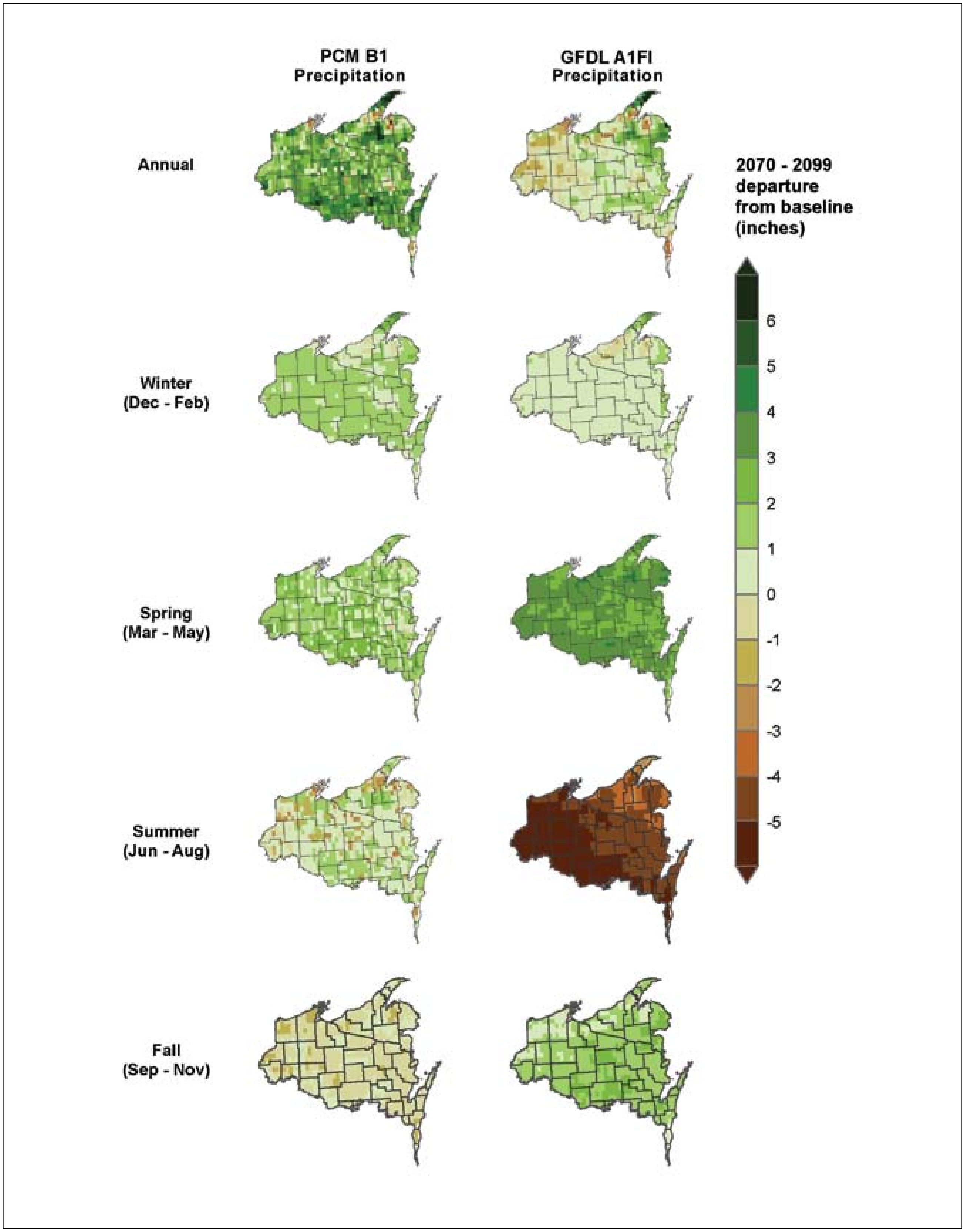


Figure 28.—Projected difference in mean precipitation at the end of the century (2070 through 2099) compared to baseline (1971 through 2000) for two climate scenarios. Sufficient data were not available for Isle Royale, Michigan.

Evapotranspiration and Precipitation Ratios

Temperature and precipitation are important climatic factors governing forest ecosystems, and it is projected that both will continue to change within the assessment area over the coming century. Trees and other plants derive water from soils, and the amount of soil moisture is governed by the hydrologic balance between evapotranspiration—that is, the combined amount of water lost through evaporation from soils and transpiration from plants—and precipitation. Warmer temperatures generally increase evapotranspiration, which means that a corresponding increase in precipitation is needed to maintain the same level of soil moisture under warmed conditions.

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 a reduction in precipitation. As temperatures increase the atmosphere is able to hold more 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 examine changes in the ratio of evapotranspiration to precipitation. This ratio of evapotranspiration to precipitation (ET:P) can be used as a metric to describe the balance between demand and supply of available water in forest ecosystems. Projected changes in this ratio can indicate whether a forest may experience drier or wetter conditions in the future compared to recent conditions. A positive change in ET:P values indicates that evapotranspiration has increased relative to available moisture and that forests are expected to be under increased moisture stress. Conversely, a negative change in ET:P values indicates that more moisture is available to forests.

We used the ecosystem model PnET-CN to calculate projected changes in ET:P for the assessment area, comparing the baseline period (1971 through 2000) to the years 2070 through 2099 under both PCM B1 and GFDL A1FI (Fig. 29). Because evapotranspiration is an output of the PnET-CN model, the values incorporate projected changes in forest productivity due to temperature and precipitation changes, growing season length, carbon dioxide (CO_2) fertilization, and other factors. Chapter 2 describes the PnET-CN model in greater detail, and additional results from this model are presented in Chapter 5.

The PnET-CN model projects little change in annual ET:P across the assessment area under both climate scenarios (Fig. 29). Projected changes are also relatively small for the fall, winter, and spring seasons, with some geographic variability. Summer months are projected to have the greatest change in ET:P of all seasons, with the two climate scenarios projecting substantially different outcomes. Under PCM B1, slightly wetter conditions are projected based on a decrease in the ET:P ratio. Conversely, the GFDL A1FI scenario projects substantially drier conditions during the summer (large increase in ET:P). This overall trend is consistent with the precipitation trends discussed above.

The changes in ET:P values indicate 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 summer temperature increase of 10.8 °F (6.0 °C) results in higher evapotranspiration for forests across the assessment area, which essentially intensifies the effects of the projected decreases in precipitation.

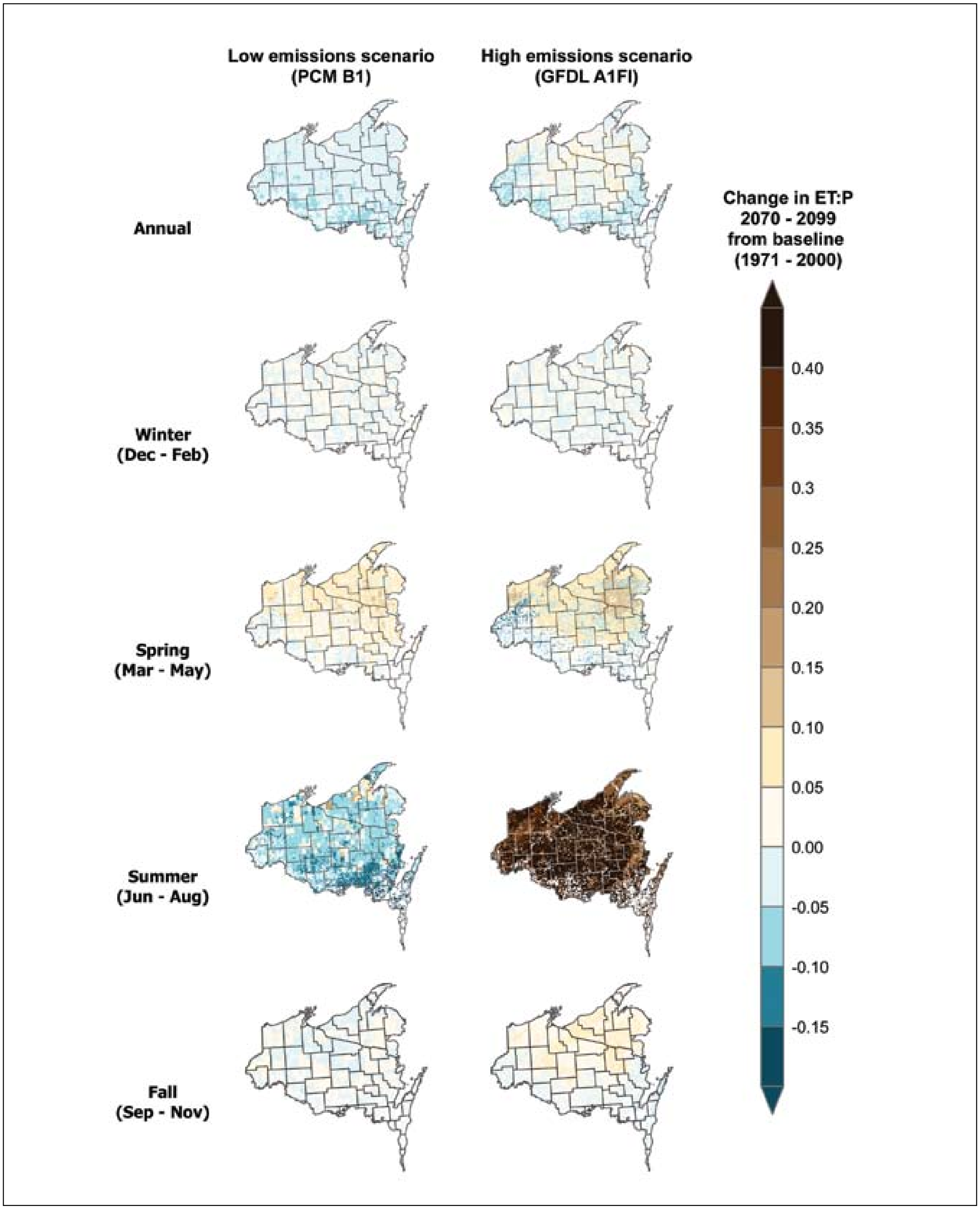


Figure 29.—Projected changes in the ratio of evapotranspiration to precipitation (ET:P) under two future climate scenarios for the assessment area during 2070 through 2099. Data source: Stoner et al. (2013) and Peters et al. (2013). Positive values indicate that ET is projected to increase relative to available moisture, increasing the potential for forests to be under moisture stress. Negative values indicate that more moisture is projected to be available.

Importantly, the 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 that do not include the CO_2 fertilization benefit resulted in substantially drier conditions (higher ET:P ratios) for the assessment area during the growing season (not shown). These results suggest that forests could undergo 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.

GROWING SEASON LENGTH

The assessment area has experienced an expansion of the growing (i.e., freeze-free) season over the past century, as noted in Chapter 3, and models project that these changes will continue into the future. Growing season length in the assessment area is projected to increase by 14 to more than 49 days under a range of emissions scenarios (Center for Climatic Research 2013) (Fig. 30). The projected expansion of the growing season is a result of both earlier spring freeze-free dates and later fall freezes (Center for Climatic Research 2013). These results are similar to those from another study across the Midwest region, which 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 (Wuebbles and Hayhoe 2004). The last spring frost dates were projected to shift earlier into the year at about the same rate that first fall frost dates were projected to retreat later into the year (Wuebbles and Hayhoe 2004).

EXTREME WEATHER EVENTS

Many extreme weather events are expected to change as a result of a changing climate. In general, there is less confidence in model projections of the magnitude and direction of change in extreme events over the next century compared with general temperature and precipitation changes. The infrequent nature of extreme events increases the difficulty of detecting changes in the frequency or intensity of events over time, as well as attributing these alterations to climate change (Coumou and Rahmstorf 2012, Stott et al. 2010). However, there is mounting evidence for projected increases in many extreme weather events across the Midwest (Kunkel et al. 2013, WICCI 2013).

Temperature Extremes

In addition to projecting mean temperatures, downscaled daily climate data can be used to estimate the frequency of extreme high and low temperatures in the future. Studies from across the Midwest region point to an increasing frequency of hot days across the assessment area, with roughly 20 to 30 more days per year above 95 °F (35 °C) and a greater frequency of multi-day heat waves (extended periods of extremely hot weather) by the end of the century (Diffenbaugh et al. 2005, Perera et al. 2012, Winkler et al. 2012). These trends are consistent with another assessment covering the entire Midwest region, which projected that the assessment area could experience up to 10 more days above 95 °F (35 °C) by the end of the 21st century (Kunkel et al. 2013). Similarly, an assessment for Wisconsin projected 6 to 22 more days above 90 °F (32.2 °C) for northern Wisconsin by the end of the century (WICCI 2011b). Heat waves are also projected to occur more frequently across the Midwest (Wuebbles and Hayhoe 2004, Karl et al. 2009), driven largely by the increase in the frequency of extremely high nighttime temperatures (Karl et al. 2009, Meehl and Tebaldi 2004).

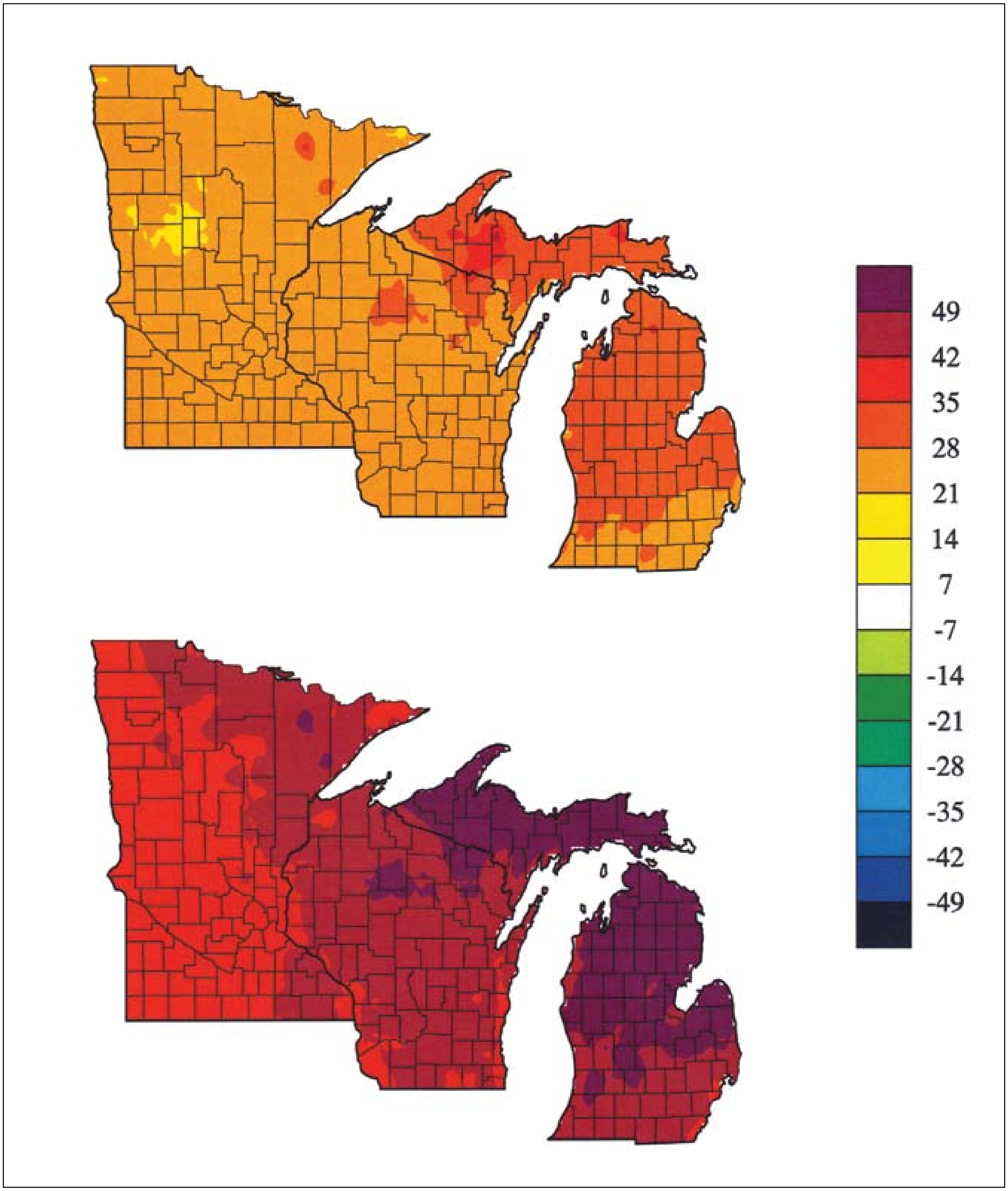


Figure 30.—Projected change in the growing season length in days (number of days between the last spring freeze and the first autumn freeze, where a freeze is when the daily low temperature drops below 32 °F [0 °C]), based on nine global climate models from the Coupled Model Intercomparison Project Phase Three (CMIP3), computed as the difference between 2081 to 2100 and 1981 to 2000. Results are shown for the B1 (upper map) and A2 (lower map) emissions scenarios. The A2 emissions scenario projects greenhouse gas emissions similar to the A1FI scenario. The source of the data is a daily, statistically-downscaled climate product from the Center for Climatic Research, University of Wisconsin – Madison.

Extremely cold temperatures are projected to become less frequent, without completely disappearing, as the climate warms. Downscaled climate scenarios project that the Midwest will experience between 25 and 38 fewer days below 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). Another study shows similar results, with as many as 24 fewer nights below 0 °F (-17.8 °C) projected in northern Wisconsin by 2100 (WICCI 2011b). It is important to note, however, that the enhanced warming occurring in polar regions greatly influences weather patterns in the mid-latitudes and can lead to periods of extreme cold, even as the overall climate becomes warmer (Francis and Vavrus 2012, Vavrus et al. 2006).

Intense Precipitation

As described in Chapter 3, there is a clear trend toward more extreme precipitation events in the assessment area and the entire Midwest region (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 indicate that the entire Midwest region is projected to receive 23 percent more rainfall events greater than 1 inch by 2100, with larger events increasing by progressively larger amounts (Kunkel et al. 2013). Other climate data project up to 1.5 more days per year having events greater than 1 inch by the end of the century across the assessment area under a low emissions scenario and greater than 1.5 additional days per year under a high emissions scenario (Fig. 31).

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 also 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 experience 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 due to landscape position, soils, and other factors. For example, 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. For these reasons, if rainfall becomes more episodic, these areas may suffer from additional drought stress even if there is an overall increase in moisture or precipitation.

Thunderstorms

General circulation models do not operate at a scale small enough to model thunderstorms explicitly and many of the climatic processes that produce thunderstorms are not well modeled. Nevertheless, evidence suggests that temperature increases may lead to conditions more favorable to convective storms such as thunderstorms due to increased atmospheric water vapor in the lower portions of the atmosphere (Kunkel et al. 2008; Trapp et al. 2007, 2009). Researchers examined changes in thunderstorm potential over the 21st century using a mid-range emissions scenario (A1B; Trapp et al. 2009). They found a slight increase in the frequency of conditions favorable for severe thunderstorms in the Midwest. A similar study found an increase in severe thunderstorm potential in the region at the end of the century under a higher emissions scenario (A2; Trapp et al. 2007).

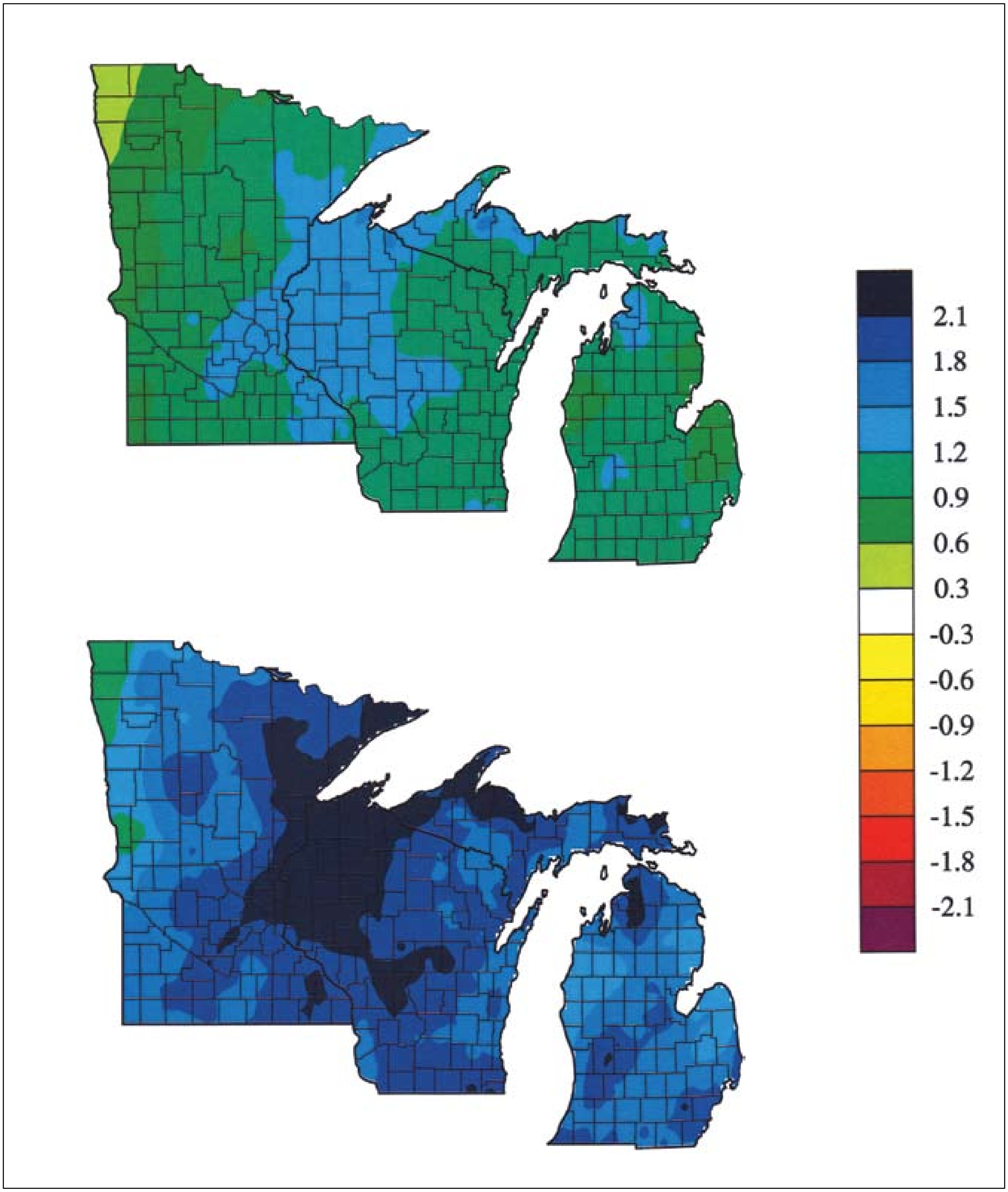


Figure 31.—Projected change in the frequency of heavy precipitation events per year (days with at least 1 inch of precipitation), based on nine global climate models from the Coupled Model Intercomparison Project Phase Three (CMIP3), computed as the difference between 2081 to 2100 and 1981 to 2000. Results are shown for the B1 (upper map) and A2 (lower map) emissions scenarios. The A2 emissions scenario projects greenhouse gas emissions similar to the A1FI scenario. The source of the data is a daily, statistically-downscaled climate product from the Center for Climatic Research, University of Wisconsin – Madison.

Tornadoes and Hail

Very little is known about how the frequency, severity, and seasonal patterns of tornadoes and hail may change over the next century. A recent synthesis report on extreme weather events stated that "there is low confidence in projections of small spatial-scale phenomena such as tornadoes and hail because competing physical processes may affect future trends and because current climate models do not simulate such phenomena" (IPCC 2012: 8). As the sophistication of global and regional climate models increases, so will our understanding of how patterns in tornadoes and hail may change in the future.

PROJECTED CHANGES AFFECTING WATER AND SOILS

As discussed above, several climatic changes are projected to occur over the next century in the assessment area, including warmer temperatures, altered patterns of seasonal precipitation, and increased potential for intense rain events. All of these changes, when combined, have the potential to cause substantial changes to hydrologic regimes and soil moisture.

Lake Temperature and Ice Cover

Many changes in lake temperature and ice cover have been observed on the Great Lakes and inland lakes. Surface temperatures of Lake Superior during spring, summer, and fall are projected to continue increasing through the end of the century (Trumpickas et al. 2009). Increased temperatures are expected to cause further decreases in the duration, thickness, and extent of ice cover during winter (Wuebbles and Hayhoe 2004). In fact, ice cover on both Lake Michigan and Lake Superior is projected to decline and at the current rate of ice cover loss, Lake Superior is expected to remain largely free of ice in a typical winter by mid-century (Austin and Colman 2007). Changes in temperature may also affect lake levels. Lake levels are projected to peak earlier in the year in response to earlier snowmelt and higher precipitation in the winter and spring. Peak lake levels, however, may be lower than levels observed during the past century as evaporation increases with temperature and as longer ice-free periods permit more evaporation (Karl et al. 2009, Wuebbles and Hayhoe 2004).

Cold-season Precipitation

Increases in winter temperatures are expected to continue to alter cold-season precipitation patterns across the assessment area. Total snowfall is projected to decrease more than 10 percent across the assessment area under a low emissions scenario and more than 30 percent under a high emissions scenario by the end of the 21st century (Center for Climatic Research 2013), even as most climate projections indicate increases in winter precipitation (Fig. 27) (Center for Climatic Research 2013, Notaro et al., in press). The largest reductions in snowfall are generally projected to occur in the early and late portions of the snow season—November, December, March, and April (Notaro et al., in press). As one specific example, projections for Ashland, Wisconsin, show a shortening of the season during which frozen precipitation is more likely as well as an overall increase in the probability of rain during December through February (Fig. 32) (WICCI 2013).

Studies have shown that across much of the Midwest region, an increasing percentage of winter precipitation is being delivered as rain rather than snow (Feng and Hu 2007, Notaro et al. 2011). As winter temperatures rise across the assessment area, it is projected that an increasing proportion of winter precipitation will be delivered as rain in the assessment area (Notaro et al., in press, Sinha and Cherkauer 2010, WICCI 2011b). One modeling study also 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),

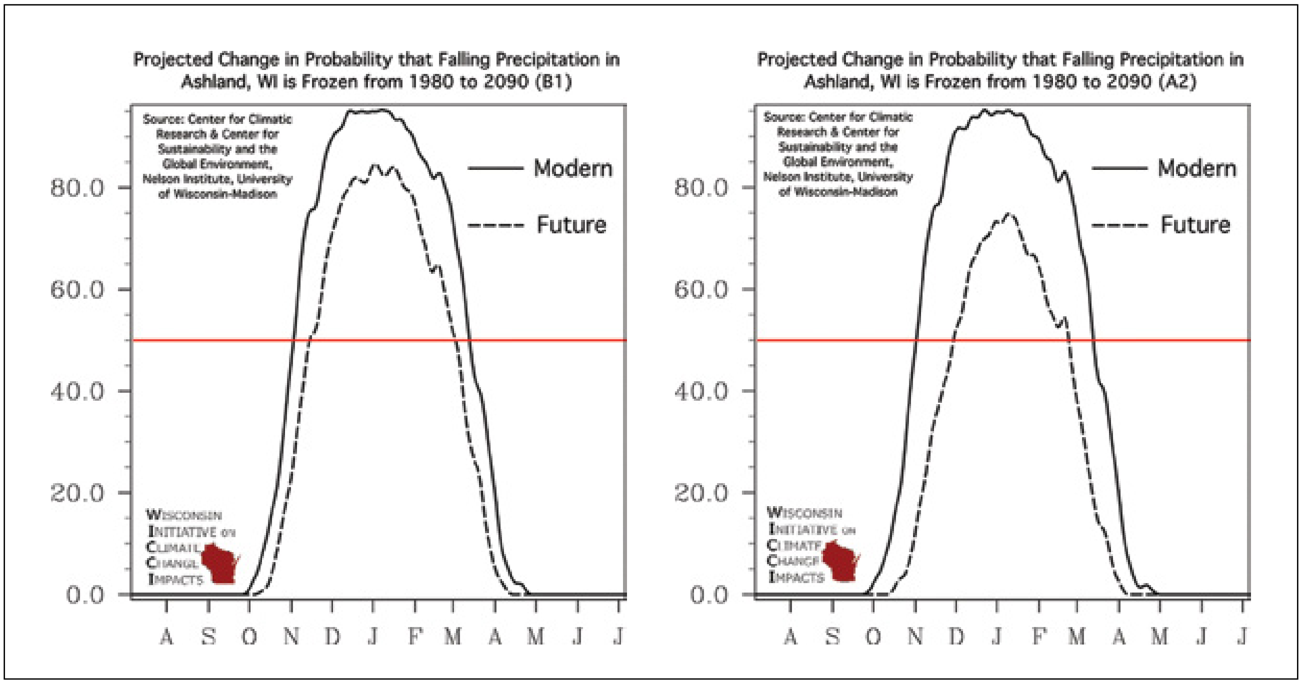


Figure 32.—Projected change in the probability that precipitation is frozen in Ashland, Wisconsin, in 1980 (modern) and 2090 (future) under a low (B1; left) and high (A2; right) emissions scenario. The A2 emissions scenario projects greenhouse gas emissions similar to the A1FI scenario. The red line indicates a 50-percent chance of either rain or snow under current climate (solid line) or future climate (dashed line) conditions. Source: WICCI (2013).

but correspond with the projected increase in winter temperature and the shift from snowfall to rain.

It is more difficult to project snowfall in areas subject to lake-effect precipitation, largely because of interactions among multiple factors, including lake temperature, lake ice cover, and over-water and over-land air temperatures (Notaro et al. 2012, Notaro et al., in press). It is possible that areas that typically receive lake-effect snow may see increased snowfall amounts during the early- and mid-21st century as reduced ice cover allows for greater evaporation from the surface of the Great Lakes (Burnett et al. 2003, Wright et al. 2011). As temperatures continue to warm through the 21st century, however, the potential exists for increasingly warm winter temperatures to negate the effect of decreased lake ice, leading to less lake-effect snowfall and more rain events (Kunkel et al. 2002).

Snow depth during the winter season is expected to decline even more than snowfall amounts, because snow depth will also be reduced by warm temperatures between snowfall events (Notaro et al. 2011, Notaro et al., in press). Even areas that maintain constant or possibly increased snowfall could still experience a decrease in snow depth if winter temperatures prevent snow from accumulating (Kling et al. 2003). November through April snow depth is projected to decrease more than 20 percent by the end of the century across the assessment area under both low and high emissions scenarios, with greater decreases projected for areas farther south (Center for Climatic Research 2013). Similarly, the number of days with snow depth of 3 inches or more is also projected to decrease substantially across the assessment area by the end of the century (Fig. 33).

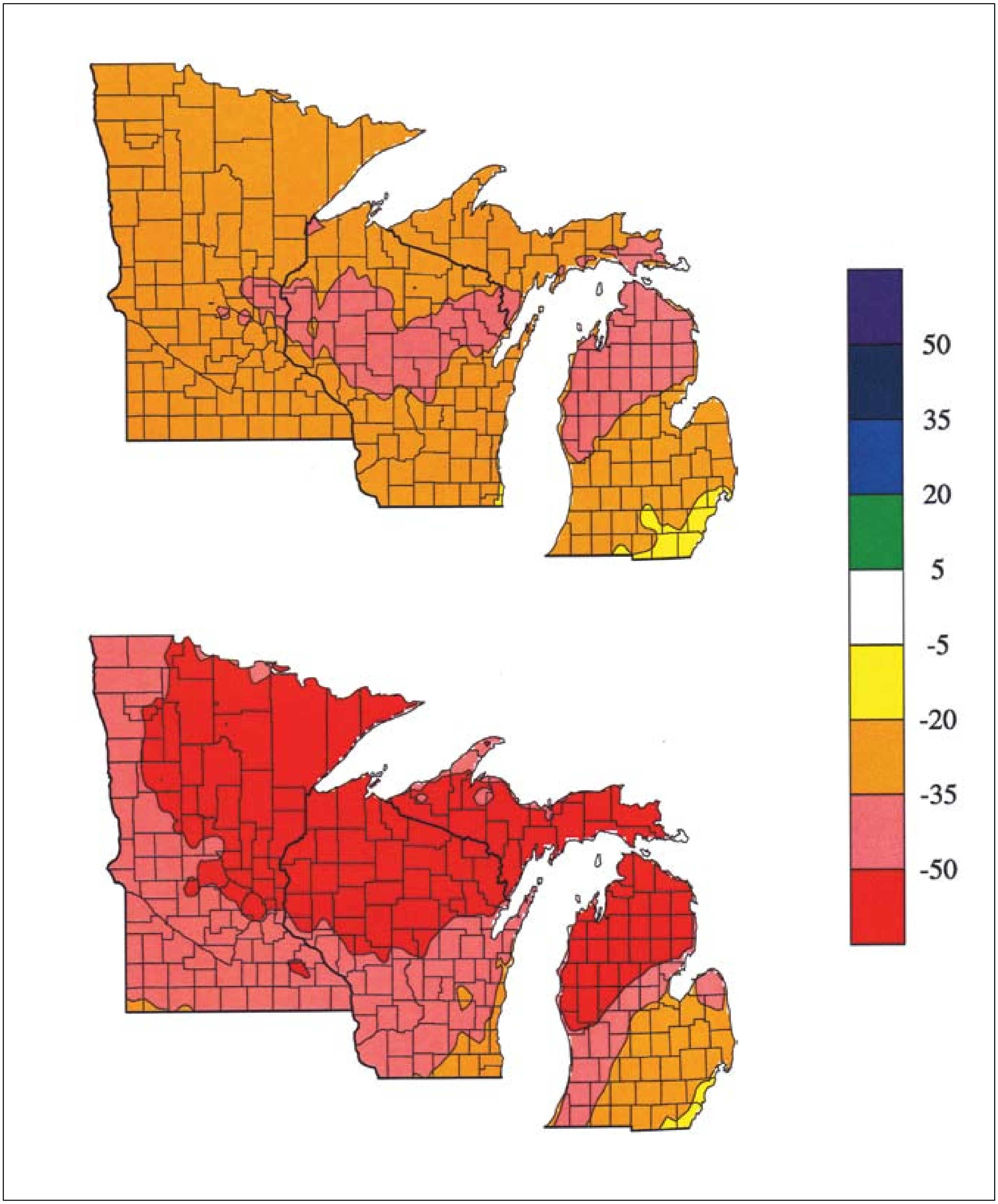


Figure 33.—Projected change in the duration (in days per year) of snowpack of at least 3 inches, based on nine global climate models from the Coupled Model Intercomparison Project Phase Three (CMIP3), computed as the difference between 2081 to 2100 and 1981 to 2000. Results are shown for the B1 (upper map) and A2 (lower map) emissions scenarios. The A2 emissions scenario projects greenhouse gas emissions similar to the A1FI scenario. The source of the data is a daily, statistically-downscaled climate product from the Center for Climatic Research, University of Wisconsin – Madison.

Soil Temperature and Frost

The increase in winter temperatures projected across the assessment area under both PCM B1 and GFDL A1FI is generally expected to increase soil temperatures and reduce soil frost. One study projected that cold-season soil temperatures may increase between 1.8 and 5.4 °F (1 and 3 °C) and that the soil frost season may be shortened by 1 to 2 months across the assessment area by 2100 (Fig. 34) (Sinha and Cherkauer 2010). Total frost depth is projected to decline by 40 to 80 percent across the assessment area. The exception may be areas that currently have deep winter snowpack, which insulates soils and prevents soil frost; in these areas, reductions in snow may expose soils to sufficiently cold temperatures and allow for deeper soil frost (Hardy et al. 2001, Isard et al. 2007a). The number of freeze-thaw cycles is also expected to increase, due in part to daytime and nighttime temperature variability (Cherkauer and Sinha 2010). These projections are generally consistent with studies of snowpack and soil frost in New England forests (Campbell et al. 2010).

Runoff, Streamflow, and Flooding

The shifts in winter precipitation and temperature described above are expected to shift the timing of snowmelt, runoff, and peak streamflow earlier into the year (Karl et al. 2009, Kling et al. 2003, Wuebbles et al. 2009). Researchers project that total

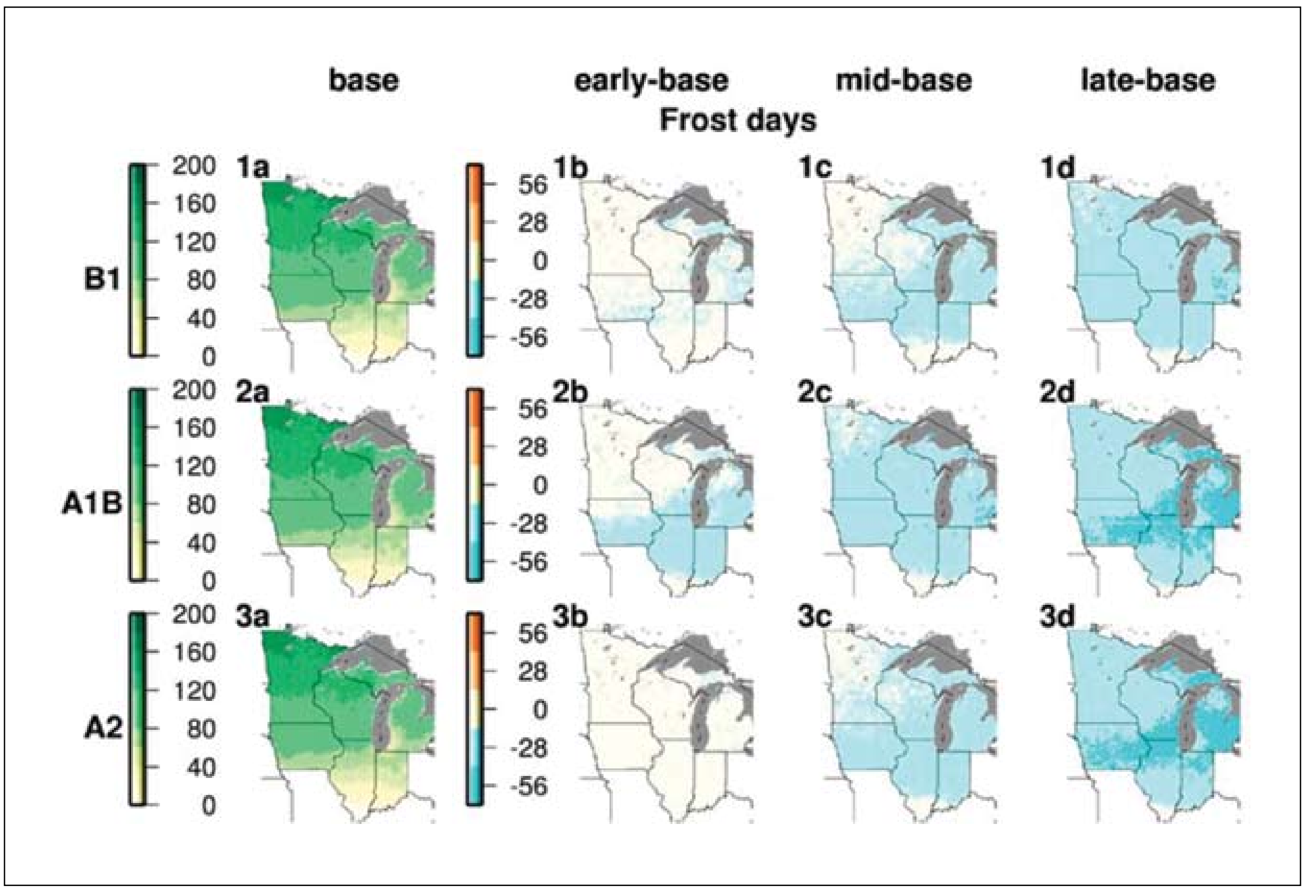


Figure 34.—Baseline and projected number of annual soil frost days for the Midwest under a range of climate scenarios, from Cherkauer and Sinha (2010). Base refers to the average annual number of soil frost days, 1977 through 2006. Early-base, mid-base, and late-base refer to the difference in mean soil frost days from the baseline period for 2010 through 2039, 2040 through 2069, and 2070 through 2099, respectively. 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.

winter runoff values may more than double across much of the assessment area by the end of the 21st century, with the most-dramatic increases in the Keweenaw Peninsula and along the Lake Superior shoreline in Michigan (Fig. 35) (Cherkauer and Sinha 2010). This localized increase is associated with the high winter precipitation amounts in this region and a greater likelihood of winter melt and rain events; because winter runoff levels are generally low, this projected increase was substantial—more than 400 percent in some areas (Cherkauer and Sinha 2010).

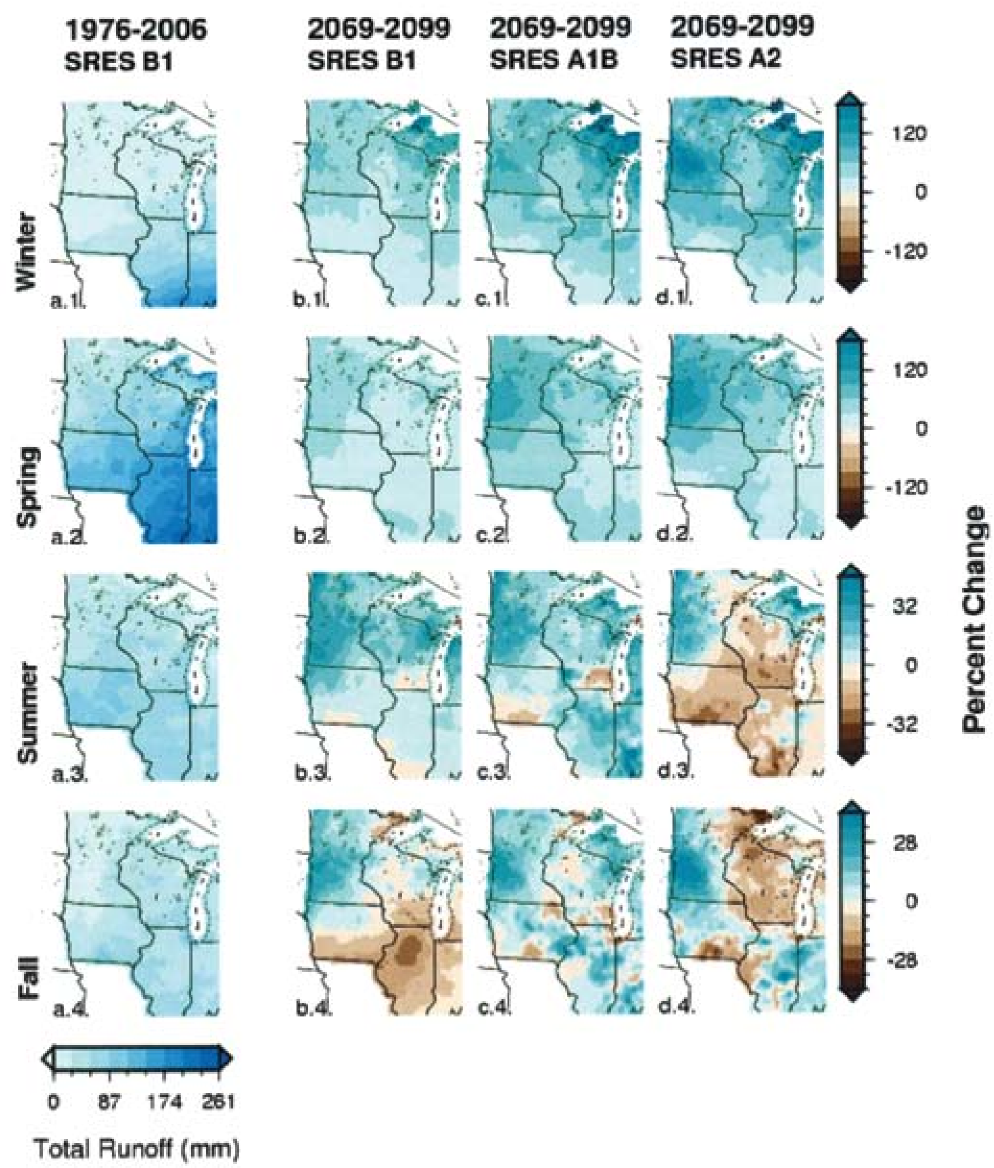


Figure 35.—Spatial distribution of average seasonal cumulative runoff for the Midwest projected for 2069 through 2099 as a percentage change from the base (1977 through 2006) for three emissions scenarios. The A2 emissions scenario is roughly equivalent to the A1FI scenario in terms of greenhouse gas emissions, and the A1B scenario is approximately a middle range between A1FI and B1. Source: Cherkauer and Sinha (2010).

Earlier peak flows coupled with increases in spring precipitation are expected to contribute to increased flood frequency across the Midwest (Karl et al. 2009, Kling et al. 2003). Similarly, high-intensity rainfall events are linked to both flash flooding and widespread floods, although the severity depends on soil saturation and stream levels at the time of the event. For example, a modeling study examining climate change impacts on streamflow across the Midwest projected that runoff and streamflow may shift substantially across the assessment area, with increased runoff during the winter and spring (Cherkauer and Sinha 2010).

As with precipitation, the potential changes in runoff and streamflow during summer and autumn are more complex and less certain. Summer runoff is generally projected to increase across the assessment area under a low emissions scenario, but to vary geographically under a high emissions scenario (Fig. 35) (Cherkauer and Sinha 2010). In fall, total runoff is projected to decline by 8 to 32 percent across the assessment area. Another study indicates similar results for the upper Mississippi River Basin, including the Chippewa and Wisconsin River watersheds (Wuebbles et al. 2009). Stream flashiness has the potential to increase during summer and autumn if future conditions increase the occurrence of both high-flow days and low-flow days (Cherkauer and Sinha 2010).

Soil Moisture and Drought

Changes in soil moisture are largely driven by the balance of precipitation and evapotranspiration, and thus there is some uncertainty about future changes. At the same time, projections of higher temperatures combined with decreases or small increases in precipitation during the growing season suggest a potential for reduced soil moisture and increased drought. As discussed earlier in this chapter, warmer temperatures combined with reduced or unchanged precipitation amounts would increase evapotranspiration levels, and such changes are projected under higher emissions scenarios (Fig. 29). Earlier spring snowmelt and runoff may contribute to late-summer moisture deficits (Cherkauer and Sinha 2010), and shifts in precipitation patterns may result in longer periods between rainfall, with greater amounts of precipitation occurring over fewer precipitation events (Karl et al. 2009). For these reasons, increases in drought are more likely to occur in areas where precipitation is not sufficient to recharge late summer soil moisture deficits (Cherkauer and Sinha 2010).

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. By the end of the 21st century, the assessment area is generally 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. These effects include the direct impacts of climate change, as well as indirect impacts from forest pests, invasive species, altered disturbance regimes, and other interacting factors. To gain a better understanding of how forests in the assessment area may respond to climate change, we rely on forest impact models and 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 are expected to respond to climate change in various ways. Potential effects include changes in tree species composition and diversity, as well as shifts in the spatial distribution, abundance, and productivity of tree species. For this assessment, we rely on a combination of three forest impact models to describe these potential changes: Climate Change Tree Atlas, LANDIS-II, and PnET-CN (Table 9). Tree Atlas uses statistical techniques to model changes in suitable habitat for individual species over broad geographic areas. LANDIS-II is a spatially explicit, dynamic model that includes succession, migration, natural disturbances, timber harvest, and competition to simulate the abundance and distribution of individual tree species. PnET-CN simulates carbon, water, and nitrogen in forest ecosystems and calculates the productivity of several forest types.

No single model offers a perfect projection of future change in forest ecosystems, but each tool provides useful information. Similar results across models suggest more plausible outcomes, and differences between model projections provide opportunities to better understand the nuances of ecological responses given the strengths and limitations of the models (Iverson et al. 2011). Chapter 2 contains more thorough descriptions of the different forest impact models and how they were applied for this assessment.

Importantly, all of these modeling investigations relied on a consistent set of future climate data. All three research teams used the same two climate model-emissions scenario combinations: GFDL A1FI and PCM B1 (described in detail in Chapters 2 and 4). The GFDL A1FI model-scenario combination is on the higher end of the spectrum for future temperature increases, and PCM B1 represents a less substantial temperature increase. This consistency in the input climate data means that the forest impact models are describing potential forest changes over the same range of plausible future climates. A more complete description of general circulation models and emissions scenarios is also provided in Chapter 2.

These model results are best used to describe trends across large areas and over long time scales. These 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. In this chapter, we present model results for the end of the 21st century.

Table 9.—Overview of impact models used for this assessment and the different features included in future simulations [a]

Feature	Climate Change Tree Atlas	LANDIS-II	PnET-CN
Summary	Suitable habitat distribution model (DISTRIB) and supplementary information (modifying factors)	Spatially explicit, 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
Climate scenarios	PCM B1, GFDL A1FI	PCM B1, GFDL A1FI	PCM B1, GFDL A1FI
Area modeled	Full assessment area: Ecological Section IX in Michigan and Sections VIII, IX, and X in Wisconsin (Albert 1995) (Fig. 2)	Most of the assessment area: Ecological Sections IX and X and Ecological Subsection VIII.3.1 in Wisconsin (Albert 1995); Baraga, Gogebic, Houghton, Iron, and Ontonagon Counties in the Upper Peninsula of Michigan; Chisago County in eastern Minnesota (Fig. 41)	Full assessment area: Ecological Section IX in Michigan and Sections VIII, IX, and X in Wisconsin (Albert 1995) (Fig. 2)
Dispersal and colonization	No*	Yes, for 27 species currently present in the assessment area	No
Competition, survival, and reproduction	Not modeled, but addressed through the modifying factors.	Yes	No
Forest management	No	Yes	No**
Disturbances	Not modeled, but modifying factors include sensitivity to disturbance.	Yes: wind (Fire, insects, browse, and other disturbances were not modeled.)	No**
CO_2 fertilization	No	No	Yes
Succession and community shifts	No	Yes	No
Biogeochemical feedbacks	No	No**	Yes

[a] See Chapter 2 for model descriptions.
* The SHIFT component of the Climate Change Tree Atlas includes dispersal and colonization, but this is not discussed in this document with the exception of the results presented in Box 10.
** This parameter can be an output for this model, but was not investigated in this assessment.

Data for intermediate time periods are provided in Appendix 4 (Tree Atlas) and Appendix 5 (LANDIS-II).

Tree Atlas

Importance values of 134 eastern tree species were modeled for potential habitat suitability in the assessment area by using the DISTRIB component of the Tree Atlas (Iverson and Prasad 1998, Iverson et al. 2008). Importance value is an index of the relative abundance of a species in a given community, and can range from 0 (not present) to 100 (only species present in the area) in a single 12.4-mile grid cell (Iverson and Prasad 1998). Single-cell importance values were calculated and then summed across the assessment area to reach the area-weighted importance value for a species. In the assessment area, 78 of the 134 species are of interest because suitable habitat is currently present or is projected to be present in the assessment area by the end of the century. Chapter 2 contains more detail on the Tree Atlas methods.

The projected change in potential suitable habitat for the 78 species was calculated for the years 2070 through 2099 by using the GFDL A1FI and PCM B1 scenarios and compared to present values (Table 10). Species are 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 are mixed. Further, some tree species that are currently not present in the assessment area are identified as having potential suitable habitat in the future under one or both scenarios. Appendix 4 contains complete results from the DISTRIB model, including projections for three different periods (2010 through 2039, 2040 through 2069, and 2070 through 2099).

Additionally, when examining these results, it is important to keep in mind that model reliability is generally higher for 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.

Modifying factors have also been incorporated into the Tree Atlas to provide additional information on potential forest change. Modifying factors include a species' life-history traits, known stressors, and other environmental factors that make a species more or less likely to persist on the landscape (Matthews et al. 2011b). These factors are not explicitly included in the DISTRIB outputs, and are based on a literature review of each species. Examples of modifying factors are drought tolerance, dispersal ability, shade tolerance, site specificity, and susceptibility to insect pests and diseases, all of which are highly related to a species' adaptive capacity (see Chapter 6).

Positive and negative modifying factors have been identified for each tree species (Appendix 4). Modifying factors that are primarily negative suggest that a species may be limited by biological traits or susceptibility to disturbance, and that it may fare worse than the DISTRIB results suggest. Conversely, modifying factors that are primarily positive indicate that the species may have a greater capacity to adapt to future conditions, potentially allowing it to occupy more habitat than modeled by DISTRIB. For example, although the DISTRIB results project no change in red maple suitable habitat under the PCM B1 scenario and a decrease in habitat under GFDL A1FI, the species has the highest adaptive capacity potential of all the species assessed (Table 11). Several positive modifying factors, such as shade tolerance and a high dispersal ability, suggest that red maple may occupy more habitat in the future than the DISTRIB results indicate. Additionally, the combination of the DISTRIB results and modifying factors can be used to better understand the potential risk to a species from climate change (Box 9).

Table 10.—Potential change in suitable habitat for 78 tree species in the assessment area

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

Species are grouped according to change classes based on the percentage change in the area-weighted importance value projected by the DISTRIB model for the end of century (2070 through 2099) under two climate-emissions scenarios. Species with positive and negative modifying factor scores are marked with plus (+) and minus (–) signs, respectively. See Appendix 4 for further explanation of the data and complete results for all 78 species.

Table 11.—Species with the five highest and five lowest ratings for adaptive capacity potential, based on Tree Atlas modifying factors[a]

Species	Modifying 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. Butternut	butternut canker, drought-intolerant, fire-intolerant, poor light competitor
3. Balsam fir	spruce budworm and other insect pests, fire-intolerant, drought-intolerant
4. White ash	emerald ash borer, drought-intolerant, fire-intolerant
5. Eastern hemlock	hemlock wooly adelgid, drought-intolerant

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

Box 9: Assessing Risk for Tree Species and Forest Habitats

The Climate Change Tree Atlas results presented in this chapter and in greater detail in Appendix 4 provide information about how individual tree species may respond to a changing climate. Projections of suitable habitat from the DISTRIB model describe the environmental and climatic factors that could affect species distribution and abundance across the landscape. The modifying factors detail life-history traits that may influence the ability of a tree species to cope with disturbances and biological stressors at both broad and fine scales. The combined use of these Tree Atlas components, as well as the associated SHIFT model, allows for a more comprehensive understanding of the response of tree species to climate change and can inform policy and management (Iverson et al. 2011).

As climate change research grows, there is an increasing emphasis on providing information in terms of “risk” to help inform decisionmaking. The use of a risk matrix model was encouraged as part of the development of the most recent National Climate Assessment as a tool for organizing information about key vulnerabilities and risks (Dalton and Mote 2012, Melillo et al. 2014). In this model, qualitative or quantitative estimates are used to describe the likelihood of impact (X-axis) and the magnitude of consequence (Y-axis).

As one example of the potential application of this approach, Tree Atlas results for northern Wisconsin (Swanston et al. 2011) were translated into a risk matrix for three future periods: 2010 to 2040, 2040 to 2070, and 2070 to 2100 (Iverson et al. 2012a, 2012b) (Fig. 36). This effort was intended as a “proof of concept” on how complex information could be represented in a way that helped to organize thinking regarding climate change vulnerability and risk. In translating the Tree Atlas information into this framework, projected changes in suitable habitat from DISTRIB were used to indicate the likelihood of impact. Thus, a large decrease in suitable habitat suggests a greater likelihood that that species will have reduced habitat under future climatic conditions. The magnitude of consequence was inversely related to the adaptability of the species

Box 9 (continued)

to climate change based upon the modifying factors; thus, the lower the capacity to cope, the greater the risk for habitat loss and the greater the consequences from climate change (Iverson et al. 2012a, 2012b). To assess changes in consequence over time, adaptability scores were adjusted to account for projected increases in disturbance over time (Iverson et al. 2012b).

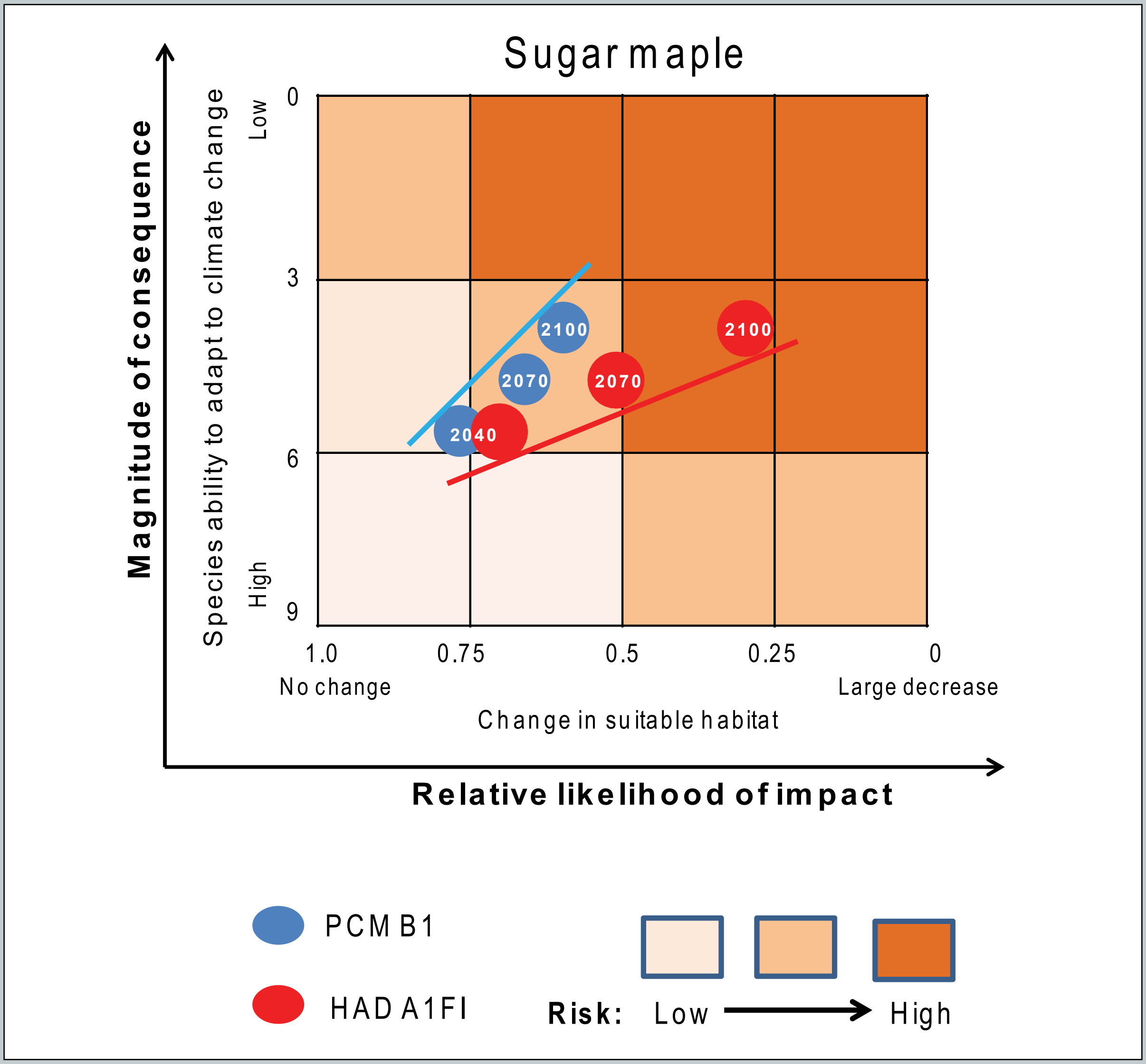


Figure 36.—Risk matrix for sugar maple in the northern Wisconsin portion of the assessment area. The numbers on the X-axis reflect projected suitable habitat, where 1.0 indicates no change from current values and 0 indicates complete loss of habitat. The numbers on the Y-axis are based on modifying factors, with increasing influence of disturbance factors over time. Values are plotted for three 30-year periods: 2040 (2010 to 2040), 2070 (2040 to 2070), and 2100 (2070 to 2100). The HAD A1FI scenario is roughly equivalent to the GFDL A1FI scenario presented elsewhere in this assessment. See Iverson et al. (2012b) for complete methods and additional examples.

Decreases in Suitable Habitat

For the assessment area, 9 of the 78 modeled species are projected to undergo large or small declines in suitable habitat under the full range of examined climate futures. The projected declines in habitat (as measured by a ratio of potential future importance value to current importance value; see Appendix 4) are more severe for these species under the GFDL A1FI scenario than under PCM B1. These reductions in suitable habitat do not imply that all or most mature trees will die or the species will be extirpated; rather, these results indicate that these species will be living outside of their ideal climatic envelope. As a result, trees living on less suitable habitats may have greater susceptibility to new or existing stressors such as drought, pests, diseases, or competition from other species including invasives. Climate-related stress may also increase the risk of regeneration failure.

Many of the species projected to decline are boreal or northern species that are currently near the southern limit of their range in the assessment area, including black spruce, balsam fir, quaking aspen, paper birch, and white spruce. These species are currently very common across the landscape and play a dominant role in many forests, and the reduction of suitable habitat for these species may affect a large portion of northern Wisconsin and the western Upper Peninsula. Suitable habitat for northern white-cedar, yellow birch, and black ash is also projected to decline under both climate scenarios, although not by as much as the boreal species. Mountain maple is currently rare across the landscape and is projected to have the greatest percentage decrease in suitable habitat, although positive modifying factors suggest that it may persist in localized areas with the most suitable conditions.

Highly negative modifying factors are associated with two of the species projected to decline, balsam fir and black ash, suggesting that there are life-history traits or disturbance stressors that may cause these species to lose even more suitable habitat than the DISTRIB model results indicate. For example, the expanding presence of emerald ash borer in the assessment area is expected to greatly reduce the importance of black ash in the area; its impact on black ash and other ash species is expected to be greater than the impacts from changing climatic conditions over the next few decades.

No Change in Suitable Habitat

Three species—northern pin oak, red pine, and striped maple—are projected to undergo less than a 20-percent change in suitable habitat under either of the two scenarios. Red pine is relatively common across the landscape. Several negative modifying factors, such as susceptibility to insect pests and low dispersal characteristics, are associated with red pine, which may cause it to fare worse in the future than the model results suggest. Positive modifying factors were identified for northern pin oak, but oak wilt may still be a concern for this species. Striped maple is relatively infrequent across the current landscape, and suitable habitat is not projected to change substantially in the future.

Mixed Results across Scenarios

There are several species (20 of 78) for which the model projects different outcomes under GFDL A1FI and PCM B1. For 10 of these species, the DISTRIB model projects that suitable habitat will decrease under GFDL A1FI, but there is generally less than a 20-percent change projected under PCM B1. Many of these species, including bigtooth aspen, eastern hemlock, eastern white pine, northern red oak, red maple, and sugar maple, are currently common in the assessment area. Northern red oak, red maple, and sugar maple have positive modifying factors that indicate the species may fare better than the model suggests. Red maple in particular has the most positive modifying factors among all 134 species that were assessed across the eastern United States. Eastern hemlock, butternut, and tamarack are associated with negative modifying factors and are projected to have greater decreases in suitable habitat under the GFDL A1FI scenario.

Ten of the species in this category are projected to have larger increases or smaller decreases in suitable habitat under GFDL A1FI compared to PCM B1. Currently, many of these species, including eastern redbud, rock elm, swamp white oak, and wild plum, are relatively infrequent in the assessment area. These species are more frequently found south of the assessment area, suggesting that suitable habitat will move northward under future conditions. Eastern hophornbeam is currently a common species in the assessment area, frequently associated with northern hardwood forests, and it is projected to have no change in suitable habitat under PCM B1 and have increased suitable habitat under GFDL A1FI. The positive modifying factors associated with this species, such as shade tolerance and an ability to occupy a wide range of sites, suggest that it may fare better than DISTRIB projects.

Increases in Suitable Habitat

Suitable habitat for 20 species is projected to increase under both models by the end of the century. Of these species, few are currently widespread in the assessment area. The more common species that are projected to have increases in suitable habitat under future climatic conditions include American elm, white oak, bur oak, white ash, black oak, and boxelder. Other species that are projected to increase in suitable habitat are more common in the mixed hardwood forests found along the southern boundary of the assessment area and include black walnut, shagbark hickory, and bitternut hickory.

Importantly, the DISTRIB model results project only changes in suitable habitat, which does not necessarily mean that a given species will be able to migrate to newly available habitat and colonize successfully. Migration models suggest that most species will not be able to colonize new habitats at the rate that climate changes (Iverson et al. 2004a, 2004b). A few species within the large increaser category, such as black cherry, black willow, and white ash, are associated with negative modifying factors, which suggest that they may be less able to take advantage of increases in suitable habitat. At the same time, several species associated with positive modifying factors, such as boxelder, white oak, silver maple, and bitternut hickory, may be able to increase beyond what the models suggest.

New Suitable Habitat

The DISTRIB model results also project that suitable habitat will be available in the future under at least one of the climate scenarios for 26 species that are not currently present in the assessment area. This projection does not necessarily mean that a given species will be able to migrate to newly available habitat and colonize successfully, but rather that conditions may be suitable for a species to occupy the site if it is established. Many species that are not currently present in the assessment area would require long-distance migration, whether intentional or unintentional, in order to establish and occupy suitable habitat in the assessment area. 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). Further, species are generally 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 may be tested and used over the coming decades (Pedlar et al. 2012).

Of the 26 new habitat species, 21 are projected to gain new suitable habitat under both climate scenarios. Five species are projected to have new habitat only under the more extreme GFDL A1FI scenario, and these species are located in areas that are far south of the assessment area. Of the species that are projected to have new habitat under one or both scenarios, nine have positive modifying factors and two have negative modifying factors.

Geographic Trends

Outputs from DISTRIB can be visualized spatially, and these results can provide greater context for interpreting the projected changes in suitable habitat. Three sets of maps (Figs. 37 through 39) provide examples of the changes in suitable habitat for three species: 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 related to local conditions as well as to projected climate change. Quaking aspen is projected to retain a large amount of suitable habitat in the assessment area under PCM B1. Suitable habitat decreases more under GFDL A1FI, with most remaining suitable habitat found in the central part of the assessment area along the Michigan-Wisconsin border. Sugar maple is projected to lose areas of suitable habitat along the southern boundary of the assessment area under both climate scenarios, with a much greater loss of habitat projected under GFDL A1FI. White oak is virtually absent from the assessment area today, occurring primarily along the tension zone, a transitional zone between the more open landscape of southern Wisconsin and the mixed deciduous-coniferous forests of the assessment area (Wisconsin Department of Natural Resources [WDNR] 2009a). Under PCM B1, white oak is projected to gain suitable habitat in the southern portion of the assessment area. Under GFDL A1FI, however, suitable habitat for white oak is projected to occur at moderate levels across the assessment area.

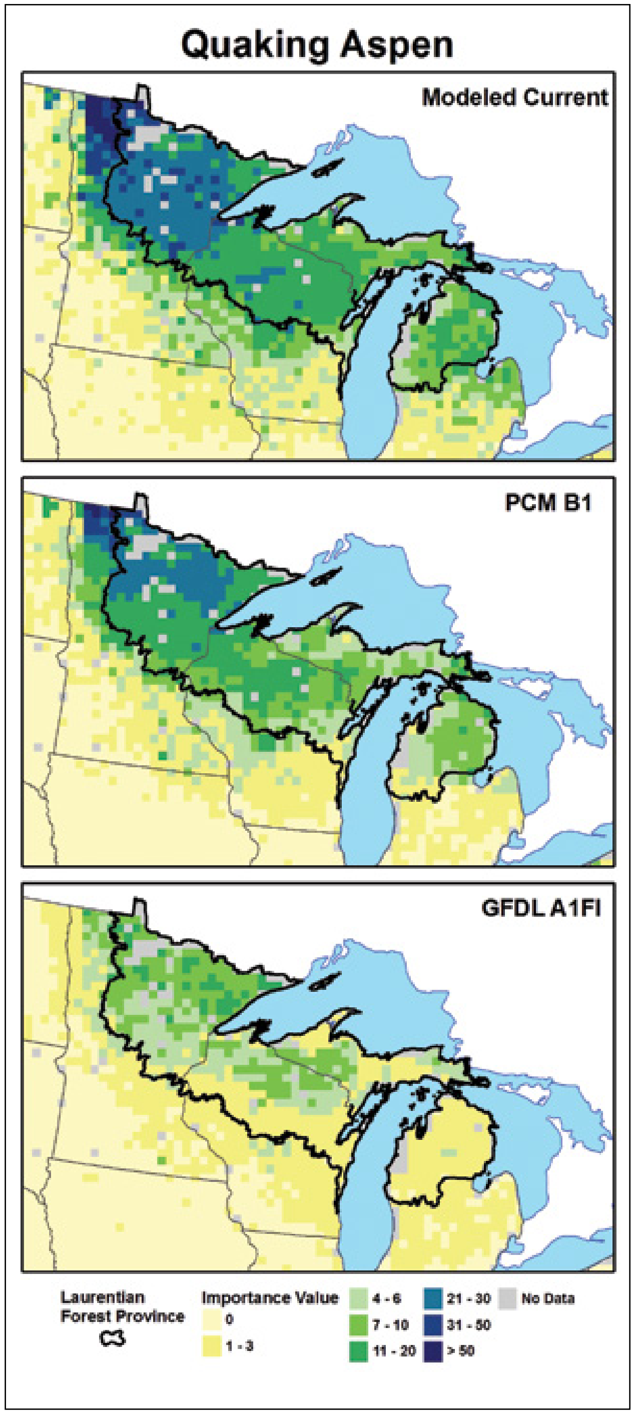


Figure 37.—Modeled importance values for quaking aspen across the Laurentian Mixed Forest Province under current climate conditions (top) and projected for the years 2070 through 2099 under the PCM B1 (middle) and GFDL A1FI (bottom) climate scenarios, from the Tree Atlas model. Importance values can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

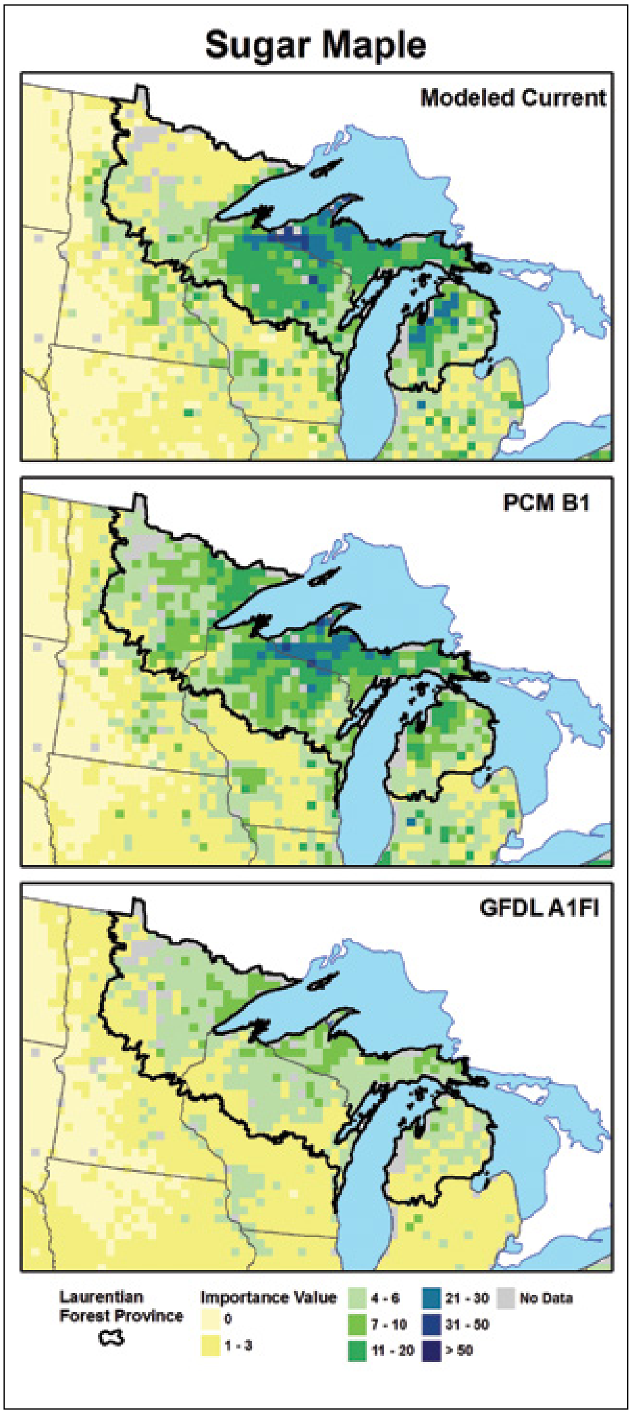


Figure 38.—Modeled importance values for sugar maple across the Laurentian Mixed Forest Province under current climate conditions (top) and projected for the years 2070 through 2099 under the PCM B1 (middle) and GFDL A1FI (bottom) climate scenarios, from the Tree Atlas model. Importance values can range from 0 to 100. An importance value of zero (light yellow) indicates that the species is not present currently (top), or will not have suitable habitat at the end of the century (middle, bottom).

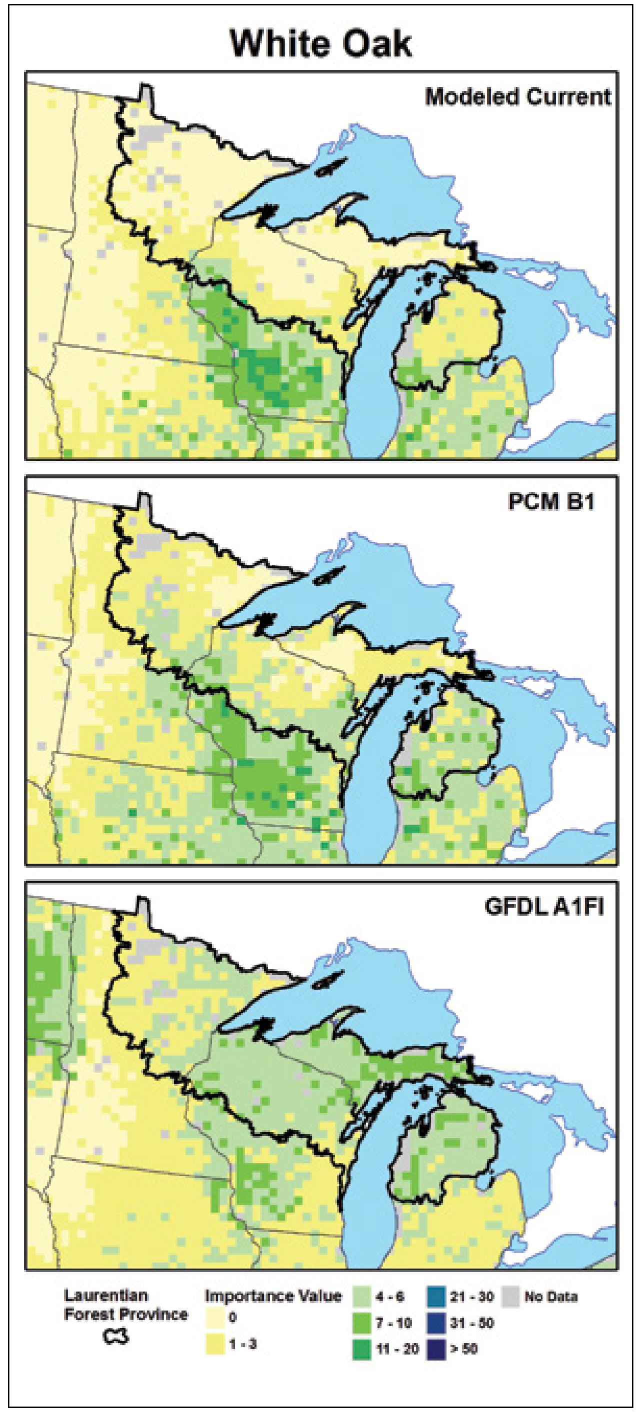


Figure 39.—Modeled importance values for white oak across the Laurentian Mixed Forest Province under current climate conditions (top) and projected for the years 2070 through 2099 under the PCM B1 (middle) and GFDL A1FI (bottom) climate scenarios, from the Tree Atlas model. Importance values can range from 0 to 100. An importance value of zero (light yellow) indicates that the species is not present currently (top), or will not have suitable habitat at the end of the century (middle, bottom).

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 (Box 10). Additionally, these results do not incorporate the positive influence of modifying factors into the maps for sugar maple or white oak. Suitable habitat maps for all the species addressed in this assessment are available online at the Climate Change Tree Atlas Web site (www.nrs.fs.fed.us/atlas/tree; also see 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 an illustration of broad trends.

Hardwood forest canopy. Photo by Linda Parker, Chequamegon-Nicolet National Forest.

Box 10: Colonization of Tree Species to New Locations

The DISTRIB results from the Climate Change Tree Atlas provide useful information about the potential of suitable habitat to change over the next century for a large number of tree species. However, these results provide only an indication of whether suitable habitat is likely to be available and do not account for the ability of tree species to colonize sites where they are not currently present. The SHIFT model is another component of the Climate Change Tree Atlas that simulates the likelihood of tree species colonization into newly available habitats (Iverson et al. 2010, Prasad et al. 2013). The SHIFT model is a process-based model that estimates colonization likelihoods of tree species across fragmented landscapes. Current land cover data are used to identify which areas may be suitable for colonization, and species movement is based upon Holocene migration rates among trees migrating into forested environments (Prasad et al. 2013).

As one example, black oak is currently found only at the southern extent of the assessment area along the tension zone that runs through the center of Wisconsin (Fig. 40). Suitable habitat for black oak is expected to more than double within the assessment area during the next century under PCM B1, and even greater increases are projected under GFDL A1FI.

When migration and colonization are modeled for black oak under the PCM B1 scenario, the species is expected to colonize new sites, particularly those close to the current range. Habitat fragmentation and limits on dispersal limited the ability of black oak to naturally colonize newly available habitat that was not near the current habitat (Prasad et al. 2013).

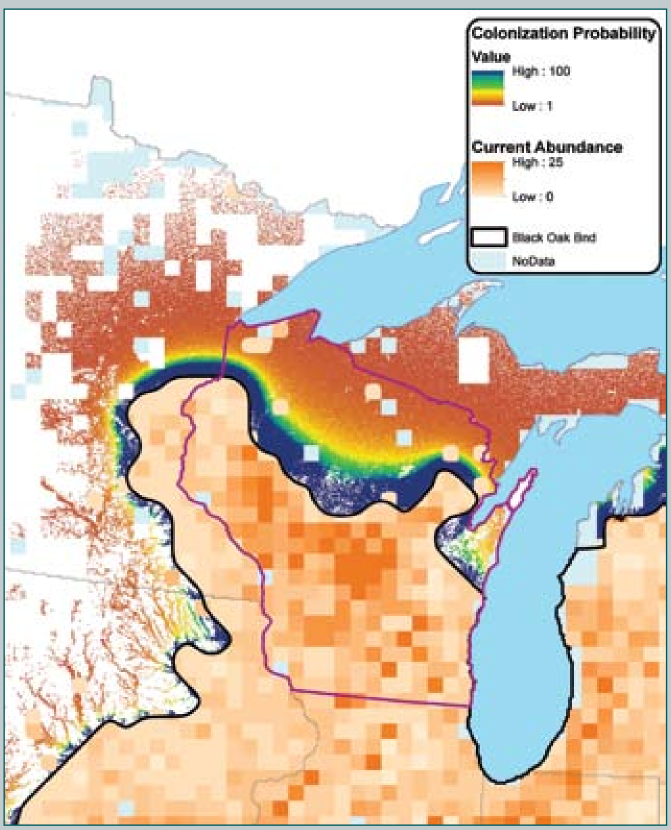


Figure 40.—Projected colonization of black oak to future suitable habitat under the PCM B1 scenario. Results under the A1FI scenario (not shown) were similar. See Prasad et al. (2013) for a full description.

LANDIS-II

Results from the LANDIS-II model include projections of aboveground biomass for 27 tree species, as well as biomass data and maps aggregated into 10 forest types. The LANDIS-II model was used across most of the assessment area; however, portions of northern Wisconsin near Green Bay as well as the portions of the assessment area that fall within Michigan's Keweenaw, Marquette, and Dickinson Counties were not modeled (Fig. 41).

The LANDIS-II model projects changes in aboveground biomass for individual tree species through the year 2100 for three climate scenarios: a current climate scenario and the GFDL A1FI and PCM B1 climate scenarios (Fig. 42). The current climate scenario is based upon observed temperature and precipitation values from 1960 through 2010 and also incorporates climate variability at levels observed during that period. Climate conditions under GFDL A1FI and PCM B1 are described in Chapter 4.

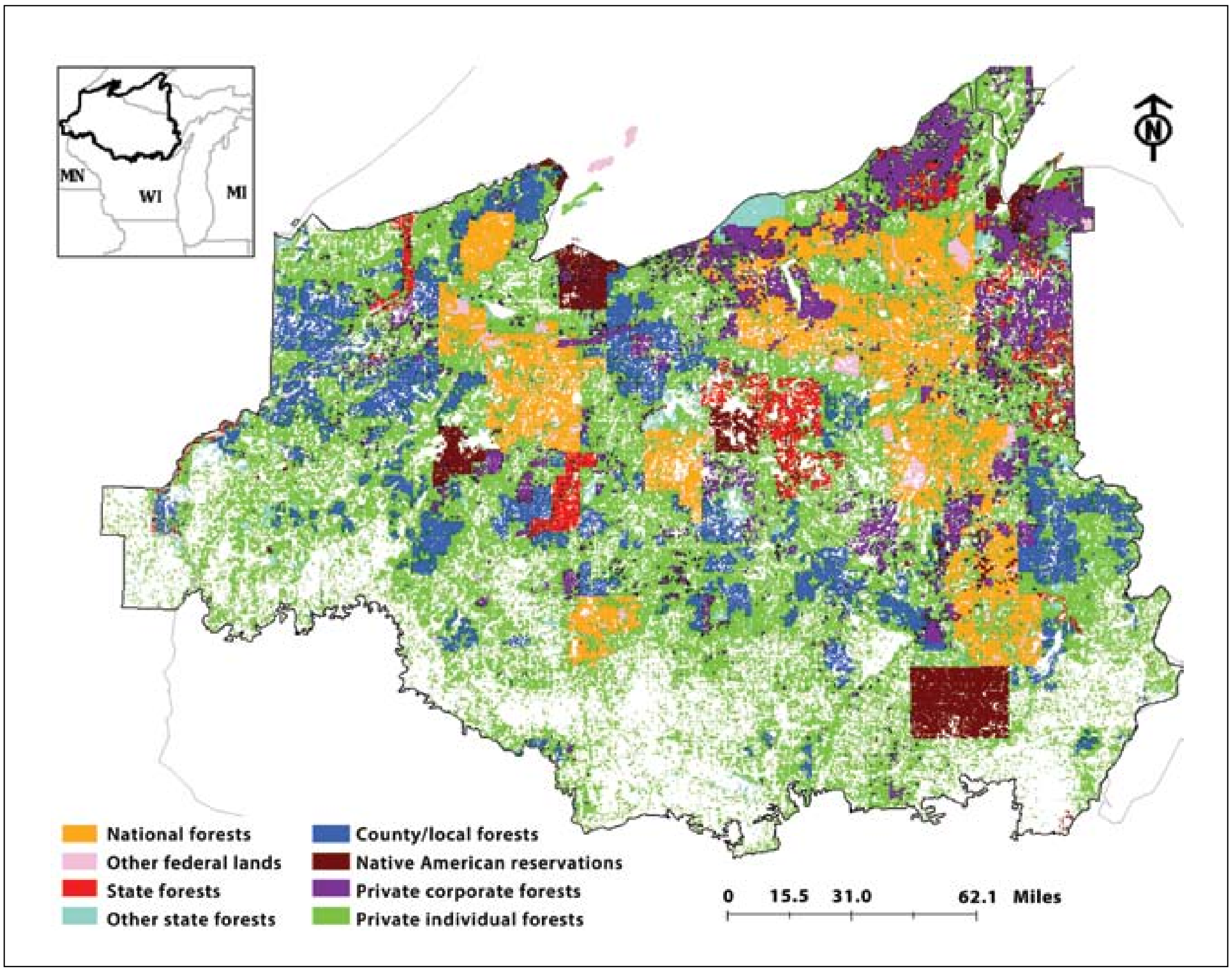


Figure 41.—Analysis area modeled by LANDIS-II for this assessment and major forest ownership.

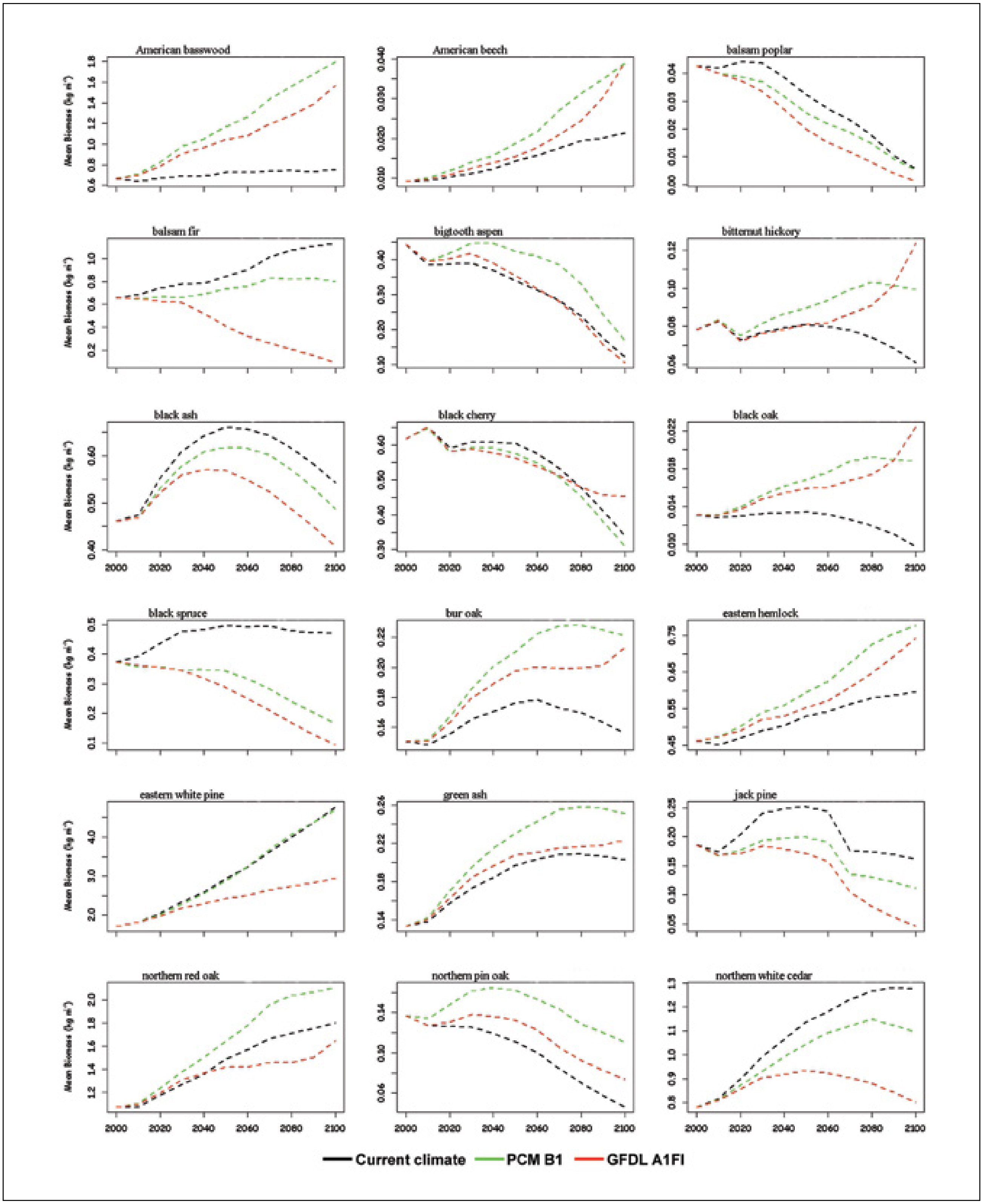


Figure 42.—LANDIS-II biomass projections (kilograms per square meter) through the year 2100 for 27 modeled tree species under three climate scenarios. Note that the Y-axis differs by species. The model results maintain current levels of forest harvest throughout the simulation. One kilogram per square meter is roughly equivalent to 4 tons per acre. (Figure 42 continued on next page.)

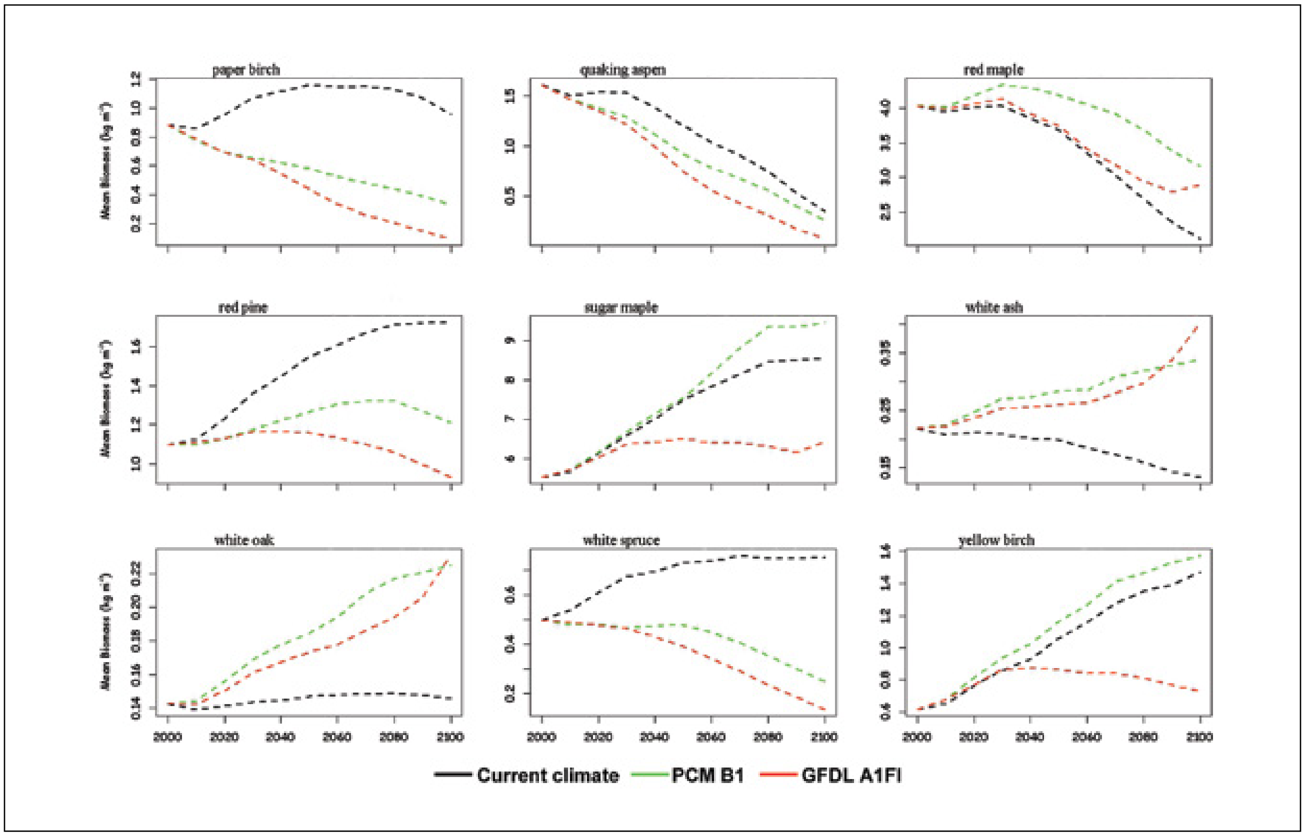


Figure 42 (continued).—LANDIS-II biomass projections (kilograms per square meter) through the year 2100 for 27 modeled tree species under three climate scenarios. Note that the Y-axis differs by species. The model results maintain current levels of forest harvest throughout the simulation. One kilogram per square meter is roughly equivalent to 4 tons per acre.

Biomass provides an indication of the productivity of individual tree species based in different locations across the landscape, which are provided as averages across the LANDIS-II analysis area. Species are limited to the most common tree species that are currently found within the LANDIS-II study area, as well as a few oak species that are found primarily at the southern extent of the assessment area.

The LANDIS-II model incorporates natural wind disturbance, but other disturbances, such as fire, insect pest outbreaks, forest diseases, and herbivory, were not modeled. Additionally, model simulations maintain current harvest levels throughout the 21st century. The current harvest levels are based on recent harvest rates for individual ownership types from U.S. Forest Service, Forest Inventory and Analysis (FIA) data for all of Wisconsin between 2005 and 2011 (Appendix 5). Multiple types of forest harvest, including clearcut, seed tree, single-tree (gap), group or patch selection, and shelterwood, are modeled, and are selected to realistically represent methods commonly used for the individual tree species in this region.

The LANDIS-II model results presented in this chapter do not incorporate the effects of elevated atmospheric carbon dioxide (CO_2) on plant physiology, commonly referred to as "CO_2 fertilization." In this assessment, the LANDIS-II model used a steady CO_2 concentration of 369.5 ppm (i.e., year 2000 levels; 2012 levels were approximately 390 ppm) through the year 2100 for all model simulations. Although LANDIS-II is able to incorporate rising CO_2 concentrations into future scenarios, several challenges are associated with modeling CO_2 fertilization. Few observational studies have evaluated the effects of CO_2 fertilization beyond 600 ppm, and the results from observational studies are quite mixed, particularly about the role of water and nitrogen in biomass production (Finzi et al. 2007, Franks et al. 2013, Leakey et al. 2009). For comparison, the A1FI emissions scenario projects approximately 900 ppm by 2100.

The LANDIS-II model simulated only change in upland forests in the assessment area, which is an important consideration when evaluating the results of species that are commonly found in lowland systems. Forested wetlands were not modeled because of limitations with the model in simulating ecosystem dynamics in areas with saturated soils. This is particularly important to keep in mind for species like black ash, black spruce, and northern white-cedar. Further, LANDIS-II results were not incorporated into the vulnerability determinations for the lowland conifer or the lowland and riparian hardwood forest types that are presented in Chapter 6.

Aboveground Biomass

The LANDIS-II model simulated changes in aboveground biomass for 27 common tree species under the current climate, PCM B1, and GFDL A1FI scenarios (Fig. 42). These species were also organized according to the proportional changes under the PCM B1 and GFDL A1FI scenarios relative to the current climate scenario (Table 12; see also Appendix 5).

Although the current climate is expected to change (Chapters 2 and 4), the current climate scenario is useful for highlighting trends that might be expected if the climate were to remain stable over the next 100 years. This projection can provide a baseline for comparing the relative increases or

Table 12.—Potential change in biomass for 27 tree species in the LANDIS-II analysis area[a]

Common name	PCM B1	GFDL A1FI
Declines under Both Scenarios		
Balsam fir	Decrease	Large decrease
Black spruce	Large decrease	Large decrease
Jack pine	Decrease	Large decrease
Paper birch	Large decrease	Large decrease
Quaking aspen	Decrease	Large decrease
Red pine	Decrease	Decrease
White spruce	Large decrease	Large decrease
Increases under Both Scenarios		
American basswood	Large increase	Large increase
American beech	Large increase	Large increase
Bitternut hickory	Large increase	Large increase
Black oak	Large increase	Large increase
Bur oak	Increase	Increase
Eastern hemlock	Increase	Increase
Northern pin oak	Large increase	Large increase
Red maple	Increase	Increase
White ash	Large increase	Large increase
White oak	Large increase	Large increase
No Change under Both Scenarios		
Northern red oak	No change	No change
Mixed Results Across Scenarios		
Balsam poplar	No change	Large decrease
Bigtooth aspen	Increase	No change
Black ash	No change	Decrease
Black cherry	No change	Increase
Eastern white pine	No change	Decrease
Green ash	Increase	No change
Northern white-cedar	No change	Decrease
Sugar maple	No change	Decrease
Yellow birch	No change	Large decrease

[a] Species are grouped into change classes based on the proportional change between the year 2100 biomass under the PCM B1 and GFDL A1FI scenarios and the biomass under the current climate scenario in the year 2100. Large increases or decreases indicate that the proportional change under one or both climate change scenarios is greater than 50 percent. "No change" indicates that biomass is within 20 percent of what is projected under the current climate scenario. See Appendix 5 for complete results for all 27 species.

decreases in biomass under the two climate change scenarios. The current climate scenario makes it easier to observe changes in tree species biomass and forest composition that occur as a result of natural succession and management, as opposed to changes driven by climate. Natural succession is important in the forests for this region as areas continue to recover from historic widespread and intensive logging. Forests in Michigan and Wisconsin are actively growing, with forest growth outpacing natural mortality, land-use change, and timber harvest (Perry et al. 2012, Pugh et al. 2012). Thus, the increases in biomass that are observed for nearly all species under the current climate scenario are due to the continued maturation of forests across the region. Succession is also occurring within the two climate change scenarios, but the effects of climate change on forest dynamics are evident when compared to the current climate scenario.

According to recent FIA data for the assessment area, the annual net growth is greater than annual harvest removals (growth-to-removal ratio for the assessment area = 1.6; see Chapter 1). This positive ratio 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 current 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.

Decreases in Biomass

Biomass is projected to decrease for seven species by the year 2100 under both PCM B1 and GFDL A1FI, relative to the current climate scenario. These species are generally characterized as northern and boreal species, including paper birch, balsam fir, white spruce, and black spruce (Table 12). Under both scenarios, black spruce, white spruce, and paper birch are projected to have more than a 50-percent decrease in biomass by the end of the century when compared to the current climate scenario. Three species—balsam fir, jack pine, and quaking aspen—are projected to have greater decreases in biomass under GFDL A1FI than under PCM B1 (Fig. 42). These trends indicate that climate-related shifts are driving the biomass projections for these species, and that the hotter and drier conditions projected by GFDL A1FI amplify the decline. The LANDIS-II model does not incorporate artificial regeneration as part of management, which may underestimate the potential future biomass of red pine and jack pine because these species are often planted.

Mixed Results across Scenarios

Different outcomes are projected for nine species under the two climate scenarios. Six species—balsam poplar, black ash, eastern white pine, northern white-cedar, sugar maple, and yellow birch—are projected to have no substantial change in biomass under the PCM B1 scenario (i.e., biomass projected to be within 20 percent of the current climate scenario) but to have substantial biomass decreases under GFDL A1FI (Table 12). This result suggests that the changes in climate projected under the milder PCM B1scenario may not be severe enough to negatively affect these species, but that the hotter and drier conditions projected under GFDL A1FI may lower productivity. Similarly, bigtooth aspen and green ash are projected to have slight biomass increases under PCM B1 and no change in biomass under GFDL A1FI. This result suggests that the slight increases in temperature under PCM B1 may make conditions more favorable for the growth of these species. In contrast, the greater temperature increases and summer moisture limitations projected under GFDL A1FI might not benefit these species. Only one species in this group, black cherry, is projected to have greater productivity gains under the GDFL A1FI scenario than under PCM B1.

No Change in Biomass

Northern red oak is the only species to have no substantial change in biomass projected under either PCM B1 or GFDL A1FI (Table 12). For this species, aboveground biomass is projected to increase 17 percent under PCM B1 and decline 8 percent under GFDL A1FI relative to the current climate scenario. All three scenarios project steady increases in biomass through the end of the century, with little difference between scenarios until mid-century (Fig. 42).

Increases in Biomass

Ten species are projected to have increased biomass under both PCM B1 and GFDL A1FI relative to the control scenario (Table 12). Several of these species, including American beech, bur oak, eastern hemlock, red maple, and white oak, are projected to have comparable biomass increases under both PCM B1 and GFDL A1FI scenarios. American basswood, northern pin oak, and white ash are projected to have higher levels of biomass under the PCM B1 scenario (Table 12; see also Appendix 5). The slightly warmer temperatures and slightly wetter growing season conditions projected under PCM B1 might benefit these species, whereas the more severe change to hotter temperatures, wetter springs, and drier summers projected under GFDL A1FI may not have as great a benefit for these species. Bitternut hickory and black oak are projected to have large biomass increases under both scenarios, and are among the few species that are projected to have greater biomass increases under GFDL A1FI than PCM B1.

Trends over Time

Individual species show different patterns in biomass change over time (Fig. 42). For some species that are projected to have reduced biomass by 2100, reductions in biomass as a result of climate change become evident by mid-century. This result is particularly notable with characteristic boreal species, such as balsam fir, black spruce, paper birch, and white spruce. Other species, such as balsam poplar and quaking aspen, show more gradual changes throughout the century. For species that increase as a result of climate change, the patterns of biomass increases are variable. Several species such as bitternut hickory, black oak, red maple, and white oak show distinct increases in biomass under the GFDL A1FI scenario near the end of the 21st century. These hardwood species are currently near the northern edge of their historic ranges in the assessment area, and the late-century increase suggests enhanced migration and establishment of these species in the assessment area or a greater competitive advantage under the projected hotter and drier conditions. These trends are similar to those projected by other simulations in northern Wisconsin and the Great Lakes (e.g., Duveneck et al. 2014; Handler et al. 2014a, 2014b; Scheller and Mladenoff 2005).

The regional total of aboveground biomass for all species across the LANDIS-II analysis area also varies over time (Fig. 43). For the PCM B1 scenario, biomass is expected to rise steadily across the landscape, reaching a plateau around the year 2080. This trajectory closely tracks the combined results for the current climate scenario. The GFDL A1FI scenario projects a slight increase to the year 2030, followed by a steady decline until around 2090. A slight increase is then projected during the last decade of the century. When viewed in concert with the projected declines in northern or boreal species, this trend appears to support the possibility of a landscape-level transition to a hardwood-dominated landscape around the year 2100 for the GFDL A1FI scenario. Noticeable biomass gains for southern hardwood species may be delayed until late-century because of lag times associated with projected rates of migration, colonization, and growth to the overstory forest layers. It is important to reiterate that LANDIS-II assesses only the 27 species listed above and for upland forests, and does not account for the possibility of other species that may enter the analysis area.

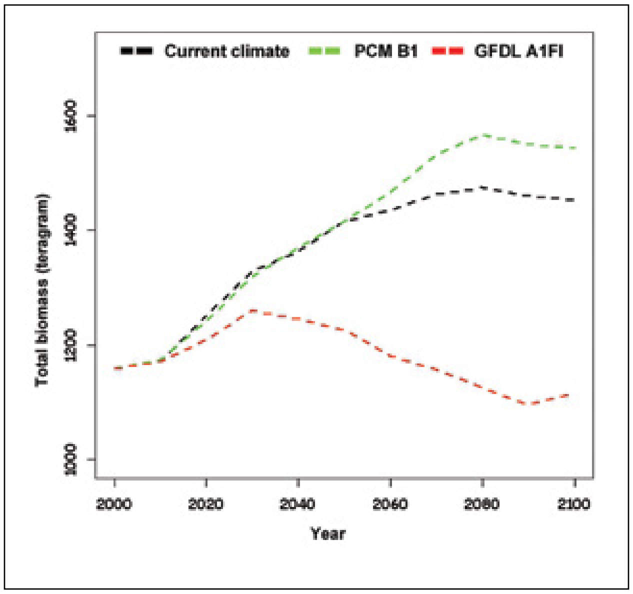


Figure 43.—LANDIS-II biomass projections through the year 2100 for all tree species combined under three climate scenarios. The model results maintain current levels of forest harvest throughout the simulation. One teragram equals one million metric tons, or about 1.1 million tons.

Geographic Trends

Maps of projected forest cover indicate the potential for landscape-level change under the two climate scenarios (Fig. 44). The LANDIS-II model 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 forest-type maps, individual locations (cells) in the LANDIS-II simulations were classified into 10 forest types based on characteristic species composition (Appendix 5). These forest types are not perfectly correlated to the forest types used in other portions in this assessment, and cannot be directly compared. Because the LANDIS-II model does not effectively simulate lowland forest types or nonforested systems, the lowland and riparian forest types are not included in this classification. Additionally, LANDIS-II simulations account for only the 27 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 currently low-abundance species to increase within the assessment area.

When the individual species are grouped into forest types, changes in forest communities over time become more apparent (Fig. 44). The boreal forest types show substantial reductions over time, with very little of the landscape containing upland spruce-fir, aspen/birch, or jack pine forest by the year 2100 under PCM B1 or GFDL A1FI. Under both climate scenarios, the northern hardwoods forest type is projected to increase substantially across the landscape, but individual species respond differently as described above. Although the forest type remains common on the landscape, species composition is expected to change in conjunction with climatic changes.

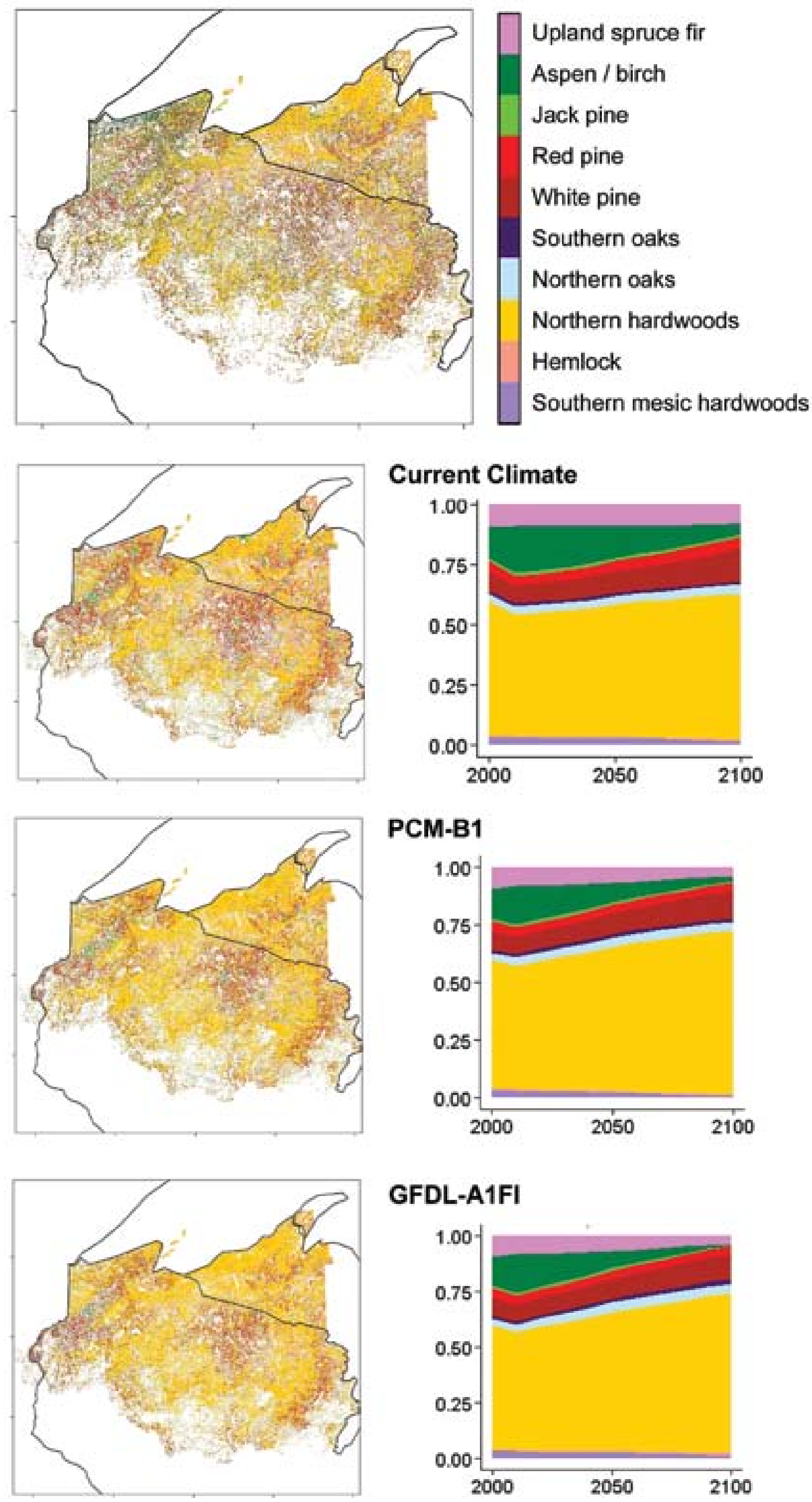


Figure 44.—Proportion of area in each forest type projected by the LANDIS-II model through 2100 under the current climate (top) and two climate scenarios: PCM B1 (center) and GFDL A1FI (bottom). The model results maintain current levels of forest harvest throughout the simulation.

PnET-CN

The PnET-CN model projects changes in aboveground net primary productivity (productivity). Productivity is commonly used as a measure of how fast forest ecosystems are photosynthesizing and accumulating biomass and can provide some information pertaining to ecosystem function. In this assessment, we report absolute productivity as well as relative percentage changes in productivity. The PnET-CN model uses 1971 through 2000 as a baseline period, and simulates productivity changes from 2000 through 2099.

For this assessment, PnET-CN results describe six aggregated forest types rather than individual species. These forest types are based on FIA forest-type groups (Pugh et al. 2012). The six forest types used by PnET-CN in this assessment are: aspen/birch, maple/beech/birch, oak/hickory, elm/ash/cottonwood, pine, and spruce/fir. These roughly correspond to the forest types used in this assessment (Fig. 45).

PnET-CN was used to evaluate change in productivity across the full assessment area. Biological changes associated with nitrogen cycling, tropospheric ozone pollution, and CO_2 fertilization

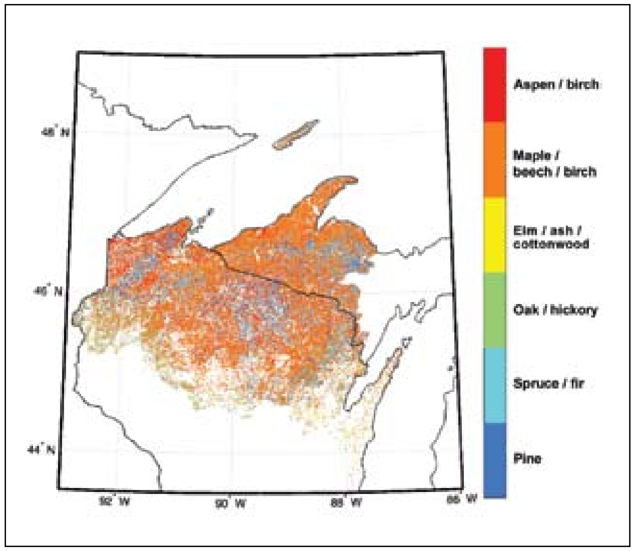


Figure 45.—Spatial distribution of the aggregated forest-type groups used in PnET-CN simulations. These forest-type groups remain fixed for the duration of the PnET-CN simulations.

were included in the modeling. Natural disturbances, forest management, and tree species competition and migration were not included in the model.

Productivity

Productivity is projected to increase under both PCM B1 and GFDL A1FI through the end of the century in comparison to the 1971 through 2000 baseline period (Fig. 46). Across all forest types in the assessment area, PCM B1 resulted in an average productivity increase of 66 percent (399 grams biomass per meter per year) compared to the baseline period, although this value ranged from 9 to 97 percent. The productivity increases projected under 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 145 percent (825 grams biomass per meter per year), and ranged from 41 to 253 percent. Productivity increases generally leveled off around the year 2080 under the PCM B1 scenario, but increases continue under GFDL A1FI until the end of the model period.

Visitors viewing Lake of the Clouds in western Upper Michigan. Photo by Scott Pearson, used with permission.

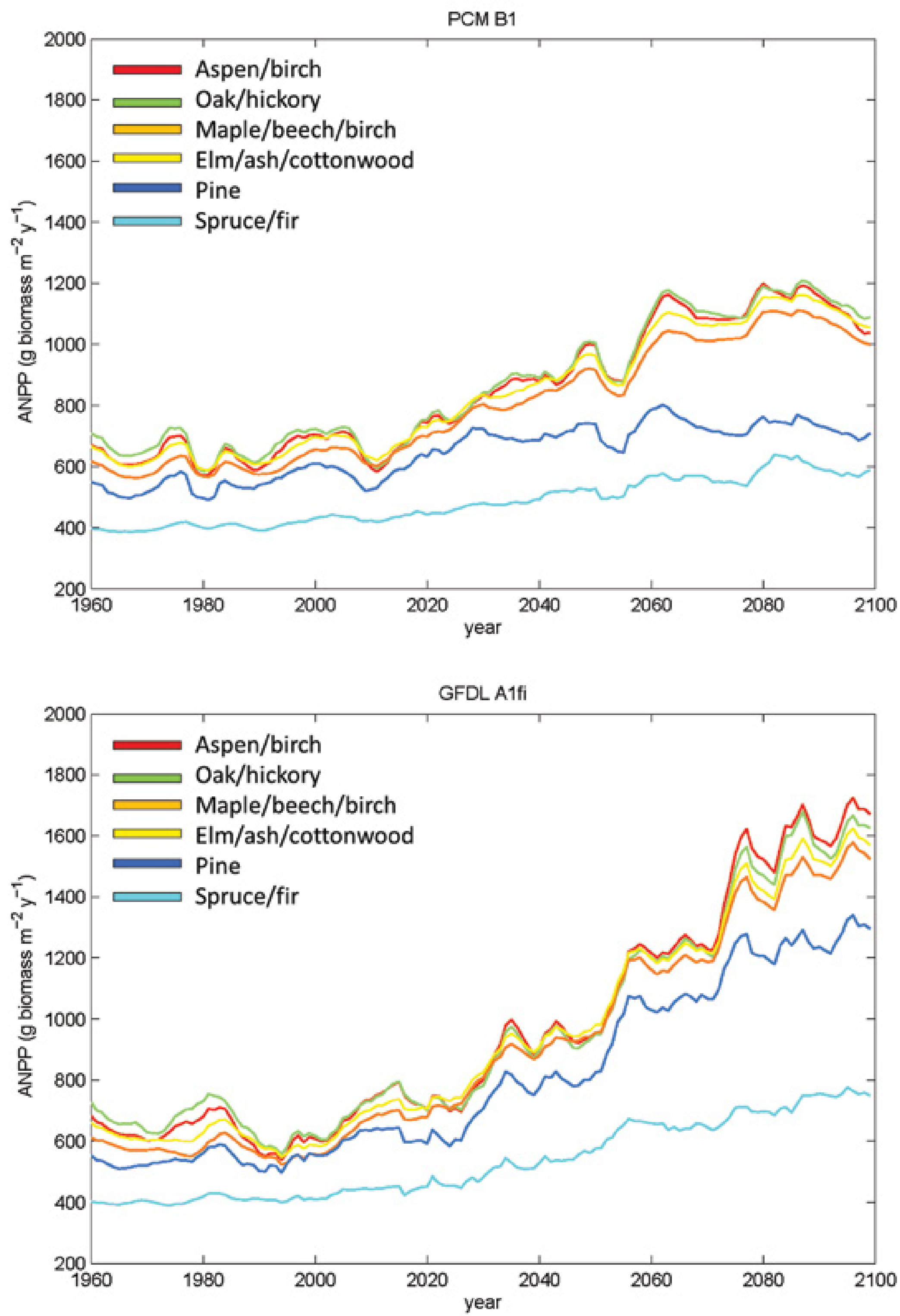


Figure 46.—Projected trends in aboveground net primary productivity (ANPP) from PnET-CN for six aggregated forest-type groups under the PCM B1 (top) and GFDL A1FI (bottom) future climate scenarios. Outputs have been smoothed based on a 5-year running mean. One kilogram (one thousand grams) per square meter is roughly equivalent to 4 tons per acre.

All forest types show increases in productivity in both scenarios. The greatest projected increases are in the broadleaf forest types: aspen/birch, oak/hickory, maple/beech/birch, and elm/ash/cottonwood. In comparison, the conifer-dominated spruce/fir and pine forest types have much smaller increases, with spruce/fir consistently having the lowest productivity throughout the simulations.

The main drivers of the increased forest productivity projected by PnET-CN are growing season length and CO_2 fertilization. Warmer temperatures enhance carbon uptake earlier in the spring and later in the fall, but carbon uptake is 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 PCM B1 (roughly 1 month). In general, this longer growing season allowed forests to accumulate more biomass per year in the simulation.

Elevated atmospheric CO_2 concentrations enable trees to absorb more carbon through pores on their leaves. As a result water loss is reduced and photosynthesis is increased for a given amount of water use. Carbon dioxide fertilization effects are larger under GFDL A1FI compared to PCM B1 because of the higher levels of greenhouse gases that are projected under the A1FI emissions scenario. In a separate set of simulations where the level of atmospheric CO_2 was fixed at 350 parts per million and all other variables were held constant (not shown in this assessment), there was little change in productivity under PCM B1 and declines in productivity under GFDL A1FI by the end of the 21st century. The lower levels of CO_2 in these simulations reduced the fertilization effect, and increased water stress led to reduced forest productivity. This outcome suggests that the predicted increases in productivity presented here are largely due to CO_2 fertilization. PnET-CN tends to predict a larger CO_2 fertilization effect on productivity than other ecosystem models, so this effect may be a generous estimate (Medlyn et al. 2011, Norby and Zak 2011). It is difficult to know the fertilization effect on forests at high CO_2 concentrations because no field studies have directly tested ecosystem responses at levels similar to those projected under the A1FI emissions scenario at the end of the century. For comparison, updates to the CO_2 routine in the PnET-CN model (Franks et al. 2013) conducted subsequent to this assessment decreased this CO_2 fertilization effect by approximately 20 percent relative to the data presented in this assessment at CO_2 concentrations equal to 1100 ppm (E. Peters, University of Minnesota, unpublished work).

Although PnET-CN accounts for biogeochemical feedbacks like water and nutrient limitation, this model does not account for multiple other factors that could cause mortality or otherwise reduce the productivity of forest ecosystems in the future. For example, the model does not account for competition, forest management, natural disturbances, or climate effects on regeneration. 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 a best-case representation of the potential ecosystem productivity response of existing forests to climate change.

Geographic Trends

Productivity is projected to increase under both future climate scenarios across the assessment area (Fig. 47). Under the PCM B1 scenario, small increases are projected throughout much of the assessment area, with localized areas of no change. Productivity increases are projected to be much greater under the GFDL A1FI scenario. Increases of about 100 percent are projected in the western portion of the assessment area, which is also where productivity was highest during the 1971 through 2000 baseline period. Increases of 150 percent and

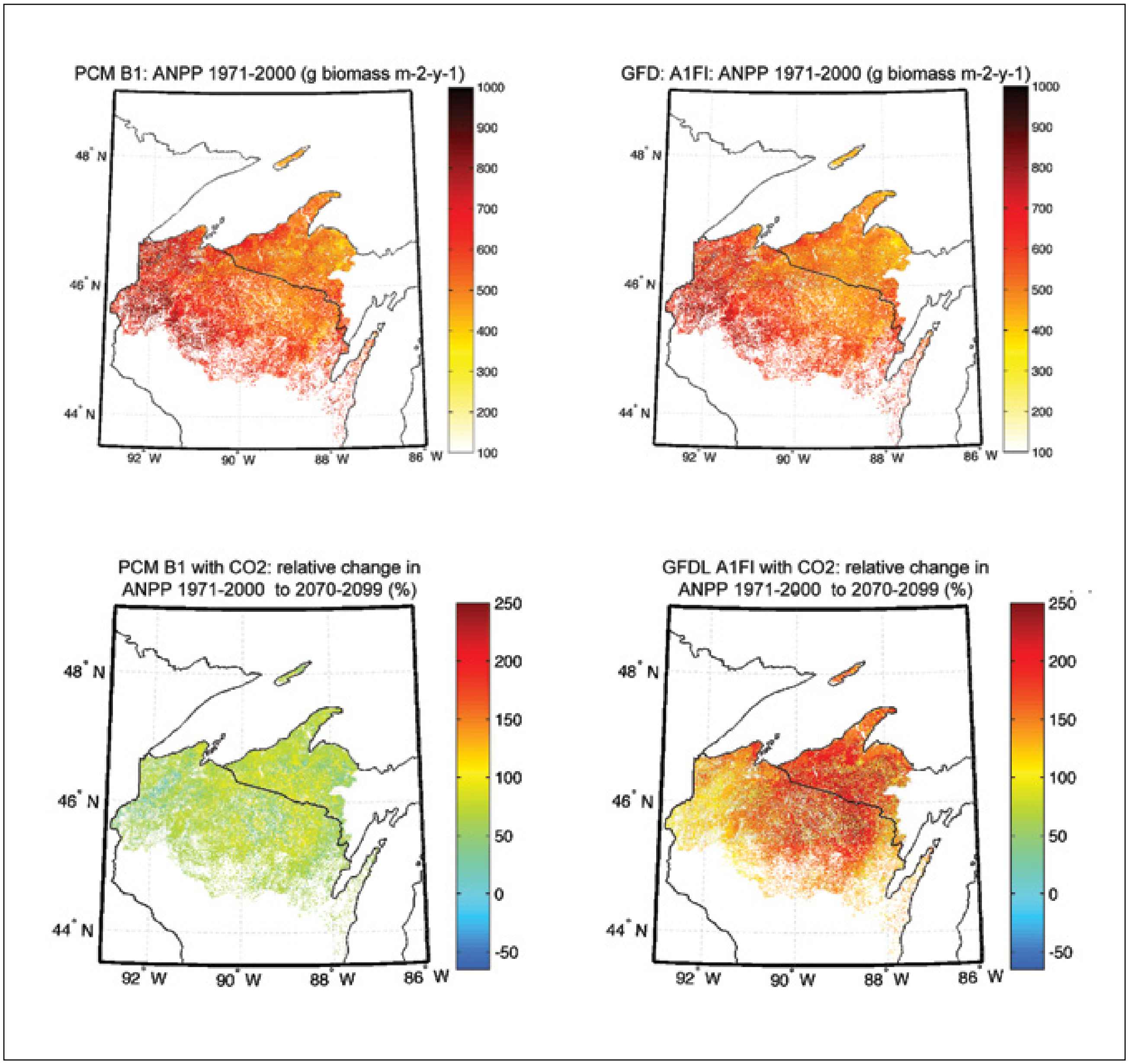


Figure 47.—Projected aboveground net primary productivity (ANPP) changes across the assessment area under the PCM B1 and GFDL A1FI future climate scenarios, from the PnET-CN model. For the baseline period of 1971 through 2000, productivity is shown as an absolute value (top panels). For the future scenarios, changes in productivity are shown for 2070 to 2099 relative to the 1971 to 2000 baseline (lower panels). Baseline values are slightly different between the two climate scenarios because of slight variations in the downscaled climate data.

more are projected in the central portion of the assessment area under GFDL A1FI, compared to smaller increases on the eastern and western edges of the assessment area. Greater biomass increases appear to occur in parts of the landscape that are dominated by maple/beech/birch forests.

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. In the PnET-CN simulations, areas with lower water-holding capacity are less buffered from water limitation and more prone to reductions or smaller increases in productivity (Peters et al. 2013a). Therefore, soil water-holding capacity could play a critical role in determining how forests in the assessment area respond to future climatic changes.

Discussion of Model Results

The three different models used in this assessment were selected because of the ability to model and represent different facets of potential forest change as a result of a changing climate. Therefore, the ability to make comparisons between the different models facilitates a deeper understanding of which parts of a forest ecosystem may be most responsive or vulnerable to change. However, the differences between the models, in terms of design, outputs, strengths, and weaknesses, also make direct comparisons among model results difficult. This section describes areas of agreement and disagreement between the results and provides context for how the results from multiple models can be integrated to better understand forest change.

Agreements

Despite the differences between the modeling approaches, Tree Atlas, LANDIS-II, and PnET-CN show some strong similarities in forest change over the next century under a range of future climates. All three models agree that characteristic boreal species or northern species that are currently at their southern range limits will face increasing climate stress. For example, the Tree Atlas and LANDIS-II models both project that several species, including black spruce, white spruce, paper birch, and northern-white cedar, will decrease. Additionally, the PnET-CN results project a weaker potential productivity response for spruce/fir forests compared to other forest types. These species and forest types are characteristic of boreal environments and are currently major components of regional ecosystems. As the climate warms through the 21st century, they are projected to face increasing climate-related stress. These findings are similar to a number of other studies that evaluated tree species responses to climate change in northern Wisconsin and saw transitions away from boreal species toward species more representative of warmer climates (e.g., Chiang et al. 2008, Duveneck et al. 2014, Scheller and Mladenoff 2005, Williams et al. 2012).

Moreover, both Tree Atlas and LANDIS-II tend to agree that many species within the assessment area may fare better under the PCM B1 conditions and have greater decreases under GFDL A1FI. These results support the idea that GFDL A1FI represents a future climate that is beyond the tolerance of many species. These results also suggest that many temperate species currently present in the assessment area could tolerate a mild degree of warming with corresponding increases in growing season precipitation, as represented by the PCM B1 scenario.

Tree Atlas and LANDIS-II also agree that some species have the potential to increase under a range of future climates. These temperate hardwood species, including American beech, bitternut hickory, black oak, bur oak, white ash, and white oak, may be more tolerant of warmer year-round conditions and a slightly drier growing season. PnET-CN outputs also indicate that elm/ash/cottonwood, maple/beech/birch, and oak/hickory forests have the potential for large productivity increases across the assessment area.

Both Tree Atlas and LANDIS-II project that several species currently present south of the assessment area may become more widespread throughout the landscape, assuming higher regeneration success under future forest conditions. At the same time, many of the species that are projected to decrease are still expected to be major components of forest ecosystems at the end of the century. For these reasons, it is possible that forests in the assessment area may be able to contain a higher diversity of species in the future, with a blend of temperate and boreal species.

Disagreements

As mentioned above, there are differences in productivity projections between the LANDIS-II and PnET-CN simulations used for this assessment. The LANDIS-II results are driven by projections of an overall decline in productivity under GFDL A1FI and a very small increase under PCM B1. The PnET-CN simulations in this assessment, however, project large productivity increases under both scenarios, with productivity gains nearly twice as large under the GFDL A1FI scenario. One major reason for this difference is that the LANDIS-II model includes several processes that lead to tree mortality, such as competition, natural disturbances, and forest management. These processes are not included in the PnET-CN model.

Another important reason for this discrepancy is the way that these models account for the potential CO_2 fertilization effect. Again, the PnET-CN simulations appear to be driven mainly by the potential CO_2 fertilization effect, and the productivity estimates used by the LANDIS-II model 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). Unique factors incorporated into the LANDIS-II model, such as wind disturbance, forest harvest, and tree species competition and movement, may also cause some smaller differences between the model results.

There do not appear to be any major discrepancies between individual species when the LANDIS-II and Tree Atlas model results are compared, although there are some differences. Particularly under the PCM B1 scenario, LANDIS-II projects better outcomes for some species, such as northern pin oak, northern white-cedar, red maple, white ash, and white oak. This difference may be due to several factors. Most importantly, the LANDIS-II model simulates changes in tree growth and biomass, whereas the Tree Atlas describes potential suitable habitat that is available to a species. Therefore, the biomass values at the year 2100 that are provided by LANDIS-II include biomass for trees that are established well before the year 2100, even trees that are currently present. Trees that are able to establish by mid-century may be able to persist and even grow on a site as establishment conditions become less and less suitable over time. By the end of the century, however, the habitat conditions may no longer be suitable for many species, especially at the regeneration stage.

Limitations

All models are simplified representations of reality, and no model can fully consider the entire range of ecosystem processes, stressors, interactions, and future changes to forest ecosystems. Each model omits processes or drivers that may critically influence ecosystem change in the future. Future uncertainty is not limited to climate scenarios; there is also uncertainty associated with future human interactions with forests. Some examples of factors that are not considered in these models are:

- Land management and policy responses to climate change or impacts to forests
- Land-use change or forest fragmentation
- Future changes in forest industry, both in products and in markets
- Changes in phenology and potential timing mismatches for key ecosystem processes
- Responses of understory vegetation, soil microorganisms, and soil mycorrhizal associations
- Extreme weather events, which are not captured well in climate data or forest impact models
- Future wildfire behavior, fire suppression, and ability to apply prescribed fire
- Novel successional pathways for current forest ecosystems
- New major insect pests or disease agents
- Future herbivory pressure, particularly from white-tailed deer
- Interactions among all these factors

Most of these factors could drive large changes in forest ecosystems 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 can simulate a range of possible future outcomes. It is important to keep the above limitations in mind when weighing the results from different models and use them to inform an overall assessment. The comparison across 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 the assessment area respond to climate change.

SUMMARY OF CURRENT SCIENTIFIC KNOWLEDGE

The results presented above provide us with important projections of tree species distributions and forest response across a range of future climates, but these models do not account for all factors that may influence tree species and forest communities under a changing climate. Climate change has the potential to alter the distribution, abundance, and productivity of forests and their associated species in several ways (CCSP 2008a, Vose et al. 2012). These impacts can broadly be divided into the direct effects of changing temperature, precipitation, and CO_2 levels on forests 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 current state of scientific knowledge on additional direct and indirect effects of climate change on forests in the assessment area and the wider Midwest region.

Wind Events

Wind disturbance is a primary driver of many regional forests (Johnson 1995). Both small-scale and stand-replacing wind events influence the structure and species composition of many forests in the assessment area and increase landscape complexity (Frelich and Reich 1995a, 1995b; White and Host 2008). Storm severity, forest composition, stand age, soils, topography, and a host of other factors influence the physical effects from 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 known whether any increase in severe forest disturbances from wind in the assessment area will be outside the already high range of variability (Chapter 4).

Under climate change, stand-replacing wind events 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. Moreover, tree mortality as a result of future wind events may further increase the risk of wildfire.

Altered Precipitation

Climate change is expected to alter precipitation regimes and hydrologic conditions throughout the assessment area. As discussed in Chapters 3 and 4, heavy precipitation events have been increasing across the assessment area over the past century and this trend is expected to continue. 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 may 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 available soil 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 and root depth, but the general principles are useful.

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 forest ecosystems to greater risk of hydrologic extremes, including flooding and drought. For example, species 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. 2000b). Tree species and assemblages that are accustomed to seasonal or annual variations in water availability may be better able to tolerate this variability. In particular, riparian forests are more tolerant of varying degrees of hydrologic fluctuation, and pine-dominated forests are generally 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, such as northern hardwoods or lowland conifers, may be more stressed by hydrologic variation.

Drought Stress

There is evidence for an increased risk of drought stress in the future in the assessment area. Temperatures are expected to rise over the next century, which will increase evapotranspiration in ecosystems. Moisture stress may occur when increases in evapotranspiration are not offset by a corresponding increase in precipitation and soil moisture. Within the climate scenarios used in this assessment, the potential for more frequent droughts and moisture stress during the growing season appears to be much greater under the GFDL A1FI scenario. Even under the milder PCM B1 scenario, warmer temperatures may also lead to increased evapotranspiration and physiological stress if increases in precipitation do not offset water losses (Chapter 4). Although precipitation projections have greater uncertainty, these results are generally consistent with other projections of future precipitation in the region (Center for Climatic Research 2013, Kunkel et al. 2013). Additionally, there is evidence that precipitation is more likely to occur during more intense precipitation events (Kucharik et al. 2010b), which may increase the interval between rainfall events (Knapp et al. 2008).

Drought can affect forests in many ways, including altering ecosystem processes, reducing forest productivity, increasing susceptibility to other stressors, and increasing tree mortality (Dale et al. 2001). Nearly all forests are susceptible to drought. For example, 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), which reduces the ability of trees to move water and causes reduced productivity or mortality. Forest species from rain forests, temperate forests, and dry woodlands all showed a similarly low threshold for resisting hydraulic failure (Choat et al. 2012).

The potential effects of drought on forests will depend upon many factors, including drought duration and severity, as well as site-level characteristics of the forest. In the Upper Midwest, the duration of drought events may have a greater effect on tree mortality than drought severity or average dryness over a period of years (Gustafson and Sturtevant 2013). High stand density may compound susceptibility to moisture stress as high-density stands face increased competition for available moisture (D'Amato et al. 2011, Magruder et al. 2012). Furthermore, drought-stressed trees are typically more vulnerable to insect pests and diseases (Dukes et al. 2009b, Minnesota Department of Natural Resources 2011).

Tree species also respond differently to drought. For example, drought has been linked to dieback in sugar maple, birch species, and ash species in Maine over the past century (Auclair et al. 2010). Recently, a widespread aspen decline was observed in northern Minnesota and linked to the combined effects of a multi-year drought and insect defoliation (Worrall et al. 2013), and future projections suggest greater losses of suitable habitat for aspen in the upper Great Lakes region by mid-century (Worrall et al. 2013). Conversely, ecosystem 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 reduces the rate of water loss from trees through evapotranspiration, but it is unclear to what degree enhanced water use efficiency may be able to offset the combined effects of warmer temperatures and drier conditions (Ryan and Vose 2012, Wyckoff and Bowers 2010).

Snow and Soil Frost

Winter processes, such as snowfall and soil frost, are projected to continue to change substantially under a changing climate (Chapter 4). Shifts in the timing of the soil frost season may have cascading impacts on various ecosystem processes. Unfrozen soils are better able to absorb snowmelt and rainfall, leading to increased infiltration (Sinha and Cherkauer 2010). Increased infiltration can 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 be losing additional soil nutrients. Northern hardwood species are generally shallow-rooted 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). Interactions of these effects may be increasing hardwood decline in the assessment area (Box 11). Altered winter processes on forest ecosystems in the assessment area may also affect regeneration conditions for some species. For example, yellow birch is best able to disperse seeds over snow, and therefore may be impaired by less consistent snowpack (Burns and Honkala 1990, Groffman et al. 2012).

Winter visitors to the sea caves at Apostle Islands National Lakeshore. Photo by Maria Janowiak, U.S. Forest Service.

Box 11: 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 and Environment 2009, 2010; Michigan Department of Natural Resources [MDNR] 2012b). Permanent plots have been established on industrial, Federal, and State land in the Upper Peninsula of Michigan, northern Wisconsin, and eastern Minnesota in order to investigate the cause of this dieback (Bal 2013). Mean sugar maple crown dieback percentage of live trees at all plots varied from 15 percent in 2009 to approximately 7 percent in 2012. Healthy sugar maple stands typically have less than 10-percent dieback.

Analysis has indicated that sugar maple dieback is related to many factors, including exotic earthworms, climate, and soil nutrient variability (Bal 2013). Out of all plot variables measured, the forest floor condition was the significant factor related to mean sugar maple crown dieback (2009-12). The removal of the duff layer by high densities of European earthworms exposes roots, disturbs biogeochemical cycling, reduces soil moisture, increases soil temperature, affects mycorrhizal communities, and generally exacerbates further stresses on trees (Bohlen et al. 2004, Larson et al. 2010). Evaluation of 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, 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 (Bal 2013). The presence of earthworms and poor soil fertility are also likely contributing to poor crown conditions and decline in many areas.

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). Most studies examining the effects of climate change on soil erosion have focused on agricultural settings, rather than forest ecosystems. 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 from climate-related impacts or disturbance events such as prolonged drought, wildfire, or increased tree mortality, could lead to greater susceptibility to erosion. Additionally, the projected decline in snowcover 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 (Sinha and Cherkauer 2010).

Wildfire

Wildfire is an important driver for some forest ecosystems in the assessment area. Jack pine, red pine, and aspen-birch forests are often linked to wildfire dynamics, but 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, and climate also indirectly affects fire regimes through its influence on vegetation vigor, structure, and composition (Sommers et al. 2011).

Many aspects of the fire regime within the assessment area are expected to be affected by changes in climate, with response to climate change varying 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 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 there will be increases in fire activity 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 and that wildfire risk may double 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 may become more frequent (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 often determine whether a change in fire risk might translate to an actual increase in wildfire activity. Because future policies on wildfire suppression and prescribed fire are unknown, there is greater uncertainty about the potential effects of wildfire on forests in the assessment area.

Invasive Species

Nonnative invasive species are currently a major threat to forests in the assessment area (Chapter 1). It is generally expected that many 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. 2009a). The invasion of nonnative plant species into new environments depends on a complex combination of factors related to both the specific species and environmental conditions in question. Climatic factors that could influence the ability of a species to invade include warmer temperatures, earlier springs, and reduced snowpack (Ryan and Vose 2012). As one example, Japanese barberry is limited by cold temperatures, which may increase its ability to expand to new areas as temperatures increase. Further, some invasive plant species have been identified as having increased productivity in response to elevated CO_2 (Ryan and Vose 2012).

Further, as discussed throughout this chapter, many potential effects of climate change are expected to increase stress and disturbance within forest ecosystems, which certainly raises the potential for invasive species to exploit altered environments. Disturbances such as flooding and wildfire can open forest canopies, expose mineral soil, and reduce tree cover, providing greater opportunities for invasion (Ryan and Vose 2012). Once established, invasive species can also limit regeneration of native tree species through increased competition.

Nonnative species may facilitate the invasion and establishment of other nonnative species. This interaction appears to be the case with European earthworms and European buckthorn, which appear to have a co-facilitating relationship (Heimpel et al. 2010). Similarly, studies in northern Minnesota found that a combination of invasive earthworms and warming conditions could benefit nonnative understory plant species (Eisenhauer et al. 2012).

Forest Pests and Diseases

Forest pests and diseases, some of which are nonnative, are also generally expected to increase in a changing climate; this expected outcome reflects the ability of these species to increase in abundance and distribution in response to altered climatic conditions combined with anticipated increases in forest stress and disturbance that may make forests more susceptible to pests and diseases (Weed et al. 2013). At the same time, the effect of climate on specific forest insects remains uncertain in many cases (Ryan and Vose 2012). For example, gypsy moth is currently 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). Similarly, hemlock wooly adelgid is limited by winter low temperatures of -10 to -15 °F (MDNR 2011a). Locations currently identified as being at greater risk from this pest are based on average winter minimum temperatures (MDNR 2012a) but do not account for the rapid rise in winter minimum temperatures projected across a range of climate scenarios (Chapter 4).

It is more difficult to anticipate the response of forest pathogens under a warmer future due to complex modes of infection, transmission, survival, and tree response (Dukes et al. 2009a). Reviews examining forest pests and diseases in light of potential climate change impacts highlight the potential for interactions involving other stress agents that make trees more susceptible to these agents (Sturrock et al. 2011,Weed et al. 2013). Pests and pathogens are generally expected to become more damaging in forest ecosystems as the climate changes, because they will be able to adapt more quickly to new climatic conditions, migrate more quickly to suitable habitat, and reproduce at faster rates than host tree species. One example of a potential disease migrant to the assessment area is sudden oak death, a fungal pathogen currently limited by cold temperatures to the West Coast and southeastern United States.

However, the current risk maps for sudden oak death are based on the climate during 1971 through 2000, 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 most of Michigan and Wisconsin as marginally suitable habitat. Particularly under scenarios with greater temperature increases, it is expected that this disease could survive in the region (Venette and Cohen 2006).

Herbivory

As mentioned above, changes in snowfall amount and duration throughout the assessment area may change the wintertime foraging behavior for herbivores such as moose, white-tailed deer, and snowshoe hare. Climate change is expected to influence both white-tailed deer and moose populations in the assessment area (Frelich et al. 2012, Rempel 2011). Warmer winter temperatures and reduced snow depth are expected to reduce the energy requirements for deer, and increase access to forage during winter months (WICCI 2011a). Larger deer herds could have impacts on forest ecosystems across the assessment area. Research has found that deer browsing pressure may limit the ability of forest ecosystems to respond to climate change (Fisichelli et al. 2012). Tree species that are anticipated to expand their ranges northward in the assessment area, such as many hardwood species, are browsed much more heavily than boreal conifers such as balsam fir and white spruce. Deer herbivory may also favor species which are not preferred browse species, such as eastern hophornbeam and black cherry, or invasive species like buckthorn or Japanese barberry. Tree Atlas, LANDIS-II, and PnET-CN models project that most mesic hardwood species and eastern white pine will gain in suitable

A white-tailed deer in western Upper Michigan. Photo by Maria Janowiak, U.S. Forest Service.

habitat, biomass, and productivity in the assessment area over the 21st century, but none of these models accounts for selective herbivory.

Further, climate change may influence the interaction between white-tailed deer and moose populations. Climate change is expected to have multiple negative impacts on moose populations. Although the winter browse opportunities may increase as snow depths decrease, moose are intolerant of heat and may be susceptible to summer heat stress (Rodenhouse 2009). Moose distribution is also limited by the presence of the deer brainworm, a disease that is carried by deer and lethal to moose (Frelich et al. 2012). Warmer temperatures and less severe winters could result in increased mortality of moose from brainworm as deer populations expand into areas currently dominated by moose. Similarly, warmer temperatures may also increase populations of winter ticks, another major cause of moose mortality (Rodenhouse 2009). Dynamics between moose and deer populations are also tightly linked to forest composition. The ability of either species to thrive will depend in part upon the tree species that are available for browse, and changes in the distribution or abundance of deer and moose will have a strong influence on forest composition in the future (Frelich et al. 2012, Rodenhouse 2009).

Carbon Dioxide Fertilization

As discussed earlier in this chapter, CO_2 itself can affect plant productivity and species composition in addition to its direct, positive effect on photosynthesis. Elevated CO_2 reduces the rate of water loss from trees, which may enhance growth in some species and potentially offset some of the effects of drier growing seasons (Ainsworth and Rogers 2007, Franks et al. 2013, 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 moisture stress late in the growing season. Research on bur oak in Minnesota suggests that this effect may have improved the ability of adult trees to withstand seasonal moisture stress (Wyckoff and Bowers 2010). Precipitation and humidity influence the effects of elevated CO_2 on ecosystem water balance (Ryan and Vose 2012).

As mentioned in the discussion of PnET-CN results, several factors might actually limit the 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 ecosystem transitions might also influence the ability of forests to take advantage of additional atmospheric CO_2 . Furthermore, 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, Franks et al. 2013).

It is unclear how substantial this factor will be over the long term. Carbon dioxide enrichment experiments 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). Moreover, few observational studies have evaluated the effects of CO_2 fertilization beyond 600 ppm, making it hard to predict how forests may respond under even higher levels of atmospheric CO_2 , such as the 900-ppm levels projected under the A1FI emissions scenario for 2100.

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 the productivity of forest ecosystems, which can be limited by nutrients such as phosphorus, calcium, and nitrogen. Studies across the northeastern United States can give some insight into potential effects of climate change on nutrient cycling.

Decomposition of detritus 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, nitrogen deposition, 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, precipitation, 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. A number of 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 nitrogen, 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 forest ecosystems in the future.

Interactions

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

Recognizing the potential for these interactions will be necessary to accurately assess the risks that climate change poses to forest ecosystems. Scientific research is beginning to clarify how biotic and abiotic stressors can operate in concert, but these types of studies are still relatively rare (Gellesch et al. 2013). For example, it has long been suggested that stressed trees are more susceptible to insect pests and diseases. 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. This example is simply one chain of interactions, and many more connections could be drawn to phenological changes, fire seasons, and other climate-mediated impacts.

SUMMARY

Climate change has the potential to affect forest ecosystems in numerous 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 ecosystems 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 ecosystem shifts across the assessment area.

Additionally, research on the direct and indirect impacts of climate change on forest ecosystems 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. Chapter 6 uses the information presented in this chapter to assess the vulnerability of the forests of the assessment area to climate change.

A creek in northern Wisconsin in the spring. Photo by Maria Janowiak, U.S. Forest Service.

CHAPTER 6: FOREST ECOSYSTEM VULNERABILITIES

Changes in species distribution and abundance due to climate change can have important implications for the habitats in which those species live, leading to shifts in community composition and changes in ecosystem processes (Climate Change Science Program [CCSP] 2008a, Ryan and Vose 2012). In addition, climate change itself can alter system drivers and exacerbate or ameliorate current stressors (CCSP 2008a, Ryan and Vose 2012). This chapter describes the climate change vulnerability of nine forest systems in the assessment area over the next century. Vulnerability is the susceptibility of a system to the adverse effects of climate change (Intergovernmental Panel on Climate Change [IPCC] 2007a). It is a function of potential climate change impacts and the adaptive capacity of the system (Fig. 48). We consider a system to be vulnerable if it is at risk of a shift in composition that leads to a substantially different identity for the system, or if the system is anticipated to suffer substantial declines in health or productivity. The vulnerability of a system 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 managers.

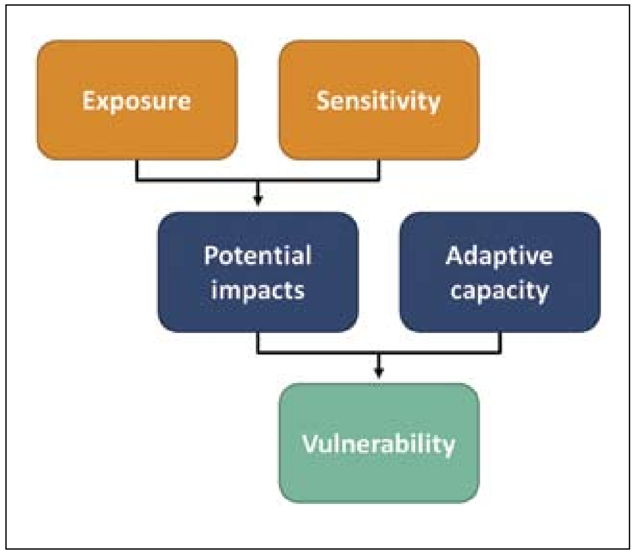


Figure 48.—Key components of vulnerability, illustrating the relationship among exposure, sensitivity, and adaptive capacity. Adapted from Glick et al. (2011b).

This chapter is organized into two sections. We first present an overall synthesis of climate change vulnerability of the assessment area, 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 following section, we present individual vulnerability determinations for the nine forest types considered in this assessment.

Throughout this chapter, statements about potential impacts and adaptive capacity factors are qualified with a confidence statement, phrased according to the IPCC's guidance for authors (Mastrandrea et al. 2010) (Fig. 49). Confidence was determined by gauging both the level of evidence and level of agreement among information. Evidence refers to the body of information available based upon theory, data, models, expert judgment, and other sources. It was considered robust when multiple observations or models were available as well as an established theoretical understanding to support a statement. Agreement refers to the agreement among the multiple lines of evidence. A high level of agreement was suggested if theories, observations, and models

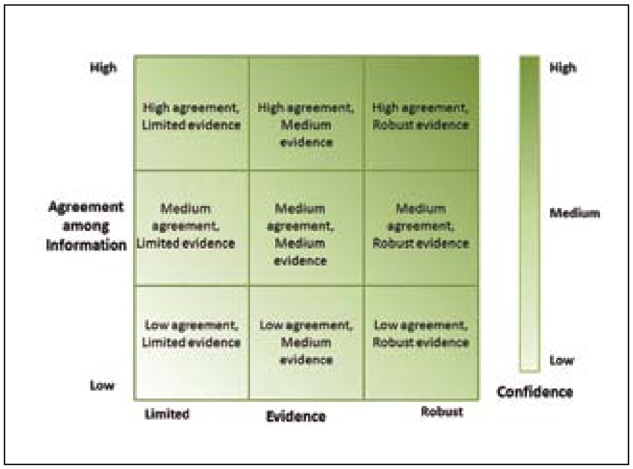


Figure 49.—Confidence determination diagram used in the assessment. Adapted from Mastrandrea et al. (2010).

tended to point toward similar outcomes. Agreement does not refer to the level of agreement among the authors of this assessment.

SYNTHESIS OF CLIMATE CHANGE IMPACTS ON FOREST ECOSYSTEMS

Climate change creates the potential for a wide-ranging set of direct and indirect impacts on ecosystems, which are a function of the degree to which a system is exposed to climatic change and its sensitivity to these changes. Impacts may be beneficial or harmful to a particular forest or ecosystem type. 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 current 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. The summary below presents the potential impacts of climate change on major drivers and stressors in the assessment area over the next century based on the current scientific consensus of published literature, which is described in more detail in the preceding chapters.

Potential Impacts on Drivers and Stressors

Many physical and biological factors contribute to the current state of forest ecosystems in northern Wisconsin and the western Upper Peninsula of Michigan. These factors include drivers—the most fundamental variables that shape a particular system, and stressors—agents that can reduce forest health or productivity or impair ecosystem functions. Many factors, such as flooding or fire, may be drivers in one situation and stressors in another. Similarly, some disturbances, such as flooding or fire, act as drivers in certain systems, but can be 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 substantial increases (Chapter 3), and continued temperature increases are projected for the assessment area even under the most conservative future climate scenario (Chapter 4).

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 expected 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 (Bradley et al. 1999, Dragoni and Rahman 2012). Earlier springs and longer growing seasons are expected to cause shifts in phenology 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. 2006b, Walther et al. 2002), and some of these effects have already been observed (Bradley et al. 1999, Ellwood et al. 2013). Longer growing seasons may also result in greater growth and productivity of trees and other vegetation, but only if balanced by available water and nutrients (Chapter 5).

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 more than temperatures in other seasons (Chapter 4). Projected temperature increases indicate that a greater proportion of moisture will be delivered as rain rather than snow during the winter. Combined with increased snowmelt from higher temperatures, the amount of snow on the ground is expected to decrease across the assessment area by the end of the 21st century (Notaro et al. 2011, Sinha and Cherkauer 2010, Wisconsin Initiative on Climate Change Impacts [WICCI] 2011). In addition, the assessment area is projected to experience fewer days of soil frost by the end of the century (Sinha and Cherkauer 2010). Although these conditions could increase water infiltration into the soil and reduce runoff, they may also lead to greater soil water losses through increased evapotranspiration. This decrease in snow cover and frozen soil may affect a variety of ecosystem processes, including decomposition, nutrient cycling, and the onset of the growing season.

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, Kucharik et al. 2010b, Winkler et al. 2012). Although individual model projections for the assessment area may differ, there is general agreement that total annual precipitation is projected 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). There is disagreement in the projections of summer precipitation in the models used in this assessment (a slight increase under PCM B1 or a sharp decrease under GFDL A1FI; Chapter 4) and other data sets (Center for Climatic Research 2013, WICCI 2013).

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 the assessment area in particular (Groisman et al. 2012, Kunkel et al. 2008, Saunders et al. 2012), and many models agree that this trend will continue over the next century (IPCC 2007a, Kling et al. 2003, Kunkel et al. 2013, WICCI 2011). Most heavy precipitation events currently occur during summer in the assessment area, although changes in precipitation patterns are projected to increase the frequency of extreme precipitation events in spring, summer, and fall (Kucharik et al. 2010b). Projected increases in total runoff and peak stream flow during the winter and spring (Cherkauer and Sinha 2010) could potentially increase the magnitude or frequency of flooding. Increases in runoff following heavy precipitation events could also lead to an increase in soil erosion (Nearing et al. 2004). The risk from floods, erosion, and other impacts will ultimately depend on local geological and topographic conditions as well as future decisions regarding infrastructure and land use, which remain unknown.

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.*

Given that warmer temperatures and seasonal changes in precipitation are expected across the assessment area, it is reasonable to expect that soil moisture regimes will also shift. Longer growing seasons and warmer temperatures may result in greater evapotranspiration losses and lower soil-water availability later in the growing season (Chapter 4). Outputs from the PnET-CN

Canyon Falls in western Upper Michigan. Photo by Scott Pearson, used with permission.

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 cannot retain the water from intense precipitation events. There is substantial 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).

Droughts will increase in duration and area (limited evidence, low agreement). *A study using multiple climate models indicates that drought may increase in extent and area, 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. 2008a). Studies examining a range of climate model projections disagree with this conclusion, projecting that the region 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 under the GFDL A1F1 scenario (Chapter 4).

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 2007a). 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 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 decisions regarding wildfire management also make fire projections more uncertain for the assessment area.

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

Changes in climate may allow some nonnative plant species, insect pests, and pathogens to expand their ranges farther north (Dukes et al. 2009a) as the climate warms and the assessment area loses some of the protection offered by a traditionally cold climate and short growing season. The abundance and distribution of some nonnative plant species may be able to increase directly in response to a warmer climate and also indirectly through increased invasion of stressed or disturbed forests (Ryan and Vose 2012). Similarly, forest pests and pathogens are generally able to respond rapidly to changes in climate and also disproportionately damage stressed ecosystems (Weed et al. 2013). Thus, there is high potential for pests and pathogens to interact with other climate-mediated stressors. Unfortunately, we lack basic information on the climatic thresholds that apply to many invasive plants, insect pests, and pathogens. Further, our ability to predict the mechanisms of infection (in the case of pests and diseases), dispersal, and spread for specific agents remains low. Furthermore, it is not possible to predict all future nonnative 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 are expected to change forest ecosystems throughout the assessment area. 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). *Ecosystem 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 species.*

Across northern latitudes, warmer temperatures are expected to be more favorable to individuals near the northern extent of their species' range and less favorable to those near the southern extent (Iverson and Prasad 1998). Results from climate impact models project a decline in suitable habitat and landscape-level biomass for northern species such as black spruce, white spruce, tamarack, jack pine, yellow birch, and paper birch (Chapter 5). PnET-CN results also suggest that spruce/fir forests may have smaller 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, although 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, medium agreement). *Ecosystem models agree that many temperate species will gain suitable habitat and biomass 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 currently 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 both suitable habitat and biomass in the assessment area include bitternut hickory, black oak, bur oak, and white oak (Chapter 5). PnET-CN outputs also indicate that deciduous forest types have the potential for large productivity increases across the assessment area. In addition, Tree Atlas results project that suitable habitat may become available for species not currently found in the assessment area by the end of the century (Chapter 5). 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 suitable habitats will shift (Iverson et al. 2004a, 2004b; McLachlan et al. 2005; Scheller and Mladenoff 2008). Pests and diseases such as emerald ash borer, beech bark disease, and Dutch elm disease are also expected to limit some species projected to be increasers by impact models.

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

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 tree species distribution across the assessment area. The models indicate that climate trends may generally favor hardwood species across the landscape by the end of the century. Past climatic changes resulted in large shifts in species composition (Davis 1983, Williams et al. 2004). 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) and that tree species may also 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. 2011). Similarly, the 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). Major shifts in species composition may not be observable until well into the 21st century because of the long timeframes associated with many ecosystem processes and responses to climate change. Major stand-replacing disturbance events or forest management could accelerate shifts in forest composition, however (He et al. 2002, Climate Change Science Program [CCSP] 2008b).

Forest productivity will increase across the assessment area (medium evidence, low agreement). *Some model projections and other evidence suggest forest productivity may increase in the assessment area, although there is uncertainty about the effects of and limitations to carbon dioxide (CO_2) fertilization. It is also anticipated that productivity will be reduced in localized areas.*

Numerous studies have tried to project the effects of climate change on forest productivity and carbon balance through modeling simulations and manipulative experiments (Handler et al. 2012, Ryan and Vose 2012). Studies of CO_2 fertilization, including the PnET-CN results presented in this assessment, indicate that productivity may generally increase across the assessment area (Chapter 5). Warmer temperatures may 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, which do not include the possible effects of CO_2 fertilization, project gradual productivity declines under the GFDL A1FI scenario across the assessment area (Chapter 5). 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 the migration of species to newly suitable habitat may reduce productivity until a new equilibrium is reached. For these reasons, future forest productivity is dependent upon complex interactions among the degree of warming, ecosystem water balance, and disturbance events (Chiang et al. 2008, Duveneck et al. 2014, He et al. 2002, Scheller and Mladenoff 2005).

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). It is strongly related to the concept of resilience (CCSP 2008a). Below, we summarize factors that could reduce or increase 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 are more vulnerable to change.*

In general, species-rich communities have exhibited greater resilience to extreme environmental conditions and greater potential to recover from disturbance than less diverse ecosystems (Tilman 1996, 1999). Consequently, less diverse ecosystems may be inherently more susceptible to future changes and stressors (Duveneck et al. 2014, 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. For example, northern hardwood forests generally support a large number of tree species and therefore have many possible future trajectories, but aspen-birch and red pine 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 are more apt to have 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. The degree to which fragmentation limits dispersal depends upon the level of fragmentation, the composition of the surrounding area (e.g., forest versus nonforest), and the dispersal characteristics of individual species (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), but 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 migration (Jump and Peñuelas 2005, Scheller and Mladenoff 2008). Humans may be able to assist in the migration of species to newly suitable areas to counteract the effects of fragmentation. Assisted migration is a contentious issue for some species, especially those of conservation concern (Pedlar et al. 2012, Schwartz et al. 2012).

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 the assessment area 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. Species restricted to 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 that are adapted to more frequent disturbance will be at lower risk.*

Disturbances such as wildfire, flooding, and pest outbreaks are projected 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. Therefore, these systems may be less tolerant of more frequent widespread disturbances. Mesic systems can create conditions that could buffer against fire and drought to some extent, but these systems are not expected to 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 may be better able to withstand climate-driven disturbances. This principle is limited, however, 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 fire becomes too frequent or drought becomes too severe.

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.

We assessed the vulnerability of nine forest systems to climate change impacts, drawing 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 20 panelists evaluated anticipated climate trends for the assessment area and ecosystem model projections (Chapters 3 through 5), and used their expertise to interpret the information. 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 6.

Overall vulnerability determinations ranged from moderate-low (oak and white pine) to high (upland spruce-fir and lowland conifers) (Table 13). Impacts were rated as being most negative for upland spruce-fir and lowland conifers, and most moderate for oak forests. Adaptive capacity was rated lowest for upland spruce-fir, lowland conifers, and red pine forests, and highest for white pine. Panelists tended to rate the amount of evidence as medium to medium-high (between limited and robust) for most forest systems. Incomplete knowledge of future

Table 13.—Climate change vulnerability determinations for the forest systems considered in this assessment

Forest system	Potential impacts	Adaptive capacity	Vulnerability	Evidence	Agreement
Aspen-birch	Moderate-Negative	Moderate	Moderate-High	Medium-High	Medium-High
Jack pine	Moderate-Negative	Moderate-High	Moderate	Medium	Medium-High
Lowland conifers	Negative	Moderate-Low	High	Medium	Medium-High
Lowland-riparian hardwoods	Moderate-Negative	Moderate	Moderate-High	Limited-Medium	Medium
Northern hardwoods	Moderate-Negative	Moderate-High	Moderate	Medium-High	Medium
Oak	Moderate	Moderate-High	Moderate-Low	Medium	Medium-High
Red pine	Moderate-Negative	Moderate-Low	Moderate-High	Medium-High	Medium-High
Upland spruce-fir	Negative	Moderate-Low	High	Medium-High	Medium-High
White pine	Moderate-Positive	High	Moderate-Low	Medium-High	Medium

wildfire regimes, interactions among stressors, and precipitation regimes were common factors limiting this component of overall confidence. The ratings of agreement among information also tended to be in the medium to medium-high range. Contrasting information about precipitation regimes under the PCM B1 and GFDL A1FI climate change scenarios was a major factor that limited the level of agreement among information. The classification system for forest ecosystems for this assessment also limited the agreement in some instances where species-level impacts and vulnerability varied widely within a single forest type. In general, ratings were slightly higher for agreement than for evidence.

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 across the assessment area. In addition, we summarize the main factors contributing to the adaptive capacity of each system. It is critical to note that climate change impacts and the adaptive capacity of a forest system were assessed across the entire assessment area. Because forest systems vary widely at a local level due to differences in climate, landform, soils, disturbance, past management, and numerous other factors, the vulnerability in a particular location may be different—even markedly so—from the broad-scale information highlighted in this chapter. For this reason, the following summaries provide a starting point for considering vulnerability at finer spatial scales.

Aspen-Birch

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

Ecosystem models project substantial declines for aspen and birch across the assessment area, and the potential exists for multiple stressors to interact under climate change, particularly drought and forest pests. This forest system, however, is also distributed across a wide range of sites and adapted to disturbance.

Moderate-Negative Potential Impacts

Drivers: There is a greater likelihood of reduced soil moisture and enhanced evapotranspiration as the climate warms, especially late in the growing season. Drought stress and mortality may consequently increase, with the greatest risk on dry and poor-quality sites. Additionally, projected temperatures in the assessment area may be beyond the physiological limits of aspen and birch species by the end of the 21st century, particularly under hotter conditions like those projected under the GFDL A1FI scenario. Disturbance from stand-replacing wildfire or wind events could benefit this forest type, although small-scale disturbances could increase the rate of succession to other forest types.

Dominant Species: The dominant species within this forest system, such as balsam fir, paper birch, and quaking aspen, are near their southern range limits in the assessment area and are projected to decline in suitable habitat and biomass under a range of possible climate futures. Model results are mixed for balsam poplar and bigtooth aspen, but models agree that these species are not projected to increase substantially under future climate scenarios. Red maple is a common associate and is projected to fare better under future climate conditions relative to the other species in this forest system, suggesting that it may have a competitive advantage in the future.

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, and stressed forests may be more susceptible to diseases like hypoxylon canker. White-tailed deer herbivory may also increase with warmer winters and reduced snow cover. The possibility exists for interactions among multiple stressors to lead to more severe climate change impacts. For example, warmer temperatures may simultaneously increase drought stress on trees and create conditions more suitable to some forest pests and diseases, which could combine to increase the risk of insect and disease outbreaks, tree mortality, and ultimately, wildfire risk.

Moderate Adaptive Capacity

Aspen-birch forests are prevalent across the landscape on a wide variety of soils and landforms. The early-successional characteristics of these species, including abundant wind-dispersed seed production and vegetative reproduction, make them highly resilient to many forms of disturbance. Forests dominated by paper birch may be at greater risk than aspen-dominated forests, because paper birch forests are currently much less common across the landscape and face greater challenges to regeneration. Additionally, natural succession in recent decades is reducing the amount of early-successional forests present across the landscape. Younger aspen-birch forests are therefore less common on the landscape, which may limit future opportunities for maintaining this forest type.

Natural resource professionals in an aspen forest at the Chequamegon-Nicolet National Forest. Photo by Maria Janowiak, U.S. Forest Service.

Paper birch trees. Photo by Maria Janowiak, U.S. Forest Service.

Aspen-birch forest at Isle Royale National Park. Photo by Maria Janowiak, U.S. Forest Service.

Jack Pine

Moderate Vulnerability (medium evidence, medium-high agreement)

Ecosystem models project declines in suitable habitat and biomass for jack pine forests under more-extreme climatic change. The ability of this system to be competitive on poor-quality sites and withstand disturbance increases the adaptive capacity, although jack pine may be less able to persist and regenerate under substantial warming.

Moderate-Negative Potential Impacts

Drivers: Jack pine forests are generally found on sites with coarse-textured soils, and they may be able to tolerate the projected soil moisture decreases during summer. Although some current jack pine sites may become too hot or dry in the future, other sites currently dominated by red pine, white pine, or other species may become more suitable for jack pine. The potential for increased fire frequency or intensity under warmer and drier conditions would favor jack pine forests relative to many other forest types. Greater wildfire activity could be positive for these forests, but too much change to the fire regime might hamper regeneration and cause these forests to shift to barrens.

Dominant Species: Considering the range of possible future climates, jack pine is generally expected to decline in suitable habitat and biomass across the assessment area over the next 100 years. This species is currently at the southern extent of its range in Wisconsin. Model results are unclear as to whether eastern white pine and red pine, two commonly associated species, will decrease in habitat suitability or biomass; these species are not projected to increase substantially, although species characteristics suggest they may persist on more favorable sites. Conditions may become more suitable for some species, such as red maple, northern red oak, or northern pin oak.

Stressors: Insect pests like jack pine budworm and diseases like *Scleroderis* may become more damaging under a warmer climate. Additionally, the possibility exists for new pests, such as western bark beetles, to arrive in the assessment area. The window of opportunity to apply prescribed fire to jack pine forests may shift under future climate change, but it is unclear how this change would affect the ability to use fire as a management tool.

Moderate-High Adaptive Capacity

Jack pine forests are highly tolerant of drought and disturbances, and thus have greater adaptive capacity to climate change. These forests can persist on dry and poor soils and in the future may be able to colonize relatively mesic sites that become drier as a result of climate change. The ability of jack pine to be competitive in extreme conditions also suggests that it will be able to persist in many places as conditions become less suitable for other species. Jack pine seedlings are more susceptible to drought stress than are established trees, however, and regeneration failure may occur more frequently. Low tree species diversity in this forest type also provides few options if conditions shift beyond the physiological limits of jack pine.

A young jack pine forest in western Upper Michigan. Photo by Maria Janowiak, U.S. Forest Service.

Cone of a jack pine tree. Photo by Colleen Matula, Wisconsin Department of Natural Resources.

Logging in a jack pine stand. Photo by Maria Janowiak, U.S. Forest Service.

Lowland Conifers

High Vulnerability (medium evidence, medium-high agreement)

Lowland conifer forests have limited tolerance to hydrologic change, including altered precipitation patterns and water table depth. Additionally, the dominant species in these forests are expected to decline under a range of climate futures. Future precipitation and groundwater levels are the primary uncertainties for this forest system.

Negative Potential Impacts

Drivers: Lowland conifer forests function in a relatively narrow window of hydrologic and soil conditions. These conditions are expected to be perturbed in a variety of ways, including through increased likelihood of severe precipitation events and flooding, increased risk of drought, and changes in the water table or relative influence of precipitation versus groundwater. Sphagnum moss, characteristic of peatland forests, may be susceptible to warmer conditions. Stand-replacing fire, typically a rare event in these systems, may become more frequent if sites become particularly dry.

Dominant Species: Most lowland conifer species are near their southern range limits in the assessment area, which suggests they may not tolerate warmer conditions. Most of the dominant conifer species in this system, including balsam fir, black spruce, northern white-cedar, and tamarack, are expected to undergo significant declines in suitable habitat and biomass across the landscape, although there are several limitations to modeling forest change in lowland forests. Associated hardwood species, such as paper birch and quaking aspen, are also expected to decline. These forests may not maintain their current identity if dominant species decline due to warmer conditions or hydrologic change.

Stressors: Roads and other watershed modifications are already harming lowland conifer forests in some parts of the assessment area. Additional hydrologic changes spurred by a changing climate could increase stress on these forests. In peatlands, warmer growing seasons may increase evapotranspiration rates and reduce the rate of peat accumulation, and peat layers may begin to erode as decomposition rates increase. The potential for extensive droughts also increases the possibility for more frequent outbreaks of pests like tamarack sawfly and spruce budworm, which may subsequently increase fire risk. Forests dominated by northern white-cedar may be particularly susceptible to changes in seasonal stream flow. Moreover, it is unclear how warmer winters and reduced snow cover across much of the assessment area may influence landscape-level patterns of deer herbivory. Some lowland conifers, particular northern white-cedar, are preferred browse species during winter.

Moderate-Low 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 may remain cooler than the surrounding uplands (i.e., frost pockets) and also be protected from summer droughts if increased winter and spring precipitation is retained through the summer. Prolonged droughts, however, are generally expected to 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 susceptible to encroachment by invasive species or competing upland forest types.

Tamarack trees and pond. Photo by Scott Pearson, used with permission.

Black spruce in a lowland setting. Photo by Linda Parker, Chequamegon-Nicolet National Forest.

Northern white-cedar forest. Photo by Linda Parker, Chequamegon-Nicolet National Forest.

Lowland conifer forest and bog. Photo by Linda Parker, Chequamegon-Nicolet National Forest.

Lowland and Riparian Hardwoods

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

Climate change is expected 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. There is high uncertainty regarding future precipitation patterns and the associated effects.

Moderate-Negative Potential Impacts

Drivers: Climate change has the potential to alter the hydrologic regimes in lowland and riparian systems 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: Many lowland and riparian hardwood species, such as American elm, black willow, eastern cottonwood, silver maple, swamp white oak, and white ash, are expected to gain suitable habitat across the assessment area under a range of climate futures. 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 in these systems expected to undergo decreased habitat suitability include northern white-cedar, black ash, balsam fir, yellow birch, and paper birch.

Stressors: Invasive species such as reed canarygrass, Japanese barberry, and buckthorn 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 may 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 may increase with warmer winters, which may hinder regeneration of some 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

Many species in riparian and lowland forests can tolerate intermittent wet and dry conditions, as well as periodic floods and moisture stress. Extended droughts could cause significant damage to shallow-rooted species, but increased winter and spring precipitation may buffer summer droughts in low-lying areas on the landscape. Groundwater-fed systems may also have some additional resilience where cooler, wetter soil conditions are maintained over time. These forests are relatively diverse with tree species occupying a variety of microsites, which reduces the risk of some species declining under future conditions. Riparian forests tend to contain species with more southerly distributions, such as silver maple and eastern cottonwood, which may increase their ability to adapt to changing conditions.

Yellow birch and other species along a stream. Photo by Maria Janowiak, U.S. Forest Service.

A lowland hardwood forest in northern Wisconsin. Photo by Maria Janowiak, U.S. Forest Service.

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

A floodplain hardwood forest. Photo by Joshua Cohen, Michigan Natural Features Inventory.

Northern Hardwoods

Moderate Vulnerability (medium-high 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-Negative Potential Impacts

Drivers: Climate change poses several threats to these forests. Altered precipitation patterns and other hydrologic changes have the potential to greatly change soil moisture regimes. Disturbance dynamics in these forests may also change. If conditions become substantially drier, wildfire risk may increase. Increases in extreme weather events may lead to more frequent or widespread windthrow, which could affect the gap-phase dynamics that foster regeneration of shade-tolerant species.

Dominant Species: Model projections are mixed for many species common to these forests. Sugar maple, yellow birch, and to a lesser degree, eastern hemlock have more substantial projected declines in habitat suitability and biomass under the warmer and drier GFDL A1FI scenario than under the PCM B1 scenario, suggesting that greater changes in climate will lead to more-negative consequences. Pests and diseases, such as emerald ash borer and Dutch elm disease, may limit the ability of certain common associate species, such as American elm and white ash, to increase. Some more southerly-distributed hardwood species that are currently infrequent or absent in the assessment area, including white oak, sycamore, sweet birch, and yellow-poplar, are projected to gain new suitable habitat. Although individual species may increase or decrease as the climate changes, there is evidence that the northern hardwoods forest type as a whole may be better able to maintain productivity relative to other forest types.

Stressors: Climate change may amplify several major stressors to northern hardwoods. Reduced snow cover and more frequent freeze-thaw events could exacerbate ongoing hardwood dieback in the assessment area. Forest tent caterpillar, gypsy moth, and other pests may cause more frequent and severe damage in climate-stressed forests, and new pests such as hemlock wooly adelgid may be able to persist if introduced. White-tailed deer herbivory may also increase with warmer winters or reduced snow cover. Unanticipated interactions may also occur between multiple stressors, such as drought, invasive species, and forests pests and diseases. Overall, it is anticipated that these impacts may be greatest on sites where conditions are currently less suitable for this type or where soil conditions become substantially drier.

Moderate-High Adaptive Capacity

Northern hardwood forests are prevalent across the assessment area on a wide variety of soils and landforms, and many tree species are often present. North-facing slopes and other localized areas may undergo less change and continue to support northern hardwoods in the future. Additionally, although some sites may become too dry to support northern hardwoods, other sites that are currently too wet may become suitable over time and be colonized by these species. Sites that currently have reduced species or structural diversity because of past management may have lower adaptive capacity.

A northern hardwood forest in the Ottawa National Forest. Photo by Maria Janowiak, U.S. Forest Service.

Sugar maple seedlings. Photo by Maria Janowiak, U.S. Forest Service.

Canopy of a northern hardwood forest. Photo by Maria Janowiak, U.S. Forest Service.

Oak

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

Oaks are relatively tolerant of drought and warmer temperatures and many species are projected to have increased habitat suitability in the future, although some stressors are also expected to increase. This forest system may expand in the future, but the extent may be influenced by interactions between oak and more mesic species.

Moderate Potential Impacts

Drivers: Oak-dominated forests are relatively drought-tolerant and may tolerate some degree of greater precipitation variability under climate change. Oaks are limited by cold temperatures in the assessment area, so warming may allow this forest type to expand into previously unsuitable areas. Past management and wildfire suppression have allowed oak systems to flourish in areas that were previously barrens or 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-dominated forests. Excessive fire may encourage a shift to pine forests and barrens, whereas a continued lack of fire may promote hardwood forests.

Dominant Species: Models project that black, bur, and white oak may gain suitable habitat and biomass in the assessment area, although results are mixed for northern red and northern pin oak. Most oaks are near their northern range limits in the assessment area, so they may gain suitable habitat under projected warming. Several new oak (pin oak, post oak, scarlet oak, and others) and hickory (mockernut hickory, pignut hickory, and others) species may gain suitable habitat across the assessment area and become a component of these systems where introduced. At the same time, red maple and other mesic species may be able to outcompete oak and hickory species where fire is suppressed. Additionally, results from the PnET-CN model indicate that oak-hickory forests may have greater productivity under future conditions than other forest systems.

Stressors: Climate change could amplify several stressors to oak forests. Forest tent caterpillar, gypsy moth, and other insect pests may cause more frequent and severe damage under climate change, and stressed forests may also be more susceptible to oak wilt and oak decline. Earlier springs may increase the risk of late spring frost damage on seedlings. White-tailed deer populations may also increase with warmer winters, which could hinder regeneration and reduce the potential for this forest type to expand.

Moderate-High Adaptive Capacity

Oak species are generally expected to fare better under climate change, and the species and genetic diversity of these forests provides for many possible future trajectories. These forests could gain territory lost by other forest types under drier future conditions, although the oak-dominated cover type may suffer from increased competition with hardwoods if fire suppression continues.

An oak seedling in fall. Photo by Maria Janowiak, U.S. Forest Service.

Leaves of a northern red oak tree. Photo by Maria Janowiak, U.S. Forest Service.

Oak forest. Photo by Greg Edge, Wisconsin Department of Natural Resources.

Red Pine

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

The potential for increased pest and disease activity is a major threat to red pine forests, 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-Negative Potential Impacts

Drivers: This forest type is relatively drought-tolerant and may not be greatly affected by more frequent moisture stress or more extensive droughts, except on the driest of sites. Additionally, increased frequency of surface fires could be a positive impact for these forest types, but it is possible that very frequent fires could hamper regeneration. Management is responsible for maintaining red pine across much of the assessment area, often using planted seedlings. Seasonal shifts in precipitation patterns, particularly the trend toward wetter springs and drier summers, may impair seedling success even though mature trees are more tolerant of moisture stress.

Dominant Species: Model projections are mixed for red pine and many common associate species. For most species, the warmer and drier GFDL A1FI scenario results in more substantial projected declines in habitat suitability and biomass relative to the PCM B1 scenario, suggesting that greater changes in climate will lead to more-negative consequences. Mature red pine trees are generally drought-tolerant, but the species may be limited by warm temperatures, especially if future temperatures exceed the physiological limits of the species.

Stressors: Climate change is expected to intensify several stressors. Insect pests and diseases may become more virulent and damaging under a warmer climate, particularly where trees are already stressed or overstocked. White-tailed deer populations are also anticipated to increase with warmer winters, so herbivory on preferred species may continue to hinder regeneration. Moisture stress could favor jack pine or northern pin oak on already marginal red pine sites. In some areas, the shift toward mesic species in these forests may continue as ongoing fire suppression facilitates increases in red maple, black cherry, and other hardwoods species projected to increase under climate change.

Moderate-Low Adaptive Capacity

Red 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; for example, some current aspen-birch, oak, or northern hardwood sites may become more suitable for red pine forest in the future. There is relatively little genetic diversity among red pine individuals and the forest system tends to have lower species diversity, which could make it more vulnerable to changing conditions. Red pine forests are often planted. Natural regeneration of red pine is sometimes limited following harvest, particularly in the southern portion of the assessment area.

Red and white pine trees along a lakeshore. Photo by Linda Parker, Chequamegon-Nicolet National Forest.

A forest dominated by red pine at the Apostle Islands National Lakeshore. Photo by Maria Janowiak, U.S. Forest Service.

Red pine forest in northern Wisconsin. Photo by Maria Janowiak, U.S. Forest Service.

Upland Spruce-Fir

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

The boreal species within upland spruce-fir forests are not expected to tolerate warmer temperatures, increased competition from other forest types, and increased forest pest activity. These forests are not well equipped to adapt to climate change.

Negative Potential Impacts

Drivers: 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 system. Increases in stand-replacing wildfire could provide opportunities for regeneration where conditions remain suitable for the dominant species.

Dominant Species: Considering the range of possible climate futures, the majority of dominant species that constitute upland spruce-fir forests (balsam fir, black spruce, paper birch, quaking aspen, and white spruce) are projected to decline in suitable habitat and biomass across the assessment area. These boreal species are near their southern range limits in Wisconsin and Michigan. The same modeling studies offer mixed results for several associate species, such as bigtooth aspen, northern white-cedar, and red maple, 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: Extensive droughts and warmer temperatures expected under climate change will be particularly stressful for this forest type. Spruce budworm and other insect pests may become more active and damaging under a warmer climate, especially where forests are already stressed by drought or other changes. 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.

Moderate-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 fire or other disturbances that provide a suitable seed bed. However, these forests have relatively low diversity or contain primarily boreal species, which leads to fewer possible trajectories in the future. Many planted upland spruce-fir forests in the region have also been negatively affected by spruce decline and other forest health issues, which are expected to reduce their resilience to climate change impacts.

Forester coring a spruce tree to determine its age. Photo by Maria Janowiak, U.S. Forest Service.

A timber harvest in an upland spruce-fir stand. Photo by Maria Janowiak, U.S. Forest Service.

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.

White Pine

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

Climate change may intensify some stressors for white pine forests, such as drought and insect pests. Several characteristics of this forest type suggest that it will have higher resilience, including high species diversity, the ability to persist across a range of site conditions, and the ability to respond favorably after disturbance.

Moderate-Positive Potential Impacts

Drivers: White pine forests are relatively drought-tolerant and may tolerate some degree of greater precipitation variability under climate change. This forest system is present across a fairly wide range of sites, and some sites may be more greatly affected by altered soil moisture regimes. Disturbance dynamics in these forests may also change. Increased storm events may damage or kill mature trees, while also creating opportunities for regeneration. Increases in periodic fire may be beneficial by reducing ladder fuels and competition, although substantially more frequent or severe fire may favor red or jack pine forests.

Dominant Species: Suitable habitat and aboveground biomass are not expected to change substantially for eastern white pine under the PCM B1 scenario, but decreases are projected under the warmer and drier GFDL A1FI scenario, suggesting that greater changes in climate will lead to more negative consequences. Under the most extreme temperature increases, warming in the assessment area may exceed the physiological limits of white pine. Minor components of this forest type, such as northern red oak, northern pin oak, and red maple, also have mixed projections, although jack pine is generally expected to decline.

Stressors: Some common insect pests and diseases may become more damaging under a warmer climate, especially where increased moisture stress increases susceptibility. Moisture stress could also favor red pine, jack pine, or northern pin oak on marginal white pine sites, especially if fire also becomes more prevalent. White-tailed deer populations are also anticipated to increase with warmer winters, so herbivory on white pine seedlings may hinder regeneration.

High Adaptive Capacity

White pine forests are present across the landscape on a wide variety of soils and landforms, and many tree species are often present. White pine forest is less prevalent than other types and occupies less than its historical distribution but has been increasing across the assessment area in recent decades. Although white pine is not projected to have increased habitat suitability or productivity, its wide ecological amplitude may enhance its ability to persist across a range of sites. The ability of white pine to disperse seed and be a pioneer species in gaps and open areas also suggests that it will be able to effectively colonize newly suitable habitat.

Cones of a white pine tree. Photo by Maria Janowiak, U.S. Forest Service.

A mixed forest dominated by red and white pine. Photo by Linda Parker, Chequamegon-Nicolet National Forest.

SUMMARY

Forest ecosystems across the assessment area 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 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 are expected to be better able 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 ecosystem 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 forests in this region, 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 potential 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 ecosystem 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 additional step and summarizes some 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 (Table 26 in Appendix 7). 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 cope with climate impacts. We recognize that climate change will have varying implications for different forest systems, ownerships, and management objectives. Additionally, climate change is only one of many factors considered in making land management decisions. 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 natural resource 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. More thorough assessments are available for both Michigan (Hoving et al. 2013) and Wisconsin (Wisconsin Initiative on Climate Change Impacts [WICCI] 2011a). The wildlife communities found within the assessment area are 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, for example. 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 the assessment area, such as the gray jay and the American marten, are not common farther south. If boreal conifer species decrease in the assessment area, these wildlife species may decrease as their habitats change. Conversely, species like white-tailed deer and wild turkey are hindered by severe winters. A decline in the frequency of severe winters may favor those species. Because forests in the assessment area are habitat for many wildlife species at the northern or southern 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 there will continue to be various effects on wildlife (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 suitable habitat for 147 bird species across the eastern United States (Matthews et al. 2011a). Results from this work suggest that resident bird species are projected to fare better under a changing climate than are species that migrate over greater distances, which is consistent with recent observations of change (Chapter 3). Additionally, changes in suitable habitat of various bird species in the future are closely tied to changes in forest conditions (Matthews et al. 2011a).

More Information

- The Wildlife Working Group report from the Wisconsin Initiative on Climate Change Impacts documents past and current climate change impacts on wildlife, as well as anticipated changes in wildlife diversity and abundance: www.wicci.wisc.edu/report/Wildlife.pdf
- *Changing Climate, Changing Wildlife*, a 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
- Many states are working to incorporate climate change information into their state wildlife action plans. These plans identify wildlife species and associated habitats that are in greatest conservation need. Many species of greatest conservation need may be particularly affected by climate change.

Common loon in western Upper Michigan. Photo by Scott Pearson, used with permission.

  - 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
  - Wisconsin Wildlife Action Plan: http://dnr.wi.gov/topic/WildlifeHabitat/ActionPlan.html
  - Michigan State Wildlife Action Plan: www.michigan.gov/dnr/0,1607,7-153-10370_30909---,00.html
- The Climate Change Bird Atlas is a companion to the Climate Change Tree Atlas and uses information about climate change and effects on forest habitat to project changes in bird species distributions: www.nrs.fs.fed.us/atlas/bird/
- Season's End, a collaborative effort comprising many hunting and conservation organizations, offers many resources on how climate change may affect wildlife: http://www.cakex.org/virtual-library/784
- The Forest Service Climate Change Resource Center provides a summary of potential climate change effects on 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 be susceptible to 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 (i.e., refugia) may be able to persist.

More Information

- The Wildlife Working Group report from the Wisconsin Initiative on Climate Change Impacts documents past and current climate change impacts on wildlife, as well as anticipated changes in wildlife diversity and abundance: www.wicci.wisc.edu/report/Wildlife.pdf
- The Plants and Natural Communities Working Group report from the Wisconsin Initiative on Climate Change Impacts describes the potential effects of climate change on groups of natural communities: www.wicci.wisc.edu/report/Plants-and-Natural-Communities.pdf
- *Changing Climate, Changing Wildlife*, a report from the Michigan Department of Natural Resources – Wildlife Division, assesses how climate change may impact 400 wildlife species in the state: www.michigan.gov/documents/dnr/3564_Climate_Vulnerability_Division_Report_4.24.13_418644_7.pdf

WATER RESOURCES

There are many potential interactions and relationships between climate change, forest ecosystems, and water resources in the assessment area. 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 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).

Many landowners and agencies are responsible for managing water-related infrastructure such as dams, drainage ditches, and culverts. The current specifications for infrastructure are generally based on past climate patterns, and the current 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.

Heavy precipitation events, which are already increasing and projected to increase more in the future (Chapter 4), may overload existing infrastructure that has not been built to that capacity. For example, older road systems may be susceptible to increased rainfall events due to improper location or outdated building standards. Many of these aging structures are being replaced, with the expectation that new culverts will need to last up to 100 years into the future and be able to sustain heavier precipitation events. As one example, an assessment performed by the Chequamegon-Nicolet National Forest reviewed culvert sizing criteria to determine how the replacement of culverts and other infrastructure may need to be altered as precipitation patterns change and extreme precipitation events occur more frequently (Higgins 2013). Hydrologic modeling was used to identify watersheds that may be more vulnerable to flood flows from climate change based upon stream width, runoff potential, and the number of stream crossings within a watershed. The most vulnerable watersheds were generally found to have a high runoff potential and a higher density of stream crossings within the watersheds, and this information is being used to inform the sizing of new culverts (Higgins 2013).

Replacing infrastructure often results in greater costs in order 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.

Aquatic Organisms

Thermal habitat in cold-water lakes and streams may also continue to be impaired as temperatures continue to warm. For example, models of water temperature in cold-water streams and stratified lakes in Wisconsin project water temperature increases of 1.4 to 7.2 °F (0.8 to 4.0 °C) by the end of the 21st century (Higgins 2013, Lyons et al. 2010, Mitro et al. 2010). These changes may be compounded by changes in forests: if tree cover is reduced or if conifer species are replaced by deciduous species, stream shading could decrease,

The Bad River in northern Wisconsin. Photo by Maria Janowiak, U.S. Forest Service.

further increasing water temperatures. Altered precipitation patterns may influence stream flows, and increased storm intensity and frequency, rain-on-snow events, and other hydrologic changes may promote stream bank and shoreline erosion, leading to increased turbidity and reduced water quality. Lakes may also be affected by reduced ice cover, with altered water temperature and oxygen profiles in shallow and moderate-depth lakes (Fang et al. 2004a, 2004b, 2004c; Stefan et al. 2001).

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 equally across species or even across life stages for a given organism. For example, evaluation of the effects of warmer water temperatures on 50 stream fish species in Wisconsin indicated declines in several cold-water and cool-water species and increases in most warm-water fish species (Higgins 2013, Lyons et al. 2010). An assessment of 400 wildlife species in Michigan (Hoving et al. 2013) found that, compared to other taxa, fish are among the most vulnerable fauna in Michigan. More than 80 percent of the fish species were assessed as vulnerable to climate change.

More Information

- The Coldwater Fish and Fisheries Working Group report from the Wisconsin Initiative on Climate Change Impacts describes potential climate change impacts on several fish species: www.wicci.wisc.edu/report/Coldwater-Fish-and-Fisheries.pdf
- The Coastal Communities Working Group report from the Wisconsin Initiative on Climate Change Impacts describes the potential impacts to coastal systems, including coastal infrastructure: www.wicci.wisc.edu/report/Coastal-Communities.pdf

- *Changing Climate, Changing Wildlife*, a report from the Michigan Department 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
- 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/
- 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

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 potential choices in policy and funding, as well as concerns of the public, 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 the Great Lakes region, the fire season is controlled by a combination of day length, weather, and fuel conditions. Typically, short day lengths, 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 for 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 receptive to ignition and spread. The projected trend toward more-intense precipitation could raise the potential for longer intervening dry periods 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.

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 current 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 current limits of our understanding are a major uncertainty.

Projected changes in climate could also affect the ability to apply prescribed fire in the assessment area. 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: www.lakestatesfiresci.net/index.html
- The Forest Service 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/

FOREST PRODUCTS

The forest products industry is important to the economy of the assessment area (Chapter 1). Tree species and forest composition are projected to change during the 21st century (Chapters 5 and 6). Changes in forest composition across the landscape will be influenced by forest management, and in turn will influence forest management and the forest products industry. Several commercially important species, such as quaking aspen, are projected to decline substantially under a range of possible climate futures over the next century. Conversely, hardwood species like American basswood and white oak are projected to increase in 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, the effects of climate change on the forest products industry depend 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 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 over the past 100 years, and continued responsiveness can help the sector remain viable.

More Information

- The Forest Service 2010 Resources Planning Act Assessment includes future 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/
- The Climate Change Tree Atlas provides information on the projected suitable habitat for tree species under climate change: www.nrs.fs.fed.us/atlas/bird/

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 time window for conventional forest management operations. Most management in lowland areas and on soils prone to compaction or erosion is accomplished during the winter. Climate change is projected to result in shorter seasons of frozen ground, more midwinter thaws, less snowpack, and more rain during winter months (Chapter 4). 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.

Natural resource professionals at the Chequamegon-Nicolet National Forest. Photo by Maria Janowiak, U.S. Forest Service.

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 with coarse, sandy soils. Alternatively, summer dry periods and droughts could extend operating windows in low-lying areas or clay soils. Extended or severe droughts could present problems in sandy areas, however, 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 after a wind event or pest or disease outbreak, 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 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, University of Connecticut, and A. Rissman, University of Wisconsin – Madison, 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 indicate 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 indicate their 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.

FOREST CARBON

The accumulated carbon pool within forest soils, belowground biomass, dead wood, and aboveground live biomass is enormous (Chapter 1) (Birdsey et al. 2006). Climate change and associated impacts to forest ecosystems may change the ability of forests in the assessment area to store carbon. A longer growing season and carbon dioxide (CO_2) fertilization may lead to increased productivity and carbon 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 carbon storage in some areas and decreases in others. As long as forests recover after a disturbance, total carbon losses may be negligible over the long term. If forests convert to nonforested conditions or if carbon stored in peat soils is lost to the atmosphere, then carbon storage is reduced over much longer time scales.

Different forest types in the assessment area store different amounts of carbon (Chapter 1). On average, spruce/fir forests are the most carbon-dense, but most of this carbon occurs in organic soils (Birdsey et al. 2014). Maple/beech/birch forests generally contain the most aboveground carbon, so an increase in these species and a decline in spruce/fir forests may affect carbon storage in some areas. Modeling studies in northern Wisconsin examining the effects of species composition changes on landscape-scale carbon stocks, suggest that some forests may increase in biomass and overall productivity, despite declines in boreal or northern species (Birdsey et al. 2014, Chiang et al. 2008, Scheller and Mladenoff 2005). The LANDIS-II model results presented in Chapter 5 raise the possibility that existing species in the assessment area 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 carbon stocks is not expected. Moreover, management options have the potential to increase forest carbon stores and reduce carbon emissions (Birdsey et al. 2014).

More Information

- The report *Past and Prospective Carbon Stocks in Forests of Northern Wisconsin* provides a baseline assessment of carbon stocks in the area, as well as an analysis of the impacts of disturbance and management on carbon stocks: www.treesearch.fs.fed.us/pubs/45578
- The Forest Service Climate Change Resource Center provides a summary of how climate change may affect the ability of forests to store carbon: 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 carbon: www.treesearch.fs.fed.us/pubs/38959

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 four regionally important nontimber forest products with broad cultural and economic importance are discussed briefly here.

Natural wild rice is a cultural keystone species in the assessment area. 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 including 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 period of dormancy in water at temperatures at or below 35 °F (1.6 °C). 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 region 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, and
- predation or displacement by species favored by warmer water temperatures (e.g., carp and reed canarygrass).

Balsam fir boughs enter regional, national, and international markets as wreaths, holiday greens, and fragrant souvenirs. The balsam bough industry provides seasonal employment for thousands of residents regionally and is especially important in rural areas where job opportunities are limited. For example, the Minnesota bough industry was reported to be worth more than $23 million in the mid-2000s (Jacobson 2005). Models predict a northward shift in the area of suitable habitat for balsam fir, with substantial reductions in suitable habitat by the end of the century (Chapter 5; see also Appendix 4).

Hunting morel mushrooms is a passion for many people throughout the assessment area (Fine 2003). Annual morel festivals and sales to restaurants provide supplemental income for many people, communities, and small businesses in the region. 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 due to 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 sensitive to temperature and humidity, changes in these regimes also can be expected to alter the timing and intensity of morel fruiting.

Sugar maple is another cultural keystone species of the Midwest and Northeast. Maple syrup and sugar, made from boiling sugar maple sap, provided treasured sources of sweetness and a critical source of late-winter nourishment well before the arrival of the first Europeans on the continent. Fur trader records show that maple sugar was an important exchange good from the early days of settlement (Emery 2002). Today, gathering and boiling sugar maple sap continues to have profound cultural and economic importance in the region. During the 2013 season, U.S. market production of maple syrup was approximately 3,253,000 gallons of maple syrup (265,000 and 148,000 gallons in Wisconsin and Michigan, respectively). The total value of maple syrup on the market for 2012 (the most recent year for which statistics are available) was nearly $74 million for the Nation as a whole and more than $5.5 million for Wisconsin and Michigan combined (National Agricultural Statistics Service 2013). Not included in these figures are the volume and value of maple syrup that never enters the market. Gathering and boiling sap and sharing syrup knits together families and communities. Tribes in the region still hold sugar festivals as an important marker of the seasons, as do many non-Native communities. Sap flow necessary for maple syrup production requires a combination of warm days and freezing nights that is highly seasonal. Climate records show such conditions now occur earlier than in the past and this trend likely will continue, although there is disagreement on whether the total length of the season will be shortened and sap yield reduced (Groffman et al. 2012, Rustad et al. 2012, Skinner et al. 2010).

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 from Michigan that are used by several Native American tribes in the region, and the Great Lakes Indian Fish and Wildlife Commission compiled information for numerous species used by the Great Lakes Ojibwe (Meeker et al. 1993). Among these species, 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).

More Information

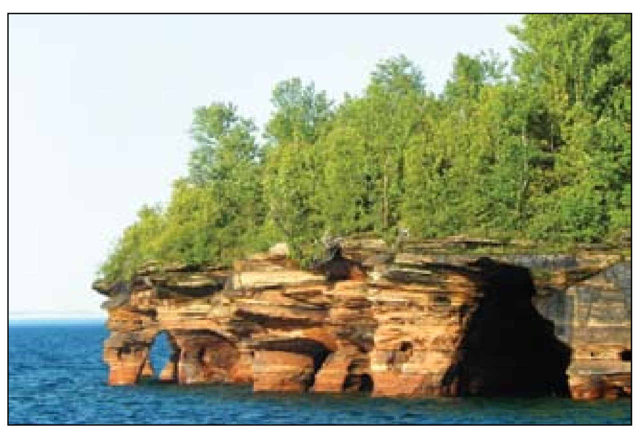
- The “Gikinoo’wizhiwe Onji Waaban” (Guiding for Tomorrow) initiative increases awareness of how climate change is affecting the people, culture, and economies of the Lake Superior region by using examples from traditional Ojibwe lifeways and other cultures: www.g-wow.org/

ARCHAEOLOGICAL AND HISTORICAL RESOURCES

Climate change may also present a variety of challenges for managers of heritage 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 as a result of salvage or disaster-response management activities. A change in the frequency, severity, or duration of heavy precipitation and flooding could affect archaeological and historical 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 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



Shoreline at the Apostle Islands National Lakeshore. Photo by Maria Janowiak, U.S. Forest Service.

WILDERNESS

There are several federally designated wilderness areas in the assessment area, including McCormick, Sylvania, and Headwaters Wilderness areas (all located on National Forest System Lands), as well as the State-designated and State-managed Porcupine Mountains Wilderness State Park. These areas are often regarded as some of the last remaining primary forests in the region because they include some areas that were not harvested in the early 20th century. As such, they play a special role in natural resource and recreation management. The potential for extensive ecosystem change resulting from climate 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, including wilderness areas, 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. Weather-related tree mortality from storm events, drought, or insect and disease attack could increase the complexity of providing for public safety. Weather conditions also affect the need for maintenance of recreational infrastructure like trails and trailheads, particularly when heavy rain events cause excessive erosion, or when wind events uproot trees and leave craters in parts of the trail.

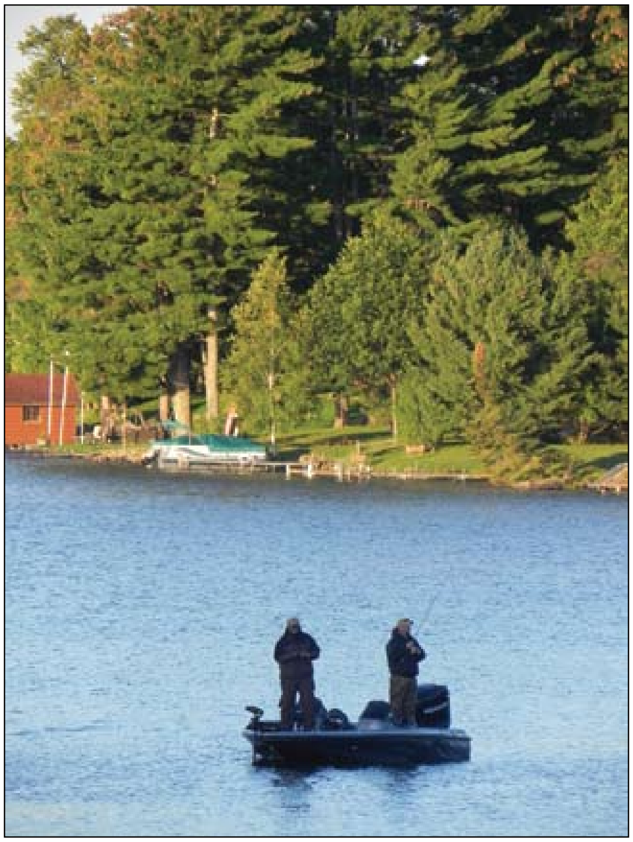
It is difficult to anticipate how climate-related impacts will influence management in wilderness areas, because of the legal requirement to protect and manage federally designated wilderness areas to preserve natural conditions and ensure the area remains undeveloped and "untrammeled" (i.e., where human manipulation is not apparent). Due to this minimal-management approach, wilderness often plays a key role in helping scientists to understand ecological systems and natural processes and to monitor change in those systems. At the same time, 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). In either approach, wilderness areas could play an important role in landscape-level adaptation planning.

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 Climate Change Resource Center provides a summary of how climate change may affect wilderness area management:
  www.fs.fed.us/ccrc/topics/wilderness/
- The Wilderness.net Minimum Requirements Decision Guide is designed to assist managers in making Wilderness stewardship decisions in the context of the legal requirements of the Wilderness Act:
  www.wilderness.net/MRA

RECREATION

Forests are the centerpieces of outdoor recreation in the assessment area (Chapter 1). People throughout this region enjoy hunting; fishing; camping; wildlife watching; and exploring trails on foot, bicycles, skis, snowshoes, horseback, and off-highway



Fishermen on a lake in northern Wisconsin. Photo by Maria Janowiak, U.S. Forest Service.

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, which could reduce opportunities for popular winter-based recreation activities in the long term. Climate change has already caused reductions in lake ice (Chapter 4), and activities such as ice fishing have the potential to be harmed as conditions continue to change. Observed changes in snowfall and snow depth have been more variable across the landscape, but it is expected that much of the assessment area will have substantially less snow by the end of the century. Reduced snowfall could create additional challenges to popular and economically important activities, such as snowmobiling and cross-country and downhill skiing. Recreationists may change the ways in which they participate in these activities, perhaps by changing the time or location of their participation, or switch to activities that do not require snow.

Some warm-weather forms of nature-based recreation have the potential to increase due to changing conditions (Dawson and Scott 2010, Jones and Scott 2006, Mcboyle et al. 2007). 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 thus 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. Projected changes in Wisconsin water temperatures and fish species habitat (described above) may reduce opportunities for cold-water stream fishing but increase opportunities for warm-water lake fishing.

More Information

- The Wildlife Working Group report from the Wisconsin Initiative on Climate Change Impacts documents past and current climate change impacts on game species and other wildlife: www.wicci.wisc.edu/report/Wildlife.pdf
- *Changing Climate, Changing Wildlife*, a 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
- 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 collaborative effort comprising many hunting and conservation organizations, includes many resources on how climate change may affect wildlife: http://www.cakex.org/virtual-library/784

HUMAN HEALTH

Climate change can influence human health in numerous ways (Patz et al. 2011), which can affect people who live, work, or recreate in the forests of the assessment area. Vector-borne diseases, such as Lyme disease and West Nile virus, pose an important risk to natural resource managers, local residents, and tourists alike, and this issue may become increasingly important over the 21st century. Vector-borne diseases are transmitted by arthropod vectors (e.g., ticks or mosquitoes) and cycle back and forth between arthropod vectors and animal hosts, usually mammals or birds. 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. Changes in climate can influence vector-borne disease risk by affecting the abundance and distribution of ticks or mosquitoes, the percentage of infected vectors, the abundance and distribution of animal hosts, the presence of suitable habitat for these vectors, and the behaviors that bring humans 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 example, blacklegged ticks (i.e., "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 aspen) that contain 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.

More Information

- The Human Health Working Group report from the Wisconsin Initiative on Climate Change Impacts documents the effect of climate change on human health: www.wicci.wisc.edu/report/Human-Health.pdf

- The Michigan Department of Community Health has a Web site on the climate change implications for human health: www.michigan.gov/mdch/0,1607,7-132-54783_54784_55975---,00.html
- The Natural Resources Defense Council hosts an online Web viewer that provides state-level information about various threats to human health associated with climate change: www.nrdc.org/health/climate/
- 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 also expected to affect urban forests in the assessment area. In contrast with natural environments, 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. Urban settings are often where exotic insect pests are first introduced. 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.

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 even facilitate migration of trees across the landscape (Woodall et al. 2010). 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 (Woodall et al. 2010).

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 as many cities have reduced their budgets and staffing.

More Information

- The Forest Service Climate Change Resource Center provides a summary of how climate change may affect urban forests: www.fs.fed.us/ccrc/topics/urban-forests/
- 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
- 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

FOREST-ASSOCIATED TOWNS AND CITIES

The ability of human communities to respond to environmental changes is directly related to their adaptive capacity—resources that can be leveraged by the community to monitor, anticipate, and proactively manage stressors and disturbances. Although ecosystem 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 particularly tied to the health and functioning of surrounding forests, whether for economic, cultural, recreational, or other 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. Some communities (e.g., indigenous communities with forest-dependent cultural practices, tourism-dependent communities) and social groups within communities (e.g., individuals working in the forest products industry) 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 to changes, they must identify community vulnerabilities and sensitivities to climate-related impacts and also build community capacity to organize and engage community members and other resources. In the Great Lakes region, much of the work done to date to assess the vulnerability of human communities has focused on coastal communities (e.g., Minnesota Sea Grant 2012, Moy et al. 2010). Some community-based climate change assessment and adaptation efforts are underway in the assessment area (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 several questions (Davenport et al. 2013). These include:

- 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 Wisconsin Initiative on Climate Change Impacts sponsored working groups that created vulnerability assessments for Green Bay, Milwaukee, and other Great Lakes coastal communities: www.wicci.wisc.edu/publications.php
- 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
- 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 Resilience Alliance has created a workbook for practitioners to assess resilience of social-ecological systems: www.resalliance.org/index.php/resilience_assessment

LAND ACQUISITION

Climate change has many important implications for land conservation planning in the Great Lakes, and climate change science can be used to help prioritize land conservation investments and help guide project design. For example, it may be important to identify parcels that have large carbon mitigation potential and prioritize these for land acquisition and conservation. This is particularly important in the upper Great Lakes region, where private forest lands have some of the highest stored carbon levels in the entire country. Climate change trends and ecosystem models can also be used to identify lands that have long-term potential to provide refugia for at-risk species and habitats, enhance landscape connectivity, or protect 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, an appropriate conservation strategy might be to seek a public agency that can provide the necessary financial and technical resources.

Private nonprofits, government agencies, landowners, and potential funders will increasingly 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 the region and shaping conservation efforts to deliver a more resilient landscape.

Hiking trail at Isle Royale National Park. Photo by Maria Janowiak, U.S. Forest Service.

LAND MANAGEMENT PLANS

Until recently, climate change has not played a large role in natural resource planning. Many federal and state-level land management agencies are beginning to address the issue. For example, the recently updated Forest Service regulations for National Forest System Land Management Planning (also known as the 2012 Planning Rule) directly address the impacts and ramifications of climate change (36 CFR 219). In fact, climate change was among the stated purposes for revising the rule (FR Vol. 77, No. 68, 21163 & 21164). When the Chequamegon-Nicolet and Ottawa National Forests revise their management plans in the future, they will be required to address the issue of climate change under this new rule. Similarly, the state-level management plans for Michigan and Wisconsin have not historically addressed climate change. However, the statewide forest strategies for these states identify climate change as an issue that could influence the long-term sustainability of forests.

Incorporating climate change considerations into natural resource planning will always be a difficult endeavor. The uncertainties associated with planning over long time horizons are only compounded with climate change. Management plans for federal, state, and local agencies, as well as private lands, are typically written to guide management for a 10- to 25-year period, and it may be difficult to address the potential long-term effects of climate change within this shorter 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, it may be more difficult to adhere to the stated goals, objectives, and priorities in current plans. Future land management plans may have to incorporate adaptive management principles, include greater flexibility, or coordinate across land ownerships to address shifting conditions and priorities.

More Information

- Forest action plans have been prepared for both Wisconsin and Michigan. These statewide assessment and strategy documents include discussions of climate change: www.forestactionplans.org/regional-state
- The three Regional State Forest Management Plans developed for Michigan State Forest lands explicitly include climate change considerations as part of the management direction for each plan: www.michigan.gov/dnr/0,4570,7-153-30301_30505_62551-284917--,00.html
- More information on the Forest Service's 2012 Planning Rule can be found here: www.fs.usda.gov/planningrule
- *Forest Adaptation Resources: Climate Change Tools and Approaches for Land Managers* provides concepts and tools for integrating climate change considerations into natural resource planning and management: www.nrs.fs.fed.us/pubs/40543

SUMMARY

The breadth of these topics highlights the wide range of effects climate change may have on forest management in the assessment area. 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 the region will be affected by economic, political, ecological, and societal factors. These factors will be specific to each land owner and agency, and are 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 either scattering and absorbing radiation or by 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 (GCMs) by using a limited-area, high-resolution model (a regional climate model, or RCM) driven by boundary conditions from a GCM to derive smaller-scale information.

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.

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

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**).

exposure
the nature and degree to which a system is exposed to significant climate variations.

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
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.

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

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**).

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

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-scale (GCM-scale) variables. Future values of the large-scale variables obtained from GCM projections of future climate are then used to drive the statistical relationships and so estimate the smaller-scale details of future climate.

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.

tension zone
a transitional band that corresponds to several climatic factors. Vegetation north and south of the tension zone reflects varied habitat conditions as a result of climatic differences.

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

topkill
death of aboveground tree stem and branches.

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.

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 and 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.

LITERATURE CITED

Aber, J.D.; Ollinger, S.V.; Driscoll, C.T. 1997. **Modeling nitrogen saturation in forest ecosystems in response to land use and atmospheric deposition.** Ecological Modelling. 101(1): 61-78.

Aber, J.R.; Neilson, P.; McNulty, S.; Lenihan, J.M.; Bachelet, D.; Drapek, R.J. 2001. **Forest processes and global environmental change: predicting the effects of individual and multiple stressors.** Bioscience. 51(9): 735-751.

Adams, R.J.J.; Wenger, T. 2011. **Red-bellied woodpecker (*Melanerpes carolinus*).** Kalamazoo, MI: Kalamazoo Nature Center. Available at http://mibirdatlas.org/Portals/12/MBA2010/RBWOaccount.pdf. (Accessed April 17, 2014).

Ainsworth, E.A.; Long, S.P. 2005. **What have we learned from 15 years of free-air CO_2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO_2.** New Phytologist. 165(2): 351-372.

Ainsworth, E.A.; Rogers, A. 2007. **The response of photosynthesis and stomatal conductance to rising [CO_2]: mechanisms and environmental interactions.** Plant, Cell & Environment. 30(3): 258-270.

Albert, D.A. 1995. **Regional landscape ecosystems of Michigan, Minnesota, and Wisconsin: a working map and classification.** St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 250 p. Available at http://nrs.fs.fed.us/pubs/gtr/other/gtr-nc178/index.html. (Accessed April 17, 2014).

Albert, D.A.; Denton, S.R.; Barnes, B.V.; Simpson, K.E. 1986. **Regional landscape ecosystems of Michigan.** Ann Arbor, MI: University of Michigan, School of Natural Resources: 32 p.

Alverson, W.S.; Waller, D.M.; Solheim, S.L. 1988. **Forests too deer: edge effects in northern Wisconsin.** Conservation Biology. 2(4): 348-358.

Andersen, B.J. 2005. **The historical development of the tension zone concept in the Great Lakes region of North America.** The Michigan Botanist. 44(3): 127-138.

Andreadis, K.M.; Lettenmaier, D.P. 2006. **Trends in 20th century drought over the continental United States.** Geophysical Research Letters. 33(10): L10403.

Andresen, J.; Hilberg, S.; Kunkel, K. 2012. **Historical climate and climate trends in the Midwestern USA.** In: Winkler, J.; Andresen, J.; Hatfield, J.; Bidwell, D.; Brown, D., coords. U.S. National Climate Assessment Midwest technical input report. Available at http://glisa.umich.edu/media/files/NCA/MTIT_Historical.pdf. (Accessed April 10, 2014).

Andresen, J.A. 2007. **Historical climate trends in Michigan and the Great Lakes region.** http://www.espp.msu.edu/climatechange/presentations/CCGL.Andresen.pdf. (Accessed April 11, 2014).

Annan, J.D.; Hargreaves, J.C. 2013. **A new global reconstruction of temperature changes at the Last Glacial Maximum.** Climate of the Past. 9(1): 367-376.

Assel, R.A. 2005. **Classification of annual Great Lakes ice cycles: winters of 1973-2002.** Journal of Climate. 18(22): 4895-4905.

Assel, R.A. 2009. **Contemporary Lake Superior ice cover climatology.** Aquatic Ecosystem Health and Management Society, Ecovision World Monograph Series. 16 p. Available at http://www.glerl.noaa.gov/pubs/fulltext/2009/20090048.pdf. (Accessed April 17, 2014).

Auclair, A.N.D.; Heilman, W.E.; Brinkman, B. 2010. **Predicting forest dieback in Maine, USA: a simple model based on soil frost and drought.** Canadian Journal of Forest Research. 40: 687-702.

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

Babin-Fenske, J.; Anand, M. 2011. **Agent-based simulation of effects of stress on forest tent caterpillar (*Malacosoma disstria* Hubner) population dynamics.** Ecological Modelling. 222(14): 2561-2569.

Baker, F.; Hansen, M.; Shaw, J.D.; Mielke, M.; Shelstad, D. 2012. **The incidence of dwarf mistletoe in Minnesota black spruce stands detected by operational inventories.** Northern Journal of Applied Forestry. 29(3): 109-112.

Bal, T. 2013. **Evaluation of sugar maple dieback in the Upper Great Lakes region and development of a forest health youth education program.** Houghton, MI: Michigan Technological University. 173 p. Ph.D. dissertation.

Barnes, M.C.; Todd, A.; Whitney Lilja, R.; Barten, P. 2009. **Forests, water and people: drinking water supply and forest lands in the Northeast and Midwest United States.** Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Area State and Private Forestry. Available at http://na.fs.fed.us/pubs/misc/watersupply/forests_water_people_watersupply.pdf. (Accessed April 11, 2014).

Becker, G.C. 1983. **Fishes of Wisconsin.** Madison, WI: University of Wisconsin Press. 1052 p.

Benedict, M.A.; Frelich, L.E. 2008. **Site factors affecting black ash ring growth in northern Minnesota.** Forest Ecology and Management. 255(8-9): 3489-3493.

Bennett, K.D. 1985. **The spread of *Fagus grandifolia* across eastern North America during the last 18,000 years.** Journal of Biogeography. 12(2): 147-164.

Bergeron, Y.; Leduc, A. 1998. **Relationships between change in fire frequency and mortality due to spruce budworm outbreak in the southeastern Canadian boreal forest.** Journal of Vegetation Science. 9(4): 492-500.

Beyer, D.E., Jr.; Winterstein, S.R.; Lederle, P.E.; Maskey, J.J. 2011. **Moose in Michigan: history, biology, and considerations for hunting.** Report to the Michigan Department of Natural Resources and Environment Moose Hunting Advisory Council. Available at http://www.michigan.gov/documents/dnr/Moose_white_paper_28_Feb_2011_Final_350494_7.pdf. (Accessed April 10, 2014).

Birdsey, R.; Pan, Y.; Janowiak, M.K.; Stewart, S.; Hines, S.J.; Parker, L.R.; Gower, S.T.; Lichstein, J.; McCullough, K.; Zhang, F.; Chen, J.; Mladenoff, D.J.; Wayson, C.; Swanston, C. 2014. **Past and prospective carbon stocks in forests of northern Wisconsin.** Gen. Tech. Rep. NRS-127. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 52 p.

Birdsey, R.; Pregitzer, K.; Lucier, A. 2006. **Forest carbon management in the United States: 1600-2100.** Journal of Environmental Quality. 35(4), 1461-1469.

Boer, G. 2009. **Changes in interannual variability and decadal potential predictability under global warming.** Journal of Climate. 22(11): 3098-3109.

Bohlen, P.J.; Groffman, P.M.; Fahey, T.J.; Fisk, M.C.; Suárez, E.; Pelletier, D.M.; Fahey, R.T. 2004. **Ecosystem consequences of exotic earthworm invasion of north temperate forests.** Ecosystems. 7: 1-12.

Bonan, G.B. 2008. **Forests and climate change: forcings, feedbacks, and the climate benefits of forests.** Science. 320(5882): 1444-1449.

Booth, R.K.; Jackson, S.T.; Sousa, V.A.; Sullivan, M.E.; Minckley, T.A.; Clifford, M.J. 2012. **Multi-decadal drought and amplified moisture variability drove rapid forest community change in a humid region.** Ecology. 93: 219-226.

Borken, W.; Matzner, E. 2009. **Introduction: impact of extreme meteorological events on soils and plants.** Global Change Biology. 15(4): 781-781.

Both, C.; Artemyev, A.V.; Blaauw, B.; Cowie, R.J.; Dekhuijzen, A.J.; Eeva, T.; Enemar, A.; Gustafsson, L.; Ivankina, E.V.; Järvinen, A. 2004. **Large-scale geographical variation confirms that climate change causes birds to lay earlier.** Proceedings of the Royal Society of London. Series B: Biological Sciences. 271(1549): 1657.

Bourque, C.P.A.; Cox, R.M.; Allen, D.J.; Arp, P.A.; Meng, F.R. 2005. **Spatial extent of winter thaw events in eastern North America: historical weather records in relation to yellow birch decline.** Global Change Biology. 11(9): 1477-1492.

Box, G.E.; Draper, N.R. 1987. **Empirical model-building and response surfaces.** New York, NY: John Wiley & Sons. 669 p.

Bradley, N.L.; Leopold, A.C.; Ross, J.; Huffaker, W. 1999. **Phenological changes reflect climate change in Wisconsin.** Proceedings of the National Academy of Sciences of the United States of America. 96(17): 9701-9704.

Brzostek, E.R.; Finzi, A.C. 2012. **The effect of experimental warming and precipitation change on proteolytic enzyme activity: positive feedbacks to nitrogen availability are not universal.** Global Change Biology. 18(8): 2617-2625.

Burnett, A.W.; Kirby, M.E.; Mullins, H.T.; Patterson, W.P. 2003. **Increasing Great Lake-effect snowfall during the twentieth century: A regional response to global warming?** Journal of Climate. 16(21): 3535-3542.

Burns, R.M.; Honkala, B.H. 1990. **Silvics of North America: 1. Conifers; 2. Hardwoods.** Washington, DC: U.S. Department of Agriculture, Forest Service. 877 p.

Burton, A.J.; Pregitzer, K.S.; Zogg, G.P.; Zak, D.R. 1996. **Latitudinal variation in sugar maple fine root respiration.** Canadian Journal of Forest Research. 26(10): 1761-1768.

Butler, B.J. 2008. **Family forest owners of the United States, 2006.** Gen. Tech. Rep. NRS-27. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 73 p.

Butler, C.J. 2003. **The disproportionate effect of global warming on the arrival dates of short-distance migratory birds in North America.** Ibis. 145(3): 484-495.

Campbell, J.L.; Ollinger, S.V.; Flerchinger, G.N.; Wicklein, H.; Hayhoe, K.; Bailey, A.S. 2010. **Past and projected future changes in snowpack and soil frost at the Hubbard Brook Experimental Forest, New Hampshire, USA.** Hydrological Processes. 24(17): 2465-2480.

Campbell, J.L.; Rustad, L.E.; Boyer, E.W.; Christopher, S.F.; Driscoll, C.T.; Fernandez , I.J.; Groffman, P.M.; Houle, D.; Kiekcusch, J.; Magill, A.H.; Mitchell, M.J.; Ollinger, S.V. 2009. **Consequences of climate change for biogeochemical cycling in forests of northeastern North America.** Canadian Journal of Forest Research. 39: 264-284.

Canham, C.D.; Loucks, O.L. 1984. **Catastrophic windthrow in the presettlement forests of Wisconsin. Ecology.** 65(3): 803-809.

Cartwright, L. 2005. **An examination of flood damage data trends in the United States.** Journal of Contemporary Water Research & Education. 130(1): 20-25.

Center for Climatic Research. 2013. **LCC statistical downscaling.** Madison, WI: Nelson Institute for Environmental Studies, University of Wisconsin – Madison. Available at http://ccr.aos.wisc.edu/resources/data_scripts/LCC/. (Accessed April 10, 2014).

Changnon, S.A. 2003. **Geographical and temporal variations in thunderstorms in the contiguous United States during the 20th century.** Physical Geography. 30(2): 138-152.

Cherkauer, K.A.; Sinha, T. 2010. **Hydrologic impacts of projected future climate change in the Lake Michigan region.** Journal of Great Lakes Research. 36: 33-50.

Chiang, J.M.; Iverson, L.R.; Prasad, A.; Brown, K.J. 2008. **Effects of climate change and shifts in forest composition on forest net primary production.** Journal of Integrative Plant Biology. 50(11): 1426-1439.

Choat, B.; Jansen, S.; Brodribb, T.J.; Cochard, H.; Delzon, S.; Bhaskar, R.; Bucci, S.J.; Feild, T.S.; Gleason, S.M.; Hacke, U.G.; Jacobsen, A.L.; Lens, F.; Maherali, H.; Martínez-Vilalta, J.; Mayr, S.; Mencuccini, M.; Mitchell, P.J.; Nardini, A.; Pittermann, J.; Pratt, R.B.; Sperry, J.S.; Westoby, M.; Wright, I.J.; Zanne, A.E. 2012. **Global convergence in the vulnerability of forests to drought.** Nature. 491(7426): 752-755.

Cleland, D.T.; Crow, T.R.; Saunders, S.C.; Dickmann, D.I.; Maclean, A.L.; Jordan, J.K.; Watson, R.L.; Sloan, A.M.; Brosofske, K.D. 2004. **Characterizing historical and modern fire regimes in Michigan (USA): a landscape ecosystem approach.** Landscape Ecology. 19: 311-325.

Climate Change Science Program [CCSP]. 2008a. **The effects of climate change on agriculture, land resources, water resources and biodiversity in the United States. A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research.** [Backlund, P.; Janetos, A.; Schimel, D.; Hatfield, J.; Boote, K.; Fay, P.; Hahn, L.; Izaurralde, C.; Kimball, B.A.; Mader, T.; Morgan, J.; Ort, D.; Polley, W.; Thomson, A.; Wolfe, D.; Ryan, M.; Archer, S.; Birdsey, R.; Dahm, C.; Heath, L.; Hicke, J.; Hollinger, D.; Huxman, T.; Okin, G.; Oren, R.; Anderson, J.; Schlesinger, W.; Lettenmaier, D.; Major, D.; Poff, L.; Running, S.; Hansen, L.; Inouye, D.; Kelly, B.P.; Meyerson, L.; Peterson, B.; Shaw, R.] Washington, DC: U.S. Environmental Protection Agency. 362 p.

Climate Change Science Program [CCSP]. 2008b. **Weather and climate extremes in a changing climate. Regions of focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands. A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research.** [Karl, T.R.; Meehl, G.A.; Miller, C.D.; Hassol, S.J.; Waple, A.M.; Murray, W.L., eds.]. Washington, DC: U.S. Department of Commerce, NOAA National Climatic Data Center. 164 p.

ClimateWizard. 2012. **ClimateWizard Custom Analysis application.** The Nature Conservancy, University of Washington, University of Southern Mississippi, Climate Central, and Santa Clara University. Available at http://climatewizardcustom.org/. (Accessed April 2, 2012).

Cohen, J. 2000. **Natural community abstract for mesic northern forest.** Lansing, MI: Michigan Natural Features Inventory. 9 p. Available at http://mnfi.anr.msu.edu/abstracts/ecology/Mesic_Northern_Forest.pdf. (Accessed November 22, 2013).

Cohen, J. 2001. **Natural community abstract for oak barrens.** Lansing, MI: Michigan Natural Features Inventory. 10 p. Available at http://mnfi.anr.msu.edu/abstracts/ecology/Oak_barrens.pdf. (Accessed April 10, 2014).

Cohen, J. 2002a. **Natural community abstract for dry northern forest.** Lansing, MI: Michigan Natural Features Inventory. 15 p. Available at http://mnfi.anr.msu.edu/abstracts/ecology/Dry_northern_forest.pdf. (Accessed April 10, 2014).

Cohen, J. 2002b. **Natural community abstract for dry-mesic northern forest.** Lansing, MI: Michigan Natural Features Inventory. 13 p. Available at http://mnfi.anr.msu.edu/abstracts/ecology/Dry-mesic_northern_forest.pdf. (Accessed April 10, 2014).

Cohen, J. 2006. **Natural community abstract for poor conifer swamp.** Lansing, MI: Michigan Natural Features Inventory. 23 p. Available at http://mnfi.anr.msu.edu/abstracts/ecology/Poor_Conifer_Swamp.pdf. (Accessed April 10, 2014).

Cohen, J. 2007. **Natural community abstract for boreal forest.** Lansing, MI: Michigan Natural Features Inventory. 24 p. Available at http://mnfi.anr.msu.edu/abstracts/ecology/boreal_forest.pdf. (Accessed April 10, 2014).

Cole, C.T.; Anderson, J.; Lindroth, R.L.; Waller, D.M. 2010. **Rising concentrations of atmospheric CO_2 have increased growth in natural stands of quaking aspen (*Populus tremuloides*).** Global Change Biology. 16(8): 2186-2197.

Coniglio, M.C.; Stensrud, D.J. 2004. **Interpreting the climatology of derechos.** Weather and Forecasting. 19(3): 595-605.

Cordell, K. 2012. **Outdoor recreation trends and futures: a technical document supporting the Forest Service 2010 RPA Assessment.** Gen. Tech. Rep. SRS-150. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station, 167 p. Available at http://www.srs.fs.usda.gov/pubs/40453. (Accessed April 11, 2014).

Cornett, M.W.; Frelich, L.E.; Puettmann, K.J.; Reich, P.B. 2000a. **Conservation implications of browsing by *Odocoileus virginianus* in remnant upland *Thuja occidentalis* forests.** Biological Conservation. 93(3): 359-369.

Cornett, M.W.; Reich, P.B.; Puettmann, K.J.; Frelich, L.E. 2000b. **Seedbed and moisture availability determine safe sites for early *Thuja occidentalis* (Cupressaceae) regeneration.** American Journal of Botany. 87(12): 1807-1814.

Côté, S.D.; Rooney, T.P.; Tremblay, J.P.; Dussault, C.; Waller, D.M. 2004. **Ecological impacts of deer overabundance.** Annual Review of Ecology, Evolution, and Systematics. 113-147.

Coumou, D.; Rahmstorf, S. 2012. **A decade of weather extremes.** Nature Climate Change. 2: 491-496.

Courteau, J.B.; Cohen, J.G.; Kost, M.A. 2006. **Abstract on the Oak Association of northern Michigan.** Lansing, MI: Michigan Natural Features Inventory.

Crow, T.R.; Buckley, D.S.; Nauertz, E.A.; Zasada, J.C. 2002. **Effects of management on the composition and structure of northern hardwood forests in Upper Michigan.** Forest Science. 48(1): 129-145.

Curtis, J. 1959. **The vegetation of Wisconsin: an ordination of plant communities.** Madison, WI: University of Wisconsin Press. 640 p.

D'Amato, A.W.; Bradford, J.B.; Fraver, S.; Palik, B.J. 2011. **Forest management for mitigation and adaptation to climate change: Insights from long-term silviculture experiments.** Forest Ecology and Management. 262(5): 803-816.

Dai, A.; Trenberth, K.E.; Qian, T. 2004. **A global dataset of Palmer Drought Severity Index for 1870-2002: relationship with soil moisture and effects of surface warming.** Journal of Hydrometeorology. 5(1117-1129).

Dale, V.H.; Joyce, L.A.; McNulty, S.; Neilson, R.P.; Ayres, M.P.; Flannigan, M.D.; Hanson, P.J.; Irland, L.C.; Lugo, A.E.; Peterson, C.J.; Simberloff, D.; Swanson, F.J.; Stocks, B.J.; Wotton, B.M. 2001. **Climate change and forest disturbances.** BioScience. 51(9): 723-734.

Dalton, M.; Mote, P. 2012. **A workshop in risk-based framing of climate impacts in the Northwest: implementing the National Climate Assessment risk-based approach.** Available at http://downloads.usgcrp.gov/NCA/Activities/northwestncariskframingworkshop.pdf. (Accessed April 11, 2014).

Daniels, A.E.; Morrison, J.F.; Joyce, L.A.; Crookston, N.L.; Chen, S.C.; McNulty, S.G. 2012. **Climate projections FAQ.** Gen. Tech. Rep. RMRS-GTR-277WWW. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 32 p. Available at http://www.fs.fed.us/rm/pubs/rmrs_gtr277.html. (Accessed April 15, 2014).

Davenport, M.A.; Sames, A.; Bussey, J.; Pradhanaga, A.; Emery, M.; Jakes, P. 2013. **Community readiness for environmental change: a pilot study in a Minnesota forest-associated community.** University of Minnesota, Department of Forest Resources, College of Food, Agricultural and Natural Resource Sciences. 22 p. Available at http://www.forestry.umn.edu/prod/groups/cfans/@pub/@cfans/@forestry/documents/asset/cfans_asset_455326.pdf. (Accessed April 11, 2014).

Davis, M.B. 1983. **Quaternary history of deciduous forests of eastern North-America and Europe.** Annals of the Missouri Botanical Garden. 70(3): 550-563.

Davis, M.B. 1986. **Climatic instability, time, lags, and community disequilibrium.** In: Diamond, J.M.; Case, T.J., eds. Community ecology. New York, NY: Harper & Row: 269-284.

Davis, M.B.; Shaw, R.G.; Etterson, J.R. 2005. **Evolutionary responses to changing climate.** Ecology. 86(7): 1704-1714.

Dawson, J.; Scott, D. 2010. **Climate change and tourism in the Great Lakes region: a summary of risks and opportunities.** Tourism in Marine Environments. 6(2-3): 119-132.

Delworth, T.L.; Broccoli, A.J.; Rosati, A.; Stouffer, R.J.; Balaji, V.; Beesley, J.A.; Cooke, W.F.; Dixon, K.W.; Dunne, J.; Dunne, K.A.; Durachta, J.W.; Findell, K.L.; Ginoux, P.; Gnanadesikan, A.; Gordon, C.T.; Griffies, S.M.; Gudgel, R.; Harrison, M.J.; Held, I.M.; Hemler, R.S.; Horowitz, L.W.; Klein, S.A.; Knutson, T.R.; Kushner, P.J.; Langenhorst, A.R.; Lee, H.C.; Lin, S.J.; Lu, J.; Malyshev, S.L.; Milly, P.C.D.; Ramaswamy, V.; Russell, J.; Schwarzkopf, M.D.; Shevliakova, E.; Sirutis, J.J.; Spelman, M.J.; Stern, W.F.; Winton, M.; Wittenberg, A.T.; Wyman, B.; Zeng, F.; Zhang, R. 2006. **GFDL's CM2 global coupled climate models. Part I: Formulation and simulation characteristics.** Journal of Climate. 19(5): 643-674.

Devall, M.S. 2009. **Effect of global climate change on rare trees and shrubs.** Unasylva (English edition). 60 (231/232): 29.

Dickmann, D.I.; Leefers, L.A. 2003. **The forests of Michigan.** Ann Arbor, MI: University of Michigan Press. 297 p.

Dieleman, W.I.J.; Vicca, S.; Dijkstra, F.A.; Hagedorn, F.; Hovenden, M.J.; Larsen, K.S.; Morgan, J.A.; Volder, A.; Beier, C.; Dukes, J.S. 2012. **Simple additive effects are rare: a quantitative review of plant biomass and soil process responses to combined manipulations of CO_2 and temperature.** Global Change Biology.

Dietze, M.C.; Moorcroft, P.R. 2011. **Tree mortality in the eastern and central United States: patterns and drivers.** Global Change Biology. 17(11).

Diffenbaugh, N.S.; Pal, J.S.; Trapp, R.J.; Giorgi, F. 2005. **Fine-scale processes regulate the response of extreme events to global climate change.** Proceedings of the National Academy of Sciences of the United States of America. 102(44): 15774-15778.

Dragoni, D.; Rahman, A.F. 2012. **Trends in fall phenology across the deciduous forests of the Eastern USA.** Agricultural and Forest Meteorology. 157(0): 96-105.

Drever, C.R.; Bergeron, Y.; Drever, M.C.; Flannigan, M.; Logan, T.; Messier, C. 2009. **Effects of climate on occurrence and size of large fires in a northern hardwood landscape: historical trends, forecasts, and implications for climate change in Témiscamingue, Québec.** Applied Vegetation Science. 12(3): 261-272.

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

Duveneck, M.J.; Scheller, R.M.; White, M.A.; Handler, S.D.; Ravenscroft, C. 2014. **Climate change effects on northern Great Lake (USA) forests: a case for preserving diversity.** Ecosphere. 5(2): art23.

Easterling, D.R.; Wehner, M.F. 2009. **Is the climate warming or cooling?** Geophysical Research Letters. 36(L08706): 3.

Eggers, S.D.; Reed, D.M. 1997. **Wetland plants and communities of Minnesota and Wisconsin.** Jamestown, ND: U.S. Army Corps of Engineers, St. Paul District. Available at http://www.npwrc.usgs.gov/resource/plants/mnplant/index.htm.

Eichenlaub, V.L. 1970. **Lake effect snowfall to the lee of the Great Lakes: its role in Michigan.** Bulletin of the American Meteorological Society. 51(5): 403-412.

Eichenlaub, V.L. 1979. **Weather and climate of the Great Lakes region.** Notre Dame, IN: University of Notre Dame Press. 335 p.

Eisenhauer, N.; Fisichelli, N.A.; Frelich, L.E.; Reich, P.B. 2012. **Interactive effects of global warming and 'global worming' on the initial establishment of native and exotic herbaceous plant species.** Oikos. 121(7): 1121-1133.

Ellis, A.W.; Johnson, J.J. 2004. **Hydroclimatic analysis of snowfall trends associated with the North American Great Lakes.** Journal of Hydrometeorology. 5(3): 471-486.

Ellwood, E.R.; Temple, S.A.; Primack, R.B.; Bradley, N.L.; Davis, C.C. 2013. **Record-breaking early flowering in the eastern United States.** PLoS ONE. 8(1): e53788.

Elmqvist, T.; Folke, C.; Nyström, M.; Peterson, G.; Bengtsson, J.; Walker, B.; Norberg, J. 2003. **Response diversity, ecosystem change, and resilience.** Frontiers in Ecology and the Environment. 1(9): 488-494.

Emery, M.R. 2002. **Historical overview of nontimber forest product uses in the northeastern United States.** In: Jones, E.T.; McLain, R.J.; Weigand, J., eds. Nontimber forest products in the United States. Lawrence, KS: University Press of Kansas: 3-25.

Emery, M.R.; Barron, E.S. 2010. **Using local ecological knowledge to assess morel decline in the US Mid-Atlantic region.** Economic Botany. 64(3): 205-216.

Erdman, J. **America's six snowiest cities.** 2011. Available at http://www.weather.com/outlook/weather-news/news/articles/snowiest-six-cities_2011-11-29. (Accessed December 15, 2011).

Etterson, M.; Danz, N.; Lind, J.; Haowski, J.M.; Niemi, G.J. 2007. **Breeding bird monitoring in Great Lakes National Forest: 1991-2006.** 2006 annual report to the Chequamegon/Nicolet, Chippewa, and Superior National Forests. Available at http://www.nrri.umn.edu/mnbirds/reports/2006_AnnualReport.pdf. (Accessed April 12, 2014).

Fang, X.; Stefan, H.G.; Eaton, J.G.; McCormick, J.H.; Alam, S.R. 2004a. **Simulation of thermal/dissolved oxygen habitat for fishes in lakes under different climate scenarios: Part 1. Cool-water fish in the contiguous US.** Ecological Modelling. 172(1): 13-37.

Fang, X.; Stefan, H.G.; Eaton, J.G.; McCormick, J.H.; Alam, S.R. 2004b. **Simulation of thermal/dissolved oxygen habitat for fishes in lakes under different climate scenarios: Part 2. Cold-water fish in the contiguous US.** Ecological Modelling. 172(1): 39-54.

Fang, X.; Stefan, H.G.; Eaton, J.G.; McCormick, J.H.; Alam, S.R. 2004c. **Simulation of thermal/dissolved oxygen habitat for fishes in lakes under different climate scenarios: Part 3. Warm-water fish in the contiguous US.** Ecological Modelling. 172(1): 55-68.

Feng, S.; Hu, Q. 2007. **Changes in winter snowfall/precipitation ratio in the contiguous United States.** Journal of Geophysical Research. 112(D15): D15109.

Fernholz, K.; Bowyer, J.; Howe, J. 2007. **TIMOs and REITs: what, why, and how they might impact sustainable forestry.** Dovetail Partners, Inc. Available at http://www.dovetailinc.org/files/DovetailTIMOREIT0507wo.pdf. (Accessed April 11, 2014).

Fine, G.A. 2003. **Morel tales: the culture of mushrooming.** Chicago, IL: University of Illinois Press. 336 p.

Finzi, A.C.; Norby, R.J.; Calfapietra, C.; Gallet-Budynek, A.; Gielen, B.; Holmes, W.E.; Hoosbeek, M.R.; Iversen, C.M.; Jackson, R.B.; Kubiske, M.E.; Ledford, J.; Liberloo, M.; Oren, R.; Polle, A.; Pritchard, S.; Zak, D.R.; Schlesinger, W.H.; Ceulemanse, R. 2007. **Increases in nitrogen uptake rather than nitrogen-use efficiency support higher rates of temperate forest productivity under elevated CO_2.** Proceedings of the National Academy of Sciences. 105(35): 14014-14019.

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

Fitzpatrick, M.C.; Hargrove, W.W. 2009. **The projection of species distribution models and the problem of non-analog climate.** Biodiversity and Conservation. 18: 2255-2261.

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

Fleming, R.A.; Candau, J.-N.; McAlpine, R.S. 2002. **Landscape-scale analysis of interactions between insect defoliation and forest fire in central Canada.** Climatic Change. 55(1-2): 251-272.

Foster, J.R.; Burton, J.I.; Forrester, J.A.; Liu, F.; Muss, J.D.; Sabatini, F.M.; Scheller, R.M.; Mladenoff, D.J. 2010. **Evidence for a recent increase in forest growth is questionable.** Proceedings of the National Academy of Sciences. 107(21): E86-87.

Francis, J.A.; Vavrus, S.J. 2012. **Evidence linking Arctic amplification to extreme weather in mid-latitudes.** Geophysical Research Letters. 39(6).

Franks, P.J.; Adams, M.A.; Amthor, J.S.; Barbour, M.M.; Berry, J.A.; Ellsworth, D.S.; Farquhar, G.D.; Ghannoum, O.; Lloyd, J.; McDowell, N.; Norby, R.J.; Tissue, D.T.; von Caemmerer, S. 2013. **Sensitivity of plants to changing atmospheric CO_2 concentration: from the geological past to the next century.** New Phytology. 197(4): 1077-1094.

Frelich, L.E.; Hale, C.M.; Scheu, S.; Holdsworth, A.R.; Heneghan, L.; Bohlen, P.J.; Reich, P.B. 2006. **Earthworm invasion into previously earthworm-free temperate and boreal forests.** Biological Invasions. 8(6): 1235-1245.

Frelich, L.E.; Lorimer, C.G. 1991. **Natural disturbance regimes in hemlock hardwood forests of the upper Great Lakes region.** Ecological Monographs. 61(2): 145-164.

Frelich, L.E.; Peterson, R.O.; Dovciak, M.; Reich, P.B.; Vucetich, J.A.; Eisenhauer, N. 2012. **Trophic cascades, invasive species and body-size hierarchies interactively modulate climate change responses of ecotonal temperate-boreal forest.** Philosophical Transactions of the Royal Society B: Biological Sciences. 367(1605): 2955-2961.

Frelich, L.E.; Reich, P.B. 1995a. **Neighborhood effects, disturbance, and succession in forests of the western Great-Lakes Region.** Ecoscience. 2(2): 148-158.

Frelich, L.E.; Reich, P.B. 1995b. **Spatial patterns and succession in a Minnesota southern-boreal forest.** Ecological Monographs. 65(3): 325-346.

Frelich, L.E.; Reich, P.B. 2009. **Wilderness conservation in an era of global warming and invasive species: a case study from Minnesota's Boundary Waters Canoe Area Wilderness.** Natural Areas Journal. 29(4): 385-393.

Frelich, L.E.; Reich, P.B. 2010. **Will environmental changes reinforce the impact of global warming on the prairie-forest border of central North America?** Frontiers in Ecology and the Environment. 8(7): 371-378.

Froese, R.; Hyslop, M.; Miller, C.; Garmon, B.; McDiarmid, H., Jr.; Shaw, A.; Leefers, L.A.; Lorenzo, M.; Brown, S.; Shy, M. 2007. **Large-tract forestland ownership change: land use, conservation, and prosperity in Michigan's Upper Peninsula.** Ann Arbor, MI: National Wildlife Federation. 54 p. Available at http://forestlands.mtu.edu/products/UP_Corporate_Forest_Land_Report.pdf. (Accessed April 11, 2014).

Gellesch, E.; Hein, R.; Jaeschke, A.; Beierkuhnlein, C.; Jentsch, A. 2013. **Biotic interactions in the face of climate change.** Progress in Botany. 74: 321-349.

Gibson, W.P.; Daly, C.; Kittel, T.; Nychka, D.; Johns, C.; Rosenbloom, N.; McNab, A.; Taylor, G. 2002. **Development of a 103-year high-resolution climate data set for the conterminous United States.** Proceedings of the 13th American Meteorological Society Conference on Applied Climatology: 181-183.

Girvetz, E.H.; Zganjar, C.; Raber, G.T.; Maurer, E.P.; Kareiva, P.; Lawler, J.J. 2009. **Applied climate-change analysis: the ClimateWizard tool.** PLoS ONE. 4(12): e8320.

Glick, P.; Stein, B.A.; Edelson, N.A., eds. 2011. **Scanning the conservation horizon: a guide to climate change vulnerability assessment.** Washington, DC: National Wildlife Federation.Available at http://www.nwf.org/vulnerabilityguide. (Accessed April 11, 2014).

Gough, C.M.; Vogel, C.S.; Schmid, H.P.; Curtis, P.S. 2008. **Controls on annual forest carbon storage: lessons from the past and predictions for the future.** Bioscience. 58(7): 609-622.

Great Lakes Integrated Sciences and Assessments (GLISA). 2013. **Historical climatology: Marqette, Michigan: Great Lakes Integrated Sciences + Assessments.** Available at http://glisa.umich.edu/great_lakes_climate/climatologies.php. (Accessed August 8, 2013).

Groffman, P.M.; Rustad, L.E.; Templer, P.H.; Campbell, J.L.; Christenson, L.M.; Lany, N.K.; Socci, A.M.; Vadeboncoeur, M.A.; Schaberg, P.G.; Wilson, G.F.; Driscoll, C.T.; Fahey, T.J.; Fisk, M.C.; Goodale, C.L.; Green, M.B.; Hamburg, S.P.; Johnson, C.E.; Mitchell, M.J.; Morse, J.L.; Pardo, L.H.; Rodenhouse, N.L. 2012. **Long-term integrated studies show complex and surprising effects of climate change in the northern hardwood forest.** BioScience. 62(12): 1056-1066.

Groisman, P.Y.; Easterling, D.R. 1994. **Variability and trends of total precipitation and snowfall over the United States and Canada.** Journal of Climate. 7(1): 184-205.

Groisman, P.Y.; Knight, R.W.; Karl, T.R. 2012. **Changes in intense precipitation over the central United States.** Journal of Hydrometeorology. 13(1): 47-66.

Groisman, P.Y.; Knight, R.W.; Karl, T.R.; Easterling, D.R.; Sun, B.; Lawrimore, J.H. 2004. **Contemporary changes of the hydrological cycle over the contiguous United States: trends derived from in situ observations.** Journal of Hydrometeorology. 5(1): 64-85.

Gustafson, E.J.; Sturtevant, B.R. 2013. **Modeling forest mortality caused by drought stress: implications for climate change.** Ecosystems. 16: 60-74.

Hale, C.M.; Frelich, L.E.; Reich, P.B. 2005. **Exotic European earthworm invasion dynamics in northern hardwood forests of Minnesota, USA.** Ecological Applications. 15(3): 848-860.

Hale, C.M.; Frelich, L.E.; Reich, P.B. 2006. **Changes in hardwood forest understory plant communities in response to European earthworm invasions.** Ecology. 87(7): 1637-1649.

Hall, K. 2012. **Climate change in the Midwest: Impacts on biodiversity and ecosystems.** In: Winkler, J.; Andresen, J.; Hatfield, J.; Bidwell, D.; Brown, D., coords. U.S. National Climate Assessment Midwest technical input report. Available at http://glisa.umich.edu/media/files/NCA/MTIT_Biodiversity.pdf. (Accessed April 11, 2014).

Handler, S.; Duveneck, M.J.; Iverson, L.; Peters, E.; Scheller, R.M.; Wythers, K.R.; Brandt, L.; Butler, P.; Janowiak, M.; Shannon, P.D.; Swanston, C.; Barrett, K.; Kolka, R.; McQuiston, C.; Palik, B.; Reich, P.B.; Turner, C.; White, M.; Adams, C.; D'Amato, A.; Hagell, S.; Johnson, P.; Johnson, R.; Larson, M.; Matthews, S.; Montgomery, R.; Olson, S.; Peters, M.; Prasad, A.; Rajala, J.; Daley, J.; Davenport, M.; Emery, M.R.; Fehringer, D.; Hoving, C.L.; Johnson, G.; Johnson, L.; Neitzel, D.; Rissman, A.; Rittenhouse, C.; Ziel, R. 2014a. **Minnesota forest ecosystem vulnerability assessment and synthesis: a report from the Northwoods Climate Change Response Framework project.** Gen. Tech. Rep. NRS-133. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 228 p.

Handler, S.; Duveneck, M.J.; Iverson, L.; Peters, E.; Scheller, R.M.; Wythers, K.R.; Brandt, L.; Butler, P.; Janowiak, M.; Shannon, P.D.; Swanston, C.; Eagle, A.C.; Cohen, J.G.; Corner, R.; Reich, P.B.; Baker, T.; Chhin, S.; Clark, E.; Fehringer, D.; Fosgitt, J.; Gries, J.; Hall, C.; Hall, K.R.; Heyd, R.; Hoving, C.L.; Ibáñez, I.; Kuhr, D.; Matthews, S.; Muladore, J.; Nadelhoffer, K.; Neumann, D.; Peters, M.; Prasad, A.; Sands, M.; Swaty, R.; Wonch, L.; Daley, J.; Davenport, M.; Emery, M.R.; Johnson, G.; Johnson, L.; Neitzel, D.; Rissman, A.; Rittenhouse, C.; Ziel, R. 2014b. **Michigan forest ecosystem vulnerability assessment and synthesis: a report from the Northwoods Climate Change Response Framework project.** Gen. Tech. Rep. NRS-129. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 229 p.

Handler, S.D.; Swanston, C.W.; Butler, P.R.; Brandt, L.A.; Janowiak, M.K.; Powers, M.D.; Shannon, P.D. 2012. **Climate change vulnerabilities within the forestry sector for the Midwestern United States.** In: Winkler, J.; Andresen, J.; Hatfield, J.; Bidwell, D.; Brown, D., coords. U.S. National Climate Assessment Midwest technical input report. Available at http://glisa.umich.edu/media/files/NCA/MTIT_Forestry.pdf. (Accessed April 11, 2014).

Hansen, J.; Sato, M.; Ruedy, R. 2012. **Perception of climate change.** Proceedings of the National Academy of Sciences. 109(37): E2415-E2423.

Hanson, P.J.; Weltzin, J.F. 2000. **Drought disturbance from climate change: response of United States forests.** The Science of the Total Environment. 262(3): 205-220.

Hardy, J.; Groffman, P.; Fitzhugh, R.; Henry, K.; Welman, A.; Demers, J.; Fahey, T.; Driscoll, C.; Tierney, G.; Nolan, S. 2001. **Snow depth manipulation and its influence on soil frost and water dynamics in a northern hardwood forest.** Biogeochemistry. 56(2): 151-174.

Hayhoe, K. 2010a. **1/8 degree CONUS daily downscaled climate projections *PROVISIONAL*.** USGS Geodata Portal [Online]: Texas Tech University, Center for Integrated Data Analytics. Available at http://cida.usgs.gov/thredds/catalog.html?dataset=cida.usgs.gov/thredds/dcp/conus. (Accessed July 11, 2011).

Hayhoe, K. 2010b. **A standardized framework for evaluating the skill of regional climate downscaling techniques.** Urbana-Champaign, IL: University of Illinois at Urbana-Champaign. 153 p. Ph.D. dissertation.

He, H.S.; Mladenoff, D.J.; Gustafson, E.J. 2002. **Study of landscape change under forest harvesting and climate warming-induced fire disturbance.** Forest Ecology and Management. 155(1-3): 257-270.

Headwaters Economics. 2011. **Economic Profile System - Human Dimensions Toolkit.** Available at http://headwaterseconomics.org/tools/eps-hdt. (Accessed December 15, 2011).

Heimpel, G.E.; Frelich, L.E.; Landis, D.A.; Hopper, K.R.; Hoelmer, K.A.; Sezen, Z.; Asplen, M.K.; Wu, K.M. 2010. **European buckthorn and Asian soybean aphid as components of an extensive invasional meltdown in North America.** Biological Invasions. 12(9): 2913-2931.

Hellmann, J.J.; Byers, J.E.; Bierwagen, B.G.; Dukes, J.S. 2008. **Five potential consequences of climate change for invasive species.** Conservation Biology. 22(3): 534-543.

Hicke, J.A.; Allen, C.D.; Desai, A.R.; Dietze, M.C.; Hall, R.J.; Hogg, E.H.; Kashian, D.M.; Moore, D.; Raffa, K.F.; Sturrock, R.N.; Vogelmann, J. 2011. **Effects of biotic disturbances on forest carbon cycling in the United States and Canada.** Global Change Biology. 18(1): 7-34.

Hicke, J.A.; Johnson, M.C.; Hayes, J.L.; Preisler, H.K. 2012. **Effects of bark beetle-caused tree mortality on wildfire.** Forest Ecology and Management. 271: 81-90.

Higgins, D. 2013. **Assessment of watershed vulnerability to climate change: Chequamegon-Nicolet National Forest.** In: Furniss, M.J.; Roby, K.B.; Cenderelli, D.; Chatel, J.; Clifton, C.F.; Clingenpeel, A.; Hays, P.E.; Higgins, D.; Hodges, K.; Howe, C.; Jungst, L.; Louie, J.; Mai, C.; Martinez, R.; Overton, K.; Staab, B.P.; Steinke, R.; Weinhold, M., eds. Assessing the vulnerability of watersheds to climate change: results of national forest watershed vulnerability pilot assessments, Appendix: Assessment of watershed vulnerability to climate change - Pilot National Forest reports. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 240-269.

Hodgkins, G.A.; Dudley, R.W. 2006. **Changes in the timing of winter-spring streamflows in eastern North America, 1913-2002.** Geophysical Research Letters. 33(6).

Hole, F.D. 1968. **Soils of Wisconsin.** Madison, WI: University of Wisconsin Press. 223 p.

Hole, F.D. 1976. **Soils of Wisconsin.** Madison, WI: University of Wisconsin Press. 223 p.

Host, G.E.; Polzer, P.L.; Cleland, D.T. 1995. **Regional climatic analysis of the northern Lake States.** Duluth, MN. Available at http://www.ncrs.fs.fed.us/gla/reports/climate.htm. (Accessed April 11, 2014).

Host, G.E.; Pregitzer, K.S.; Ramm, C.W.; Hart, J.B.; Cleland, D.T. 1987. **Landform-mediated differences in successional pathways among upland forest ecosystems in northwestern Lower Michigan.** Forest Science. 33(2): 445-457.

Hoving, C.L.; Lee, Y.M.; Badra, P.J.; Klatt, B.J. 2013. **Changing climate, changing wildlife: a vulnerability assessment of 400 species of greatest conservation need and game species in Michigan.** Lansing, MI: Michigan Department of Natural Resources, Wildlife Division. 82 p. Available at www.michigan.gov/documents/dnr/3564_Climate_Vulnerability_Division_Report_4.24.13_418644_7.pdf. (Accessed April 11, 2014).

Howe, R.W.; Roberts, L.J. 2005. **Sixteen years of habitat-based bird monitoring in the Nicolet National Forest.** Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station: 963-973.

Ibáñez, I.; Clark, J.S.; Dietze, M.C. 2008. **Evaluating the sources of potential migrant species: implications under climate change.** Ecological Applications. 18(7): 1664-1678.

Ibáñez, I.; Clark, J.S.; Dietze, M.C.; Feeley, K.; Hersh, M.; LaDeau, S.; McBride, A.; Welch, N.E.; Wolosin, M.S. 2006. **Predicting biodiversity change: outside the climate envelope, beyond the species-area curve.** Ecology. 87(8): 1896-1906.

Intergovernmental Panel on Climate Change [IPCC]. 2007a. **Climate change 2007: synthesis report. Contribution of Working Groups I, II, and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.** [Core Writing Team, Pachauri, R.K. and Reisinger, A. (eds.)]. Geneva, Switzerland: Intergovernmental Panel on Climate Change. Available at http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_synthesis_report.htm. (Accessed April 11, 2014).

Intergovernmental Panel on Climate Change [IPCC]. 2007b. **Climate change 2007: the physical science basis: summary for policy makers.** New York, NY. Available at http://www.ipcc.ch/publications_and_data/ar4/wg1/en/contents.html. (Accessed April 11, 2014).

Intergovernmental Panel on Climate Change [IPCC]. 2012. **Managing the risks of extreme events and disasters to advance climate change adaptation.** Cambridge, UK and New York, NY: Cambridge University Press. 582 p.

Intergovernmental Panel on Climate Change [IPCC]. 2013. **Climate change 2013: the physical science basis.** In: Stocker, T.F.; Dahe, Q.; Plattner,G.-K., eds. Working Group I contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Summary for policymakers. Available at https://www.ipcc.ch/report/ar5/wg1/. (Accessed April 11, 2014).

Irland, L.C.; Adams, D.; Alig, R.; Betz, C.J.; Chen, C.-C.; Hutchins, M.; McCarl, B.A.; Skog, K.; Sohngen, B.L. 2001. **Assessing socioeconomic impacts of climate change on U.S. forests, wood-product markets, and forest recreation.** Bioscience. 51(9): 753-764.

Isard, S.; Schaetzl, R.; Andresen, J. 2007. **Soils cool as climate warms in the Great Lakes region: 1951-2000.** Annals of the Association of American Geographers. 97(3): 467-476.

Iverson, L.R.; Matthews, S.N.; Prasad, A.M.; Peters, M.P.; Yohe, G.W. 2012a. **Appendix 2: Risk-based framework and risk case studies. Risk assessment for forested habitats in northern Wisconsin.** In: Vose, J.M.; Peterson, D.L.; Patel-Weynand, T., eds. Effects of climatic variability and change on forest ecosystems: a comprehensive science synthesis for the U.S. forest sector. Gen. Tech. Rep. PNW-GTR-870. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 253-255.

Iverson, L.R.; Matthews, S.N.; Prasad, A.M.; Peters, M.P.; Yohe, G.W. 2012b. **Development of risk matrices for evaluating climatic change responses of forested habitats.** Climatic Change. (114): 231-243.

Iverson, L.R.; Prasad, A.M. 1998. **Predicting abundance of 80 tree species following climate change in the eastern United States.** Ecological Monographs. 68(4): 465-485.

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

Iverson, L.R.; Prasad, A.M.; Matthews, S.N.; Peters, M.P. 2010. **Merger of three modeling approaches to assess potential effects of climate change on trees in the eastern United States.** Forest landscapes and global change-new frontiers in management, conservation and restoration. Proceedings of the IUFRO Landscape Ecology Working Group International Conference; 2010 September 21-27; Braganca, Portugal: 135-140.

Iverson, L.R.; Prasad, A.M.; Matthews, S.N.; Peters, M.P. 2011. **Lessons learned while integrating habitat, dispersal, disturbance, and life-history traits into species habitat models under climate change.** Ecosystems. 14: 1005-1020.

Iverson, L.R.; Schwartz, M.W.; Prasad, A.M. 2004a. **How fast and far might tree species migrate in the eastern United States due to climate change?** Global Ecology and Biogeography. 13(3): 209-219.

Iverson, L.R.; Schwartz, M.W.; Prasad, A.M. 2004b. **Potential colonization of newly available tree-species habitat under climate change: an analysis for five eastern US species.** Landscape Ecology. 19(7): 787-799.

Jacobson, K. 2005. **Balsam boughs in Minnesota: a resource and market study.** St. Paul, MN: Minnesota Department of Natural Resources, Division of Forestry. Available at http://files.dnr.state.mn.us/forestry/um/balsamboughs_mn_resource_market_study.pdf. (Accessed April 11, 2014).

Jensen, O.P.; Benson, B.J.; Magnuson, J.J.; Card, V.M.; Futter, M.N.; Soranno, P.A.; Kenton, M.S. 2007. **Spatial analysis of ice phenology trends across the Laurentian Great Lakes region during a recent warming period.** Limnology and Oceanography. 52(5): 2013-2026.

Jerome, D.S. 2006. **Landforms of the Upper Peninsula, Michigan (DRAFT).** U.S. Department of Agriculture, Natural Resources Conservation Service. Available at ftp://ftp-fc.sc.egov.usda.gov/MI/technical/soils/UP_LandformReport11-06.pdf. (Accessed April 11, 2014).

Johnson, B. 2004. **The Ottawa National Forest breeding bird census: an analysis of twelve years of data.** Report to Ottawa National Forest Bird Monitoring Group. Available at http://www.fs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb5111953.doc. (Accessed April 11, 2014).

Johnson, S.; Stefan, H. 2006. **Indicators of climate warming in Minnesota: lake ice covers and snowmelt runoff.** Climatic Change. 75(4): 421-453.

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

Jump, A.S.; Peñuelas, J. 2005. **Running to stand still: adaptation and the response of plants to rapid climate change.** Ecology Letters. 8(9): 1010-1020.

Karl, T.R.; Knight, R.W.; Easterling, D.R.; Quayle, R.G. 1996. **Indices of climate change for the United States.** Bulletin of the American Meteorological Society. 77(2): 279-292.

Karl, T.R.; Melillo, J.M.; Peterson, T.C. 2009. **Global climate change impacts in the United States: a state of knowledge report from the U.S. Global Change Research Program.** New York, NY: Cambridge University Press: 189 p.

Kling, G.W.; Hayhoe, K.; Johnson, L.B.; Magnuson, J.J.; Polasky, S.; Robinson, S.K.; Shuter, B.J.; Wander, M.M.; Wuebbles, D.J.; Zak, D.R.; Lindroth, R.L.; Moser, S.C.; Wilson, M.L. 2003. **Confronting climate change in the Great Lakes region: impacts on our communities and ecosystems.** Union of Concerned Scientists; Ecological Society of America. Available at http://ucsusa.org/assets/documents/global_warming/greatlakes_final.pdf. (Accessed April 11, 2014).

Knapp, A.K.; Beier, C.; Briske, D.D.; Classen, A.T.; Luo, Y.; Reichstein, M.; Smith, M.D.; Smith, S.D.; Bell, J.E.; Fay, P.A. 2008. **Consequences of more extreme precipitation regimes for terrestrial ecosystems.** Bioscience. 58(9): 811-821.

Knight, J.; Kenney, J.J.; Folland, C.; Harris, G.; Jones, G.S.; Palmer, M.; Parker, D.; Scaife, A.; Stott, P. 2009. **Do global temperature trends over the last decade falsify climate predictions?** Special Supplement to the Bulletin of the American Meteorological Society. 90(8): 22-23.

Knudsen, G.J. 1963. **History of beaver in Wisconsin.** Wisconsin Conservation Department. 15 p. Available at http://dnr.wi.gov/files/PDF/pubs/ss/SS0407.pdf. (Accessed April 11, 2014).

Kohn, B.E.; Payne, N.F.; Ashbrenner, J.E.; Les, B. 1993. **The fisher in Wisconsin.** Madison, WI: Wisconsin Department of Natural Resources. 24 p. Available at http://digital.library.wisc.edu/1711.dl/EcoNatRes.DNRBull183. (Accessed April 11, 2014).

Kost, M.A. 2002. **Natural community abstract for rich conifer swamp.** Lansing, MI: Michigan Natural Features Inventory. 10 p. Available at http://mnfi.anr.msu.edu/abstracts/ecology/Rich_conifer_swamp.pdf. (Accessed April 10, 2014).

Kucharik, C.; Serbin, S.; Vavrus, S.; Hopkins, E.; Motew, M. 2010a. **Patterns of climate change across Wisconsin from 1950 to 2006.** Physical Geography. 31(1): 1-28.

Kucharik, C.; Vimont, D.; Holman, K.; Hopkins, E.; Lorenz, D.J.; Notaro, M.; Vavrus, S.; Young, J. 2010b. **Climate change in Wisconsin.** Madison, WI: Wisconsin Initiative on Climate Change Impacts, Climate Working Group. 51. Available at http://www.wicci.wisc.edu/report/Climate.pdf. (Accessed April 10, 2014).

Kunkel, K.; Bromirski, P.; Brooks, H.; Cavazos, T.; Douglas, A.; Easterling, D.; Emanuel, K.; Groisman, P.Y.; Holland, G.; Knutson, T. 2008. **Observed changes in weather and climate extremes.** In: [Karl, T.R.; Meehl, G.A.; Miller, C.D.; Hassol, S.J.; Waple, A.M.; Murray, W.L. eds.] Weather and climate extremes in a changing climate. Regions of focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands. Washington, DC: U.S. Climate Change Science Program and the Subcommittee on Global Change Research: 35-90.

Kunkel, K.E.; Andsager, K.; Easterling, D.R. 1999. **Long-term trends in extreme precipitation events over the conterminous United States and Canada.** Journal of Climate. 12(8): 2515-2527.

Kunkel, K.E.; Palecki, M.A.; Ensor, L.; Easterling, D.; Hubbard, K.G.; Robinson, D.; Redmond, K. 2009. **Trends in twentieth-century U.S. extreme snowfall seasons.** Journal of Climate. 22(23): 6204-6216.

Kunkel, K.E.; Stevens, L.E.; Stevens, S.E.; Sun, L.; Janssen, E.; Wuebbles, D.; Hilberg, S.D.; Timlin, M.S.; Stoeck, L.; Westcott, N.E.; Dobson, J.G. 2013. **Regional climate trends and scenarios for the US National Climate Assessment. Part 3. Climate of the Midwest U.S.** Washington, DC: U.S. Department of Commerce, National Oceanic and Atmospheric Administration. 103 p.

Kunkel, K.E.; Westcott, N.E.; Kristovich, D.A.R. 2002. **Assessment of potential effects of climate change on heavy lake-effect snowstorms near Lake Erie.** Journal of Great Lakes Research. 28(4): 521-536.

Kuvlesky, W.P., Jr.; Keith, L.B. 1983. **Demography of snowshoe hare populations in Wisconsin.** Journal of Mammalogy. 64(2): 233-244.

Lambert, S.J.; Hansen, B.K. 2011. **Simulated changes in the freezing rain climatology of North America under global warming using a coupled climate model.** Atmosphere-Ocean. 49(3): 289-295.

Larson, E.R.; Kipfmueller, K.F.; Hale, C.M.; Frelich, L.E.; Reich, P.B. 2010. **Tree rings detect earthworm invasions and their effects in northern hardwood forests.** Biological Invasions. 12(5): 1053-1066.

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

Le Quéré, C.; Raupach, M.R.; Canadell, J.G.; Marland, G. 2009. **Trends in the sources and sinks of carbon dioxide.** Nature Geoscience. 2: 831-836.

Leakey, A.; Ainsworth, E.A.; Bernacchi, C.J.; Rogers, A.; Long, S.P.; Ort, D.R. 2009. **Elevated CO_2 effects on plant carbon, nitrogen, and water relations: six important lessons from FACE.** Journal of Experimental Botany. 60(10): 2859-2876.

Lenihan, J.M.; Bachelet, D.; Neilson, R.P.; Drapek, R. 2008. **Simulated response of conterminous United States ecosystems to climate change at different levels of fire suppression, CO_2 emission rate, and growth response to CO_2.** Global and Planetary Change. 64(1-2): 16-25.

Lofgren, B.M.; Quinn, F.H.; Clites, A.H.; Assel, R.A.; Eberhardt, A.J.; Luukkonen, C.L. 2002. **Evaluation of potential impacts on Great Lakes water resources based on climate scenarios of two GCMs.** Journal of Great Lakes Research. 28(4): 537-554.

Lyons, J.; Stewart, J.S.; Mitro, M. 2010. **Predicted effects of climate warming on the distribution of 50 stream fishes in Wisconsin, USA.** Journal of Fish Biology. 77(8): 1867-1898.

Magnuson, J.J.; Krohelski, J.T.; Kunkel, K.E.; Robertson, D.M. 2003. **Wisconsin's waters and climate: historical changes and possible futures.** In: Meine, C., ed. Wisconsin's waters: a confluence of perspectives. Transactions of the Wisconsin Academy of Sciences, Arts and Letters (90): 23-36.

Magnuson, J.J.; Robertson, D.M.; Benson, B.J.; Wynne, R.H.; Livingstone, D.M.; Arai, T.; Assel, R.A.; Barry, R.G.; Card, V.; Kuusisto, E.; Granin, N.G.; Prowse, T.D.; Stewart, K.M.; Vuglinski, V.S. 2000. **Historical trends in lake and river ice cover in the Northern Hemisphere.** Science. 289(5485): 1743-1746.

Magruder, M.; Chhin, S.; Monks, A.; O'Brien, J. 2012. **Effects of initial stand density and climate on red pine productivity within Huron National Forest, Michigan, USA.** Forests. 3(4): 1086-1103.

Malmsheimer, R.W.; Bowyer, J.L.; Fried, J.S.; Gee, E.; Izlar, R.L.; Miner, R.A.; Munn, I.A.; Oneil, E.; Stewart, W.C. 2011. **Managing forests because carbon matters: integrating energy, products, and land management policy.** Journal of Forestry. 109(7): S7-S48.

Maslin, M.; Austin, P. 2012. **Climate models at their limit?** Nature. 486: 2.

Mastrandrea, M.D.; Field, C.B.; Stocker, T.F.; Edenhofer, O.; Ebi, K.L.; Frame, D.J.; Held, H.; Kriegler, E.; Mach, K.J.; Matschoss, P.R.; Plattner, G.K.; Yohe, G.W.; Zwiers, F.W. 2010. **Guidance note for lead authors of the IPCC Fifth Assessment Report on consistent treatment of uncertainties.** Intergovernmental Panel on Climate Change (IPCC). Available at http://www.ipcc.ch/activities/activities.shtml. (Accessed November 23, 2013).

Matthews, S.N.; Iverson, L.R.; Prasad, A.M.; Peters, M.P. 2011a. **Changes in potential habitat of 147 North American breeding bird species in response to redistribution of trees and climate following predicted climate change.** Ecography. 34(6): 933-945.

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

Mcboyle, G.; Scott, D.; Jones, B. 2007. **Climate change and the future of snowmobiling in non-mountainous regions of Canada.** Managing Leisure. 12(4): 237-250.

McCaffery, K.R.; Ashbrenner, J.E.; Creed, W.A.; Kohn, B.E. 1997. **The aspen-ruffed grouse connection.** Journal of Forestry. 95(8): 16-20.

McLachlan, J.S.; Clark, J.S.; Manos, P.S. 2005. **Molecular indicators of tree migration capacity under rapid climate change.** Ecology. 86(8): 2088-2098.

McMahon, S.M.; Parker, G.G.; Miller, D.R. 2010. **Evidence for a recent increase in forest growth.** Proceedings of the National Academy of Sciences. 107(8): 3611-3615.

McNab, W.H.; Avers, P.E. 1994. **Ecological subregions of the United States: section descriptions.** Washington, DC: U.S. Department of Agriculture, Forest Service. 267 p. Available at http://www.fs.fed.us/land/pubs/ecoregions/. (Accessed April 11, 2014).

McNab, W.H.; Cleland, D.T.; Freeouf, J.A.; Keys, J.E., Jr.; Nowacki, G.J.; Carpenter, C.A. 2007. **Description of "Ecological subregions: sections of the conterminous United States."** Gen. Tech. Rep. WO-76B. Washington, DC: U.S. Department of Agriculture, Forest Service. 80 p. Available at http://fsgeodata.fs.fed.us/other_resources/ecosubregions.php. (Accessed April 11, 2014).

Medlyn, B.E.; Duursma, R.A.; Zeppel, M.J.B. 2011. **Forest productivity under climate change: a checklist for evaluating model studies.** Wiley Interdisciplinary Reviews: Climate Change. 2(3): 332-355.

Meehl, G.A.; Tebaldi, C. 2004. **More intense, more frequent, and longer lasting heat waves in the 21st century.** Science. 305(5686): 994-997.

Meeker, J.E.; Elias, J.E.; Heim, J.A. 1993. **Plants used by the Great Lakes Ojibwa.** Odanah, WI: Great Lakes Indian Fish and Wildlife Commission. 440 p.

Melillo, J.M.; Richmond, T.C.; Yohe, G.W., eds. 2014. **Climate change impacts in the United States: the third National Climate Assessment.** Washington, DC: U.S. Global Change Research Program. 841 p. Available at http://nca2014.globalchange.gov/downloads. (Accessed May 7, 2014).

Michigan Department of Natural Resources and Environment. 2009. **Michigan forest health highlights 2009.** Forest Management Division. Available at http://fhm.fs.fed.us/fhh/fhh_09/mi_fhh_09.pdf. (Accessed April 14, 2014).

Michigan Department of Natural Resources and Environment. 2010. **Michigan deer management plan.** Available at http://www.michigan.gov/documents/dnre/WLD_Deer_Management_Plan_FINAL_5.8_320639_7.pdf. (Accessed April 10, 2014).

Michigan Department of Natural Resources [MDNR]. 2011a. **Michigan forest health highlights 2011.** 25 p. Available at http://fhm.fs.fed.us/fhh/fhh_11/MI_FHH_2011.pdf. (Accessed April 11, 2014).

Michigan Department of Natural Resources [MDNR]. 2011b. **Michigan's wildlife action plan.** Available at http://www.michigan.gov/dnr/0,1607,7-153-10370_30909---,00.html. (Accessed April 11, 2014).

Michigan Department of Natural Resources [MDNR]. 2012a. **Map and legal descriptions of commercial forest lands listed.** Available at http://www.michigan.gov/dnr/0,1607,7-153-30301_39170-178808--,00.html. (Accessed April 11, 2014).

Michigan Department of Natural Resources [MDNR]. 2012b. **Michigan forest health highlights 2012.** 42 p. Available at http://fhm.fs.fed.us/fhh/fhh_12/MI_FHH_2012.pdf. (Accessed April 11, 2014).

Michigan Department of Natural Resources [MDNR]. 2012c. **Michigan statewide comprehensive outdoor recreation plan 2013-2017.** Available at http://www.michigandnr.com/publications/pdfs/grants/scorp%20final%20report.pdf. (Accessed April 11, 2014).

Michigan Department of Natural Resources [MDNR]. 2013. **Regional state forest management plan: Western Upper Peninsula.** Available at http://www.michigan.gov/dnr/0,4570,7-153-30301_30505_62551-284917--,00.html. (Accessed April 11, 2014).

Michigan Department of Natural Resources [MDNR]. 2014. **Wolves in Michigan.** Available at http://www.michigan.gov/dnr/0,1607,7-153-10370_12145_12205-32569--,00.html. (Accessed May 1, 2014).

Michigan State University. 2010. **Michigan state climatologist's office's 1981-2010 normals and statistics: West Upper Division.** East Lansing, MI: Michigan State University, Department of Geography. Available at http://climate.geo.msu.edu/climate_mi/index.html. (Accessed April 11, 2014).

Minnesota Department of Natural Resources. 2011. **Minnesota forest health annual report.** St. Paul, MN: Minnesota Department of Natural Resources, Division of Forestry, Forest Health Unit. 66 p. Available at http://www.dnr.state.mn.us/treecare/forest_health/annualreports.html. (Accessed April 11, 2014).

Minnesota Sea Grant. 2012. **A self-assessment to address climate change readiness in your community.** Duluth, MN. 16 p.

Miranda, B.R.; Sturtevant, B.R.; Stewart, S.I.; Hammer, R.B. 2012. **Spatial and temporal drivers of wildfire occurrence in the context of rural development in northern Wisconsin, USA.** International Journal of Wildland Fire. 21(2): 141-154.

Mishra, V.; Cherkauer, K.A. 2011. **Influence of cold season climate variability on lakes and wetlands in the Great Lakes region.** Journal of Geophysical Research: Atmospheres. 116(D12): D12111.

Mishra, V.; Cherkauer, K.A.; Bowling, L.C.; Huber, M. 2011. **Lake ice phenology of small lakes: impacts of climate variability in the Great Lakes region.** Global and Planetary Change. 76(3-4): 166-185.

Mitro, M.; Lyons, J.; Sharma, S. 2010. **Coldwater Fish and Fisheries Working Group report.** Wisconsin Initiative on Climate Change Impacts. 30 p. Available at http://www.wicci.wisc.edu/report/Coldwater-Fish-and-Fisheries.pdf. (Accessed April 10, 2014).

Mladenoff, D.J.; Stearns, F. 1993. **Eastern hemlock regeneration and deer browsing in the northern Great Lakes region: a re-examination and model simulation.** Conservation Biology. 7(4): 889-900.

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

Moy, P.; Clark, G.; Hart, D.; Mickelson, D.; Luloff, A.; Angel, K.; Barrett, K.; Wu, C.; Boldt, S. 2010. **Climate change and Wisconsin's Great Lakes coastal communities.** Wisconsin Initiative on Climate Change Impacts. Available at http://www.wicci.wisc.edu/report/Coastal-Communities.pdf. (Accessed April 11, 2014).

Munck, I.A.; Smith, D.R.; Sickley, T.; Stanosz, G.R. 2009. **Site-related influences on cone-borne inoculum and asymptomatic persistence of *Diplodia* shoot blight fungi on or in mature red pines.** Forest Ecology and Management. 257(3): 812-819.

Murphy, H.T.; VanDerWal, J.; Lovett-Doust, J. 2010. **Signatures of range expansion and erosion in eastern North American trees.** Ecology Letters. 13(10): 1233-1244.

Myers, P.; Lundrigan, B.L.; Hoffman, S.M.G.; Haraminac, A.P.; Seto, S.H. 2009. **Climate-induced changes in the small mammal communities of the Northern Great Lakes Region.** Global Change Biology. 15(6): 1434-1454.

NASA Goddard Institute for Space Studies. 2010. **2009: second warmest year on record; end of warmest decade.** Available at http://www.nasa.gov/topics/earth/features/temp-analysis-2009.html. (Accessed April 11, 2014).

National Agricultural Statistics Service. 2009. **Wisconsin agricultural statistics.** Available at http://www.nass.usda.gov/Statistics_by_State/Wisconsin/Publications/Annual_Statistical_Bulletin/09as_inside3web.pdf. (Accessed April 11, 2014).

National Agricultural Statistics Service. 2013. **Maple syrup production.** 4 p. Available at http://www.nass.usda.gov/Statistics_by_State/New_England_includes/Publications/0605mpl.pdf. (Accessed April 4, 2014).

National Oceanic and Atmospheric Administration [NOAA]. 2010. **Monthly temperature and precipitation normals (and degree day information if available).** Marquette, MI: National Weather Service Forecast Office. Available at http://www.crh.noaa.gov/mqt/normals/totalIMT.php. (Accessed April 11, 2014).

National Oceanic and Atmospheric Administration [NOAA] National Climatic Data Center. 2006a. **Climate of the States: Wisconsin.** Available at http://cdo.ncdc.noaa.gov/climatenormals/clim60/states/Clim_WI_01.pdf. (Accessed April 11, 2014).

National Oceanic and Atmospheric Administration [NOAA] National Climatic Data Center. 2006b. **Climates of the States.** Environmental Data Service. Available at http://hurricane.ncdc.noaa.gov/cgi-bin/climatenormals/climatenormals.pl?directive=prod_select2&prodtype=CLIM60&subrnum=. (Accessed April 11, 2014).

National Oceanic and Atmospheric Administration [NOAA]. National Climatic Data Center. 2012. **State of the climate: global analysis for annual 2012.** Available at http://www.ncdc.noaa.gov/sotc/global/2012/13. (Accessed December 2012).

National Oceanic and Atmospheric Administration [NOAA] National Climatic Data Center. 2013. **Climate at a glance.** Available at http://www.ncdc.noaa.gov/cag/. (Accessed April 11, 2014).

National Weather Service. 2012. **Storm Prediction Center.** Available at http://www.spc.noaa.gov/wcm/ (Accessed April 1, 2012).

Nearing, M.; Jetten, V.; Baffaut, C.; Cerdan, O.; Couturier, A.; Hernandez, M.; Le Bissonnais, Y.; Nichols, M.; Nunes, J.; Renschler, C. 2005. **Modeling response of soil erosion and runoff to changes in precipitation and cover.** Catena. 61(2): 131-154.

Nearing, M.; Pruski, F.; O'Neal, M. 2004. **Expected climate change impacts on soil erosion rates: a review.** Journal of Soil and Water Conservation. 59(1): 43-50.

Nicholls, S. 2012. **Outdoor recreation and tourism.** In: Winkler, J.; Andresen, J.; Hatfield, J.; Bidwell, D.; Brown, D., coords. U.S. National Climate Assessment Midwest technical input report. Available at http://glisa.umich.edu/media/files/NCA/MTIT_RecTourism.pdf. (Accessed April 11, 2014).

Norby, R.J.; DeLucia, E.H.; Gielen, B.; Calfapietra, C.; Giardina, C.P.; King, J.S.; Ledford, J.; McCarthy, H.R.; Moore, D.J.P.; Ceulemans, R. 2005. **Forest response to elevated CO_2 is conserved across a broad range of productivity.** Proceedings of the National Academy of Sciences. 102(50): 18052-18056.

Norby, R.J.; Zak, D.R. 2011. **Ecological lessons from free-air CO_2 enrichment (FACE) experiments.** Annual Review of Ecology, Evolution, and Systematics. 42: 181-203.

Norton, D.C.; Bolsenga, S.J. 1993. **Spatiotemporal trends in lake effect and continental snowfall in the Laurentian Great Lakes, 1951-1980.** Journal of Climate. 6(10): 1943-1956.

Notaro, M.; Holman, K.; Zarrin, A.; Fluck, E.; Vavrus, S.; Bennington, V. 2012. **Influence of the Laurentian Great Lakes on regional climate.** Journal of Climate. 26(3): 789-804.

Notaro, M.; Lorenz, D.J.; Hoving, C.L.; Schummer, M. [In press]. **21st century projections of snowfall and winter severity across central-eastern North America.** Journal of Climate.

Notaro, M.; Lorenz, D.J.; Vimont, D. 2010. **What may grow well in tomorrow's gardens?** Wisconsin Natural Resources. August 2010. Available at http://dnr.wi.gov/wnrmag/2010/08/gardens.htm. (Accessed April 11, 2014).

Notaro, M.; Lorenz, D.J.; Vimont, D.; Vavrus, S.; Kucharik, C.; Franz, K. 2011. **21st century Wisconsin snow projections based on an operational snow model driven by statistically downscaled climate data.** International Journal of Climatology. 31(11): 1615-1633.

Nowacki, G.J.; Abrams, M.D. 2008. **The demise of fire and "mesophication" of forests in the eastern United States.** BioScience. 58(2): 123-138.

Nowacki, G.J.; Abrams, M.D.; Lorimer, C.G. 1990. **Composition, structure, and historical development of northern red oak stands along an edaphic gradient in north-central Wisconsin.** Forest Science. 36: 276-292.

Ollinger, S.; Goodale, C.; Hayhoe, K.; Jenkins, J. 2008. **Potential effects of climate change and rising CO_2 on ecosystem processes in northeastern U.S. forests.** Mitigation and Adaptation Strategies for Global Change. 13(5): 467-485.

Ollinger, S.V.; Aber, J.D.; Reich, P.B.; Freuder, R.J. 2002. **Interactive effects of nitrogen deposition, tropospheric ozone, elevated CO_2, and land use history on the carbon dynamics of northern hardwood forests.** Global Change Biology. 8: 545-562.

Opperman, J.J.; Luster, R.; McKenney, B.A.; Roberts, M.; Meadows, A.W. 2010. **Ecologically functional floodplains: connectivity, flow regime, and scale.** JAWRA Journal of the American Water Resources Association. 46(2): 211-226.

Palik, B.J.; Ostry, M.E.; Venette, R.C.; Abdela, E. 2011. ***Fraxinus nigra* (black ash) dieback in Minnesota: Regional variation and potential contributing factors.** Forest Ecology and Management. 261(1): 128-135.

Passi, P. 2012. **Floods wreaked torrent of trouble in Duluth trout streams; city starting to eye repairs.** Northland Outdoors. Available at http://www.northlandoutdoors.com/event/article/id/246934/publisher_ID/36/. (Accessed April 10, 2014).

Patz, J.A.; Malecki, K.; McLellan, S.; Shaw, S.; Vavrus, S. 2011. **Human Health Working Group report.** Wisconsin Initiative on Climate Change Impacts. 46 p. Available at http://www.wicci.wisc.edu/report/Human-Health.pdf. (Accessed April 10, 2014).

Pedlar, J.H.; McKenney, D.W.; Aubin, I.; Beardmore, T.; Beaulieu, J.; Iverson, L.; O'Neill, G.A.; Winder, R.S.; Ste-Marie, C. 2012. **Placing forestry in the assisted migration debate.** Bioscience. 62(9): 835-842.

Perera, E.M.; Sanford, T.; White-Newsome, J.L.; Kalkstein, L.S.; Vanos, J.K.; Weir, K. 2012. **Heat in the Heartland: 60 years of warming in the Midwest.** Union of Concerned Scientists. 40 p. Available at http://www.ucsusa.org/global_warming/science_and_impacts/impacts/global-warming-and-heat-waves.html. (Accessed April 11, 2014).

Perry, C.H.; Everson, V.A.; Brown, I.K.; Cummings-Carlson, J.; Dahir, S.E.; Jepsen, E.A.; Kovach, J.; Labissoniere, M.D.; Mace, T.R.; Padley, E.A.; Rideout, R.B.; Butler, B.J.; Crocker, S.J.; Liknes, G.C.; Morin, R.S.; Nelson, M.D.; Wilson, B.T.; Woodall, C.W. 2008. **Wisconsin's forests, 2004.** Resour. Bull. NRS-23. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 104 p.

Perry, C.H.; Everson, V.A.; Butler, B.J.; Crocker, S.J.; Dahir, S.E.; Diss-Torrance, A.L.; Domke, G.M.; Gormanson, D.D.; Hatfield, M.A.; Herrick, S.K.; Hubbard, S.S.; Mace, T.R.; Miles, P.D.; Nelson, M.D.; Rideout, R.B.; Saunders, L.T.; Stueve, K.M.; Wilson, B.T.; Woodall, C.W. 2012. **Wisconsin's forests 2009.** Resour. Bull. NRS-67. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 62 p.

Peters, E.B.; Wythers, K.R.; Zhang, S.; Bradford, J.B.; Reich, P.B. 2013. **Potential climate change impacts on temperate forest ecosystem processes.** Canadian Journal of Forest Research. 43(10): 939-950.

Peterson, C.J. 2000. **Catastrophic wind damage to North American forests and the potential impact of climate change.** The Science of the Total Environment. 262: 287-311.

Peterson, T.C.; Anderson, D.M.; Cohen, S.J.; Cortez-Vazquez, M.; Murnane, R.J.; Parmesan, C.; Philips, D.; Pulwarty, R.S.; Stone, J.M.R. 2008. **Why weather and climate extremes matter.** In: [Karl, T.R.; Meehl, G.A.; Miller, C.D.; Hassol, S.J.; Waple, A.M.; Murray, W.L. eds.] Weather and climate extremes in a changing climate. Regions of focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands. Washington, DC: U.S. Climate Change Science Program and the Subcommittee on Global Change Research: 11-34.

Peterson, T.C.; Heim, R.R.; Hirsch, R.; Kaiser, D.P.; Brooks, H.; Diffenbaugh, N.S.; Dole, R.M.; Giovannettone, J.P.; Guirguis, K.; Karl, T.R.; Katz, R.W.; Kunkel, K.; Lettenmaier, D.; McCabe, G.J.; Paciorek, C.J.; Ryberg, K.R.; Schubert, S.; Silva, V.B.S.; Stewart, B.C.; Vecchia, A.V.; Villarini, G.; Vose, R.S.; Walsh, J.; Wehner, M.; Wolock, D.; Wolter, K.; Woodhouse, C.A.; Wuebbles, D. 2013. **Monitoring and understanding changes in heat waves, cold waves, floods, and droughts in the United States: state of knowledge.** Bulletin of the American Meteorological Society. 94(6): 821-834.

Pope, V.; Gallani, M.L.; Rowntree, P.R.; Stratton, R.A. 2000. **The impact of new physical parameterizations in the Hadley Centre climate model: HadAM3.** Climate Dynamics. 16: 123-146.

Posey, J. 2012. **Climate change impacts on transportation in the Midwest.** In: Winkler, J.; Andresen, J.; Hatfield, J.; Bidwell, D.; Brown, D., coords. U.S. National Climate Assessment Midwest technical input report. Available at http://glisa.umich.edu/media/files/NCA/MTIT_Transportation.pdf. (Accessed April 14, 2014).

Powers, M.D.; Nagel, L.M. 2009. **Pennsylvania sedge cover, forest management and deer density influence tree regeneration dynamics in a northern hardwood forest.** Forestry. 82(3): 241-254.

Prasad, A.M.; Gardiner, J.D.; Iverson, L.R.; Matthews, S.N.; Peters, M. 2013. **Exploring tree species colonization potentials using a spatially explicit simulation model: implications for four oaks under climate change.** Global Change Biology. 19(7): 2196-2208.

Prentiss & Carlisle. 2008. **Michigan timber market analysis.** Final report prepared for the Michigan Department of Natural Resources. 147 p. Available at http://prentissandcarlisle.com/assets/Industry_Analysis_Report.pdf. (Accessed April 10, 2014).

Price, D.L., ed. 2010. **Michigan forest resource assessment and strategy.** Lansing, MI: Michigan Department of Natural Resources and Environment. Available at http://www.michigan.gov/documents/dnr/MichiganForestResourceAssessmentandStrategyIC4043final_325444_7.pdf. (Accessed April 10, 2014).

Price, J.T.; Root, T.L. 2000. **Effects of climate change on bird distributions and migration patterns.** In: Sousounis, P.J.; Bisanz, J.M., eds. Preparing for a changing climate—the potential consequences of climate variability and change: Great Lakes. Ann Arbor, MI: University of Michigan: 65-68.

Pugh, S.A.; Hansen, M.H.; Pedersen, L.D.; Heym, D.C.; Butler, B.J.; Crocker, S.J.; Meneguzzo, D.; Perry, C.H.; Haugen, D.E.; Woodall, C.W.; Jepsen, E. 2009. **Michigan's forests 2004.** Resour. Bull. NRS-34. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 214 p.

Pugh, S.A.; Pedersen, L.D.; Heym, D.C.; Piva, R.J.; Woodall, C.W.; Barnett, C.J.; Kurtz, C.M.; Moser, W.K. 2012. **Michigan's forests 2009.** Resour. Bull. NRS-66. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 68 p. Available at http://www.fs.fed.us/nrs/pubs/rb/rb_nrs66.pdf. (Accessed April 10, 2014).

Radeloff, V.C.; Hammer, R.B.; Stewart, S.I. 2005. **Rural and suburban sprawl in the US Midwest from 1940 to 2000 and its relation to forest fragmentation.** Conservation Biology. 19(3): 793-805.

Radeloff, V.C.; Mladenoff, D.J.; Hong, S.H.; Boyce, M.S. 1999. **Forest landscape change in the northwestern Wisconsin Pine Barrens from pre-European settlement to the present.** Canadian Journal of Forest Research. 29(11): 1649-1659.

Raupach, M.R.; Marland, G.; Ciais, P.; Le Quéré, C.; Canadell, J.G.; Klepper, G.; Field, C.B. 2007. **Global and regional drivers of accelerating CO_2 emissions.** Proceedings of the National Academy of Sciences. 104(24): 10288-10293.

Ravenscroft, C.; Scheller, R.M.; Mladenoff, D.J.; White, M.A. 2010. **Forest restoration in a mixed-ownership landscape under climate change.** Ecological Applications. 20(2): 327-346.

Rempel, R.S. 2011. **Effects of climate change on moose populations: exploring the response horizon through biometric and systems models.** Ecological Modelling. 222(18): 3355-3365.

Reusch, T.B.H.; Ehlers, A.; Hammerli, A.; Worm, B. 2005. **Ecosystem recovery after climatic extremes enhanced by genotypic diversity.** Proceedings of the National Academy of Sciences. 102(8): 2826-2831.

Rhemtulla, J.M.; Mladenoff, D.J.; Clayton, M.K. 2009. **Legacies of historical land use on regional forest composition and structure in Wisconsin, USA (mid-1800s-1930s-2000s).** Ecological Applications. 19(4): 1061-1078.

Rich, R.L.; Frelich, L.; Reich, P.B.; Bauer, M.E. 2010. **Detecting wind disturbance severity and canopy heterogeneity in boreal forest by coupling high-spatial resolution satellite imagery and field data.** Remote Sensing of Environment. 114(2): 299-308.

Rich, R.L.; Frelich, L.E.; Reich, P.B. 2007. **Wind-throw mortality in the southern boreal forest: effects of species, diameter and stand age.** Journal of Ecology. 95: 1261-1273.

Richardson, K.; Steffen, W.; Schellnhuber, H.J.; Alcamo, J.; Barker, T.; Kammen, D.; Leemans, R.; Liverman, D.; Monasinghe, M.; Osman-Elasha, B.; Stern, N.; Waever, O. 2009. **Climate change: global risks, challenges and decisions.** University of Copenhagen. Available at http://edepot.wur.nl/10197. (Accessed April 11, 2014).

Rodenhouse, N.L. 2009. **Climate change effects on native fauna of northeastern forests.** Canadian Journal of Forest Research. 39(2): 249-263.

Rogers, D.A.; Rooney, T.P.; Olson, D.; Waller, D.M. 2008. **Shifts in southern Wisconsin forest canopy and understory richness, composition, and heterogeneity.** Ecology. 89: 2482-2492.

Rolley, R.E. 2010. **White-tailed deer population status 2010.** Madison, WI: Wisconsin Department of Natural Resources. Available at http://dnr.wi.gov/org/land/wildlife/harvest/reports/wtaildeerpop2.pdf. (Accessed February 23, 2011).

Rolley, R.E.; Olson, J.F.; Worland, M.L. 2008. **Beaver population analysis 2008.** Wisconsin Department of Natural Resources. Available at http://dnr.wi.gov/topic/WildlifeHabitat/documents/reports/beaverpop2.pdf. (Accessed April 11, 2014).

Romano, S.P. 2010. **Our current understanding of the Upper Mississippi River System floodplain forest.** Hydrobiologia. 640(1): 115-124.

Rooney, T.P.; McCormick, R.J.; Solheim, S.L.; Waller, D.M. 2000. **Regional variation in recruitment of hemlock seedlings and saplings in the Upper Great Lakes, USA.** Ecological Applications. 10(4): 1119-1132.

Rooney, T.P.; Solheim, S.L.; Waller, D.M. 2002. **Factors affecting the regeneration of northern white cedar in lowland forests of the Upper Great Lakes region, USA.** Forest Ecology and Management. 163(1-3): 119-130.

Rooney, T.P.; Waller, D.M. 2003. **Direct and indirect effects of white-tailed deer in forest ecosystems.** Forest Ecology and Management. 181(1-2): 165-176.

Root, T.L.; Price, J.T.; Hall, K.R.; Schneider, S.H.; Rosenzweig, C.; Pounds, J.A. 2003. **Fingerprints of global warming on wild animals and plants.** Nature. 421(6918): 57-60.

Ruddiman, W.F. 2003. **The anthropogenic greenhouse era began thousands of years ago.** Climatic Change. 61: 261-293.

Ruddiman, W.F. 2013. **The Anthropocene.** Annual Review of Earth and Planetary Sciences. 41: 4.1-4.24.

Rustad, L.; Campbell, J.; Dukes, J.S.; Huntington, T.; Lambert, K.F.; Mohan, J.; Rodenhouse, N. 2012. **Changing climate, changing forests: the impacts of climate change on forests in the northeastern United States and eastern Canada.** Gen. Tech. Rep. NRS-99. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 48 p.

Rustad, L.; Campbell, J.; Marion, G.; Norby, R.; Mitchell, M.; Hartley, A.; Cornelissen, J.; Gurevitch, J. 2001. **A meta-analysis of the response of soil respiration, net nitrogen mineralization, and aboveground plant growth to experimental ecosystem warming.** Oecologia. 126(4): 543-562.

Ryan, M.G.; Vose, J.M. 2012. **Effects of climatic variability and change.** In: Vose, J.M.; Peterson, D.L.; Patel-Weynand, T., eds. Effects of climatic variability and change on forest ecosystems: a comprehensive science synthesis for the U.S. forest sector. Gen. Tech. Rep. PNW-GTR-870. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 7-95.

Saunders, S.; Findlay, D.; Easley, T.; Spencer, T. 2011. **Great Lakes National Parks in peril: the threats of climate disruption.** Louisville, CO: Rocky Mountain Climate Organization; New York, NY: Natural Resources Defense Council. 58 p. Available at http://www.rockymountainclimate.org/images/GreatLakesParksInPeril.pdf. (Accessed November 24, 2013).

Saunders, S.; Findlay, D.; Easley, T.; Spencer, T. 2012. **Doubled trouble: more Midwestern extreme storms.** Louisville, CO: Rocky Mountain Climate Organization; New York, NY: Natural Resources Defense Council. 42 p. Available at http://www.rockymountainclimate.org/images/Doubled%20Trouble.pdf. (Accessed November 24, 2013).

Scheller, R.M.; Domingo, J.B.; Sturtevant, B.R.; Williams, J.S.; Rudy, A.; Gustafson, E.J.; Mladenoff, D.J. 2007. **Design, development, and application of LANDIS-II, a spatial landscape simulation model with flexible temporal and spatial resolution.** Ecological Modelling. 201(3-4): 409-419.

Scheller, R.M.; Mladenoff, D.J. 2005. **A spatially interactive simulation of climate change, harvesting, wind, and tree species migration and projected changes to forest composition and biomass in northern Wisconsin, USA.** Global Change Biology. 11(2): 307-321.

Scheller, R.M.; Mladenoff, D.J. 2008. **Simulated effects of climate change, fragmentation, and inter-specific competition on tree species migration in northern Wisconsin, USA.** Climate Research. 36(3): 191-202.

Schorger, A.W. 1945. **The ruffed grouse in early Wisconsin.** Transactions of the Wisconsin Academy of Sciences, Arts, and Letters. 37: 35-90.

Schulte, L.A.; Mladenoff, D.J. 2005. **Severe wind and fire regimes in northern forests: historical variability at the regional scale.** Ecology. 86(2): 431-445.

Schwartz, M.D.; Ahas, R.; Aasa, A. 2006a. **Onset of spring starting earlier across the Northern Hemisphere.** Global Change Biology. 12(2): 343-351.

Schwartz, M.W.; Iverson, L.R.; Prasad, A.M.; Matthews, S.N.; O'Connor, R.J. 2006b. **Predicting extinctions as a result of climate change.** Ecology. 87(7): 1611-1615.

Schwartz, M.W.; Hellmann, J.J.; McLachlan, J.M.; Sax, D.F.; Borevitz, J.O.; Brennan, J.; Camacho, A.E.; Ceballos, G.; Clark, J.R.; Doremus, H. 2012. **Managed relocation: integrating the scientific, regulatory, and ethical challenges.** BioScience. 62(8): 732-743.

Shakun, J.D.; Carlson, A.E. 2010. **A global perspective on last glacial maximum to Holocene climate change.** Quaternary Science Reviews. 29: 1801-1816.

Shakun, J.D.; Clark, P.U.; He, F.; Marcott, S.A.; Mix, A.C.; Liu, Z.; Otto-Bliesner, B.; Schmittner, A.; Bard, E. 2012. **Global warming preceded by increasing carbon dioxide concentrations during the last deglaciation.** Nature. 484(7392): 49-54.

Shaw, S.; Fredine, C.G. 1971. **Wetlands of the United States.** Washington, DC: U.S. Department of the Interior, U.S. Fish and Wildlife Service. 67 p.

Shefferly, N. 2007. ***Lepus americanus.*** Animal diversity web. Ann Arbor, MI: University of Michigan Museum of Zoology. Available at http://animaldiversity.ummz.umich.edu/site/accounts/information/Lepus_americanus.html. (Accessed April 11, 2014).

Sinha, T.; Cherkauer, K.A. 2010. **Impacts of future climate change on soil frost in the midwestern United States.** Journal of Geophysical Research-Atmospheres. 115(D8).

Sinha, T.; Cherkauer, K.A.; Mishra, V. 2009. **Impacts of historic climate variability on seasonal soil frost in the Midwestern United States.** Journal of Hydrometeorology. 11(2): 229-252.

Skalski, J.R.; Millspaugh, J.J.; Clawson, M.V.; Belant, J.L.; Etter, D.R.; Frawley, B.J.; Friedrich, P.D. 2011. **Abundance trends of American martens in Michigan based on statistical population reconstruction.** The Journal of Wildlife Management. 75(8): 1767-1773.

Skinner, C.B.; DeGaetano, A.T.; Chabot, B.F. 2010. **Implications of twenty-first century climate change on Northeastern United States maple syrup production: impacts and adaptations.** Climatic Change. 100(3-4): 685-702.

Slaughter, B.S.; Cohen, J.G.; Kost, M.A. 2007. **Natural community abstract for hardwood-conifer swamp.** Lansing, MI: Michigan Natural Features Inventory. 20 p. Available at http://mnfi.anr.msu.edu/abstracts/ecology/Hardwood-conifer_swamp.pdf. (Accessed April 10, 2014).

Small, D.; Islam, S.; Vogel, R.M. 2006. **Trends in precipitation and streamflow in the eastern US: paradox or perception.** Geophysical Research Letters. 33: L03403.

Smith, W.B.; Guldin, R.W. 2012. **Forest sector reeling during economic downturn.** The Forestry Source. 17(1).

Soberón, J. 2007. **Grinnellian and Eltonian niches and geographic distributions of species.** Ecology Letters. 10(12): 1115-1123.

Sommers, L.M.; Darden, J.T.; Harman, J.R.; Sommers, L.K. 1984. **Michigan, a geography.** Boulder, CO: Westview Press. 254 p.

Sommers, W.T.; Coloff, S.G.; Conard, S.G. 2011. **Fire history and climate change.** Report submitted to the Joint Fire Science Program for Project 09-02-1-09. 190. 340 p. Available at http://www.firescience.gov/projects/09-2-01-9/project/09-2-01-9_Final_Report_JFSP_09-2-01-09_Fire_History_and_Climate_Change_by_Chapter_111013.pdf. (Accessed December 3, 2013).

St. Claire, S.B.; Sharpe, W.E.; Lynch, J.P. 2008. **Key interactions between nutrient limitation and climatic factors in temperate forests: a synthesis of the sugar maple literature.** Canadian Journal of Forest Research. 38(3): 401-414.

Stanosz, G.R.; Blodgett, J.T.; Smith, D.R.; Kruger, E.L. 2001. **Water stress and *Sphaeropsis sapinea* as a latent pathogen of red pine seedlings.** New Phytologist. 149(3): 531-538.

Stearns, F.W. 1997. **Physical environment supporting Lake States forests.** In: Webster, H.H.; Vasievich, J.M., eds. Lake States regional forest resources assessment: technical papers. Gen. Tech. Rep. NC-189. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station: 1-7.

Stefan, H.G.; Fang, X.; Eaton, J.G. 2001. **Simulated fish habitat changes in North American lakes in response to projected climate warming.** Transactions of the American Fisheries Society. 130(3): 459-477.

Stoner, A.M.K.; Hayhoe, K.; Yang, X.; Wuebbles, D.J. 2013. **An asynchronous regional regression model for statistical downscaling of daily climate variables.** International Journal of Climatology. 33(11): 2473-2494.

Stott, P.A.; Gillett, N.P.; Hegerl, G.C.; Karoly, D.J.; Stone, D.A.; Zhang, X.; Zwiers, F. 2010. **Detection and attribution of climate change: a regional perspective.** WIREs Climate Change. 1(March/April 2010): 192-211.

Stowell, L.; McKay, M. 2009. **Current status.** Available at http://www.dnr.state.wi.us/org/land/wildlife/elk/q2.pdf. (Accessed February 23, 2011).

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

Stynes, D.J. 1997. **Recreation activity and tourism spending in the Lakes States.** In: Webster, H.H.; Vasievich, J.M., eds. Lake States regional forest resources assessment: technical papers. Gen. Tech. Rep. NC-189. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station: 139-164.

Swanson, D.K.; Grigal, D.F. 1991. **Biomass, structure, and trophic environment of peatland vegetation in Minnesota.** Wetlands. 11(2): 279-302.

Swanston, C.; Janowiak, M.K.; Iverson, L.; Parker, L.; Mladenoff, D.; Brandt, L.; Butler, P.; St. Pierre, M.; Prasad, A.; Matthews, S.; Peters, M.; Higgins, D.; Dorland, A. 2011. **Ecosystem vulnerability assessment and synthesis: a report from the Climate Change Response Framework project in northern Wisconsin.** Gen. Tech. Rep. NRS-82. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 142 p.

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 www.nrs.fs.fed.us/pubs/40543. (Accessed April 11, 2014).

Tans, P.; Keeling, R. 2013. **Trends in atmospheric carbon dioxide.** Available http://www.esrl.noaa.gov/gmd/ccgg/trends/. (Accessed February 14, 2013).

Tepley, A.J.; Cohen, J.G.; Huberty, L. 2004. **Natural community abstract for floodplain forest.** Lansing, MI: Michigan Natural Features Inventory. 15 p. Available at http://mnfi.anr.msu.edu/abstracts/ecology/floodplain_forest.pdf. (Accessed April 10, 2014).

Tierney, G.; Fahey, T.; Groffman, P.; Hardy, J.; Fitzhugh, R.; Driscoll, C. 2001. **Soil freezing alters fine root dynamics in a northern hardwood forest.** Biogeochemistry. 56(2): 175-190.

Tilman, D. 1996. **Biodiversity: population versus ecosystem stability.** Ecology. 77(2): 350-363.

Tilman, D. 1999. **The ecological consequences of changes in biodiversity: a search for general principles.** Ecology. 80(5): 1455-1474.

Tomer, M.D.; Schilling, K.E. 2009. **A simple approach to distinguish land-use and climate-change effects on watershed hydrology.** Journal of Hydrology. 376(1-2): 24-33.

Trapp, R.J.; Diffenbaugh, N.S.; Brooks, H.E.; Baldwin, M.E.; Robinson, E.D.; Pal, J.S. 2007. **Changes in severe thunderstorm environment frequency during the 21st century caused by anthropogenically enhanced global radiative forcing.** Proceedings of the National Academy of Sciences of the United States of America. 104(50): 19719-19723.

Trapp, R.J.; Diffenbaugh, N.S.; Gluhovsky, A. 2009. **Transient response of severe thunderstorm forcing to elevated greenhouse gas concentrations.** Geophysical Research Letters. 36(1): L01703.

Trumpickas, J.; Shuter, B.J.; Minns, C.K. 2009. **Forecasting impacts of climate change on Great Lakes surface water temperatures.** Journal of Great Lakes Research. 35(3): 454-463.

Tu, M.; Callie, H.; Randall, J.M. 2001. **Weed control methods handbook: tools and techniques for use in natural areas.** Davis, CA: The Nature Conservancy, Wildland Invasive Species Team. Available at http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.114.2956&rep=rep1&type=pdf. (Accessed April 11, 2014).

U.S. Census Bureau. 2011. **2010 Demographic profile data.** Available at http://factfinder2.census.gov/faces/tableservices/jsf/pages/productview.xhtml?pid=DEC_10_DP_DPDP1&prodType=table. (Accessed April 11, 2014).

U.S. Environmental Projection Agency [EPA]. 2013. **Climate change indicators in the United States.** Available at http://www.epa.gov/climatechange/science/indicators/weather-climate/temperature.html. (Accessed September 12, 2013).

U.S. Forest Service. 2013. **FIA DataMart: FIADB Version 5.1.** Available at http://apps.fs.fed.us/fiadb-downloads/datamart.html. (Accessed April 11, 2014).

U.S. Forest Service. 2014. **Climate Change Atlas.** Available at http://www.fs.fed.us/nrs/atlas/. (Accessed April 11, 2014).

U.S. Geological Survey. 2011. **National Land Cover Dataset 2006 land cover.** Available at http://www.mrlc.gov/nlcd2006_downloads.php. (Accessed April 11, 2014).

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

Vavrus, S.; Walsh, J.; Chapman, W.; Portis, D. 2006. **The behavior of extreme cold air outbreaks under greenhouse warming.** International Journal of Climatology. 26(9): 1133-1147.

Venette, R.C.; Cohen, S.D. 2006. **Potential climatic suitability for establishment of *Phytophthora ramorum* within the contiguous United States.** Forest Ecology and Management. 231(1): 18-26.

Villarini, G.; Smith, J.A.; Baeck, M.L.; Krajewski, W.F. 2011. **Examining flood frequency distributions in the Midwest US.** JAWRA Journal of the American Water Resources Association. 47(3): 447-463.

Vose, J.M.; Peterson, D.L.; Patel-Weynand, T., eds. 2012. **Effects of climatic variability and change on forest ecosystems: a comprehensive science synthesis for the U.S.** Gen. Tech. Rep. PNW-GTR-870. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 265 p. Available at www.treesearch.fs.fed.us/pubs/42610. (Accessed April 14, 2014).

Waller, D.M. 2007. **White-tailed deer impacts in North America and the challenge of managing a hyperabundant herbivore.** In: Gaston, A.J.; Golumbia, T.E.; Martin, J.-L.; Sharpe, S.T., eds. Lessons from the Islands: introduced species and what they tell us about how ecosystems work. Proceedings from the Research Group on Introduced Species 2002 Symposium, Queen Charlotte City, Queen Charlotte Islands, BC. Special Publication. Ottawa, ON: Canadian Wildlife Service, Environment Canada: 135-147.

Waller, D.M.; Alverson, W.S. 1997. **The white-tailed deer: a keystone herbivore.** Wildlife Society Bulletin. 25(2): 217-226.

Walther, G.R.; Post, E.; Convey, P.; Menzel, A.; Parmesan, C.; Beebee, T.J.C.; Fromentin, J.M.; Hoegh-Guldberg, O.; Bairlein, F. 2002. **Ecological responses to recent climate change.** Nature. 416(6879): 389-395.

Wang, G.G.; Chhin, S.; Bauerle, W.L. 2006. **Effect of natural atmospheric CO_2 fertilization suggested by open-grown white spruce in a dry environment.** Global Change Biology. 12(3): 601-610.

Wang, J.; Bai, X.; Hu, H.; Clites, A.; Colton, M.; Lofgren, B. 2012. **Temporal and spatial variability of Great Lakes ice cover, 1973-2010.** Journal of Climate. 25(4): 1318-1329.

Washington, W.M.; Weatherly, J.W.; Meehl, G.A.; Semtner, A.J., Jr.; Bettge, T.W.; Craig, A.P.; Strand, W.G., Jr.; Arblaster, J.; Wayland, V.B.; James, R.; Zhang, Y. 2000. **Parallel climate model (PCM) control and transient simulations.** Climate Dynamics. 16(10): 755-774.

Weber, C.R.; Cohen, J.G.; Kost, M.A. 2006. **Abstract on the Aspen Association of northern Michigan.** Lansing, MI: Michigan Natural Features Inventory. 16 p. Available at http://mnfi.anr.msu.edu/reports/2006-16%20Aspen%20Abstract.pdf. (Accessed April 11, 2014).

Weber, C.R.; Cohen, J.G.; Kost, M.A. 2007. **Natural Community abstract for northern hardwood swamp.** Lansing, MI: Michigan Natural Features Inventory. 9 p. Available at http://mnfi.anr.msu.edu/abstracts/ecology/Northern_hardwood_swamp.pdf. (Accessed April 10, 2014).

Weed, A.S.; Ayres, M.P.; Hicke, J.A. 2013. **Consequences of climate change for biotic disturbances in North American forests.** Ecological Monographs. 83(4): 441-470.

White, M.A.; Host, G.E. 2008. **Forest disturbance frequency and patch structure from pre-European settlement to present in the Mixed Forest Province of Minnesota, USA.** Canadian Journal of Forest Research. 38(8): 2212-2226.

White, M.A.; Mladenoff, D.J. 1994. **Old-growth forest landscape transitions from pre-European settlement to present.** Landscape Ecology. 9(3): 191-205.

Wiens, J.A.; Stralberg, D.; Jongsomjit, D.; Howell, C.A.; Snyder, M.A. 2009. **Niches, models, and climate change: assessing the assumptions and uncertainties.** Proceedings of the National Academy of Sciences. 106(Supplement 2): 19729-19736.

Willging, R.C. 2008. **On the hunt: the history of deer hunting in Wisconsin.** Madison, WI: Wisconsin Historical Society Press: 320 p.

Williams, B.W.; Gilbert, J.H.; Zollner, P.A. 2007. **Historical perspective on the reintroduction of the fisher and American marten in Wisconsin and Michigan.** Gen. Tech. Rep. NRS-5. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 29 p. Available at http://purl.access.gpo.gov/GPO/LPS81521. (Accessed April 10, 2014).

Williams, J.W.; Blois, J.L.; Gill, J.L.; Gonzales, L.M.; Grimm, E.C.; Ordonez, A.; Shuman, B.; Veloz, S. 2013. **Model systems for a no-analog future: species associations and climates during the last deglaciation.** Annals of the New York Academy of Sciences. DOI: 10.1111/nyas.12226.

Williams, J.W.; Ordonez, A.; Notaro, M.; Veloz, S.; Vimont, D.J. 2012. **Climatic analogs, climate velocity, and potential shifts in vegetation structure and biomass for Wisconsin under 21st-century climate-change scenarios.** Madison, WI: Environmental and Economic Research and Development Program, Focus on Energy. 41 p. Available at http://www.geography.wisc.edu/faculty/williams/lab/pubs/WilliamsetalEERDFinalReport201206Final.pdf. (Accessed April 11, 2014).

Williams, J.W.; Shuman, B.N.; Webb, T., III; Bartlein, P.J.; Leduc, P.L. 2004. **Late Quaternary vegetation dynamics in North America: scaling from taxa to biomes.** Ecological Monographs. 74: 309-334.

Wilson, B.T.; Lister, A.J.; Riemann, R.I. 2012. **A nearest-neighbor imputation approach to mapping tree species over large areas using forest inventory plots and moderate resolution raster data.** Forest Ecology and Management. 271: 182-198.

Winkler, J.A.; Arritt, R.; Pryor, S. 2012. **Climate projections for the Midwest: availability, interpretation and synthesis.** In: Winkler, J.; Andresen, J.; Hatfield, J.; Bidwell, D.; Brown, D., coords. U.S. National Climate Assessment Midwest technical input report. Available at http://glisa.umich.edu/media/files/NCA/MTIT_Future.pdf. (Accessed April 11, 2014).

Wisconsin Council on Forestry. 2006. **Biennial report 2005-2006.** Available at http://www.wisconsinforestry.org/files/publications/CouncilFRBiennialRpt05-06.pdf. (Accessed April 11, 2014).

Wisconsin Department of Natural Resources [WDNR]. 1995. **Wisconsin's biodiversity as a management issue – a Report to Department of Natural Resources managers.** Available at http://dnr.wi.gov/files/pdf/pubs/rs/rs0915.pdf. (Accessed April 11, 2014).

Wisconsin Department of Natural Resources [WDNR]. 1998a. **Land cover data (WISCLAND).** Available at http://dnr.wi.gov/maps/gis/datalandcover.html. (Accessed April 10, 2014).

Wisconsin Department of Natural Resources [WDNR]. 1998b. **Wisconsin's deer management program: the issues involved in decision-making.** Available at http://dnr.wi.gov/org/land/wildlife/hunt/deer/Deerbook.pdf. (Accessed April 11, 2014).

Wisconsin Department of Natural Resources [WDNR]. 2003. **Managed forest law/tax crop law.** Available at ftp://dnrftp01.wi.gov/geodata/. (Accessed April 10, 2014).

Wisconsin Department of Natural Resources [WDNR]. 2004. **Garlic mustard.** Available at http://dnr.wi.gov/invasives/fact/garlic.htm. (Accessed April 10, 2014).

Wisconsin Department of Natural Resources [WDNR]. 2005. **Wisconsin's strategy for wildlife species of greatest conservation need.** Available at http://dnr.wi.gov/topic/WildlifeHabitat/documents/WWAP.pdf. (Accessed April 11, 2014).

Wisconsin Department of Natural Resources [WDNR]. 2006. **The 2005-2010 Wisconsin statewide comprehensive outdoor recreation plan.** Available at http://dnr.wi.gov/topic/parks/planning/scorp/scorp0510.html. (Accessed April 11, 2014).

Wisconsin Department of Natural Resources [WDNR]. 2007. **Forest health conditions of Wisconsin: annual report 2007.** Madison, WI: Division of Forestry, Wisconsin Forest Health Protection Program. Available at http://dnr.wi.gov/topic/ForestHealth/documents/AnnualReport2007.pdf. (Accessed April 11, 2014).

Wisconsin Department of Natural Resources [WDNR]. 2009a. **Ecological landscapes of Wisconsin, Northern Forest Communities.** 23 p. Available at http://www.dnr.state.wi.us/landscapes/pdfs/Nforests.pdf. (Accessed February 23, 2011).

Wisconsin Department of Natural Resources [WDNR]. 2009b. **Natural Communities of Wisconsin.** Available at http://dnr.wi.gov/topic/endangeredresources/communities.asp. (Accessed April 11, 2014).

Wisconsin Department of Natural Resources [WDNR]. 2011. **2011-2016 Wisconsin statewide comprehensive outdoor recreation plan.** Available at http://dnr.wi.gov/topic/parks/planning/scorp/. (Accessed April 11, 2014).

Wisconsin Department of Natural Resources [WDNR]. 2013. **Silviculture and forest aesthetics handbook 2431.5.** Available at http://dnr.wi.gov/topic/forestmanagement/silviculture.html. (Accessed April 11, 2014).

Wisconsin Department of Natural Resources [WDNR]. 2012. **Wisconsin's statewide forest assessment 2010.** Available at http://dnr.wi.gov/topic/ForestPlanning/assessment2010.html. (Accessed April 11, 2014).

Wisconsin Department of Revenue. 2009. **Summary of Wisconsin tax exemption devices.** Available at http://www.revenue.wi.gov/ra/09sumrpt.pdf. (Accessed April 10, 2014).

Wisconsin Initiative on Climate Change Impacts [WICCI]. 2011a. **Wildlife Working Group report.** Madison, WI: Nelson Institute for Environmental Studies, University of Wisconsin – Madison and the Wisconsin Department of Natural Resources. 52 p. Available at www.wicci.wisc.edu/report/Wildlife.pdf. (Accessed April 11, 2014).

Wisconsin Initiative on Climate Change Impacts [WICCI]. 2011b. **Wisconsin's changing climate: impacts and adaptation.** Madison, WI: Nelson Institute for Environmental Studies, University of Wisconsin – Madison and the Wisconsin Department of Natural Resources. Available at http://www.wicci.wisc.edu/report/2011_WICCI-Report.pdf. (Accessed April 11, 2014).

Wisconsin Initiative on Climate Change Impacts [WICCI]. 2013. **Climate Working Group - interactive mapping page.** Madison, WI: Nelson Institute for Environmental Studies, University of Wisconsin – Madison. Available at http://ccr.aos.wisc.edu/climate_modeling/Wisconsin_Climate/. (Accessed April 11, 2014).

Woodall, C.; Zhu, K.; Westfall, J.; Oswalt, C.; D'Amato, A.; Walters, B.; Lintz, H. 2013. **Assessing the stability of tree ranges and influence of disturbance in eastern US forests.** Forest Ecology and Management. 291: 172-180.

Woodall, C.J.; Nowak, D.J.; Liknes, G.C.; Westfall, J.A. 2010. **Assessing the potential for urban trees to facilitate forest tree migration in the eastern United States.** Forest Ecology and Management. 259: 1447-1454.

Woodall, C.W.; Oswalt, C.M.; Westfall, J.A.; Perry, C.H.; Nelson, M.D.; Finley, A.O. 2009. **An indicator of tree migration in forests of the eastern United States.** Forest Ecology and Management. 257(5): 1434-1444.

World Meteorological Organization [WMO]. 2008. **WMO statement on the status of the global climate in 2007.** Geneva, Switzerland. Available at http://www.wmo.int/pages/prog/wcp/wcdmp/documents/WMO1031_EN_web.pdf. (Accessed April 11, 2014).

Worrall, J.J.; Rehfeldt, G.E.; Hamann, A.; Hogg, E.H.; Marchetti, S.B.; Michaelian, M.; Gray, L.K. 2013. **Recent declines of *Populus tremuloides* in North America linked to climate.** Forest Ecology and Management. Advance Online Publication(0).

Woudenberg, S.W.; Conkling, B.L.; LaPoint, E.B.; Turner, J.A.; Waddell, K.L. 2010. **The Forest Inventory and Analysis database: database description and users manual Version 4.0 for Phase 2.** Gen. Tech. Rep. RMRS-GTR-245. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 336. Available at http://www.fia.fs.fed.us/library/database-documentation/. (Accessed April 11, 2014).

Wright, D.; Posselt, D.; Steiner, A. 2011. **Sensitivity of lake-enhanced snowfall to lake ice cover in the Great Lakes region.** AGU Fall Meeting Abstracts: 0959.

Wuebbles, D.; Hayhoe, K.; Cherkauer, K. 2009. **Climate change and the Upper Mississippi River Basin.** In: Criss, R.E.; Kusky, T.M., eds. Finding the balance between floods, flood protection, and river navigation. St. Louis, MO: Saint Louis University, Center for Environmental Sciences. Conference Proceedings: 47-54. Available at http://www.ces.slu.edu/annualreport/FloodForum_Book_final.pdf#page=51. (Accessed January 2, 2014).

Wuebbles, D.J.; Hayhoe, K. 2004. **Climate change projections for the United States Midwest.** Mitigation and Adaption Strategies for Global Change. 9: 335-363.

Wyckoff, P.H.; Bowers, R. 2010. **Response of the prairie-forest border to climate change: impacts of increasing drought may be mitigated by increasing CO_2.** Journal of Ecology. 98(1): 197-208.

Wydeven, A.P.; Wiedenhoeft, J.E.; Schultz, R.N.; Bruner, J.E.; Thiel, R.P.; Boles, S.R.; Windsor, M.A. 2011. **Status of the timber wolf in Wisconsin performance report: 1 July 2010-30 June 2011.** Madison, WI: Wisconsin Department of Natural Resources, Bureau of Endangered Resources. Available at http://dnr.wi.gov/topic/wildlifehabitat/wolf/documents/erreport143.pdf. (Accessed April 11, 2014).

Xu, C.; Gertner, G.Z.; Scheller, R.M. 2009. **Uncertainties in the response of a forest landscape to global climatic change.** Global Change Biology. 15(1): 116-131.

Zhu, K.; Woodall, C.W.; Clark, J.S. 2011. **Failure to migrate: lack of tree range expansion in response to climate change.** Global Change Biology. 18(3): 1042-1052.

A moose in spring in western Upper Michigan. Photo by Maria Janowiak, U.S. Forest Service.

APPENDIX 1: SPECIES LISTS

Table 14.—Common and scientific names of plant species mentioned in this assessment

Common Name	Scientific Name
American basswood	*Tilia americana*
American beech	*Fagus grandifolia*
American elm	*Ulmus americana*
American hornbeam	*Carpinus caroliniana*
American mountain-ash	*Sorbus americana*
balsam fir	*Abies balsamea*
balsam poplar	*Populus balsamifera*
bigtooth aspen	*Populus grandidentata*
bitternut hickory	*Carya cordiformis*
black ash	*Fraxinus nigra*
black cherry	*Prunus serotina*
black hickory	*Carya texana*
black locust	*Robinia pseudoacacia*
black oak	*Quercus velutina*
black spruce	*Picea mariana*
black walnut	*Juglans nigra*
black willow	*Salix nigra*
blackgum	*Nyssa sylvatica*
blackjack oak	*Quercus marilandica*
blue flag iris	*Iris versicolor*
boxelder	*Acer negundo*
bur oak	*Quercus macrocarpa*
butternut	*Juglans cinerea*
chestnut oak	*Quercus prinus*
chinquapin oak	*Quercus muehlenbergii*
chokecherry	*Prunus virginiana*
eastern cottonwood	*Populus deltoides*
eastern hemlock	*Tsuga canadensis*
eastern hophornbeam (ironwood)	*Ostrya virginiana*
eastern redbud	*Cercis canadensis*
eastern white pine	*Pinus strobus*
European buckthorn	*Rhamnus cathartica*
flowering dogwood	*Cornus florida*
garlic mustard	*Alliaria petiolata*
goblin fern	*Botrychium mormo*
green ash	*Fraxinus pennsylvanica*
hackberry	*Celtis occidentalis*
jack pine	*Pinus banksiana*
Japanese barberry	*Berberis thunbergii*
large-flowered trillium	*Trillium grandiflorum*
mockernut hickory	*Carya tomentosa*
mountain maple	*Acer spicatum*
northern catalpa	*Catalpa speciosa*
northern pin oak	*Quercus ellipsoidalis*
northern red oak	*Quercus rubra*
northern white-cedar	*Thuja occidentalis*
Ohio buckeye	*Aesculus glabra*
paper birch	*Betula papyrifera*
peachleaf willow	*Salix amygdaloides*
Pennsylvania sedge	*Carex pensylvanica*
pignut hickory	*Carya glabra*
pin cherry	*Prunus pensylvanica*
pin oak	*Quercus palustris*
pink lady slipper	*Cypripedium acaule*
post oak	*Quercus stellata*
quaking aspen	*Populus tremuloides*
red maple	*Acer rubrum*
red mulberry	*Morus rubra*
red pine	*Pinus resinosa*
reed canarygrass	*Phalaris arundinacea*
river birch	*Betula nigra*
rock elm	*Ulmus thomasii*
sassafras	*Sassafras albidum*
scarlet oak	*Quercus coccinea*
sensitive fern	*Onoclea sensibilis*

(Continued on next page)

Table 14 (continued).—Common and scientific names of plant species mentioned in this assessment

Common Name	Scientific Name
shagbark hickory	*Carya ovata*
shingle oak	*Quercus imbricaria*
silver maple	*Acer saccharinum*
slippery elm	*Ulmus rubra*
sphagnum moss	*Sphagnum* spp.
striped maple	*Acer pensylvanicum*
sugar maple	*Acer saccharum*
sugarberry	*Celtis laevigata*
swamp white oak	*Quercus bicolor*
sweetgum	*Liquidambar styraciflua*
tamarack	*Larix laricina*
white ash	*Fraxinus americana*
white oak	*Quercus alba*
white spruce	*Picea glauca*
wild rice	*Zizania palustris*
yellow birch	*Betula alleghaniensis*

Table 15.—Common and scientific names of other species mentioned in this assessment

Common Name	Scientific Name
American marten	*Martes americana*
American woodcock	*Scolopax minor*
Armillaria	*Armillaria mellea*
bark beetles	*Ips* spp. and *Dendroctonus* spp.
beaver	*Castor canadensis*
birch leaf miner	*Fenusa pusilla*
blacklegged tick	*Ixodes scapularis*
Blanding's turtle	*Emys blandingii*
brook trout	*Salvelinus fontinalis*
cisco	*Coregonus artedi*
common loon	*Gavia immer*
earthworms (nonnative)	*Dendrobaena octaedra, Lumbricus rubellus,* and *L. terrestris*
eastern larch beetle	*Dendroctonus simplex*
emerald ash borer	*Agrilus planipennis*
forest tent caterpillar	*Malacosoma disstria*
fox snake	*Elaphe* spp.
Franklin's ground squirrel	*Spermophilus franklinii*
golden-winged warbler	*Vermivora chrysoptera*
gray jay	*Perisoreus canadensis*
gray wolf	*Canis lupus*
green frog	*Lithobates clamitans*
gypsy moth	*Lymantria dispar dispar*
hermit thrush	*Catharus guttatus*
hypoxylon canker	*Hypoxylon mammatum*
jack pine budworm	*Choristoneura pinus pinus*
larch casebearer	*Coleophora laricella*
Lyme disease	*Borrelia burgdorferi*
moose	*Alces alces*
morel mushroom	*Morchella* spp.
porcupine	*Erethizon dorsatum*
river jewelwing damselfly	*Calopteryx aequibilis*
smooth green snake	*Liochlorophis vernalis*
snowshoe hare	*Lepus americanus*
spruce budworm	*Choristoneura fumiferana*
sudden oak death	*Phytophthora ramorum*
tamarack sawfly	*Pristiophora erichsonii*
West Nile virus	*Flavivirus* spp.
white pine blister rust	*Cronartium ribicola*
white pine tip weevil	*Pissodes strobi*
white-tailed deer	*Odocoileus virginianus*
wild turkey	*Meleagris gallopavo*
wood frog	*Lithobates sylvaticus*
wood turtle	*Glyptemys insculpta*

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 application (www.climatewizardcustom.org) (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. The PRISM model 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/.

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 16).

The developers of the ClimateWizard application advise users to interpret the linear trend maps in relation to the respective map of statistical confidence (Figs. 50 and 51). In this case, statistical confidence is described 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.

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

Table 16.—Mean annual, seasonal, and monthly values and linear trend analysis for selected climate variables from 1901 through 2011 for the assessment area*

Month/ Season	Mean temperature 1900-2011 Mean (°F)	Mean temperature 1900-2011 Change (°F)	Mean temperature Change *p*-value	Minimum temperature 1900-2011 Mean (°F)	Minimum temperature 1900-2011 Change (°F)	Minimum temperature Change *p*-value	Maximum temperature 1900-2011 Mean (°F)	Maximum temperature 1900-2011 Change (°F)	Maximum temperature Change *p*-value	Precipitation 1900-2011 Mean (inches)	Precipitation 1900-2011 Change (inches)	Precipitation Change *p*-value
January	12.33	0.97	0.57	2.42	2.05	0.28	22.23	-0.11	0.94	1.25	0.19	0.44
February	15.31	**4.57**	**0.01**	4.33	**5.21**	**0.01**	26.28	**3.93**	**0.01**	1.07	-0.16	0.34
March	26.52	2.09	0.15	15.64	**2.37**	**0.10**	37.38	1.82	0.24	1.70	0.26	0.29
April	40.88	2.03	0.07	29.26	**2.37**	**0.01**	52.50	1.68	0.23	2.42	0.51	0.12
May	52.84	**1.77**	**0.08**	40.08	**2.43**	**0.01**	65.61	1.12	0.34	3.38	-0.18	0.63
June	62.25	0.87	0.40	49.86	**2.04**	**0.03**	74.65	-0.31	0.81	4.00	-0.20	0.72
July	67.27	0.52	0.49	55.01	**1.78**	**0.00**	79.54	-0.74	0.44	3.71	0.03	0.94
August	65.08	**1.91**	**0.02**	53.10	**3.14**	**0.00**	77.06	0.68	0.47	3.67	0.42	0.31
September	56.95	0.13	0.88	45.48	1.10	0.18	68.44	-0.84	0.41	3.64	0.01	0.99
October	45.89	-0.36	0.73	35.21	0.56	0.55	56.57	-1.28	0.32	2.57	0.68	0.11
November	31.38	0.99	0.41	23.14	1.67	0.15	39.62	0.30	0.82	2.04	0.11	0.72
December	18.01	0.92	0.52	9.46	1.74	0.29	26.55	0.10	0.94	1.41	**0.34**	**0.08**
Winter	15.22	**2.17**	**0.06**	5.41	**3.02**	**0.02**	25.02	1.32	0.19	1.24	0.12	0.35
Spring	40.07	**1.95**	**0.02**	28.33	**2.38**	**0.00**	51.83	1.51	0.12	2.50	0.20	0.32
Summer	64.86	**1.11**	**0.06**	52.65	**2.33**	**0.00**	77.08	-0.12	0.88	3.79	0.08	0.76
Fall	44.73	0.26	0.70	34.61	**1.11**	**0.08**	54.87	-0.60	0.43	2.75	0.27	0.27
Annual	41.22	**1.37**	**0.01**	30.25	**2.21**	**0.00**	52.20	0.53	0.33	30.87	2.00	0.12

**P*-values represent the probability of observing that trend by chance alone. Boldface *p*-values indicate a 10-percent probability (or less) that the trend was due to chance alone. Data source: ClimateWizard (2012).

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 (www.ncdc.noaa.gov/).

We selected the 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.

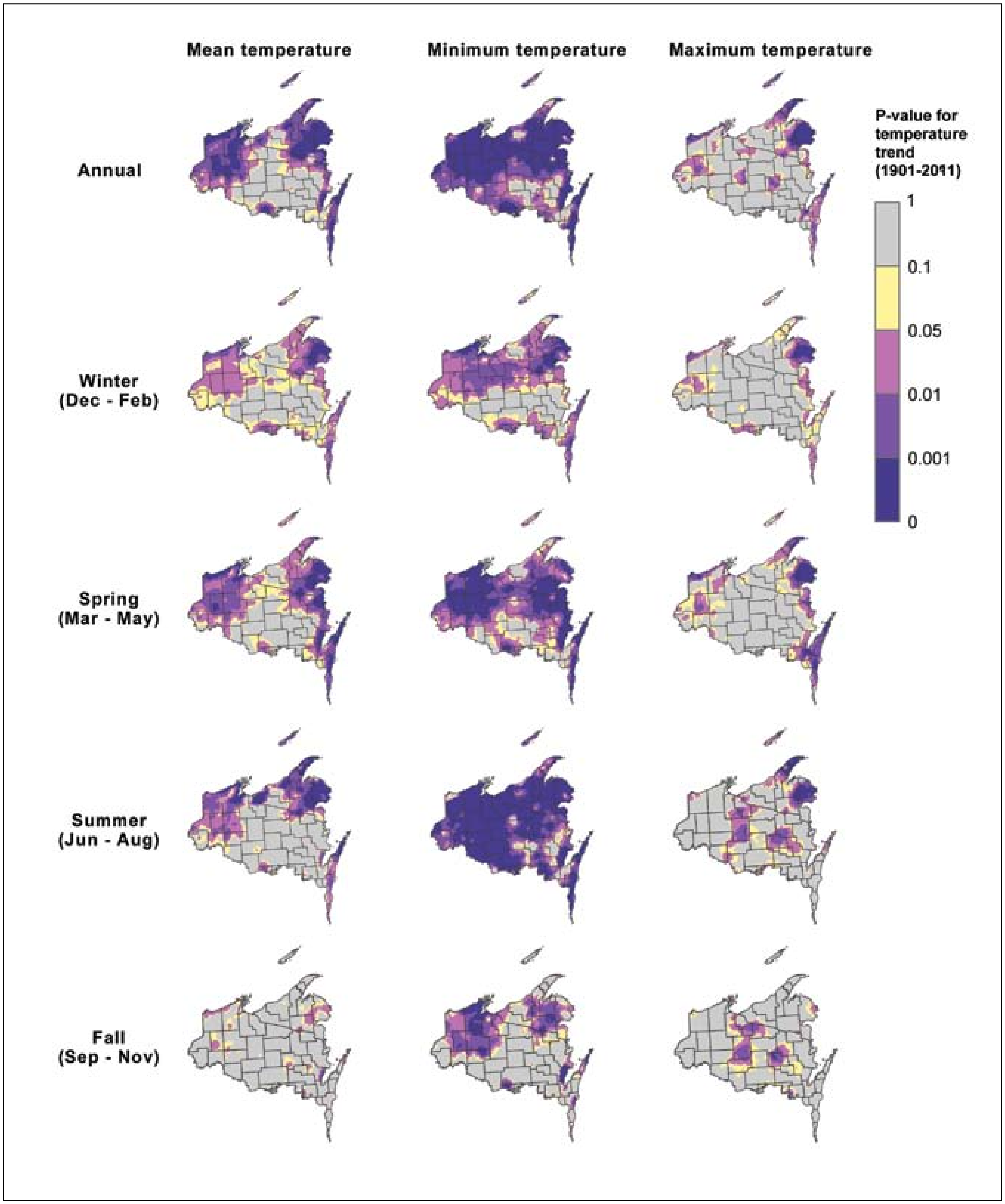


Figure 50.—Statistical confidence (p-values for the linear regression) for trends in temperature from 1901 through 2011. Gray values represent areas of low statistical confidence. Data source: ClimateWizard (2012).

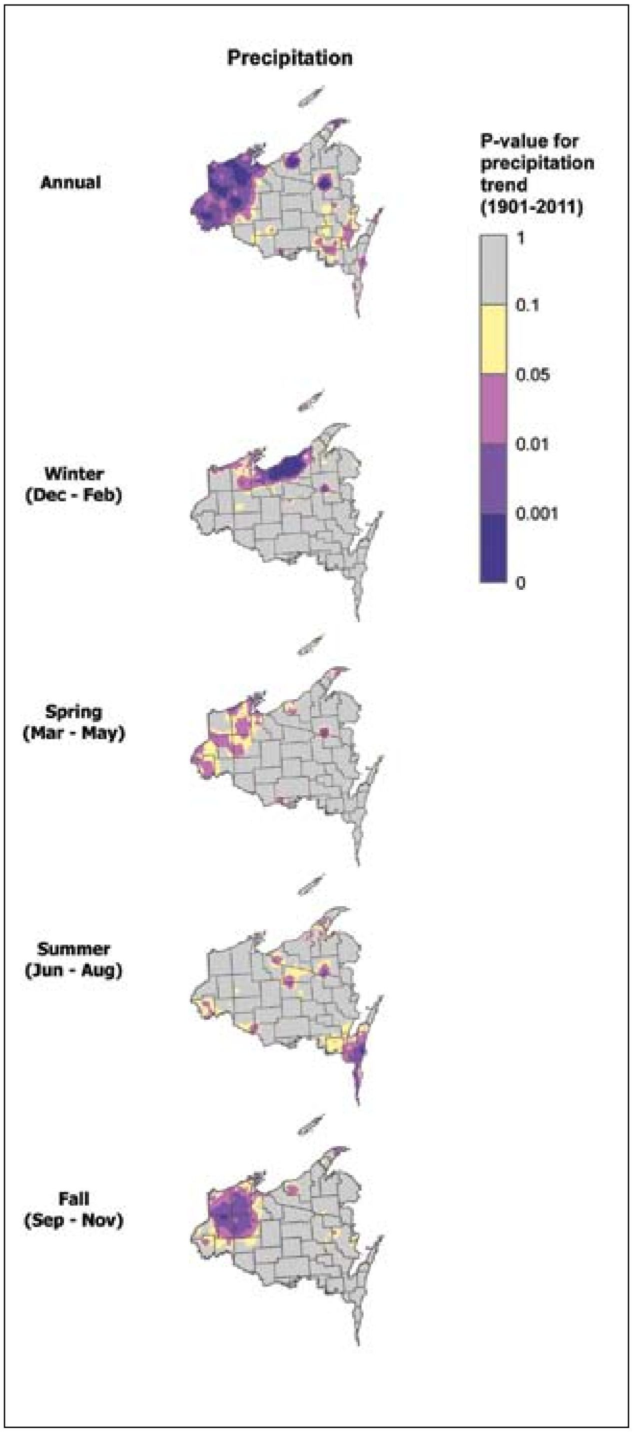


Figure 51.—Statistical confidence (*p*-values for the linear regression) for trends in precipitation from 1901 through 2011. Gray values represent areas of low statistical confidence. Data source: ClimateWizard (2012).

LITERATURE CITED

ClimateWizard. 2012. **ClimateWizard Custom Analysis.** The Nature Conservancy, University of Washington, University of Southern Mississippi, Climate Central, and Santa Clara University. Available at http://climatewizardcustom.org/. (Accessed April 2, 2012).

Gibson, W.P.; Daly, C.; Kittel, T.; Nychka, D.; Johns, C.; Rosenbloom, N.; McNab, A.; Taylor, G. 2002. **Development of a 103-year high-resolution climate data set for the conterminous United States.** Proceedings of the 13th American Meteorological Society Conference on Applied Climatology: 181-183.

Girvetz, E.H.; Zganjar, C.; Raber, G.T.; Maurer, E.P.; Kareiva, P.; Lawler, J.J. 2009. **Applied climate-change analysis: the ClimateWizard tool.** PLoS ONE. 4(12): e8320.

Kunkel, K.E.; Stevens, L.E.; Stevens, S.E.; Sun, L.; Janssen, E.; Wuebbles, D.; Hilberg, S.D.; Timlin, M.S.; Stoeck, L.; Westcott, N.E.; Dobson, J.G. 2013. **Regional climate trends and scenarios for the U.S. National Climate Assessment. Part 3. Climate of the Midwest U.S.** Washington, DC: U.S. Department of Commerce, National Oceanic and Atmospheric Administration. 103 p.

Trenberth, K.E.; Jones, P.D.; Ambenje, P.; Bojariu, R.; Easterling, D.; Klein Tank, A.; Parker, D.; Rahimzadeh, F.; Renwick, J.A.; Rusticucci, M.; Soden, B.; Zhai, P. 2007. **Observations: surface and atmospheric climate change.** In: Solomon, S.; Qin, D.; Manning, M.; Chen, Z.; Marquis, M.; Averyt, K.B.; Tignor, M.; Miller, H.L., eds. Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, NY: Cambridge University Press. Available at https://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch3.html. (Accessed April 17, 2014).

APPENDIX 3: ADDITIONAL FUTURE CLIMATE INFORMATION

This appendix provides maps of projected change for the early (2010 through 2039) and middle (2040 through 2069) years of the 21st century as supplementary information to Chapter 4.

Table 17.—Projected change in mean average, minimum, and maximum temperatures under two future climate scenarios for the assessment area over the next century

	1971-2000 Temperature (°F)	Temperature departure from 1971-2000 (°F)			
		Scenario	2010-2039	2040-2069	2070-2099
Mean temperature					
Annual	41.4	PCM B1	1.2	1.9	2.6
		GFDL A1FI	2.3	6.6	8.7
Winter (Dec.-Feb.)	15.3	PCM B1	1.2	2.4	3.2
		GFDL A1FI	2.7	7.5	8.7
Spring (Mar.-May)	40.9	PCM B1	0.0	1.1	2.0
		GFDL A1FI	0.6	4.2	6.0
Summer (June-Aug.)	65.0	PCM B1	1.5	1.9	2.4
		GFDL A1FI	3.5	8.9	11.6
Fall (Sept.-Nov.)	44.1	PCM B1	2.5	2.4	3.2
		GFDL A1FI	2.8	6.0	8.5
Minimum temperature					
Annual	30.5	PCM B1	1.2	1.9	2.7
		GFDL A1FI	2.6	7.2	9.7
Winter (Dec.-Feb.)	5.4	PCM B1	1.4	3.0	4.1
		GFDL A1FI	3.3	9.1	10.9
Spring (Mar.-May)	29.1	PCM B1	0.3	1.3	2.3
		GFDL A1FI	1.6	5.6	7.9
Summer (June-Aug.)	53.1	PCM B1	0.7	1.3	1.6
		GFDL A1FI	3.3	8.5	11.5
Fall (Sept.-Nov.)	34.2	PCM B1	2.7	2.3	3.2
		GFDL A1FI	2.7	5.8	8.8
Maximum temperature					
Annual	52.3	PCM B1	1.2	1.8	2.4
		GFDL A1FI	1.9	6.0	7.5
Winter (Dec.-Feb.)	25.1	PCM B1	1.0	1.8	2.1
		GFDL A1FI	2.1	5.9	6.6
Spring (Mar.-May)	52.6	PCM B1	-0.4	0.9	1.6
		GFDL A1FI	-0.4	2.7	4.0
Summer (June-Aug.)	76.9	PCM B1	2.2	2.5	3.0
		GFDL A1FI	3.7	9.4	11.6
Fall (Sept.-Nov.)	54.1	PCM B1	2.4	2.4	3.1
		GFDL A1FI	2.8	6.3	8.2

Table 18.—Projected change in precipitation under two future climate scenarios for the assessment area over the next century

	1971-2000 precipitation (inches)	Precipitation departure from 1971-2000 (inches)			
		Scenario	2010-2039	2040-2069	2070-2099
Annual	32.0	PCM B1	0.2	2.7	2.7
		GFDL A1FI	2.3	-1.6	0.5
Winter (Dec.-Feb.)	3.8	PCM B1	0.7	0.9	1.1
		GFDL A1FI	0.4	0.3	0.6
Spring (Mar.-May)	7.5	PCM B1	-0.1	1.1	1.5
		GFDL A1FI	1.5	2.1	3.2
Summer (June-Aug.)	11.8	PCM B1	-0.1	1.1	0.4
		GFDL A1FI	0.2	-3.8	-4.8
Fall (Sept.-Nov.)	8.8	PCM B1	-0.2	-0.4	-0.3
		GFDL A1FI	0.2	-0.2	1.6

An informational sign in western Upper Michigan. Photo by Maria Janowiak, U.S. Forest Service.

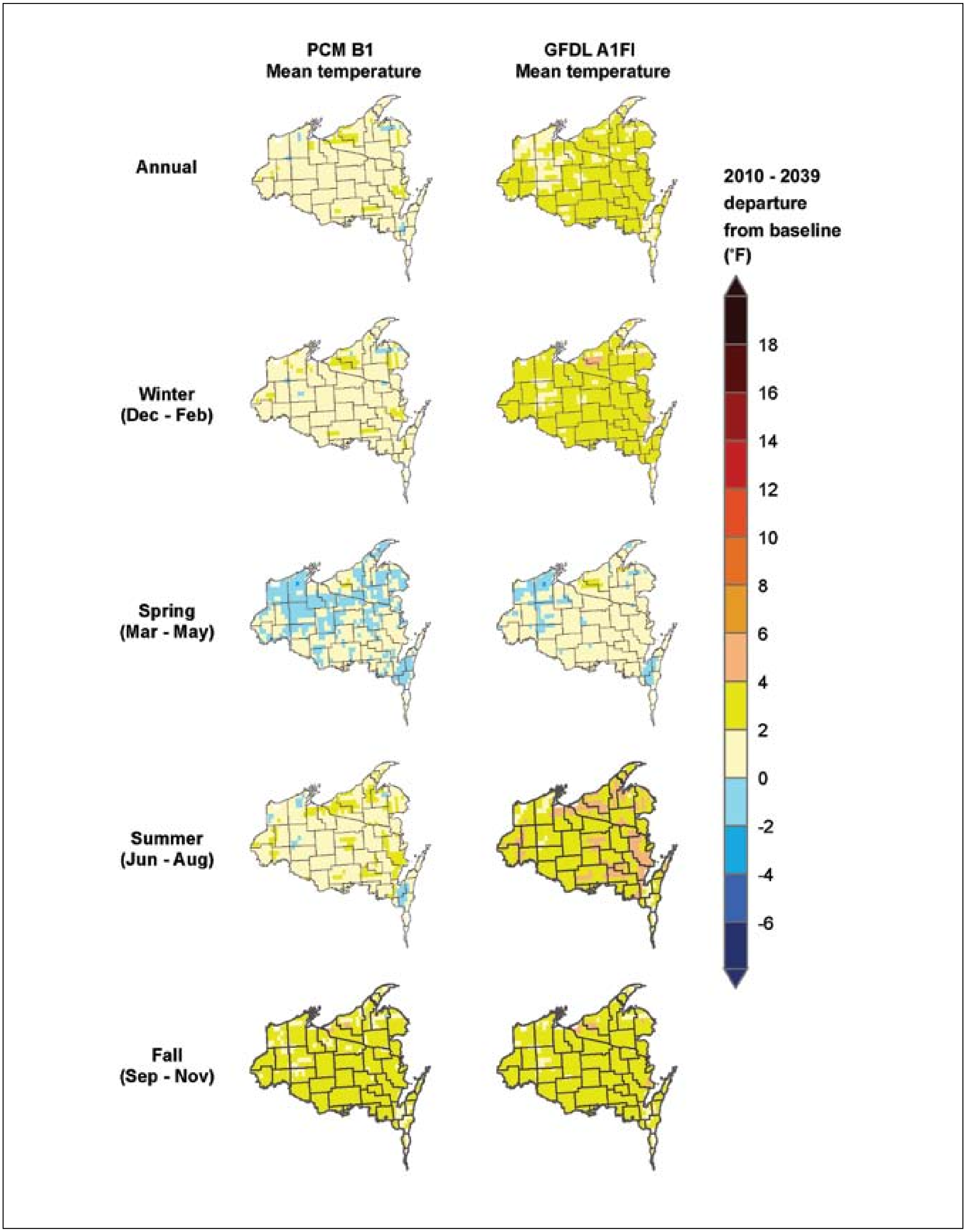


Figure 52.—Projected difference in mean daily temperature at the beginning of the century (2010 through 2039) compared to baseline (1971 through 2000) for two climate scenarios.

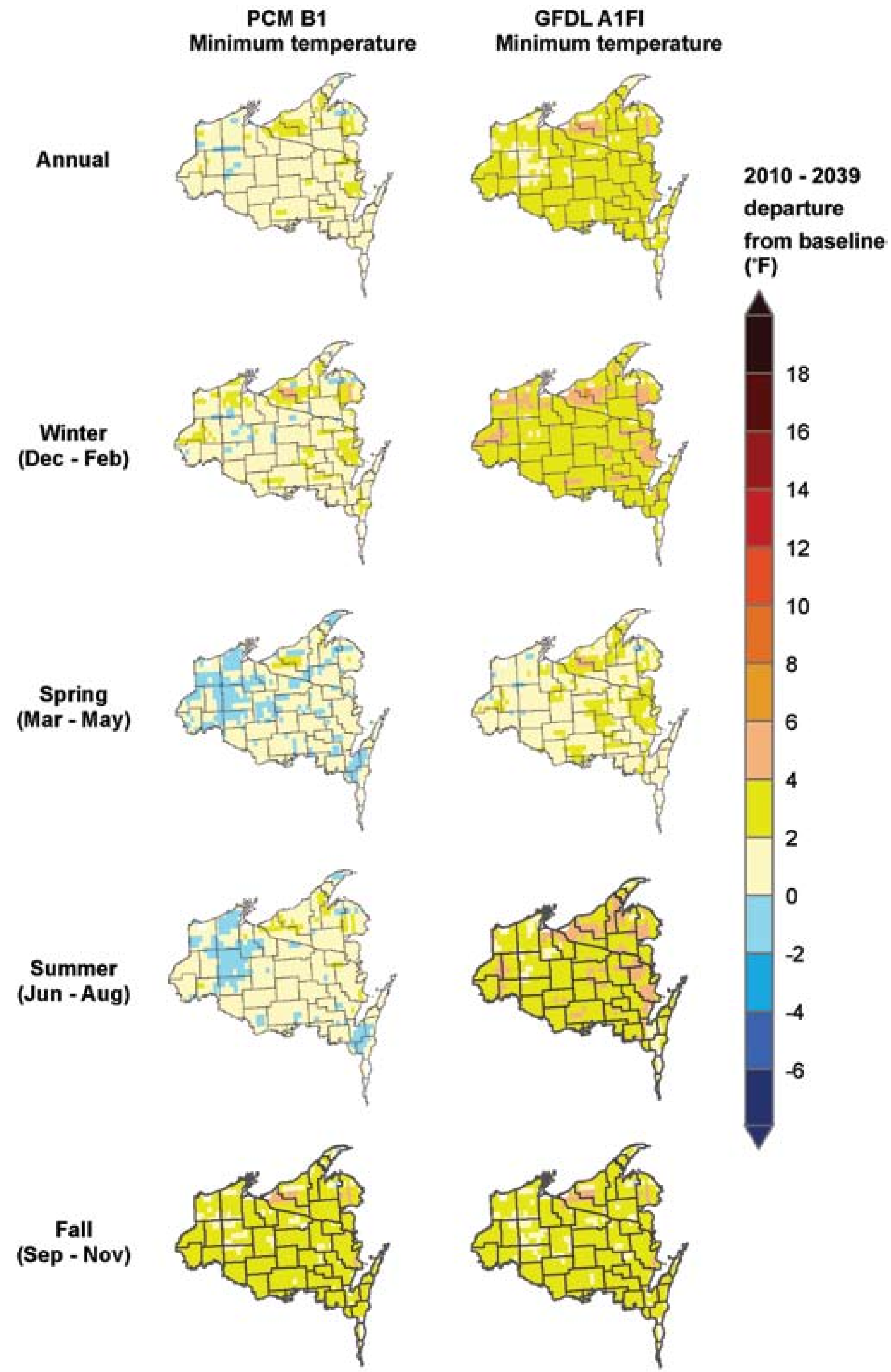


Figure 53.—Projected difference in mean minimum daily temperature at the beginning of the century (2010 through 2039) compared to baseline (1971 through 2000) for two climate scenarios.

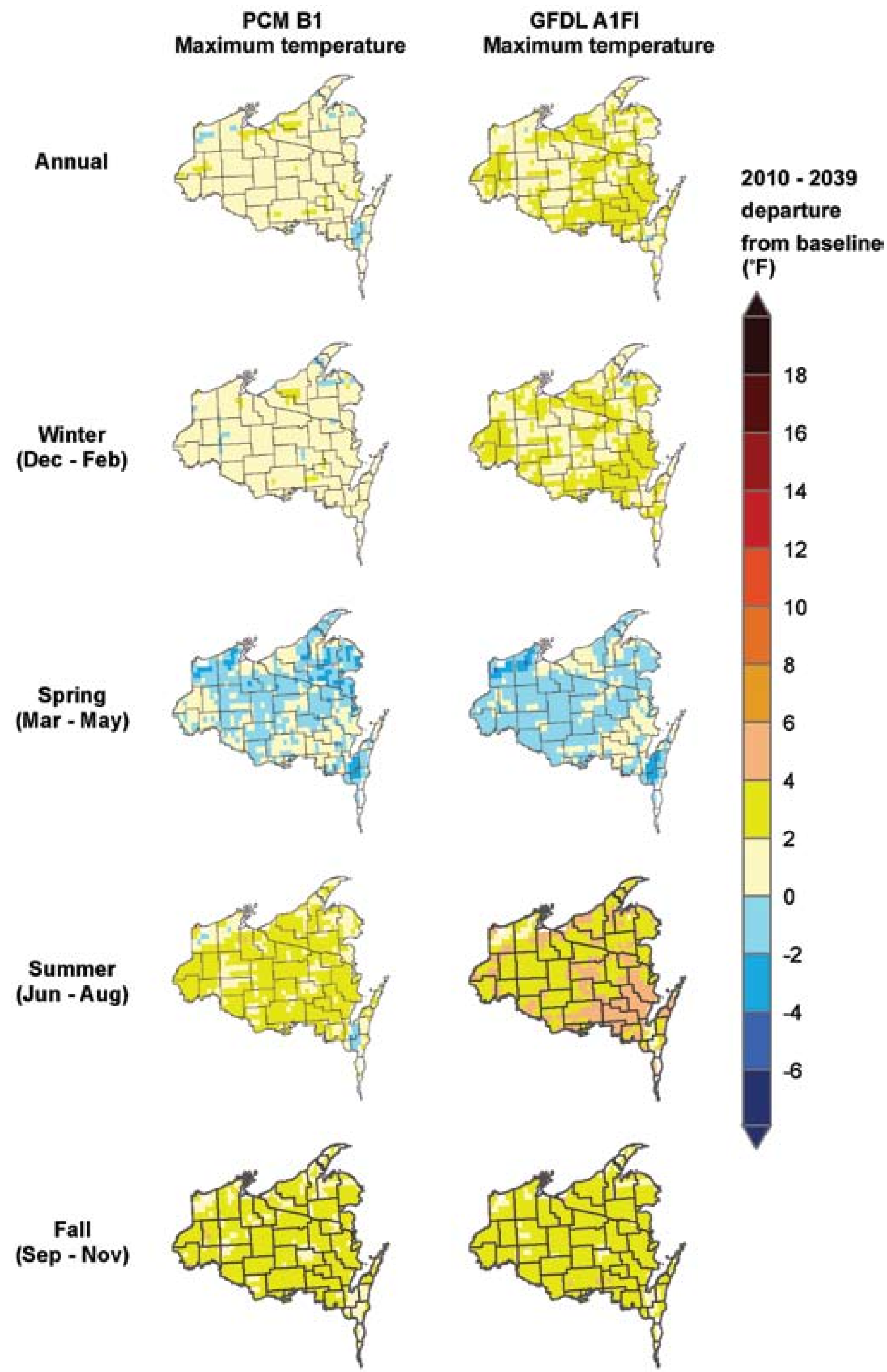


Figure 54.—Projected difference in mean maximum daily temperature at the beginning of the century (2010 through 2039) compared to baseline (1971 through 2000) for two climate scenarios.

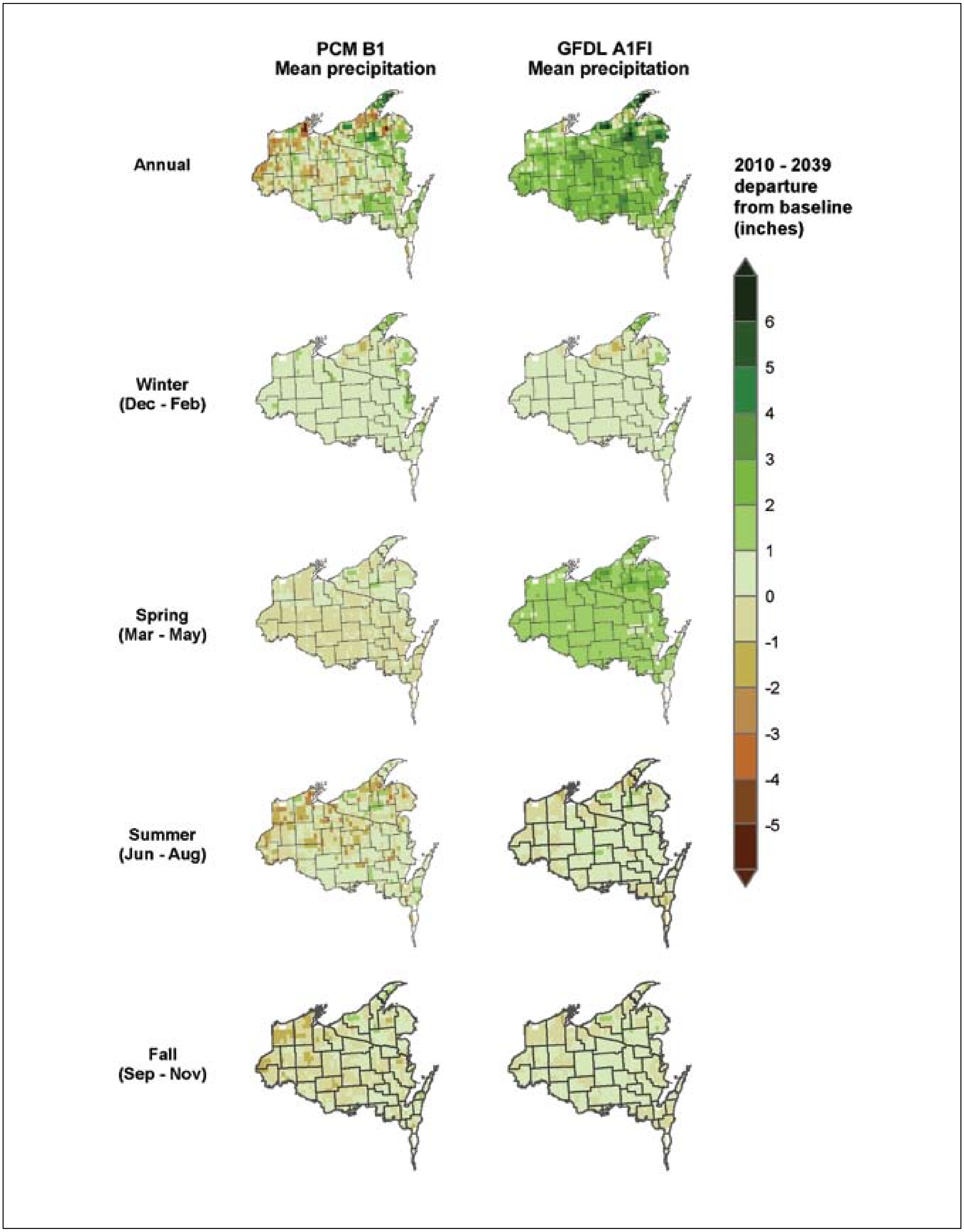


Figure 55.—Projected difference in precipitation at the beginning of the century (2010 through 2039) compared to baseline (1971 through 2000) for two climate scenarios.

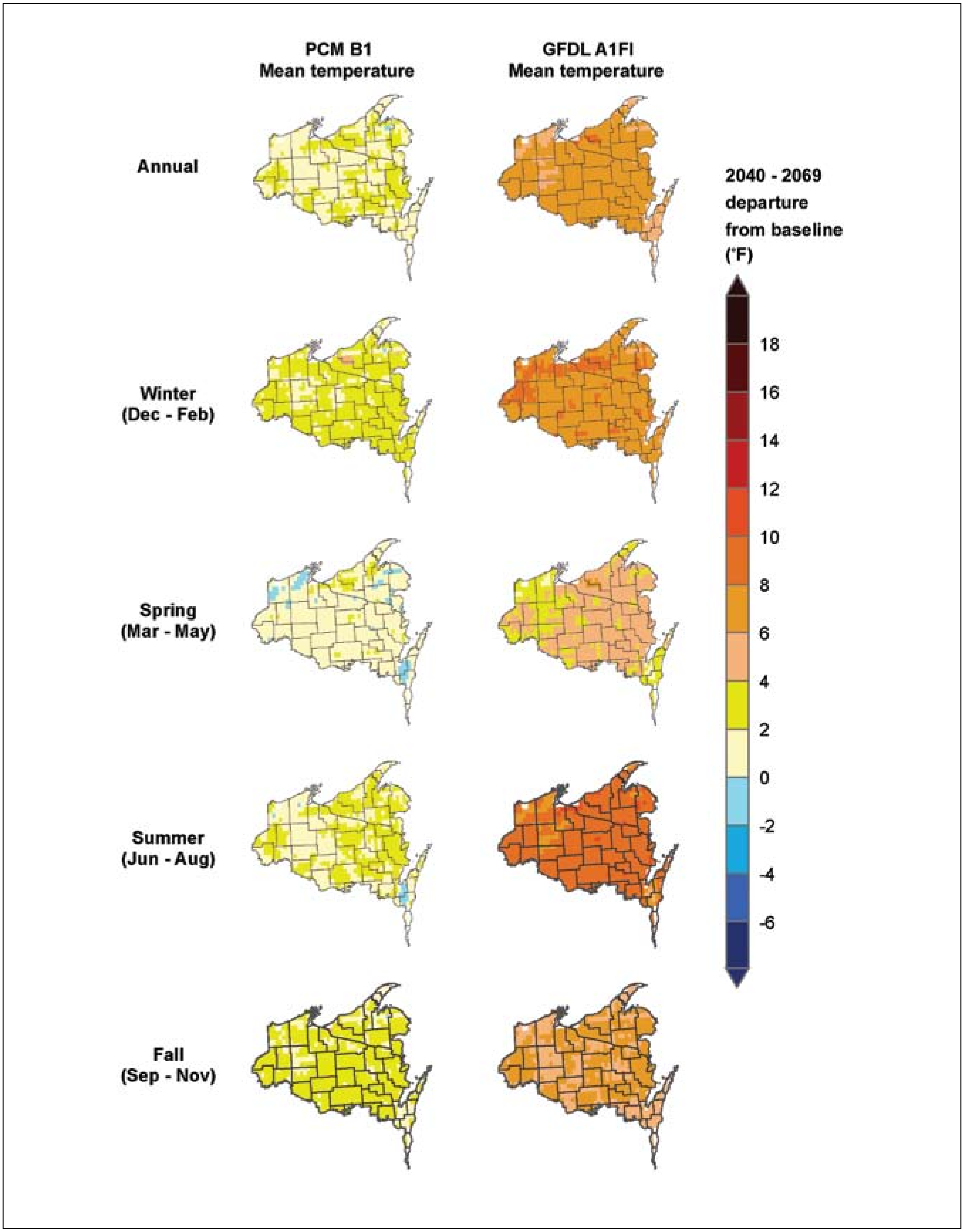


Figure 56.—Projected difference in mean daily temperature for the middle of the century (2040 through 2069) compared to baseline (1971 through 2000) for two climate scenarios.

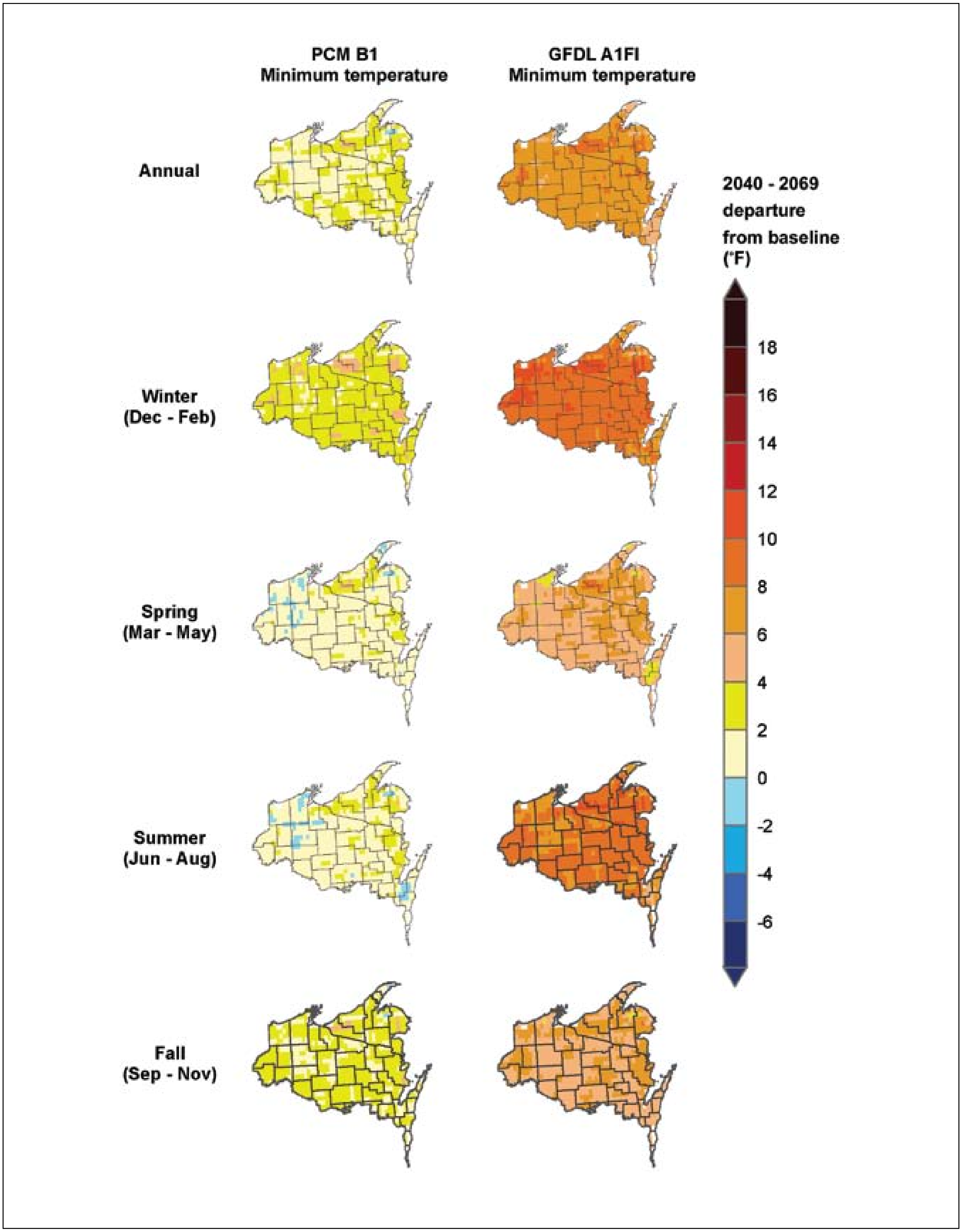


Figure 57.—Projected difference in mean minimum daily temperature for the middle of the century (2040 through 2069) compared to baseline (1971 through 2000) for two climate scenarios.

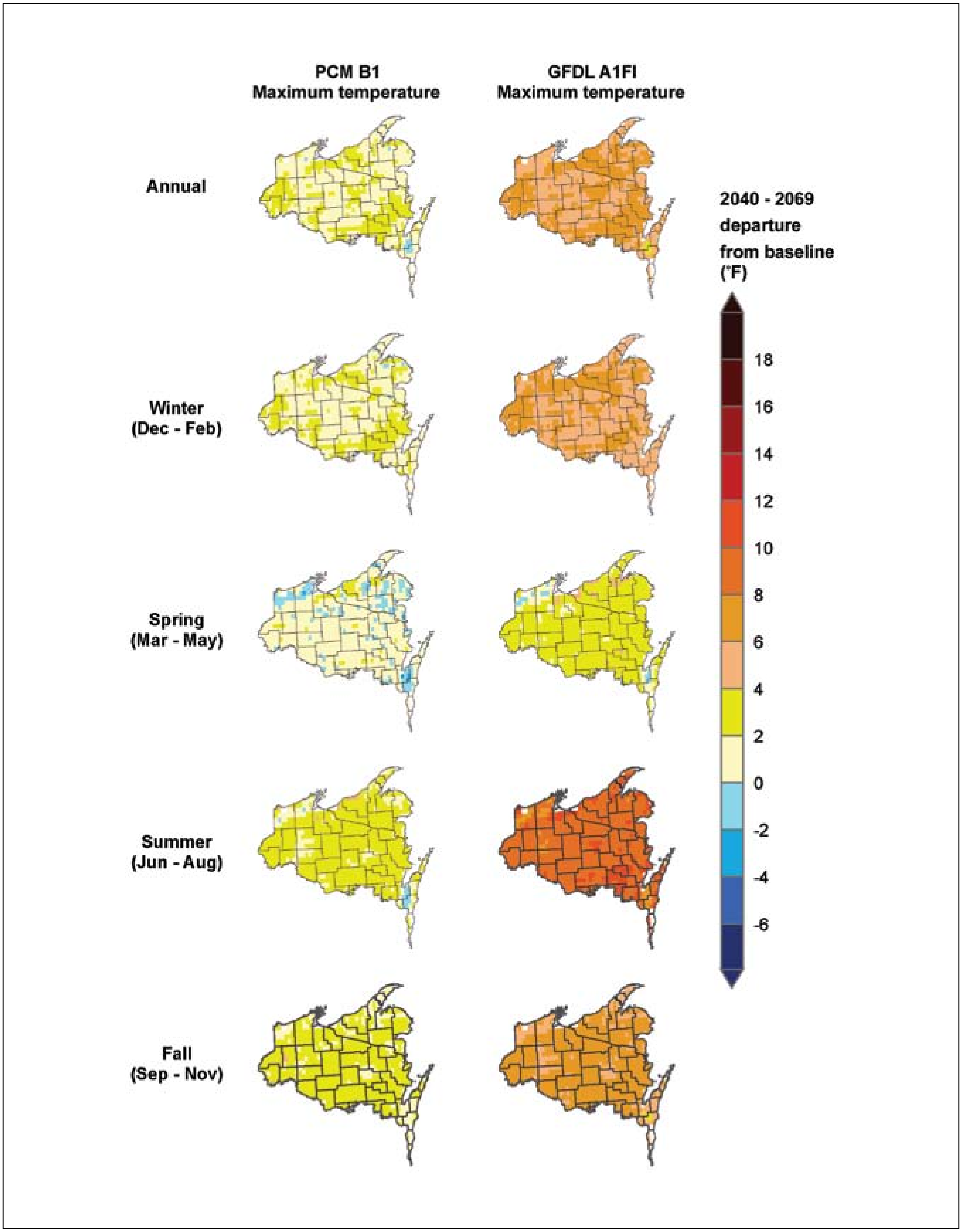


Figure 58.—Projected difference in mean maximum daily temperature for the middle of the century (2040 through 2069) compared to baseline (1971 through 2000) for two climate scenarios.

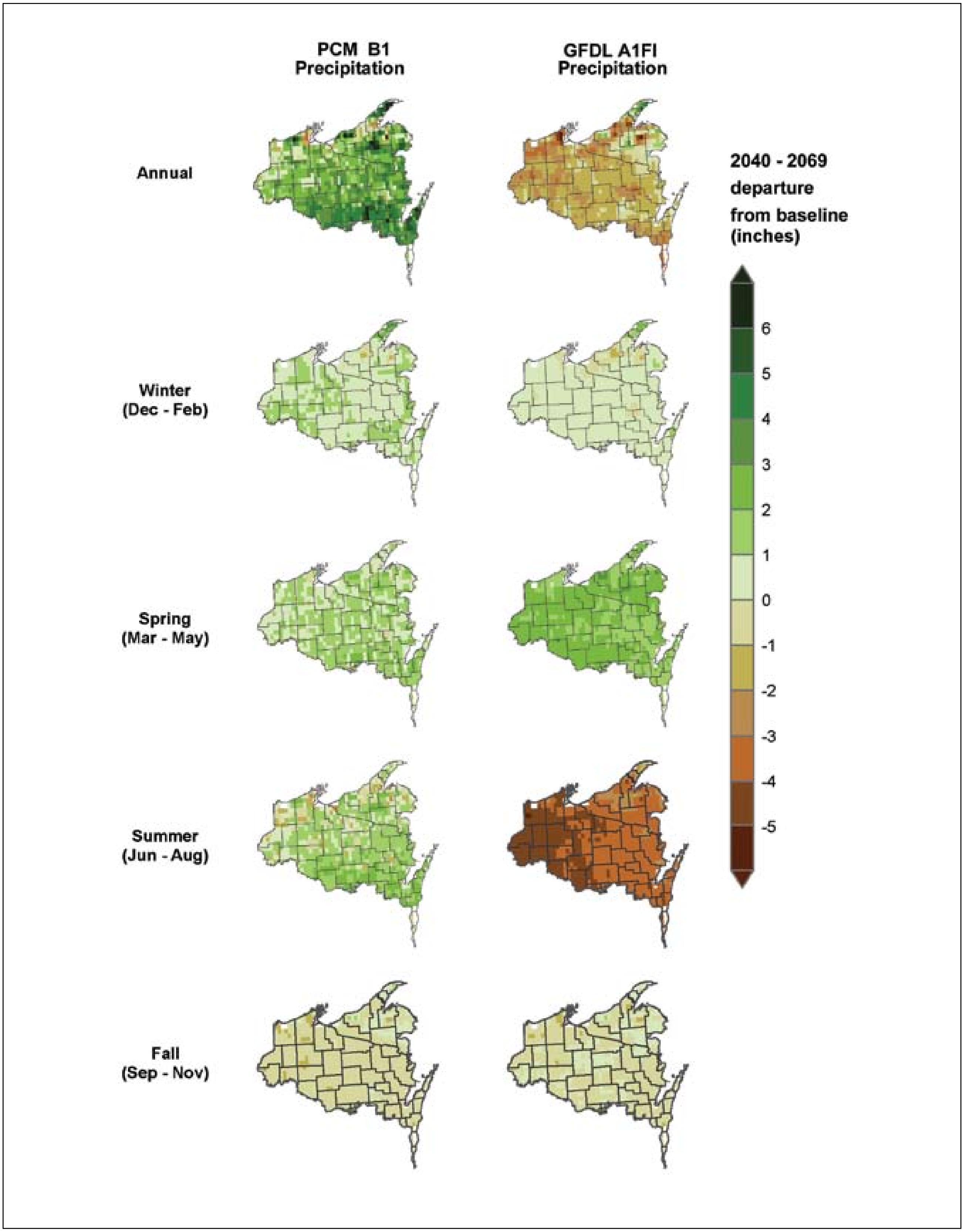


Figure 59.—Projected difference in precipitation for the middle of the century (2040 through 2069) compared to baseline (1971 through 2000) for two climate scenarios.

APPENDIX 4: SUPPLEMENTARY MODEL RESULTS – TREE ATLAS

This appendix contains additional model details and results from the Climate Change Tree Atlas.

RESULTS OF THE DISTRIB MODEL

Table 19 provides additional outputs from the DISTRIB model for the 78 species considered for this assessment. More information about the modeling approach is available online through the Climate Change Tree Atlas Web site (www.nrs.fs.fed.us/atlas/tree/tree_atlas.html), including detailed methods, maps of changes in importance value, 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).

For this assessment, current area-weighted importance values (IVs) were derived from Forest Inventory and Analysis (FIA) data. Using the DISTRIB model, these were used to develop modeled current (1961-1990) IVs, as well as future IVs for three time periods (2010 through 2039, 2040 through 2069, 2070 through 2099) under the PCM B1 and GFDL A1FI climate scenarios. Across the eastern United States, 134 tree species were initially modeled. If a species never had an area-weighted IV greater than 3 (FIA, current modeled, or future) across the assessment area, it was deleted from the list because the species has either no current or no future suitable habitat in the region, or there were not enough data. This step resulted in the list of 78 tree species for which data are 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 following rules applied, based on the ratio of future IVs to current modeled IVs:

Future:Current modeled IV	Class
<0.5	large decrease
0.5 to 0.8	small decrease
>0.8 to <1.2	no change
1.2 to 2.0	small increase
>2	large increase

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. A species was considered rare if it had a 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. The change classes are calculated differently for these species because their current infrequency tends to inflate the projected percentage change. The cutoff for the assessment area was 27 pixels, or 10 percent of the total 274 pixels.

When a species was below the cutoff above, the following rules applied:

Future:Current modeled IV	Class
<0.2	large decrease
0.2 to <0.6	small decrease
0.6 to <4	no change
4 to 8	small increase
>8	large increase (not used when current modeled IV ≤3)

"Extirpated" was not used in this case because of low confidence.

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.

Modifying Factors and Adaptability Scores

Tables 20 and 21 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 the DISTRIB model (Matthews et al. 2011). This approach was used to assess the capacity for each species to adapt and considered nine biological traits reflecting innate characteristics like competition ability for light and edaphic specificity. Twelve disturbance characteristics addressed the general response of a species to events such as drought, insect pests, and fire. This information distinguishes 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. 60). For this assessment, adaptability scores 3.2 and less are considered low, and scores of 5.3 and greater 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 19.—Complete Tree Atlas results for the 78 tree species in the assessment area

				DISTRIB results*													
				Modeled IV						Future:Current Suitable Habitat						Change Class 2070-2099	
				2010-2039		2040-2069		2070-2099		2010-2039		2040-2069		2070-2099			
Common Name	FIA 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
American basswood	885	880	Medium	875	1189	950	1246	931	1219	0.99	1.35	1.08	1.42	1.06	1.39	No change	Increase
American beech	108	167	High	190	328	358	362	358	321	1.14	1.96	2.14	2.17	2.14	1.92	Large increase	Increase
American elm	922	950	Medium	1021	1522	1348	2179	1349	2313	1.08	1.60	1.42	2.29	1.42	2.44	Increase	Large increase
American hornbeam	153	138	Medium	150	224	193	294	191	288	1.09	1.62	1.40	2.13	1.38	2.09	Increase	Large increase
Balsam fir	1649	1682	High	1265	434	990	200	837	186	0.75	0.26	0.59	0.12	0.50	0.11	Decrease	Large decrease
Balsam poplar	155	191	High	144	84	87	195	89	156	0.75	0.44	0.46	1.02	0.47	0.82	Large decrease	No change
Bigtooth aspen	666	670	High	677	614	661	354	650	244	1.01	0.92	0.99	0.53	0.97	0.36	No change	Large decrease
Bitternut hickory	103	115	Low	136	285	261	277	259	363	1.18	2.48	2.27	2.41	2.25	3.16	Large increase	Large increase
Black ash	1207	1163	High	1019	892	914	786	868	695	0.88	0.77	0.79	0.68	0.75	0.60	Decrease	Decrease
Black cherry	407	561	High	748	1246	1317	950	1354	807	1.33	2.22	2.35	1.69	2.41	1.44	Large increase	Increase
Black hickory	0	0	High	0	0	0	90	0	213	NA	NA	NA	New	NA	New	NA	New habitat
Black locust	2	6	Low	11	114	69	447	80	625	1.83	19.00	11.50	74.50	13.33	104.17	Large increase	Large increase
Black oak	67	270	High	340	925	520	928	608	1365	1.26	3.43	1.93	3.44	2.25	5.06	Large increase	Large increase
Black spruce	670	706	High	498	143	358	63	288	63	0.71	0.20	0.51	0.09	0.41	0.09	Large decrease	Large decrease
Black walnut	2	11	Medium	46	282	138	656	178	757	4.18	25.64	12.55	59.64	16.18	68.82	Large increase	Large increase
Black willow	57	82	Low	93	309	206	527	219	580	1.13	3.77	2.51	6.43	2.67	7.07	Large increase	Large increase
Blackgum	0	2	High	0	0	1	62	1	90	0.00	0.00	0.50	31.00	0.50	45.00	NA	New habitat
Blackjack oak	0	0	Medium	0	5	7	126	4	267	NA	New	New	New	New	New	New habitat	New habitat
Boxelder	61	205	Medium	194	513	316	766	320	1028	0.95	2.50	1.54	3.74	1.56	5.02	Increase	Large increase
Bur oak	261	457	Medium	398	824	684	875	651	1056	0.87	1.80	1.50	1.92	1.43	2.31	Increase	Large increase
Butternut	54	27	Low	31	65	42	2	46	0	1.15	2.41	1.56	0.07	1.70	0.00	Increase	Extirpated
Chestnut oak	0	2	High	0	0	1	72	0	71	0.00	0.00	0.50	36.00	0.00	35.50	NA	New habitat
Chinquapin oak	0	0	Medium	0	7	1	143	1	285	NA	New	New	New	New	New	New habitat	New habitat
Chokecherry	134	139	Low	126	176	172	141	163	42	0.91	1.27	1.24	1.01	1.17	0.30	No change	Large decrease
Common persimmon	0	0	Medium	0	0	0	0	0	10	NA	NA	NA	NA	NA	New	NA	New habitat
Eastern cottonwood	20	57	Low	62	221	120	1027	126	955	1.09	3.88	2.11	18.02	2.21	16.75	Large increase	Large increase
Eastern hemlock	467	409	High	460	372	530	195	495	154	1.13	0.91	1.30	0.48	1.21	0.38	Increase	Large decrease
Eastern hophornbeam	397	443	Medium	420	576	538	677	524	681	0.95	1.30	1.21	1.53	1.18	1.54	No change	Increase
Eastern redbud	28	0	Medium	1	5	3	160	3	331	New	New	New	New	New	New	Large decrease	Large increase
Eastern redcedar	0	29	Medium	43	573	111	1902	147	2067	1.48	19.76	3.83	65.59	5.07	71.28	New habitat	New habitat
Eastern white pine	628	636	High	690	682	742	548	720	319	1.09	1.07	1.17	0.86	1.13	0.50	No change	Decrease
Flowering dogwood	0	0	High	3	18	27	216	26	298	New	New	New	New	New	New	New habitat	New habitat
Gray birch	0	5	Medium	4	16	7	19	11	20	0.80	3.20	1.40	3.80	2.20	4.00	New habitat	New habitat
Green ash	638	593	Medium	509	523	452	1117	449	890	0.86	0.88	0.76	1.88	0.76	1.50	Decrease	Increase
Hackberry	2	12	Medium	24	358	164	770	178	935	2.00	29.83	13.67	64.17	14.83	77.92	Large increase	Large increase
Honeylocust	0	2	Low	3	127	43	422	41	559	1.50	63.50	21.50	211.00	20.50	279.50	New habitat	New habitat
Jack pine	695	812	High	693	749	672	501	654	492	0.85	0.92	0.83	0.62	0.81	0.61	No change	Decrease
Mockernut hickory	0	1	High	1	11	17	126	18	189	1.00	11.00	17.00	126.00	18.00	189.00	New habitat	New habitat
Mountain maple	59	53	High	27	2	17	0	13	0	0.51	0.04	0.32	0.00	0.25	0.00	Large decrease	Extirpated
Northern catalpa	0	2	Low	0	0	0	2	0	3	0.00	0.00	0.00	1.00	0.00	1.50	NA	New habitat
Northern pin oak	329	319	Medium	292	483	361	343	341	341	0.92	1.51	1.13	1.08	1.07	1.07	No change	No change
Northern red oak	940	1078	High	1292	1829	1435	1491	1441	1216	1.20	1.70	1.33	1.38	1.34	1.13	Increase	No change
Northern white-cedar	1010	1003	High	869	460	744	439	704	361	0.87	0.46	0.74	0.44	0.70	0.36	Decrease	Large decrease

(Table 19 continued on next page)

Table 19 (continued).

				DISTRIB results													
				Modeled IV						Future:Current Suitable Habitat						Change Class 2070-2099	
				2010-2039		2040-2069		2070-2099		2010-2039		2040-2069		2070-2099			
Common Name	FIA 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
Ohio buckeye	0	0	Low	1	11	2	109	2	136	New	New	New	New	New	New	New habitat	New habitat
Osage-orange	0	8	Medium	9	50	55	144	57	231	1.13	6.25	6.88	18.00	7.13	28.88	New habitat	New habitat
Paper birch	1699	1628	High	1339	1118	1173	329	1068	258	0.82	0.69	0.72	0.20	0.66	0.16	Decrease	Large decrease
Peachleaf willow	6	0	Low	0	0	0	3	0	47	NA	NA	NA	New	NA	New	NA	Increase
Pignut hickory	0	1	High	2	43	49	175	64	211	2.00	43.00	49.00	175.00	64.00	211.00	New habitat	New habitat
Pin cherry	56	48	Medium	49	62	56	36	55	10	1.02	1.29	1.17	0.75	1.15	0.21	No change	Large decrease
Pin oak	0	7	Medium	5	40	34	206	32	294	0.71	5.71	4.86	29.43	4.57	42.00	New habitat	New habitat
Post oak	0	0	High	0	7	8	515	6	957	NA	New	New	New	New	New	New habitat	New habitat
Quaking aspen	3888	3921	High	3138	2278	2405	1076	2230	866	0.80	0.58	0.61	0.27	0.57	0.22	Decrease	Large decrease
Red maple	3149	2910	High	3032	2603	3104	2054	3034	1803	1.04	0.90	1.07	0.71	1.04	0.62	No change	Decrease
Red mulberry	1	0	Low	2	188	35	566	45	714	New	New	New	New	New	New	Large increase	Large increase
Red pine	571	685	Medium	659	695	617	700	626	575	0.96	1.02	0.90	1.02	0.91	0.84	No change	No change
River birch	4	1	Low	1	112	23	11	16	20	1.00	112.00	23.00	11.00	16.00	20.00	Large increase	Large increase
Rock elm	73	52	Low	43	45	42	61	39	62	0.83	0.87	0.81	1.17	0.75	1.19	Decrease	No change
Sassafras	0	3	High	4	19	39	211	35	247	1.33	6.33	13.00	70.33	11.67	82.33	New habitat	New habitat
Scarlet oak	0	0	High	0	0	7	56	9	122	NA	NA	New	New	New	New	New habitat	New habitat
Shagbark hickory	86	117	Medium	203	608	429	525	455	621	1.74	5.20	3.67	4.49	3.89	5.31	Large increase	Large increase
Shellbark hickory	0	0	Low	0	1	0	24	0	26	NA	New	NA	New	NA	New	NA	New habitat
Shingle oak	0	1	Medium	0	15	10	138	11	172	0.00	15.00	10.00	138.00	11.00	172.00	New habitat	New habitat
Silver maple	72	127	Medium	166	617	416	908	401	996	1.31	4.86	3.28	7.15	3.16	7.84	Large increase	Large increase
Slippery elm	75	81	Medium	143	414	249	697	290	769	1.77	5.11	3.07	8.61	3.58	9.49	Large increase	Large increase
Striped maple	14	24	High	15	27	27	25	24	18	0.63	1.13	1.13	1.04	1.00	0.75	No change	No change
Sugar maple	3574	3375	High	3210	2012	3095	1462	2851	1172	0.95	0.60	0.92	0.43	0.85	0.35	No change	Large decrease
Sugarberry	0	0	Medium	0	0	0	13	0	52	NA	NA	NA	New	NA	New	NA	New habitat
Swamp white oak	32	25	Low	29	45	33	154	32	147	1.16	1.80	1.32	6.16	1.28	5.88	No change	Increase
Sweet birch	0	2	High	2	4	3	53	4	41	1.00	2.00	1.50	26.50	2.00	20.50	New habitat	New habitat
Sweetgum	0	0	High	0	0	0	10	0	22	NA	NA	NA	New	NA	New	NA	New habitat
Sycamore	0	0	Medium	0	3	14	31	10	83	NA	New	New	New	New	New	New habitat	New habitat
Tamarack (native)	508	566	High	475	510	514	381	500	367	0.84	0.90	0.91	0.67	0.88	0.65	No change	Decrease
White ash	382	427	High	521	580	667	830	677	791	1.22	1.36	1.56	1.94	1.59	1.85	Increase	Increase
White oak	349	459	High	621	1260	796	1314	912	1410	1.35	2.75	1.73	2.86	1.99	3.07	Increase	Large increase
White spruce	363	369	Medium	259	178	224	158	209	154	0.70	0.48	0.61	0.43	0.57	0.42	Decrease	Large decrease
Wild plum	2	6	Low	2	12	2	160	2	269	0.33	2.00	0.33	26.67	0.33	44.83	Decrease	Large increase
Yellow birch	628	589	High	508	300	546	136	470	125	0.86	0.51	0.93	0.23	0.80	0.21	Decrease	Large decrease
Yellow-poplar	0	1	High	0	3	19	33	15	75	0.00	3.00	19.00	33.00	15.00	75.00	New habitat	New habitat

*Current importance values (Current IV) are based on modeled results. 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 through 2099) and current figures for area-weighted importance value. Descriptions of the change classes are given elsewhere in this appendix.

NA = not applicable, no suitable habitat projected.

Mig. = new migrant, new suitable habitat projected.

Table 20.—Modifying factors for the 74 tree species in the assessment area

Common Name	Model Reliability	Modifying Factors*		Adaptability Scores			
		Positive Traits	Negative Traits	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	0.0	3.6	o
American elm	Medium	ESP	DISE INS	-0.8	0.3	4.0	o
American hornbeam	Medium	COL SES	FTK DRO	0.6	0.6	5.1	o
Balsam fir	High	COL	INS FTK DRO	-3.0	-0.4	2.7	—
Balsam poplar	High	FRG VRE	COL DRO	0.1	-0.6	4.0	o
Bigtooth aspen	High	FRG DISP	COL DRO FTK	1.0	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	-3.0	1.7	—
Black cherry	High	DRO ESP	INS FTK COL	-1.6	-0.3	3.0	—
Black hickory	High		ESP COL	1.0	-2.3	4.1	o
Black locust	Low		COL INS	0.0	-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	4.0	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	+
Butternut	Low		FTK COL DRO DISE	-1.4	-1.3	2.3	—
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	1.0	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	0.0	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	0.1	3.3	o
Flowering dogwood	High	COL		0.1	1.0	5.0	o
Gray birch	Medium	DISP ESP	FTK COL INS DISE	-1.1	0.0	3.6	o
Green ash	Medium		INS FTK COL	-0.1	-0.3	4.0	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 catalpa	Low		COL ESP	0.9	-1.6	4.2	o
Northern pin oak	Medium	DRO FTK	COL	2.5	-0.6	6.0	+

(Table 20 continued on next page)

Table 20 (continued).

Common Name	Model Reliability	Modifying Factors* Positive Traits	Modifying Factors* Negative Traits	Adaptability Scores DistFact	BioFact	Adapt	Adapt Class
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
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
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	0.0	4.7	o
Red maple	High	SES ESP ESP COL DISP		3.0	3.0	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	0.7	4.8	o
Striped maple	High	COL SES	DRO	1.0	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	-0.3	4.9	o
Sweet birch	High	DISP	FTK COL INS DISE	-1.3	-0.3	3.2	—
Sweetgum	High	VRE ESP	FTK COL DRO	-0.4	0.2	4.1	o
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	-0.5	2.7	—
White oak	High	ESP ESP SES FTK	INS DISE	1.7	1.0	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	0.0	3.4	o
Yellow-poplar	High	SES DISP ESP	INP	0.1	1.3	5.3	+

*Modifying factor codes are described in Table 21. Adaptability scores are described in the appendix text.

Table 21.—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 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 used in Table 20. 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.

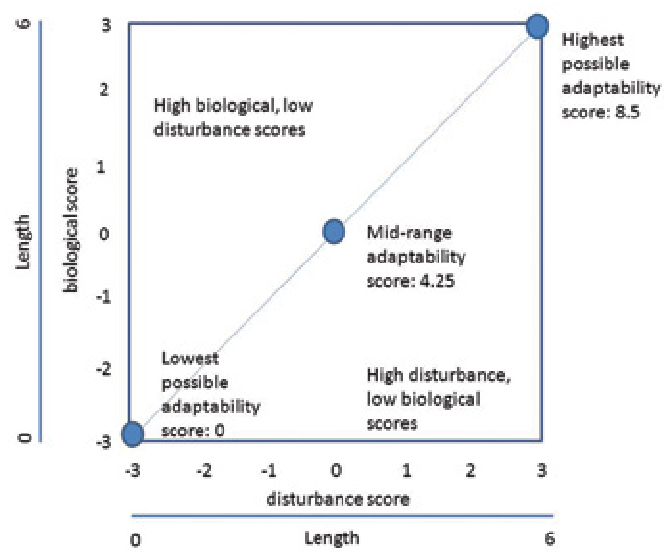


Figure 60.—Schematic showing how adaptability was determined for information for the 78 tree species in the assessment area modeled using the Climate Change Tree Atlas. Modifying factor codes are described in Table 21. Adaptability scores are described in the appendix text.

LITERATURE CITED

Iverson, L.R.; Prasad, A.; Schwartz, M.W. 1999. **Modeling potential future individual tree-species distributions in the eastern United States under a climate change scenario: a case study with *Pinus virginiana*.** Ecological Modelling. 115(1): 77-93.

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

Iverson, L.R.; Prasad, A.M.; Matthews, S.N.; Peters, M.P. 2011. **Lessons learned while integrating habitat, dispersal, disturbance, and life-history traits into species habitat models under climate change.** Ecosystems. 14(6): 1005-1020.

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

A wetland on Madeline Island in Wisconsin. Photo by Maria Janowiak, U.S. Forest Service.

APPENDIX 5: SUPPLEMENTARY MODEL RESULTS – LANDIS-II

This appendix contains additional model details and results from the LANDIS-II model.

FOREST TYPE CLASSIFICATION

The forest-type maps presented in Chapter 5 (Fig. 41) rely on a simple classification scheme, which is different from the FIA forest-type groups and the forest ecosystem classifications used in other parts of this assessment. To create these forest-type maps, individual locations ("cells") in the LANDIS-II simulations were classified into 10 forest categories based on characteristic species composition. These classifications are based on the dominance of key indicator species (Table 22). The assignment of species 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.

Table 22.—Classification rules for creating the forest-type maps based on LANDIS-II outputs (Fig. 41)

Forest type	Species included in forest type
Aspen-birch	paper birch, balsam poplar, bigtooth aspen, quaking aspen
Hemlock	eastern hemlock
Jack pine	jack pine
Northern hardwoods	sugar maple, red maple, yellow birch, white ash, black ash, green ash, American beech, American basswood
Northern oaks	northern pin oak, northern red oak
Red pine	red pine
Southern mesic hardwoods	bitternut hickory, black cherry
Southern oaks	bur oak, white oak, black oak
Upland spruce-fir	balsam fir, white spruce, black spruce, northern white cedar
White pine	eastern white pine

FOREST HARVEST

The LANDIS-II model was used to project changes in tree species under three harvest scenarios (Tables 23 and 24). Results from the Current Harvest scenario are presented in Chapter 5.

Table 23.—Harvest scenarios used for LANDIS-II modeling

Forest ownership	No harvest (%)	Current harvest (%)*	Double harvest (%)
National Forest	0	1.15	2.30
Other Federal	0	1.30	2.61
State	0	1.02	2.03
County and municipal	0	2.25	4.50
Other local government	0	2.87	5.75
Native American reservations	0	1.00	2.00
Private groups	0	3.07	6.13
Private individuals	0	2.21	4.41

*Current harvest rate reflects the annual percentage of total acreage harvested for the entire state of Wisconsin based on the 2005-2011 FIA database. Harvest types include clearcut, seed tree, single-tree (gap) selection, group selection, patch selection, and shelterwood methods.

BIOMASS PROJECTIONS

Table 24.—Projected aboveground biomass for 27 species modeled with the LANDIS-II model

			Current Climate		PCM B1		GFDL A1FI	
Species	Year 2000 biomass (g/m^2)	Year	Biomass (g/m^2)	Change from 2000	Biomass (g/m^2)	Biomass change relative to current climate	Biomass (g/m^2)	Biomass change relative to current climate
American basswood	671	2040	690	103%	1048	52%	970	41%
		2070	738	110%	1435	94%	1200	63%
		2100	755	113%	1799	138%	1567	107%
American beech	9	2040	12	134%	16	28%	14	13%
		2070	17	192%	27	55%	21	20%
		2100	21	234%	39	83%	39	85%
Balsam fir	658	2040	785	119%	693	-12%	524	-33%
		2070	1018	155%	829	-19%	262	-74%
		2100	1135	173%	797	-30%	90	-92%
Balsam poplar	43	2040	39	90%	32	-18%	27	-30%
		2070	23	55%	19	-19%	12	-50%
		2100	6	13%	5	-6%	1	-79%
Bigtooth aspen	443	2040	370	83%	448	21%	390	6%
		2070	283	64%	385	36%	281	-1%
		2100	120	27%	168	40%	104	-13%

(Table 24 continued on next page)

Table 24 (continued).

Species	Year 2000 biomass (g/m²)	Year	Current Climate: Biomass (g/m²)	Current Climate: Change from 2000	PCM B1: Biomass (g/m²)	PCM B1: Biomass change relative to current climate	GFDL A1FI: Biomass (g/m²)	GFDL A1FI: Biomass change relative to current climate
Bitternut hickory	78	2040	79	101%	87	10%	78	-1%
		2070	78	100%	99	27%	87	11%
		2100	61	78%	99	63%	124	103%
Black ash	462	2040	642	139%	609	-5%	570	-11%
		2070	644	139%	601	-7%	524	-19%
		2100	542	117%	487	-10%	407	-25%
Black cherry	617	2040	608	98%	591	-3%	577	-5%
		2070	533	86%	508	-5%	513	-4%
		2100	339	55%	309	-9%	452	33%
Black oak	13	2040	13	102%	16	21%	15	16%
		2070	13	97%	19	49%	17	33%
		2100	10	74%	19	93%	22	131%
Black spruce	375	2040	482	129%	348	-28%	319	-34%
		2070	496	132%	283	-43%	210	-58%
		2100	472	126%	167	-65%	94	-80%
Bur oak	151	2040	171	113%	200	18%	189	11%
		2070	173	115%	228	32%	199	15%
		2100	156	103%	221	42%	213	37%
Eastern hemlock	462	2040	505	109%	560	11%	530	5%
		2070	562	122%	675	20%	609	8%
		2100	596	129%	778	30%	742	24%
Eastern white pine	1715	2040	2589	151%	2554	-1%	2298	-11%
		2070	3621	211%	3682	2%	2635	-27%
		2100	4785	279%	4713	-2%	2949	-38%
Green ash	133	2040	184	138%	215	17%	197	7%
		2070	209	156%	256	23%	215	3%
		2100	203	152%	251	24%	224	10%
Jack pine	186	2040	249	134%	197	-21%	179	-28%
		2070	176	95%	136	-23%	105	-41%
		2100	162	87%	111	-31%	46	-72%
Northern pin oak	137	2040	119	87%	165	38%	136	14%
		2070	84	62%	143	70%	106	25%
		2100	46	34%	110	139%	74	60%
Northern red oak	1073	2040	1354	126%	1500	11%	1363	1%
		2070	1660	155%	1962	18%	1456	-12%
		2100	1798	168%	2108	17%	1649	-8%
Northern white cedar	782	2040	1064	136%	991	-7%	919	-14%
		2070	1230	157%	1120	-9%	904	-27%
		2100	1273	163%	1095	-14%	801	-37%
Paper birch	884	2040	1118	126%	621	-44%	544	-51%
		2070	1152	130%	482	-58%	256	-78%
		2100	953	108%	328	-66%	91	-90%
Quaking aspen	1614	2040	1389	86%	1120	-19%	990	-29%
		2070	908	56%	671	-26%	423	-53%
		2100	346	21%	259	-25%	66	-81%

(Table 24 continued on next page)

Table 24 (continued).

Species	Year 2000 biomass (g/m²)	Year	Current Climate		PCM B1		GFDL A1FI	
			Biomass (g/m²)	Change from 2000	Biomass (g/m²)	Biomass change relative to current climate	Biomass (g/m²)	Biomass change relative to current climate
Red maple	4034	2040	3849	95%	4294	12%	3917	2%
		2070	3034	75%	3917	29%	3183	5%
		2100	2113	52%	3161	50%	2892	37%
Red pine	1097	2040	1446	132%	1222	-16%	1164	-20%
		2070	1673	153%	1322	-21%	1101	-34%
		2100	1726	157%	1210	-30%	932	-46%
Sugar maple	5542	2040	7016	127%	7134	2%	6436	-8%
		2070	8152	147%	8818	8%	6413	-21%
		2100	8572	155%	9477	11%	6433	-25%
White ash	219	2040	201	92%	273	36%	254	26%
		2070	173	79%	308	77%	281	62%
		2100	134	61%	339	153%	404	201%
White oak	143	2040	145	101%	177	23%	167	15%
		2070	148	104%	208	40%	186	26%
		2100	146	102%	225	54%	231	59%
White spruce	497	2040	693	140%	475	-31%	429	-38%
		2070	760	153%	407	-46%	292	-62%
		2100	751	151%	249	-67%	136	-82%
Yellow birch	614	2040	928	151%	1023	10%	874	-6%
		2070	1273	207%	1410	11%	840	-34%
		2100	1469	239%	1574	7%	727	-51%

Change from year 2000 is calculated as the change in biomass from year 2000 (100% equals no net change). 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. These data are based on three climate change scenarios under current harvest practices.

APPENDIX 6: VULNERABILITY AND CONFIDENCE DETERMINATION

EXPERT PANEL PROCESS

To assess vulnerabilities to climate change for each natural community type, we elicited input from a panel of 23 experts from a variety of land management and research organizations across the assessment area (Table 25). We sought a team of panelists who would be able to contribute a diversity of subject area expertise, management history, and organizational perspectives. Most panelists had extensive knowledge about the ecology, management, and climate change impacts on forests in the assessment area. This panel was assembled at an in-person workshop in Houghton, Michigan, in May 2013. Here we describe the structured discussion process that the panel used.

Forest Systems Assessed

The authors of this assessment used the forest ecosystem classification described in Chapter 1. For each forest type, we collected information related

Table 25.—Participants in the May 2013 expert panel workshop

Name	Organization
Amy Amman	Ottawa National Forest
Tara Bal	Michigan Technological University
Brian Bogaczyk	Ottawa National Forest
Dustin Bronson	Wisconsin Department of Natural Resources
Andy Burton	Michigan Technological University
Patricia Butler*	Michigan Technological University & Northern Institute of Applied Climate Science
Jim Ferris	Michigan Department of Natural Resources
Jon Fosgitt	Compass Land Consultants
Shawn Hagan	The Forestland Group
Christine Handler	Ottawa National Forest
Louis Iverson	U.S. Forest Service, Northern Research Station
Maria Janowiak*	U.S. Forest Service, Northern Research Station & Northern Institute of Applied Climate Science
Erin Johnston	Keweenaw Bay Indian Community
Evan Kane	Michigan Technological University
Ellen Lesch	Ottawa National Forest
Colleen Matula	Wisconsin Department of Natural Resources
David Mladenoff	University of Wisconsin-Madison
Ryan O'Connor	Wisconsin Natural Heritage Program
Linda Parker	Chequamegon-Nicolet National Forest
Kirk Wythers	University of Minnesota
Weimin Xi	University of Wisconsin-Madison

* Workshop facilitators

to the major system drivers, dominant species, and stressors that characterize that community from the relevant ecological literature. The panel was asked to comment on and suggest modifications to the community descriptions, and those suggestions were incorporated into the descriptions.

Potential Impacts

To examine potential impacts, the panel was given several sources of background information on past and future climate change in the region (summarized in 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 forest 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: GFDL A1FI and PCM B1. Panelists were then led through a structured discussion process to consider this information for each forest community considered in the assessment.

Potential impacts on community drivers and stressors were summarized 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 community 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 community 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 (Box 12). The panel evaluated how much the models agreed with each other, between climate scenarios, and across space and time. Finally, panelists were asked to consider the potential for interactions among anticipated climate trends, species impacts, and stressors. Input on these future ecosystem interactions relied primarily on the panelists' expertise and judgment because there are not many examples of published literature on complex interactions, nor are future interactions accurately represented by ecosystem models.

Adaptive Capacity

Panelists discussed the adaptive capacity of each forest system based on their ecological knowledge and management experience with the community types in the assessment area. 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). 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

Following extensive group discussion, each panelist 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.

Box 12: Note on Forest Impact Models Used in This Assessment

During the expert panel workshop, preliminary LANDIS-II results were used that included the effects of carbon dioxide (CO_2) fertilization on the 27 tree species that were modeled. The inclusion of CO_2 fertilization projected unrealistically large increases in biomass for many tree species. The CO_2 routine in the PnET-CN model predicts a larger CO_2 fertilization effect on productivity than do other ecosystem models (Franks et al. 2013, Medlyn et al. 2011). Further, few observational studies have evaluated the effects of CO_2 levels over 600 ppm, although the GFDL scenario projects CO_2 levels over 900 ppm by the year 2100. Chapter 5 contains a more detailed description of the CO_2 fertilization effect and its influence in PnET-CN modeling.

The LANDIS-II model results presented in this assessment rely on the PnET-CN model to provide estimates of species establishment. The preliminary LANDIS-II model results used in the expert panel workshop included the potential benefits of CO_2 fertilization on tree growth, which panelists identified as an issue because fertilization effect was so great that it overrode many of the potentially negative effects of warming and associated climatic changes. During the workshop, members of the expert panel also expressed their tendency to "discount" the biomass increases that were projected under both scenarios, and especially under the GFDL A1FI scenario. After the expert panel workshop, we chose to use new LANDIS-II results that did not include CO_2 fertilization. All LANDIS-II results presented in Chapters 5 and 6 and Appendix 5 were subsequently vetted with the expert panelists to ensure their vulnerability rankings were still consistent with the final LANDIS-II model results.

The new LANDIS-II results (that is, without CO_2 fertilization) tended to be more consistent with the results from the Climate Change Tree Atlas presented in this assessment. Further, these new results are also comparable to those developed for Michigan and Minnesota by a different modeling team (Handler et al. 2014a, 2014b).

Panelists were directed to mark their rating in two-dimensional space on the individual worksheet and on a large group poster (Fig. 61a). 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). Individual ratings were compared and discussed and used to arrive at a group determination. In many cases, the group determination was at or near the centroid of all individual determinations. Sometimes the group determination deviated from the centroid because further discussion convinced some group members to alter their original response.

Confidence

Panelists were also directed to give a confidence rating to each of their individual vulnerability determinations (Fig. 61b). Panelists were asked to evaluate the amount of evidence they felt was available to support their vulnerability determination and the level of agreement among the available evidence (Mastrandrea et al. 2010). Panelists evaluated confidence individually and as a group, in a similar fashion to the vulnerability determination.

Vulnerability and Confidence Figures

For reference, figures of individual and group determinations for all nine forest systems considered in this assessment are displayed (Figs. 62 through 70). 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.

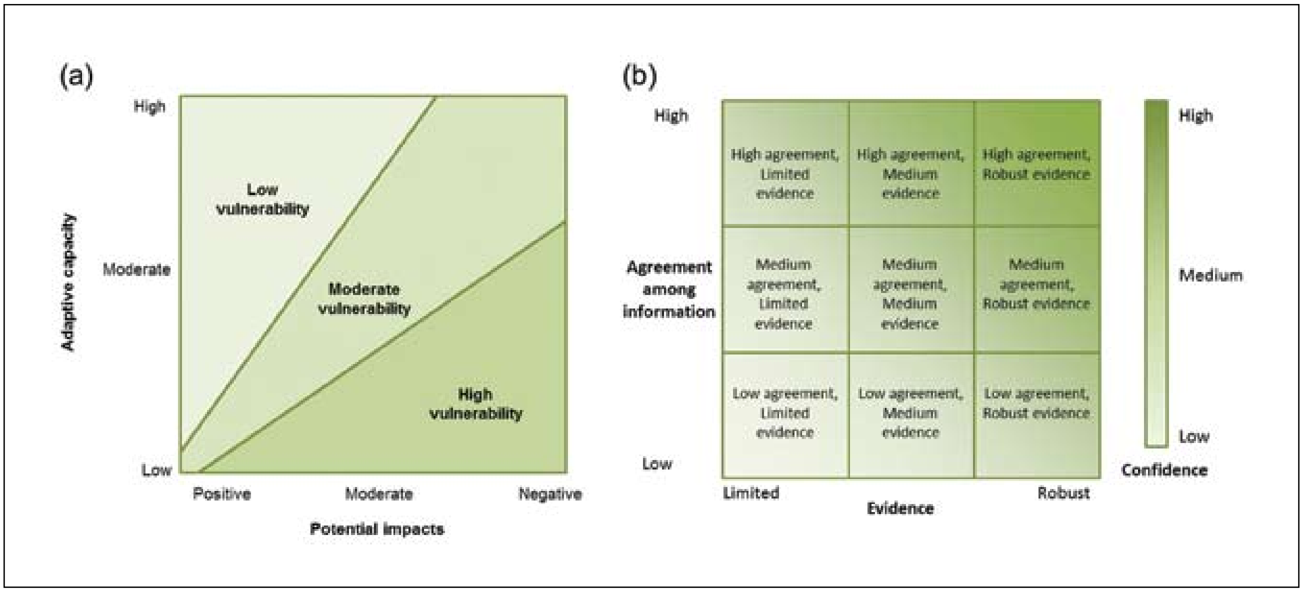


Figure 61.—Figure used for (a) vulnerability determination by expert panelists, based on Swanston and Janowiak (2012), and (b) confidence rating among expert panelists, adapted from Mastrandrea et al. (2010).

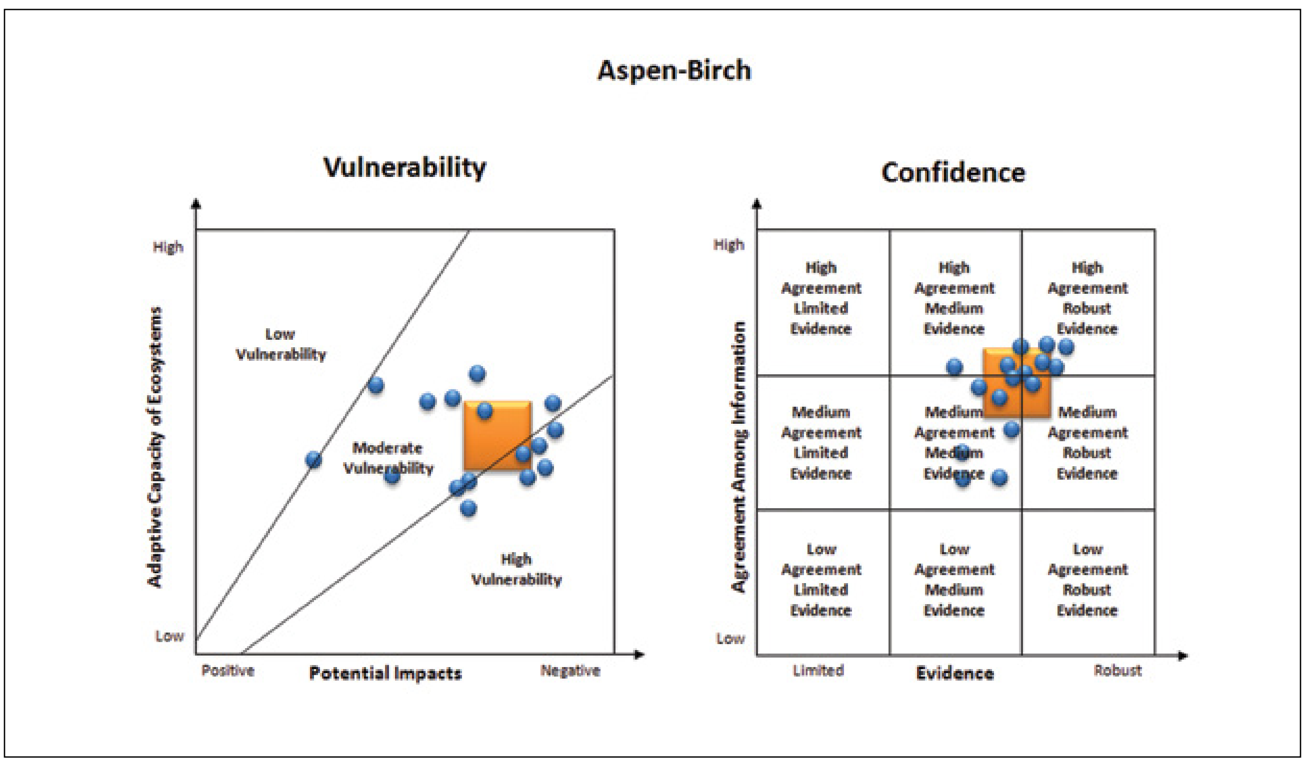


Figure 62.—Aspen-birch vulnerability and confidence determinations. Circles indicate individual determinations by each panelist and squares indicate the group determination after consensus was reached.

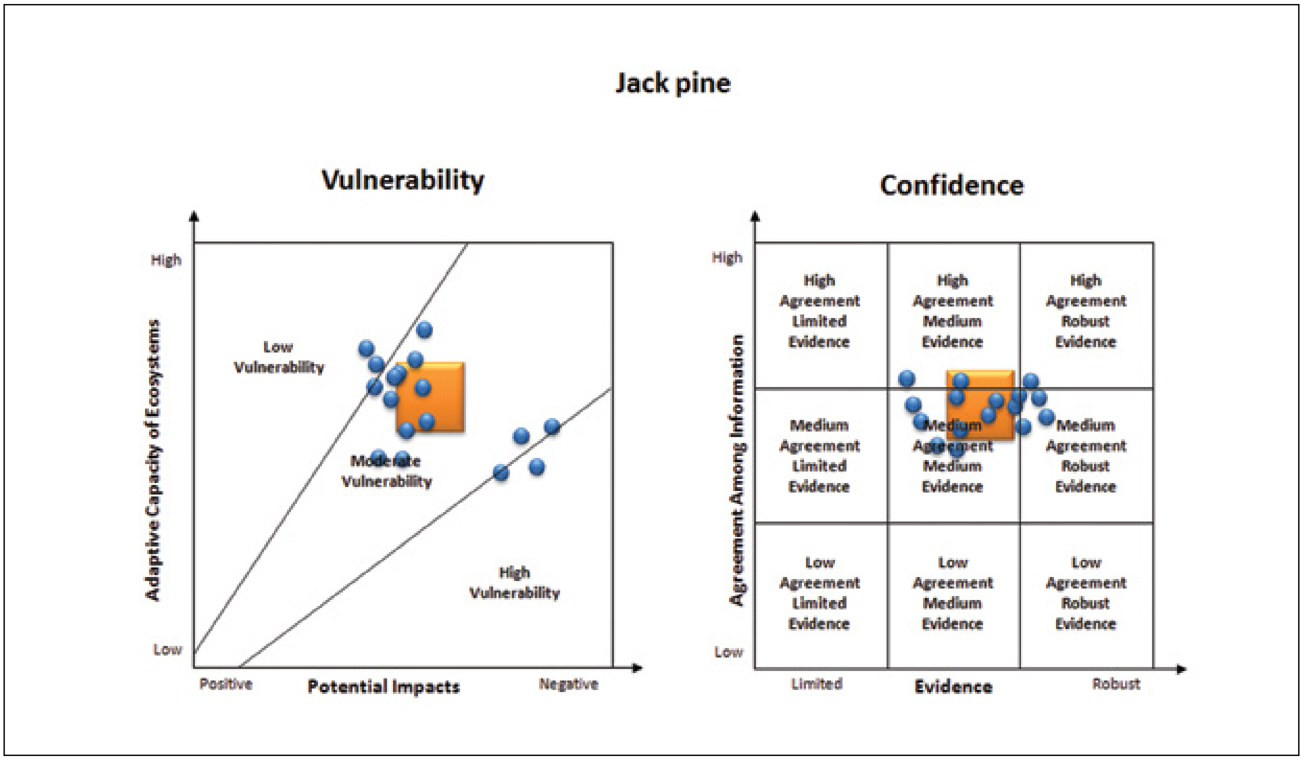


Figure 63.—Jack pine vulnerability and confidence determinations. Circles indicate individual determinations by each panelist and squares indicate the group determination after consensus was reached.

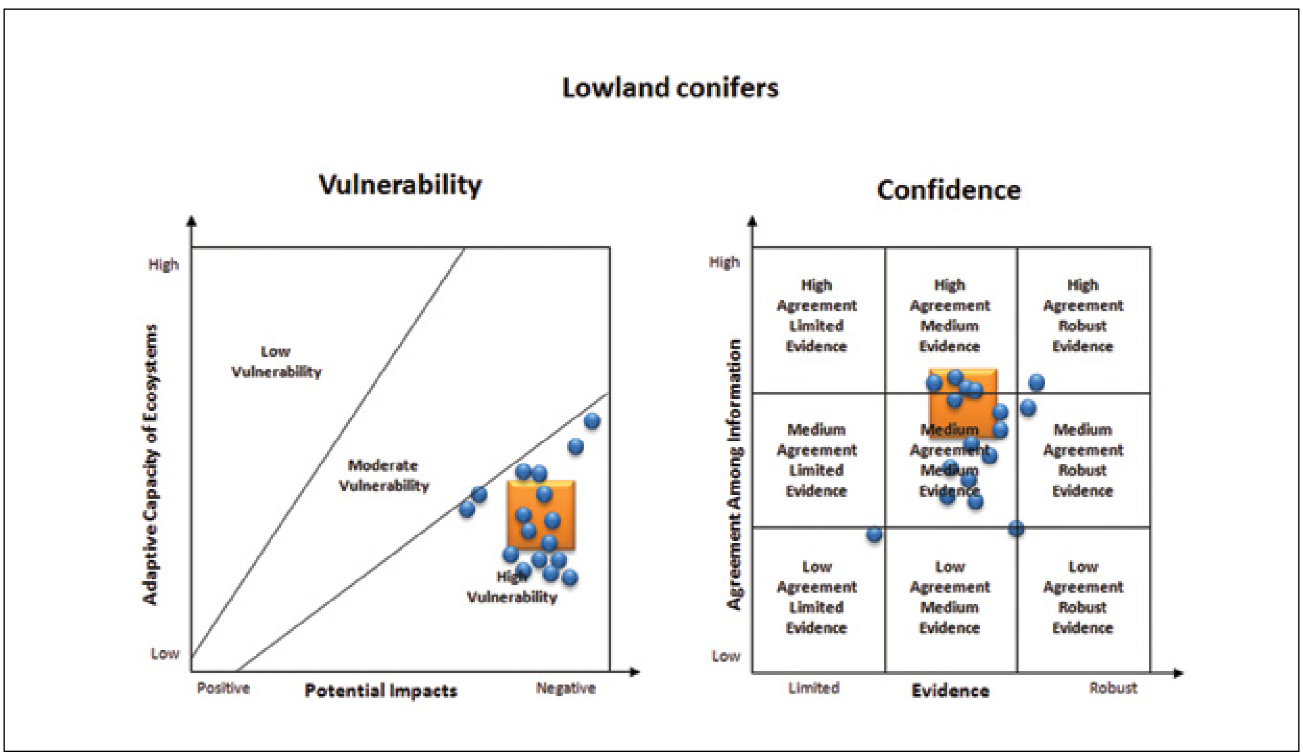


Figure 64.—Lowland conifers vulnerability and confidence determinations. Circles indicate individual determinations by each panelist and squares indicate the group determination after consensus was reached.

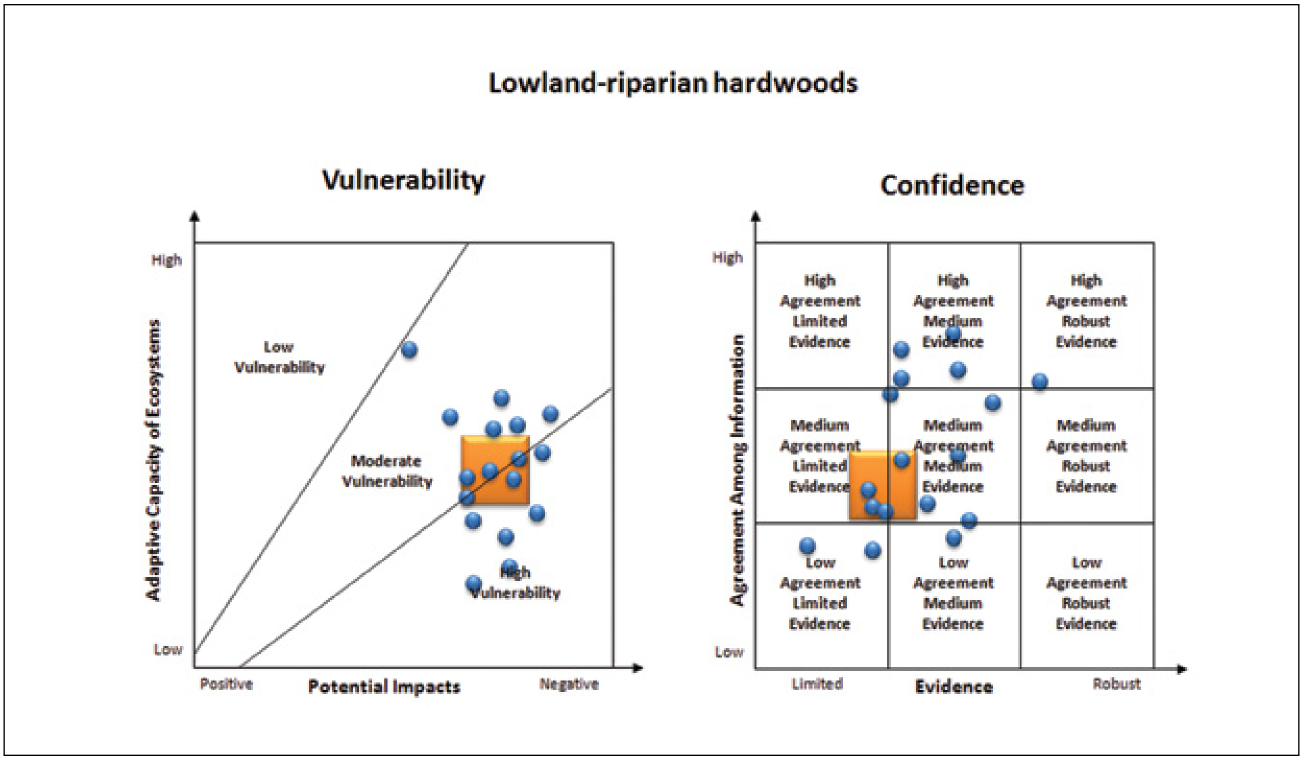


Figure 65.—Lowland-riparian hardwoods vulnerability and confidence determinations. Circles indicate individual determinations by each panelist and squares indicate the group determination after consensus was reached.

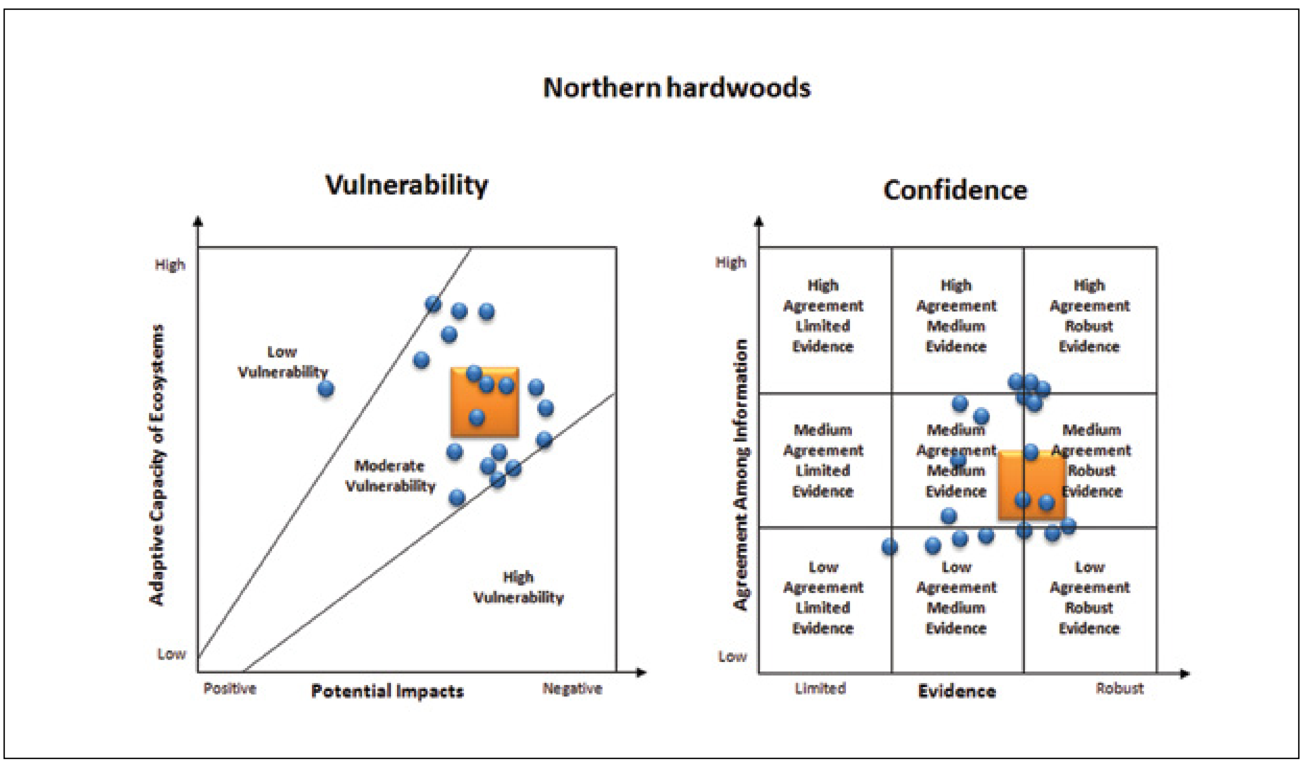


Figure 66.—Northern hardwoods vulnerability and confidence determinations. Circles indicate individual determinations by each panelist and squares indicate the group determination after consensus was reached.

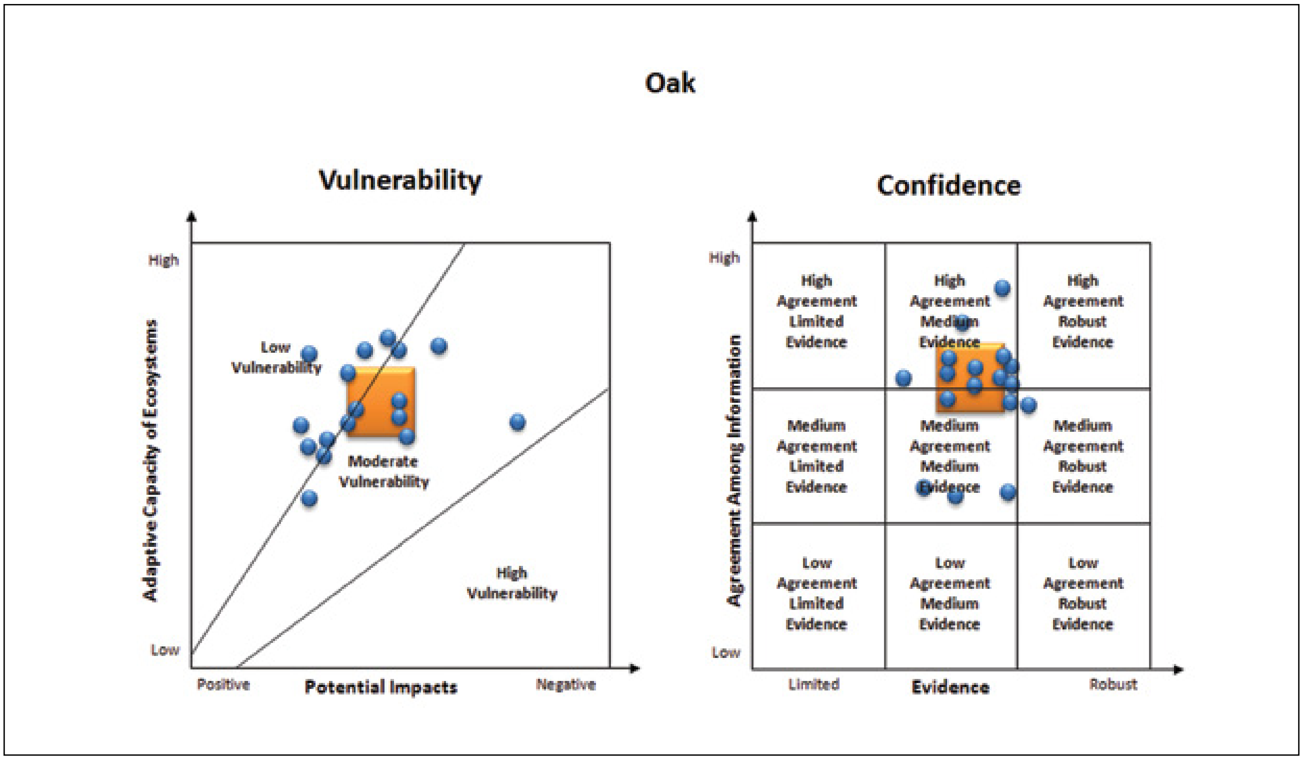


Figure 67.—Oak vulnerability and confidence determinations. Circles indicate individual determinations by each panelist and squares indicate the group determination after consensus was reached.

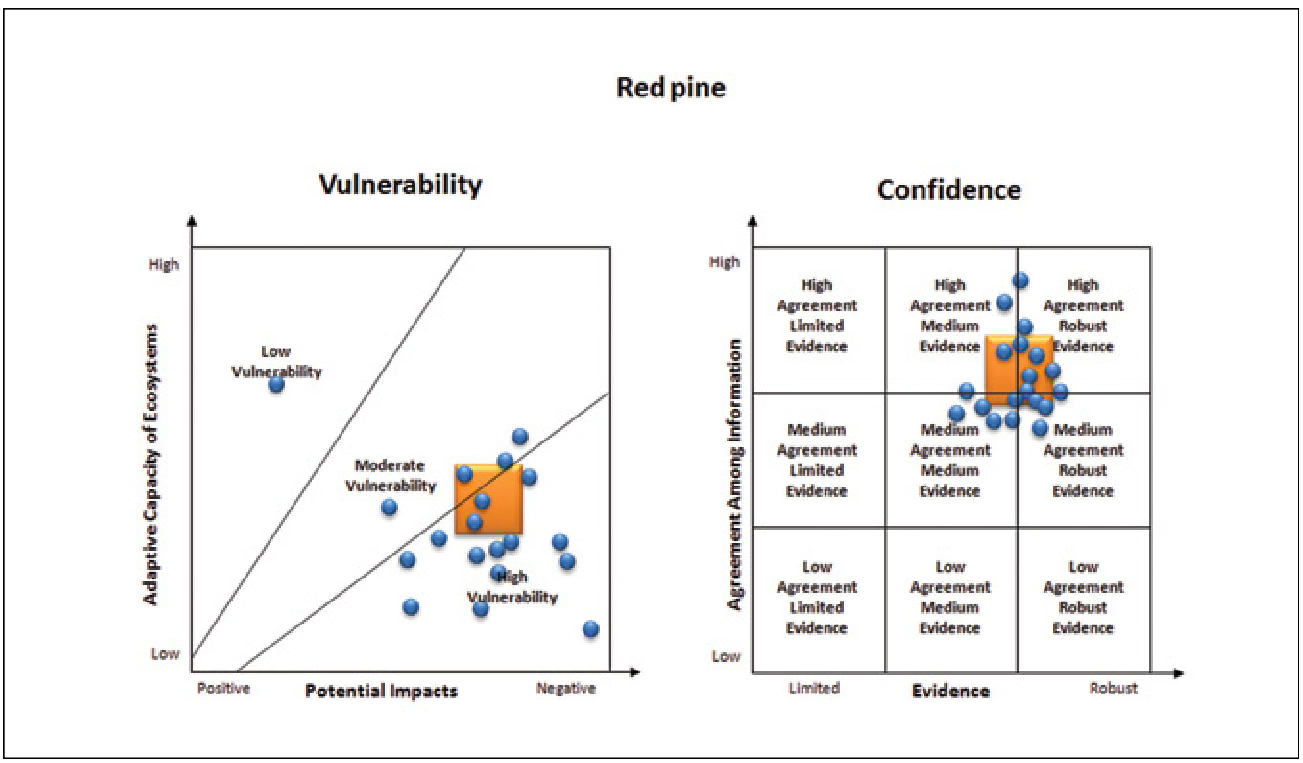


Figure 68.—Red pine vulnerability and confidence determinations. Circles indicate individual determinations by each panelist and squares indicate the group determination after consensus was reached.

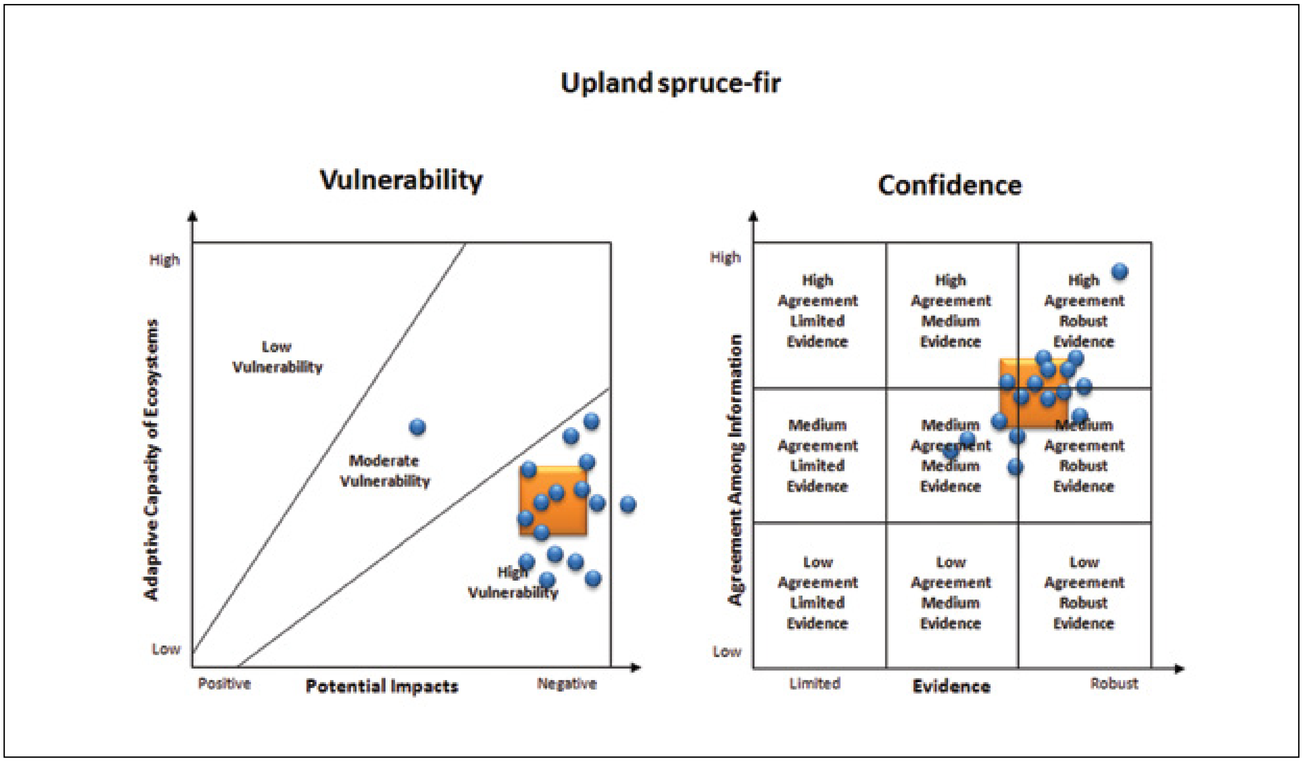


Figure 69.—Upland spruce-fir vulnerability and confidence determinations. Circles indicate individual determinations by each panelist and squares indicate the group determination after consensus was reached.

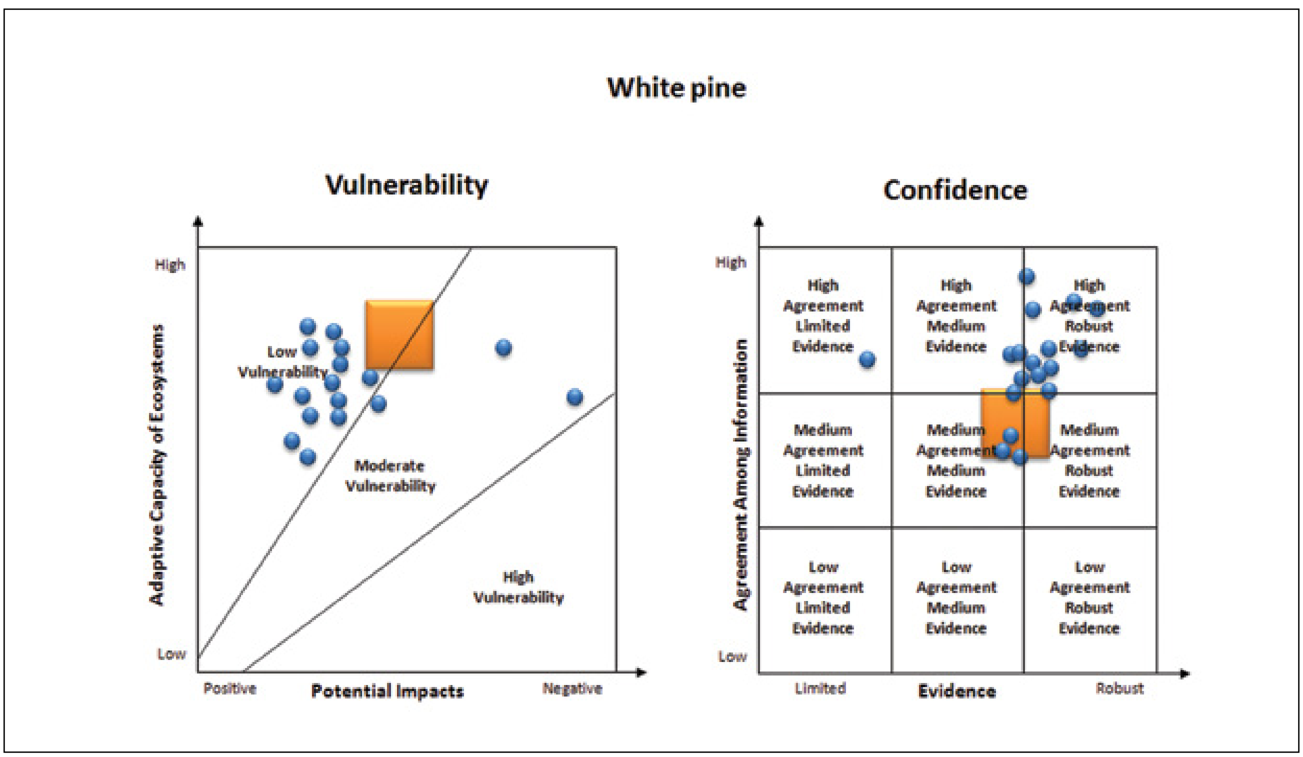


Figure 70.—White pine vulnerability and confidence determinations. Circles indicate individual determinations by each panelist and squares indicate the group determination after consensus was reached.

VULNERABILITY STATEMENTS

Recurring themes and patterns that transcended individual community types were identified and developed into 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. Panelists were asked to review each statement for accuracy, whether the confidence determination should be raised or lowered, if there was additional literature that was overlooked, and if there were any additional statements that needed to be made. Any changes that were suggested by a single panelist were brought forth for discussion and approved by the entire panel.

LITERATURE CITED

Franks, P.J.; Adams, M.A.; Amthor, J.S.; Barbour, M.M.; Berry, J.A.; Ellsworth, D.S.; Farquhar, G.D.; Ghannoum, O.; Lloyd, J.; McDowell, N.; Norby, R.J.; Tissue, D.T.; von Caemmerer, S. 2013. **Sensitivity of plants to changing atmospheric CO_2 concentration: from the geological past to the next century.** New Phytology. 197(4): 1077-1094.

Handler, S.; Duveneck, M.J.; Iverson, L.; Peters, E.; Scheller, R.M.; Wythers, K.R.; Brandt, L.; Butler, P.; Janowiak, M.; Shannon, P.D.; Swanston, C.; Barrett, K.; Kolka, R.; McQuiston, C.; Palik, B.; Reich, P.B.; Turner, C.; White, M.; Adams, C.; D'Amato, A.; Hagell, S.; Johnson, P.; Johnson, R.; Larson, M.; Matthews, S.; Montgomery, R.; Olson, S.; Peters, M.; Prasad, A.; Rajala, J.; Daley, J.; Davenport, M.; Emery, M.R.; Fehringer, D.; Hoving, C.L.; Johnson, G.; Johnson, L.; Neitzel, D.; Rissman, A.; Rittenhouse, C.; Ziel, R. 2014a. **Minnesota forest ecosystem vulnerability assessment and synthesis: a report from the Northwoods Climate Change Response Framework project.** Gen. Tech. Rep. NRS-133. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 228 p.

Handler, S.; Duveneck, M.J.; Iverson, L.; Peters, E.; Scheller, R.M.; Wythers, K.R.; Brandt, L.; Butler, P.; Janowiak, M.; Shannon, P.D.; Swanston, C.; Eagle, A.C.; Cohen, J.G.; Corner, R.; Reich, P.B.; Baker, T.; Chhin, S.; Clark, E.; Fehringer, D.; Fosgitt, J.; Gries, J.; Hall, C.; Hall, K.R.; Heyd, R.; Hoving, C.L.; Ibanez, I.; Kuhr, D.; Matthews, S.; Muladore, J.; Nadelhoffer, K.; Neumann, D.; Peters, M.; Prasad, A.; Sands, M.; Swaty, R.; Wonch, L.; Daley, J.; Davenport, M.; Emery, M.R.; Johnson, G.; Johnson, L.; Neitzel, D.; Rissman, A.; Rittenhouse, C.; Ziel, R. 2014b. **Michigan forest ecosystem vulnerability assessment and synthesis: a report from the Northwoods Climate Change Response Framework project.** Gen. Tech. Rep. NRS-129. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 229 p.

Mastrandrea, M.D.; Field, C.B.; Stocker, T.F.; Edenhofer, O.; Ebi, K.L.; Frame, D.J.; Held, H.; Kriegler, E.; Mach, K.J.; Matschoss, P.R.; Plattner, G.-K.; Yohe, G.W.; Zwiers, F.W. 2010. **Guidance note for lead authors of the IPCC Fifth Assessment Report on consistent treatment of uncertainties.** Geneva, Switzerland: Intergovernmental Panel on Climate Change (IPCC). Available at www.ipcc.ch/activities/activities.shtml. (Accessed May 6, 2014).

Medlyn, B.E.; Duursma, R.A.; Zeppel, M.J.B. 2011. **Forest productivity under climate change: a checklist for evaluating model studies.** Wiley Interdisciplinary Reviews: Climate Change. 2(3): 332-355.

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 www.nrs.fs.fed.us/pubs/40543. (Accessed May 6, 2014).

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

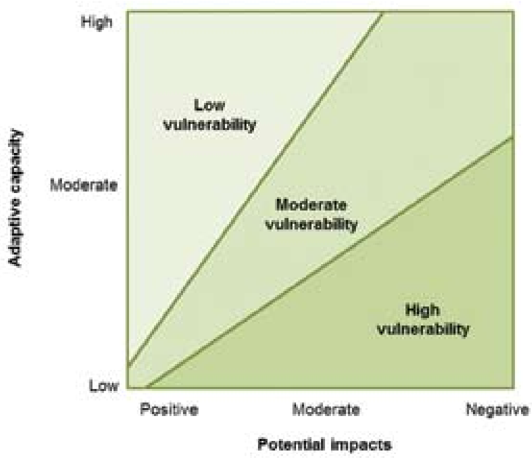
What do you think are the greatest potential impacts to the ecosystem?

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

(Continued on next page)

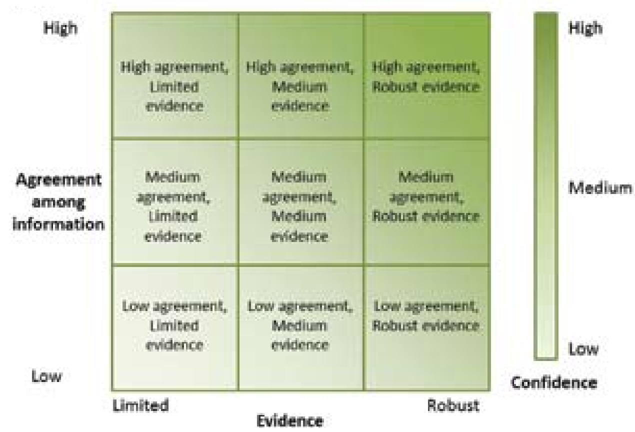
Vulnerability Determination

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 7: 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 26.—Contributors to implications summaries in 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
Dave Fehringer	The Forestland Group	Forest management operations & infrastructure
Chris 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

Janowiak, Maria K.; Iverson, Louis R.; Mladenoff, David J.; Peters, Emily; Wythers, Kirk R.; Xi, Weimin; Brandt, Leslie A.; Butler, Patricia R.; Handler, Stephen D.; Shannon, P. Danielle; Swanston, Chris; Parker, Linda R.; Amman, Amy J.; Bogaczyk, Brian; Handler, Christine; Lesch, Ellen; Reich, Peter B.; Matthews, Stephen; Peters, Matthew; Prasad, Anantha; Khanal, Sami; Liu, Feng; Bal, Tara; Bronson, Dustin; Burton, Andrew; Ferris, Jim; Fosgitt, Jon; Hagan, Shawn; Johnston, Erin; Kane, Evan; Matula, Colleen; O'Connor, Ryan; Higgins, Dale; St. Pierre, Matt; Daley, Jad; Davenport, Mae; Emery, Marla R.; Fehringer, David; Hoving, Christopher L.; Johnson, Gary; Neitzel, David; Notaro, Michael; Rissman, Adena; Rittenhouse, Chadwick; Ziel, Robert. 2014. **Forest ecosystem vulnerability assessment and synthesis for northern Wisconsin and western Upper Michigan: a report from the Northwoods Climate Change Response Framework project.** Gen. Tech. Rep. NRS-136. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 247 p.

Forest ecosystems across the Northwoods will face direct and indirect impacts from a changing climate over the 21st century. This assessment evaluates the vulnerability of forest ecosystems in the Laurentian Mixed Forest Province of northern Wisconsin and western Upper Michigan under 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 assess vulnerability to climate change. Upland spruce-fir, lowland conifers, aspen-birch, lowland-riparian hardwoods, and red pine forests were determined to be the most vulnerable ecosystems. White pine and oak forests 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-term natural resource planning.

KEY WORDS: climate change, vulnerability, adaptive capacity, Climate Change Tree Atlas, LINKAGES, LANDIS-II, PnET-CN, expert elicitation, Wisconsin, Michigan

Northern Research Station

www.nrs.fs.fed.us