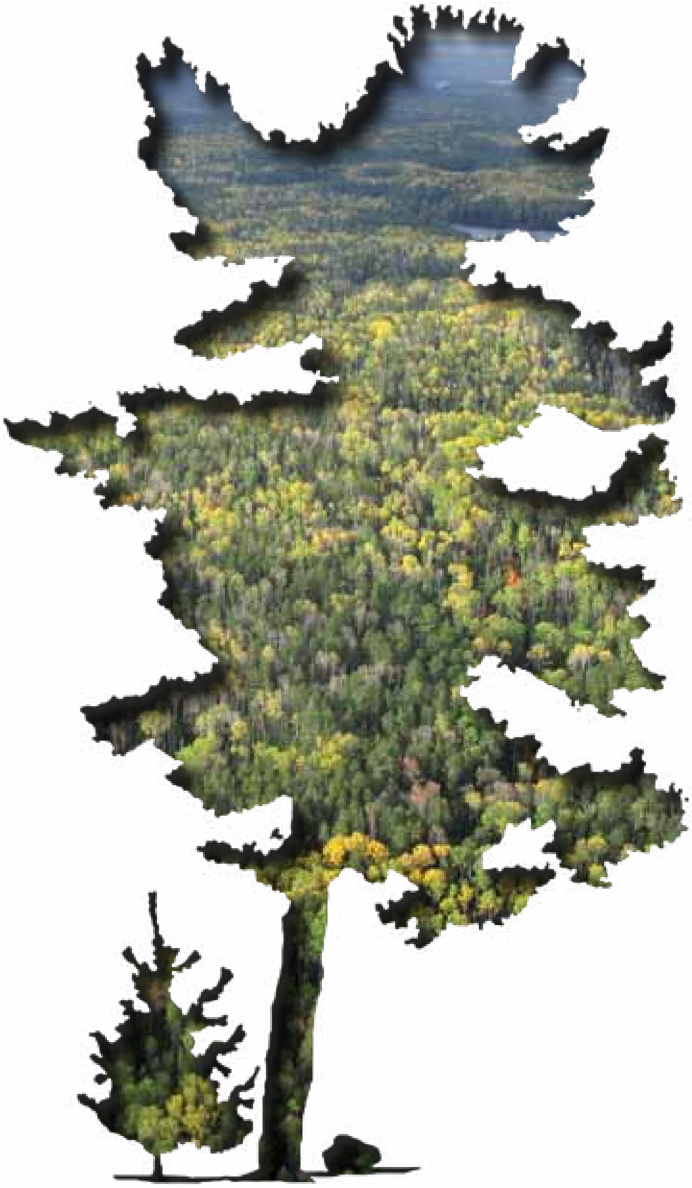
United States Department of Agriculture

Minnesota Forest Ecosystem Vulnerability Assessment and Synthesis:

A Report from the Northwoods Climate Change Response Framework Project



Forest Service

Northern Research Station

General Technical Report NRS-133

May 2014

ABSTRACT

The forests in northern Minnesota will be affected directly and indirectly by a changing climate during the 21st century. This assessment evaluates the vulnerability of forest ecosystems in the Laurentian Mixed Forest Province of Minnesota 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 northern Minnesota forests to assess ecosystem vulnerability through a formal consensus-based expert elicitation process.

The summary of the contemporary landscape identifies major forest trends and stressors currently threatening forests in the region. Observed trends in climate during 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 3.0 to 8.8 °F for the assessment area. Projections for precipitation indicate an increase in winter and spring precipitation, and summer and fall precipitation projections vary by scenario. We identified potential impacts on forests by incorporating these climate projections into three forest impact models (Tree Atlas, LANDIS-II, and PnET-CN). Model projections suggest that northern boreal species such as black spruce and paper birch may fare worse under future conditions, but other species such as American basswood and white pine may benefit from projected changes in climate. Published literature on climate impacts related to wildfire, invasive species, and diseases also contributed to the overall determination of climate change vulnerability.

We assessed vulnerability for eight forest systems in northern Minnesota: six Native Plant Community Systems and two managed forest systems. The basic assessment was conducted through a formal elicitation process of 23 science and management experts from across the state, who considered vulnerability in terms of potential impacts on a system and the system's adaptive capacity. Acid Peatlands, Forested Rich Peatlands, and Wet Forests were determined to be the most vulnerable. Systems adapted to disturbance through fire and drought or flooding, such as Fire-Dependent Forests or Floodplain 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-range planning.

Cover Photo

Fall colors in northeastern Minnesota. Photo by Jack Greenlee, Superior National Forest.

Manuscript received for publication September 2013

Published by:	For additional copies, contact:
USDA FOREST SERVICE 11 CAMPUS BLVD., SUITE 200 NEWTOWN SQUARE, PA 19073-3294	USDA Forest Service Publications Distribution 359 Main Road Delaware, OH 43015-8640
May 2014	Fax: 740-368-0152

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

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PREFACE

CONTEXT AND SCOPE

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

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

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

The large list of authors reflects the highly collaborative nature of this assessment. Stephen Handler served as the primary writer and editor of the assessment. Matthew Duveneck, Louis Iverson, Emily Peters, Robert Scheller, Kirk Wythers, and Peter Reich led the forest impact modeling and contributed writing and expertise to much of the assessment. All modeling teams coordinated their efforts impressively. Leslie Brandt, Patricia Butler, Maria Janowiak, Danielle Shannon, and Chris Swanston provided significant investment into the generation and coordination of content, data analysis and interpretation, and coordination among many other Climate Change Response Framework assessments. Kelly Barrett, Randy Kolka, Casey McQuiston, Brian Palik, Clarence Turner, and Mark White provided substantial input throughout the document. Cheryl Adams, Anthony D’Amato, Suzanne Hagell, Patricia Johnson, Rosemary Johnson, Mike Larson, Stephen Matthews, Rebecca Montgomery, Steve Olson, Matthew Peters, Anantha Prasad, Jack Rajala, Jad Daley, Mae Davenport, Marla Emery, David Fehringer, Christopher Hoving, Gary Johnson, Lucinda Johnson, David Neitzel, Adena Rissman, Chadwick Rittenhouse, and Robert Ziel provided input to specific chapters.

In addition to the authors listed, many people made valuable contributions to the assessment. John Almendinger and Paul Dubuque (Minnesota Department of Natural Resources) provided information and photos regarding the Native Plant Communities in Minnesota, as did Lawson Gerdes (Minnesota County Biological Survey). George

Host and Terry Brown (Natural Resources Research Institute) provided a map on the distribution of Native Plant Community Systems for Chapter 1. Tara Bal and Andrew Storer (Michigan Technological University) provided a summary of ongoing research for Chapter 5. Don Rees (Chugach National Forest, formerly with the Chippewa National Forest) provided guidance for the overall structure of the document.

We would especially like to thank John Pastor (University of Minnesota – Duluth), Mark Fulton (Bemidji State University), Peter Wycoff (University of Minnesota – Morris), and Craig Loehle (National Council for Air and Stream Improvement), who provided formal technical reviews of the assessment. Their thorough reviews greatly improved the quality of this assessment.

CONTENTS

EXECUTIVE SUMMARY

This assessment evaluates key ecosystem vulnerabilities for forest ecosystems in the Laurentian Mixed Forest Province in Minnesota 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 land owners 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 and local knowledge and expertise, are used to identify the factors that contribute to the vulnerability of major forest systems within the assessment area over the next 100 years. A final chapter summarizes the implications of these impacts and vulnerabilities for forest management across the region.

CHAPTER 1: THE CONTEMPORARY LANDSCAPE

Summary

This chapter describes the forests and related ecosystems across the Laurentian Mixed Forest Province in Minnesota and summarizes current threats and management trends. This 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

- More than 85 percent of the forest land in Minnesota occurs within the assessment area, most of which is owned by private land owners.
- Major stressors and threats to forest ecosystems in the region are:
  - Fragmentation and land-use change
  - Fire regime shifts
  - Nonnative species invasion
  - Forest pests and disease
  - Overbrowsing by deer
  - Extreme weather events
- Management practices during the past several decades have tended to favor aspen across the landscape and reduce species diversity and structural complexity.
- The forest products industry is a major contributor to the region's economy, and most 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

Summary

This chapter provides a brief background on climate change science, models that simulate future climate change, and models that project the effects of climate change on tree species and 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.
- Major contributors to warming are greenhouse gases from fossil fuel burning, agriculture, and changes in land use.

CHAPTER 3: OBSERVED CLIMATE CHANGE

Summary

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

Main Points

- Mean, maximum, and minimum temperatures have been increasing across all seasons, with winter temperatures warming the most rapidly.
- The assessment area has received more precipitation, particularly in the summer and fall.
- More precipitation has been delivered in heavy events of 3 inches or greater.
- Snowfall has been decreasing across northern Minnesota, although there has been an increase in large winter storms.
- Climate change has also been indicated by trends in lake ice, growing season length, and wildlife range shifts.

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

Summary

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

Palisade Head on the North Shore of Lake Superior. Photo by Casey McQuiston, Superior National Forest.

Main Points

- Temperature is projected to increase across all seasons over the next century, with dramatic warming projected in winter.
- Precipitation is projected to increase in winter and spring across a range of climate scenarios, but summer precipitation may decrease.
- Intense precipitation events may continue to become more frequent.
- 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

Summary

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

Main Points

- Boreal species such as quaking aspen, paper birch, tamarack, and black spruce are projected to decrease in suitable habitat and biomass across the assessment area.
- Species with ranges that extend to the south such as American basswood, black cherry, northern red oak, and eastern white pine may increase in suitable habitat and biomass across the assessment area.
- Many common species in northern Minnesota may decline under the 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.
- Model projections do not account for many other factors that may be modified by a changing climate, including:
    - Drought stress
    - Changes in hydrology and flood regime
    - Wildfire frequency and severity
    - Altered nutrient cycling
    - Changes in invasive species, pests, and pathogens

CHAPTER 6: FOREST ECOSYSTEM VULNERABILITIES

Summary

This chapter focuses on the climate change vulnerability of major forest systems in the assessment area during the next 100 years, particularly on shifts in dominant species, system drivers, and stressors. The adaptive capacity of forest systems was also examined as a key component of overall vulnerability. Synthesis statements are provided to capture general trends, and detailed vulnerability determinations are also provided for eight major forest systems (Table 1). We consider a system to be vulnerable if it is at risk of a composition change leading to a new identity, or if the system is anticipated to suffer substantial declines in health or productivity.

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.

Table 1.—Vulnerability determinations by natural community type

Community Type	Vulnerability	Evidence	Agreement
Fire-Dependent Forest	Moderate	Medium	Medium
Mesic Hardwood Forest	Moderate	Medium	Medium
Floodplain Forest	Low-Moderate	Limited-Medium	Medium
Wet Forest	High	Limited-Medium	Medium
Forested Rich Peatland	High	Medium	Medium-High
Acid Peatland	High	Medium	Medium-High
Managed Aspen	Moderate-High	Medium	High
Managed Red Pine	Moderate-High	Medium	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.
- **Growing seasons will get longer (robust evidence, high agreement).** There is high agreement among information sources that projected temperature increases will lead to longer growing seasons in the assessment area.
- **The amount and timing of precipitation will change (medium evidence, high agreement).** All global climate models agree that there will be changes in precipitation patterns across the assessment area.
- **Intense precipitation events will continue to become more frequent (medium evidence, medium agreement).** There is some agreement that the number of heavy precipitation events will continue to increase in the assessment area. If they do increase, impacts from flooding and soil erosion may also become more damaging.
- **Droughts will increase in duration and area (limited evidence, low agreement).** A study using multiple climate models indicates that drought may increase in length and extent, and an episodic precipitation regime could mean longer dry periods between events.
- **Soil moisture patterns will change (medium evidence, high agreement), with drier soil conditions later in the growing season (medium evidence, medium agreement).** Studies show that climate change will affect soil moisture, but there is disagreement among climate and impact models on how soil moisture will change during the growing season.
- **Climate conditions will increase fire risks by the end of the century (medium evidence, medium agreement).** Some national and global studies suggest that wildfire risk will increase in the region, but few studies have specifically looked at wildfire potential in the assessment area.
- **Many invasive species, insect pests, and pathogens will increase or become more damaging (limited evidence, high agreement).** Evidence indicates that an increase in temperature and greater moisture stress 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).** Impact models agree that boreal or northern species will experience reduced suitable habitat and biomass across the assessment area, and that they may be less able to take advantage of longer growing seasons and warmer temperatures than temperate forest communities.
- **Southern species will be favored by climate change (medium evidence, high agreement).** Impact models agree that many temperate species will experience increasing 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 communities will change across the landscape (limited evidence, high agreement).** Although few models have specifically examined how communities may change, model results from individual species and ecological principles suggest that recognized forest communities may change in composition as well as occupied range.
- **Forest productivity will increase across the assessment area (medium evidence, medium agreement).** Model projections and other evidence support modest productivity increases for forests across the assessment area, although there is uncertainty about the effects of CO_2 fertilization. It is expected that productivity will be reduced in localized areas.

Adaptive Capacity Factors

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

Summary

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

Main Points

- Plants, animals, and people that depend on forests may face additional challenges as the climate shifts.
- Greater financial investments may be required to manage forests and infrastructure and to prepare for severe weather events.
- Management activities such as wildfire suppression or recreation activities such as snowmobiling may need to be altered as temperatures and precipitation patterns change.
- 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 to 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:

- Provide a forum for people working across the Northwoods to effectively and efficiently share experiences and lessons learned.
- Develop new user-friendly information and tools to help land managers factor climate change considerations into decisionmaking.
- 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 Minnesota and will serve as a companion for similar assessments completed in northern Michigan and Wisconsin. Additionally, regional Framework projects are underway in the Central Hardwoods region (Missouri, Illinois, and Indiana) and the Central Appalachians region (Ohio, West Virginia, and Maryland).

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

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

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

This assessment bears some similarity to other synthesis documents about climate change science, such as the National Climate Assessment (draft report at http://ncadac.globalchange.gov/) and the Intergovernmental Panel on Climate Change (IPCC) reports (e.g., IPCC 2007). Where appropriate, we refer to these larger-scale documents when discussing national and global changes. This assessment differs from these reports in many ways, however. This assessment was not commissioned by any federal government agency nor does it give advice or recommendations to any federal government agency. It also does not evaluate policy options or provide input into federal priorities. Instead, this report was developed by the authors to fulfill a joint need of understanding local impacts of climate change on forests and assessing which tree species and forest systems may be the most vulnerable in northern Minnesota. 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 Minnesota under a range of future climate scenarios, and determine the vulnerability of forest communities to these changes during the next 100 years. Included is a synthesis of information about the landscape as well as projections of climate and vegetation changes used to assess these vulnerabilities. Uncertainties and gaps in understanding are discussed throughout the document.

This assessment covers 23.3 million acres throughout northern Minnesota (Fig. 1). The assessment area boundaries are defined by the Laurentian Mixed Forest Province (Ecological Province 212) in Minnesota (Bailey 1995, Bailey et al. 1994). Ecological Section X in Minnesota of Albert's *Regional Landscape Ecosystems* describes virtually the same area (Albert 1995). In addition to these ecological boundaries, we used county-level information that most closely represented the assessment area when ecoregional data were not available, limiting our selections to the 23 counties that are most analogous to the assessment area (Box 1).

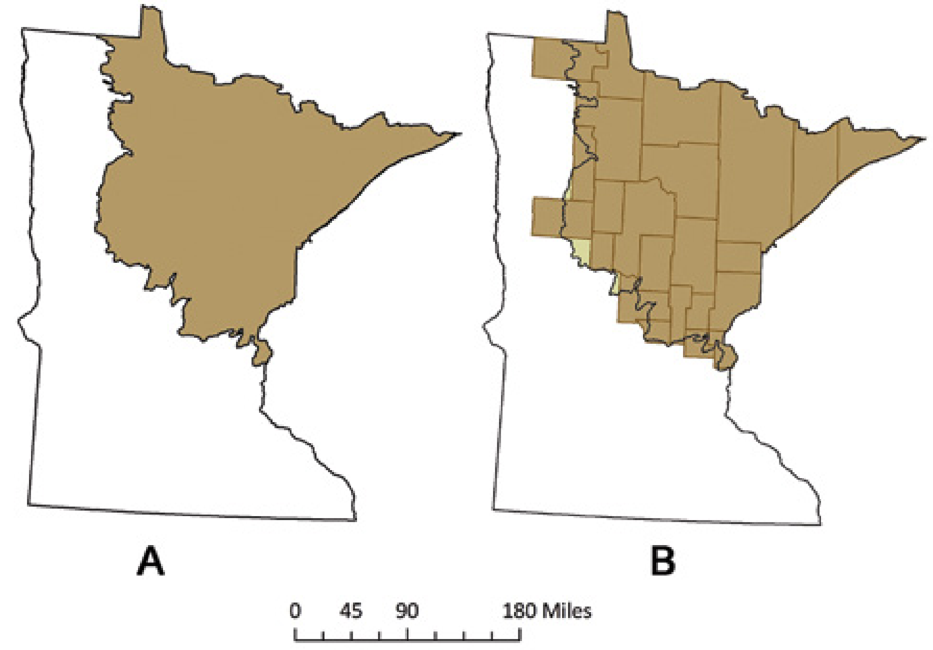


Figure 1.—(A) Assessment area and (B) the 23 counties used to approximate the Laurentian Mixed Forest Province in Minnesota when county-level data were required.

Box 1: Counties Used to Represent the Assessment Area

Aitkin
Becker
Beltrami
Benton
Carlton
Cass
Chisago
Clearwater
Cook
Crow Wing
Hubbard
Isanti
Itasca
Kanabec
Kochiching
Lake
Lake of the Woods
Mille-Lacs
Morrison
Pine
Roseau
St. Louis
Wadena

This assessment area covers more than 85 percent of the forested area within Minnesota (U.S. Forest Service 2011). Within this landscape, major land owners include the State of Minnesota (approximately 3.4 million acres), counties (approximately 2.8 million acres), the Superior National Forest (approximately 2.0 million acres), and the Chippewa National Forest (approximately 667,000 acres) (U.S. Forest Service 2011). Supplementary information specific to these land owners was used when available and relevant to the broader landscape. This assessment synthesizes information covering all of northern Minnesota in recognition of the area's dispersed patterns of forest composition and land ownership.

ASSESSMENT CHAPTERS

This assessment contains the following chapters:

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

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 Minnesota, summarized from The Nature Conservancy's interactive ClimateWizard database and published literature. This chapter also discusses some relevant ecological indicators of observed climate change.

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

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

Chapter 6: Forest Ecosystem Vulnerabilities synthesizes the potential effects of climate change on the forested ecosystems of the Laurentian Mixed Forest Province and provides detailed vulnerability determinations for eight major forest systems.

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

CHAPTER 1: THE CONTEMPORARY LANDSCAPE

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

LANDSCAPE SETTING

Physical Environment

This section draws information primarily from Bailey's *Description of the Ecoregions of the United States* (Bailey 1995, McNab and Avers 1994). Albert's description of regional landscape ecosystems in Michigan, Minnesota, and Wisconsin (Albert 1995) is also used to supplement this information, along with the description by the Minnesota Department of Natural Resources (DNR) of the Ecological Land Classification in the state (Minnesota DNR 2003).

Minnesota lies at the intersection of four Ecological Provinces (Fig. 2). The assessment area is the portion of the Laurentian Mixed Forest Province located in Minnesota, which can be thought of as a transition zone between temperate broadleaf forests to the south and true boreal forests to the north (Minnesota DNR 1999). The major prairie-forest border within North America bisects Minnesota and continues farther north into Canada and south into the Midwestern United States.

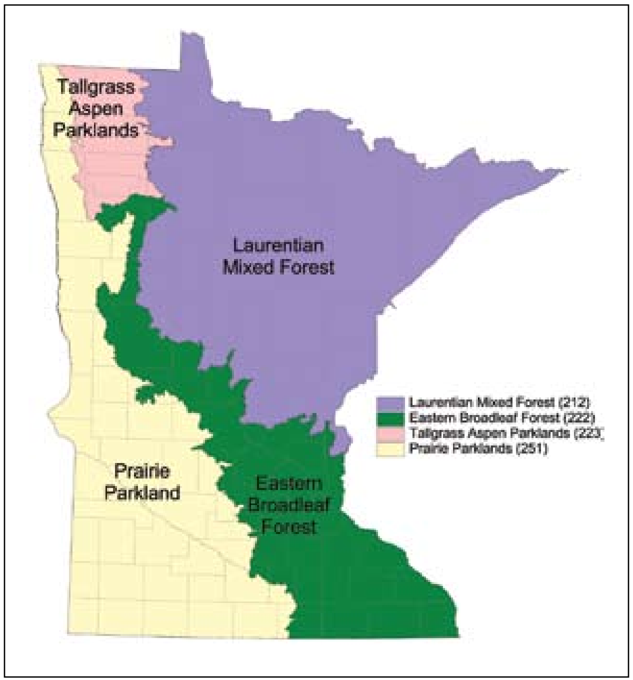


Figure 2.—Ecological provinces in Minnesota, as defined by Bailey (1995). Modified from Minnesota Department of Natural Resources (1999).

Climate

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

Annual precipitation averages 27.2 inches across the Laurentian Mixed Forest Province (ClimateWizard

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

Season	Average precipitation (inches)	Mean temperature (°F)	Mean maximum temperature (°F)	Mean minimum temperature (°F)
Annual	27.2	39.0	50.2	27.7
Winter (Dec.-Feb.)	2.3	9.9	20.7	-1.0
Spring (Mar.-May)	5.8	39.6	51.8	27.5
Summer (June-Aug.)	12.0	64.5	76.6	52.4
Fall (Sept.-Nov.)	7.1	41.5	51.5	31.5

2012), ranging from 21 inches along the western border of the province to 32 inches along the Lake Superior shoreline (Minnesota DNR 2003). This gradient from drier in the northwest to wetter in the east is consistent across all seasons in the assessment area. Summer is by far the wettest season, with almost 45 percent of annual precipitation falling from June through August (Table 2). Winter is the driest month on average across the assessment area. Annual snowfall is influenced strongly by proximity to Lake Superior and varies from 40 to 70 inches, with much higher totals possible in areas prone to lake-effect snow (McNab and Avers 1994).

The mean annual temperature is 39 °F (3.9 °C) (ClimateWizard 2012), ranging from 34 °F (1.1 °C) along the northern border with Canada to 40 °F (4.4 °C) toward the southern end of the Province (Minnesota DNR 2003). Winter temperatures are very cold, with minimum extremes ranging from -30 °F (-34.4 °C) near Lake Superior to -45 °F (-42.8 °C) and colder to the west. The general pattern during the growing season within the assessment area is warmer and drier in the southwest, shifting to cooler and wetter in the northeast. Growing season length ranges from 80 to 140 days, with the shortest growing seasons occurring toward the northern, inland portions of the region (McNab and Avers 1994). Compared to similar latitudes in the nearby states of Wisconsin and Michigan, Minnesota generally features a more continental climate with hotter summers and colder winters. Droughts are also more common in Minnesota than in Wisconsin or Michigan (Stearns 1997b).

Geology and Landform

Bedrock geology in northern Minnesota commonly includes granite, greenstone, quartzite, iron oxides, metasediments, and igneous rocks. In the assessment area, bedrock is most commonly exposed in upland areas near the shoreline of Lake Superior.

Glacial activity has shaped the terrain of northern Minnesota. The last glacier receded from the state approximately 12,000 years ago. Glaciers moved along the Great Lake valleys and subsequently spread to upland areas. Glaciers were active for thousands of years during the most recent Ice Age, so the terrain of Minnesota reflects a complicated pattern of glacial advance and retreat. A large glacial lake (Glacial Lake Agassiz) also existed along the northern section of the assessment area. Thin soils and kettle lakes are common throughout the assessment area, as are rolling glacial till plains and flat, poorly drained peatlands (Minnesota DNR 2003). The most prominent uplands are linear ranges paralleling the Lake Superior shoreline and similar ranges farther north (McNab and Avers 1994). Many forest communities are associated with particular landforms and geologic features, and knowledge of the extent and pattern of these features is necessary when considering how climate change may shape forest ecosystems across the assessment area.

Hydrology

Water resources are an abundant and defining feature of the assessment area. The assessment area is bounded by Lake Superior to the east, and the Laurentian Mixed Forest Province contains thousands of inland lakes, including most of the largest lakes within the state (Minnesota DNR 2012b). The U.S. Geological Survey (USGS) National Land Cover Database (NLCD) categorizes 36.5 percent of the assessment area as wetland and 9.3 percent as open water (USGS 2011a).

Within the assessment area, the largest watersheds are the St. Louis, Rainy, Big Fork, and Crow Wing Rivers, along with the headwaters of the Mississippi River. According to USGS streamflow stations in northern Minnesota on the St. Louis and Big Fork Rivers, peak surface flow typically arrives in a major pulse during April, May, and June, with flows substantially reduced from July through September (Fig. 3) (USGS 2011b). During the growing season, the lowest streamflow typically occurs in August and September. Within the assessment area, less than 10 percent of the annual precipitation falls during winter (ClimateWizard 2012). Two-thirds of the annual precipitation generally falls during the growing season of May through September (18 inches).

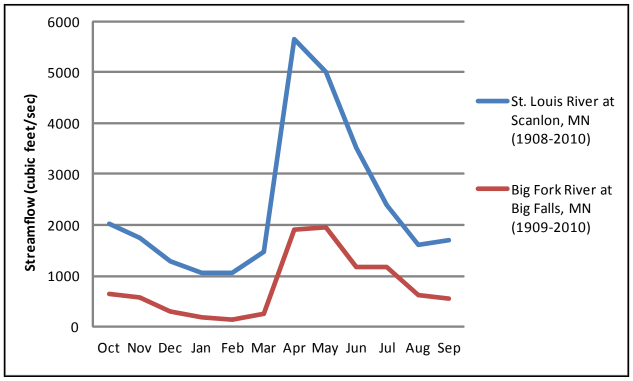


Figure 3.—Average annual streamflow for two large watersheds in northern Minnesota. The St. Louis River drains into Lake Superior and has a drainage area of 3,430 square miles. The Big Fork River flows north to Canada and has a drainage area of 1,480 square miles (U.S. Geological Survey 2011b).

Soils

The combination of underlying bedrock, glacial activity, vegetation, and climate has resulted in a variety of soils within this assessment area. Upland and wetland forest soils have developed on either glacial drift or bedrock (Albert 1995). Glacial till, as well as material deposited from lakebeds and rivers, is extensive throughout the area. Soils in the assessment area are quite variable in texture, chemistry, stoniness, and drainage conditions. Glacial deposits can be 200 to 600 feet thick in some locations, but bedrock outcrops are common in the eastern portion of the assessment area. Fine-scale information on soil types in each Ecological Section, Sub-section, and Sub-subsection is available in Albert's descriptions of Regional Landscape Ecosystems (Albert 1995) and the U.S. Department of Agriculture, Natural Resources Conservation Service Web Soil Survey portal (websoilsurvey.nrcs.usda.gov/app/HomePage.htm).

Ecosystem Composition

Land Cover

This assessment area covers 23.3 million acres across northern Minnesota. According to the NLCD, wetlands account for 36.5 percent of the overall land cover in this assessment area (USGS 2011a). Much of the terrain in northern Minnesota is composed of forested bogs and lowland forests, and these lands are categorized as wetlands in the NLCD. Forests account for 36.5 percent of the assessment area, and planted/cultivated land and water each account for roughly 10 percent. Only 2.6 percent of the assessment area is classified as developed land. According to data from the U.S. Forest Service, Forest Inventory and Analysis (FIA) Program, forest land covers 63 percent of the assessment area (14.6 million acres) (U.S. Forest Service 2011). The FIA figure for forest land is different from the NLCD figure for forests because it captures many of the forested wetland and planted forest stands that the NLCD classification may have termed "wetland" or "planted."

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

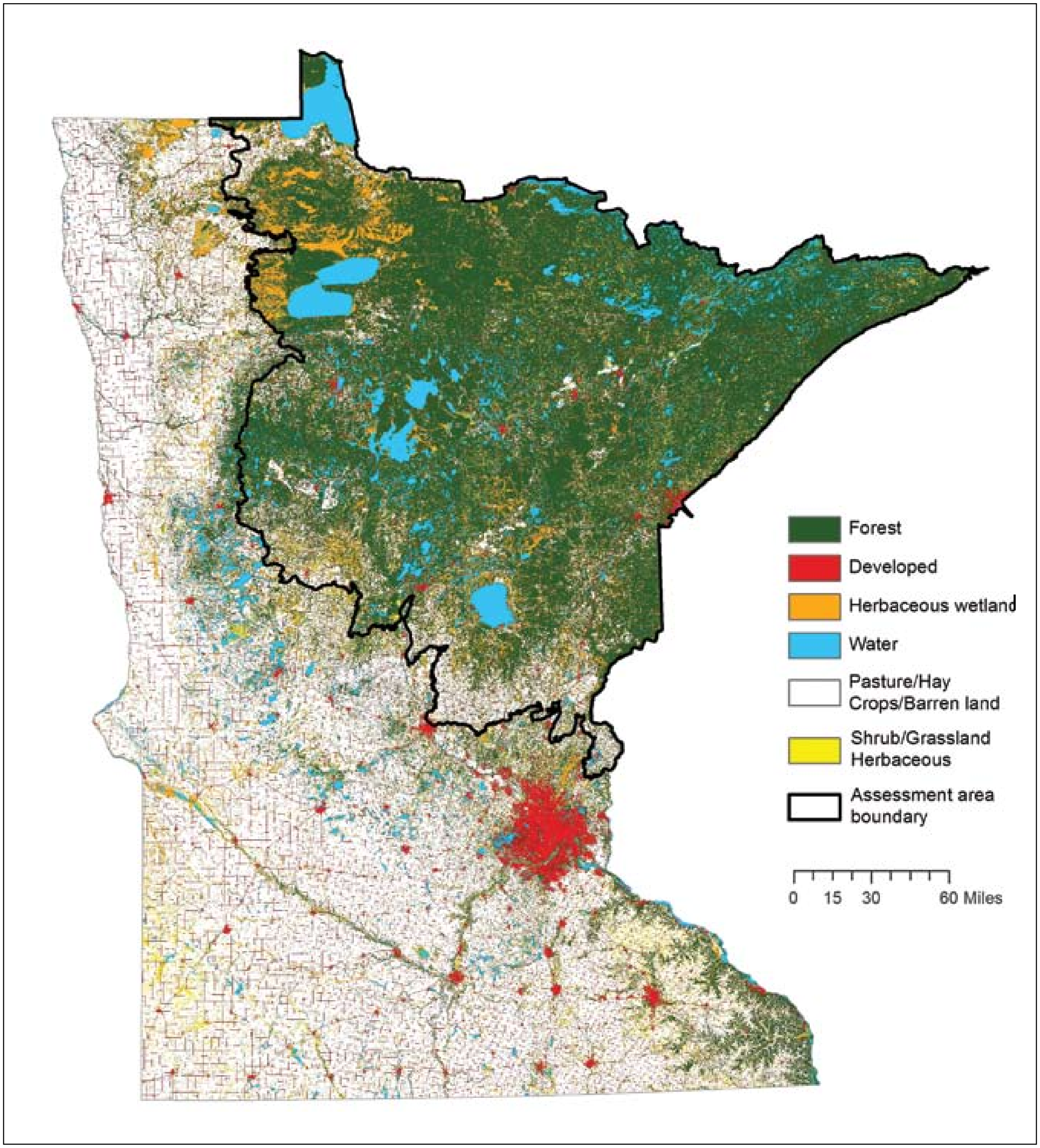


Figure 4.—Land cover in Minnesota based on the U.S. Geological Survey National Land Cover Database (2006).

The original land cover in Minnesota has been estimated from 19th-century General Land Office surveys (Stearns 1997a). Estimates are that approximately half to two-thirds of Minnesota was forested (Miles et al. 2011). In general, deciduous forests are more commonly found in areas of more productive soils and coniferous forests occur in less favorable locations with poorer soils. Albert (1995) offers a more complete summary of presettlement vegetation throughout the assessment area. Appendix 1 lists common and scientific names of plant, fauna, and other species mentioned in this assessment. Conifers dominated both upland and lowland forests, but northern hardwoods were present throughout the area and were dominant on 10 to 25 percent of the mesic sites. Sugar maple and other northern hardwoods were nearly absent from the northern and northwestern portions of the Laurentian Mixed Forest Province, probably because of frequent and intense fires, late spring frosts, and poor drainage conditions in the peatlands. On the uplands, jack pine dominated the droughty, fire-prone outwash plains, beach ridges, and thin soils on bedrock. White pine and red pine dominated pitted outwash and sandy moraines that burned less frequently and less intensely than the outwash plains. Aspen-birch forests occurred intermittently throughout upland areas. The glacial lake plains all supported extensive areas of swamp and peatland dominated by black spruce and tamarack, along with some northern white-cedar, balsam poplar, paper birch, and aspen.

Current estimates are that one-third of Minnesota is forested. A dramatic decline in forest cover occurred during the late 1800s and early 1900s, when roughly half of the state's forests were lost to lumbering and conversion to agriculture (Minnesota DNR 2010a). The overall extent of forest land in Minnesota has been stable during the past 40 years. Forest land in the northern half of the state declined by about 200,000 acres from 1977 to 2008, whereas the southern half of the state gained about 600,000 acres during this period (Miles et al. 2011). According to MODIS data from the National Aeronautics and Space Administration (NASA), more than 85 percent of Cook, Koochiching, and Lake Counties is forest land, and less than 1 percent of Benton and Isanti Counties is forest land (Headwaters Economics 2011). Counties with smaller percentages of forest land are located in the agricultural areas along the southern edge of the assessment area.

Although forest is the primary land cover type in the assessment area, much of this forest exists as fragmented edges or patches (Minnesota DNR 2010a). Most of the state's interior forest occurs within the assessment area (Fig. 5). Between 1992 and 2001, northeastern Minnesota lost portions of interior forest. This trend continued from 2001 to 2006, as ecological sections within the assessment area lost 1 to 8 percent of their interior forest land (Riitters and Wickham 2012). Fragmentation changes forest ecosystems in a variety of ways, such as altering microclimates, facilitating invasive species, and disrupting disturbance regimes (Riitters and Wickham 2012). Habitat fragmentation is crucial in the context of climate change because it may determine the ability of tree species to migrate and respond naturally to changing conditions (Iverson et al. 2004a, Scheller and Mladenoff 2008).

Forest Communities

Natural Communities

The Minnesota DNR has prepared a classification of Native Plant Communities (NPCs) in the state based on analysis of extensive field plot data (Minnesota DNR 2003). The authors of this assessment decided to use the NPC classification as a basis for describing forest ecosystems in this vulnerability assessment, a decision supported by partner organizations throughout Minnesota. Native Plant Communities are groups of native plants not greatly altered by modern human activity or by introduced organisms; they often repeat over space and time. They are classified in a hierarchy from landscape-level NPC Systems (e.g., Fire-Dependent Forests) to more specific NPC Classes (e.g., Central Dry Pine Woodland) to even more specific Types and Sub-types. NPCs are organized by considering vegetation, hydrology, landforms, soils, and natural disturbance regimes.

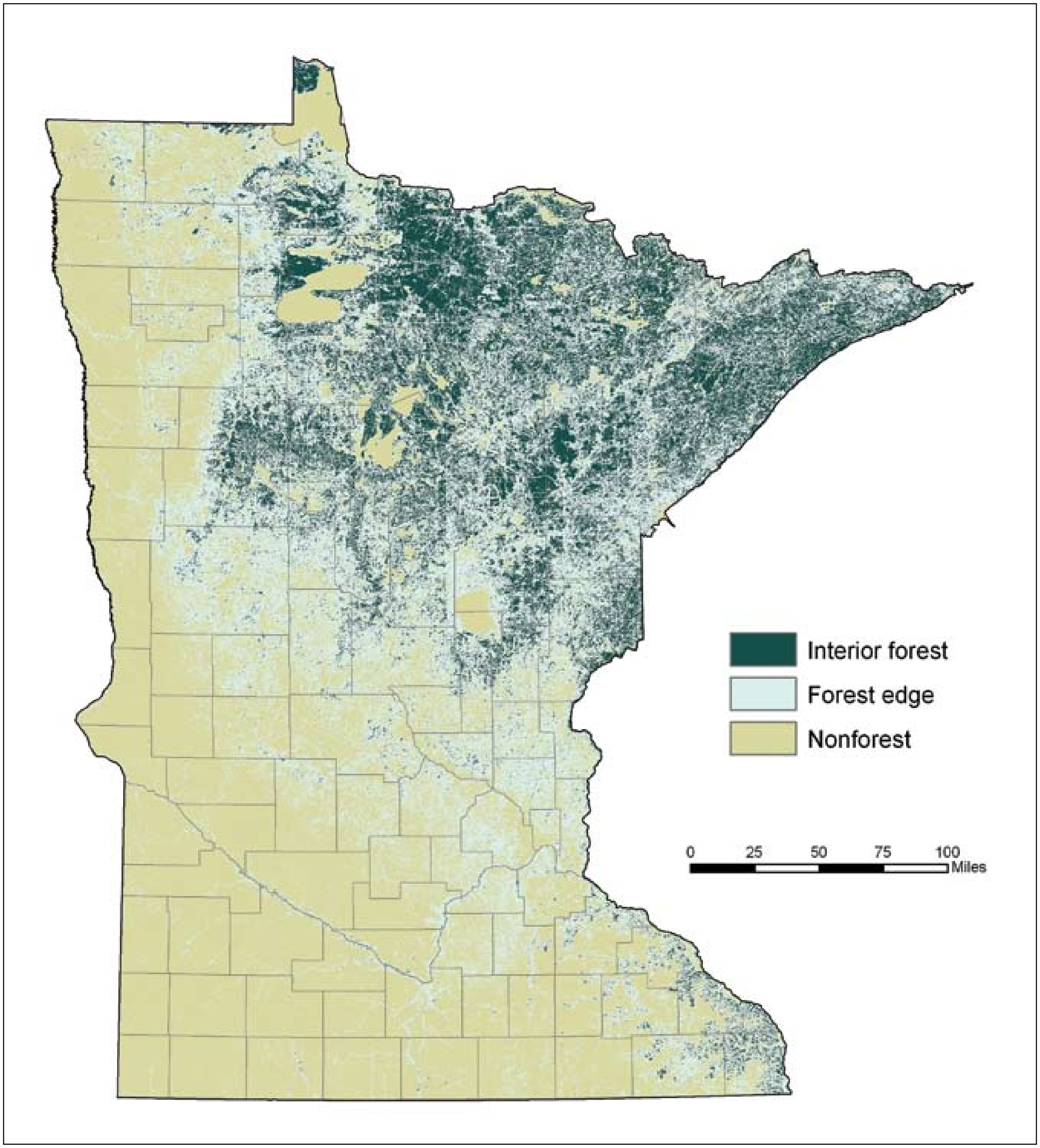


Figure 5.—Forest fragmentation in Minnesota. No distinction is made between natural or developed edges in this analysis, and a forest pixel must be at least 295 feet from a nonforest pixel to be considered an interior forest. Data are from the 2006 National Land Cover Database. Prepared by D. Meneguzzo, U.S. Forest Service.

Thirteen NPC Systems and 64 NPC Classes are recognized throughout the Laurentian Mixed Forest Province in Minnesota (Minnesota DNR 2003). Of these, six NPC Systems are of concern for this assessment because they feature substantial forest cover and are characterized by dominant tree species (Table 3). The authors of this assessment decided to focus on the System level for the purposes of determining climate change vulnerability, because more precise levels of the NPC hierarchy (e.g., Classes and Types) occur at smaller spatial scales than available climate information. For complete descriptions of associated landforms, soil types, disturbance regimes, and common species for all NPC Systems, see the *Field Guide to the Native Plant Communities of Minnesota: the Laurentian Mixed Forest Province* (Minnesota DNR 2003).

Table 3.—Forested Native Plant Community Systems occurring within the Laurentian Mixed Forest Province (Minnesota Department of Natural Resources 2003)

Fire-Dependent Forest System		
Red pine *	Balsam fir *	Bur oak
Jack pine *	Black spruce *	White spruce
Quaking aspen *	Northern red oak	Northern pin oak
Paper birch *	Red maple	Northern white-cedar
Eastern white pine *	Bigtooth aspen	
Mesic Hardwood Forest System		
Sugar maple *	Red maple *	White spruce *
American basswood *	Bur oak *	Northern white-cedar
Paper birch *	Green ash *	Ironwood
Quaking aspen *	Black ash *	Eastern white pine
Northern red oak *	Yellow birch *	White oak
Floodplain Forest System		
Silver maple *	American elm *	Eastern cottonwood *
Black ash *	American basswood *	Boxelder
Green ash *	Black willow *	Bur oak
Wet Forest System		
Black ash *	Black spruce *	White spruce
Northern white-cedar *	Paper birch	Green ash
Balsam fir *	Yellow birch	American basswood
Balsam poplar *	Quaking aspen	Tamarack
Red maple *	American elm	
Forested Rich Peatland System		
Tamarack *	Balsam fir	Paper birch
Black spruce *	Speckled alder	Eastern white pine
Northern white-cedar *	Red maple	White spruce
Acid Peatland System		
Tamarack *	Black spruce *	Bog birch

Species that are characteristic of each system are marked with an asterisk (*), but these are not exhaustive species lists. Scientific names can be found in Appendix 1.

These NPC Systems have recently been mapped across the assessment area (Table 4, Fig. 6). Fire-Dependent Forests are the most abundant NPC System in the assessment area, concentrated primarily in the northeastern portion of the state. Mesic Hardwood Forests are concentrated in the southern and central portion of the assessment area, with a thin band occurring along the North Shore of Lake Superior. Forested Rich Peatlands are mostly concentrated in a large area between Red Lake and Lake of the Woods. Distribution maps for individual species across the state are available from FIA data (Miles et al. 2011).

Table 4.—Acreage occupied by each of the forested Native Plant Community Systems within the assessment area (unpublished data, T. Brown and G. Host, Natural Resources Research Institute)

Native Plant Community System	Acres
Fire-Dependent Forest	7,549,215
Mesic Hardwood Forest	4,745,114
Floodplain Forest	8,978
Wet Forest	1,754,886
Forested Rich Peatland	3,987,130
Acid Peatland	1,472,061

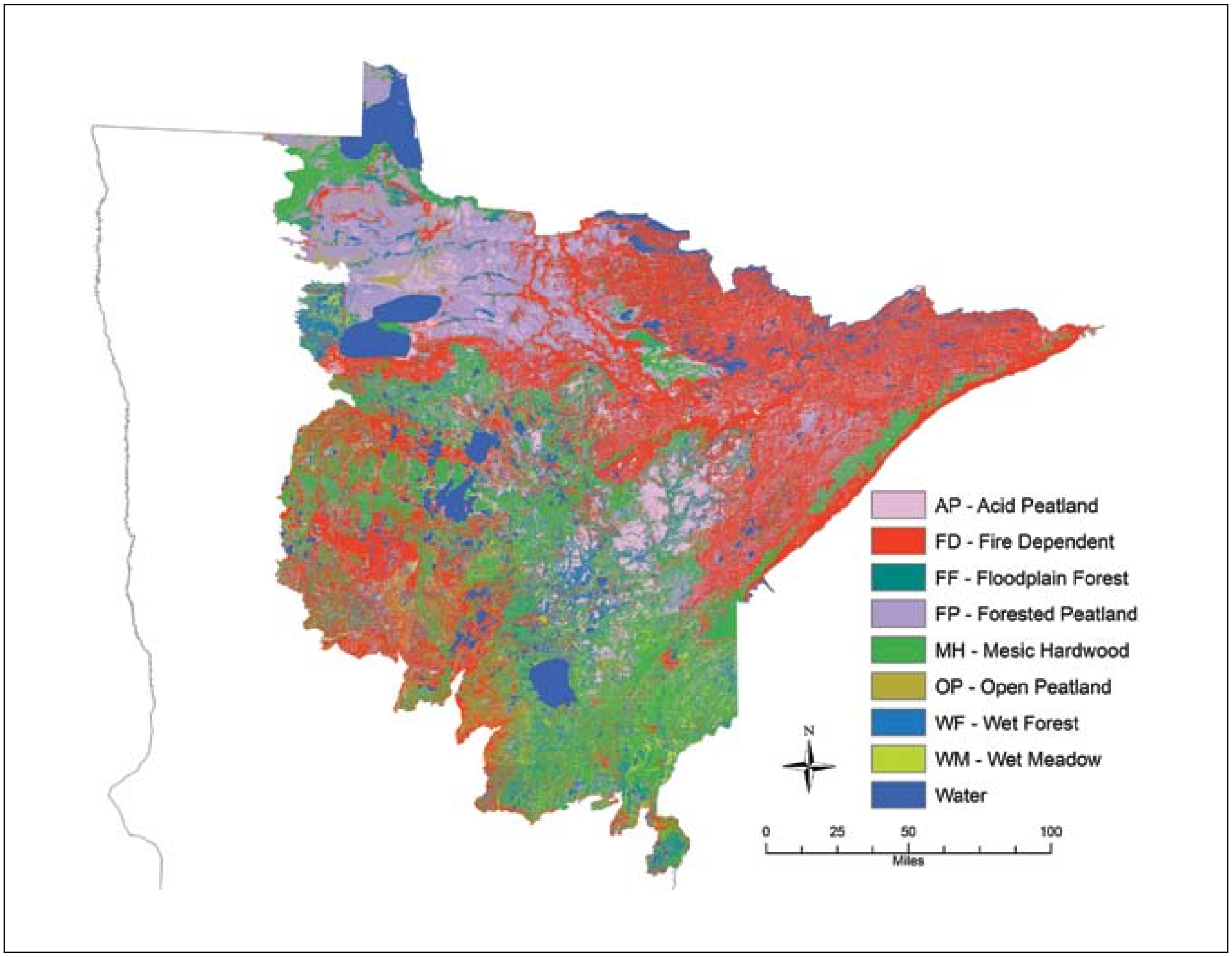


Figure 6.—Map of Native Plant Community Systems within the assessment area (version 2.6, prepared by T. Brown and G. Host, Natural Resources Research Institute).

Managed Forest Systems

In addition to NPC Systems, the authors of this assessment decided to explicitly consider two managed forest systems: managed aspen and managed red pine forests. These two managed forest systems are included in this assessment for two reasons. Intensively managed forests, such as short-rotation aspen or planted red pine, do not conform to the typical site characteristics, species composition, structure, or successional pathways described by the NPC classification. Therefore, it is reasonable to expect that these managed forest systems will respond differently to future conditions than forests more closely approximating NPC Systems. Additionally, these two kinds of managed forests are substantial economic resources in the assessment area and cover a large percentage of the land area.

The most recent FIA survey for Minnesota describes the profound importance of quaking aspen (Miles et al. 2011). Quaking aspen is the most abundant tree species in Minnesota, composing 30 percent of forest land area and 19 percent of the total live-tree volume across the state. Aspen forests are most heavily concentrated within the Laurentian Mixed Forest Province. As of the 2008 FIA survey, the live-tree volume of aspen on forest land across the state was almost 3.5 billion cubic feet, triple the volume of the next most abundant species (paper birch). Aspen is also the most economically important tree species in Minnesota, accounting for 53 percent of the total harvest from forest land in Minnesota in 2007. Aspen roundwood production is roughly 115 million cubic feet, more than five times the production of other commercially important species. The overall volume of aspen has declined in recent years, primarily due to natural succession and harvesting of older aspen stands. Aspen is an early successional, shade-intolerant species that can grow on a wide range of soil types and landforms (Burns and Honkala 1990). Because it reproduces heavily from root suckers and will succeed to other forest types in the absence of disturbance, aspen is typically managed in even-aged rotations from 35 to 60 years, depending on site conditions and management objectives.

Managed aspen stand. Photo by Eli Sagor, University of Minnesota, used with permission.

Red pine is also an important managed forest type within Minnesota and especially throughout the assessment area. Red pine accounts for only 3 percent of the forest land area across the state, but this species has been increasing in abundance and economic importance for the past several decades (Miles et al. 2011). Red pine has the 4th highest live-tree volume in Minnesota, with more than 1 billion cubic feet. Red pine has the highest annual net growth (4.6 percent) among commercially important tree species in Minnesota, and also experiences the lowest mortality (0.3 percent). This species had the 3rd highest roundwood production in the state in 2007, approximately 18 million cubic feet. Red pine is shade-intolerant and requires a fairly precise set of conditions for successful natural regeneration and seedling establishment (Burns and Honkala 1990). Managed red pine therefore relies almost exclusively on planting seedlings in single-species, even-aged stands, with rotation ages ranging from 60 to 70 years in more intensively managed stands to 120 years or more in long-rotation systems. Red pine planting typically follows extensive site preparation, with thinning treatments commencing 20 to 30 years after harvest and continuing roughly every 15 years until final harvest. Most red pine plantations in Minnesota have been planted on sites that are suitable for this species, on sandier, relatively nutrient-poor soils.

Forest Composition and Abundance

FIA Forest Types

FIA inventory data are useful to organize forest land into broad forest-type groups to facilitate comparison among similar species (Table 5) (U.S. Forest Service 2011). The FIA forest-type categories do not perfectly align with the NPC Systems described above, but they are a useful source of information while a complete inventory of NPC Systems for the entire state does not exist. The aspen/birch forest-type group is the most common throughout the assessment area, covering more than 6 million acres of forest land. The spruce/fir forest-type group is the only other category accounting for more than 10 percent of the forest land in the assessment area.

Compared to the forest-type group distribution across the entire state, the assessment area contains a higher proportion of aspen/birch, spruce/fir, and the white/red/jack pine group (U.S. Forest Service 2011). This area contains 99 percent of the spruce/fir forest-type group found within Minnesota, and more than 90 percent of the aspen/birch and white/red/jack pine groups. The oak/hickory forest-type group is much less common in the assessment area than throughout the entire state, but the Laurentian Mixed Forest Province still contains 47 percent of the state's acres of this forest-type group. Other hardwood forest-type groups are present at low levels, such as maple/beech/birch and elm/ash/cottonwood. Their presence reflects the area's position as a transition zone between the broadleaf forest biome and the boreal forest biome.

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

	Assessment area*		Minnesota (statewide)*	
Forest-type group	Acres	Percent cover	Acres	Percent cover
Aspen/birch group	6,023,059	41.2	6,616,679	38.7
Spruce/fir group	3,907,439	26.8	3,931,600	23.0
Elm/ash/cottonwood group	1,149,853	7.9	1,645,652	9.6
Oak/hickory group	1,005,843	6.9	2,111,137	12.4
White/red/jack pine group	951,350	6.5	1,011,431	5.9
Maple/beech/birch group	915153	6.3	1,170,828	6.9
Oak/pine group	276,717	1.9	314,991	1.8
Other hardwoods group	190,886	1.3	237,055	1.4
Exotic softwoods group	6,036	< 0.0	8,237	< 0.0
Other eastern softwoods group	3,411	< 0.0	22,337	0.1
Exotic hardwoods group	814	< 0.0	8,752	0.1
Total	14,602,821		17,078,699	

*This tally does not include nonstocked forest land.

FIA inventories across the state in recent years suggest that species composition in Minnesota's forests is shifting (Miles et al. 2011). Differences in the number of trees in poletimber and sawtimber size classes from 2003 to 2008 reveal some interesting trends. Many of the increasing species are southern species at the northern edge of their ranges in Minnesota, including eastern redcedar, boxelder, American elm, green ash, eastern cottonwood, black walnut, bur oak, silver maple, black ash, bitternut hickory, and red maple. Species on the decline include red and white oak, along with northern species like jack pine, quaking aspen, and paper birch.

Drivers of Change in Forest Ecosystems

Past Forest Ecosystem Change

The current status of Minnesota's forests reflects a dynamic past. As the last glacial sheets receded between 12,000 and 14,000 years ago, species like spruce and tamarack were relatively quick to colonize the expanding northward terrain in the Great Lakes region (Davis and Shaw 2001, Davis et al. 2005, Stearns 1997a). Pollen records also reveal that balsam fir, jack pine, and red pine were present in northern Minnesota shortly thereafter, followed by white pine and maples around 7,000 to 5,000 years ago (Davis 1983, Stearns 1997a). Hemlock migrated westward to the eastern border of Minnesota by about 1,500 years before present, being limited from entering much of the assessment area by precipitation and summer temperatures (Davis et al. 2005).

Pollen records illustrate that species moved independently of one another, and that species that coexist today did not necessarily coexist in the past or respond similarly to past climate changes (Dickmann and Leefers 2003). Refuge location, seed size, germination requirements, competitive ability, and dispersal vectors were all important factors determining how species responded to this period of dramatic postglacial climatic change. After the initial colonization of the Great Lakes area, periodic climate fluctuations resulted in advance and retreat of the prairie-forest border, with grassland and savanna occupying most of Minnesota during a warm and dry period between 8,000 and 3,500 years before present (Dickmann and Leefers 2003, Frelich and Reich 2010).

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

The Government Land Survey began in Minnesota in 1847 and initiated an era of intense logging of Minnesota's forests (Stearns 1997a). White pine logging operations expanded along the St. Croix and Mississippi River corridors until peaking around the turn of the 20th century (Stearns 1997a). The expansion of railroad lines soon facilitated harvest of upland areas farther from waterways and connected timber markets to the plains. As white pine declined, logging shifted to other species such as red pine and hardwoods. Only half of Minnesota's forest land remained after the boom of widespread lumbering and land-use conversion to agriculture (Miles et al. 2011). The effects of this era on native ecosystems are well documented, with widespread catastrophic wildfires, eroded and dammed streams and waterways, and cascading impacts on vegetation

Box 2: Forest Carbon

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

Forest land within the assessment area is estimated to hold nearly 1.4 billion metric tons C, or roughly 95 metric tons per acre (U.S. Forest Service 2011). There is little difference in the amount of C stored per acre (C density) across the different major forest ownership categories. State lands generally hold more C than the average (104.8 metric tons per acre), national forests are roughly equal to the average (95.9 metric tons per acre), and private lands hold less (88.2 metric tons per acre). The pattern of C allocation in forest ecosystems is generally consistent across ownerships. Soil organic C is by far the largest carbon pool, followed by live aboveground, litter, live belowground, and deadwood pools.

Among different forest types, however, the amount of C stored per acre differs widely (Fig. 7). The spruce/fir forest-type group holds roughly 50 percent more C per acre than any other forest-type group because forest soils in these forest types typically are very rich in C. Climate is one of the factors that dictate the size of these per-acre C pools. Spruce/fir forests tend to grow in colder areas on poorer soils, where decomposition and tree growth are slow, so most C is stored in the soil. Maple/beech/birch forests tend to grow in warmer areas on more productive soils, so decomposition rates are faster and more C is stored in living biomass.

Peatlands in particular are capable of storing hundreds of metric tons of C per acre, and northern Minnesota contains more peat than any other state outside Alaska (Minnesota DNR 2011a). These areas are not reflected in the FIA figures mentioned above, but estimates are that Minnesota's peatlands hold roughly 4.25 billion metric tons of carbon (Anderson et al. 2008).

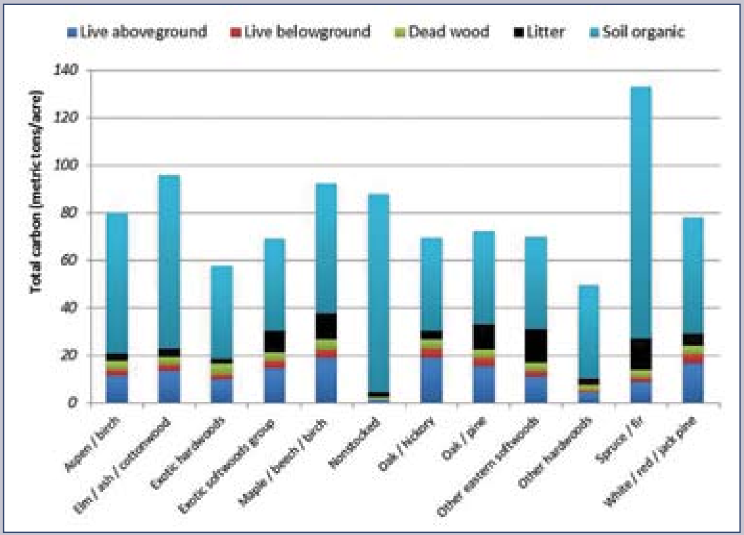


Figure 7.—Average carbon density (amount of carbon stored per acre) of major forest-type groups within the assessment area (U.S. Forest Service 2011).

and wildlife communities (Frelich and Reich 1996, Stearns 1997a). The ecological effect of the era was essentially to set back the course of forest succession by hundreds of years for flora, fauna, and soils. In Minnesota, another effect was to shift forests to more homogeneous composition and structure, with a shift in dominance from conifer to broadleaf deciduous species (White and Host 2008).

After the wave of logging and wildfire, the first State-owned forest reserve was established in 1903 (Stearns 1997a). The Chippewa National Forest was established in 1908 and the Superior National Forest followed the next year. The Great Depression era brought about increased attempts at reforestation and fire suppression. The end of World War II generally coincided with the rise of the paper and pulp industry and the beginning of the industrial forestry era in Minnesota. Harvest has continued during the past half century, and forests in the state have generally been maturing during the past several decades. The total live-tree aboveground biomass on timberland in 2008 increased 5.4 percent from 2003 and 24 percent since the 1977 FIA inventory (Miles et al. 2011).

Natural Disturbance Regimes

Natural disturbance has historically been a regular component of forest ecosystems in Minnesota. Disturbances like fire, windthrow, ice damage, and insect defoliation can be highly variable across a large landscape, influenced by climate, soils, landform, and vegetation. NPC Systems have distinct disturbance regimes, characterized in part by the soils, landforms, and vegetation of each system (Minnesota DNR 2003). The Field Guide to the Native Plant Communities of Minnesota: the Laurentian Mixed Forest Province (Minnesota DNR 2003) contains detailed descriptions of disturbance regimes for each NPC System.

White and Host (2008) estimated that within the Laurentian Mixed Forest Province fire was historically 5 to 10 times more prevalent in fire-prone ecological sub-sections characterized by shallow, coarse-textured soils over bedrock or well-drained sands. Areas with infrequent presettlement fire featured loamy or clay soils and complex topography. Recent studies suggest that the severity of a single fire could be quite heterogeneous across local and landscape scales (Carlson et al. 2011, Flannigan et al. 2009, Kirschbaum and Gafvert 2010). Presettlement fire return frequency in pine forests has been estimated at 20 to 150 years, although many natural fires were not stand-replacing (Stearns 1997a). Fire-return interval in presettlement Minnesota boreal forests has been estimated at 50 to 100 years, but the past century of fire suppression has reduced this frequency (Frelich and Reich 1995b, White and Host 2008). Frequent fires in boreal systems tend to favor jack pine and aspen, and longer fire-return intervals allow black spruce, balsam fir, paper birch, and white cedar to develop in an uneven-aged stand formed by smaller-scale disturbances of wind, insects, and disease.

Windthrow events in Minnesota boreal forests tend to cause greater mortality among early successional species like aspen, red pine, and jack pine (Rich et al. 2007). Wind events cause less mortality for species like northern white-cedar and red maple, although older stands of all forest types have greater susceptibility to this type of disturbance (Rich et al. 2007). Windthrow events appear to have been more frequent toward the western edge of the assessment area (White and Host 2008). Large-scale windthrow is the primary source of stand-replacing disturbance for hardwood forests, with a calculated return interval of roughly 1,200 years. Absent these large-scale wind events, disturbance in hardwood forests is primarily small- to medium-sized gap creation from localized tree mortality and pest outbreaks.

Beaver-caused flooding is also a regular, but localized, disturbance factor in the assessment area (Kirschbaum and Gafvert 2010), particularly in the Floodplain Forest, Wet Forest, Forested Rich Peatland, and Acid Peatland Systems.

Pests and Diseases

Several important pests and diseases are worth noting for forest ecosystems in this assessment area (Table 6). Native pests are often recurring and cyclic, and introduced pests and diseases pose unknown threats to Minnesota forests. Major forest pests that have exhibited significant activity within the assessment area during recent years include spruce budworm, forest tent caterpillar, and eastern larch beetle (Miles et al. 2007, 2011; Minnesota DNR 2011b). Additionally, ash decline and aspen decline have been significant forest health issues in the assessment area.

A dramatic increase in gypsy moth trapping figures suggests that this forest pest will soon be established in Minnesota (Minnesota DNR 2011b). The emerald ash borer has been found in St. Paul, Minnesota, and threatens all species of ash (Minnesota DNR 2011b). Black ash mortality across the state is about 1 percent of total volume per year, but recent results from Michigan suggest that the mortality rate could increase rapidly if the emerald ash borer continues to spread (Miles et al. 2011, Pugh et al. 2012).

Table 6.—Major forest health issues documented within the Laurentian Mixed Forest Province as of 2011, consolidated from Minnesota Department of Natural Resources (2011b)

Forest health agent	Species affected	Location	Trend and notes
Aspen blotch miner	Quaking aspen	Cook, Lake, St. Louis Counties, especially North Shore of Lake Superior	Heavy populations detected, unknown number of acres
Birch leaf miner	Paper birch	Cook, Lake, and St. Louis Counties	Heavy populations detected, unknown number of acres
Eastern larch beetle	Tamarack	North-central MN, primarily Lake of the Woods, Beltrami, Koochiching Counties	Mortality on 20,000 acres in 2011, rising trend since 2001 with a total of 120,000 acres killed
Forest tent caterpillar	Aspens, oaks, birches, and other hardwoods	Central MN, southwest portion of assessment area	Defoliation on more than 60,000 acres in 2011, recent outbreak has been building since 2006
Jack pine budworm	Jack pine	NA	0 defoliated acres in 2011, sharp declines since 2005, expecting another outbreak in roughly 3 years
Larch casebearer	Tamarack	Northeast MN, primarily St. Louis, Itasca, and Aitkin Counties	11,000 acres discolored in 2011, substantial decline since 2009 peak
Spruce budworm	Balsam fir and white spruce	Primarily St. Louis and Lake Counties	In 2011 more than 135,000 acres of defoliation and more than 90,000 acres of mortality. First outbreak in this area since the 1970s, though outbreaks have been recorded every 10 to 15 years in MN
Ash decline	Black ash	Central and northeast MN	More than 25,000 acres detected in 2011, steadily increasing trend since 2005
Aspen decline	Quaking aspen and paper birch	Northeast MN, primarily Lake and Cook Counties	57,000 acres detected in 2011, down from larger detections in 2005, 2008-2010

Nonnative Plant Species

Nonnative plant species are a risk to forest ecosystems when they become invasive. These species affect forest ecosystems through direct competition for resources, alteration of fire or hydrologic conditions, disruption of natural succession and pollination, and other cascading influences. In Minnesota forests, most nonnative plant species are understory species. According to the recent FIA inventory, 67 introduced or invasive plant species were identified on 184 vegetation diversity plots throughout the state (Miles et al. 2011). Almost half (45 percent) of the plots had nonnative species. Key invasive species are presented in Table 7.

Deer browse damage on a red pine seedling. Photo by Casey McQuiston, Superior National Forest.

Table 7.—Summary of the major current stressors and impacts for forested Native Plant Community Systems and managed forests in northern Minnesota

Forest System	References
Fire-Dependent Forest System	
Insect pests such as aspen blotch miner, birch leaf miner, forest tent caterpillar, jack pine budworm, spruce budworm, and white pine tip weevil cause reduced growth or mortality of target species.	(Burns and Honkala 1990; Miles et al. 2007, 2011; Minnesota Department of Natural Resources 2011b)
Aspen decline causes reduced growth, crown dieback, or mortality of aspen species and paper birch.	(Minnesota Department of Natural Resources 2011b)
Diseases such as white pine blister rust, *Armillaria*, sirococcus and sphaeropsis shoot blights, and *Diplodia* shoot blight lead to damage and tree mortality.	(Burns and Honkala 1990; Miles et al. 2007, 2011; Minnesota Department of Natural Resources 2011b, Munck et al. 2009; Stanosz et al. 2001)
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. 2001, 2004; Nowacki and Abrams 2008; Weyenberg et al. 2004)
Hazel encroachment increases competition following disturbance and reduces suitable conditions for natural regeneration, particularly in north-central Minnesota.	(Palik and Johnson 2007, Tappeiner 1971)
Deer herbivory results in reduced growth and mortality of seedlings and saplings of target browse species.	(Cornett et al. 2000a, Côté et al. 2004, Palik and Johnson 2007, Waller and Alverson 1997, White 2012)

(Table 7 continued on next page)

Table 7 (continued).

Forest System	References
Mesic Hardwood Forest System	
Insect pests such as forest tent caterpillar, spruce budworm, white pine tip weevil, and gypsy moth cause reduced growth or mortality of target species.	(Burns and Honkala 1990; Miles et al. 2007, 2011; Minnesota Department of Natural Resources 2011b)
Diseases such as white pine blister rust and *Armillaria* lead to damage and tree mortality.	(Burns and Honkala 1990; Miles et al. 2007, 2011; Minnesota Department of Natural Resources 2011b)
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, Larson et al. 2010)
Deer herbivory results in reduced growth and mortality of seedlings and saplings of target browse species.	(Cornett et al. 2000a, Côté et al. 2004, Powers and Nagel 2009, Waller and Alverson 1997, White 2012)
Invasive plants such as garlic mustard, Pennsylvania sedge, and European buckthorn reduce suitable conditions for natural regeneration, facilitate other exotic species, and alter understory plant communities.	(Heimpel et al. 2010, Minnesota Department of Natural Resources 2012a, Powers and Nagel 2009)
Excessive drought causes reduced growth or mortality.	(Auclair et al. 2010, Burns and Honkala 1990, Cornett et al. 2000b, Hanson and Weltzin 2000)
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, Burns and Honkala 1990, Tierney et al. 2001)
Floodplain Forest System	
Flood control and alteration of river channels have altered flood regimes, creating timing mismatches between high-water periods and seed dispersal and dormancy and lack of suitable conditions for natural regeneration.	(Opperman et al. 2010, Romano 2010)
Invasive plants such as reed canarygrass and European buckthorn reduce suitable conditions for natural regeneration, facilitate other exotic species, and alter understory plant communities.	(Minnesota Department of Natural Resources 2012e)
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, White 2012)

(Table 7 continued on next page)

Table 7 (continued).

Forest System	References
Wet Forest System	
Ash decline has caused widespread crown dieback and reduced growth for black ash.	(Minnesota Department of Natural Resources 2011b, Palik et al. 2011)
Invasive plants such as reed canarygrass and Pennsylvania sedge reduce suitable conditions for natural regeneration, facilitate other exotic species, and alter understory plant communities.	(Benedict and Frelich 2008, Minnesota Department of Natural Resources 2012e, Powers and Nagel 2009)
Altered hydrologic regimes lead to excessive waterlogging or excessive drought and result in reduced growth and susceptibility to dieback and decline.	(Palik et al. 2011)
Deer herbivory results in reduced growth and mortality of seedlings and saplings of target browse species (northern white-cedar in particular).	(Cornett et al. 2000a, Côté et al. 2004, Waller and Alverson 1997, White 2012)
Insect pests such as spruce budworm cause reduced growth or mortality of target species.	(Burns and Honkala 1990; Miles et al. 2007, 2011; Minnesota Department of Natural Resources 2011b)
Excessive drought causes reduced growth or mortality.	(Minnesota Department of Natural Resources 2003)
Forested Rich Peatland System	
Raised water tables can result in tree mortality, and **lowered water tables** can lead to improved tree growth but also susceptibility to drought.	(Glaser 1983, Swanson and Grigal 1991)
Road or ditch building leads to altered drainage patterns.	(Glaser 1983)
Diseases such as mistletoe reduce growth and mortality of spruce species and tamarack.	(Baker et al. 2012, Swanson and Grigal 1991)
Insect pests such as tamarack sawfly, eastern larch beetle, and larch casebearer have reduced growth and caused mortality of spruce species and tamarack.	(Minnesota Department of Natural Resources 2011b, Swanson and Grigal 1991)
Acid Peatland System	
(see Forested Rich Peatland)	

(Table 7 continued on next page)

Table 7 (continued).

Forest System	References
Managed Aspen	
Diseases such as hypoxylon canker and shoot blights reduce growth or cause mortality.	(Burns and Honkala 1990)
Aspen decline causes crown dieback or mortality.	(Minnesota Department of Natural Resources 2011b)
Insect pests such as aspen blotch miner, forest tent caterpillar, and forest tent caterpillar cause reduced growth or mortality.	(Burns and Honkala 1990; Miles et al. 2007, 2011; Minnesota Department of Natural Resources 2011b; Worrall et al. 2013)
Deer herbivory results in reduced growth and mortality of seedlings and saplings of aspen.	(Cornett et al. 2000a, Côté et al. 2004, Waller and Alverson 1997, White 2012)
Excessive drought causes reduced growth or mortality.	(Anderegg et al. 2012, Burns and Honkala 1990, Worrall et al. 2013)
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.	(Frelich et al. 2006, Hale et al. 2005, Larson et al. 2010)
Managed Red Pine	
Diseases such as *Armillaria*, sirococcus and sphaeropsis shoot blights, scleroderris canker, and *Diplodia* shoot blight reduce growth and lead to topkill or mortality.	(Miles et al. 2007, 2011; Minnesota Department of Natural Resources 2011b; Munck et al. 2009; Stanosz et al. 2001)
Insect pests such as bark beetles and sawflies cause damage or mortality.	(Burns and Honkala 1990, Minnesota Department of Natural Resources 2011b)
Deer herbivory results in reduced growth and mortality of seedlings and saplings of red pine seedlings.	(Cornett et al. 2000a, Côté et al. 2004, Palik and Johnson 2007, Waller and Alverson 1997, White 2012)
Lack of thinning treatments results in increased competition for moisture, nutrients, and light, as well as increased susceptibility to drought.	(Peck et al. 2012, Powers et al. 2011, Sucoff and Hong 1974)
Hazel encroachment increases competition following disturbance and reduces suitable conditions for natural regeneration, particularly in north-central Minnesota.	(Palik and Johnson 2007, Tappeiner 1971)

Current Stressors

Each of the NPC Systems and managed forest types faces a particular suite of threats and stressors (Table 7). We define stressors as agents that tend to disrupt the natural functioning of forest ecosystems or impair their health and productivity. This information is collected from published literature as well as from local forest managers. The impacts of particular threats and stressors are highly dependent on local conditions and are not consistent across an area as large and diverse as the Laurentian Mixed Forest Province.

These particular threats should be considered in addition to landscape-level threats such as forest fragmentation, the legacy of past management practices, and altered disturbance regimes. It is often difficult to examine the effects of just one of these landscape-level threats in isolation, because they have all interacted across the assessment area during the past century. Fragmentation caused by agricultural and urban development, forest management, and other factors has tended to reduce the ratio of interior to edge conditions in forests (Miles et al. 2011, Radeloff et al. 2005) The legacy of forest management and land use in northern Minnesota has been well documented, with the general outcomes being a transition to more early-succession forests with reduced structural, spatial, and species diversity (Friedman and Reich 2005, Reich et al. 2001, Schulte et al. 2007). Natural disturbance regimes have been disrupted by fire suppression in upland systems and by hydrologic disruption in riparian and lowland forests. Natural regeneration and succession of forest ecosystems are strongly tied to disturbance regimes, so in many cases alteration of these regimes has resulted in less regeneration of disturbance-adapted species and reduced landscape diversity (Nowacki and Abrams 2008, Romano 2010).

FIA inventories track tree mortality across the state. Mortality across all forest land in Minnesota was 1.9 percent of live tree volume in 2008, which is substantially higher than mortality levels in previous assessments and higher than the mortality rates documented for Iowa and Wisconsin forests (Miles et al. 2011). Mortality is greatest in national forests, at 2.3 percent. It is often difficult to determine the cause of death for a particular tree, but leading factors tend to be climate, disturbance events, insects and disease, or a combination of these factors.

Conservation Status

The Minnesota County Biological Survey has assigned conservation ranks to the 40 NPC Classes that occur within the Laurentian Mixed Forest Province (Table 8). These rankings are designed to categorize the risk of elimination of the community from Minnesota (Minnesota County Biological Survey 2009). The rankings range from "critically imperiled" (S1) to "secure, common, widespread, and abundant" (S5). These rankings consider inherent geographic ranges, the amount of potential range currently occupied, long-term trends, and other factors.

Forest-dependent Wildlife and Plants

Minnesota forests provide important habitat for wildlife species. As of 2009, 5 of the 11 Minnesota species listed under the federal Endangered Species Act were forest-dependent species: the gray wolf (delisted in Minnesota as of 2012), Canada lynx, Karner blue butterfly, dwarf trout lily, and Leedy's roseroot (Minnesota DNR 2010a).

The Minnesota Wildlife Action Plan Web site (www.dnr.state.mn.us/cwcs/index.html) lists Species of Greatest Conservation Need by key habitats, including upland and lowland deciduous and conifer forest habitats. Roughly two-thirds of the state's animal Species of Greatest Conservation Need occur in the assessment area. Additionally, the Minnesota *Rare Species Guide* (www.dnr.state.mn.us/rsg/filter_search.html) lists 234 rare species within the Laurentian Mixed Forest Province. The Minnesota County Biological Survey is responsible for collecting and interpreting information on the distribution and ecology of rare species and communities throughout the state. It has not yet completed field surveys in many of the counties within the assessment area, but the counties that have been surveyed contain many areas rated as Outstanding or High Biodiversity Significance (Minnesota County Biological Survey 2012). Additionally, the Forest Plans of the Superior National Forest and Chippewa National Forest include several forest-dependent wildlife species with particular management emphasis (Table 9) (Chippewa National Forest 2004, Superior National Forest 2004).

Table 8.—Native Plant Community Classes occurring within the Laurentian Mixed Forest Province

Forest System	Conservation status*
Fire-Dependent Forest System	
FDn12 Northern Dry-Sand Pine Woodland	S2
FDn22 Northern Dry-Bedrock Pine (Oak) Woodland	S2 - S3
FDn32 Northern Poor Dry-Mesic Mixed Woodland	S1 - S3
FDn33 Northern Dry-Mesic Mixed Woodland	S2 - S5
FDn43 Northern Mesic Mixed Forest	S2 - S5
FDc12 Central Poor Dry Pine Woodland	S2
FDc23 Central Dry Pine Woodland	S1 - S2
FDc24 Central Rich Dry Pine Woodland	S1 - S3
FDc25 Central Dry Oak-Aspen (Pine) Woodland	S2
FDc34 Central Dry-Mesic Pine-Hardwood Forest	S2 - S3
Mesic Hardwood Forest System	
MHn35 Northern Mesic Hardwood Forest	S4
MHn44 Northern Wet-Mesic Boreal Hardwood-Conifer Forest	S2 - S4
MHn45 Northern Mesic Hardwood (Cedar) Forest	S2 - S4
MHn46 Northern Wet-Mesic Hardwood Forest	S4
MHn47 Northern Rich Mesic Hardwood Forest	S3
MHc26 Central Dry-Mesic Oak-Aspen Forest	S4
MHc36 Central Mesic Hardwood Forest (Eastern)	S4
MHc37 Central Mesic Hardwood Forest (Western)	S4
MHc47 Central Wet-Mesic Hardwood Forest	S3
Floodplain Forest System	
FFn57 Northern Terrace Forest	S3
FFn67 Northern Floodplain Forest	S3
FFs59 Southern Terrace Forest	S1 - S3
Wet Forest System	
WFn53 Northern Wet Cedar Forest	S3 - S4
WFn55 Northern Wet Ash Swamp	S3 - S4
WFn64 Northern Very Wet Ash Swamp	S4
WFs57 Southern Wet Ash Swamp	S4
WFw54 Northwestern Wet Aspen Forest	S4
Forested Rich Peatland System	
FPn62 Northern Rich Spruce Swamp (Basin)	S3
FPn63 Northern Cedar Swamp	S3 - S4
FPn71 Northern Rich Spruce Swamp (Water Track)	S3
FPn72 Northern Rich Tamarack Swamp (Eastern Basin)	S3
FPn81 Northern Rich Tamarack Swamp (Water Track)	S4
FPn82 Northern Rich Tamarack Swamp (Western Basin)	S4 - S5
FPs63 Southern Rich Conifer Swamp	S2 - S3
FPw63 Northwestern Rich Conifer Swamp	S3
Acid Peatland System	
APn80 Northern Spruce Bog	S4
APn81 Northern Poor Conifer Swamp	S4 - S5
APn90 Northern Open Bog	S2 - S5
APn91 Northern Poor Fen	S3 - S5

*Conservation status ranks represent the statewide conservation status for Native Plant Community Types within a given Class. S1 = critically imperiled. S2 = imperiled. S3 = vulnerable to extirpation. S4 = apparently secure; uncommon but not rare. S5 = secure, common, widespread, and abundant. A range of ranks are presented when individual Native Plant Community Types within a Class had different conservation status ranks. Adapted from Minnesota County Biological Survey (2009).

Table 9.—Forest-dependent species with a particular management focus within the forest plans of the Superior National Forest and Chippewa National Forest (Chippewa National Forest 2004, Superior National Forest 2004)

Species*	Superior National Forest	Chippewa National Forest	Habitat
Canada lynx	x	x	Boreal forest
Gray wolf	x	x	Variety of forested and nonforested habitats
Wood turtle	x		Upland and lowland forests adjacent to water
Boreal owl	x		Mature upland aspen and aspen/conifer forest
Great gray owl	x	x	Mature upland forest near lowland conifer forest
Three-toed woodpecker	x		Mature conifer forest and dead conifer forest
Olive-sided flycatcher	x	x	Boreal forests
Northern goshawk	x	x	Mature upland forest
Blanding's turtle		x	Forested wetlands
Four-toed salamander		x	Northern hardwoods
Red-shouldered hawk		x	Mature upland forest
Black-backed woodpecker		x	Mature conifer forest and dead conifer forest
Goblin fern	x	x	Mature northern hardwoods

*Scientific names are in Appendix 1.

Both mature forests and young forest habitats are needed to fulfill habitat requirements of forest-dependent wildlife. These requirements can vary by season or throughout the lifespan of a species. Although American woodcock populations have declined throughout much of their range, they have remained relatively stable in Minnesota due to the abundance of young forest habitat (Minnesota DNR 2010a). The golden-winged warbler, which has experienced steep declines throughout its range, has remained stable in the state, where an estimated 40 percent of the global population breeds.

SOCIOECONOMIC CONDITIONS

Forest Ownership Trends

Minnesota has the highest percentage of public ownership of any state in the eastern United States, at 56 percent (Miles et al. 2011). Minnesota also has the highest percentage of State-owned land (21 percent) and county-owned land (18 percent) of any state in the nation. Total federal land ownership is greater than 15 percent in five counties within the assessment area, with more than 43 percent in Lake County (Headwaters Economics 2011). State land ownership is more than 15 percent in 12 counties, with more than 53 percent in Koochiching County. Tribal land is another significant ownership category in the assessment area, accounting for almost 600,000 acres in Beltrami County and more than 100,000 acres in Clearwater and Lake of the Woods Counties.

Table 10 displays the breakdown of forest land ownership within the assessment area and for Minnesota as a whole (U.S. Forest Service 2011). The assessment area contains 100 percent of national forest land in the state, 92 percent of the state-owned forest land, and 96 percent of all county and municipal forest land. Private land accounts for the biggest proportion of forest land in the assessment area, at more than 5.3 million acres (37.1 percent). Across the entire state, 75 percent of private forest land is owned by families, and 25 percent is in other private ownerships (Butler 2008).

Table 10.—Forest land ownership within the assessment area and for the entire state, according to FIA data (U.S. Forest Service 2011)

	Assessment area		Minnesota (statewide)	
Ownership	**Acres**[a]	**Percent cover**	**Acres**[a]	**Percent cover**
Private	5,360,640	37.1	7,543,420	44.2
National forest	2,606,339	18.1	2,606,339	15.3
State	3,357,248	23.3	3,638,769	21.3
County and municipal	2,841,410	19.7	2,973,624	17.4
Other federal[b]	264,922	1.8	316,548	1.9
Total forest land area (acres)	14,430,559		17,078,700	

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

The breakdown of forest-type groups within these different ownerships is not uniform. For example, within the assessment area the State owns 23 percent of the forest land, but these lands contain 41 percent of the spruce/fir forest-type group. Private forest land contains a disproportionately high percentage of southern forest-type groups, and national forests account for a higher percentage of the white/red/jack pine forest type group and the oak/pine group.

General Trends in Land Use

In Minnesota, two major factors have been contributing to forest fragmentation in recent years: large-scale divestiture of forest industry land and parcelization of nonindustrial private forests (Minnesota DNR 2010a). Parcelization is the division of larger landholdings into smaller units. The average landholding size in Minnesota decreased from 39 acres in 1982 to 31 acres in 2003 (Minnesota DNR 2010a). Although parcelization may not have direct impacts immediately, this pattern often results in consequences for forests as well as for forest industry (Gobster and Rickenbach 2004, Haines et al. 2011). Long-term studies in northern Wisconsin have shown that parcelization is often a precursor to fragmentation and land-use change in forests (Haines et al. 2011).

Within the assessment area, 13.1 percent of private land was developed as residential land as of the year 2000 (Headwaters Economics 2011). Between 1980 and 2000, the proportion of residential land grew nearly twice as fast in the assessment area as the national average. Beltrami County (175 percent), Clearwater County (190 percent), and Lake County (131 percent) had the highest rates of residential land development, and the overall rate for the assessment area was 59 percent. Most of this residential land exists in parcel sizes between 1.7 and 40 acres.

Land-use change is projected to proceed gradually in northern Minnesota through 2020, as rural land is converted to exurban and urban development (Theobald 2005). Land development will be constrained in the assessment area due to the high proportion of federal, state, and county-owned land, so growth is projected to occur near existing municipalities within the southern half of the area.

Census Data on Human Population Patterns

The human population within the assessment area is approximately 783,000 (Headwaters Economics 2011). Population has been steadily increasing since 1970. The population growth in the region was slower than the statewide average for the same period (29 percent compared to 38 percent). The population trend has not been uniform within the assessment area. The fastest growing counties from 1970 to 2009 in the assessment area were Chisago (186 percent) and Isanti Counties (132 percent). The population declined over the past 40 years in Koochiching, Lake, Lake of the Woods, and St. Louis Counties. The 2010 U.S. Census confirms that this trend continued during the most recent census period (Mackun et al. 2011). The population density for the assessment area remains between 1 and 49 people per square mile, with the exception of Crow Wing County (Mackun et al. 2011). The population throughout the assessment area is also aging faster than the U.S. average (Headwaters Economics 2011).

Economic Sectors

Overall

Compared with Minnesota as a whole, the economy of the assessment area is slightly depressed. Average earnings per job declined 0.2 percent between 2000 and 2009, whereas the statewide average rose 1.1 percent during that period (Headwaters Economics 2011). Per capita income for the assessment area increased at a faster rate than the statewide average during the decade, but remains almost 25 percent below the statewide norm. Unemployment in this region is also higher than the Minnesota average. Several counties underwent dramatic employment gains in the past 40 years. Benton, Cass, Chisago, and Isanti Counties all reported more than 300-percent increases in employment figures, and these counties also reported increases in personal income.

Agriculture

Minnesota is a major agricultural state, ranking 7th overall in the United States for total market value of agricultural products (U.S. Department of Agriculture 2007). Counties in southern Minnesota are much more engaged in commercial agriculture than the counties within the assessment area. Nevertheless, agriculture-related employment accounts for more than 8.0 percent of total employment in seven counties and 3.6 percent throughout the assessment area (Headwaters Economics 2011). During the 40 years between 1970 and 2009, employment in this sector declined slightly for the assessment area.

Census of Agriculture summaries are organized by congressional district, and Minnesota's 8th district most closely matches the assessment area. The number of farms and the total land area in farms decreased by 12 percent in this district from 2002 to 2007. Within these counties in northeastern Minnesota, oilseed crops, grains, beef cattle, and aquaculture are the most common farm types. Additionally, this area of Minnesota is top ranked in the state for producing Christmas trees and short-rotation woody crops (U.S. Department of Agriculture 2007).

Recreation and Tourism

Tourism is an $11 billion industry in Minnesota, and the state has above-average participation rates in nature-based outdoor activities (Minnesota DNR 2010a). Hunting and wildlife watching continue

Brook trout in northern Minnesota. Photo by Kelly McQuiston, Minnesota Department of Natural Resources, used with permission.

to contribute more than $1 billion to the state's economy. Northern Minnesota relies heavily on the economic contributions of travel and tourism. Johnson and Beale (2002) identified many of the counties within the assessment area as "recreation counties," based on employment and income from tourism-related industries, proximity to natural amenities, and other factors. Employment within the travel and tourism sector accounted for nearly 18 percent of total private employment in the assessment area in 2009 with seven counties registering 25 percent or more of total employment within this area (Headwaters Economics 2011). The assessment area includes two national forests, one of which contains the Boundary Waters Canoe Area Wilderness; the Grand Portage National Monument; Voyageurs National Park; many state parks and recreation areas; and several popular tourist destinations like the North Country National Scenic Trail and the North Shore of Lake Superior.

Forest Products Industry

The forest products industry is also an important source of income and employment in Minnesota. The wood products and paper industries in the state account for more than $6 billion in economic output (Minnesota DNR 2010a). The economic impact of the forestry sector was rated "high" or "moderate" throughout most of the Laurentian Mixed Forest Province in a spatial assessment by the Minnesota DNR. As of 2010, almost 38,000 people were employed in the forest products sector statewide, including secondary manufacturing.

In 2009, employment in timber-related jobs represented about 3.4 percent of total private employment throughout the assessment area, or about 8,800 jobs (Headwaters Economics 2011). Employment in this sector accounts for almost 35 percent of the private employment in Roseau County and 24 percent in Koochiching County. St. Louis, Carlton, and Itasca Counties also have high levels of employment in this sector. From 1998 to 2009, employment in the forest products industry declined about 28 percent across the assessment area. This decrease was largely the result of declining employment in sawmills and paper mills. Meanwhile, employment related to growth and harvesting and wood products manufacturing held steady. Recent mill closings and national and global economic conditions have reduced the volume of timber exports from the state (Minnesota DNR 2010a).

A variety of products made from birch bark. Photo by Eli Sagor, University of Minnesota, used with permission.

An example of an important nontimber forest product in Minnesota is balsam fir boughs, nearly all of which are harvested from within the assessment area (Minnesota DNR 2010a). Balsam boughs used in the wreath industry contribute more than $23 million in sales annually. Most balsam bough harvesting occurs in St. Louis, Aitkin, Itasca, Cass, Lake, Koochiching, Cook, Beltrami, Lake of the Woods, Clearwater, Carlton, and Pine Counties.

Mining

Mining is a major industry in northern Minnesota, accounting for more than $5 billion in economic output as of 2005. In recent years, there has been increasing interest in expanding mining operations within northeastern Minnesota. The state ranks first in the nation in production of iron ore and taconite (Minnesota DNR 2012c). The mining industry accounted for 1.4 percent of total private employment in the assessment area in 2009, almost all of which is related to metallic ore mining (Headwaters Economics 2011). Employment in this sector declined about 50 percent from 1998 to 2009. Lake County and St. Louis County in northeastern Minnesota have the highest proportion of mining-related employment, close to 4 percent of total private employment. Taconite and iron ore operations are mostly confined to the Mesabi Iron Range in northeastern Minnesota (Minnesota DNR 2012c). Within the assessment area, there are also significant operations to extract granite, horticultural peat, crushed stone, copper, nickel, manganese, and sulfur.

Forest Harvest and Products

As mentioned above, the forestry sector is a major economic contributor in Minnesota and within the assessment area in particular. The value of forest products manufactured across the state rose steadily through the 1980s and 1990s from just under $2 billion to almost $8 billion, but appears to have been gradually declining during the most recent decade (Minnesota DNR 2010a). An overall market slowdown underlies this trend, and the closing of several major mills within the assessment area has further affected timber markets in Minnesota.

Industrial roundwood production in Minnesota is directed to a variety of major product types (Fig. 8). Pulpwood accounts for 77 percent of the production across all product categories, with saw logs accounting for 19 percent. Within the assessment area, the largest volume of net growth occurs on private forest land, followed by county and municipal land, state land, and national forests (U.S. Forest Service 2011). Harvest removal volumes follow this same pattern.

The rate of harvest removal also differs by species within the assessment area (Table 11). The aspen/birch forest-type group accounted for more than 53 percent of the total annual harvest removals within the assessment area, followed by the maple/beech/birch group at almost 12 percent. Other forest-type groups account for minor fractions of the harvest removals within the assessment area. Across the entire state, quaking aspen has the highest harvest rate at 3.4 percent removals of standing volume in the 2008 FIA inventory (Miles et al. 2011).

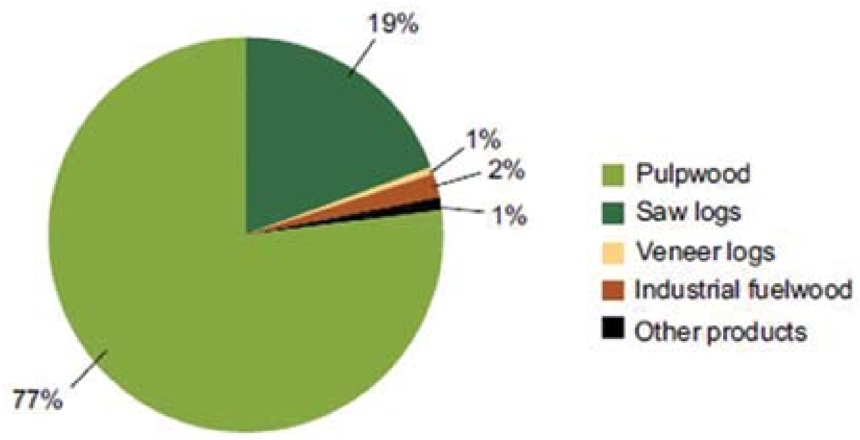


Figure 8.—Statewide industrial roundwood production by major product category, as of 2007 (Miles et al. 2011).

Table 11.—Annual net growth and removals for the assessment area in cubic feet per year, organized by forest-type group (U.S. Forest Service 2011)

Forest-type group	Net growth*	Removals	Growth:Removals
Aspen/birch group	102,368,753	112,530,769	0.91
Elm/ash/cottonwood group	16,610,182	6,016,633	2.76
Exotic hardwoods group	52,351	-	NA
Exotic softwoods group	439,979	-	NA
Maple/beech/birch group	20,142,182	24,570,096	0.82
Oak/hickory group	27,223,592	15,334,528	1.78
Oak/pine group	11,148,280	1,379,715	8.08
Other	-5,043,866	16,578,941	NA
Other eastern softwoods group	146,367	22,164	6.60
Other hardwoods group	823,618	7,624,027	0.11
Spruce/fir group	50,713,017	12,740,352	3.98
White/red/jack pine group	55,467,213	12,169,403	4.56
Total	280,091,666	208,966,626	1.34

*Negative net growth indicates that a forest-type group had more mortality than gross growth during the inventory period.

The growth-to-removals ratio of live trees on forest land provides a simple metric for determining whether the withdrawals of harvesting are outpacing the gains of growth (Table 11). This ratio takes into account gross growth, mortality, and removals. Among ownership classes in the assessment area, the growth-to-removals ratio is less than 1 for the aspen/birch and maple/beech/birch forest-type groups, showing that removals were generally outpacing growth in these forest types (U.S. Forest Service 2011). The ratio was reversed for other major forest-type groups as many native forest types had net growth many times greater than annual removals. For all forest-type groups within the assessment area, the combined ratio was 1.34, which means overall volume on forest land is increasing. Across the entire state, this ratio was 1.5 as of 2008 (Miles et al. 2011).

Forest Certification

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

The total area of certified forest land amounts to more than 8.4 million acres—almost half of all the forest land in the state (Table 12). As of 2011, Minnesota ranked first in the nation in acres of forest certified under the Forest Stewardship Council (FSC) standards (Pingrey 2011). Almost 5 million acres of state forest land are dual certified under FSC and the Sustainable Forestry Initiative (SFI), and more than 2.5 million acres of county-owned forest land are certified under one or more certification schemes (Barnard 2012). Private industrial forest owners manage another 740,000 acres of certified forests. Most forest land within the assessment area has been certified under one or more certification standards (Fig. 9).

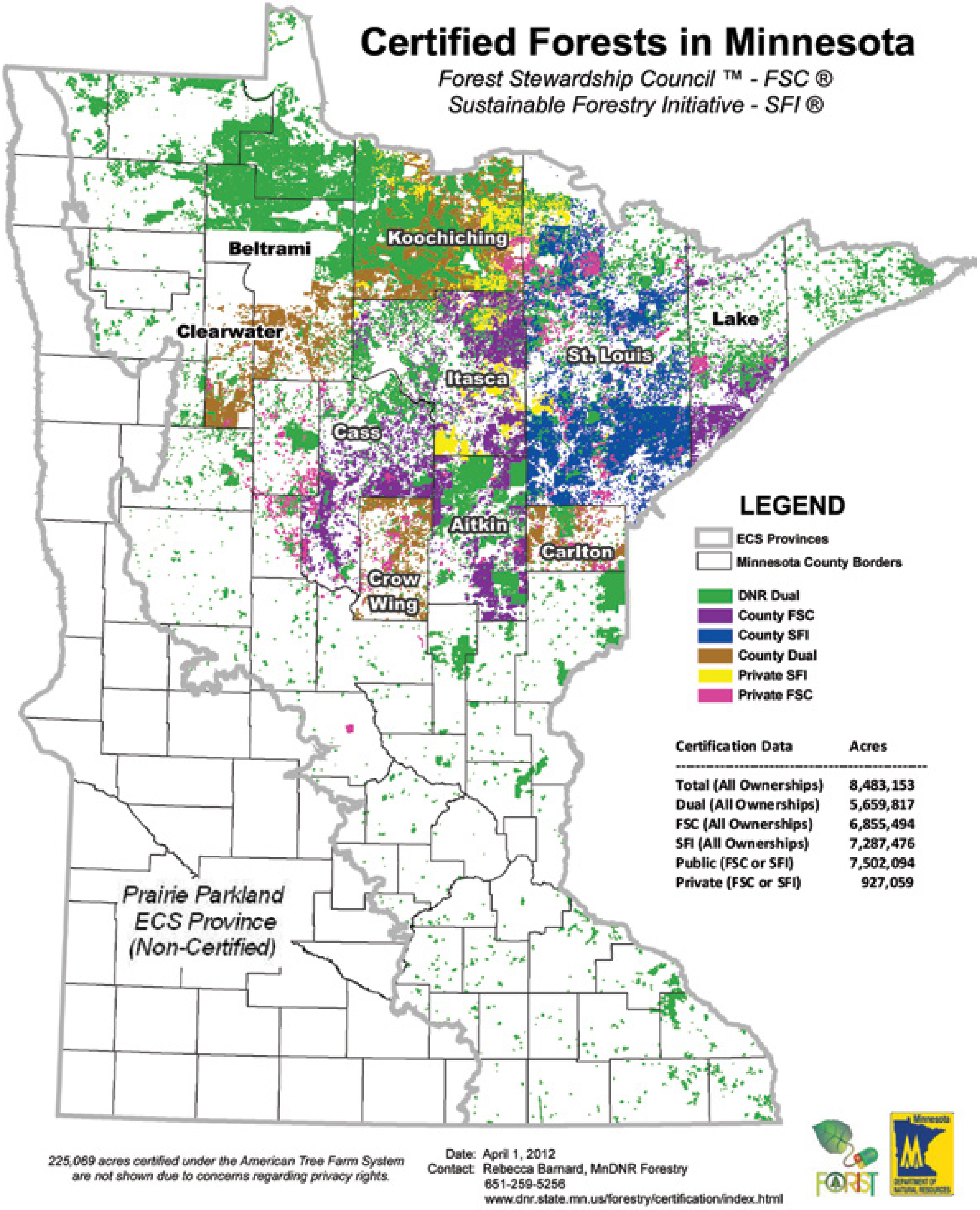
Table 12.—Acres of forest land in Minnesota certified under three major certification schemes as of February 2011

	Certification standard*				
Landowner	**FSC only**	**Dual FSC/SFI**	**SFI only**	**American Tree Farm System - PEFC**	**Total**
Public					
Minnesota state forests		4,960,177	19,076		4,979,253
County					
Beltrami		147,000			147,000
Carlton		73,000			73,000
Clearwater		90,140			90,140
Crow Wing		103,000			103,000
Koochiching		286,500			286,500
Aitken	221,657				221,657
Cass	253,494				253,494
Lake	151,216				151,216
Itasca	301,660				301,660
St. Louis			895,174		895,174
Private					
Industrial					
Potlatch Forest Holdings	252,217				252,217
Forest Capital Partners			298,955		298,955
UPM-Kymmene			189,385		189,385
Nonindustrial	15,433				15,433
MN Tree Farmers				225,069	225,069
Total by standard	1,195,677	5,659,817	1,402,590	225,069	8,483,153

*FSC = Forest Stewardship Council, SFI = Sustainable Forestry Initiative, PEFC = Programme for the Endorsement of Forest Certification schemes. Modified from Barnard (2012).

SUMMARY

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



Certification Data	Acres
Total (All Ownerships)	8,483,153
Dual (All Ownerships)	5,659,817
FSC (All Ownerships)	6,855,494
SFI (All Ownerships)	7,287,476
Public (FSC or SFI)	7,502,094
Private (FSC or SFI)	927,059

225,069 acres certified under the American Tree Farm System are not shown due to concerns regarding privacy rights.

Date: April 1, 2012
Contact: Rebecca Barnard, MnDNR Forestry
651-259-5256
www.dnr.state.mn.us/forestry/certification/index.html

Figure 9.—Certified forests in Minnesota, from Barnard (2012). FSC = Forest Stewardship Council. SFI = Sustainable Forestry Initiative. The 225,069 acres in the American Tree Farm System are not shown due to privacy concerns.

CHAPTER 2: CLIMATE CHANGE SCIENCE AND MODELING

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

CLIMATE CHANGE

Climate is not the same thing as weather. Climate is defined as the average, long-term meteorological conditions and patterns for a given area. Weather, in contrast, is the set of the meteorological conditions for a given point in time in one particular place. The IPCC (2007) defines climate change as "a change in the state of the climate that can be identified (e.g., 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* (2007) was that "warming of the climate system is unequivocal." This was the first *Assessment Report* in which the IPCC considered the evidence strong enough to make such a statement. In addition to evidence of increased global surface, air, and ocean temperatures, this conclusion was based on thousands of long-term (more than 20 years) data series from all continents and most oceans. These data showed significant changes in snow, ice, and frozen ground; hydrology; coastal processes; and terrestrial, marine, and biological systems. The IPCC's *Fifth Assessment Report* is underway, and scheduled to be released in 2014. On a national level, the United States Global Research Program has released a series of reports detailing the past and projected changes in climate, with a comprehensive report (National Climate Assessment, NCA) scheduled to be released in 2014 (see Box 3 for more information).

The Warming Trend

The Earth is warming, and the rate of warming is increasing. Measurements from weather stations across the globe indicate that the global mean temperature has risen by 1.4 °F (0.8 °C) over the past 50 years, nearly twice the rate of the last 100 years (Fig. 10) (IPCC 2007). The first 12 years in the 21st century rank among the warmest 14 years in the 133-year period of record of global temperature (National Oceanic and Atmospheric Administration [NOAA] National Climatic Data Center 2012a). Temperatures in the United States have risen by 2 °F (1.1 °C) in the last 50 years (Karl et al. 2009). The year 2012 ranked as the warmest year on record in the United States, 1.0 °F (0.6 °C) warmer than the previous record year of 1998 and 3.3 °F above the 20th-century average (NOAA National Climatic Data Center 2012b).

Box 3: Global, National, and Regional Assessments

Intergovernmental Panel on Climate Change

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

Climate Change 2007: Synthesis Report

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

U.S. Global Change Research Program

The U.S. Global Change Research Program (USGCRP; 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 several national synthesis reports on climate change in the United States, which are available for download below.

Global Change Impacts on the United States

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

Synthesis and Assessment Products

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

National Climate Assessment

http://ncadac.globalchange.gov/

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

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

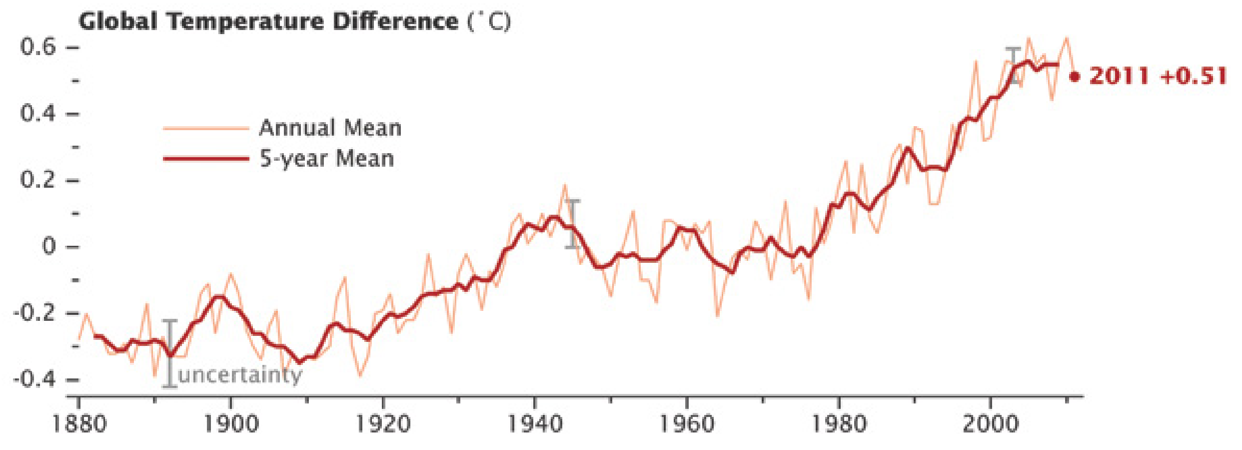


Figure 10.—Trends in global temperature compared to the 1951 through 1980 mean. Data source: NASA Goddard Institute for Space Studies. Image credit: NASA Earth Observatory, Robert Simmon; www.giss.nasa.gov/research/news/20120119/.

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

Average global temperature increases of a few degrees may seem small, but even small increases can result in large changes to the average severity of storms, the nature and timing of seasonal precipitation, droughts and heat waves, ocean temperature and volume, and snow and ice—all of which affect humans and ecosystems. The synthesis report of the International Scientific Congress on Climate Change concluded that “recent observations show that societies and ecosystems are highly vulnerable to even modest levels of climate change, with poor nations and communities, ecosystem services and biodiversity particularly at risk” (Richardson et al. 2009). Temperature rises of more than 3.6 °F (2 °C) above average will be difficult for contemporary societies to cope with, and are expected to cause major societal and environmental disruptions through the rest of the century and beyond (Richardson et al. 2009).

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

Chapter 3 provides specific information about observed climate trends for the assessment area in Minnesota 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. 11). This effect is necessary for human survival: without it, Earth would have an average temperature of about 0 °F (-18 °C) and would be covered in ice. Several naturally occurring greenhouse 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.

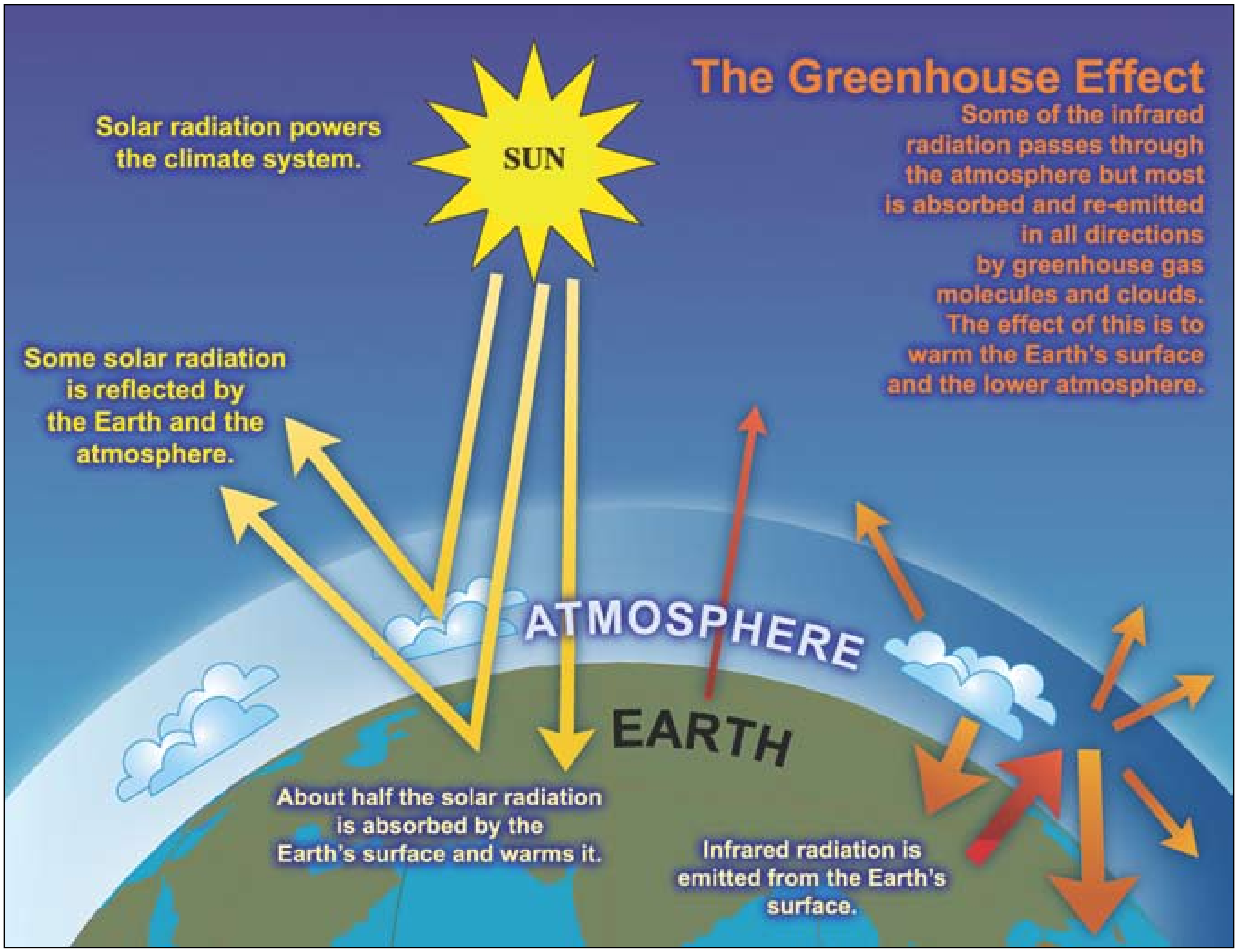


Figure 11.—Idealized model of the natural greenhouse effect. Figure courtesy of the Intergovernmental Panel on Climate Change (2007).

Human Influences on Greenhouse Gases

Human activities have increased CO_2, CH_4, and N_2O in the atmosphere since the beginning of the industrial era (Fig. 12), leading to an enhanced greenhouse effect. More CO_2 has been released by humans into the atmosphere than any other greenhouse gas. Carbon dioxide levels have been increasing at a rate of 1.4 parts per million (ppm) per year for the past 50 years (IPCC 2007), reaching 395 ppm in January 2013 (Tans and Keeling 2013). In recent decades, fossil fuel burning has been responsible for approximately 83 to 94 percent of the human-induced increase in CO_2. The remaining 6 to 17 percent of human-caused emissions has come primarily from deforestation of land for conversion to agriculture. However, increases in fossil fuel emissions over the past decade mean that the contribution from land-use changes has become a smaller proportion of the total (Le Quéré et al. 2009).

Methane is responsible for roughly 14 percent of greenhouse gas emissions (IPCC 2007). Concentrations of this gas have also been increasing as a result of human activities, including agricultural production of livestock and increases in rice production. Livestock production contributes to CH_4 emissions primarily from fermentation in the guts of

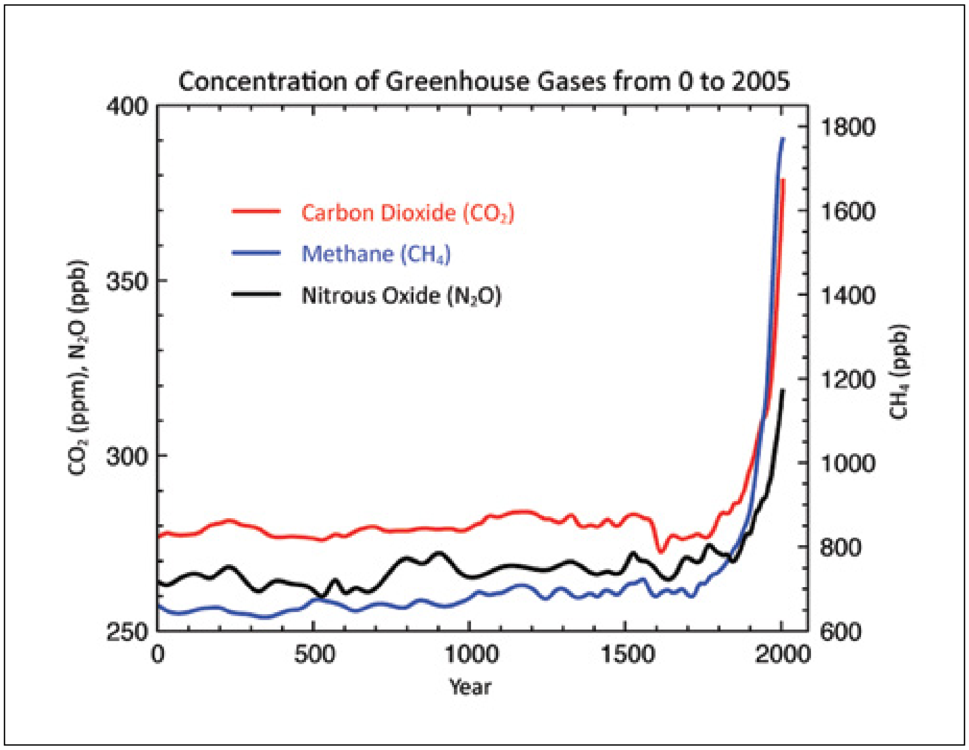


Figure 12.—Concentrations of greenhouse gases over the past 2005 years, showing increases in concentrations since 1750 attributable to human activities in the industrial era. Concentration units are parts per million (ppm) or parts per billion (ppb), indicating the number of molecules of the greenhouse gas per million or billion molecules of air. Figure courtesy of the Intergovernmental Panel on Climate Change (2007).

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

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

CLIMATE MODELS

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

General Circulation Models

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

Although climate models use highly sophisticated computers, limits on computing power mean that projections are limited to relatively coarse spatial scales. Instead of simulating climate for every single point on Earth, modelers divide the land surface, ocean, and atmosphere into a three-dimensional grid (Fig. 13). Each cell within the grid is treated as an individual unit, and able to interact with adjacent cells. Although each model is slightly different, each square in the grid is usually between

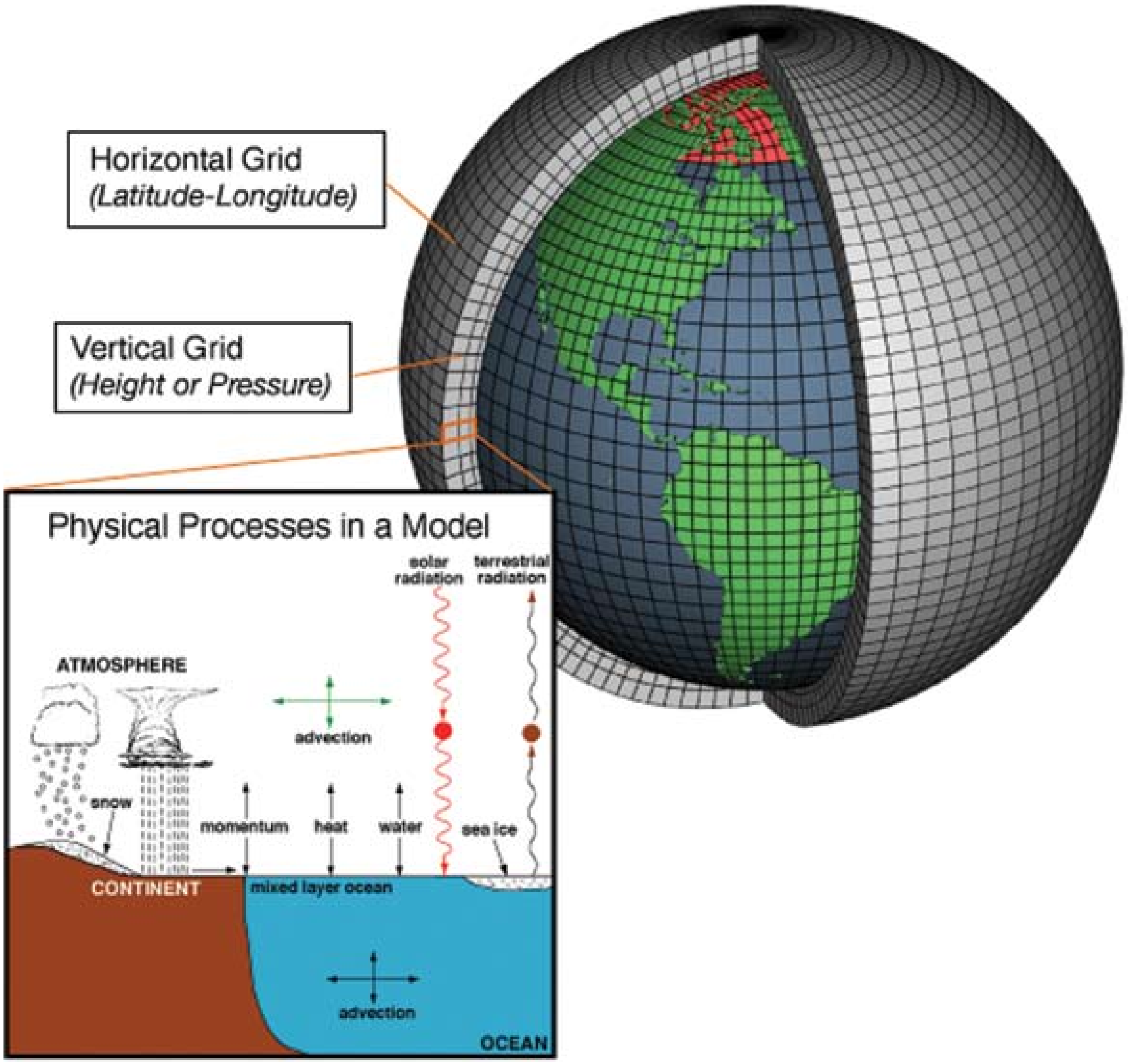


Figure 13.—Schematic describing climate models, which are systems of differential equations based on the basic laws of physics, fluid motion, and chemistry. The planet is divided into a three-dimensional grid that is used to apply basic equations and evaluate results. Atmospheric models calculate winds, heat transfer, radiation, relative humidity, and surface hydrology within each grid and evaluate interactions with neighboring points. Figure courtesy of the National Oceanic and Atmospheric Administration (2008).

2° and 3° latitude and longitude, or for the middle latitudes, about the size of the northeastern quarter of Minnesota. 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 GCMs have been used in climate projections for the IPCC reports and elsewhere (Box 4). These models (in parentheses) have been developed by internationally renowned climate research centers such as NOAA's Geophysical Fluid Dynamics Laboratory (GFDL CM2) (Delworth et al. 2006), the United Kingdom's Hadley Centre (HadCM3) (Pope et al. 2000), and the National Center for Atmospheric Research (PCM) (Washington et al. 2000). These models use slightly different grid sizes and ways of quantitatively representing physical processes. They also differ in sensitivity to changes in greenhouse gas concentrations, which means that some models will tend to project higher increases in temperature than others under increasing greenhouse gas concentrations (Winkler et al. 2012). In some instances, the choice of GCM can have a larger influence on the projected climate trends than the choice of greenhouse gas emissions scenario.

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

Box 4: More Resources on Climate Models and Emissions Scenarios

U.S. Forest Service

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

U.S. Global Change Research Program

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

Intergovernmental Panel on Climate Change

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

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

Great Lakes Integrated Science and Assessment (GLISA) Center

Midwest Technical Input Report for the National Climate Assessment
http://glisa.msu.edu/resources/nca

introduces new sources of uncertainty (Maslin and Austin 2012).

Emissions Scenarios

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

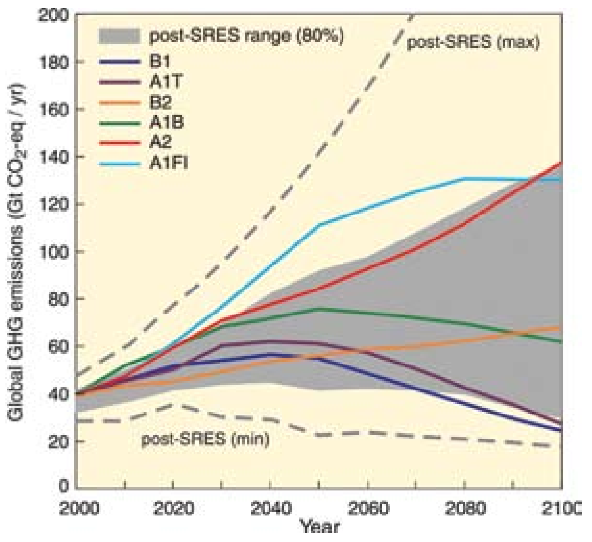


Figure 14.—Projected global greenhouse gas (GHG) emissions (in gigatons [Gt] of carbon dioxide equivalent per year) assuming no change in climate policies under six scenarios (B1, A1T, B2, A1B, A2, and A1FI) originally published in the Special Report on Emissions Scenarios (SRES; IPCC 2000) and the 80th-percentile range (gray shaded area) of recent scenarios published since SRES. Dashed lines show the full range of post-SRES scenarios. Figure courtesy of the Intergovernmental Panel on Climate Change (2007).

Emissions scenarios are a quantitative representation of alternative storylines given certain demographic, technological, or environmental developments. None of the scenarios includes any changes in national or international policies directed specifically at climate change 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. 14).

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

Downscaling

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

Statistical downscaling has several advantages and disadvantages (Box 5) (Daniels et al. 2012, Maslin and Austin 2012). It is a fairly simple and inexpensive way to produce smaller-scale projections using GCMs. One limitation is that downscaling assumes that past relationships

Box 5: Model Limitations and Uncertainty

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

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

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

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

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

between modeled and observed temperature and precipitation will remain consistent under future change. This assumption may or may not be true. Another limitation is that downscaling depends on local climatological data. If there is no weather station in the area of interest, it may be difficult to obtain a good downscaled estimate of future climate for that area. Finally, local influences on climate that occur at finer scales (such as land cover type or topography) also add to uncertainty when downscaling climate projections.

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

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

Downscaled Climate Projections Used in this Assessment

In this assessment, we report statistically downscaled climate projections for two GCM-emissions scenario combinations: GFDL A1FI and PCM B1. Both models and both scenarios were included in the IPCC *Fourth Assessment Report* (IPCC 2007). The latest version of the National Climate Assessment, currently in development, also draws on statistically downscaled data based on IPCC models and scenarios but uses the A2 scenario as an upper bound, which projects lower emissions compared to A1FI. The IPCC includes several other models, which are represented as a multi-model average in its assessment reports. The National Climate Assessment takes a similar approach in using a multi-model average. For this assessment, we instead selected two models that had relatively good skill at simulating climate in the eastern United States and that bracketed a range of temperature and precipitation futures. This approach gives readers a better understanding of the level of agreement among models and provides a set of alternative scenarios that can be used by managers in planning and decisionmaking.

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

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

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

New bur oak leaves emerging in spring 2013. Photo by Eli Sagor, University of Minnesota, used with permission.

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

MODELS FOR ASSESSING FOREST CHANGE

Downscaled climate projections from GCMs provide us with important information about future climate, but they tell us nothing about how climate change might affect forests and other ecosystems. Other models, commonly called impact models, are needed to project impacts on trees, animals, and ecosystems. Impact models use GCM projections as inputs, as well as information about tree species, life-history traits of individual species, and soil types. Many different models are used to simulate impacts on species and forest ecosystems. These models generally fall in one of two main categories: species distribution models (SDMs) and process models. In this assessment, we used one SDM, the Climate Change Tree Atlas (Prasad et al. 2007-ongoing), and two process models, LANDIS-II (Scheller et al. 2007) and PnET-CN (Aber et al. 1997). These models operate at different spatial scales and provide different kinds of information. We chose them because they have been used to assess climate change impacts on ecosystems 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 distribution of a species or community and key attributes of its habitat. This relationship is used to predict how the range of the species will shift as climate change affects those attributes. These models are much less computationally expensive than process models, so they can typically provide projections for the suitable habitat of many species for a larger area. There are some caveats that users should be aware of when using them, however (Wiens et al. 2009). The models use a species’ realized niche instead of its fundamental niche. The realized niche is the actual habitat a species occupies given predation, disease, and competition with other species. A species’ fundamental niche, in contrast, is the habitat it could potentially occupy in the absence of competitors, diseases, or predators. Given that a species’ fundamental niche may be greater than its realized niche, SDMs may underestimate current niche size and future suitable habitat. In addition, species distributions in the future might be constrained by competition, disease, and predation in ways that do not currently occur. If so, SDMs could overestimate the amount of suitable habitat in the future. Furthermore, fragmentation or other physical barriers to migration may create obstacles for species otherwise poised to occupy new habitat. Therefore, a given species might not actually be able to enter the assessment area in the future, even if Tree Atlas projects it will gain suitable habitat. Additionally, SDMs like Tree Atlas do not project that existing trees will die if suitable habitat moves out of an area. Rather, this is an indication that they will be living farther outside their ideal range and will be exposed to more climate-related stress.

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

Moose in northern Minnesota. Photo by Casey McQuiston, Superior National Forest.

Although useful for projecting future changes, both process models and SDMs share some important limitations. They assume that species will not adapt evolutionarily to changes in climate. This assumption may be true for species with long generation times (such as trees), but some short-lived species may be able to adapt even while climate is rapidly changing. Both types of models may also magnify the uncertainty inherent in their input data. Data on the distribution of trees, site characteristics, and downscaled GCM projections are estimates that add to uncertainty. No single model can include all possible variables, so there are important inputs that may be excluded from individual models, such as competition from understory vegetation, herbivory, and pest outbreaks. Given these limitations, it is important for all model results to pass through a filter of local expertise to ensure that results match with reality on the ground. Chapter 6 and Appendix 5 explain the approach used in this assessment for determining the vulnerability of forest ecosystems based on local expertise and model synthesis.

Climate Change Tree Atlas

The Climate Change Tree Atlas (Tree Atlas) incorporates a diverse set of information about potential shifts in the distribution of tree species' habitat in the eastern United States over the next century (Iverson et al. 2008, Prasad et al. 2007-ongoing). Tree Atlas is actually a set of different models and information that work together. The species distribution model DISTRIB measures relative abundance, referred to as importance values, for 134 eastern tree species. Inputs include tree species distribution data from the U.S. Forest

Service Forest Inventory and Analysis (FIA) Program and 38 predictor 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 using statistical techniques (Iverson et al. 2008). DISTRIB then projects future importance values and suitable habitat for individual tree species by using downscaled GCM data readjusted to a 12-mile grid (Prasad et al. 2007-ongoing).

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

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

LANDIS-II

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

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

For this assessment, two future climate scenarios, PCM B1 and GFDL A1FI, were used to simulate a range in potential future climate. A current climate scenario was also constructed as a baseline for comparison. The current climate scenario was designed by using climate data from 1970 through 1999 as a range of possible values. These data were accessed from the PRISM data set (Gibson et al. 2002), and values were randomly sampled from this range for all future years of the simulation. The simulations used a 4.9-acre cell size and a 150-year horizon from 2000 to 2150. The landscape in northeastern Minnesota covered 3.95 million acres of forest. This is a subset of the assessment area, located in the northeast portion of the state (Chapter 5). LANDIS-II simulations included 21 tree species currently present within this landscape. Forest management practices were described with a business-as-usual scenario, presented in more detail in Appendix 4.

PnET-CN

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

PnET-CN requires input information on climate, soil, and vegetation. Climate and atmospheric inputs include monthly air temperature, precipitation, photosynthetically active radiation, tropospheric ozone concentration, atmospheric CO_2 concentration, and atmospheric N deposition rate. Soils are defined by their water holding capacity. Vegetation inputs include a suite of parameters, such as specific leaf area or leaf lifespan, that define a particular forest type. Forest types used by PnET-CN in this assessment are similar to FIA forest-type groups, such as maple/beech/birch (Miles et al. 2011). Output from PnET-CN includes many variables related to C, water, and N cycling, including key ecosystem processes such as net primary production, net ecosystem production, evapotranspiration, and N mineralization. Full information on the PnET-CN simulations used in this assessment, including inputs, methods, and results, can be found in Peters et al. (2013).

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

SUMMARY

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

CHAPTER 3: OBSERVED CLIMATE CHANGE

Climate is the long-term weather pattern for a region for a period of decades. As discussed in Chapter 1, climate is one of the principal factors that have determined the composition and extent of forest ecosystems in the Laurentian Mixed Forest Province over the past several thousand years.

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

HISTORICAL TRENDS IN TEMPERATURE AND PRECIPITATION

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

Temperature

The mean annual temperature within the assessment area increased 2.2 °F (1.2 °C) from 1901 to 2011, and this trend has been consistent across the area (ClimateWizard 2012). This trend is similar to the rate of increase across the entire state during roughly the same time (Minnesota DNR 2011a). Mean annual temperatures fluctuated considerably during the 20th century, with almost 10 °F (5.6 °C) separating the hottest and coldest years on record (Fig. 15).

Temperatures in the assessment area have increased across all seasons, but the rate of increase has varied from season to season (Table 13). The largest increase in mean temperature occurred during winter (3.7 °F, 2.1 °C), and spring mean temperatures increased by 2.7 °F (1.5 °C). Fall and summer mean temperatures have increased by smaller amounts. Mean minimum temperatures have increased at a faster rate than mean high temperatures across all seasons. The warming trends for the assessment area closely follow observed statewide trends, with the greatest warming increases occurring in winter low

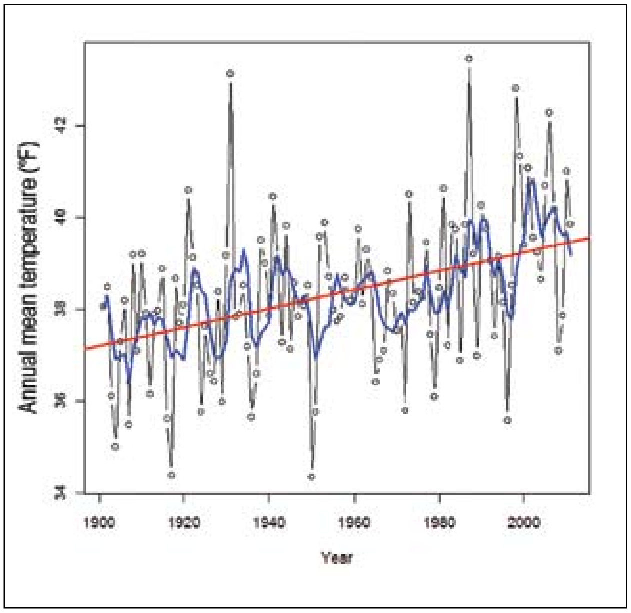


Figure 15.—Annual mean temperature within the assessment area from 1901 through 2011 (ClimateWizard 2012). The blue line represents the running 5-year mean. The red regression line shows the trend across the entire period.

temperatures (Minnesota DNR 2011a). Data from 1971 through 2000 indicate that the winter warming trend in recent years has been roughly 50 percent faster than the 20th-century trend (ClimateWizard 2012).

Observed temperature trends also differ by month within the assessment area (Fig. 16). Temperature increases were greatest during the winter and spring months, peaking in February with an increase of almost 6.0 °F (3.3 °C) in monthly mean temperature from 1901 to 2011. Mean temperature increases that were greater than the annual mean increase occurred during January, March, May, August, and December. Mean temperature did not decline in any month during this period. Increases for mean minimum temperatures were larger than increases for mean temperature or high temperatures for all months. Mean minimum temperatures increased 4.0 °F (2.2 °C) or more in January, February, and March. Mean high temperatures increased less than mean temperatures across all months, and actually decreased for July and October. These decreases were very slight in both cases.

Temperature trends differed geographically across the assessment area (Fig. 17). In winter, the greatest warming has occurred in the center of the assessment area, focused on an area around Brainerd, Grand Rapids, and Leech Lake. The North Shore of Lake Superior has also warmed faster than surrounding areas during the winter months. Spring temperature increases have been strongest in these same areas. Summer trends have been much more uniform across the assessment area, except for areas of greater warming around Lake of the Woods and the North Shore of Lake Superior, which appear to be driven mostly by increased mean minimum temperatures. Fall spatial trends were also similar to summer months, with moderate changes across the assessment area. As mentioned above, fall temperatures held essentially constant over the 20th century. Interestingly, a slight but widespread cooling trend for mean maximum temperature occurred in the northwest portion of the assessment area during summer and fall.

Table 13.—Increases in mean annual and seasonal temperature (°F) from 1901 through 2011 in the assessment area (ClimateWizard 2012)

Season	Average temperature increase	Average high temperature increase	Average low temperature increase
Annual	2.2	1.4	3.1
Winter (Dec.-Feb.)	3.7	2.7	4.8
Spring (Mar.-May)	2.7	2.2	3.2
Summer (June-Aug.)	1.5	0.4	2.6
Fall (Sept.-Nov.)	1.0	0.2	1.9

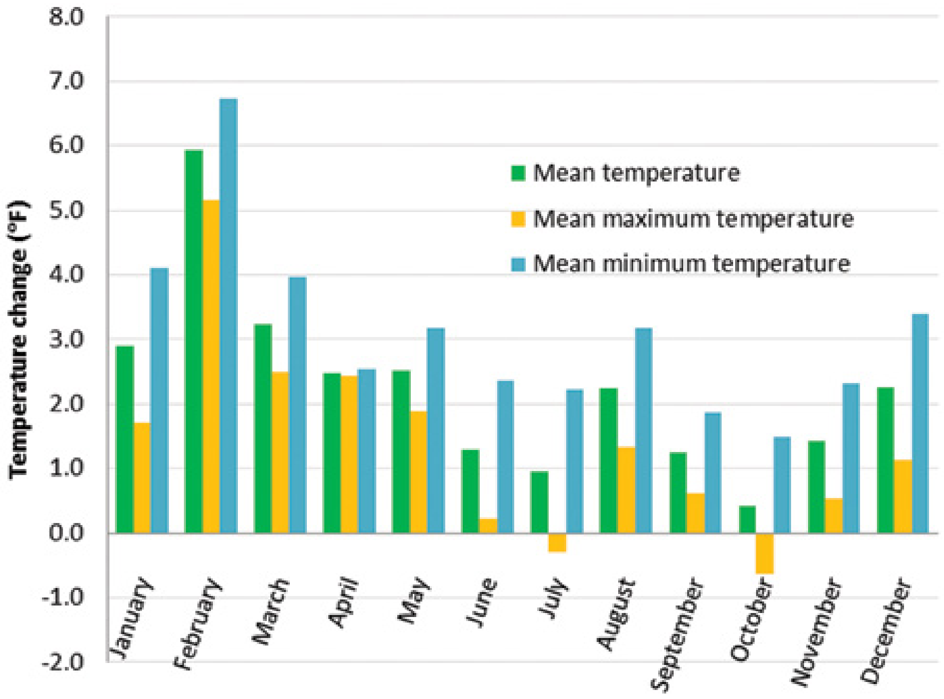


Figure 16.—Change in mean monthly temperatures from 1901 through 2011 within the assessment area (ClimateWizard 2012).

Trapper's Creek in winter. Photo by Casey McQuiston, Superior National Forest.

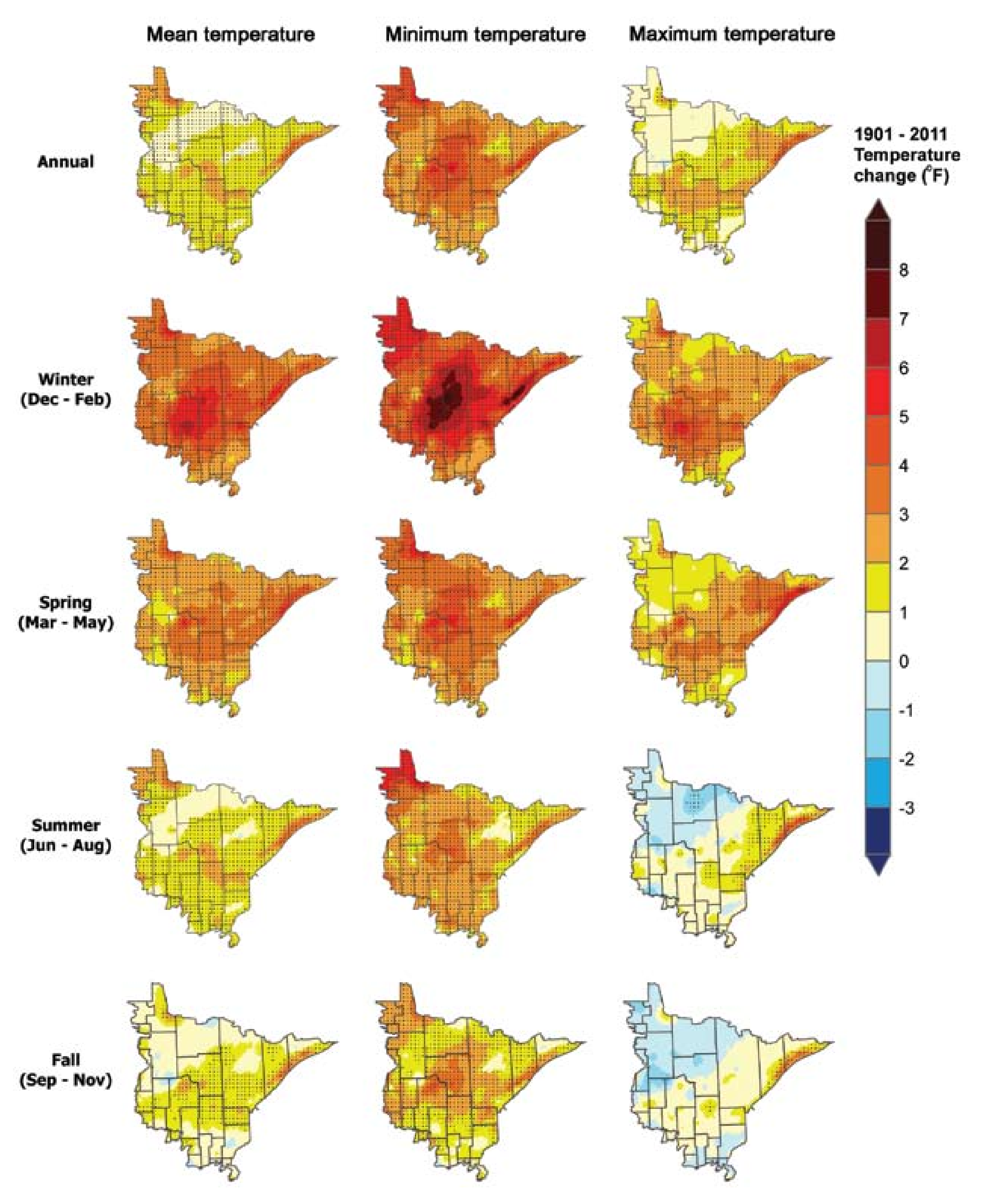


Figure 17.—Annual and seasonal observed temperature changes from 1901 through 2011 in the assessment area. Change is calculated from the slope of the regression line across the timeframe (ClimateWizard 2012). Stippling indicates there is less than 10-percent probability that the trend could have occurred by chance alone.

Precipitation

From 1900 through 2011, mean annual precipitation increased by 4.3 inches across the assessment area (Table 14) (ClimateWizard 2012). A recent statewide assessment calculated an increase in precipitation of 2.7 inches during the 20th century, so it appears that the assessment area is getting wetter than the rest of Minnesota (Minnesota DNR 2011a). Several of the driest years on record occurred between 1910 and 1940 for the assessment area (Fig. 18). During the second half of the 20th century there was great year-to-year variation in precipitation, but the overall trend appears to have been a moderate increase.

The trend in the assessment area seems to be that spring, summer, and fall are getting much wetter and winter is getting only slightly wetter. Fall had the largest absolute increase in precipitation from 1901 to 2011 (1.6 inches). Summer had the next largest absolute increase over this period (1.4 inches). Among the individual months, precipitation declined only in February. Mean October precipitation increased by 0.9 inches from 1901 to 2011, the largest increase among all months. Precipitation also increased notably in January, April, and December.

There are also interesting geographic differences in observed precipitation trends across the assessment area (Fig. 19). Across the entire year, the greatest precipitation increases were observed in the southeastern portion of the assessment area along the border with Wisconsin. Precipitation increased by a larger amount along the North Shore of Lake Superior throughout all seasons than in the surrounding areas. Winter and spring did not differ much by geography as most of the area gained 1 inch or less of precipitation during these seasons. Summer precipitation increased in the southeastern and northwestern portions of the assessment area, with increases of more than 2 inches near Lake of the Woods and in a band extending south from Hibbing. Two main areas of increased fall precipitation were located around Park Rapids and Duluth.

Table 14.—Increase in annual and seasonal precipitation (inches) from 1901 through 2011 in the assessment area (ClimateWizard 2012)

Season	Average precipitation increase
Annual	4.3
Winter (Dec.-Feb.)	0.4
Spring (Mar.-May)	0.9
Summer (June-Aug.)	1.4
Fall (Sept.-Nov.)	1.6

Interactions Between Temperature and Precipitation

Observed temperature and precipitation trends in the assessment area correspond with larger regional climate patterns. An examination of observed temperature and precipitation from 1950 through 2006 for the entire country found that areas that tended to get wetter during warm seasons also

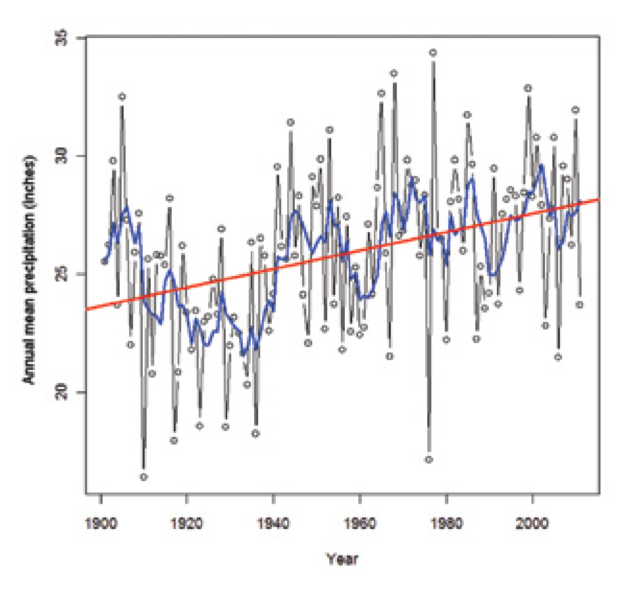


Figure 18.—Annual precipitation (inches) within the assessment area from 1901 through 2011 (ClimateWizard 2012). The blue line represents the running 5-year mean. The red regression line shows the trend across the entire period.

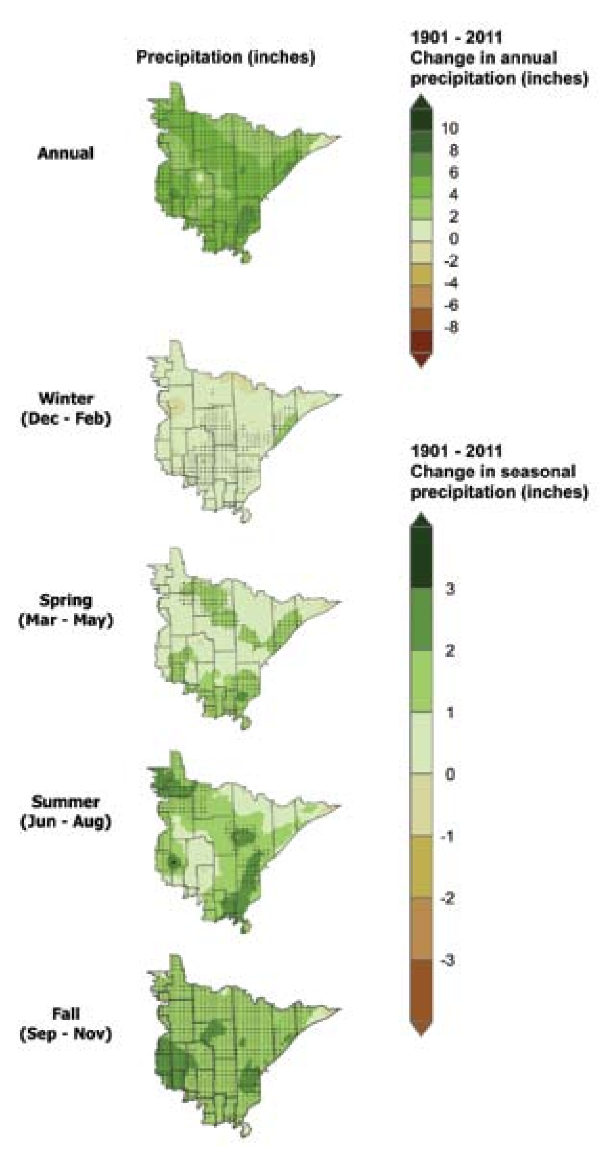


Figure 19.—Annual and seasonal precipitation changes from 1901 through 2011 in the assessment area (ClimateWizard 2012). Change is calculated from the slope of the regression line across the timeframe. Stippling indicates there is less than 10-percent probability that the trend could have occurred by chance alone.

tended to have reduced high temperatures during those seasons (Portmann et al. 2009). Conversely, areas of the country that are getting drier during warm seasons have also shown increased high temperatures. For the upper Midwest, this pattern was most evident during summer and fall. Fall exhibited the smallest temperature increases within the assessment area (Table 13) and also the largest precipitation increases (Table 14). October in particular had the greatest increase in precipitation (0.9 inches), but a decreasing mean high temperature (-0.6 °F, -0.3 °C). A similar phenomenon occurred in July. The causes of this relationship between precipitation and high temperatures are not yet fully explained, but it has been proposed that cloudiness, evaporation of surface moisture, organic aerosols from forests, and air pollution may all be involved (Portmann et al. 2009).

HISTORICAL TRENDS IN EXTREMES AND PHYSICAL PROCESSES

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

Many physical processes important for forest ecosystems are also 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 Minnesota or throughout the broader region.

Snow and Winter Storms

Cold and snowy winters are characteristic of northern Minnesota, although the state experiences fewer snowstorms than nearby Wisconsin or Michigan (Changnon and Changnon 2007). There is a gradient of increasing winter precipitation from west to east across the assessment area, owing to the prevailing wind direction, topography, and lake-effect snow from Lake Superior (ClimateWizard 2012). For the assessment area, winter precipitation increased only 0.4 inches during the 20th century (Table 14, Fig. 19).

Annual snowfall amounts have been decreasing between 1 and 3 percent per decade in northern Minnesota during the 20th century (Kunkel et al. 2013). Regional trends indicate that snowfall is quite variable from year to year, but few heavy snowfall years have occurred in the most recent 30 years (Kunkel et al. 2013). Individual snowfall events have been more intense as well. From 1900 to 1990, there was an increase in snowstorms of 6 inches or more across the upper Midwest (CCSP 2008). Extreme low-snow years in the four-state region including Minnesota became less common over the 20th century (Kunkel et al. 2009). This trend corresponds with the slight increase in winter precipitation across the assessment area and the wider region. Long-term records from across the Great Lakes indicate that lake-effect snow increased gradually across the region during the 20th century, probably due to the warming of these water bodies and the decreasing trend in lake ice cover (Burnett et al. 2003, Kunkel et al. 2013).

Soil Frost

Soil frost dynamics are important for forest ecosystems because soil temperatures can affect water infiltration rates, nutrient cycling, and tree growth. Research has shown that deeper snow depth results in shallower soil frost depth in northern forests, and thinner snowpack results in colder soil temperatures and deeper soil frost (Hardy et al. 2001). Long-term data indicate that winter soil temperatures tended to decrease during the 20th century across northern Michigan and northern Wisconsin, even as temperatures increased (Isard et al. 2007). Similarly, Sinha et al. (2010) found evidence for decreasing winter soil temperatures within the assessment area in recent decades. Therefore, even as winter temperatures have risen in the assessment area (Table 13), frost depth may have increased as snowpack conditions became more variable. Warmer winter air temperatures have led to more snowmelt in intervening periods between snowfall events. During the entire 20th century, however, there appears to have been a 12- to 24-day decline in the annual number of soil frost days (Sinha et al. 2010).

Additionally, Sinha et al. (2010) found evidence for one to two more freeze-thaw cycles per winter in northern Minnesota during the 20th century. Freeze-thaw cycles can damage roots of frost-intolerant tree species and affect the timing of nutrient release in forest soils (Auclair et al. 2010, Tierney et al. 2001).

Intense Precipitation

Intense precipitation events have become more frequent across much of the continental United States (Kunkel et al. 2008). In the upper Midwest, there was a 50-percent increase in the frequency

Water running over a forest road following the June 2012 rainstorm in northeastern Minnesota. Photo by Patrick Hampston, Superior National Forest.

of days with rainfall of 4 or more inches during the 20th century (CCSP 2008). A recent study by Groisman et al. (2012) also supports this trend, noting that moderately heavy rainfall events (0.5 to 1.0 inches) became less frequent for the central United States, while rainfall events of at least 1 inch became more common. Heavy precipitation events that used to occur only once every 12 months are now occurring every 9 months across the upper Midwest, an increase of roughly 35 percent during the past 60 years (Madsen and Willcox 2012). This trend is exemplified in Minnesota, where a 104-percent increase was observed in rainstorms of 3 inches or more between 1960 and 2011 (Fig. 20) (Saunders et al. 2012). Four rainfall events of more than 10 inches have occurred in Minnesota since 2004, including the event that caused extensive flooding in the Duluth area in 2012 (Minnesota DNR 2011a). Storms of this magnitude are predicted to occur only once every 1,000 years. Maximum daily rainfall for the assessment area typically occurs in June, July, or August (Villarini et al. 2011a).

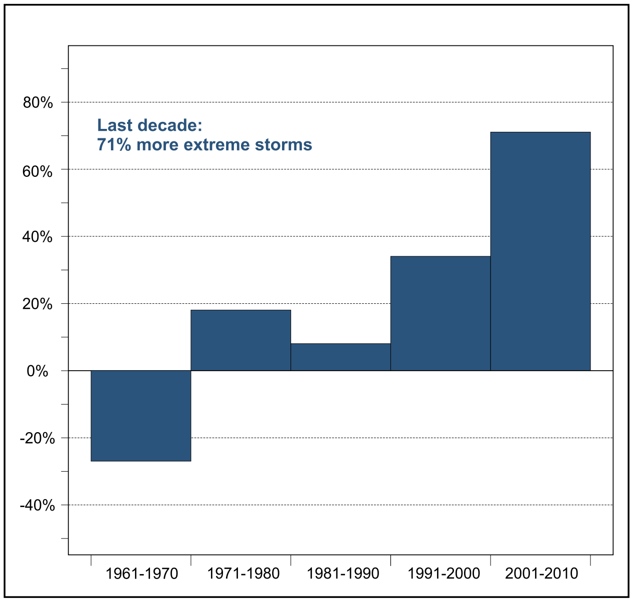


Figure 20.—Changes in the frequency of rainfall events of 3 inches or more in Minnesota from 1961 through 2011, compared to the baseline years 1961 through 1990. Figure from Saunders et al. (2012) and used with permission of the authors.

Flooding and Streamflow

Long-term data on flooding is difficult to interpret because of the variety of measures used to describe floods. From 1961 to 1979, the National Weather Service reported no severe flood years in the four-state region including Minnesota, while there were 4 such years between 1983 and 2001 (Cartwright 2005). Olsen et al. (1999) also found an increasing trend in the frequency of flood-level flows along the upper Mississippi River in Minnesota, but noted that there are several complicating factors in attributing this trend. In particular, anthropogenic land-use change over the past century has had a considerable influence on flooding frequency in the upper Midwest. Increased flood levels in the upper Midwest may be driven by land use practices, agricultural practices, and dam construction (Villarini et al. 2011b). Even taking these factors into account, however, Tomer and Schilling (2009) still found evidence that Midwestern watersheds have exhibited increased discharge during the past several decades. They attribute this trend to climate change.

Extreme Temperatures

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

Soil Moisture and Drought

Droughts are among the greatest stressors on forest ecosystems, and can often lead to secondary effects of insect and disease outbreaks on stressed trees and increased fire risk. In North America and the Midwest in particular, there has been a trend toward wetter conditions since 1950, and there is no detectable trend for increased drought based on the Palmer Drought Severity Index (Dai et al. 2004, Karl et al. 2009). Another study of hydrologic trends in the United States over the last century (1915 through 2003) also observed reduced duration and severity of droughts across the upper Midwest as a result of increased precipitation (Andreadis and Lettenmaier 2006). Data from Minnesota support this pattern. Since 2000, there have been at least six periods where more than 80 percent of the state was rated moderately dry or worse, according to the U.S. Drought Monitor archives (National Drought Mitigation Center 2013). Nevertheless, between 1895 and 2013, the trend in the assessment area has been toward slightly less common and less severe droughts during the growing season, with the years between 1920 and 1940 representing the most extreme droughts during the period of record (National Oceanic and Atmospheric Administration, National Climatic Data Center 2013).

Thunderstorms and Tornadoes

Strong thunderstorms occur most frequently in the summer months in northern Minnesota, and these weather events can be particularly damaging if they generate tornadoes. Based on long-term data from 1896 to 1995, the assessment area in Minnesota averaged 20 to 35 thunderstorm days per year (Changnon 2003). There is a clear south-to-north gradient of decreasing thunderstorm frequency across the assessment area and the entire state.

The number of tornadoes across the state has been increasing recently. Between 2001 and 2010 the mean number of tornadoes was 51 per year, up from only 37 tornadoes per year between 1981 and 2010 (National Weather Service 2012). In 2010, Minnesota set a state record for the number of tornadoes occurring in one year (104), including 48 tornadoes on a single day in June (Minnesota DNR 2011a). The U.S. Annual Tornado Maps from 1950 to 2009 show that few of these tornadoes occur within the Laurentian Mixed Forest Province, but are more common in western and southern Minnesota (National Weather Service 2012).

Windstorms

In warm months the assessment area occasionally experiences very powerful windstorms, often called derechos. These events can result in substantial windthrow disturbances, as evidenced by the 1999 storm that passed through northern Minnesota along the Canadian border. This single storm blew down roughly 665,000 acres of forest within the Boundary Waters Canoe Area Wilderness and the Quetico Provincial Park (Price and Murphy 2002). Smaller-scale wind disturbances also introduce complexity in forest stands throughout the region (Schulte and Mladenoff 2005, White and Host 2008). The frequency of derechos decreases with increasing latitude in Minnesota, and northern Minnesota has been roughly the northern limit for warm-season derecho occurrence in North America (Coniglio and Stensrud 2004). Our understanding of historical trends in derecho frequency and geographic location is limited by a lack of long-term data in the first half of the 20th century (Peterson 2000).

Paper birch regeneration blown over in a strong windstorm in summer 2012. Photo by John Rajala, Rajala Companies, used with permission.

INDICATORS OF CLIMATE CHANGE

The following case studies present some examples of early indications of climate change within northern Minnesota ecosystems. A more extensive list of observed changes throughout the state is available in *Climate Change and Renewable Energy: Management Foundations* (Minnesota DNR 2011a).

Lake Ice

Across Minnesota, long-term records have shown that lake ice is breaking up earlier in the spring and forming later in the fall. Spring ice-out dates shifted earlier by 1.3 days per decade between 1965 and 2002 (Johnson and Stefan 2006). The mean ice-out date appears to be advancing almost twice as rapidly since 1990. Observed ice-in dates in the fall changed even faster, shifting later by 7.5 days per decade from 1978 to 2002, and by 14 days per decade since 1990. The combined effect of these trends is a longer ice-free period for lakes across the region and the assessment area.

Regional data and model simulations support this trend (Kling et al. 2003, Mishra et al. 2011), as well as trends across the entire northern hemisphere (Magnuson et al. 2000). Within the three-state region of Minnesota, Michigan, and Wisconsin, observed changes in lake ice duration indicate that ice-in and ice-out dates have been shifting three to four times more rapidly since 1980 than across the 20th century (Kling et al. 2003). Therefore, the total duration of lake ice is shrinking at an accelerating rate, which long-term trends may underestimate. Ice cover on the Great Lakes is also declining substantially, with a mean decline of 71 percent in ice coverage between 1973 and 2010 (Wang et al. 2012). Reduced ice cover exposes more of the lake's surface to radiation, allowing the lake to absorb and retain more heat. Increased lake temperatures can contribute to shifts in ice formation and coverage, which can strongly influence near-shore climates and weather events, such as lake-effect snow.

Timing of the Growing Season

Changes in the temperature regime will also influence the seasonal timing of favorable temperatures for plant growth. Meteorological records show an earlier onset of warm temperatures in spring and later onset of cold temperatures in winter during the 20th century. This altered seasonality results in the overall lengthening of the potential growing season. There is increasing worldwide evidence of response of phenology, the timing of biological events such as leafing, flowering, and leaf coloring (Menzel et al. 2006, Parmesan and Yohe 2003, Root et al. 2003, Schwartz et al. 2006a). The degree to which organisms take advantage of a longer active growing season depends on the species. A global analysis of leafing and flowering trends shows a consistent advancement of 5 to 6 days per 1.8 °F (1.0 °C) of warming across many species and locations (Wolkovich et al. 2012).

Long-term records of plant phenology exist in Minnesota but are scattered and have not yet been systematically analyzed. A 50-year record (1941 to 1991) from St. Paul, Minnesota, shows evidence of an 8-day advancement of quaking aspen leafing (Fig. 21) (Hodson 1991). In Wisconsin, a 61-year record (1936 to 1947; 1976 to 1998) shows 7-day advancement of spring phenology across 55 monitored plants and animals (Bradley et al. 1999). A warming experiment in northern Minnesota suggests similar patterns of spring advancement for common forest tree species in the state (R. Montgomery and P. Reich, University of Minnesota, unpublished data).

Wildlife Populations and Range Shifts

Changes in wildlife populations in northern Minnesota may be taken as further evidence of climate change. As temperatures have warmed across the state, researchers in northern Minnesota have witnessed the northward range expansion of animal species. Monitoring inventories in Voyageurs

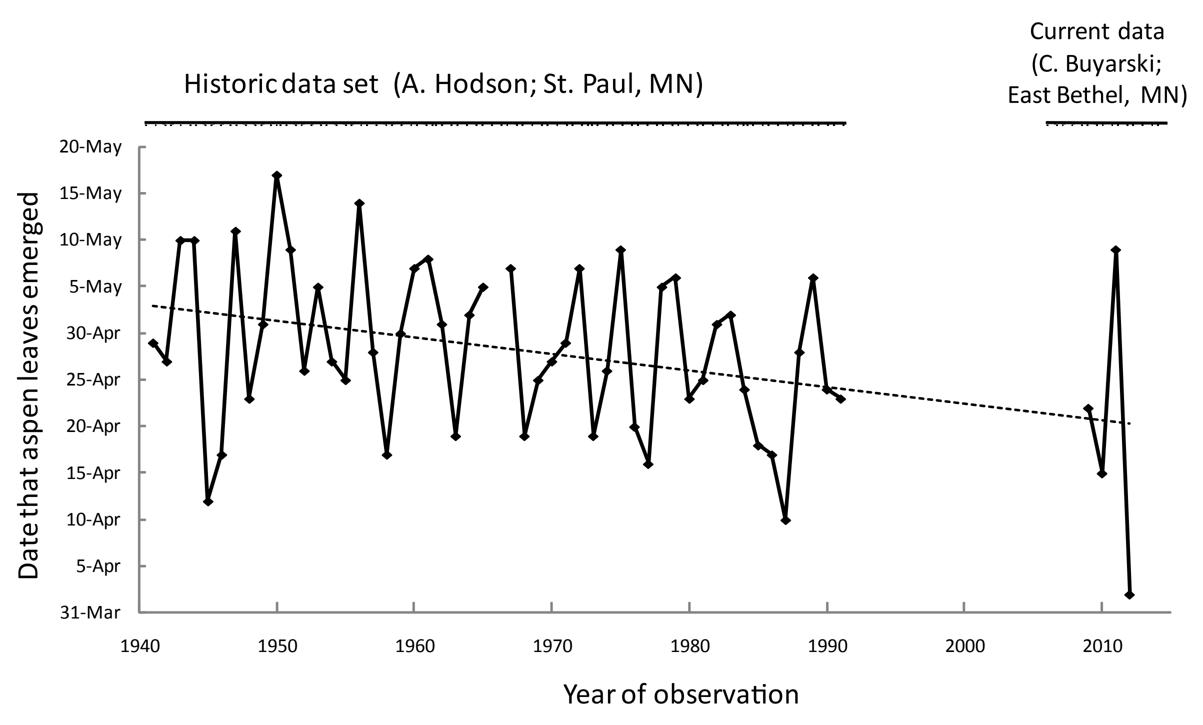


Figure 21.—Leaf-out dates for quaking aspen based on a 50-year record collected in St. Paul, Minnesota, and a 4-year record collected in East Bethel, Minnesota (~30 miles north of St. Paul). The St. Paul record is based on daily observations whereas the East Bethel record is based on weekly observations. Figure courtesy of R. Montgomery, University of Minnesota.

National Park from 1996 through 2001 recorded four rodent species that previously had resided south of the area: the white-footed mouse, rock vole, Franklin's ground squirrel, and eastern gray squirrel (Jannett et al. 2007). It also appears that badger and raccoon are expanding their ranges within the northern part of the state. Land-use change might have also facilitated the northward spread of the raccoon and ground squirrel, but these species had not previously taken advantage of the land-use changes brought about by heavy logging in the early 20th century.

Moose is an iconic species in Minnesota. The southern extent of the moose distribution range occurs within the assessment area, and evidence suggests that ambient temperature thresholds in winter and summer may be largely responsible for determining where moose can thrive (Lenarz et al. 2009, 2010). Higher winter temperatures improve survival of moose parasites like ticks, and also improve survival of white-tailed deer, which transmit additional parasites and diseases to moose (Rempel 2011). Higher summer temperatures exacerbate heat stress in moose and make it more difficult to maintain optimal body temperature. The northeastern Minnesota moose population has been on a recent downward trend, based on a recent examination of population demographics (Lenarz et al. 2010). This trend is due to a variety of factors, but increasing temperatures within the assessment area are suspected of having placed greater heat stress on moose in northeastern Minnesota. Minnesota DNR studies indicate that the population decline for northeastern moose has accelerated in recent years, with a 52-percent decline from 2010 to 2013 and a 35-percent decline from 2012 to 2013 (Minnesota DNR 2013).

Warming temperatures have also been linked to the declining moose populations elsewhere in the region. The population in northwestern Minnesota has declined dramatically in the past 20 years and now fewer than 100 individuals remain (Lenarz et al. 2010). Additionally, ecological modeling to describe the range of moose in Ontario found significant relationships between moose abundance and mean winter and summer temperatures from 1990 through 1999 (Rempel 2011).

Fish Populations and Reproductive Phenology

Cisco (also called lake herring or tullibee) is a cold-water fish native to northern Minnesota, which is the southern part of the species' range (Fig. 22). Cisco is a common species that provides important forage for other fish in inland lakes such as walleye, lake trout, and northern pike (Fang et al. 2009, Jiang et al. 2012). Cold, oxygenated water is crucial for cisco survival. Cisco populations have been monitored in almost 650 Minnesota lakes since 1946 (Minnesota DNR 2011a). These surveys have documented a 42-percent decline in inland lake cisco populations since 1975. Recent research suggests that this decline is the result of warming lake temperatures, which lead to stratification and eutrophication processes that reduce oxygen availability. Lakes that host cisco have not typically been subject to human-caused eutrophication (Minnesota DNR 2011a).

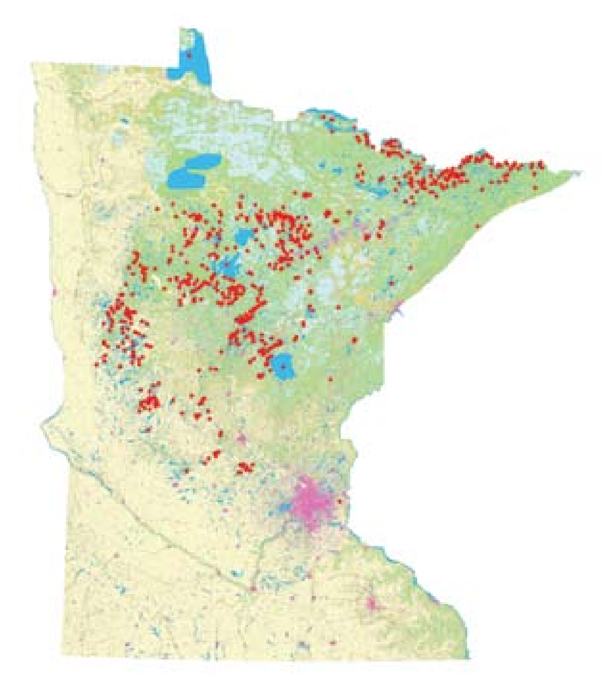


Figure 22.—Distribution of 648 lakes where cisco have been sampled in Minnesota DNR surveys since 1948. Figure courtesy of Peter Jacobson, Minnesota DNR.

Changes have also been observed in the yearly reproductive cycles of important fish species in Minnesota. Walleye spawning is often closely associated with ice-out events in rivers and lakes. Long-term egg collection data for Minnesota fisheries show that as ice-out dates have gradually shifted earlier into the spring, walleye spawning seasons have shifted earlier as well (Schneider et al. 2010). For most locations, egg laying appears to have tracked climate change relatively closely during the 20th century. Spawning advanced 0.5-1.0 days for every 1.0 days of advanced ice-out. Potential implications of this shift could include mismatches between egg hatch dates and prey availability for the larval walleye, or mismatches between spawning seasons and peak streamflow.

SUMMARY

Northern Minnesota has observed several notable shifts in climate, climate-driven processes, and extreme weather events (Box 6). In general, the assessment area is experiencing warmer weather across the year, particularly with respect to mean minimum temperatures and winter temperatures. Precipitation increased during 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 about anthropogenic climate change. Ecological indicators are beginning to reflect these changes as well, as evidenced by changing ranges of wildlife species and changing phenology.

Box 6: More Information on Observed Climate Trends and Ecological Indicators

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

- Minnesota State Climatology Office: climate.umn.edu/
- Minnesota Department of Natural Resources “Climate” Web page: www.dnr.state.mn.us/climate/index.html
- University of Minnesota Extension “Extreme Weather” Web page: www.extension.umn.edu/extreme-weather/drought-fire/climatology/
- Minnesota Phenology Network: https://www.usanpn.org/mnpn/home
- ClimateWizard: www.climatewizard.org/
- National Climatic Data Center: www.ncdc.noaa.gov/

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

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

PROJECTED TRENDS IN TEMPERATURE AND PRECIPITATION

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

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

Temperature

The Laurentian Mixed Forest Province in Minnesota is projected to warm substantially during the 21st century (Figs. 23 to 26). Compared to the 1971 to 2000 baseline period, the average annual temperature is projected to increase 3.0 °F (1.7 °C) under the PCM B1scenario and 8.8 °F (4.9 °C) under the GFDL A1FI scenario. The projected temperature increase is not consistent across all seasons. Both models project that winter months (December-February) will experience dramatic warming by the end of the century (PCM B1: 3.9 °F, 2.2 °C; GFDL A1FI: 9.8 °F, 5.4 °C), but spring months (March-May) will experience less warming (PCM B1: 2.2 °F, 1.2 °C; GFDL A1FI: 5.4 °F, 3.0 °C). The GFDL A1FI scenario also projects an increase of 11.4 °F (6.3 °C) in summer temperatures by the end of the century. Summer warming is much milder under the PCM B1 scenario (2.3 °F, 1.3 °C). See

Appendix 3 for a table of temperature projections for the assessment area, as well as maps of projected change in the early century (2010 through 2039) and mid-century (2040 through 2069).

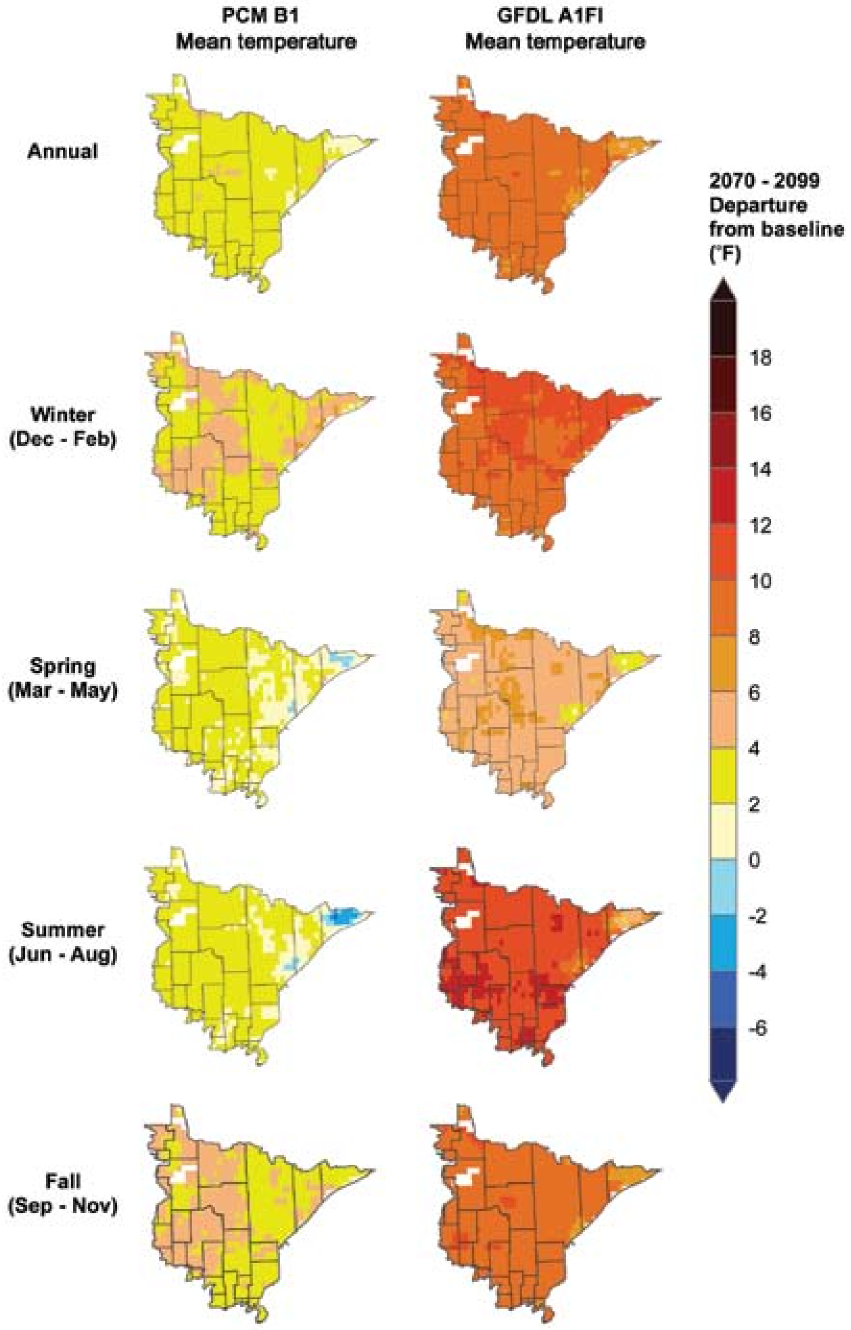


Figure 23.—Projected difference in mean daily temperature at the end of the century (2070 through 2099) compared to baseline (1971 through 2000) for two climate scenarios.

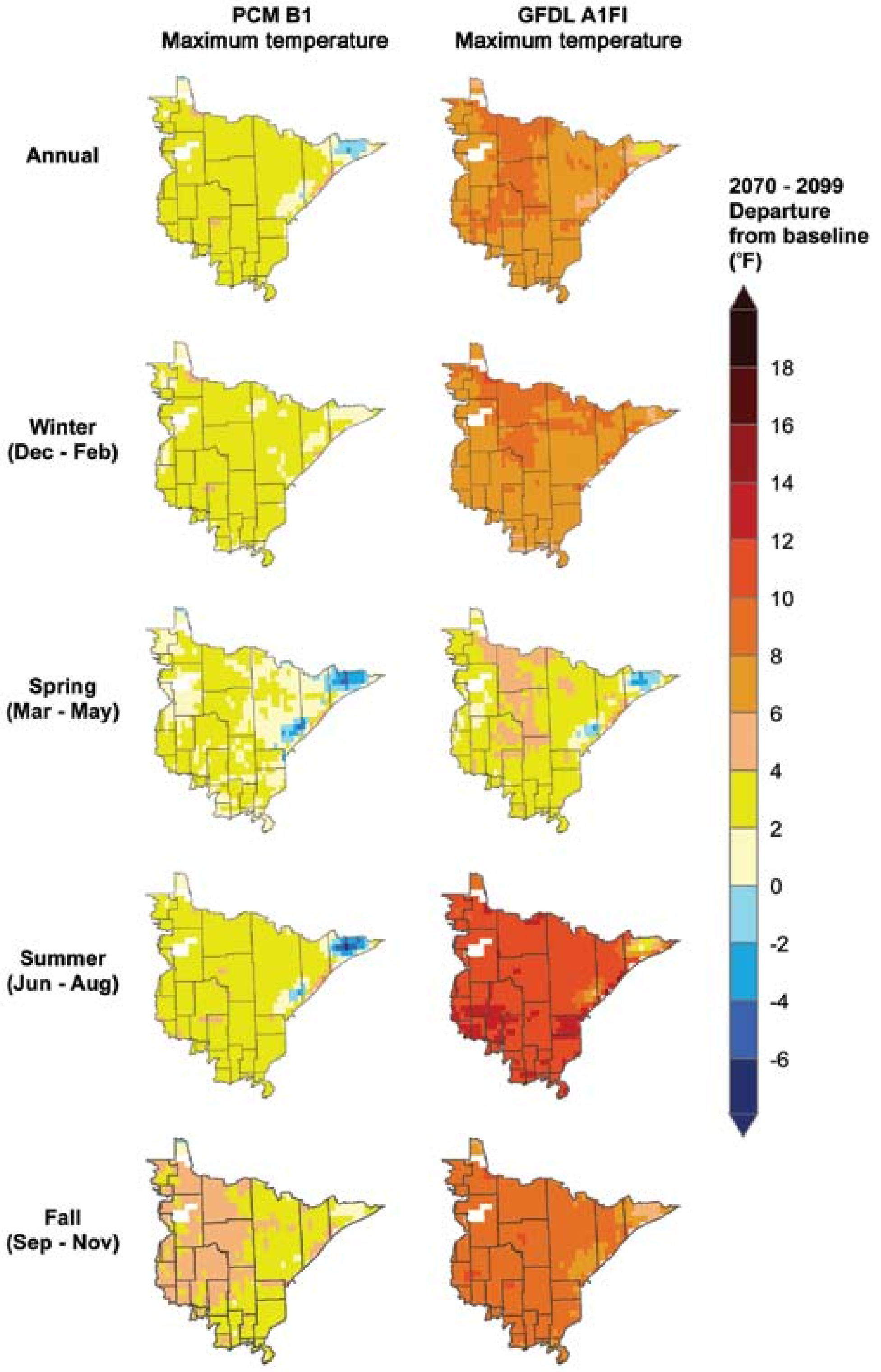


Figure 24.—Projected difference in mean daily maximum temperature at the end of the century (2070 through 2099) compared to baseline (1971 through 2000) for two climate scenarios.

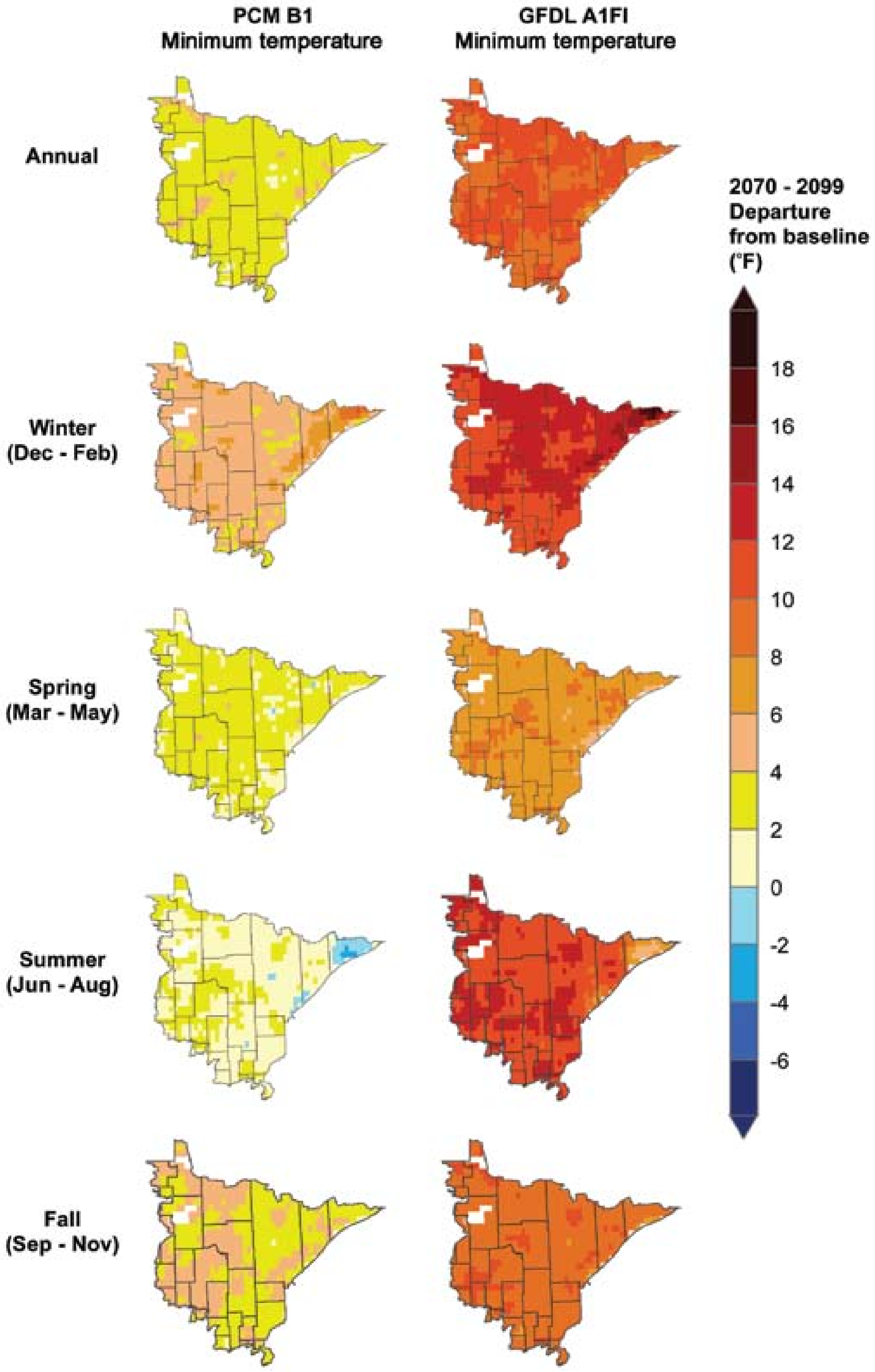


Figure 25.—Projected difference in mean daily minimum temperature at the end of the century (2070 through 2099) compared to baseline (1971 through 2000) for two climate scenarios.

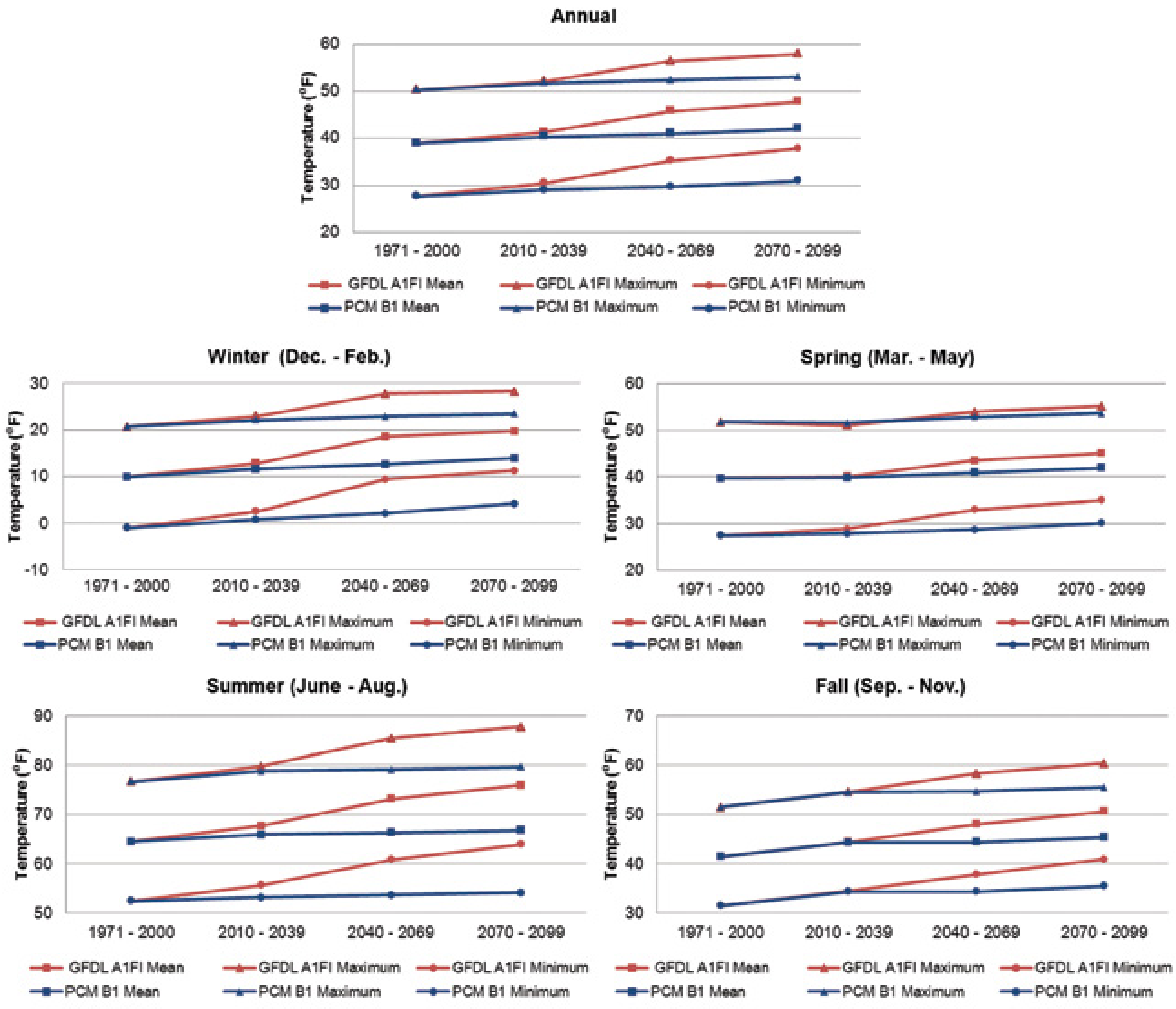


Figure 26.—Projected mean, maximum, and minimum temperatures in the assessment area averaged over 30-year periods for the entire year and by season. The 1971 through 2000 value is based on observed data from weather stations. Note that the panels have different Y-axis values.

Minimum temperatures are projected to increase more than maximum temperatures under both scenarios across nearly all seasons. Summer is the only exception to this trend, with increases in maximum temperatures projected to be slightly higher than increases in minimum temperatures under the PCM B1 scenario. By the end of the century, winter minimum temperatures are expected to increase 5.0 °F (2.8 °C) under the PCM B1 scenario and 12.1 °F (6.7 °C) under the GFDL A1FI scenario.

Temperature increases are projected to be relatively minor between the 1971 through 2000 baseline period and the 2010 through 2039 period (Fig. 26). Additionally, the projections under the two future scenarios do not diverge substantially until mid-century (2040 to 2069). The GFDL A1FI scenario leads to much larger temperature increases, with the greatest amount of change expected to occur mid-century. Alternatively, the PCM B1 projections indicate a substantially smaller increase in temperature, with relatively constant increases during the 21st century.

Projected temperature trends are geographically consistent across the assessment area (Figs. 23 to 25). An interesting spatial pattern exists along the North Shore of Lake Superior. Compared to the assessment area as a whole, this area is expected to face even larger temperature increases during winter. This trend is apparent under both model scenarios. The same area, particularly Cook County, is projected to experience cooler or only slightly warmer spring and summer months. These trends are generally consistent for minimum and maximum average temperatures as well.

Although the two climate scenarios project different amounts of warming, they are in agreement that mean, maximum, and minimum temperatures will increase in the assessment area for winter, spring, and fall. The two models display very different futures for summer months, with the PCM B1 scenario showing very little warming and scattered areas of cooling. Conversely, the GFDL A1F1 scenario projects most of the assessment area will experience warming on the order of 10 °F to 12 °F (5.6 °C to 6.7 °C) for mean, maximum, and minimum summer temperatures. This is even greater than the large temperature increases expected in winter months.

Precipitation

The two climate scenarios we chose for this assessment describe a range of future precipitation for the assessment area (Figs. 27 and 28), but it is important to keep in mind that other GCM and emissions scenario combinations could project values outside of this range. Substantial differences exist among projections of precipitation across the Midwest (Kunkel et al. 2013, Winkler et al. 2012). The PCM B1 scenario projects that the assessment area will receive 3.0 inches more annual rainfall at the end of the next century compared to the baseline years of 1971 through 2000. The assessment area may experience a slight decrease in annual rainfall during this same period according to the GFDL A1F1 scenario (-0.4 inches), with a large decrease occurring during the summer. See Appendix 3 for a table of precipitation projections for the assessment area, as well as maps of projected change in the early century (2010 through 2039) and mid-century (2040 through 2069).

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 expected to receive steadily increasing precipitation during the 21st century, with a total increase of 1.6 inches. Summer precipitation under this scenario is projected to be relatively constant, with a total change of around 0.5 inches. The GFDL A1FI

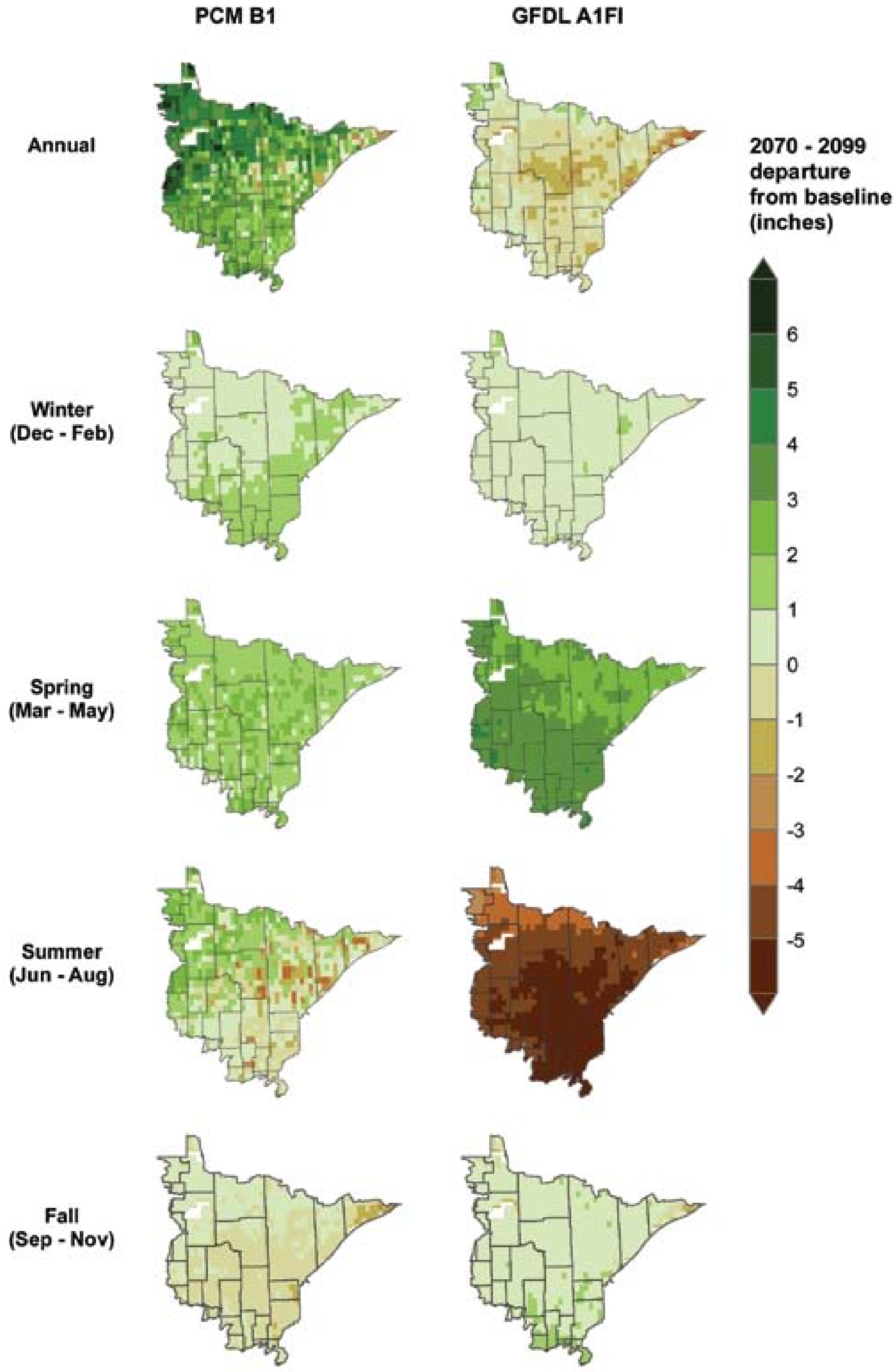


Figure 27.—Projected difference in mean precipitation at the end of the century (2070 through 2099) compared to baseline (1971 through 2000) for two climate scenarios.

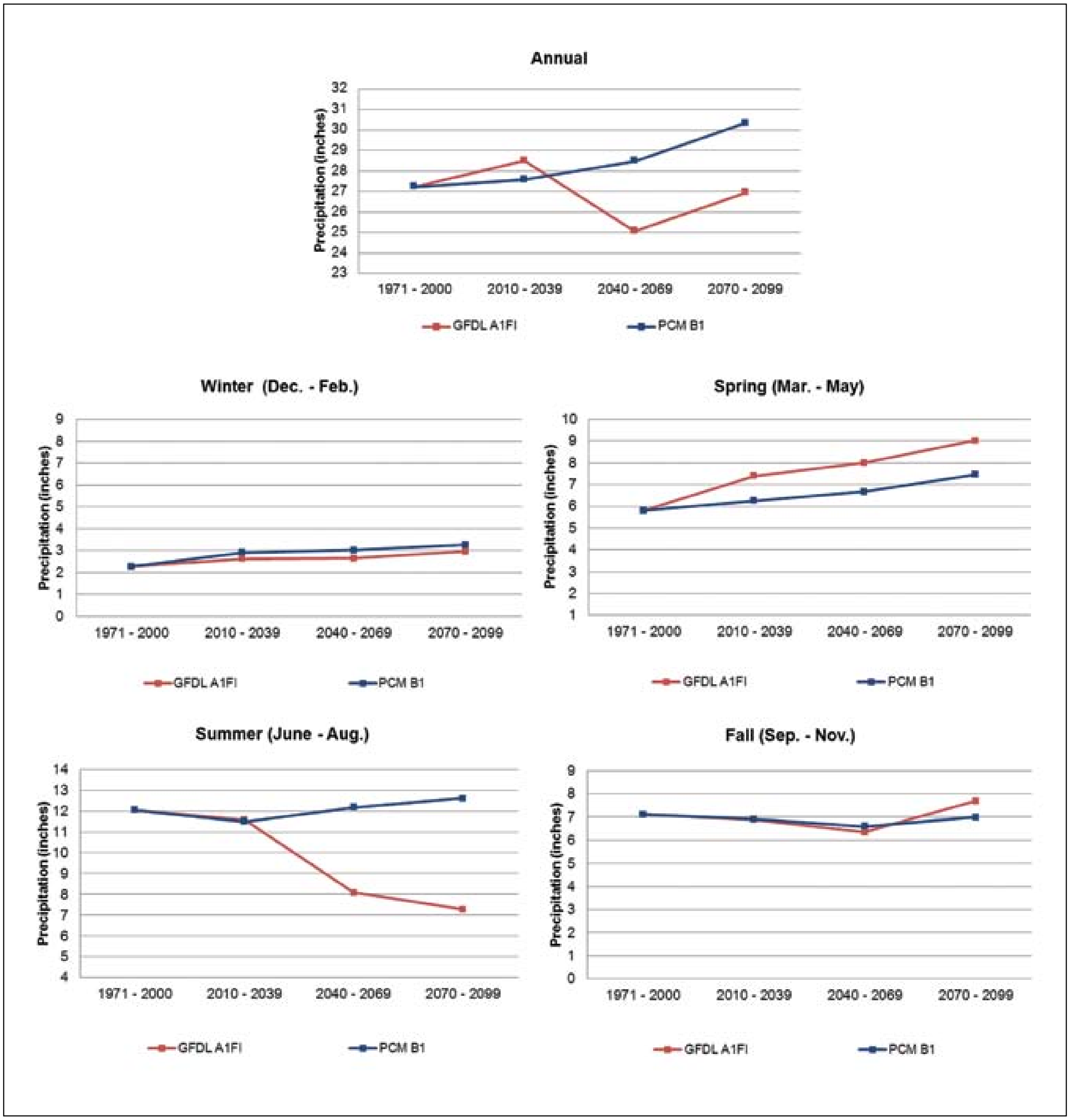


Figure 28.—Projected trends in average precipitation in the assessment area averaged over 30-year periods for the entire year and by season. The 1971 through 2000 value is based on observed data from weather stations. Note that the panels have different Y-axis values.

scenario projects a much sharper distinction between these seasons, with spring gaining 3.2 inches and summer precipitation declining by 4.8 inches. Those projections represent a 54-percent increase in spring precipitation, followed by a 40-percent decrease in summer precipitation. Winter and fall precipitation is expected to remain relatively consistent under both scenarios.

Like the future temperature projections, precipitation across the assessment area is expected to change only slightly between the baseline period (1971 through 2000) and the early part of the 21st century (2010 through 2039). The greatest change in precipitation projections under this scenario occurs in mid-century (2040 through 2069), driven by substantial declines in summer precipitation. The PCM B1 scenario projects gradual change across the 21st century.

The PCM B1 scenario projections indicate that precipitation increases will occur throughout the assessment area, with the greatest increase in the northwestern portion of the assessment area. These increases are projected mainly in the spring and summer months (Fig. 27). The North Shore of Lake Superior and southern portion of the assessment area show a decrease in precipitation during summer and fall under this scenario. Under the GFDL A1FI scenario, the spatial patterns of projected precipitation are relatively even across the assessment area for all seasons (Fig. 27). The maps of precipitation departure from baseline conditions for this scenario also highlight the sharp contrast between projected spring increases and summer decreases.

Evapotranspiration and Precipitation Ratios

Temperature and precipitation values are both important climatic factors governing forest ecosystems, and it is projected that both will shift within the assessment area in the coming century. A given amount of change in temperature or precipitation may be ecologically significant, but it is difficult to know how changes in one value might buffer or amplify changes in the other. For example, a given increase in temperature may not result in significant ecological change if precipitation also increases, but the same increase in temperature could result in a severe change if accompanied by reduced precipitation. As temperatures rise, the atmosphere is able to hold larger quantities of water, which causes evaporation and transpiration to increase. Increasing both evaporation and transpiration leads 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 look for changes in the ratio of evapotranspiration (ET) to precipitation (P). This ratio, ET:P, is essentially a metric to describe how completely a forest ecosystem is using the available water. Changes in this ratio indicate whether a forest is experiencing relatively drier or wetter conditions.

We used the ecosystem model PnET-CN to calculate projected changes in ET:P for the assessment area, comparing the 1971 through 2000 baseline period to the years 2070 through 2099. Evapotranspiration is an output of the PnET-CN model, so these values also 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 more fully describes the PnET-CN model, and further results from this model are presented in Chapter 5 and Peters et al. (2013). Figure 29 displays the projected annual and seasonal changes in ET:P under both PCM B1 and GFDL A1FI. Positive values indicate that ET is increasing relative to available moisture and that ecosystems would be subject to more moisture stress. Conversely, negative values indicate that more moisture is available. It is important to note that PnET-CN projects major water savings under elevated CO_2, which is an area of considerable uncertainty (Peters et al. 2013).

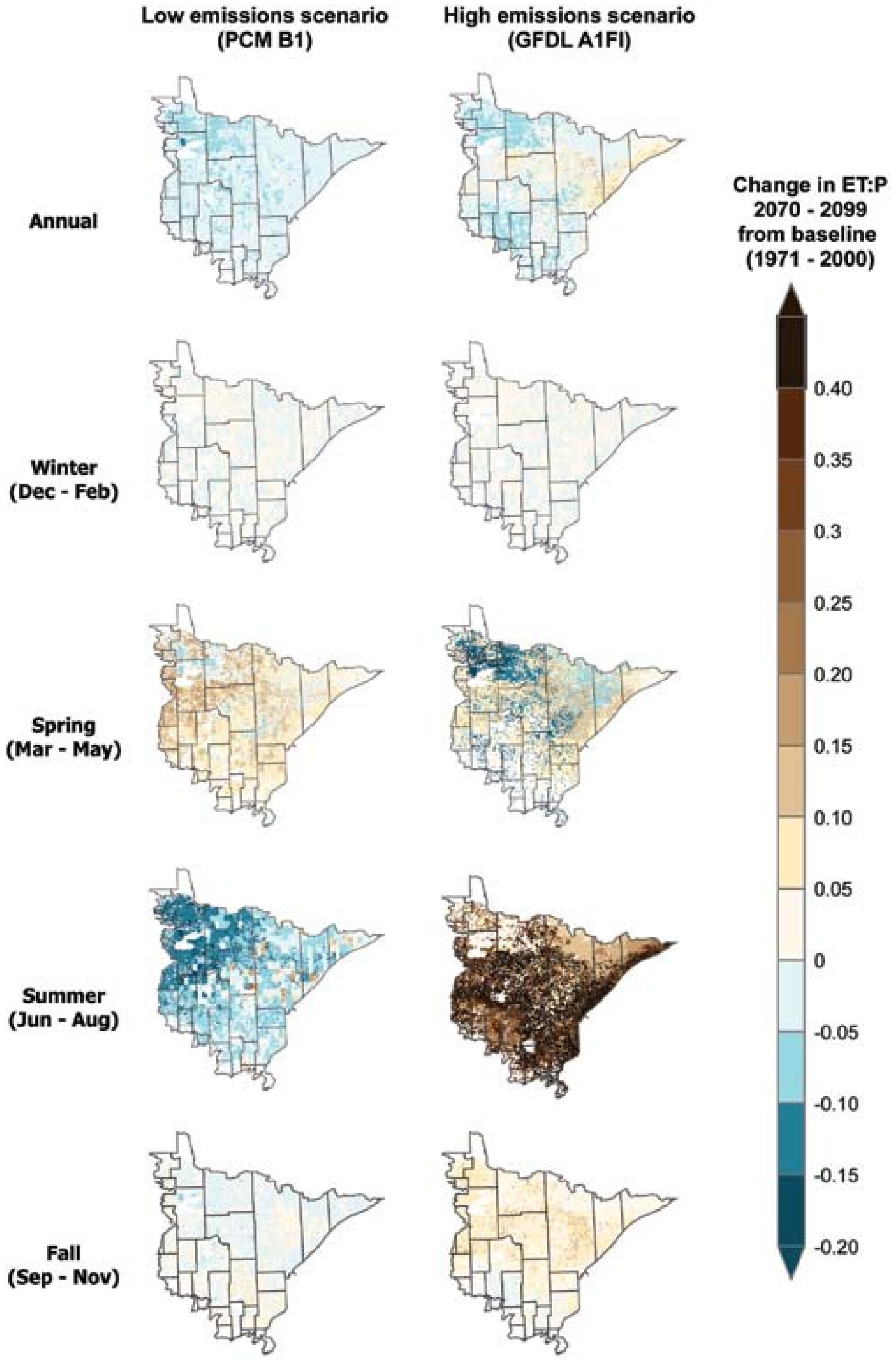


Figure 29.—Projected changes in the ratio of evapotranspiration to precipitation (ET:P) under two future climate scenarios for the assessment area over the next century. Data from Stoner et al. (2013) and Peters et al. (2013). Positive values indicate that ET is increasing relative to available moisture and that forests would be experiencing more moisture stress. Negative values indicate that more moisture is available.

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

The ET:P values highlight that the GFDL A1FI scenario may result in a much higher degree of moisture stress in summer months than indicated by precipitation values alone. The projected summer temperature increase of 11.4 °F (6.3 °C) results in higher evapotranspiration for forests across the assessment area, which essentially intensifies the projected precipitation decline. There is high spatial variation for spring months under this scenario, but the ET:P ratio for spring is also slightly positive under the GFDL A1FI scenario. This result means that in some areas evapotranspiration increases may outweigh the projected precipitation increase.

Additionally, forests along the North Shore of Lake Superior are projected to experience greater moisture limitation (increasing ET:P) in spring months under both future climate scenarios, despite projected increases in precipitation. This outcome indicates that productivity increases and longer growing seasons could lead to increases in ET that outpace the projected increases in precipitation.

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

PROJECTED CHANGES IN EXTREMES AND PHYSICAL PROCESSES

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

Snow and Freezing Rain

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

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

Additionally, modeling studies have projected that climate change will result in slightly more frequent freezing rain events across the assessment area (Lambert and Hansen 2011). The projected changes are slight (2.5 more events per decade), but this trend is consistent with the projected shift in winter precipitation from snowfall to rain. The trend of increasing lake-effect snow may continue in the short term while winter temperatures remain cold enough to produce snow (Burnett et al. 2003). Model simulations suggest that lake-effect snow may decrease by the end of the 21st century due to warming temperatures, and that lake-effect rain may become more common during winter months (Kunkel et al. 2002).

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

Soil Frost

Winter temperatures are projected to increase across the assessment area under both PCM B1 and GFDL A1FI, which would be expected to increase soil temperatures. Snowcover typically insulates forest soils, however, so reduced snowpack under climate change could also leave the soil surface more exposed to fluctuations in air temperature and result in deeper soil frost (Isard et al. 2007). A study that attempted to integrate these conflicting trends found that cold-season soil temperatures may increase between 1.8 °F and 5.4 °F (1 °C and 3 °C) and that there would be approximately 30 fewer soil frost days per winter on average across the assessment area by the end of the 21st century (Sinha and Cherkauer 2010). The projected trends for soil frost across the region are shown in Figure 30. Total frost depth is projected to decline by 40 percent across the assessment area. Also, the annual number of freeze-thaw cycles is not expected to change by the end of the century. Therefore, it appears that warmer winter air temperatures will more than counteract the loss of snow insulation and that soil frost will generally be reduced across the assessment area. These projections are generally consistent with studies of snowpack and soil frost in New England forests (Campbell et al. 2010).

Growing Season Length

The growing season has shifted in the assessment area during the past century, as noted in Chapter 3. Growing seasons are dictated by a variety of factors, including day length, air temperatures, soil temperatures, and dates of first and last frost (Linderholm 2006). Therefore, a variety of metrics can describe how growing seasons may continue to

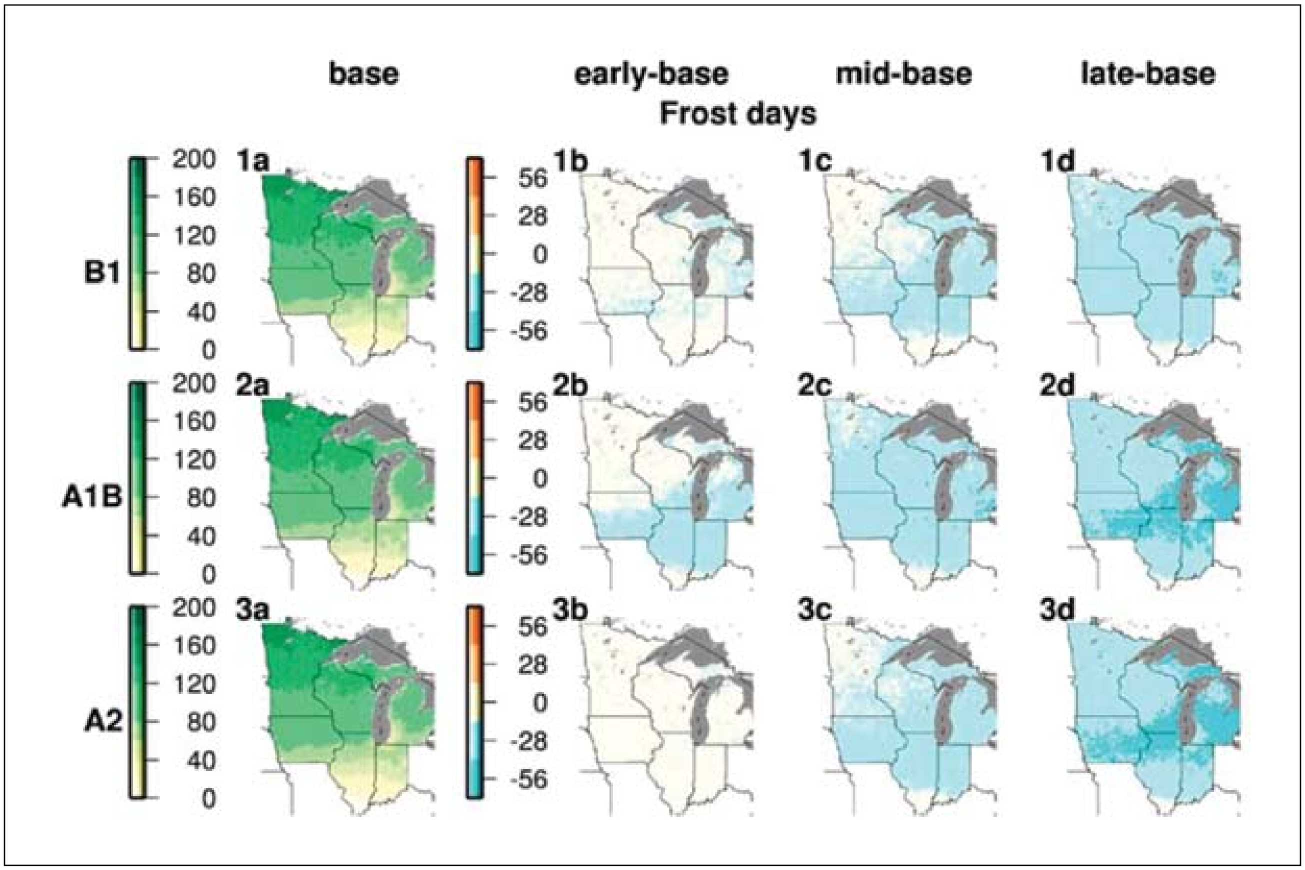


Figure 30.—Baseline and projected number of annual soil frost days for the Midwest under a range of climate scenarios, from Sinha and Cherkauer (2010). Base refers to the average annual number of soil frost days, 1977 through 2006. Early-base, mid-base, and late-base refer to the difference in mean soil frost days from the baseline period for 2010 through 2039, 2040 through 2069, and 2070 through 2099. The A2 emissions scenario is roughly equivalent to the A1FI scenario in terms of greenhouse gas emissions, and the A1B scenario is approximately a middle range between A1FI and B1.

change under a range of climate scenarios. A study covering the entire Midwest examined the changes in dates for the last spring frost and first fall frost under a range of climate scenarios (Wuebbles and Hayhoe 2004). This study projected that the growing season will be extended by 30 days under the B1 emissions scenario and 70 days under the A1FI scenario (Fig. 31). The last spring frost dates are projected to shift earlier into the year by the end of the century at approximately the same rate that first fall frost dates will retreat later into the year. Another study across the Midwest projected that the assessment area in Minnesota will have roughly 20 fewer frost days by the middle of the 21st century, under the A2 emissions scenario (Kunkel et al. 2013).

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

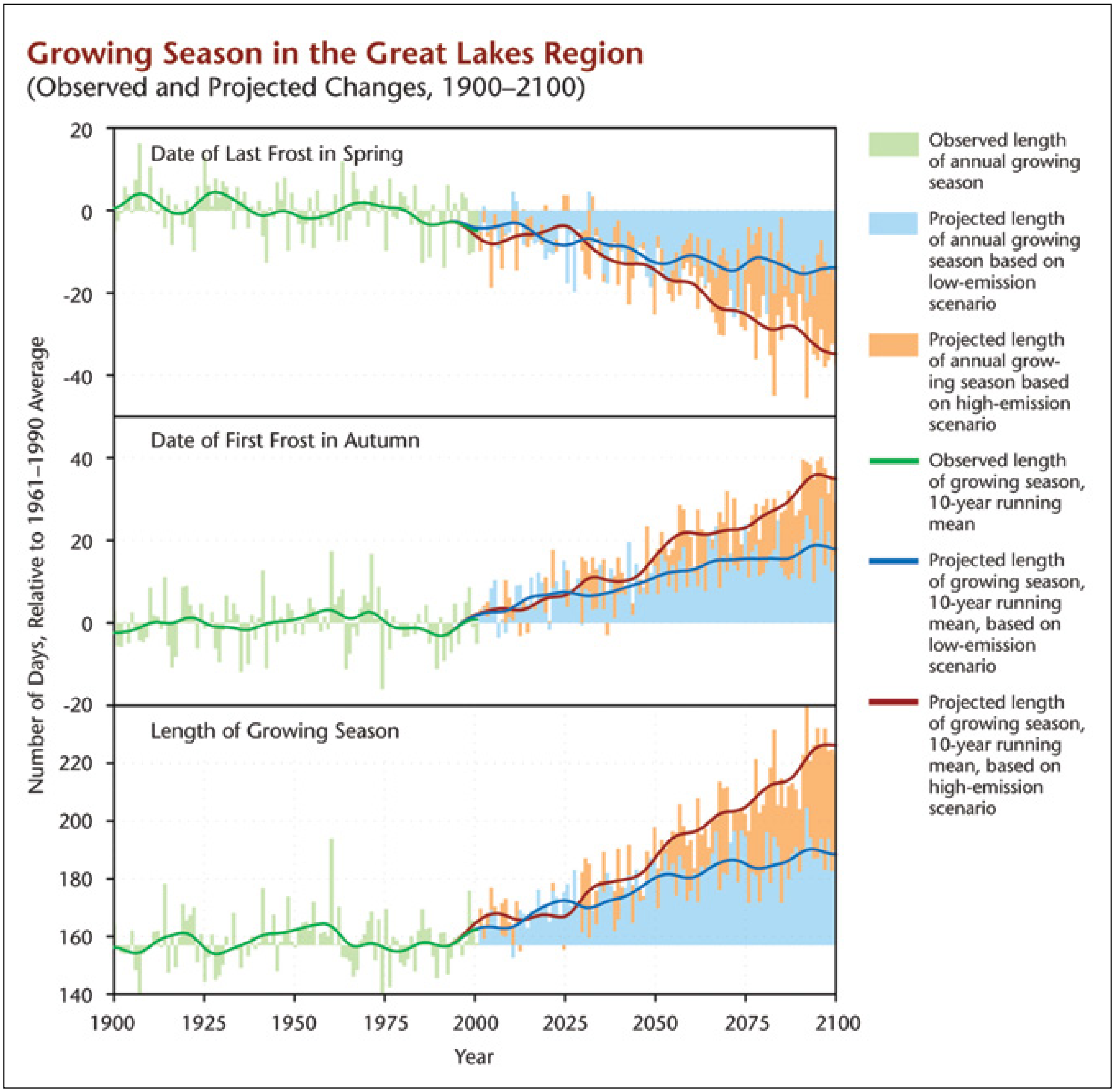


Figure 31.—Changes in length of frost-free season and dates of last spring and first autumn frost over the Midwest states. Historical data on the frost-free season are shown from 1900 through 2000, based on observed data. Projections from 2001 through 2099 are shown in orange for the higher A1FI scenario and blue for the lower B1 scenario. Bars show year-to-year variability and solid lines indicate 10-year running means. From Kling et al. (2003), modified from Wuebbles and Hayhoe (2004), and reprinted with the permission of the authors.

Intense Precipitation

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

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

Flooding and Streamflow

High-intensity rainfall events are linked to both flash flooding and widespread floods, depending on soil saturation and stream levels at the time of the event. As noted in Chapter 3, there has been a trend toward more frequent flooding in river systems across the Midwest. A modeling study examining climate change impacts on streamflow across the region suggested that runoff and streamflow may shift substantially across northern Minnesota (Wuebbles et al. 2009). Researchers projected a 30-percent increase in winter and spring runoff under the B1 emissions scenario and a 90-percent increase under the A2 emissions scenario (Fig. 32). This reflects an overall increase in winter precipitation, more frequent winter rainfall, and snowmelt events. The same study projected that summer runoff could vary between a 24-percent increase and a 16-percent decrease under the same climate scenarios. The range of fall runoff values covered slight increases and even larger decreases. Mean and peak flows in the Upper Mississippi River were projected to increase by roughly 30 percent under both scenarios by the end of the century. Further modeling studies for rivers across the Midwest project that summer low flow levels may decrease, summer high flows may increase, and overall flashiness may increase in summer months (Cherkauer and Sinha 2010).

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 point to an increasing frequency of hot days across the assessment area, with roughly 20 to 30 more days per year above 95 °F and a greater frequency of multi-day heat waves by the end of the century (Diffenbaugh et al. 2005, Perera et al. 2012, Winkler et al. 2012). Downscaled climate scenarios also project that the Midwest will experience between 25 and 38 fewer days below freezing by the end of the 21st century (Sinha and Cherkauer

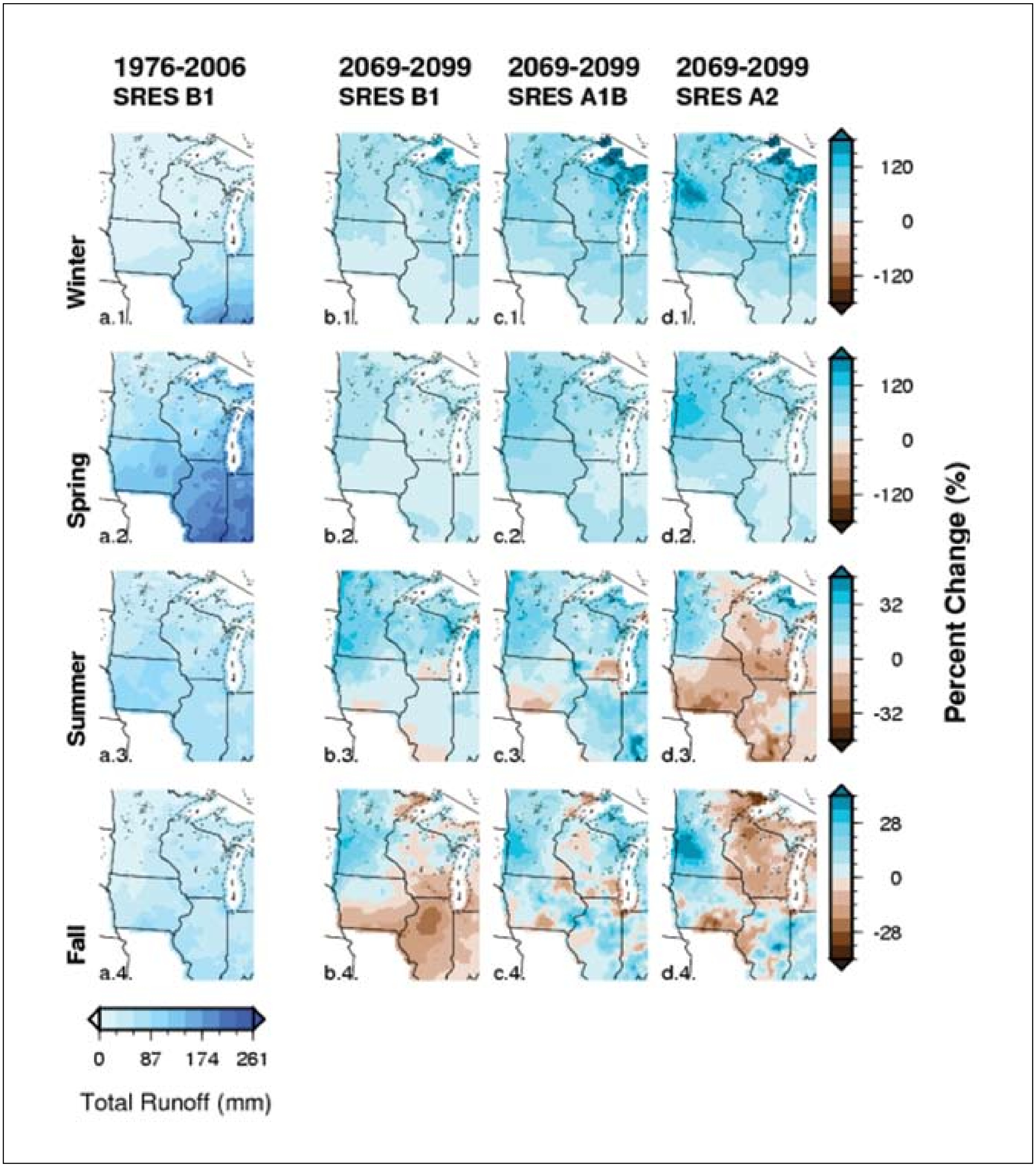


Figure 32.—Past (1976 to 2006) seasonal cumulative runoff values and projected (2069 to 2099) changes under a range of climate scenarios, from Wuebbles et al. (2009). The A2 emissions scenario is roughly equivalent to the A1FI scenario in terms of greenhouse gas emissions, and the A1B scenario is approximately a middle range between A1FI and B1.

2010), and 12 to 15 fewer days that are colder than the current 95th percentile cold event (Diffenbaugh et al. 2005). These trends are consistent with another assessment of the Midwest that projected the assessment area in Minnesota could experience up to 10 more days above 95 °F (35 °C) and up to 25 fewer days below 10 °F (-12 °C) by the middle of the 21st century (Kunkel et al. 2013).

Thunderstorms and Windstorms

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

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

SUMMARY

Northern Minnesota is projected to experience 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 climate of the Laurentian Mixed Forest Province in Minnesota is generally projected to be 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.

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

MODELED PROJECTIONS OF FOREST CHANGE

Forest ecosystems in the assessment area may respond to climate change in a variety of ways. Potential changes include shifts in the spatial distribution, abundance, and productivity of tree species. For this assessment, we rely on a combination of three forest modeling efforts to describe these potential changes. Researchers using the Tree Atlas, LANDIS-II, and PnET-CN models contributed results to this assessment (Table 15). Tree Atlas uses statistical techniques to model changes in suitable habitat for individual species over broad geographic areas. LANDIS-II is a spatially dynamic simulation model that includes migration, natural disturbances, timber harvest, and competition to project the abundance and distribution of individual tree species. PnET-CN simulates the movement of carbon (C), water, and nitrogen (N) in forest ecosystems and calculates the productivity of aggregated forest types. No single model offers a perfect projection of future change, but each tool is valuable for a particular purpose or set of questions. Complementary patterns across models are reinforced, and differences between model projections provide opportunities to better understand the nuances of ecological responses given the strengths and limitations of the models. For a more thorough description of the different models, and specifically how they were applied for this assessment, see Chapter 2.

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

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

Table 15.—Overview of impact models used for this assessment and the different features included in simulations of future conditions[a]

Feature	Tree Atlas	LANDIS-II	PnET-CN
Summary	Suitable habitat distribution model (DISTRIB) + supplementary information (modifying factors)	Spatially dynamic process model	Ecosystem-level carbon, water, and nitrogen process model
Primary outputs for this assessment	Area-weighted importance values and modifying factors by species	Aboveground biomass by species and distribution maps by forest type	Aboveground net primary productivity by forest type
Analysis area	Laurentian Mixed Forest Province in MN	Northeast portion of assessment area – see Fig. 36	Laurentian Mixed Forest Province in MN
Migration	No[b]	Yes	No
Competition, survival, and reproduction	No	Yes	No
Forest management	No	Yes	No[b]
Disturbances	No (but addressed through modifying factors)	Yes (fire, wind, and timber harvest)	No[b]
Tree physiology feedbacks	No	No	Yes
Succession or community shifts	No	Yes	No
Biogeochemical feedbacks	No	No[b]	Yes

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

Tree Atlas

Importance values of 134 eastern tree species were modeled for potential habitat suitability in the assessment area by using the DISTRIB model, a component of the Tree Atlas toolset (Iverson et al. 2008). Importance value is an index of the relative abundance of a species in a given community. For an individual 12.4-mile grid cell, the importance value for a species can range from 0 (not present) to 100 (completely covering the area). Cell-by-cell importance values are then summed across the assessment area to reach the area-weighted importance value for a species, so area-weighted importance values can be well above 100. This analysis was completed for the entire assessment area, and 74 of the 134 species currently have or are projected to have suitable habitat in the area. Chapter 2 contains more detail on the Tree Atlas methods.

The projected change in potential suitable habitat for the 74 species was calculated for the years 2070 through 2099 by comparing the GFDL A1FI and PCM B1 scenarios to present values (Table 16). Species were categorized based upon whether the results from the two climate-emissions scenarios projected an increase, decrease, or no change in suitable habitat compared to current conditions, or if the model results were mixed between scenarios.

Table 16.—Potential changes in suitable habitat for 74 tree species in the assessment area for the PCM B1 and GFDL A1FI climate scenarios, from the Tree Atlas model

Common name	PCM B1	GFDL A1FI
Declines under Both Scenarios:		
Balsam fir (-)	Decrease	Large Decrease
Balsam poplar	Large Decrease	Large Decrease
Black spruce	Large Decrease	Large Decrease
Mountain maple (+)	Large Decrease	Large Decrease
Northern white-cedar	Decrease	Large Decrease
Quaking aspen	Decrease	Large Decrease
Tamarack (-)	Decrease	Decrease
White spruce	Decrease	Decrease
No Change under Both Scenarios:		
Chokecherry	No Change	No Change
Striped maple	No Change	No Change
Increases under Both Scenarios		
American elm	Increase	Large Increase
American hornbeam	Increase	Large Increase
Bitternut hickory (+)	Large Increase	Large Increase
Black cherry (-)	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
Eastern cottonwood	Increase	Large Increase
Eastern hophornbeam (+)	Increase	Increase
Eastern red cedar	Increase	Large Increase
Eastern white pine	Increase	Increase
Hackberry (+)	Large Increase	Large Increase
Northern pin oak (+)	Large Increase	Large Increase
Red maple (+)	Increase	Increase
River birch	Increase	Increase
Silver maple (+)	Large Increase	Large Increase
Slippery elm	Large Increase	Large Increase
Sugar maple (+)	Large Increase	Increase
Swamp white oak	Increase	Large Increase
White ash (-)	Large Increase	Large Increase
White oak (+)	Large Increase	Large Increase
Wild plum	Increase	Increase

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. Species with particularly high and low modifying factors are marked with plus (+) or minus (-) signs. See Appendix 4 for complete results, including classification rules; model reliability; modification factors; and current, early-century, mid-century, and late-century importance values.

Common name	PCM B1	GFDL A1FI
Mixed Results Between Scenarios		
American basswood	No Change	Increase
Bigtooth aspen	No Change	Decrease
Black ash (-)	No Change	Decrease
Bur oak (+)	No Change	Increase
Butternut (-)	No Change	Large Decrease
Green ash	No Change	Large Increase
Jack pine	No Change	Decrease
Northern red oak (+)	Increase	No Change
Paper birch	No Change	Large Decrease
Peachleaf willow	Large Decrease	Large Increase
Pin cherry	Decrease	No Change
Red pine	No Change	Increase
Rock elm (-)	No Change	Increase
Yellow birch	Large Increase	Decrease
Species Gaining New Habitat		
American beech	New Habitat	New Habitat
Black hickory	NA	New Habitat
Black locust	New Habitat	New Habitat
Blackgum (+)	NA	New Habitat
Blackjack oak (+)	NA	New Habitat
Chestnut oak (+)	NA	New Habitat
Chinquapin oak	New Habitat	New Habitat
Eastern hemlock (-)	New Habitat	New Habitat
Eastern redbud	NA	New Habitat
Flowering dogwood	NA	New Habitat
Honeylocust (+)	New Habitat	New Habitat
Mockernut hickory (+)	NA	New Habitat
Northern catalpa	NA	New Habitat
Ohio buckeye	NA	New Habitat
Osage-orange (+)	New Habitat	New Habitat
Pignut hickory	New Habitat	New Habitat
Pin oak (-)	New Habitat	New Habitat
Post oak (+)	NA	New Habitat
Red mulberry	New Habitat	New Habitat
Sassafras	New Habitat	New Habitat
Scarlet oak	New Habitat	New Habitat
Shagbark hickory	New Habitat	New Habitat
Shingle oak	NA	New Habitat
Sugarberry	NA	New Habitat
Sweet birch (-)	NA	New Habitat
Sweetgum	NA	New Habitat
Yellow-poplar (+)	NA	New Habitat

Further, some tree species that are currently not present in the assessment area were identified as having potential suitable habitat in the future under one or both scenarios. See Appendix 4 for complete results from the DISTRIB model, including both model-scenario combinations for 2010 through 2039, 2040 through 2069, and 2070 through 2099.

Modifying factors have also been incorporated into the Tree Atlas to provide additional information on potential forest change. Modifying factors include life-history traits and environmental factors that make a species more or less able to persist on the landscape (Matthews et al. 2011b). These factors are not explicitly included in the DISTRIB outputs, and are based on a review of a species' life-history traits, known stressors, and other factors. Examples of modifying factors are drought tolerance, dispersal ability, shade tolerance, site specificity, and susceptibility to insect pests and diseases. Modifying factors are highly related to a species' adaptive capacity (see Chapter 6). Information on modifying factors is included in the summary of projected changes in habitat (Table 16), where a plus (+) or minus (-) sign after a species name indicates that certain modifying factors could lead the species to do better or worse, respectively, than DISTRIB model results indicate. As an example, the species with the five highest and five lowest modifying factor scores are displayed in Table 17. Appendix 4 contains more information on the specific modifying factors for each species.

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

Declining Species

For the assessment area in Minnesota, 8 of the 74 modeled species are projected to undergo declines in suitable habitat under both the PCM B1 and GFDL A1FI scenarios. The projected declines in importance values are more severe for these species under GFDL A1FI than under PCM B1. This result is not surprising, given that the species projected to

Table 17.—Species with the five highest values and five lowest values for adaptive capacity, based on Tree Atlas modifying factors

Species	Factors that affect rating*
Highest adaptive capacity	
1. Red maple	high seedling establishment rate, wide range of habitats, shade tolerant, high dispersal ability
2. Boxelder	high seedling establishment rate, shade tolerant, high dispersal ability, wide range of temperature tolerances, drought tolerant
3. Bur oak	drought tolerant, fire tolerant
4. Eastern hophornbeam	shade tolerant, wide range of temperature tolerances, wide range of habitats
5. Osage-orange	wide range of habitats
Lowest adaptive capacity	
1. Black ash	emerald ash borer susceptibility, poor light competitor, limited dispersal ability, poor seedling establishment, fire intolerant, dependent on specific hydrological regime
2. 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

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

lose suitable habitat are primarily boreal or northern species near the southern limit of their range in the assessment area. Most of these species including characteristic species such as balsam fir, quaking aspen, white spruce, and tamarack, are widespread across the landscape. Therefore, the reduction of suitable habitat may affect a large portion of forested landscape in northern Minnesota.

Balsam fir and black spruce are projected to have the most dramatic proportional reductions in suitable habitat. Balsam fir and tamarack also have very low modifying factor scores, suggesting that there are life-history traits or biological stressors that may cause these species to lose even more suitable habitat than the model results indicate. For example, insect pests like the larch casebearer and larch sawfly in the assessment area may cause even worse outcomes for tamarack than projected.

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

Species with Mixed Results Between Scenarios

Fourteen of the 74 total species had mixed results between the two climate scenarios, with different combinations of projected increases, decreases, and no change. In some cases, the results indicate that a species is expected to gain more suitable habitat under the GFDL A1FI scenario than under PCM B1 (e.g., American basswood, bur oak, green ash, and red pine). This subset of species could be favored by hotter, drier conditions and is typically more common to the south of the assessment area. In other cases, the results indicate that a species is expected to retain more suitable habitat under PCM B1 (e.g., bigtooth aspen, black ash, jack pine, and yellow birch). This subset of species is more characteristically northern and generally projected to undergo large declines in suitable habitat under GFDL A1FI. Black ash has low modifying factor scores, suggesting that this species could lose more suitable habitat than the models indicate. For example, anticipated emerald ash borer infestations are expected to result in declines for black ash across northern Minnesota.

Increasing Species

Suitable habitat is projected to increase for 23 species by the end of the century under both the PCM B1 and GFDL A1FI scenarios. Most of these are temperate deciduous species such as American elm, black cherry, sugar maple, and white oak. Additionally, many of these species are projected to gain more suitable habitat under GFDL A1FI than under PCM B1, suggesting that hotter, drier conditions in northern Minnesota may be suitable for an array of species. Eastern white pine and eastern red cedar are two conifer species projected to gain suitable habitat in the assessment area.

All of the 23 species projected to increase under both scenarios are currently present within the Laurentian Mixed Forest Province. Some of these species occur at very low densities and may be uncommon throughout much of the assessment area (e.g., bitternut hickory, hackberry, and river birch). They could essentially be considered new entries to the assessment area. Overall, the potential for suitable habitat increases for temperate species raises the possibility of a large shift within forest communities in northern Minnesota. Several species common to the south of the assessment area may become more widespread, assuming higher regeneration success under future forest conditions. Because many of the species projected to lose suitable habitat are still expected to persist in the assessment area by the end of the century, forests in northern Minnesota could potentially contain a higher overall diversity of species in the future, with a blend of temperate and boreal species.

Importantly, DISTRIB results only indicate a change in suitable habitat, not necessarily the ability of a given species to migrate to newly available habitat and colonize successfully. A few species projected to gain suitable habitat, such as black cherry and white ash, have low modifying factor scores, which suggest they may be less able to take advantage of increasing suitable habitat. Dutch elm disease is also expected to limit the future increase of American elm. Conversely, nine of these species, including bitternut hickory, northern pin oak, and red maple, have positive modifying factors.

Species Gaining New Habitat

DISTRIB also projects that 27 species not currently present will gain new suitable habitat within the assessment area by the end of the 21st century. A given species may not necessarily be able to migrate to newly available habitat and colonize successfully, however. Species not currently present in the assessment area would require long-distance migration, whether intentional or unintentional, to occupy suitable habitat in northern Minnesota. Habitat fragmentation and the limited dispersal ability of seeds could hinder the northward movement of the more southerly species, despite the increase in habitat suitability (Ibáñez et al. 2008). Most species can be expected to migrate more slowly than their habitats will shift (Iverson et al. 2004a, 2004b). Of course, human-assisted migration is a possibility for some species and is expected to be tested and used during the next decades (Pedlar et al. 2012).

Of the 27 species in this category, 12 are projected to have suitable habitat under both the PCM B1 and GFDL A1FI scenarios. Under GFDL A1FI, 15 additional migrant species are projected to have an increase in suitable habitat within the assessment area. The list of new entry species includes several oak and hickory species and could also reasonably include some of the very rare species mentioned in the section above. Most of the species projected to enter the assessment area only under the GFDL A1FI scenario are from ecological provinces far to the south of the assessment area. Several of these species have high modifying factor scores, indicating that they possess life-history traits that might help them be even more tolerant of future climatic conditions. For example, blackjack oak is rated highly because it is relatively drought-tolerant, regenerates well after fire, and is readily established from seed.

Geographic Trends

DISTRIB outputs can be visualized spatially, and these results can provide greater context for interpreting the projected changes in suitable habitat. Figures 33 to 35 display the changes in suitable habitat for three example species in three different change classes: quaking aspen, sugar maple, and white oak. These maps highlight that projected changes are not uniform across the assessment area, and that areas of suitable habitat are governed by soils, moisture gradients, and other factors. Quaking aspen appears to retain a large amount of suitable habitat in north-central Minnesota under the PCM B1 scenario, but under the GFDL A1FI scenario most of the suitable aspen habitat is confined to the northeast corner of the assessment area. Sugar maple is projected to gain substantial areas of suitable habitat along the North Shore of Lake Superior under both climate scenarios, and under the PCM B1 scenario the potential distribution of this species extends much farther to the west. It is possible that the dry summer conditions projected under the GFDL A1FI scenario would limit the range expansion of sugar maple (Chapter 4). White oak is virtually absent from most of the assessment area today, occurring only in the southern and western

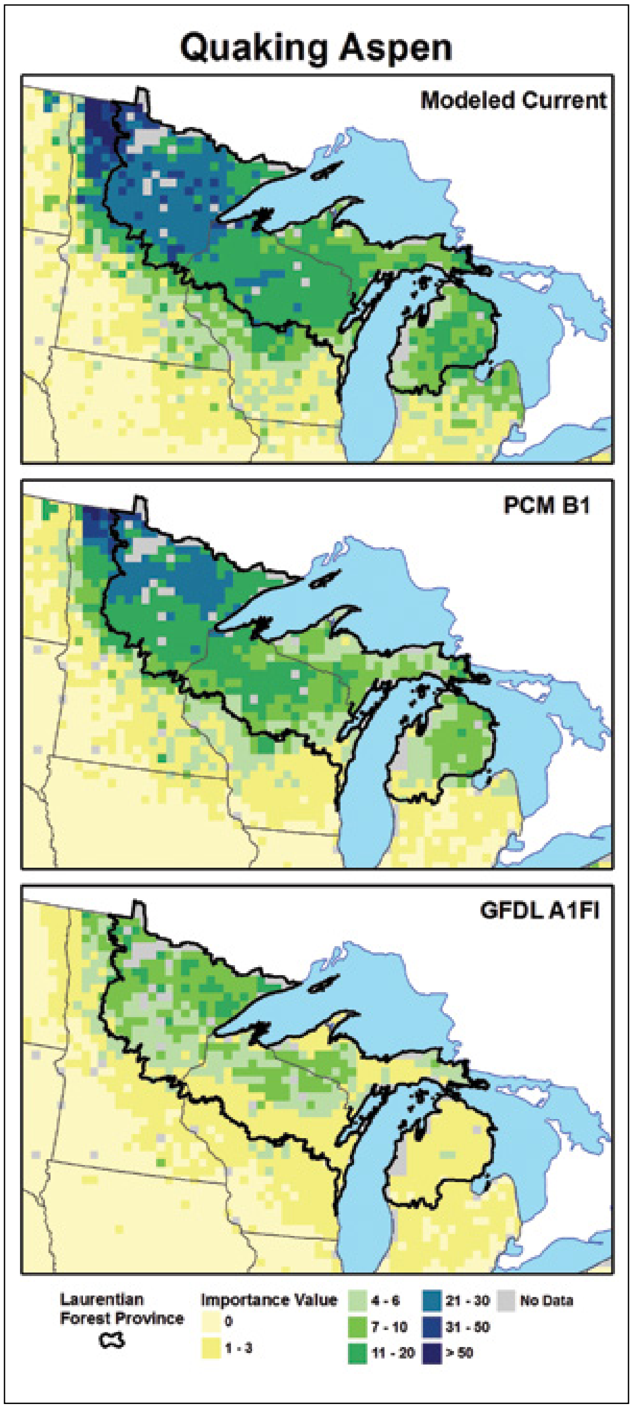


Figure 33.—Modeled importance values for quaking aspen across the Laurentian Mixed Forest Province under current climate conditions (top) and projected for the years 2070 through 2099 under the PCM B1 (middle) and GFDL A1FI (bottom) climate scenarios, from the Tree Atlas model. Importance values can range from 0 to 100. An importance value of zero (light yellow) indicates that the species is not present.

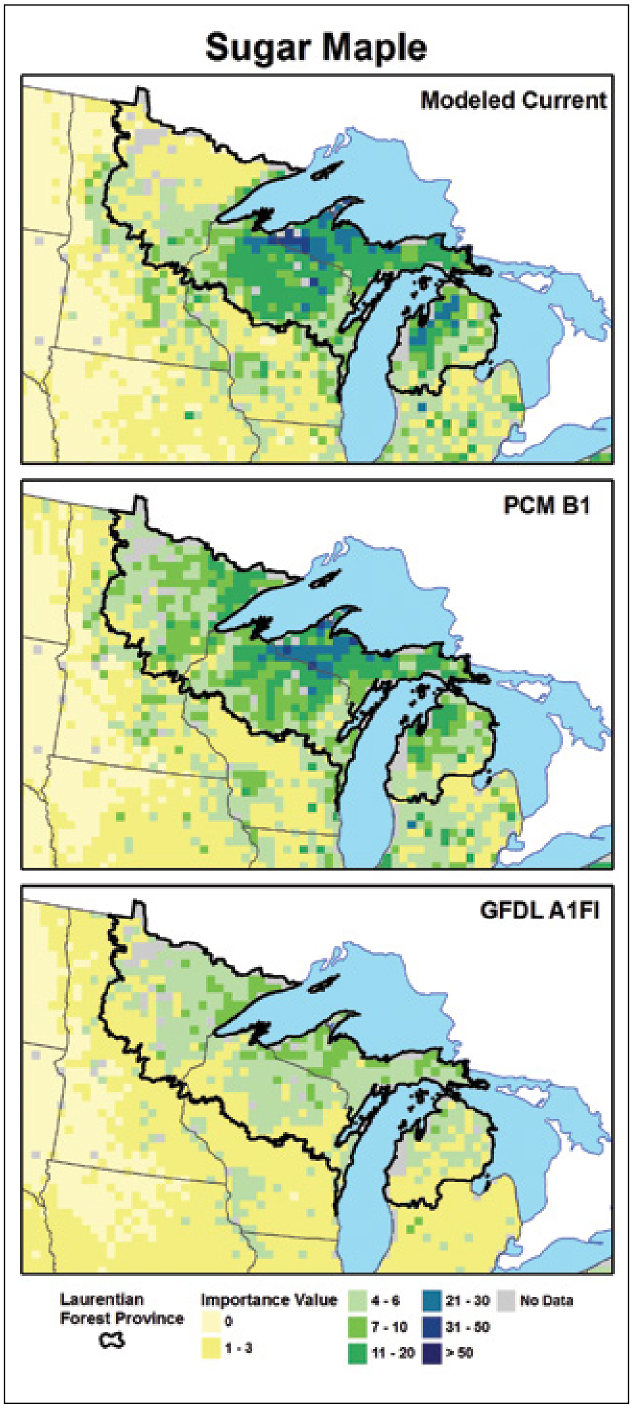


Figure 34.—Modeled importance values for sugar maple across the Laurentian Mixed Forest Province under current climate conditions (top) and projected for the years 2070 through 2099 under the PCM B1 (middle) and GFDL A1FI (bottom) climate scenarios, from the Tree Atlas model. Importance values can range from 0 to 100. An importance value of zero (light yellow) indicates that the species is not present.

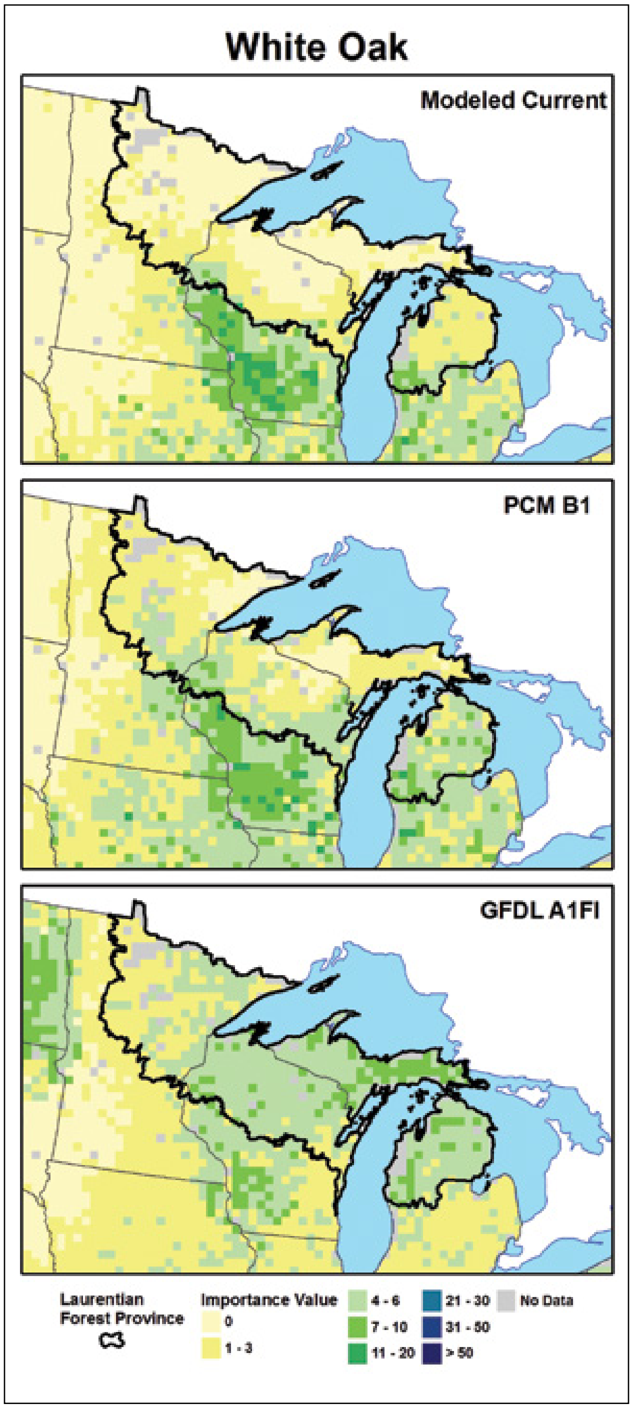


Figure 35.—Modeled importance values for white oak across the Laurentian Mixed Forest Province under current climate conditions (top) and projected for the years 2070 through 2099 under the PCM B1 (middle) and GFDL A1FI (bottom) climate scenarios, from the Tree Atlas model. Importance values can range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

portions of the assessment area. Under the PCM B1 scenario white oak is projected to gain suitable habitat in these same areas, remaining largely absent from the northeast portion of the assessment area. Under the GFDL A1FI scenario, however, white oak is projected to have as much habitat along the Canadian border as along the southern portion of the assessment area. Suitable habitat maps for all the species addressed in this assessment are available online at the Climate Change Tree Atlas Web site (Appendix 4).

As is the case for interpreting any spatial model outputs, local knowledge of soils, landforms, and other factors is necessary to determine if particular sites may indeed be suitable habitat for a given species in the future. These maps serve only as a guide to broad trends.

LANDIS-II

Results from the LANDIS-II model include aboveground biomass (biomass) for 21 tree species and distribution maps for aggregated forest type communities. Importantly, the LANDIS-II model results described in this assessment cover an analysis area that is smaller than the Laurentian Mixed Forest Province in Minnesota (Fig. 36). This landscape covers most of the Northern Superior Uplands Ecological Section and a portion of the Northern Minnesota Drift and Lake Plains Ecological Section (Minnesota Department of Natural Resources [DNR] 2003). This analysis area includes a diversity of forest types, and all six forested Native Plant Community Systems are represented within this region. Compared to the assessment area as a whole, the LANDIS-II analysis area contains a higher proportion of Fire-Dependent Forests and Acid Peatlands and a lower proportion of Mesic Hardwood Forests and Forested Rich Peatlands (Chapter 1, Fig. 6). Refer to Chapter 2 for a complete description of climate, disturbance, and management scenarios included in this assessment.

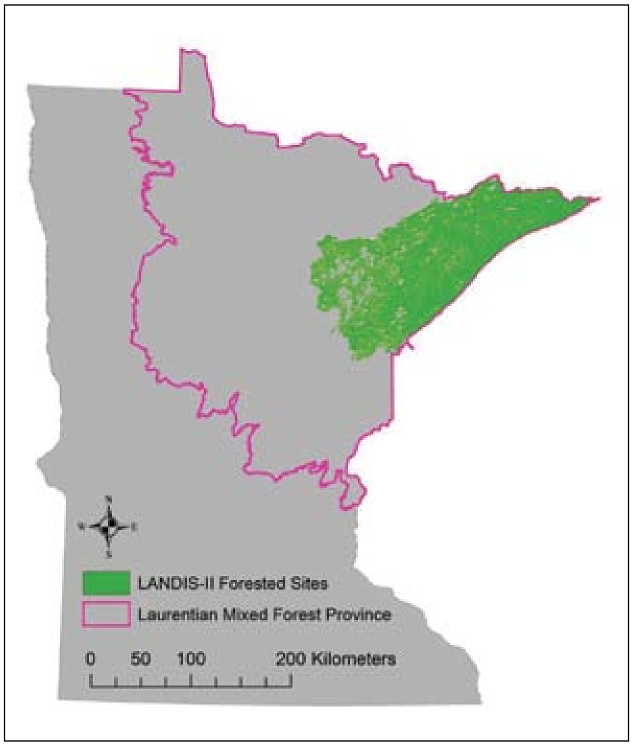


Figure 36.—Analysis area modeled by LANDIS-II for this assessment.

Aboveground Biomass

The LANDIS-II projections are plotted for each of the 21 tree species over the 21st century for three climate scenarios (Figs. 37a and 37b). Species are limited to the most common tree species found within the LANDIS-II study area. Biomass values are averaged across the LANDIS-II analysis area. See Appendix 4 for a table of biomass values for the species assessed by LANDIS-II.

The current climate scenario is useful to highlight trends that might be expected if the climate were to remain stable during the next 100 years. This scenario demonstrates the effect of successional changes, such as the continued recovery of forests after historical periods of intensive logging. Although the current climate is not projected to remain the same over the next century (Chapter 4), this climate scenario is a useful reference to judge the relative increases or decreases in biomass under the two climate change scenarios (PCM B1 and GFDL A1FI). All scenarios in the LANDIS-II results incorporate natural disturbances (i.e., fire and wind), as well as timber harvest.

According to recent Forest Inventory and Analysis (FIA) data for the assessment area, the annual net growth is greater than annual harvest removals (Chapter 1, growth-to-removal ratio for the assessment area = 1.34). This finding helps explain the increasing trends for many of the species under the current climate scenario. The biomass projections of nearly all the species modeled for this assessment indicate at least a short-term biomass increase, regardless of climate scenario. All forested landscapes have a degree of "landscape inertia" in that 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.

The species modeled by LANDIS-II can be organized according to the proportional changes relative to the current climate scenario (Table 18). As mentioned above, the current climate scenario is essentially a control scenario, and the climate scenarios may either increase or decrease landscape-scale biomass of a species relative to that control. LANDIS-II simulations may indicate that a given species may gain biomass across the analysis area compared to the year 2000, even if the projected biomass under the future climate scenarios is less than the current climate scenario. White spruce illustrates this pattern (Fig. 37b).

Declining Species

Five species (balsam fir, black spruce, paper birch, quaking aspen, and white spruce) are projected to decrease relative to the control scenario under both PCM B1 and GFDL A1FI. These are characteristic boreal species generally anticipated to fare poorly

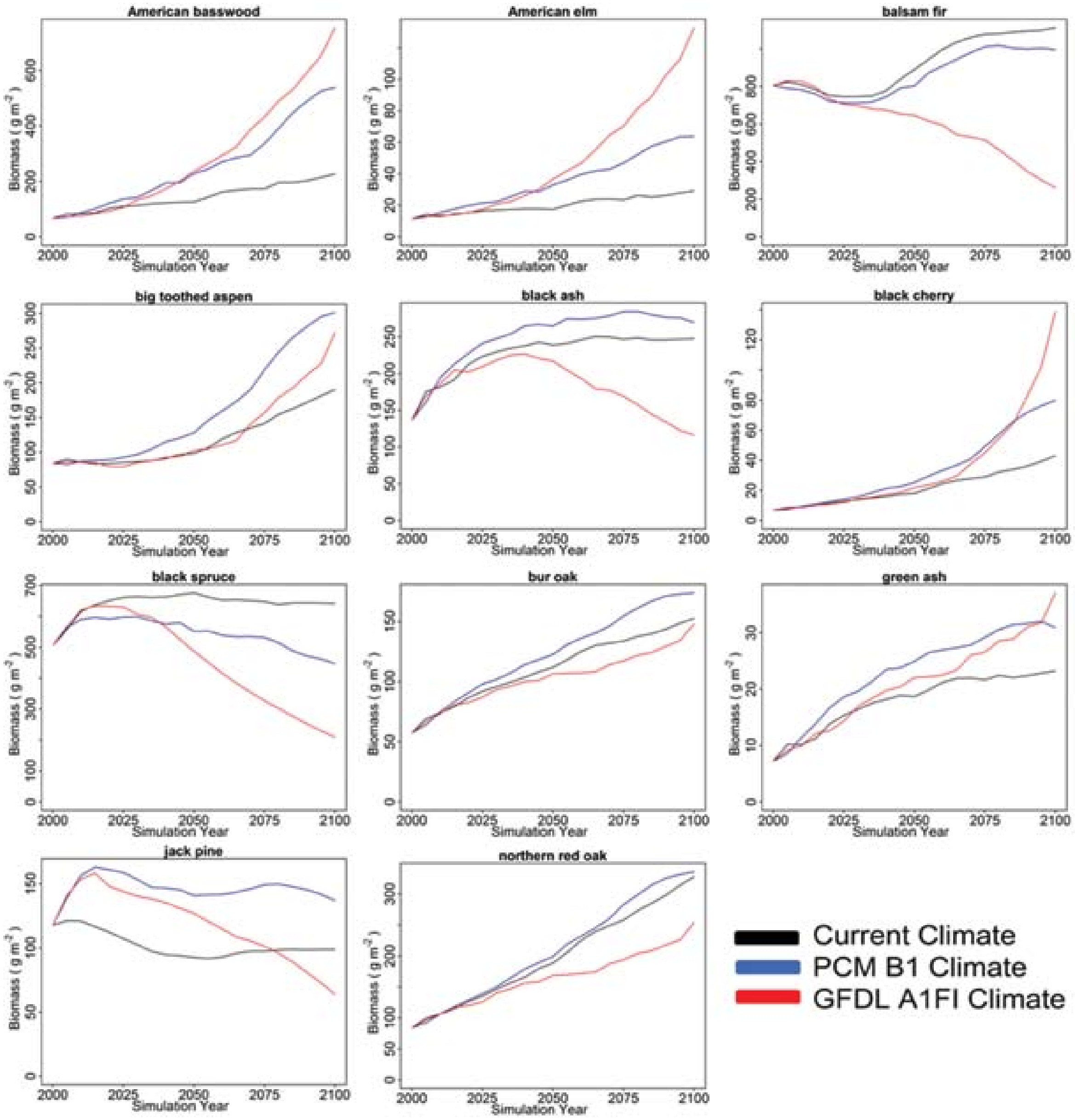


Figure 37a.—LANDIS-II biomass projections over the 21st century for the first 11 of 21 modeled tree species under three climate scenarios, presented in alphabetical order. Note that the Y-axis differs by species.

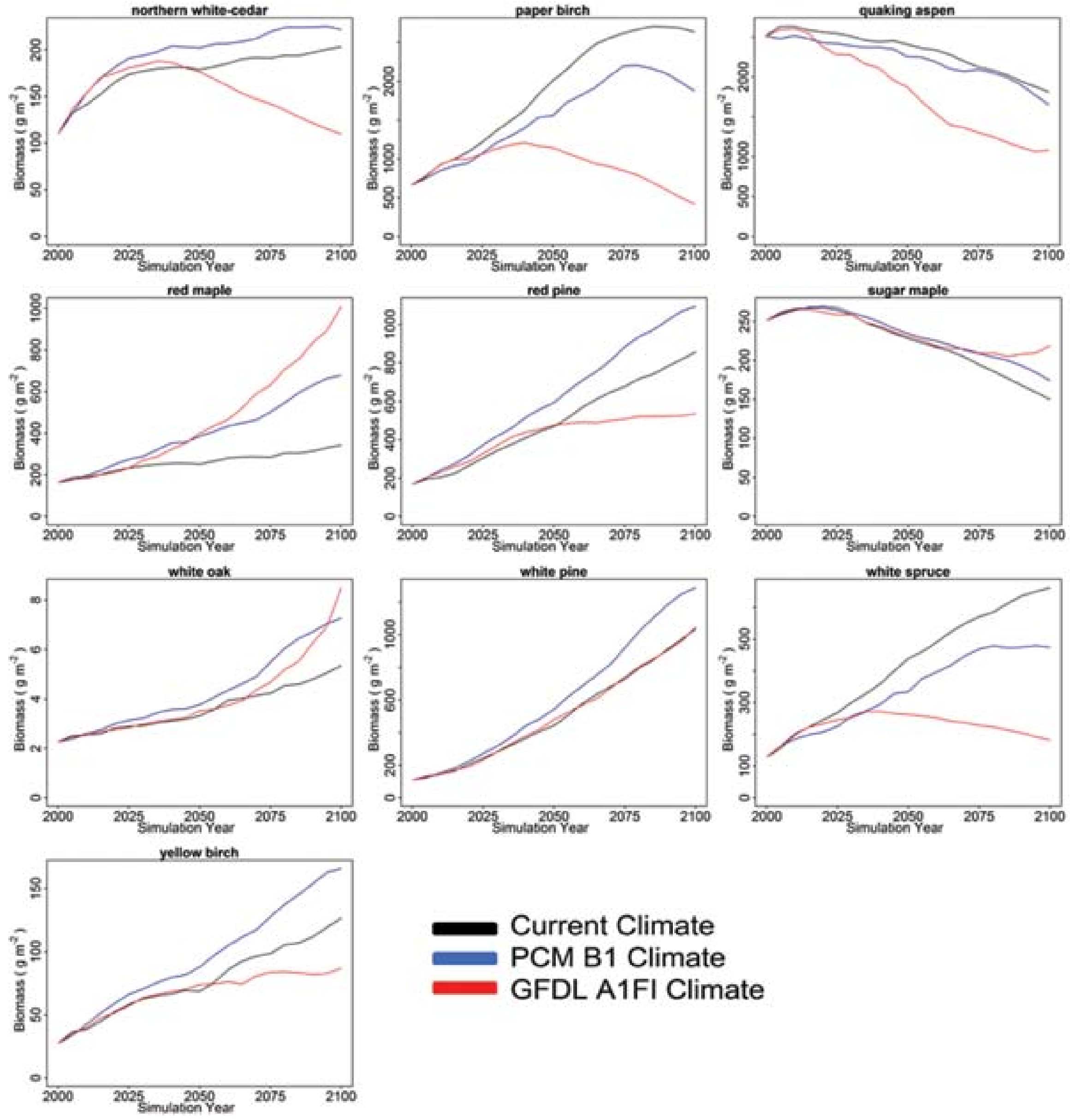


Figure 37b.—LANDIS-II biomass projections over the 21st century for the final 10 of 21 modeled tree species under three climate scenarios, presented in alphabetical order. Note that the Y-axis differs by species.

Table 18.—Potential changes in biomass for 21 tree species* in the LANDIS-II analysis area

Decrease - Both Scenarios

Balsam fir (↓)
Black spruce (↓)
Paper birch (↓)
Quaking aspen
White spruce (↓)

Increase PCM B1, Decrease GFDL A1FI

Black ash (↓)
Jack pine
Northern red oak
Northern white-cedar
Red pine
Yellow birch

Decrease PCM B1, Increase GFDL A1FI

None

Small Change

Bur oak

Increase - Both Scenarios

American basswood (↑)
American elm (↑)
Bigtooth aspen (↑)
Black cherry (↑)
Eastern white pine
Green ash (↑)
Red maple (↑)
Sugar maple
White oak (↑)

*Species are grouped into change classes based on the proportional change between end-of-century (2100) biomass under the PCM B1 and GFDL A1FI scenarios and the current end-of-century biomass under the current climate scenario. Up or down arrows (↑,↓) indicate the proportional change under one or both climate scenarios was greater than 50 percent. Small Change indicates that both scenarios projected less than 20-percent change in either direction. See Appendix 4 for complete results for all 21 species.

under warmer conditions. Four out of the five decreaser species are projected to decline greater than 50 percent under one or both climate scenarios. The GFDL A1FI scenario resulted in larger biomass declines for all five of these species. The proportional biomass declines under GFDL A1FI are more than double the expected decline under PCM B1. Balsam fir illustrates this pattern (Fig. 37a). These trends indicate that climate-related shifts are driving the biomass projections for these species, and that the hotter, drier GFDL A1FI scenario amplifies the decline.

Species with Mixed Results

Six species (black ash, jack pine, northern red oak, northern white-cedar, red pine, yellow birch) are projected to increase relative to the control scenario under PCM B1, but projected to decline under GFDL A1FI. Bur oak also displays this pattern, but the proportional changes are small enough (less than 20-percent increase and decrease) that this species was included in the small change category. Interestingly, no species are projected to decrease under PCM B1 and increase under GFDL A1FI.

These results suggest that slightly warmer temperatures and slightly wetter growing seasons under PCM B1 might benefit these species, but that a more severe change to hotter temperatures, wetter springs, and drier summers under GFDL A1FI may reduce the landscape-scale biomass of these species. Although oaks are generally expected to be favored by warmer, droughtier conditions, northern red oak is projected to decline under GFDL A1FI. These biomass declines appear to be driven by reduced seedling establishment in the latter half of the 21st century. Northern red oak is also considered substantially less drought tolerant than bur oak, white oak, or northern pin oak, the other oaks important in the region. This outcome reinforces the dynamic nature of LANDIS-II, which projects the ability of species cohorts to grow, compete, reproduce, and disperse across the landscape. If climate influences one particular phase of this lifecycle, biomass trends will reflect that effect.

Increasing Species

Nine species, including American basswood, sugar maple, and eastern white pine, are projected to increase relative to the control scenario under both PCM B1 and GFDL A1FI. These projected increasers are generally temperate species, or species with broad tolerance for temperature and moisture conditions. For seven species, projected increases were greater than 50 percent under one or both climate scenarios. With the exception of bigtooth aspen and eastern white pine, projected biomass increases were proportionally larger under GFDL A1FI than PCM B1. This result indicates that many of the projected increaser species, such as black cherry and red maple, may be favored to a greater degree under GFDL A1FI. Bigtooth aspen and eastern white pine, conversely, are expected to undergo proportionally larger biomass increases under the milder PCM B1 scenario. It is important to note that these LANDIS-II simulations do not consider the full effects of pests and diseases. Dutch elm disease is expected to limit the biomass increases of American elm, and emerald ash borer is expected to limit the future increase of green ash.

Patterns over Time

For certain species that are projected to increase under the PCM B1 scenario, there appears to be a late-century plateau or decline that could indicate the point at which a temperature or precipitation threshold has been crossed. Balsam fir, green ash, paper birch, and white spruce all exhibit late-century biomass plateaus or declines under the PCM B1 scenario. When similar "tipping points" are shown under the GFDL A1FI scenario, they seem to occur earlier, usually before the year 2050. Black ash, black spruce, northern white-cedar, paper birch, red pine, and white spruce all exhibit short-term biomass increases followed by long-term declines under the GFDL A1FI scenario. Additionally, a few species are projected to increase in biomass across the LANDIS-II analysis area at the end of the 21st century, particularly for the GFDL A1FI scenario. This seems to be the case for mesic hardwood species at the northern extent of their ranges, such as American basswood, American elm, bigtooth aspen, black cherry, bur oak, green ash, red maple, and white oak.

The combined results for all species across the LANDIS-II analysis area tell an interesting story. For the PCM B1 scenario, biomass is expected to rise steadily by about 50 percent 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 2050, followed by a slight decline to the year 2100, then a sharper increase to the year 2150. 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 under the GFDL A1FI scenario. It is possible that noticeable biomass gains for southern hardwood species are 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 21 species listed above, and does not account for the possibility of new migrants to enter the analysis area.

Productivity

LANDIS-II simulations also require estimates of aboveground net primary productivity (productivity) as an input. For this assessment, productivity estimates were calculated via a version of the PnET model. These estimates of productivity used as inputs to LANDIS-II did not account for the potential effects of carbon dioxide (CO_2) fertilization, which will be discussed in more detail below. Compared to the year 2000, these simulations indicate an overall productivity decline of roughly 40 percent under GFDL A1FI by 2100. Alternatively, productivity is projected to remain fairly steady under PCM B1, declining by only 3 percent by the year 2100. Productivity is not the sole determinant of biomass but is an important regulator of potential biomass and recovery from disturbances.

Geographic Trends

The forest-type maps indicate the potential for landscape-level change under the two climate scenarios (Fig. 38). LANDIS-II allows for species cohorts to migrate, compete, reproduce, and undergo disturbances across the landscape, and

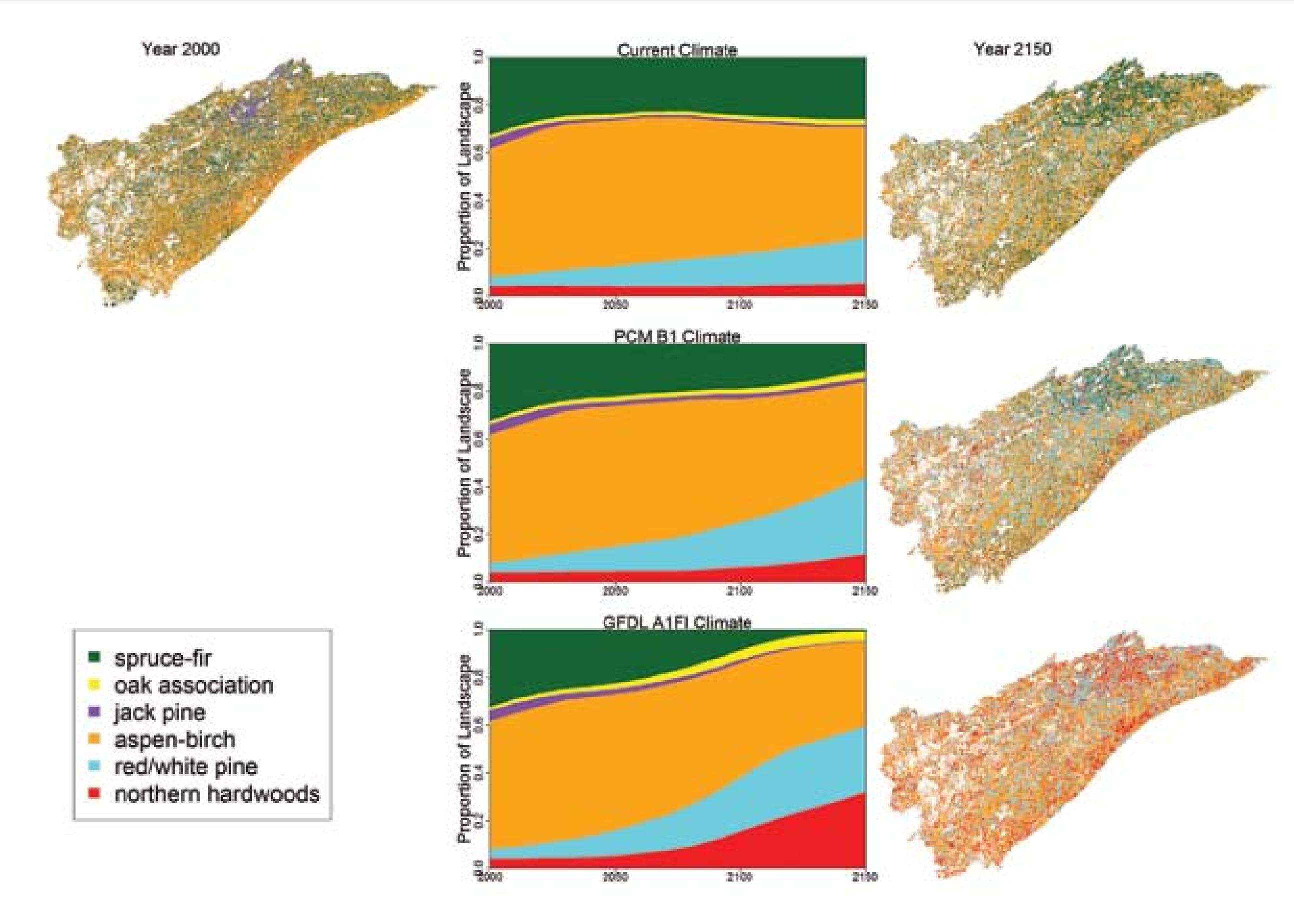


Figure 38.—Projected changes in land cover over the 21st century for six aggregated forest types under three different future climate scenarios, from the LANDIS-II model. Note that the simulations extend to the year 2150 for the graphs as well as for the resulting landscape maps.

these transitions are governed by a range of factors including soils and landform. To create these land cover maps, individual locations ("cells") in the LANDIS-II simulations were classified into six forest categories based on characteristic species composition. These forest types are not perfectly correlated with the forested Native Plant Community Systems, and should not be cross-walked directly to them (Appendix 4), in part because LANDIS-II does not simulate lowland forest systems. Additionally, LANDIS-II simulations account for only the 21 species modeled in this assessment. Therefore, these maps do not represent the potential for new species to migrate into the landscape or the potential for low-abundance species to increase within the assessment area, as suggested by Tree Atlas results.

Under the current climate scenario, the primary trend is a 10- to 15-percent increase in the proportion of the landscape occupied by white pine and red pine forests and a corresponding decline in the aspen-birch forest cover type. This trend assumes higher regeneration success than has been historically observed for pine species. Under the PCM B1 scenario these trends are accentuated, in addition to a 5-percent increase in northern hardwoods and a 20-percent decline in spruce-fir forests across the landscape. The overall landscape in 2150 under the PCM B1 scenario looks similar to the starting landscape and to the current climate scenario in 2150. The noticeable differences are more red pine and white pine and less area of spruce-fir and aspen-birch forests.

The GFDL A1FI scenario results in a more dramatic compositional shift across the landscape as spruce-fir forests are eliminated and northern hardwoods occupy more than 30 percent of the landscape by 2150. Aspen-birch forests are projected to occupy 20 percent less of the landscape, and red pine and white pine forests increase by roughly the same amount. The resulting landscape map shows that most of the increase in northern hardwoods will occur primarily along the North Shore of Lake Superior, with expanding white pine and red pine forests throughout the analysis area.

Despite the large difference between the resulting forest-type maps under the two future climate scenarios, Figure 38 also shows the high degree of similarity between these projections for the first half of the 21st century. The LANDIS-II simulations under the PCM B1 and GFDL A1FI scenarios look nearly identical until 2050. Tree species are long-lived and there will be a lag time before changes in climate are translated into forest changes. As mentioned above, community response will also lag due to species migration, establishment, competition, and reproduction. A certain amount of change during the first 50 years may be masked in these simulations because seedlings account for little biomass and a particular location may not be classified differently if the overstory remains intact. But the GFDL A1FI simulation between 2050 and 2100 highlights the possibility for substantial landscape-level changes to occur in a short period of time.

PnET-CN

The PnET-CN model projects changes in aboveground net primary productivity (productivity). Productivity is commonly used as a measure of how well forests are photosynthesizing and accumulating biomass, which is essentially a way to describe overall ecosystem function. In this assessment, we report absolute productivity as well as percentage changes in productivity. The PnET-CN uses 1971 through 2000 as a baseline period, and simulates productivity changes from 2000 through 2099. Modeling simulations presented in this assessment are described more completely in Peters et al. (2013).

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 (Miles et al. 2011), which are not perfectly matched with the nine forest communities considered in this assessment. The six FIA forest-type groups in the PnET-CN simulations are: aspen/birch, maple/beech/birch, oak/hickory, elm/ash/cottonwood, pine, and spruce/fir. These groups are assigned based only on tree species composition and they do not account for soils, disturbance processes, or other factors. Still, they are a useful way to describe broad forest categories in Minnesota. Figure 39 shows the distribution of these forest-type groups across the assessment area.

Productivity Trends

As noted above, the PnET-CN and LANDIS-II simulations were run under different conditions. In particular, the LANDIS-II simulations presented above do not account for the effects of elevated atmospheric CO_2, but the PnET-CN simulations discussed here consider the effects of rising CO_2 on forest productivity. Under both PCM B1 and GFDL A1FI, PnET-CN projects that productivity will increase from the baseline period (1971 through 2000) through the end of the century (Fig. 40). All forest-type groups show increases in productivity, with greater absolute and relative increases in deciduous broadleaf forests (aspen/birch, oak/hickory, maple/beech/birch, and elm/ash/cottonwood) compared to conifer forests (spruce/fir and pine). This trend is consistent for both climate scenarios. Under the PCM B1 scenario, the deciduous forest-type groups appear to peak at around 100-percent increases in productivity and pine and spruce/fir are projected to plateau

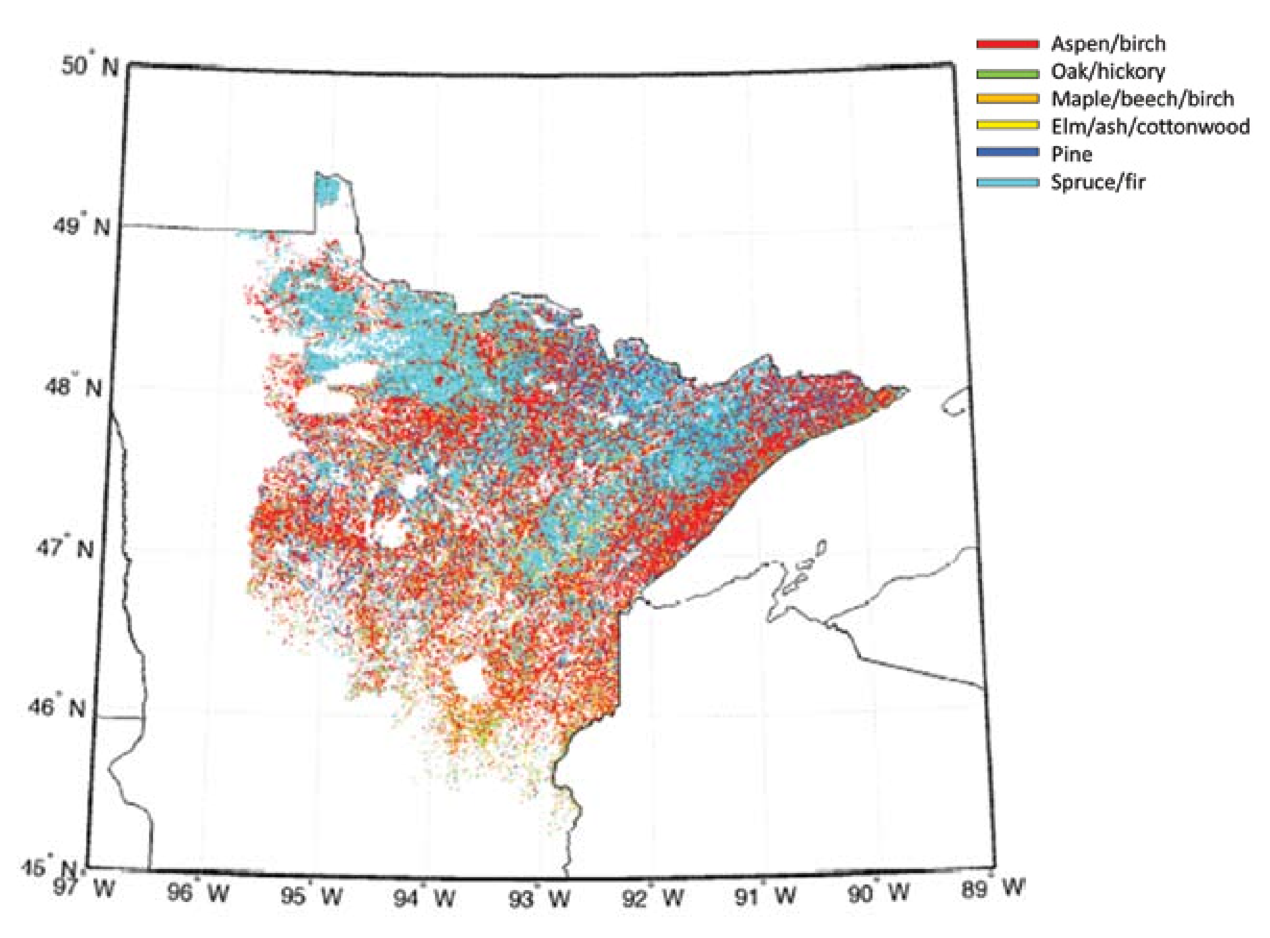


Figure 39.—Spatial distribution of the aggregated forest-type groups used in PnET-CN simulations. These forest-type groups remain fixed for the duration of the PnET-CN simulations.

around 40 percent. Under the GFDL A1FI scenario, productivity is projected to increase throughout the century with no apparent plateau. The deciduous forest-type groups exhibit increases of roughly 200 percent across the assessment area by the end of the century, with pine forests increasing in productivity by nearly 150 percent. The spruce/fir forest-type group is projected to experience a smaller gain in productivity by the end of the century, reaching a 100-percent increase.

For all forest types across the assessment area, the PCM B1 scenario resulted in an average productivity increase of 68 percent compared to the baseline period. The absolute increase in productivity from baseline to end-of-century averages 362 grams biomass per square meter per year and ranges from 78 to 821 grams biomass per square meter per year. The productivity increases projected in the GFDL A1FI scenario are roughly two times greater than the increases projected under the PCM B1 scenario. Under this scenario, the average relative increase in productivity from baseline to end-of-century is 144 percent. The absolute increase in productivity from baseline to end-of-century is on average 707 grams biomass per square meter per year and ranges from 7 to 1,336 grams biomass per square meter per year across the assessment area.

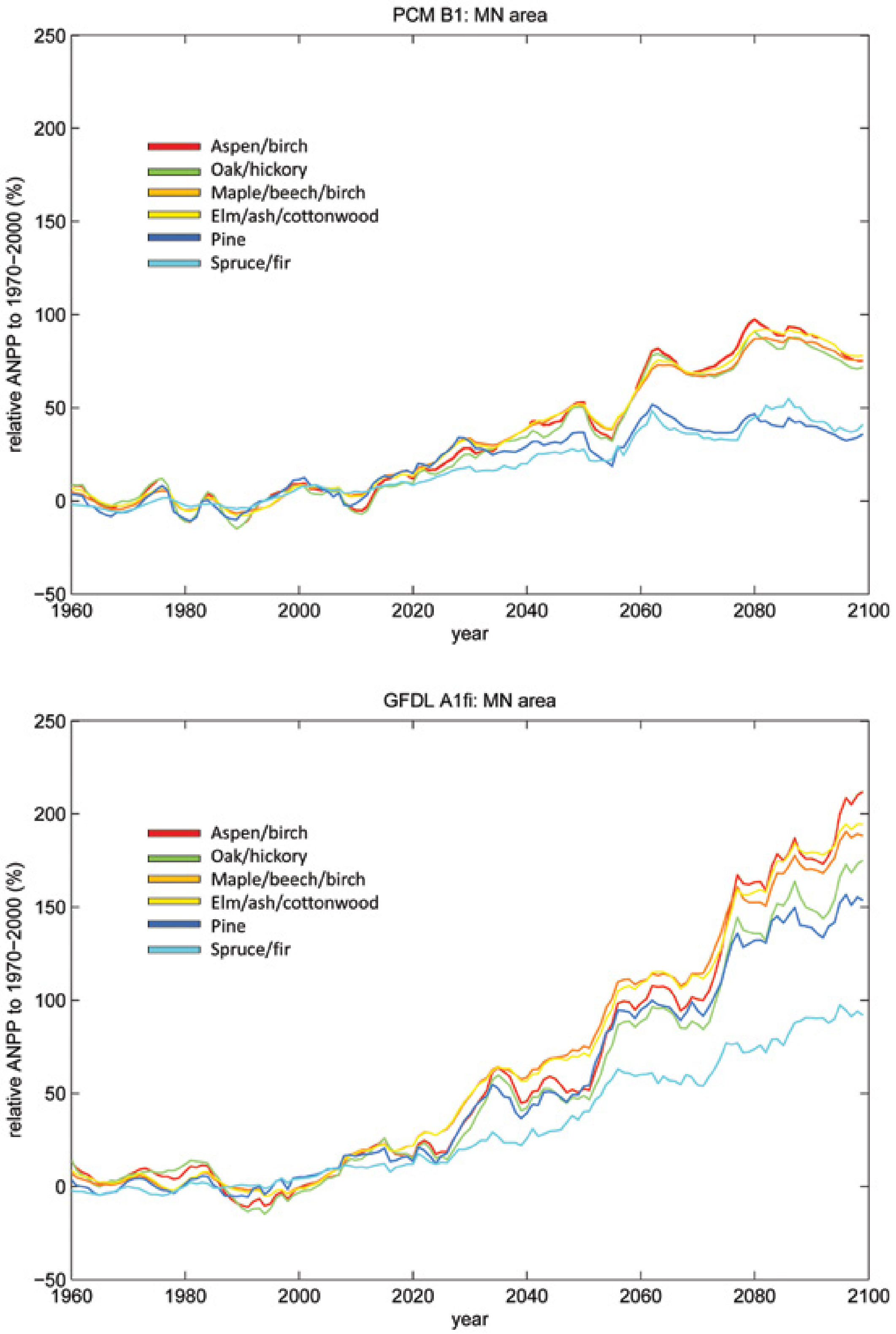


Figure 40.—Projected trends in aboveground net primary productivity (ANPP) from PnET-CN for six aggregated forest-type groups under the PCM B1 and GFDL A1FI future climate scenarios. Changes in productivity are relative to the 1971 through 2000 baseline period. Outputs have been smoothed based on a 5-year running mean.

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

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

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

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

Geographic Trends

Productivity is projected to increase from the baseline period under both future climate scenarios throughout the assessment area (Fig. 41). Under the PCM B1 scenario, productivity increases are projected to be highest along the southern half of the assessment area and along the North Shore of Lake Superior. Productivity increases are projected to be lowest along the Canadian border, particularly north and east of Red Lake and in northern St. Louis County. Under the GFDL A1FI scenario, productivity increases are above 200 percent along the North Shore of Lake Superior and in Koochiching, Itasca, Becker, Hubbard, and Cass Counties.

Geographic trends in the PnET-CN outputs appear as a result of a combination of factors. The forest type assigned to each pixel remains constant in these simulations, and different forest types have different abilities to respond to climate shifts. A variety of other parameters, such as soil type, nutrient status, and soil water-holding capacity, are also critical for determining whether a particular forest pixel will be able to successfully take advantage of climate shifts and translate favorable growing conditions into productivity increases.

The PnET-CN simulations indicate the productivity of forests in the assessment area could switch from being temperature limited to being water limited by the end of the 21st century. See Chapter 4 for a discussion of area-wide changes in the ratio of

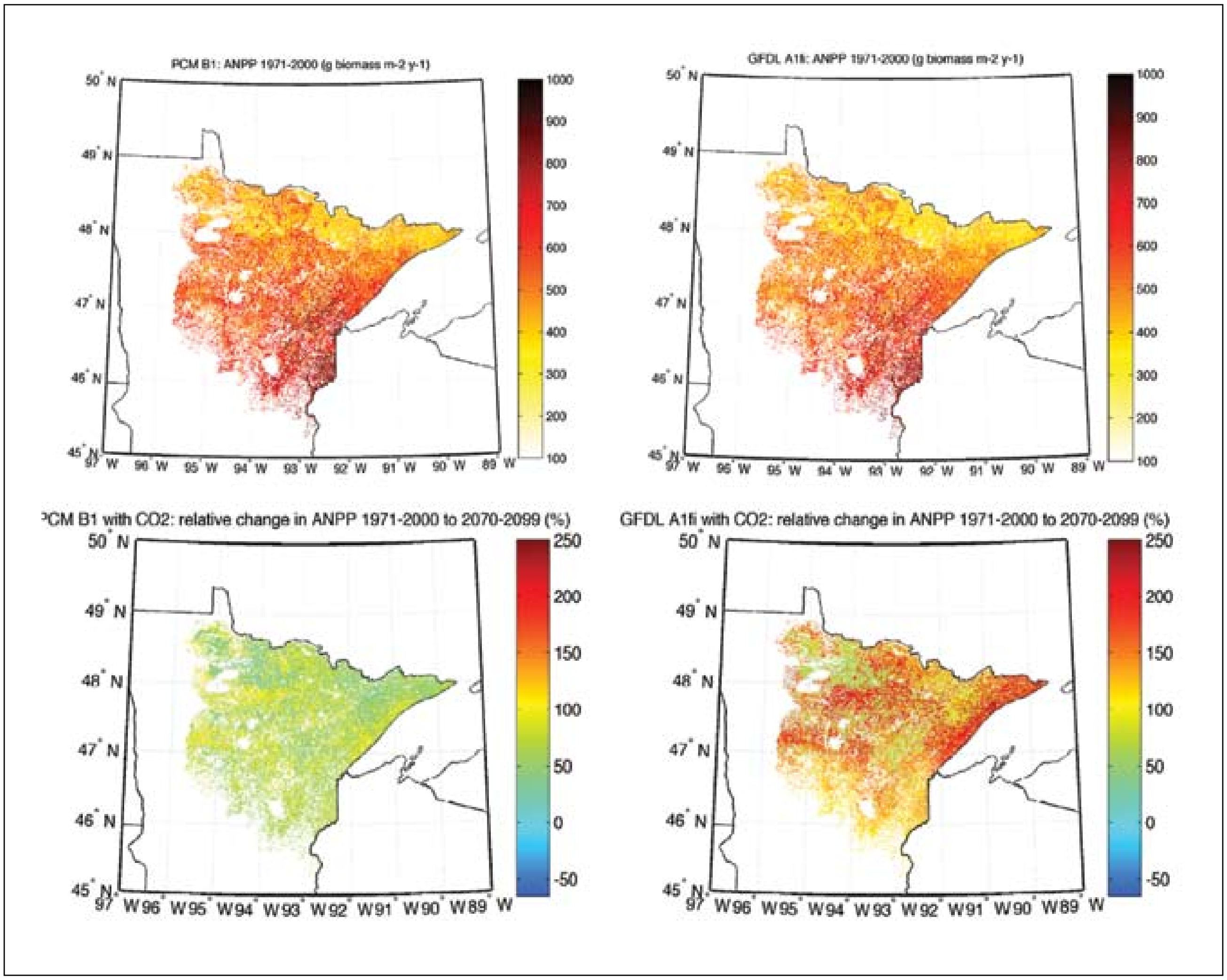


Figure 41.—Projected aboveground net primary productivity (ANPP) changes across the assessment area under the PCM B1 and GFDL A1FI future climate scenarios, from the PnET-CN model. Productivity values for the baseline period of 1971 through 2000 are absolute figures (top panels), and the future values for each scenario are relative percentages compared to the baseline period (bottom panels). Baseline values are slightly different between the two climate scenarios because of slight variations in the downscaled GCM data.

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

Discussion of Model Results

Agreements

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

Despite the differences between the modeling approaches, Tree Atlas, LANDIS-II, and PnET-CN show some strong similarities in forest change during the next century under a range of future climates. All three models indicate that characteristic boreal species or northern species at their southern range limits will face increasing climate stress. For example, the list of declining species for both the Tree Atlas and LANDIS-II models includes many of the same species: balsam fir, black spruce, paper birch, quaking aspen, and white spruce. The declines for these species were more substantial under GFDL A1FI than under PCM B1. Additionally, the PnET-CN results project a weaker potential productivity response for spruce/fir forests compared to other forest types. As the climate warms through the 21st century, these species and forest types are projected to face increasing climate-related stress. Paper birch, in particular, was projected by Tree Atlas and LANDIS-II to fare reasonably well under the PCM B1 scenario but to decline sharply under the GFDL A1F1 scenario.

Moreover, both Tree Atlas and LANDIS-II tend to agree on which species may increase under climate change. American basswood, American elm, black cherry, eastern white pine, green ash, red maple, sugar maple, and white oak are all projected to gain suitable habitat and biomass across the landscape. These are mostly temperate hardwood species from the northern and central floristic regions in Minnesota (Minnesota DNR 2003), and it is not surprising that they would be tolerant of warmer year-round conditions and a slightly drier growing season. PnET-CN outputs also indicate that deciduous forest types have the potential for large productivity increases across the Laurentian Mixed Forest Province in Minnesota, and many of these forest types are characteristic of areas south of the assessment area.

Additionally, the models suggest similar responses for a few species with mixed results under the two climate scenarios. Black ash, jack pine, northern red oak, and yellow birch are projected to increase under PCM B1 and decrease under GFDL A1FI according to LANDIS-II, and these species have similar patterns according to Tree Atlas results.

Disagreements

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

There do not appear to be any major discrepancies among species between the model results. Bigtooth aspen is projected to increase in biomass according to LANDIS-II, but Tree Atlas projects that this species may show no change under the PCM B1 scenario and a large decrease under the GFDL A1FI scenario. This discrepancy might be an effect of the different analysis area used for the LANDIS-II simulations, if bigtooth aspen is projected to gain habitat in the far northeastern part of Minnesota and decline throughout the rest of the state. It might also reflect a difference between the assumptions of the two models related to disturbance or competition. LANDIS-II and Tree Atlas indicate different outcomes for red pine under GFDL A1FI, with LANDIS-II projecting decreasing biomass and Tree Atlas projecting increasing suitable habitat. The different analysis areas for the models could also contribute to this disagreement, because Tree Atlas projects that red pine will gain suitable habitat in northeast and north-central Minnesota by the end of the century, and LANDIS-II does not account for north-central Minnesota.

Limitations

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

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

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

SUMMARY OF CURRENT SCIENTIFIC KNOWLEDGE

A growing body of scientific literature is gradually clarifying some of the potential ways that greenhouse gases and the climate change they cause may influence forest ecosystems (CCSP 2008, Vose et al. 2012). These impacts can broadly be divided into the *direct* effects of changing temperature, precipitation, and CO_2 levels, and the *indirect* effects of altered stressors or the development of additional stressors. It is also important to note that some of the impacts may in fact be positive or beneficial to native forests in the assessment area. The remainder of this chapter summarizes the state of scientific knowledge on additional direct and indirect effects of climate change on forests in the Laurentian Mixed Forest Province and the wider Great Lakes region.

Drought Stress

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

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

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

Conversely, modeling in northern Wisconsin suggests that drought events might benefit pioneer forest types like aspen and birch, even though individuals of these species are generally drought intolerant (Gustafson and Sturtevant 2013). Additionally, elevated atmospheric CO_2 may help adult trees of some species like bur oak withstand seasonal moisture stress (Wyckoff and Bowers 2010), and this effect may already be detectable across the eastern United States (Keenan et al.

2013). Site-level factors like stand density will also influence susceptibility to moisture stress, as high-density stands face increased competition for available moisture (D'Amato et al. 2011, Magruder et al. 2012). Drought-stressed trees typically are also more vulnerable to insect pests and diseases (Minnesota DNR 2011b).

Windstorms

Blowdowns from windstorms can have an important influence on the structure and species composition of forests in the assessment area, whether through small-scale events which add complexity to the landscape or through stand-replacing events (Frelich and Reich 1995a, 1995b; White and Host 2008). Species composition, stand age, soils, topography, and a host of other factors can control how a given forest is physically affected by a 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 any increase in blowdowns in the assessment area may not be outside the already high range of variability (Chapter 4).

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

Red pine damaged in a strong windstorm in summer 2012. Photo by John Rajala, Rajala Companies, used with permission.

Frost and Snowfall

As discussed in Chapter 4, winter processes in the assessment area such as snowfall and soil frost may change substantially under climate change. Paradoxically, soil frost depth and the number of soil freeze-thaw events may increase in the near future as snowpack declines and soils are less insulated from cold temperatures (Hardy et al. 2001). This trend may already be affecting species with frost-intolerant root systems like sugar maple in the assessment area (Box 7). 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).

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

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

Analysis has indicated that sugar maple dieback is related to many factors, including earthworms, climate, and site-level nutrients. Out of all plot variables measured, high densities of European earthworms removing the forest floor in northern hardwood forests were the most significant factor related to sugar maple crown dieback. The removal of the duff layer exposes roots and exacerbates further stresses on trees. Analysis of both raw tree ring data and basal area growth indicates a significant positive relationship with total winter snowfall, number of days with snowcover on the ground, and number of days below freezing temperatures across the region (Fig. 42), all of which have been decreasing in recent decades. Tree roots of sugar maple and other northern hardwoods are generally frost intolerant, and lack of adequate snowcover exposes these shallow roots to freezing conditions. Moderate drought conditions in recent years, especially in the Upper Peninsula of Michigan, have likely further contributed to maple dieback and decline. Soil and foliar nutrient analysis suggest site-specific variations in soil nutrients may have predisposed trees to decline.

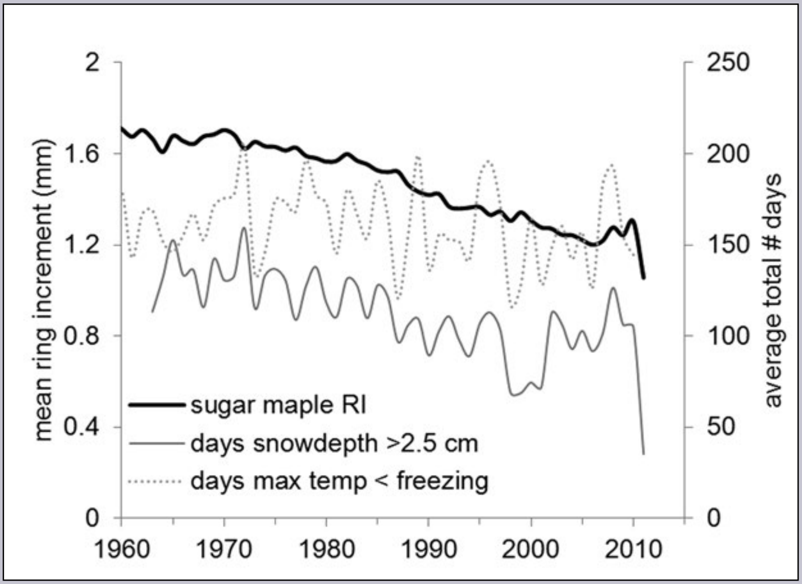


Figure 42.—Average sugar maple mean annual growth ring increment (RI) from research plots in western Upper Michigan, northern Wisconsin, and eastern Minnesota (118 plots, 313 trees), average annual total number of days with maximum temperatures below freezing, and average annual total number of days with snow depth greater than 1 inch from local weather stations (NOAA Climatic Data Center) (Bal 2013).

soil thawing are advancing rapidly in the spring and that overstory leaf-out dates are lagging behind (Groffman et al. 2012), so these systems are probably losing additional soil nutrients.

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

Hydrologic Impacts

Hydrology is tightly linked to the health and function of forest ecosystems, whether through maintenance of soil moisture during the growing season, seasonal flooding, creating necessary decomposition conditions, or other processes. Most Native Plant Community Systems in the Laurentian Mixed Forest Province are defined by particular soil moisture requirements for the seasonality and extent of saturation (Minnesota DNR 2003). This relationship may be particularly true for Forested Rich Peatlands and Acid Peatlands (Bridgham et al. 2008, Gorham 1991, Swanson and Grigal 1991). Additionally, certain 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). Hydrology may even direct forest ecosystem response in ways that appear counterintuitive. For example, dry years in Minnesota during the early part of the 20th century favored the establishment of savanna species like bur oak, but also allowed seedlings of green ash to successfully invade grasslands and savannas due to reduced competition from herbaceous plants (Ziegler et al. 2008).

Climate change is projected to alter hydrologic regimes throughout the assessment area. As discussed in Chapters 3 and 4, heavy precipitation events have been increasing across the assessment area during the past century and this trend is expected to continue. In addition to more episodic precipitation events, future climate scenarios 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: waterlogging and flooding on one hand, and moisture stress and drought on the other. Forests that are accustomed to seasonal or annual variations in water availability may be better able to tolerate this variability. In particular, Fire-Dependent Forests, Riparian Forests, and Wet Forest Systems are all tolerant of varying degrees of hydrologic fluctuation (Minnesota DNR 2003). Forests that depend on a more stable regime of soil moisture or water levels throughout the year or between years may be more stressed by hydrologic variation—particularly Mesic Hardwood Forests, Forested Rich Peatlands, and Acid Peatlands (Minnesota DNR 2003). Peatlands have been shown to respond in a matter of years to water table fluctuations of a few inches, and the productivity and functioning of these systems could be especially sensitive to the combination of water table variability and the direct effects of warming (Bridgham et al. 2008, Swanson and Grigal 1991).

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

The general principles make sense, as long as soil moisture changes are not dramatic enough to result in prolonged regeneration failures.

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

Soil Erosion

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

The Minnesota Department of Natural Resources prepared a soil erodibility map for the state, which accounts for soil types as well as slope (Minnesota DNR 2012f). Portions of the Laurentian Mixed Forest Province rank as moderately or highly vulnerable to soil erosion according to this analysis, particularly the Northern Superior Uplands Ecological Section and the western portion of the Minnesota Drift and Lake Plains Ecological Section (Fig. 43). As rainfall patterns continue to shift in the assessment area, these areas may be most susceptible to increased soil erosion.

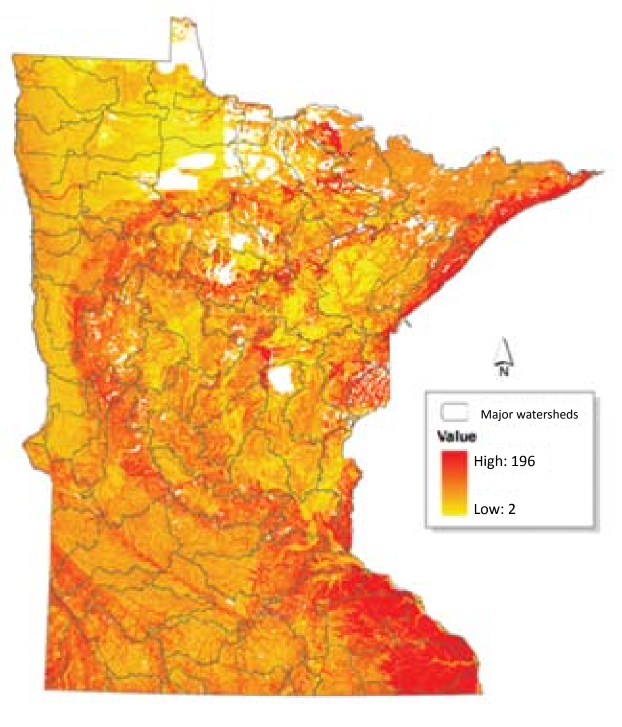


Figure 43.—Map of inherent soil erodibility across Minnesota, presented as an index value calculated based on soil type and slope (Minnesota DNR 2012f).

Wildfire

Wildfire is an important driver for forests across northern Minnesota. Fire-Dependent Forests are obviously closely tied 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 Minnesota's fire regime 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 could have a greater influence because it can be a catalyst for change in vegetation, perhaps prompting more rapid change than would be expected based only on the changes in temperature and moisture availability. As with wind disturbances, the potential exists for novel successional pathways following wildfire if climatic conditions, seed sources, or management decisions favor different forest types.

Column of the Pagami Creek Fire on September 10, 2011. Photo by Casey McQuiston, Superior National Forest.

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 regional research on climate and wildfire. Projections for boreal forests in Canada estimate that there may be a 100-percent increase in the annual area burned by the end of the century, along with a 50-percent increase in fire frequency (Flannigan et al. 2009). Research on boreal forest systems in Quebec projects that the wildfire season may shift later into the growing season, with wildfire risk doubling in August (Le Goff et al. 2009). Future fire activity may depend most on the relationship between temperature, precipitation, and evapotranspiration. If temperature and evapotranspiration increases amplify the effects of declining precipitation or overwhelm modest precipitation increases, fires are expected to increase (Drever et al. 2009).

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

Invasive Species

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

Forest Pests and Diseases

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

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. 2009). A review of forest diseases and the potential impacts of climate change highlights the potential for interactions involving other stress agents that make trees more susceptible to diseases (Sturrock et al. 2011). Pathogens are generally expected to become more damaging in forests as the climate changes, because they will be able to adapt more quickly to new climatic conditions, migrate more quickly to suitable habitat, and reproduce at faster rates than host tree species. One example of a potential disease migrant to the assessment area could be sudden oak death, a fungal pathogen currently limited to the West Coast and southeastern United States. This disease is limited by cold temperatures. Risk maps for sudden oak death are based on 1971 to 2000 climate normal, however, and do not account for projected climate shifts (Venette and Cohen 2006). The suitability maps for sudden oak death based on historical climate data already include the North Shore of Lake Superior as marginally suitable habitat, along with all of northern Wisconsin and Michigan (Fig. 44). Particularly under warmer climate change scenarios, this disease could conceivably survive in Minnesota.

Herbivory

As mentioned above, a change in snowfall amount and duration throughout the assessment area is expected to change the wintertime foraging behavior for herbivores such as moose, white-tailed deer, and snowshoe hare. Climate change is expected to favor white-tailed deer and reduce populations of moose throughout the assessment area (Frelich et al. 2012, Rempel 2011). Warmer winter temperatures and reduced snow depth may reduce energy requirements for deer, and increase access to forage during winter months (Wisconsin Initiative on Climate Change Impacts Wildlife Working Group 2011). Conversely, warmer temperatures appear to cause greater physiological stress and parasite loads in moose.

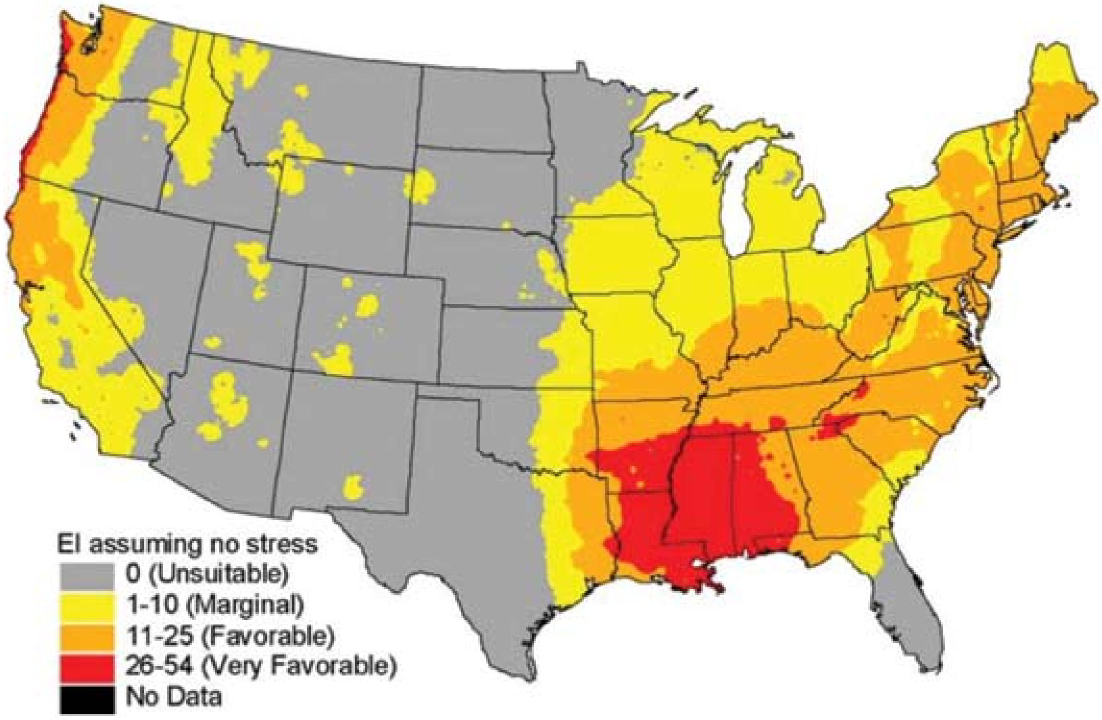


Figure 44.—Predicted climatic suitability for establishment of sudden oak death, based on the ecoclimatic index (EI) calculated by Venette and Cohen (2006). Suitability is based on 1971 to 2000 climate data and estimated climate thresholds of the pathogen.

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

Carbon Dioxide Fertilization

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

As mentioned in the discussion of PnET-CN results, several factors might actually limit 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 .

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. Changes in nutrient cycling can have important implications for forest productivity, which can be limited by nutrients such as phosphorus, calcium, and N. Studies across the northeastern United States can give some insight into potential effects of climate change on nutrient cycling.

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

A review of nutrient cycling and climatic factors for sugar maple concluded that extremes in light environment, temperature, 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. Many studies have examined the effects of extended dry periods followed by moisture pulses on nutrient cycling (Borken and Matzner 2009). Although these moisture pulses do lead to a flush of mineral N, it is not sufficient to compensate for the lack of microbial activity during dry periods. Thus, an increase in wet-dry cycles appears to lead to a reduction in nutrient availability for trees. These results suggest that the increasingly episodic precipitation regime in the assessment area may add further stress to forests in the future.

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

Interactions

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

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

SUMMARY

Climate change has the potential to affect forest ecosystems in a variety of ways. Some of these potential impacts have been investigated through a coordinated set of model projections. 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. These results generally agree that characteristic boreal or northern species and forest types are projected to experience declines in suitable habitat, landscape-level biomass, and productivity. These model projections indicate that temperate species may perform better, raising the possibility for potentially large community shifts across the Laurentian Mixed Forest Province in Minnesota.

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

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

CHAPTER 6: FOREST ECOSYSTEM VULNERABILITIES

This chapter describes the climate change vulnerability of eight major forested systems in the assessment area during the next century. The Intergovernmental Panel on Climate Change (IPCC) defines vulnerability as the susceptibility of a system to the adverse effects of climate change (IPCC 2007). It is a function of the potential impacts to a system and the adaptive capacity of that system to tolerate these impacts (Fig. 45). We consider a system to be vulnerable if it is at risk of changes leading to a new identity, or if the system is anticipated to suffer substantial declines in health or productivity. This broad definition of vulnerability is warranted because forests are valued both for their particular character and mix of species and for the services they provide. The vulnerability of an ecosystem to climate change is independent of the economic or social values associated with the system, and the ultimate decision of whether to conserve vulnerable systems or allow them to shift to an alternate state will depend on the individual objectives of land management organizations.

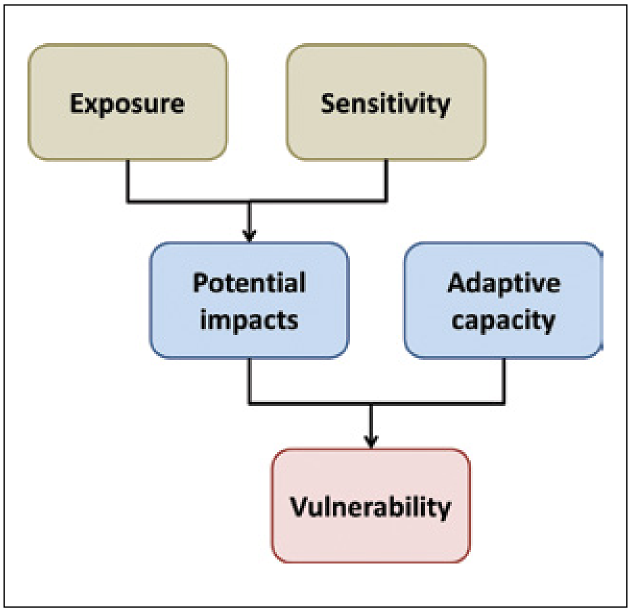


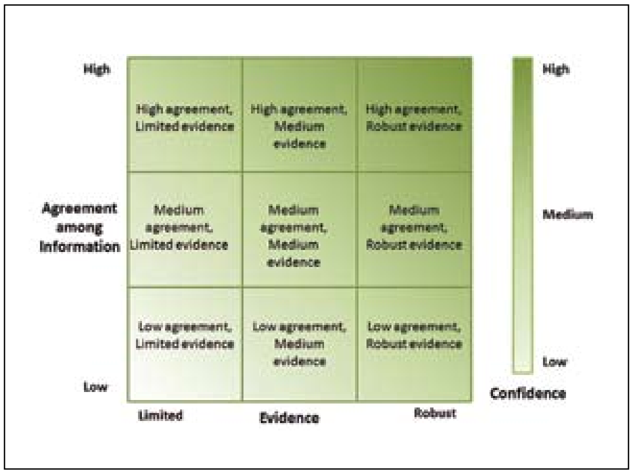
Figure 45.—Key components of vulnerability, illustrating the relationship among exposure, sensitivity, and adaptive capacity.

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

A SYNTHESIS OF CLIMATE CHANGE IMPACTS ON FOREST ECOSYSTEMS

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

Throughout this chapter, statements about potential impacts and adaptive capacity factors will be qualified with a confidence statement. These confidence statements are formatted according to a confidence determination diagram from the IPCC's recent guidance for authors (Mastrandrea et al. 2010) (Fig. 46). Confidence was determined by gauging both the level of evidence and level of agreement among information sources. Evidence is robust when there are multiple lines of evidence, as well as an established theoretical understanding to support the vulnerability determination. Agreement refers to the agreement among the available sources of evidence, not the level of agreement among authors of this assessment. Agreement was rated as high if theories, observations, and models tended to suggest similar outcomes.



High	High agreement, Limited evidence	High agreement, Medium evidence	High agreement, Robust evidence
Agreement among Information	Medium agreement, Limited evidence	Medium agreement, Medium evidence	Medium agreement, Robust evidence
Low	Low agreement, Limited evidence	Low agreement, Medium evidence	Low agreement, Robust evidence
	Limited	Evidence	Robust

Figure 46.—Confidence determination diagram used in the assessment. Adapted from Mastrandrea et al. (2010).

Potential Impacts on Drivers and Stressors

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

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

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

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

Both climate scenarios for the assessment area project that winter temperatures will increase at a faster rate than temperatures in other seasons (Chapter 4). Even with projected increases in winter precipitation, temperature increases indicate that a greater proportion of moisture will be delivered as rainfall during this season. Combined with increased snowmelt from higher temperatures, the amount of snow on the ground is expected to decrease across the assessment area (Sinha and Cherkauer 2010). In addition, northern Minnesota may have 30 to 40 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. The decrease in snowcover and frozen soil is expected to affect a variety of ecosystem processes, including decomposition activity, nutrient cycling, the onset of the growing season, and other phenological factors.

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

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

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

For the climate projections used in this assessment (Chapter 4) and other publications, large variation exists for projected changes in precipitation for the assessment area (Kling et al. 2003, Minnesota Department of Natural Resources 2011a). Although individual model projections for the assessment area may differ, there is general agreement that annual precipitation is expected to remain consistent or increase slightly during the 21st century. Models also tend to agree that precipitation patterns between seasons may shift substantially (Kunkel et al. 2013). Precipitation increases are generally expected to be larger in winter and spring, which is in agreement with both climate scenarios presented in this assessment (Chapter 4). Summer precipitation is projected to increase slightly or decrease sharply (Chapter 4).

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

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

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

With an increasingly episodic precipitation regime, it has been suggested that there may be longer intervals between heavy rainfall events in the future (Knapp et al. 2008). Studies examining a range of climate model projections disagree with this conclusion, projecting that northern Minnesota 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).

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

As discussed above, seasonal changes in precipitation are expected across the assessment area. Due to projected decreases in summer precipitation and increases in winter and spring precipitation, it is reasonable to expect that soil moisture regimes will also shift. Longer growing seasons and warmer temperatures may also result in greater evapotranspiration losses and lower soil-water availability later in the growing season (Chapter 4). Outputs from the PnET-CN model indicate that forests in the assessment area may become increasingly moisture-limited under climate change (Chapter 5). This may be the case particularly in locations where soils and landforms do not allow precipitation from intense events to be retained. Model projections differ greatly, however, and it is also possible that the assessment area will have an increase in precipitation sufficient to offset increases in evapotranspiration.

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

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

An area burned over in 2011 during the Pagami Creek Fire near Forest Center, Minnesota. Photo by Jason Butcher, Superior National Forest.

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

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

Potential Impacts on Forests

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

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

Across northern latitudes, it is generally expected that warmer temperatures will be more favorable to species that are located at the northern extent of their range and less favorable to those at the southern extent (Parmesan and Yohe 2003). Results from climate impact models project a decline in suitable habitat and landscape-level biomass for northern species such as balsam fir, black spruce, tamarack, quaking aspen, and white spruce (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. Boreal species may remain in areas with favorable soils, management, or landscape features. Additionally, northern species may be able to persist in the assessment area if competitor species are unable to colonize these areas (Iverson et al. 2008).

Southern species will be favored by climate change (medium evidence, high agreement). *Impact models agree that many temperate species will experience increasing 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 near their northern range limits in the assessment area will become more abundant and more widespread under a range of climate futures (Chapter 5). The list of species projected to increase in suitable habitat and biomass includes American basswood, black cherry, bur oak, eastern white pine, green ash, red maple, white oak, and a variety of minor southern species (Chapter 5).

PnET-CN outputs also indicate that deciduous forest types have the potential for large productivity increases across northern Minnesota. In addition, Tree Atlas results project that suitable habitat may become available for species not currently found in the assessment area (e.g., shagbark hickory, black locust, and post oak) by the end of the century. Habitat fragmentation and dispersal limitations could hinder the northward movement of southerly species, despite the increase in habitat suitability. Most species can be expected to migrate more slowly than their habitats will shift (Iverson et al. 2004a, 2004b; McLachlan et al. 2005; Scheller and Mladenoff 2008). Pests and diseases such as emerald ash borer and Dutch elm disease are also expected to limit some species projected to increase.

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

Species will respond individually to climate change, which may lead to the dissolution of traditional community relationships (Davis et al. 2005, Root et al. 2003). The model results presented in Chapter 5 raise the possibility for potentially large changes in forest communities across northern Minnesota. Generally, the models suggest that climate trends may favor hardwoods across the landscape after 2050, though ecological lag times, soil conditions, and management decisions may slow forest type conversions. 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). Therefore, the Native Plant Community Systems and Classes described in the assessment area may 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). Therefore possibility also exists for nonnative species to take advantage of shifting forest communities and unoccupied niches if native forest species are limited (Hellmann et al. 2008).

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

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

Adaptive Capacity Factors

Adaptive capacity is the ability of a species or ecosystem to accommodate or cope with potential climate change impacts with minimal disruption (Glick et al. 2011). Below, we summarize factors that could 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 diverse systems are more resilient to disturbance, and low-diversity systems have fewer options to respond to change.*

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

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

Habitat fragmentation can hinder the ability of tree species to migrate to more suitable habitat on the landscape, especially if the surrounding area is nonforested (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 data gathered for 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). 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).

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 especially difficult for species and systems with narrow habitat requirements.*

Several species and forest types in northern Minnesota 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). 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. Floodplain Forests are not expected to be able to migrate to upland areas because many species depend on seasonal flood dynamics for regeneration and a competitive advantage. Similarly, Acid Peatlands 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 expected to increase in the area (Chapters 4 and 5). Mesic Hardwood Forests 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 are expected to be better able to withstand climate-driven disturbances. This principle holds true only to a given point, because it is also possible for disturbance-adapted systems to experience too much disruption. For example, Fire-Dependent Forests such as Northern Dry-Sand Pine Woodland (FDn12) or Northern Dry-Bedrock Pine (Oak) Woodland (FDn22) might cover a greater extent under drier conditions with more frequent fire, but these systems might also convert to savannas 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 are expected to result in different impacts to forested systems within the assessment area. Some communities may have a greater capacity to adapt to these changes than others, whereas some may be susceptible to relatively minor impacts. Therefore, it is helpful to consider these factors for individual forest systems in addition to describing general principles related to vulnerability and adaptive capacity. Table 19 presents a summary of major drivers and stressors for each forest community covered in this assessment.

The following vulnerability determinations draw on the information presented in previous chapters, as well as an expert panel assembled from a variety of organizations and disciplines across the assessment area. The 23 panelists evaluated anticipated climate trends for the assessment area and model projections (Chapter 5), in combination with their own expertise. For each forest system, panelists considered the potential impacts and adaptive capacity to assign a vulnerability determination and a level of confidence in that determination using the same confidence scale described above. For a complete description of the methods used to determine vulnerability, see Appendix 5.

Table 19.—Forest systems considered in this assessment, with a summary of major drivers and stressors for each system

Forest system	Major drivers	Major stressors
Fire-Dependent Forest	coarse-textured soils or shallow soils over bedrock, fire-return intervals 20 to 150 years.	fire suppression, insect pests and diseases, understory hazel competition, deer herbivory
Mesic Hardwood Forest	mesic soils or deep impermeable layers, consistent moisture and nutrients, gap-phase disturbances with stand-replacing events every 400 to 2,000 years.	exotic earthworms, invasive plants, insect pests, diseases, freeze-thaw cycles, drought, deer herbivory
Floodplain Forest	alluvial soils, annual or occasional floods, connectivity to river and water table	changes to flood regime, buckthorn and reed canarygrass, drought, deer herbivory
Wet Forest	wet-mesic soils, saturated in spring and dry in summer, periodic flooding	changes to soil moisture regime, ongoing ash decline, invasive species, insect pests, drought
Forested Rich Peatland	peat soils, saturated throughout growing season, moisture through precipitation and groundwater, pH greater than 5.5	changes to water table, roads and beaver dams, insect pests and diseases, winterburn, drought, deer herbivory
Acid Peatland	peat soils, saturated throughout growing season, moisture through precipitation only, pH less than 5.5, nutrient-poor environments	changes to water table, roads and beaver dams, insect pests and diseases, winterburn, drought
Managed Aspen	wide range of soil types and landforms, frequent disturbance, even-aged management on 35- to 60-year rotation	forest tent caterpillar and gypsy moth, drought, deer herbivory, hypoxylon canker, exotic earthworms
Managed Red Pine	sandy to mesic soils, limited by high summer temperatures, dependent on planting for regeneration, even-aged management on 60- to 120-year rotation	*Armillaria*, red pine shoot blight, understory hazel competition, deer herbivory, bark beetles, drought stress in dense stands

Overall vulnerability determinations ranged from low-moderate (Floodplain Forests) to high (Wet Forests, Forested Rich Peatlands, and Acid Peatlands) (Table 20). Panelists tended to rate the amount of evidence as medium (between limited and robust) for most forest systems. Incomplete knowledge of future wildfire regimes, interactions among stressors, and precipitation regimes were common factors limiting this component of overall confidence. The ratings of agreement among information also tended to be in the medium range. Contrasting information related to precipitation regimes under the two climate change scenarios was one factor that limited the level of agreement among information. In general, ratings were slightly higher for agreement than for evidence. Evidence appears not to be as robust as the experts would prefer, but the information that is available leads them to reach a similar conclusion.

Table 20.—Vulnerability determination summaries for the forest systems considered in this assessment

Forest system	Potential impacts	Adaptive capacity	Vulnerability	Evidence	Agreement
Fire-Dependent Forest	Negative	Moderate-High	Moderate	Medium	Medium
Mesic Hardwood Forest	Moderate	Moderate-High	Moderate	Medium	Medium
Floodplain Forest	Moderate-Positive	Moderate	Low-Moderate	Limited-Medium	Medium
Wet Forest	Negative	Low	High	Limited-Medium	Medium
Forested Rich Peatland	Negative	Low	High	Medium	Medium-High
Acid Peatland	Negative	Low	High	Medium	Medium-High
Managed Aspen	Moderate-Negative	Moderate	Moderate-High	Medium	High
Managed Red Pine	Moderate-Negative	Moderate-Low	Moderate-High	Medium	Medium

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

Fall colors in northeastern Minnesota. Photo by Jack Greenlee, Superior National Forest.

Fire-Dependent Forest System

Moderate Vulnerability (medium evidence, medium agreement)

Changes to the fire regime for northern Minnesota are particularly threatening for this system, in addition to the loss of suitable habitat for many key species and the potential for greater pest and disease activity. A high tolerance for disturbance increases the adaptive capacity of this system.

Negative Potential Impacts

Drivers: Fire-Dependent Forests are generally found on coarse-textured or shallow soils, and may be able to tolerate the projected shift toward drier soils during the summer months. Evidence indicates that wildfires may burn larger areas in northern Minnesota under climate change, and that the fire season may shift later into the growing season. Blowdown-causing wind events could also provide more fuel buildup for large fire events. Greater wildfire activity could benefit these forest types, but it is possible that too much change to the fire regime would hamper regeneration.

Dominant Species: Considering the range of possible climate futures, most dominant species that make up Fire-Dependent Forests are expected to decline in suitable habitat and across the assessment area according to model projections (jack pine, quaking aspen, paper birch, balsam fir, and black spruce). The same modeling studies suggest red pine and white pine will remain relatively constant or experience slight increases across the assessment area, and that minor components of Fire-Dependent Forests like northern red oak, bur oak, and red maple will also increase across the assessment area.

Stressors: Climate change is expected to intensify several key stressors for Fire-Dependent Forests. Insect pests and diseases may become more virulent and damaging under a warmer climate, and the possibility exists for new pests such as western bark beetles to arrive in the assessment area. The continued shift toward mesic species within Fire-Dependent Forests may be encouraged by climate change if fire suppression activities continue and broadleaf species like red maple continue to spread. White-tailed deer populations are also anticipated to increase with warmer winters, so herbivory on preferred species may continue to hinder regeneration.

Moderate-High Adaptive Capacity

Fire-Dependent Forests are generally tolerant of drought and disturbances and can contain a diversity of species, so these forests have greater adaptive capacity to climate change. Additionally, these forests can persist on poor soils, so the possibility exists that Fire-Dependent Forests could “retreat” to favorable locations on the landscape even if overall conditions change. Southern portions of the assessment area may be more likely to shift to Mesic Hardwoods because fragmentation and broadleaf species may limit fire activity.

A northern dry-mesic mixed woodland (FDn33). Photo by John Almendinger, Minnesota Department of Natural Resources, used with permission.

A northern dry-mesic mixed woodland, red pine - white pine woodland, balsam fir subtype (FDn33a1). Photo by Ethan Perry, Minnesota Department of Natural Resources, used with permission.

Jack pine stand after the 2011 Pagami Creek Fire, the largest fire in northern Minnesota in the last century. Photo by Shawn Fraver, University of Minnesota, used with permission.

Mesic Hardwood Forest System

Moderate Vulnerability (medium evidence, medium agreement)

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

Moderate Potential Impacts

Drivers: Mesic Hardwood Forests depend on relatively moist, nutrient-rich soils and a lack of wildfire disturbance. The potential for climate change to increase the frequency of extended droughts poses a threat to these forests for multiple reasons, including increased moisture stress, wildfire occurrence, and susceptibility to other stress agents. Hardwood forests occurring on moist, rich soils may be buffered from short-term droughts or seasonal moisture stress. Warming temperatures may also allow this system to expand into previously unsuitable areas.

Dominant Species: Model projections indicate that most of the dominant species that make up Mesic Hardwood Forests are expected to gain in suitable habitat and biomass across the assessment area (American basswood, sugar maple, red maple, green ash, and bur oak). Deciduous forest types are also projected to have large potential productivity increases. Paper birch and quaking aspen are two key species anticipated to decline across the assessment area, and modeling results are mixed for northern oak and yellow birch. Several minority species in this system may also increase in biomass and suitable habitat across the assessment area (e.g., eastern white pine, ironwood, American elm, white oak, and bitternut hickory). NPC Class MHn44 may be particularly vulnerable because this class contains boreal species such as quaking aspen, balsam fir, and paper birch.

Stressors: Climate change could amplify several major stressors to Mesic Hardwood Forests. Forest tent caterpillar and other pests may cause more frequent and severe damage in climate-stressed forests, and new pests such as gypsy moth and Asian longhorn beetle present unknown risks. White-tailed deer populations may also increase with warmer winters, which may hinder hardwood regeneration as well as the northward expansion of this system. The potential also exists for synergistic negative interactions between stressors in this system, such as earthworms, herbivory, drought, and invasive species.

Moderate-High Adaptive Capacity

Mesic Hardwood Forests generally contain a large number of species, which leads to a high response diversity. These forests could also gain territory lost by other forest types under wetter or drier future conditions. This system contains several species at their northern range limits, such as sugar maple and northern red oak, which may benefit from gene flow between southern populations. Increased CO_2 concentrations may also increase the water-use efficiency of some species, reducing the risk of moisture stress. Stands with few species and reduced structural diversity may have lower adaptive capacity.

A mature red oak stand in north-central Minnesota underplanted with white pine, 2012. Photo by John Rajala, Rajala Companies, used with permission.

A mixed hardwood stand in north-central Minnesota (MHn35). Photo by Stephen Handler, U.S. Forest Service.

A northern rich mesic hardwood forest (MHn47). Photo by John Almendinger, Minnesota Department of Natural Resources, used with permission.

Floodplain Forest System

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

Climate change is expected to affect the flow regimes in riparian systems, which will have unknown consequences for this system. Low agreement on future precipitation and stream flow regimes is the primary uncertainty for this system, in combination with a lack of research and management experience.

Moderate-Positive Potential Impacts

Drivers: Climate change has the potential to alter the flow regimes in riparian systems across the assessment area. Floodplain Forests are particularly adapted to withstand annual and seasonal floods. The regeneration requirements of several species within this system are also linked to these floods. If climate change results in shifts in the timing or volume of stream flows, this forest system could be impaired.

Dominant Species: Under a range of possible climate futures, most of the dominant species within Floodplain Forests are expected to gain in suitable habitat across the assessment area (silver maple, American elm, American basswood, black willow, eastern cottonwood). LANDIS-II is not suited to simulate lowland forest systems, but this tool projects large biomass increases for American basswood, American elm, and green ash in upland areas under both climate scenarios. Elm/ash/cottonwood forests could experience large potential productivity gains under a range of climate futures. Emerald ash borer is expected to reduce the amount of green and black ash in future Floodplain Forests.

Stressors: Hydrologic alteration of river systems through dams and river channelization has already had negative impacts on Floodplain Forests. Invasive species such as reed canarygrass and European buckthorn are existing threats to these forests, and invasive species have the potential to increase in abundance in the assessment area under climate change. White-tailed deer populations are expected to increase with warmer winters, which may hinder regeneration of this system. If the trend continues toward more-intense precipitation events, extreme floods may present risk to this system through excessive waterlogging and downcutting of riverbanks.

Moderate Adaptive Capacity

Floodplain Forests are adapted to periodic disturbances and fluctuating soil moisture, so they might be capable of tolerating future changes to the hydrologic cycle. There is a lack of knowledge and management history in these forests compared to other systems in the assessment area, so it is unknown if there are certain disturbance thresholds that are excessive or beneficial for Floodplain Forests. It is not expected that other forest species will outcompete and replace these species in riparian settings, so Floodplain Forests may be at low risk for transition to other forest types. Conversely, these forests are confined to floodplains and are not expected to expand to new territory in the future.

A southern floodplain forest (FFs68). Photo by John Almendinger, Minnesota Department of Natural Resources, used with permission.

A riparian area in northern Minnesota with a classic riparian mix of hardwood species. Photo by Robert Scheller, Portland State University, used with permission.

Wet Forest System

High Vulnerability (limited-medium evidence, medium agreement)

Ongoing ash decline and emerald ash borer present serious existing threats to this system. These stressors may be exacerbated by climate change impacts to the precipitation regime. Limited research and management history and uncertainty about future precipitation reduce confidence in this determination.

Negative Potential Impacts

Drivers: Wet Forests depend on wet-mesic soils with saturated conditions in the spring and dry conditions in the summer months. Climate change has the potential to alter precipitation patterns across the assessment area, particularly during the growing season. The regeneration requirements of several species within this system are also linked to the timing of these wet and dry periods. Shifts in the timing or amount of precipitation could disrupt the function of these forests.

Dominant Species: The potential for emerald ash borer to spread throughout the assessment area presents a serious risk to black ash and green ash in Wet Forests. Considering the range of possible climate futures, most of the dominant species that make up Wet Forests are expected to decline in suitable habitat and biomass across the assessment area, particularly under the GFDL A1FI scenario (black ash, northern white-cedar, balsam fir, balsam poplar, and black spruce). Model projections indicate that red maple may become a larger component of this system, and that minor species within Wet Forests like American elm and American basswood will also increase across the assessment area. Elm/ash/cottonwood forests could experience large potential productivity gains under a range of climate futures.

Stressors: The ongoing decline in black ash in the assessment area already presents problems for the health of Wet Forests. Invasive species such as reed canarygrass and European buckthorn are existing threats to these forests, and invasive species have the potential to increase in abundance in the assessment area under climate change. White-tailed deer populations are expected to increase with warmer winters, which may hinder regeneration of northern white-cedar in particular. Dutch elm disease is expected to limit the potential increase in American elm.

Low Adaptive Capacity

Knowledge and management history of these forests are lacking compared to other forest systems in the assessment area, so we know less about how they function and respond to disturbance. Many species that exist in Wet Forests can tolerate intermittent wet and dry conditions, so this system might be adaptable to short-term floods and droughts. Extended droughts would cause significant damage to these shallow-rooted forests. Increased winter and spring precipitation could buffer summer moisture stress if excess water is retained in low-lying areas on the landscape. Additionally, Wet Forests often exist as large complexes of a single species or a few species, so they have low response diversity. These forests also exist as isolated pockets on the landscape in some areas, so they may be disconnected in terms of migration and gene flow.

A northern very wet ash swamp (NPC Class WFn64). Photo by John Almendinger, Minnesota Department of Natural Resources, used with permission.

A northern wet ash swamp (NPC Class WFn55). Photo by John Almendinger, Minnesota Department of Natural Resources, used with permission.

A northern wet cedar forest (NPC Class WFn53). Photo by John Almendinger, Minnesota Department of Natural Resources, used with permission.

Forested Rich Peatland System

High Vulnerability (medium evidence, medium-high agreement)

Forests in peat systems have limited tolerance to changes in water tables. Additionally, the dominant species in these forests are expected to decline under a range of climate futures. Low agreement on future precipitation trends is the primary uncertainty for this system.

Negative Potential Impacts

Drivers: Climate change has the potential to alter the water tables in low-lying areas across the assessment area. Forested Rich Peatlands function in a relatively narrow window of water table conditions and can respond in a matter of years to water table changes. Higher water levels could result in a transition to open peatland systems, but lower water levels could allow other forest types to invade as peat layers dry and decompose.

Dominant Species: Most species in this system are at the southern edge of their ranges in Minnesota, and therefore may not tolerate warmer conditions. The dominant species in Forested Rich Peatlands, tamarack and black spruce, are projected to undergo declines in suitable habitat and biomass across the landscape. Declines may be most severe for black spruce. Other minor species like balsam fir and paper birch are also expected to decline under the hotter, drier climate scenario. The assessment area is also approaching the southern range limit for sphagnum moss. Red maple, white pine, and speckled alder may become larger components of this system in the future, but it is unclear if Forested Rich Peatlands will maintain their inherent identity if that composition shift occurs. Impact models presented in this assessment are not designed specifically to address peatland systems, so results should be interpreted with a degree of caution.

Stressors: Roads, beaver dams, drainage ditches, or other watershed modifications that change flood regimes or water tables are already stressors in some parts of the assessment area. Their effects may be intensified by climate change. Additionally, higher growing-season temperatures may increase evapotranspiration rates and reduce the rate of peat accumulation in these systems as a result of increasing decomposition rates. Warmer winters and reduced snowpack may also increase the occurrence of winterburn in these systems, and allow for more frequent outbreaks of pests such as tamarack sawfly and eastern larch beetle.

Low Adaptive Capacity

Forested Rich Peatlands typically receive water inputs through groundwater as well as precipitation, so these forests may be somewhat buffered from seasonal or short-term moisture deficits. Increased winter and spring precipitation could also be retained in low-lying areas on the landscape and compensate for summer droughts. Forested Rich Peatlands are widely distributed across the assessment area, but are confined to particular hydrologic regimes, soil types, and landscape positions. Therefore, they are not expected to expand to new territory within the assessment area or outcompete other forest types. In some locations Forested Rich Peatlands occur within a matrix of Fire-Dependent Forests like jack pine systems, so they may be exposed to more frequent wildfire if climate change results in extended droughts and more active wildfire regimes in the assessment area.

A forested rich peatland in northern Minnesota. Photo by Casey McQuiston, Superior National Forest.

A northern rich tamarack swamp (FPn82). Photo by Ethan Perry, Minnesota Department of Natural Resources, used with permission.

A northern cedar swamp (FPn63). Photo by Ethan Perry, Minnesota Department of Natural Resources, used with permission.

Acid Peatland System

High Vulnerability (medium evidence, medium-high agreement)

Acid Peatlands are not resilient to changes in water tables and are not buffered by groundwater inputs. The dominant species in these forests are expected to decline under a range of climate futures. Future precipitation trends are the primary uncertainty for this system.

Negative Potential Impacts

Drivers: Acid Peatlands typically occur on perched water tables without connection to groundwater. Therefore, these systems are even more vulnerable to water level changes than Forested Rich Peatlands. Higher water levels could result in a transition to open peatland systems, and lower water levels could cause greater drought stress and mortality in shallow-rooted forests.

Dominant Species: The dominant tree species in Acid Peatlands, black spruce and tamarack, are projected to have significant declines in suitable habitat and biomass across the landscape according to ecosystem models. Declines may be most severe for black spruce. These species are at the southern edge of their ranges in Minnesota, and therefore may not tolerate warmer conditions. The assessment area is the southern range limit for sphagnum moss as well. Acid peatlands also contain a suite of rare and endemic plant species that are adapted to acidic, nutrient-poor conditions. These associated species are also presumably vulnerable to changes in water table level and the peat substrate. Impact models presented in this assessment are not designed specifically to address peatland systems, so results should be interpreted with a degree of caution.

Stressors: Roads, beaver dams, drainage ditches, or other watershed modifications that change flood regimes or water tables are already stressors in some parts of the assessment area. These modifications may be intensified by climate change. Additionally, higher growing-season temperatures may increase evapotranspiration rates and reduce the rate of peat accumulation in these systems as a result of increasing decomposition rates. Warmer winters may also increase the occurrence of winterburn in Acid Peatlands, and allow for more frequent outbreaks of pests like tamarack sawfly.

Low Adaptive Capacity

Acid Peatlands receive water inputs only through precipitation, so these systems may be particularly susceptible to shifts in precipitation patterns and droughts. Increased winter and spring precipitation could possibly be retained in low-lying areas on the landscape and compensate for summer droughts. Acid Peatlands are more widely distributed across the assessment area than Forested Rich Peatlands, but are typically smaller and more confined to particular hydrologic regimes. These systems are slower to recover from disturbances like fires and blowdown events than Forested Rich Peatlands. Because of their acid conditions, however, these forests may face less competition from other forest types.

A northern spruce bog (APn80). Photo by John Almendinger, Minnesota Department of Natural Resources, used with permission.

A tamarack-dominated northern poor conifer swamp (APn81b). Photo by Stephen Handler, U.S. Forest Service.

A northern poor conifer swamp (APn81). Photo by Ethan Perry, Minnesota Department of Natural Resources, used with permission.

Managed Aspen

Moderate-High Vulnerability (medium evidence, high agreement)

Aspen is adapted to disturbance and a wide range of sites. Ecosystem models project aspen will decline in northern Minnesota, and the potential exists for multiple stressors to interact under climate change. Limited long-term experience with intensive aspen management raises uncertainty for this system.

Moderate-Negative Potential Impacts

Drivers: Managed aspen stands can occur on a range of soil types, from dry to mesic. If climate change results in increased moisture stress during the growing season, aspen on drier sites may be exposed to greater drought stress and mortality. Warmer growing-season temperatures might encourage more suckering after harvests. Increased wildfire activity could help maintain aspen across the assessment area. However, with frequent disturbance from increased wildfire, drought, or more intensive management, aspen could become a less successful competitor in the future.

Dominant Species: Under a range of possible climate futures, quaking aspen is expected to have large declines in suitable habitat and biomass across the assessment area by the end of the century. Quaking aspen is a boreal species near the southern range limit in Minnesota. Model results for bigtooth aspen are mixed. LANDIS-II projects biomass increases across both climate scenarios. Tree Atlas projects slightly increasing suitable habitat for bigtooth aspen under the PCM B1 scenario and decreasing suitable habitat under the GFDL A1FI scenario.

Stressors: Climate change is expected to intensify several key stressors for managed aspen. Insect pests such as forest tent caterpillar and gypsy moth, along with diseases like hypoxylon canker, may become damaging under a warmer climate. Earthworm activity in aspen sites may make these forests more susceptible to drought stress, and white-tailed deer herbivory may also increase with warmer winters. The possibility exists for interactions among multiple stressors to lead to severe impacts. For example, drought stress is projected to become more frequent under climate change, earthworm activity makes forest stands more susceptible to drought, and insect pest outbreaks are more damaging in stressed forests. Multiple harvests of aspen may lead to a decline of nutrient status or productivity on these sites.

Moderate Adaptive Capacity

Aspen is adapted to disturbance and can exist on a wide range of soils and landforms. The ability to reproduce asexually is also an advantage in some instances, particularly for clones better adapted to future conditions. Past management has reduced species diversity and structural diversity, thereby lowering the adaptive capacity of aspen forest across the landscape. There is a limited history of short-rotation aspen management, and many questions about how these systems will respond over time are unanswered.

Aspen crowns. Photo by Eli Sagor, University of Minnesota, used with permission.

Aspen regeneration 2 months after a clearcut. Photo by Eli Sagor, University of Minnesota, used with permission.

Managed Red Pine

Moderate-High Vulnerability (medium evidence, medium agreement)

Red pine is tolerant of moisture stress, and ecosystem models project red pine will remain relatively constant across the landscape in northern Minnesota. Climate change may amplify multiple stressors and enable new interactions, and single-species systems are not positioned to be very resilient.

Moderate-Negative Potential Impacts

Drivers: Managed red pine plantations occur on a range of soil types, from dry to mesic. Red pine has typically been planted in suitable locations in Minnesota. Natural regeneration is very rare in managed red pine systems due to shoot blight and deer herbivory, so maintaining red pine in these stands depends on planting seedlings following harvest. Seasonal shifts in precipitation patterns may impair the survival of planted seedlings, particularly if the trend is for wetter springs and drier summers.

Dominant Species: Modeling results for red pine are mixed. LANDIS-II projects that red pine will increase under PCM B1and decrease under GFDL A1FI. Tree Atlas results indicate that this species may maintain consistent suitable habitat under PCM B1 or increase under GFDL A1F1, although suitable habitat may shift from north-central Minnesota to northeast Minnesota. Particular areas may become more or less suitable, but changes are projected to be moderate across the entire assessment area. The natural distribution of red pine is limited by summer high temperatures, so this species may be more vulnerable in areas projected to experience more warming under climate change.

Stressors: Climate change could amplify stressors to managed red pine plantations and result in new interactions among stressors. Diseases and insect pests are currently not responsible for much mortality in mature red pine stands, but they may become more damaging under warmer conditions. New agents such as annosum root rot or western bark beetles may also enter the assessment area in the future. White-tailed deer herbivory is a significant stressor for red pine seedlings, and deer populations are anticipated to increase with warmer winters. Competition from hazel is an obstacle to planting success, and competition from European buckthorn could also intensify under climate change. Wildfire is typically excluded from these stands and fire is not used as a management or regeneration tool, so it is unclear whether more frequent wildfire would benefit managed red pine forests.

Moderate-Low Adaptive Capacity

Red pine is generally a drought-tolerant species, and thinning can further reduce moisture stress in managed stands. Undermanaged stands are typically overstocked and more susceptible to a variety of stressors. Red pine plantations typically have very low structural and species diversity, which may result in low resilience to future disturbances or changing conditions. Additionally, red pine has low genetic diversity as a species, so there may be limited possibility to favor more suited genotypes or for the species to evolve greater tolerance for future climate conditions.

Balsam fir regeneration under a red pine stand. Photo by Eli Sagor, University of Minnesota, used with permission.

A 1909-origin red pine stand thinned in 1950. Photo by Eli Sagor, University of Minnesota, used with permission.

CONCLUSIONS

Forest ecosystems in northern Minnesota will be affected by climate change, although systems and species will respond individually to these changes. The synthesis statements in the first half of this chapter can be applied as rules of thumb in the absence of specific information about expected climate change impacts. Overall, we expect forest systems that are adapted to a narrow range of conditions or that contain few species to be more vulnerable to changing conditions. Communities with higher diversity that are adapted to tolerate a wide range of conditions and disturbances have a greater chance of persisting 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 uses the most up-to-date information from the scientific literature, a coordinated set of modeling results and climate projections, and the input of a large team of local experts. Even so, there are limitations and unknowns that make these determinations imperfect. As new information continues to be generated on the potential impacts of climate change on Minnesota forests, this assessment should be supplemented with additional resources.

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

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

CHAPTER 7: MANAGEMENT IMPLICATIONS

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

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

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

WILDLIFE

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

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

More Information

- The Minnesota State Wildlife Action Plan identifies Minnesota wildlife species, and their habitats, that are in greatest conservation need. Many species of greatest conservation need may be particularly affected by climate change. www.dnr.state.mn.us/cwcs/index.html
- Many states are working to incorporate climate change information into their state wildlife action plans. Voluntary guidance has been provided by the Association of Fish and Wildlife Agencies. www.fishwildlife.org/files/AFWA-Voluntary-Guidance-Incorporating-Climate-Change_SWAP.pdf
- The Climate Change Bird Atlas is a companion to the Climate Change Tree Atlas and uses information about direct climate effects as well as changes in habitat to project changes in bird species distributions. www.nrs.fs.fed.us/atlas/bird/

A black bear in northern Minnesota. Photo by Josh Weckman, Superior National Forest.

- Season's End, an organization built on the collaboration between many hunting and conservation groups, includes many resources on potential climate change impacts on wildlife. http://www.cakex.org/virtual-library/784
- The Forest Service Climate Change Resource Center provides a summary of how climate change may affect wildlife species. www.fs.fed.us/ccrc/topics/wildlife/

THREATENED AND ENDANGERED SPECIES

As discussed in Chapter 6, it is expected that plant or animal species that are already rare, threatened, or endangered may be especially vulnerable to shifts in temperature and precipitation. Rare plants and rare plant communities often rely on very particular combinations of environmental and habitat conditions, in many cases as relict populations from previous climate conditions (Devall 2009, Minnesota Department of Natural Resources [DNR] 2012d). Threatened and endangered species often face population declines due to a variety of other factors, including habitat loss, competition from invasive species, and disease. As temperatures become warmer and the precipitation regime changes, already rare or declining species may therefore be among the first to experience climate-related stress. The limited range of rare species makes it difficult to model the effects of climate and climate change on distribution and abundance (Schwartz et al. 2006b). In the absence of human intervention, rare or threatened species may face greater extinction risks. Alternatively, rare species that live in habitats which are buffered from climate shifts (e.g., caves or other climatic refugia) may be able to persist.

Minnesota's Rare Species Guide includes information on Minnesota's endangered, threatened, and special concern species (Minnesota DNR 2012d). Of the 439 species listed for the entire state, 234 occur in the Laurentian Forest Province.

These rare species include 2 amphibians, 18 birds, 10 fish, 2 fungi, 20 insects, 12 lichens, 8 mammals, 2 mosses, 18 mussels, 4 reptiles, 2 spiders, and 132 vascular plants. Potential climate change impacts on these species have not been comprehensively reviewed, and the particular climate tolerances of many of these species are unknown.

More Information

- *Minnesota's Rare Species Guide* is produced by and updated by the Minnesota DNR. www.dnr.state.mn.us/rsg/index.html

FIRE AND FUELS

Climate change will influence 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, funding, and public attitude will ultimately define the response that makes the most sense, and these responses may be different for different organizations and landowners.

As described in Chapter 5, weather and climate are major drivers of fire behavior. Across northern Minnesota and the Great Lakes region, the fire season is controlled by a combination of day length, weather, and fuel conditions. Typically, day length, cool temperatures, and wet fuels delay the onset of fire season until April or May. Although the summer months have the longest days and warmest temperatures, living vegetation requires extended dry periods of 2 weeks or more to increase fire ignition and spread potential. 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 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 dry intervals between rain events (Chapter 4). With warmer temperatures and a range of other climate-driven stressors, the potential exists for more forests to be receptive 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 affect 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 some combination of strong gradient winds, significant atmospheric instability, and dry air. The fires that occur in fire-prone landscapes during these events tend to produce the most severe fire effects. These events are poorly captured by modeling tools. Because large wildfires are driven primarily by these extremes, 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 manifest as surface fires or crown fires. This distinction has important consequences for forest communities and fire management, and our limited understanding is a source of major uncertainty.

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

More Information

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

WATER RESOURCES

There are many potential interactions and relationships between climate change, forest ecosystems, and water resources in Minnesota. Below, we outline a few examples of these potential implications. Water resources in the assessment area are influenced not only by land management but also by a diverse array of other 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.

A prescribed burn that occurred in Canada in a portion of the 1999 blowdown area. Photo by U.S. Forest Service, Superior National Forest.

Infrastructure

Many landowners and agencies are responsible for managing water infrastructure such as dams, drainage ditches, and culverts. Specifications for water infrastructure are based on past climate patterns, and the trend of intensifying precipitation has placed additional strains on old and fragile infrastructure. The flood event in June 2012 in Duluth and across northern Minnesota accounted for more than $100 million in damage, primarily to roads, bridges, and private property (Passi 2012). In addition, this storm caused extensive damage to area streams as a result of landslides and stream bank erosion, with expected restoration costs of roughly $1 million per stream.

Water Quality

Water resource managers in the assessment area have long been concerned about the impacts of multiple stressors, including the effects of commercial or residential development and climate patterns on in-stream temperature and increased turbidity. Several trout streams within the assessment area are considered “at risk,” and have been identified as impaired from excessive temperatures and targeted for total maximum daily load (TMDL) studies (Minnesota Pollution Control Agency 2013). Within forested regions of the assessment area, impairments due to turbidity are the most common. Processes leading to increased turbidity are particularly sensitive to climate-related phenomena including increased storm intensity and frequency, rain-on-snow events, and other trends that promote stream bank erosion. These events can also cause water quality issues by introducing excessive nutrients and contaminants.

Thermal habitat in cold-water lakes and streams will also continue to be impaired as temperatures continue to warm. If conifers are replaced by deciduous trees or tree cover is reduced in the assessment area, aquatic resources will also receive less shade throughout the year (Blann et al. 2002). As ice cover is reduced on lakes in the assessment area, water temperatures and oxygen profiles will be affected the most in shallow and moderate-depth lakes (Fang et al. 2004a, 2004b, 2004c; Stefan et al. 2001).

Aquatic Organisms

Aquatic organisms are expected 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, eggs and fry associated with gravel habitats and fine sediments appear to have been the life stages most affected by the June 2012 floods in northern Minnesota (D. Hendrickson, Minnesota DNR, personal comm., December 2012). Cold-water fish species like cisco are projected to be adversely affected in many lakes across the assessment area, though warm-water fish species may benefit (Fang et al. 2004a, 2004b, 2004c; Jiang et al. 2012).

Water temperature is generally considered to be the primary physical habitat suitability parameter for trout, and upper temperature limits seem to depend specifically on the duration of high temperatures (Wehrly et al. 2007). Ongoing work within the assessment area to investigate climate change impacts on water temperature and base flow finds that streams within the Lake Superior basin may be affected by low flow and higher stream temperatures in the future (Lucinda Johnson and Meijun Cai, Natural Resources Research Institute; and William Herb, University of Minnesota, personal comm., February 2013). Suitable habitat for brook trout in the southern part of the Lake Superior basin in Minnesota is projected to be the habitat at highest risk from low flows and higher summer temperatures. Streams in the northern portion of the basin may be less at risk.

More Information

- The Great Lakes Environmental Assessment and Mapping (GLEAM) project compiles spatial information regarding many threats to Great Lakes ecosystems, including climate change. www.greatlakesmapping.org/
- Sustaining Lakes in a Changing Environment (SLICE) is a project of the Minnesota DNR, and is a valuable resource for land managers interested in long-term data on biological and chemical changes in Minnesota lakes. www.dnr.state.mn.us/fisheries/slice/index.html

FOREST PRODUCTS

The forest industry in Minnesota accounts for roughly $6 billion in economic activity and more than 35,000 jobs (Headwaters Economics 2011, Minnesota DNR 2010a). Information presented in Chapters 5 and 6 indicates that species composition in the assessment area may change during the 21st century, which could have important implications for the forest products industry. Major harvested species like quaking aspen are projected to show significant declines under a range of possible climate futures. Conversely, hardwood species like American basswood and northern red oak are poised to increase throughout the assessment area. Large potential shifts in commercial species availability may pose risks for the forest products sector if the shifts are rapid and the industry is unprepared. The forest products industry may benefit from awareness of anticipated climate trends and shifts in forest species. In many cases, forest managers can take actions to reduce potential risks associated with climate change or proactively encourage species and forest types anticipated to fare better under future conditions (Swanston and Janowiak 2012). There may be regional differences in forest responses, as well as potential opportunities for new merchantable species to gain suitable habitat in the assessment area. If the industry can adapt effectively, it is possible that the net effect of climate change on the forest products industry across the Midwest will be positive (Handler et al. 2012).

Overall, 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 in 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). Large uncertainties are associated with each of these factors. The forest products industry has adjusted to

Kiln-dried paper birch lumber. This lumber shows excellent color from trees that grew free of major stress. Photo by John Rajala, Rajala Companies, used with permission.

Kiln-dried paper birch lumber with discolored heartwood. Stress leads to discoloration of the heartwood, lowering the value of the lumber. Photo by John Rajala, Rajala Companies, used with permission.

substantial changes during the past 100 years, and continued responsiveness can help the sector remain viable.

More Information

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

NONTIMBER FOREST PRODUCTS

Changes in climate will have implications for nontimber forest products in the assessment area and throughout the Laurentian Mixed Forest Province. 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 three Northwoods nontimber forest products with broad cultural and economic importance are discussed briefly here.

Natural wild rice is a Northwoods cultural keystone species (Minnesota DNR 2008). It is central to the migration story of the Anishinaabe (also known as Ojibwe or Chippewa), for whom wild rice is a sacred food and medicine. In Minnesota, an estimated 4,000 to 5,000 individuals harvest natural wild rice for sale and personal use. In 2007, wild rice income exceeded $4,000 per person for members of the Leech Lake Band of Ojibwe. 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 3.0 feet. Germination requires a 3- to 4-month dormant period in water at 35 °F or less. Wild rice seed does not survive prolonged drying. With regional and global models predicting increased heavy precipitation events, higher average temperatures, later winter onset, and earlier spring onset, the future of natural wild rice in the Northwoods may be at risk. Specific threats include:

- prolonged droughts leading to lowered water depths or seed desiccation,
- 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 Northwoods residents and is especially important in rural areas where job opportunities are limited. In 2005, the Minnesota bough industry was reported to be worth more than $23 million (Jacobson et al. 2005). Models predict sharp declines in balsam fir biomass and suitable habitat in the assessment area, particularly under the hotter, drier climate scenario (Chapter 5).

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

FOREST MANAGEMENT OPERATIONS

Climate variability and change present many challenges for forest managers who seek to maintain the diverse goods and services that forests provide. In particular, changes in winter conditions in the assessment area and throughout the northern Great Lakes region may shorten the available timeframe for conventional forest management operations. Most management in lowland areas is accomplished during the winter. As summarized in Chapter 4, climate change in northern Minnesota is projected to result in shorter seasons of frozen ground, more midwinter thaws, less snowpack, and more rain during winter months. Frozen ground facilitates timber harvest and transport, and snowpack provides protection for soils during harvest operations. Although special equipment is available to increase flotation on shallow snowpack or in the absence of snowpack, this equipment is costly. Additionally, a lack of frozen ground might increase the need to build roads to facilitate winter harvest, which would require additional costs compared to conventional practices.

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

Changes in severe weather patterns could increase the amount of salvage harvests that are undertaken. Harvesting green timber allows resource managers to strategically achieve desired objectives and outcomes. Salvage harvesting following a tornado or derecho, by contrast, generally arises from a more immediate need to remove hazardous fuels or clear impacted forest areas. A salvage sale also does not garner the same amount of financial return as does a green timber sale opportunity. Severe weather response may also involve additional financial burden because of costs associated with re-establishment.

Analysis of timber harvest records in northern Wisconsin have 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

Working carefully around a crop tree during a white pine thinning operation with cut-to-length harvesting equipment. Photo by John Rajala, Rajala Companies, used with permission.

a shift toward greater harvest of jack pine and less harvest of black spruce, hemlock, and red maple. Interviews with loggers revealed that growing-season restrictions on harvest designed to limit oak wilt and other diseases reduced the annual harvest window. Additionally, such ongoing stressors as overcapitalization, loan and insurance payments, and high fuel prices increased pressure on loggers to harvest year-round. Interviews with transportation officials revealed concerns that operating trucks on marginally frozen roads (or "over-weighting") contributed to conflicts over roads between industry and local governments. Thus, climate change impacts on forestry operations have complex implications for management and governance of timber production, logger livelihoods, water quality, and transportation systems.

More Information

- The Minnesota Forest Resources Council has coordinated the development of site-level timber harvesting and forest management guidelines for the state. These voluntary guidelines do not specifically consider climate change or climate variability, but they can be a useful starting point for assessing the various ways climate change could impact forest management operations. www.frc.state.mn.us/initiatives_sitelevel_management.html

INFRASTRUCTURE ON FOREST LAND

Changes in climate and extreme weather events are expected to have impacts on infrastructure on forest lands throughout the region, such as roads, bridges, and culverts. Rising temperatures alone could have important impacts. A recent report suggests that heat stress may have substantial effects on surface transportation infrastructure in the assessment area (Posey 2012). Heavy precipitation events, which are already increasing and projected to increase further in the future, may overload existing infrastructure that was not built to that capacity. For example, improper location or outdated building standards can make older road systems particularly susceptible to increased rainfall events. Engineers are already adapting to these changes: as infrastructure is replaced, it is being constructed with heavier precipitation events in mind. This extra preparedness often comes at an increased cost to upgrade to higher standards and capacity. Extreme events may also require more frequent maintenance of roads and other infrastructure, even if designed to appropriate specifications. Additionally, forest managers may find it necessary to take additional precautions to prevent erosion when designing road networks or other infrastructure.

Damage to a forest road after the June 2012 rainstorm in northeastern Minnesota. Photo by Patrick Hampston, Superior National Forest.

As described in Chapter 4, changes in precipitation may also lead to seasonal changes in streamflow, such as higher peak flows, which could affect infrastructure around streams and rivers. The heavy rainfall event centered on Duluth in June 2012 highlighted the potential for flood-related damage across the assessment area.

An increase in the frequency or intensity of wind storms, which may occur in the next century, could also increase operating and repair expenses related to infrastructure. For example, a large windstorm across north-central Minnesota in July 2012 led to major damage to infrastructure on the Chippewa

National Forest and in areas surrounding Grand Rapids, Minnesota. As a result, roads and trails had to be cleared and facilities repaired.

More Information

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

FOREST CARBON

The accumulated carbon (C) pool within forest soils, belowground biomass, dead wood, and aboveground live biomass is enormous (Birdsey et al. 2006). Climate change and associated impacts to forest ecosystems may change the ability of forests in northern Minnesota to store C. A longer growing season and carbon dioxide (CO_2) fertilization may lead to increased productivity and C storage in forests in the assessment area (Chapter 5). This increase could be offset by climate-related physical and biological disturbances (Gough et al. 2008, Hicke et al. 2011), leading to increases in C storage in some areas and decreases in others. As long as forests are maintained as forests in the assessment area, a large-scale decline in C stocks across northern Minnesota is not expected. If forests convert to nonforested conditions or if C stored in peat soils is lost to the atmosphere, then C storage is reduced over much longer time scales.

Different forest-type groups in the assessment area store different amounts of C (Chapter 1). On average, spruce/fir forests are the most C dense, but most of this C occurs in organic soils. Maple/beech/birch forests generally contain the most aboveground C, so an increase in these species and a decline in spruce/fir forests may have effects on C storage in some areas. Modeling studies in northern Wisconsin examining the effects of species composition changes on landscape-scale C stocks, suggest that some forests may increase in biomass and overall productivity, despite declines in boreal or northern species (Chiang et al. 2008, Scheller and Mladenoff 2005).

More Information

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

WILDERNESS

The Boundary Waters Canoe Area Wilderness (BWCAW) covers more than 800,000 acres in northeastern Minnesota, administered by the Superior National Forest. This wilderness area is iconic for its sheer physical size and high levels of visitor use. Like other wilderness areas, the BWCAW has been designated for preservation and protection according to specific guidelines for management. Climate change was not anticipated when the BWCAW was created, and now the potential for extensive ecosystem change raises difficult questions about the future management of this and other wilderness areas.

Climate change is poised to influence the BWCAW ecosystem in a variety of ways (Frelich and Reich 2009). Fire seasons are expected to shift, and more area is projected to burn each year under climate change (Chapter 5). Furthermore, 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 BWCAW 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. Additionally, managers accept the fact that natural hazards and obstacles are inherently a part of the wilderness experience, but try to remove trees that are posing immediate threats to visitors. Weather-related mortality from storm events, drought, or insect and disease attack could increase the need for this activity. Weather conditions also affect the need for maintenance of the trail tread, particularly when heavy rain events cause excessive erosion, or when wind events uproot trees and leave craters in parts of the trail.

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

More Information

- The Wilderness.net Climate Change Toolbox provides 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/

CULTURAL RESOURCES

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

Paper birch from Pine County, Minnesota. Photo by Eli Sagor, University of Minnesota, used with permission.

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

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

More Information

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

RECREATION

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

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

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 of 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 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 projected 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.

More Information

- A recent report submitted for the National Climate Assessment summarizes the impacts of climate change on outdoor recreational tourism across the Midwest, including the assessment area.
  http://glisa.msu.edu/media/files/NCA/MTIT_RecTourism.pdf
- Season's End, an organization built on the collaboration between many hunting and conservation groups, includes many resources on how climate change may affect wildlife.
  http://www.cakex.org/virtual-library/784

HUMAN HEALTH CONCERNS

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

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

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

More Information

- The Minnesota Department of Health Web site has more information on vector-borne diseases in Minnesota.
  www.health.state.mn.us/divs/idepc/dtopics/vectorborne/index.html
- The Minnesota Department of Health has a Web site on the climate change implications for human health.
  www.health.state.mn.us/divs/climatechange/
- The Centers for Disease Control and Prevention Climate and Health Program includes information on a variety of subjects.
  www.cdc.gov/climateandhealth/

URBAN FORESTS

Climate change is expected to affect urban forests in the assessment area as well. Urban environments can pose additional stresses, 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 will be even greater than in natural communities. Impervious surfaces can make urban environments more susceptible to floods, placing flood-intolerant species at risk. All of these abiotic stressors can make urban forests more susceptible to exotic species invasion, and insect and pathogen attack, especially because a limited range of species and genotypes is often planted in urban areas. Urban settings are often where exotic insect pests are first introduced.

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

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

More Information

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

FOREST-ASSOCIATED TOWNS AND CITIES

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

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

If resource professionals, community leaders, and local organizations are to help communities adapt, they must be able to assess community vulnerabilities and capacities to organize and engage resources. In the Great Lakes region, most human community vulnerability assessment work to date has focused on coastal communities (Minnesota Sea Grant 2012). However, research is underway in northern Minnesota to examine the capacity of forest-associated communities to adapt to ecological change (Mae Davenport, University of Minnesota; Marla Emery and Pam Jakes, U.S. Forest Service, Northern Research Station, personal comm.). Researchers are using a rapid assessment approach to investigate the social, cultural, and institutional characteristics and processes that affect a community's ability to adapt to ecological change (see "More Information" below).

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

- Is access to healthy ecosystems at risk?
- Is there a potential for resource scarcity?
- Are cultural practices or recreational opportunities at risk?
- Is there potential for loss of social connectedness or increased social or cultural conflict?
- Is there potential for disproportionate impacts to certain populations?
- Is there potential for human health problems including stress, anxiety, despair, or sense of powerlessness?

More Information

- The Resilience Alliance has created a workbook for practitioners to assess resilience of social-ecological systems.
  www.resalliance.org/index.php/resilience_assessment
- Minnesota Sea Grant produced a community self-assessment to address climate change readiness, and its Web site includes several resources useful for communities.
  www.seagrant.umn.edu/climate/
- An initial report is available for a rapid assessment of community adaptive capacity conducted in Walker, Minnesota (Davenport et al. 2013).
  www.forestry.umn.edu/People/Davenport/

LAND ACQUISITION

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

In terms of prioritizing specific parcels of land, it may be important to identify parcels that have large C mitigation potential. This is particularly important in the Laurentian Mixed Forest Province, where private forest lands have some of the highest stored C 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 habitat refugia and protection for shifting water supplies.

Black spruce bog at the Marcell Experimental Forest, Itasca County, Minnesota. Note flowering pitcher plants in the foreground. Photo by Deacon Kyllander, U.S. Forest Service.

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

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

PLANNING

Until recently, climate change has not played a large role in natural resource planning. Many federal and state-level land management agencies are now beginning to address the issue. For example, the Forest Service's 2012 Planning Rule directly addresses the impacts and ramifications of climate change. In fact, climate change was among the stated purposes for revising the Rule (FR Vol. 77, No. 68, 21163 & 21164). As the Superior and Chippewa National Forests revise their management plans in the coming years, they will be required to address the issue of climate change under the new Planning Rule.

At the state level, Minnesota's Subsection Forest Resource Management Plans also have not historically addressed climate change. However, the *2010 State Forest Resource Assessment* and *Strategies* documents both include climate change as an issue that could influence the long-term sustainability of Minnesota's forests (Minnesota DNR 2010a, 2010b).

The Minnesota Forest Resources Council also coordinates a landscape-level planning program within the state. This collaborative planning process bridges ownerships, forest types, and administrative boundaries, and relies on the input and expertise of volunteer landscape committees. The Northeast Landscape Committee is revising the plan for Minnesota's "Arrowhead" region. This will be the first of these plans to explicitly consider climate change in both short-term and long-term management goals and objectives.

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

More Information

- More information on the Forest Service's 2012 Planning Rule can be found here: www.fs.usda.gov/planningrule
- Minnesota's *Forest Resource Assessment* and *Strategies* documents include discussions of climate change. www.forestactionplans.org/states/minnesota
- Minnesota's Subsection Forest Resource Management Planning program is explained in detail on the Minnesota DNR Web site. www.dnr.state.mn.us/forestry/subsection/index.html
- The Minnesota Forest Resources Council coordinates the development of landscape-scale plans across northern Minnesota to guide long-term management of forest resources across ownerships and jurisdictions. Plans are in place for all six major forested landscapes in Minnesota. www.frc.state.mn.us/resources_documents_landscape.html

CONCLUSIONS

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

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

GLOSSARY

aerosol

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

adaptive capacity

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

agreement

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

alluvial

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

asynchronous quantile regression

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

biomass

the mass of living organic matter (plant and animal) in an ecosystem; biomass also refers to 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
a method for obtaining high-resolution climate or climate change information from relatively coarse-resolution general circulation models (GCMs); involves examining the statistical relationship between past climate data and on-the-ground measurements.

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) 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 system of living organisms interacting with each other and their physical environment. The boundaries of what could be called an ecosystem are somewhat arbitrary, depending on the focus of interest or study. Thus, the extent of an ecosystem may range from very small spatial scales to, ultimately, the entire Earth.

emissions scenario
a plausible representation of the future development of emissions of greenhouse gases and aerosols that are potentially radiatively active, based on certain 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**).

fen
a wetland fed by surface water, or groundwater, or both; characterized by the chemistry of the water, which is neutral or alkaline.

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
pertaining 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
simulations of 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 UN 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
pertaining 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.

Native Plant Community
in the ecosystem classification system developed by the Minnesota Department of Natural Resources and referenced in this assessment, an assemblage of native plants that tend to recur over space and time, which interact with each other and their physical environment in ways minimally modified by exotic species and negative human disturbances.

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

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**).

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

significant trends
least-squares regression p-values of observed climate trends. In this report, significant trends ($p < 0.10$) are shown by stippling on maps of observed climate trends. Where no stippling appears ($p > 0.10$), observed trends have a higher probability of being due to chance alone.

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.

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

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

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

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

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

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

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

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

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

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, 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 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.

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APPENDIX 1. COMMON AND SCIENTIFIC NAMES OF FLORA, FAUNA, AND DISEASES

FLORA

Common Name	Scientific Name
balsam fir	*Abies balsamea*
boxelder	*Acer negundo*
striped maple	*Acer pensylvanicum*
red maple	*Acer rubrum*
silver maple	*Acer saccharinum*
sugar maple	*Acer saccharum*
mountain maple	*Acer spicatum*
Ohio buckeye	*Aesculus glabra*
garlic mustard	*Alliaria petiolata*
speckled alder	*Alnus incana*
serviceberry	*Amelanchier alnifolia*
Japanese barberry	*Berberis thunbergii*
yellow birch	*Betula alleghaniensis*
sweet birch	*Betula lenta*
river birch	*Betula nigra*
paper birch	*Betula papyrifera*
bog birch	*Betula pumila*
goblin fern	*Botrychium mormo*
Pennsylvania sedge	*Carex pensylvanica*
American hornbeam	*Carpinus caroliniana*
bitternut hickory	*Carya cordiformis*
pignut hickory	*Carya glabra*
shagbark hickory	*Carya ovata*
black hickory	*Carya texana*
mockernut hickory	*Carya tomentosa*
northern catalpa	*Catalpa speciosa*
sugarberry	*Celtis laevigata*
hackberry	*Celtis occidentalis*
eastern redbud	*Cercis canadensis*
flowering dogwood	*Cornus florida*
hazel	*Corylus cornuta*
dwarf trout lily	*Erythronium propullans*
American beech	*Fagus grandifolia*

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

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FLORA (continued)

Common Name	Scientific Name
shingle oak	*Quercus imbricaria*
bur oak	*Quercus macrocarpa*
blackjack oak	*Quercus marilandica*
chinquapin oak	*Quercus muehlenbergii*
pin oak	*Quercus palustris*
chestnut oak	*Quercus prinus*
northern red oak	*Quercus rubra*
post oak	*Quercus stellata*
black oak	*Quercus velutina*
European buckthorn	*Rhamnus cathartica*
Leedy's roseroot	*Rhodiola integrifolia* ssp. *leedyi*
black locust	*Robinia pseudoacacia*

Common Name	Scientific Name
peachleaf willow	*Salix amygdaloides*
black willow	*Salix nigra*
sassafras	*Sassafras albidum*
American mountain-ash	*Sorbus americana*
sphagnum moss	*Sphagnum* spp.
northern white-cedar	*Thuja occidentalis*
American basswood	*Tilia americana*
eastern hemlock	*Tsuga canadensis*
American elm	*Ulmus americana*
slippery elm	*Ulmus rubra*
rock elm	*Ulmus thomasii*
wild rice	*Zizania palustris*

FAUNA

Common Name	Scientific Name
northern goshawk	*Accipiter gentilis*
boreal owl	*Aegolius funereus*
emerald ash borer	*Agrilus planipennis*
moose	*Alces alces*
Asian long-horned beetle	*Anoplophora glabripennis*
red-shouldered hawk	*Buteo lineatus*
gray wolf	*Canis lupus*
beaver	*Castor canadensis*
spruce budworm	*Choristoneura fumiferana*
jack pine budworm	*Choristoneura pinus pinus*
larch casebearer	*Coleophora laricella*
olive-sided flycatcher	*Contopus cooperi*
cisco	*Coregonus artedi*
earthworms (nonnative)	*Dendrobaena octaedra, Lumbricus rubellus,* and *L. terrestris*
eastern larch beetle	*Dendroctonus simplex*
Blanding's turtle	*Emys blandingii*
northern pike	*Esox lucius*
birch leaf miner	*Fenusa pusilla*
wood turtle	*Glyptemys insculpta*
four-toed salamander	*Hemidactylium scutatum*

Common Name	Scientific Name
bark beetles	*Ips* spp. and *Dendroctonus* spp.
blacklegged tick	*Ixodes scapularis*
snowshoe hare	*Lepus americanus*
gypsy moth	*Lymantria dispar dispar*
Canada lynx	*Lynx canadensis*
forest tent caterpillar	*Malacosoma disstria*
American marten	*Martes americana*
wild turkey	*Meleagris gallopavo*
rock vole	*Microtus chrotorrhinus*
white-tailed deer	*Odocoileus virginianus*
gray jay	*Perisoreus canadensis*
white-footed mouse	*Peromyscus leucopus*
aspen blotch miner	*Phyllonorycter apparella*
black-backed woodpecker	*Picoides arcticus*
three-toed woodpecker	*Picoides tridactlyus*
white pine tip weevil	*Pissodes strobi*
Karner blue butterfly	*Plebejus melissa samuelis*
larch sawfly	*Pristiophora erichsonii*
raccoon	*Procyon lotor*
brook trout	*Salvelinus fontinalis*
lake trout	*Salvelinus namaycush*

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FAUNA (continued)

Common Name	Scientific Name
walleye	*Sander vitreus*
eastern gray squirrel	*Sciurus carolinensis*
American woodcock	*Scolopax minor*
Franklin's ground squirrel	*Spermophilus franklinii*

Common Name	Scientific Name
great gray owl	*Strix nebulosa*
badger	*Taxidea taxus*
golden-winged warbler	*Vermivora chrysoptera*

DISEASES

Common Name	Scientific Name
Armillaria	*Armillaria mellea*
dwarf mistletoe	*Arceuthobium pusillum*
lyme disease	*Borrelia burgdorferi*
white pine blister rust	*Cronartium ribicola*
Diplodia	*Diplodia pinea* and *D. scrobiculata*
West Nile virus	*Flavivirus* spp.

Common Name	Scientific Name
scleroderris canker	*Gremmeniella abietina*
annosum root disease	*Heterobasidion irregulare*
hypoxylon canker	*Hypoxylon mammatum*
morel mushroom	*Morchella* spp.
sudden oak death	*Phytophthora ramorum*
sirococcus shoot blight	*Sirococcus conigenus*
sphaeropsis shoot blight	*Sphaeropsis sapinea*

APPENDIX 2. TREND ANALYSIS AND HISTORICAL CLIMATE DATA

To examine historical trends in precipitation and temperature for the analysis area, we used the ClimateWizard Custom Analysis Tool (ClimateWizard 2012, Gibson et al. 2002, Girvetz et al. 2009). Data for ClimateWizard are derived from PRISM (Parameter-elevation Regressions on Independent Slopes Model) (Gibson et al. 2002). PRISM 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/.

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

Linear trend analysis for 1901 through 2011 was performed by using restricted maximum likelihood (REML) estimation (Girvetz et al. 2009). Restricted maximum likelihood methods were used for trend analysis of past climate for the Intergovernmental Panel on Climate Change *Working Group 1 Report* and are considered an effective way to determine trends in climate data over time (Trenberth et al. 2007). A first-order autoregression was assumed for the residuals, meaning that values one time step away from each other are assumed to be correlated. This method was used to examine trends for every 2.5-mile grid cell. The slope and *p*-values for the linear trend over time were calculated annually, seasonally, and monthly for each climate variable, and then mapped. An overall trend for an area is based on the trend analysis of the average value for all grid cells within the area over time (Table 21).

Developers of the ClimateWizard Tool advise users to interpret the linear trend maps in relation to the respective map of statistical confidence (Figs. 47 and 48). In this case, statistical confidence is described by using *p*-values from a t-test applied to the linear regression. A *p*-value can be interpreted as the probability of the slope being different from zero by chance alone. For this assessment, *p*-values of less than 0.1 were considered to have sufficient statistical confidence. Areas with low statistical confidence in the rate of change (gray areas on the map) should be interpreted with caution.

Table 21.—Average annual, seasonal, and monthly values and linear trend analysis for selected climate variables from 1901 through 2011 for the assessment area

Month or season	Mean precip. (inches)	Precip. change (inches)	Precip. *p*-value*	Mean TMean (°F)	TMean change (°F)	TMean *p*-value*	Mean TMax (°F)	TMax change (°F)	TMax *p*-value*	Mean TMin (°F)	TMin change (°F)	TMin *p*-value*
January	0.79	0.19	0.24	5.25	2.91	0.15	16.48	1.70	0.36	-6.00	4.12	**0.07**
February	0.65	-0.03	0.81	10.25	5.94	**0.00**	22.44	5.16	**0.00**	-1.94	6.73	**0.01**
March	1.13	0.22	0.20	23.45	3.24	**0.06**	35.03	2.50	0.13	11.87	3.97	**0.03**
April	1.89	0.42	0.14	39.36	2.49	**0.04**	51.26	2.44	0.11	27.46	2.54	**0.01**
May	2.94	0.27	0.47	51.92	2.52	**0.02**	64.80	1.88	0.15	39.06	3.17	**0.00**
June	3.98	0.42	0.40	61.46	1.30	0.23	73.81	0.22	0.87	49.12	2.36	**0.01**
July	3.68	0.67	**0.10**	66.67	0.96	0.25	79.01	-0.30	0.79	54.35	2.23	**0.00**
August	3.46	0.27	0.51	64.26	2.25	0.01	76.46	1.33	0.16	52.07	3.17	**0.00**
September	3.01	0.38	0.29	55.02	1.25	0.17	66.53	0.62	0.55	43.52	1.87	**0.03**
October	2.13	0.93	**0.08**	43.52	0.43	0.69	54.13	-0.64	0.63	32.92	1.50	0.12
November	1.31	0.26	0.20	27.10	1.43	0.34	35.59	0.54	0.72	18.61	2.31	0.13
December	0.86	0.18	0.26	11.91	2.26	0.18	21.45	1.14	0.47	2.37	3.39	**0.08**
Annual	25.83	4.30	**0.00**	38.35	2.25	**0.00**	49.75	1.38	**0.03**	26.95	3.12	**0.00**
Winter	2.30	0.36	0.17	9.14	3.73	**0.01**	20.13	2.68	**0.02**	-1.85	4.78	**0.00**
Spring	5.96	0.90	**0.07**	38.24	2.72	**0.01**	50.36	2.24	**0.04**	26.14	3.20	**0.00**
Summer	11.13	1.38	**0.09**	64.13	1.51	**0.02**	76.42	0.42	0.61	51.84	2.59	**0.00**
Fall	6.45	1.62	**0.01**	41.88	1.04	0.17	52.08	0.18	0.83	31.69	1.90	**0.01**

**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. TMean = mean temperature, TMax = maximum temperature, TMin = minimum temperature.

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

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

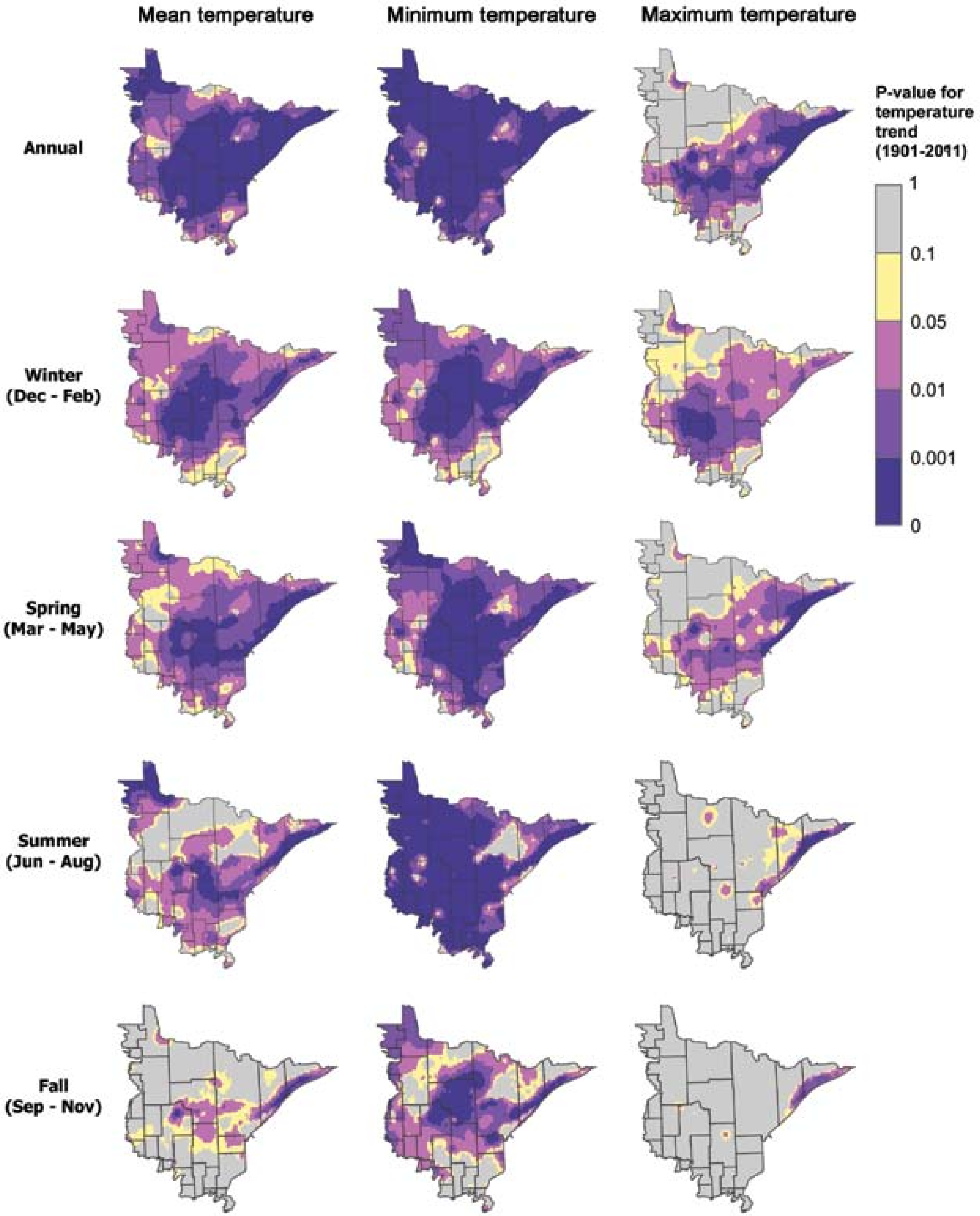

Figure 47.—Map of statistical confidence (*p*-values for the linear regression) for trends in temperature from 1901 through 2011. Gray values represent areas of low statistical confidence.

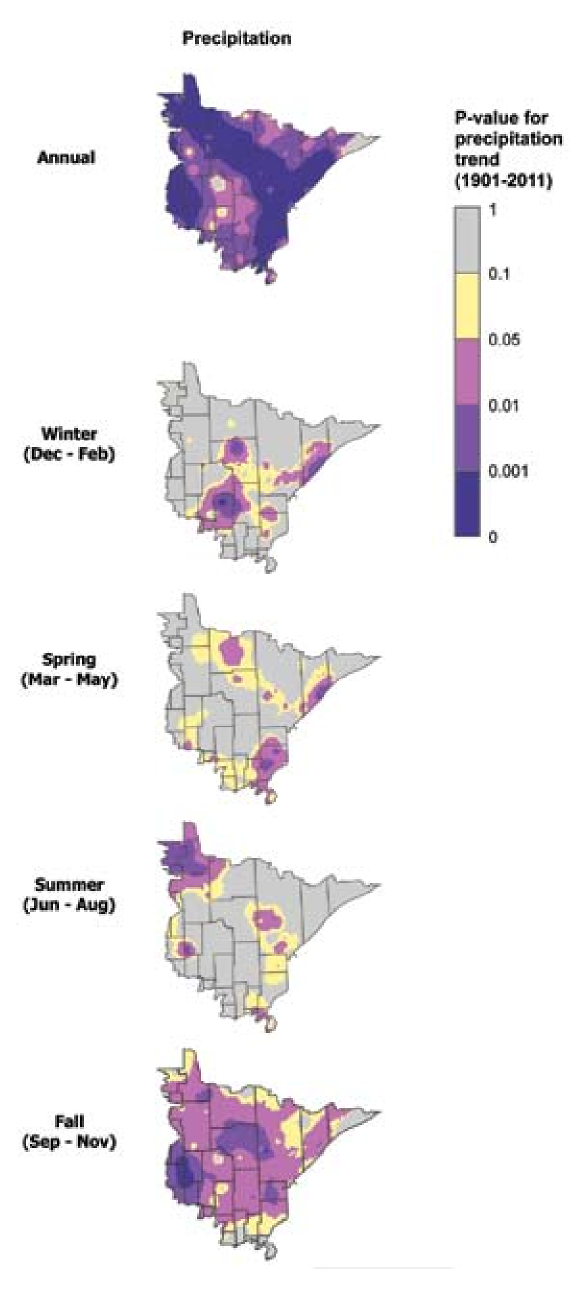

Figure 48.—Map of statistical confidence (*p*-values for the linear regression) for trends in precipitation from 1901 through 2011. Gray values represent areas of low statistical confidence.

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APPENDIX 3: ADDITIONAL FUTURE CLIMATE INFORMATION

This appendix presents supplementary information to Chapter 4: tables of projected change in temperature and precipitation for the assessment for the end of the 21st century (Tables 22 and 23) and maps of projected change for early- and mid-century (Figs. 49 through 56).

Table 22.—Projected changes in mean average, maximum, and minimum temperatures under two future climate scenarios for the assessment area over the next century

	Baseline temperature (°F) (1971-2000)	Temperature departure from baseline (°F)			
		Scenario	2010-2039	2040-2069	2070-2099
Mean					
Annual	39.0	PCM B1	1.4	2.0	3.0
		GFDL A1FI	2.2	6.8	8.8
Winter (Dec.-Feb.)	9.9	PCM B1	1.5	2.5	3.9
		GFDL A1FI	2.8	8.6	9.8
Spring (Mar.-May)	39.6	PCM B1	0.1	1.2	2.2
		GFDL A1FI	0.3	3.8	5.4
Summer (June-Aug.)	64.5	PCM B1	1.4	1.8	2.3
		GFDL A1FI	3.1	8.6	11.4
Fall (Sept.-Nov.)	41.5	PCM B1	2.9	3.0	3.9
		GFDL A1FI	2.9	6.5	9.1
Mean maximum					
Annual	50.2	PCM B1	1.4	2.1	2.7
		GFDL A1FI	1.8	6.1	7.6
Winter (Dec.-Feb.)	20.7	PCM B1	1.3	2.1	2.7
		GFDL A1FI	2.2	6.9	7.5
Spring (Mar.-May)	51.8	PCM B1	-0.2	1.1	1.8
		GFDL A1FI	-0.7	2.2	3.3
Summer (June-Aug.)	76.6	PCM B1	2.1	2.4	3.0
		GFDL A1FI	3.0	8.8	11.2
Fall (Sept.-Nov.)	51.5	PCM B1	2.9	3.1	3.9
		GFDL A1FI	3.0	6.8	8.8
Mean minimum					
Annual	27.7	PCM B1	1.3	1.9	3.2
		GFDL A1FI	2.6	7.5	10.0
Winter (Dec.-Feb.)	-1.0	PCM B1	1.7	3.0	5.0
		GFDL A1FI	3.5	10.2	12.1
Spring (Mar.-May)	27.5	PCM B1	0.3	1.2	2.6
		GFDL A1FI	1.3	5.4	7.4
Summer (June-Aug.)	52.4	PCM B1	0.7	1.2	1.6
		GFDL A1FI	3.2	8.4	11.5
Fall (Sept.-Nov.)	31.5	PCM B1	2.8	2.8	3.9
		GFDL A1FI	2.9	6.3	9.4

Table 23.—Projected changes in precipitation under two future climate scenarios for the assessment area over the next century

	Baseline precipitation (inches) (1971-2000)	Departure from baseline (inches)			
		Scenario	2010-2039	2040-2069	2070-2099
Annual	27.2	PCM B1	0.3	1.2	3.0
		GFDL A1FI	1.2	-2.2	-0.4
Winter (Dec.-Feb.)	2.3	PCM B1	0.6	0.7	1.0
		GFDL A1FI	0.3	0.4	0.7
Spring (Mar.-May)	5.8	PCM B1	0.4	0.8	1.6
		GFDL A1FI	1.6	2.2	3.2
Summer (June-Aug.)	12.1	PCM B1	-0.6	0.1	0.5
		GFDL A1FI	-0.5	-4.0	-4.8
Fall (Sept.-Nov.)	7.1	PCM B1	-0.2	-0.5	-0.1
		GFDL A1FI	-0.2	-0.8	0.6

Harvested logs from an aspen clearcut in Lake County, Minnesota. Photo by Casey McQuiston, Superior National Forest.

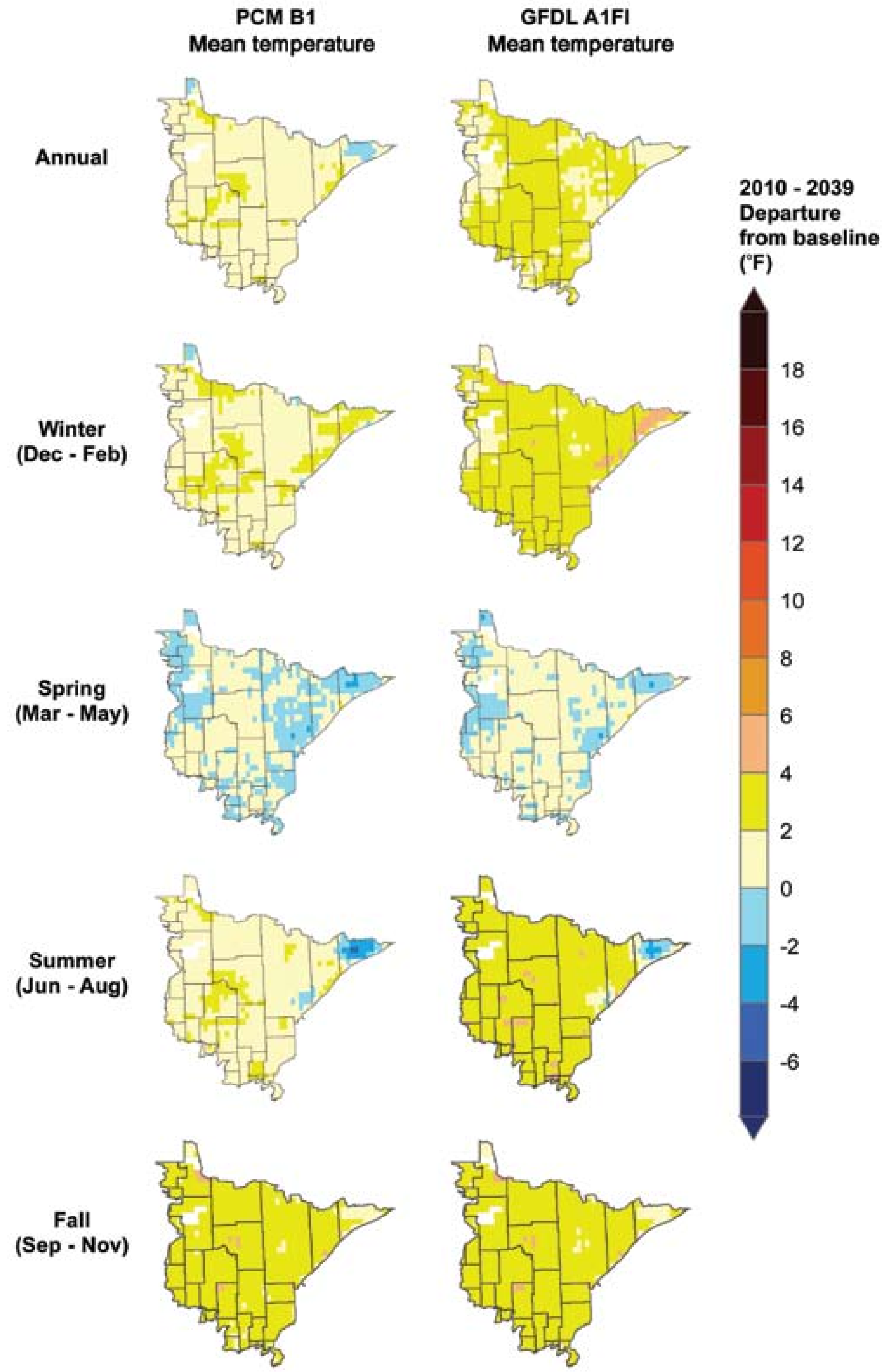

Figure 49.—Projected difference in mean daily temperature at the beginning of the century (2010 through 2039) compared to baseline (1971 through 2000) for two climate scenarios.

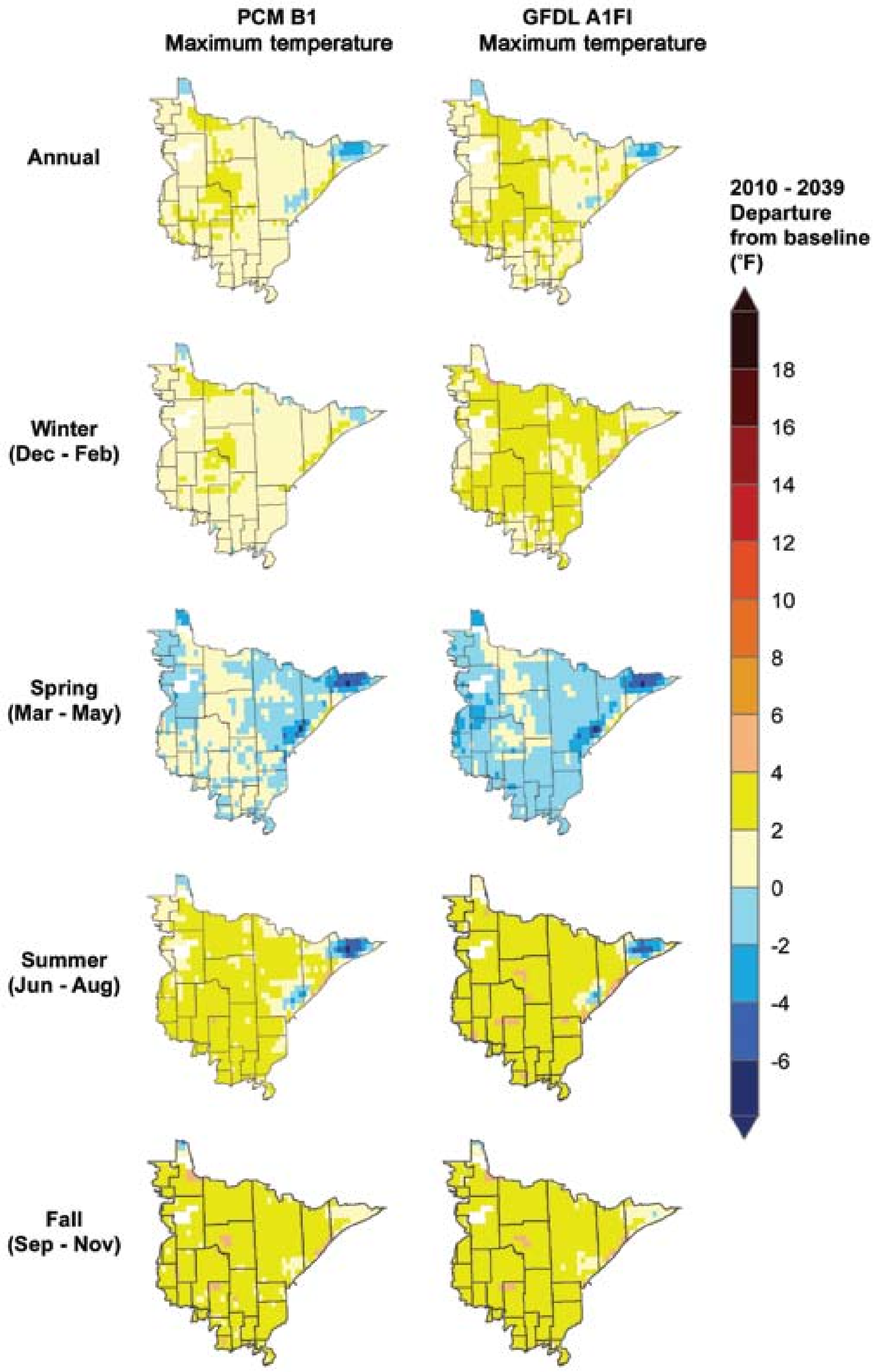

Figure 50.—Projected difference in mean maximum temperature at the beginning of the century (2010 through 2039) compared to baseline (1971 through 2000) for two climate scenarios.

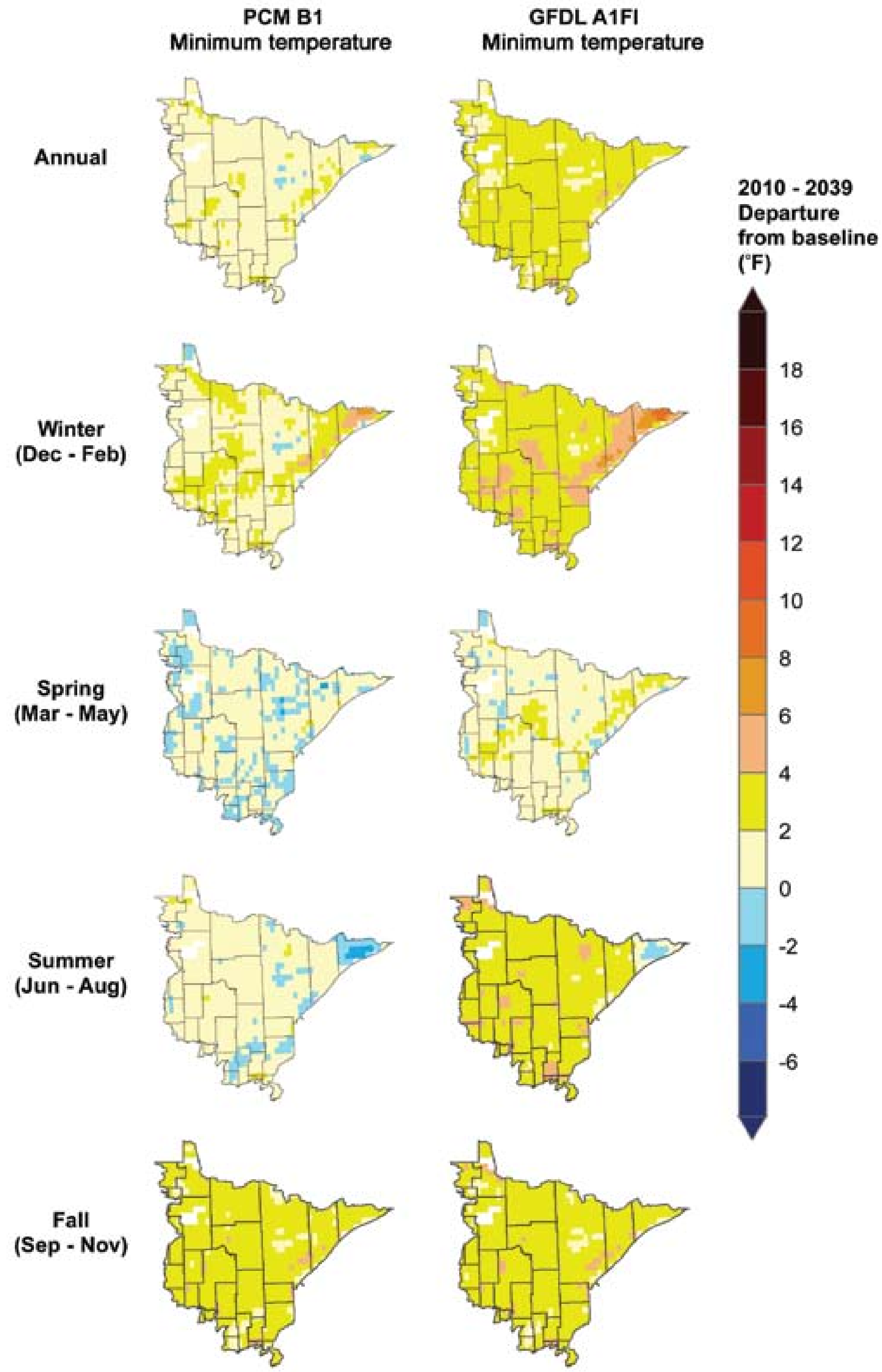

Figure 51.—Projected difference in mean minimum temperature at the beginning of the century (2010 through 2039) compared to baseline (1971 through 2000) for two climate scenarios.

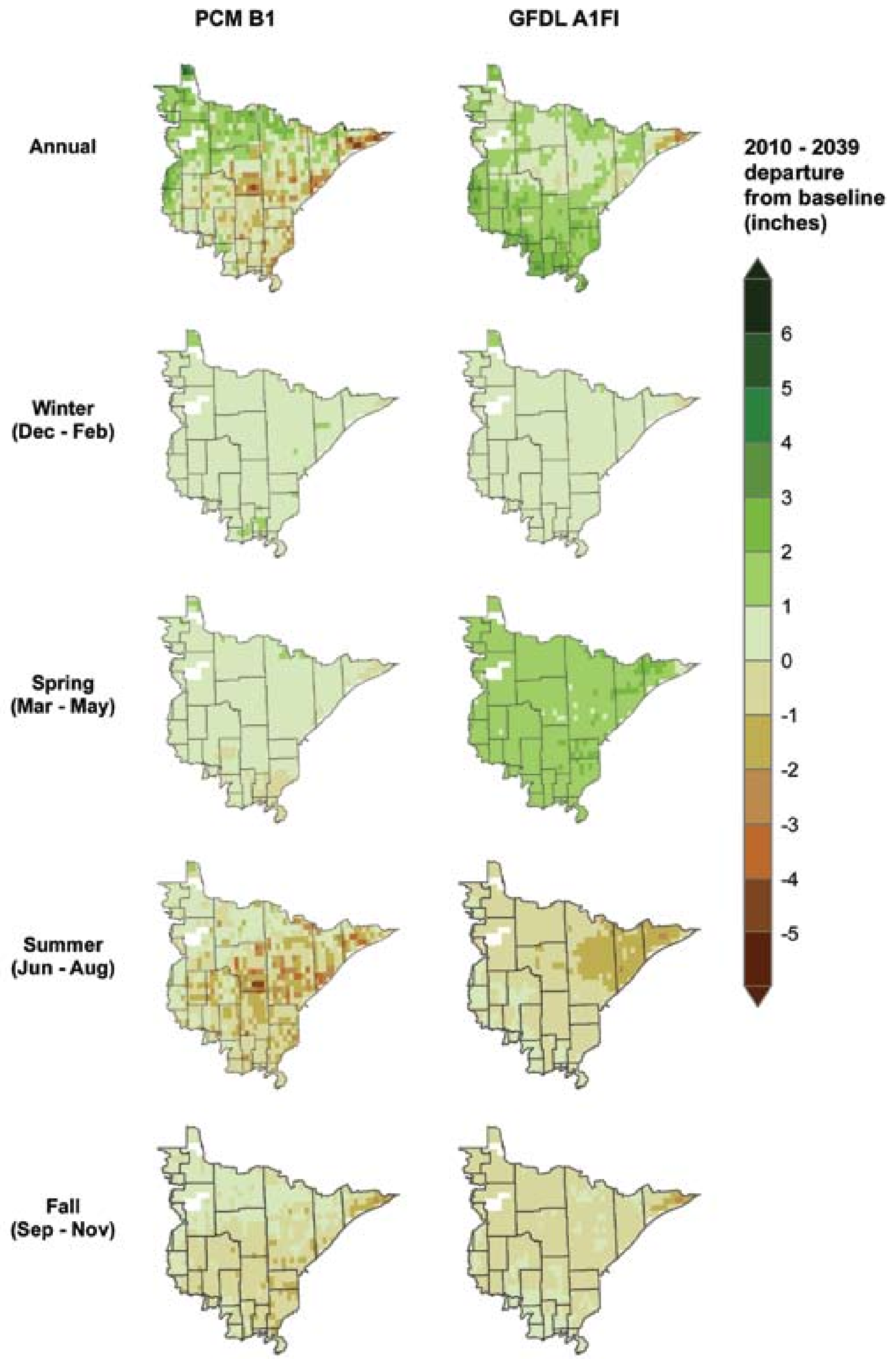

Figure 52.—Projected difference in precipitation at the beginning of the century (2010 through 2039) compared to baseline (1971 through 2000) for two climate scenarios.

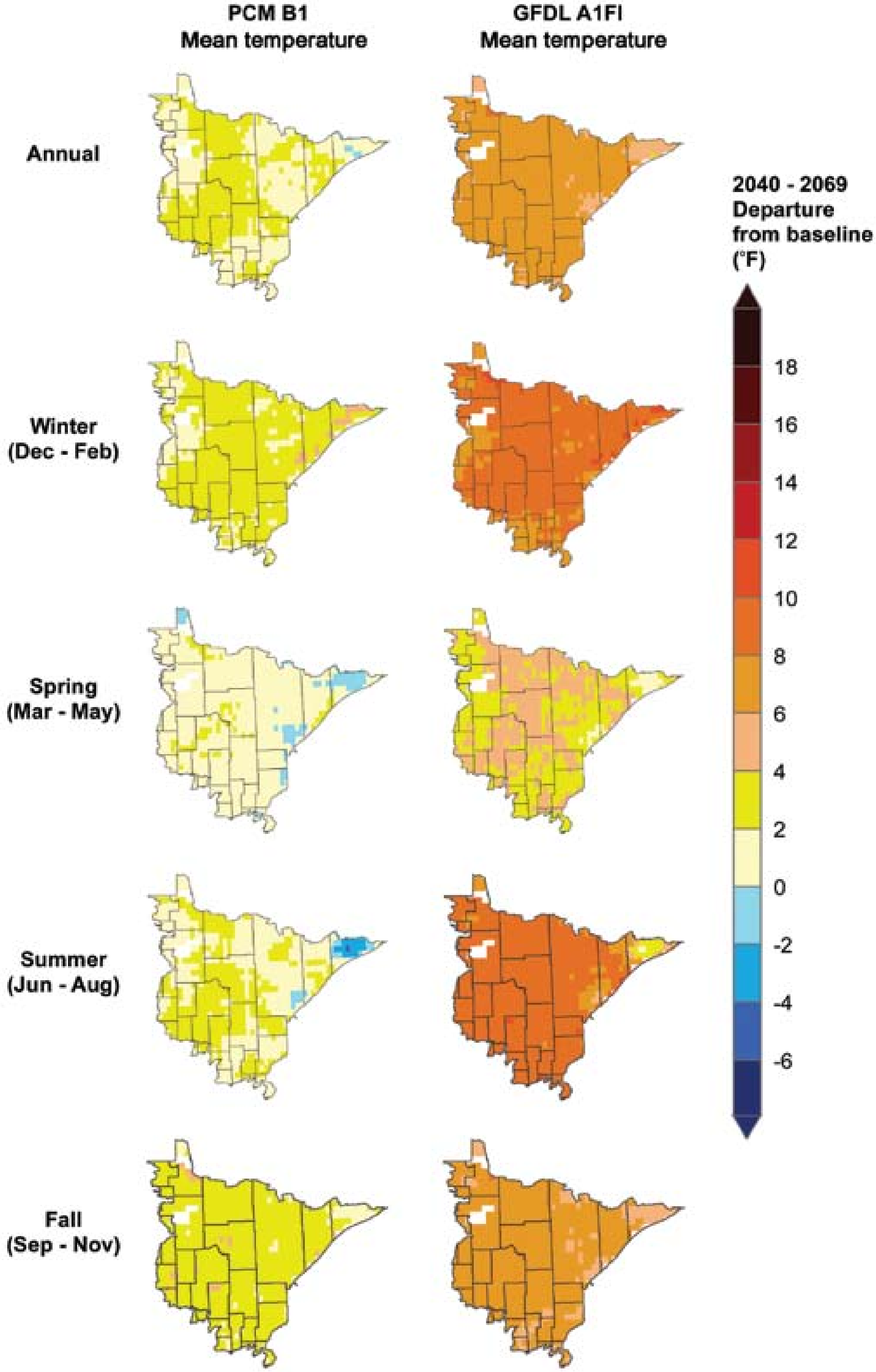

Figure 53.—Projected difference in mean daily temperature for the middle of the century (2040 through 2069) compared to baseline (1971 through 2000) for two climate scenarios.

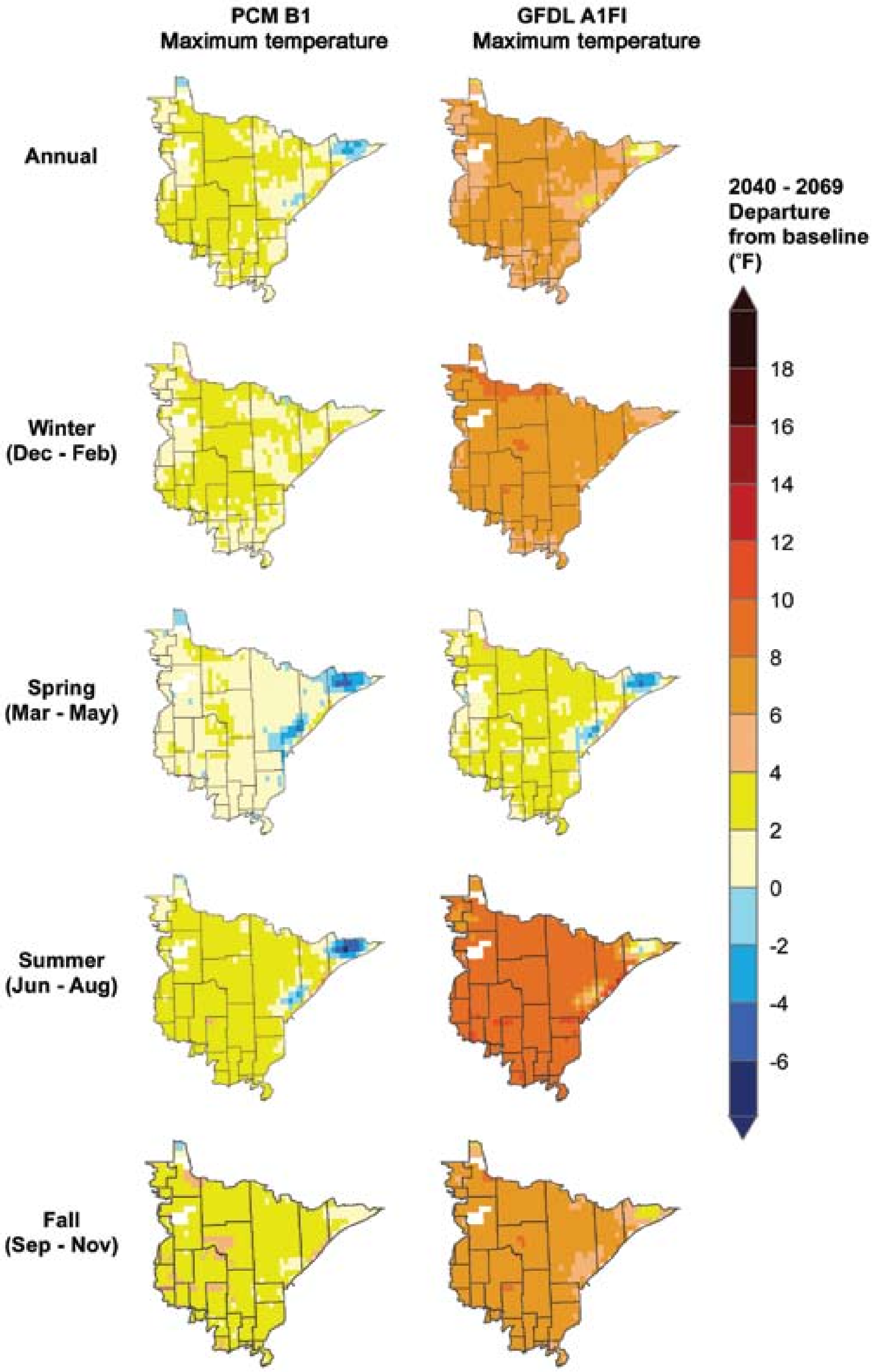

Figure 54.—Projected difference in mean maximum temperature for the middle of the century (2040 through 2069) compared to baseline (1971 through 2000) for two climate scenarios.

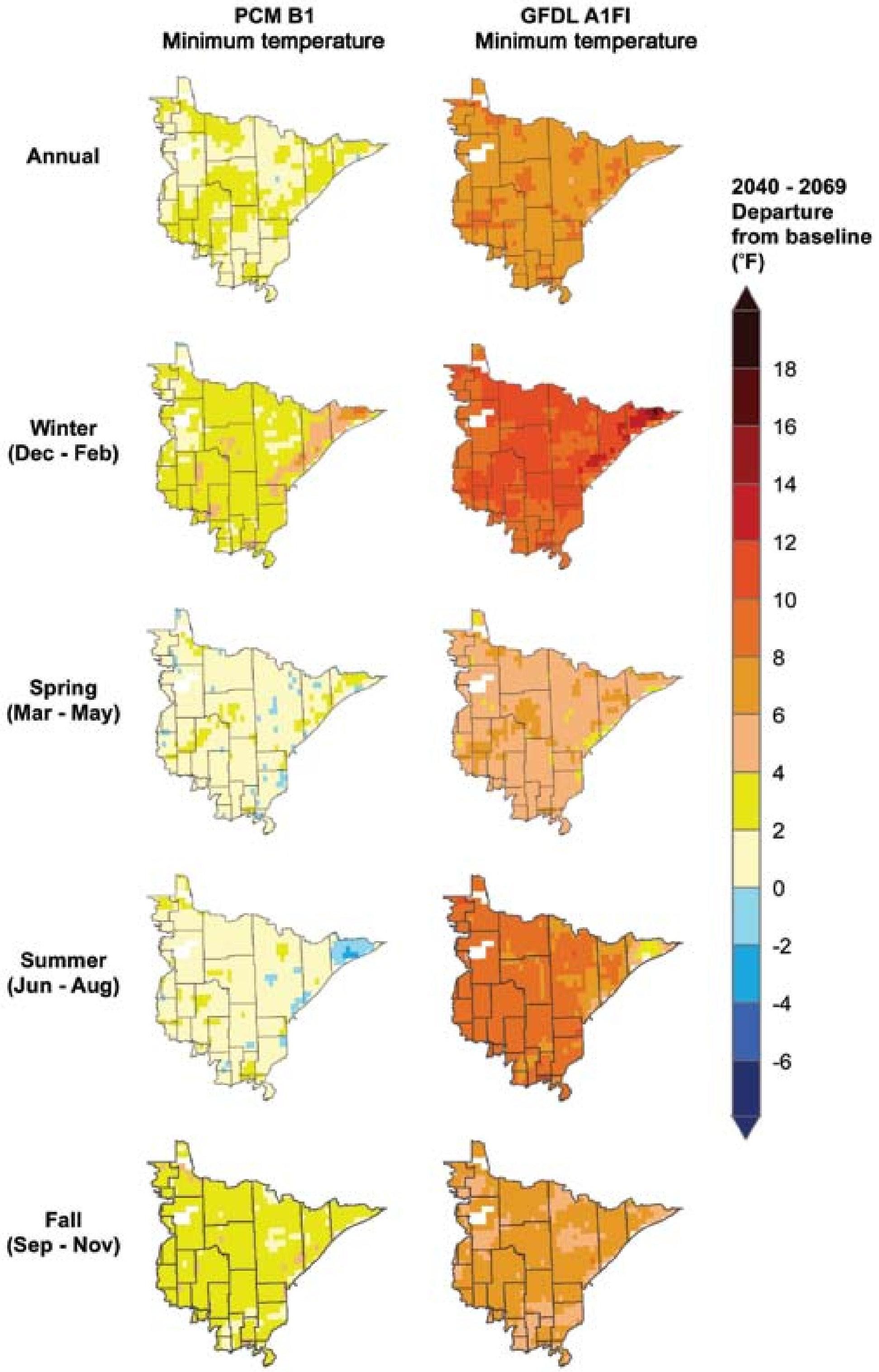

Figure 55.—Projected difference in mean minimum temperature for the middle of the century (2040 through 2069) compared to baseline (1971 through 2000) for two climate scenarios.

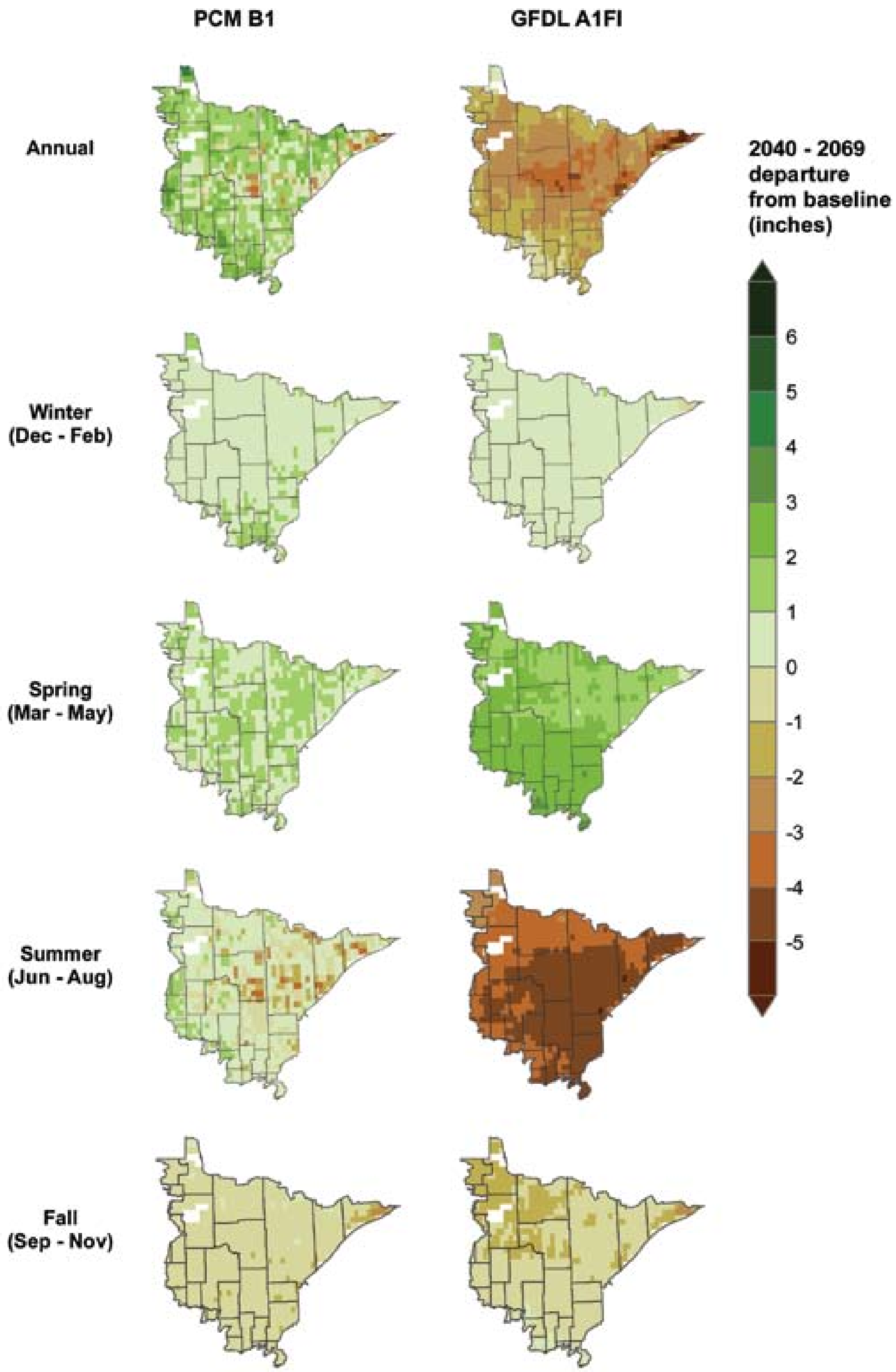

Figure 56.—Projected difference in precipitation for the middle of the century (2040 through 2069) compared to baseline (1971 through 2000) for two climate scenarios.

APPENDIX 4: SUPPLEMENTARY MODEL RESULTS

TREE ATLAS

This section provides additional model outputs for the 74 species considered for this assessment. Even more information is available online at 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 values, and additional statistics. Publications describing the Tree Atlas tools also include key definitions and methods descriptions (Iverson et al. 1999, 2008, 2011; Matthews et al. 2011).

Changes in Suitable Habitat

Measured area-weighted importance values (IVs) from the U.S. Forest Service, Forest Inventory and Analysis (FIA) as well as modeled current (1961 through 1990) and future IVs (2010 through 2039, 2040 through 2069, 2070 through 2099) from DISTRIB were calculated for each time period. Initially, 134 tree species were modeled. If a species never had an area-weighted IV greater than 3 (FIA, current modeled, or future) across the region, it was deleted from the list because the species either has not had or is not projected to have habitat in the region or there were not enough data. Therefore, only a subset of all possible species is shown.

A set of rules was established to determine change classes for the years 2070 through 2099, which was used to create tables in Chapter 5. For most species, the classification rules are listed in Table 24, based on the ratio of future IVs to current modeled IVs.

Table 24.—General classification rules used to determine change categories for suitable habitat for common tree species using the Tree Atlas DISTRIB model output (Current IV > 23)

Future:Current modeled IV	Class
<0.5	large decrease
0.5 to 0.8	decrease
>0.8 to <1.2	no change
1.2 to 2.0	increase
>2	large increase

A few exceptions applied to these general rules. When there was a zero in the numerator or denominator, a ratio could not be calculated. Instead, a species was classified as gaining new habitat if its FIA value was 0 and the future IV was greater than 3. A species' habitat was considered to be extirpated if the future IV was 0 and FIA values were greater than 3.

Special rules were created for rare species (Table 25). A species was considered rare if it had a current modeled area-weighted IV that equaled <10 percent of the number of 12.5-mile by 12.5-mile pixels in the assessment area. This would mean that a species was present in only 10 percent or fewer of the pixels across the assessment area. The change classes are calculated differently for these species because their current infrequency tends to inflate the percentage change that is projected. There are 234 pixels in the Minnesota assessment area, so the cutoff IV for determining a rare species is 23.

Table 25.—Special classification rules used to determine change categories for suitable habitat for rare tree species using the Tree Atlas DISTRIB model output (Current IV < 23)

Future:Current modeled IV	Class
<0.2	large decrease
0.2 to <0.6	decrease
0.6 to <4	no change
4 to 8	increase
>8	large increase (not used when current modeled IV ≤3)

Special rules also applied to species that were known to be present (current FIA IV > 0) but not modeled as present (current modeled = 0). In these cases, the FIA IV was used in place of the current modeled IV to calculate ratios. Then, change class rules were applied based on the FIA IV.

Complete DISTRIB model results are displayed in Table 26.

Modifying Factors

Modifying factors are key life-history or environmental factors that may cause a species to occupy more or less suitable habitat than the model results suggest. Tables 27 and 28 describe the modifying factors and adaptability scores used in the Tree Atlas. These factors were developed by using a literature-based scoring system to capture the potential adaptability of species to changes in climate that cannot be adequately captured by DISTRIB (Matthews et al. 2011). This approach was used to assess the capacity for each species to adapt and considered nine biological traits reflecting innate characteristics like competition ability for light and edaphic specificity. Twelve disturbance characteristics addressed the general response of a species to events such as drought, insect pests, and fire. This information distinguishes between species likely to be more tolerant (or sensitive) to environmental changes than the habitat models alone suggest.

For each biological and disturbance factor, a species was scored on a scale from -3 to +3. A score of -3 indicated a very negative response of that species to that factor. A score of +3 indicated a very positive response to that factor. To account for confidence in the literature about these factors, each of these scores was then multiplied by 0.5, 0.75, or 1, with 0.5 indicating low confidence and 1 indicating high confidence. Finally the score was further weighted by its relevance to future projected climate change by multiplying it by a relevance factor. A 4 indicated highly relevant and a 1 indicated not highly relevant to climate change. Means for individual biological scores and disturbance scores were then calculated to arrive at an overall biological and disturbance score for the species.

To arrive at an overall adaptability score for the species that could be compared across all modeled tree species, the mean, rescaled (0-6) values for biological and disturbance characteristics were plotted to form two sides of a right triangle; the hypotenuse was then a combination (disturbance and biological characteristics) metric, ranging from 0 to 8.5 (Fig. 57). For this assessment, adaptability scores below 3.2 are considered low, and scores above 5.3 are considered high.

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

Table 26.—Complete DISTRIB results for the 74 tree species in the assessment area*

				DISTRIB results													
				Modeled IV						Future:Current Suitable Habitat							
				2010-2039		2040-2069		2070-2099		2010-2039		2040-2069		2070-2099		Change Class	
	FIA	Current	Model	PCM	GFDL	PCM	GFDL	PCM	GFDL	PCM	GFDL	PCM	GFDL	PCM	GFDL	PCM	GFDL
Common Name	IV	IV	Reliability	B1	A1FI	B1	A1FI	B1	A1FI	B1	A1FI	B1	A1FI	B1	A1FI	B1	A1FI
American basswood	635	761	Medium	736	927	771	1031	840	1034	0.97	1.22	1.01	1.36	1.1	1.36	No Change	Increase
American beech	0	62	High	36	85	54	261	76	254	0.58	1.37	0.87	4.21	1.23	4.1	New Habitat	New Habitat
American elm	505	646	Medium	587	864	666	1487	793	1921	0.91	1.34	1.03	2.3	1.23	2.97	Increase	Large Increase
American hornbeam	64	73	Medium	68	118	83	219	132	222	0.93	1.62	1.14	3	1.81	3.04	Increase	Large Increase
Balsam fir	1752	1767	High	1287	579	1049	101	908	59	0.73	0.33	0.59	0.06	0.51	0.03	Decrease	Large Decrease
Balsam poplar	1130	1091	High	538	445	424	349	272	424	0.49	0.41	0.39	0.32	0.25	0.39	Large Decrease	Large Decrease
Bigtooth aspen	307	370	High	365	366	381	296	426	249	0.99	0.99	1.03	0.8	1.15	0.67	No Change	Decrease
Bitternut hickory	13	26	Low	29	118	52	132	117	162	1.12	4.54	2	5.08	4.5	6.23	Large Increase	Large Increase
Black ash	1492	1386	High	1339	1176	1268	943	1207	913	0.97	0.85	0.92	0.68	0.87	0.66	No Change	Decrease
Black cherry	129	166	High	252	435	328	659	515	561	1.52	2.62	1.98	3.97	3.1	3.38	Large Increase	Large Increase
Black hickory	0	0	High	0	0	0	28	0	107	NA	NA	NA	Mig.	NA	Mig.	NA	New Habitat
Black locust	0	0	Low	2	22	3	270	8	461	Mig.	Mig.	Mig.	Mig.	Mig.	Mig.	New Habitat	New Habitat
Black oak	7	62	High	117	338	217	465	317	567	1.89	5.45	3.5	7.5	5.11	9.15	Large Increase	Large Increase
Black spruce	1617	1567	High	916	396	691	99	529	85	0.59	0.25	0.44	0.06	0.34	0.05	Large Decrease	Large Decrease
Black walnut	1	7	Medium	8	88	26	393	68	523	1.14	12.57	3.71	56.14	9.71	74.71	Large Increase	Large Increase
Black willow	24	77	Low	83	226	108	512	191	544	1.08	2.94	1.4	6.65	2.48	7.07	Large Increase	Large Increase
Blackgum	0	0	High	0	0	0	19	0	53	NA	NA	NA	Mig.	NA	Mig.	NA	New Habitat
Blackjack oak	0	0	Medium	0	0	0	82	0	179	NA	NA	NA	Mig.	NA	Mig.	NA	New Habitat
Boxelder	136	347	Medium	365	808	409	1124	461	1359	1.05	2.33	1.18	3.24	1.33	3.92	Increase	Large Increase
Bur oak	961	1103	Medium	999	1523	1058	1636	1157	1801	0.91	1.38	0.96	1.48	1.05	1.63	No Change	Increase
Butternut	29	13	Low	20	27	22	0	24	1	1.54	2.08	1.69	0	1.85	0.08	No Change	Large Decrease
Chestnut oak	0	1	High	0	0	0	29	0	36	0	0	0	29	0	36	NA	New Habitat
Chinquapin oak	0	0	Medium	0	6	1	53	2	119	NA	Mig.	Mig.	Mig.	Mig.	Mig.	New Habitat	New Habitat
Chokecherry	168	195	Low	175	194	174	197	171	171	0.9	1	0.89	1.01	0.88	0.88	No Change	No Change
Eastern cottonwood	8	81	Low	47	205	76	1047	132	1315	0.58	2.53	0.94	12.93	1.63	16.24	Increase	Large Increase
Eastern hemlock	0	20	High	80	95	92	149	153	132	4	4.75	4.6	7.45	7.65	6.6	New Habitat	New Habitat
Eastern hophornbeam	241	322	Medium	341	449	362	535	412	516	1.06	1.39	1.12	1.66	1.28	1.6	Increase	Increase
Eastern red cedar	241	17	Medium	56	396	88	1819	135	2045	3.29	23.29	5.18	107	7.94	120.3	Increase	Large Increase
Eastern redbud	0	0	Medium	0	1	0	45	0	95	NA	Mig.	NA	Mig.	NA	Mig.	NA	New Habitat
Eastern white pine	246	293	High	334	411	351	514	412	417	1.14	1.4	1.2	1.75	1.41	1.42	Increase	Increase
Flowering dogwood	0	0	High	0	0	0	82	0	114	NA	NA	NA	Mig.	NA	Mig.	NA	New Habitat
Green ash	344	615	Medium	558	731	600	1154	651	1260	0.91	1.19	0.98	1.88	1.06	2.05	No Change	Large Increase
Hackberry	4	30	Medium	48	244	80	725	143	909	1.6	8.13	2.67	24.17	4.77	30.3	Large Increase	Large Increase
Honeylocust	0	2	Low	1	46	5	318	25	468	0.5	23	2.5	159	12.5	234	New Habitat	New Habitat
Jack pine	884	893	High	806	822	829	619	807	607	0.9	0.92	0.93	0.69	0.9	0.68	No Change	Decrease
Mockernut hickory	0	0	High	0	0	0	49	0	147	NA	NA	NA	Mig.	NA	Mig.	NA	New Habitat
Mountain maple	164	151	High	113	37	77	3	46	0	0.75	0.25	0.51	0.02	0.31	0	Large Decrease	Large Decrease
Northern catalpa	0	8	Low	3	3	4	5	6	53	0.38	0.38	0.5	0.63	0.75	6.63	NA	New Habitat
Northern pin oak	110	108	Medium	115	235	175	214	263	224	1.07	2.18	1.62	1.98	2.44	2.07	Large Increase	Large Increase
Northern red oak	884	924	High	1303	1817	1406	1356	1581	1090	1.41	1.97	1.52	1.47	1.71	1.18	Increase	No Change
Northern white-cedar	674	720	High	552	328	452	341	451	333	0.77	0.46	0.63	0.47	0.63	0.46	Decrease	Large Decrease
Ohio buckeye	0	0	Low	0	4	0	60	0	87	NA	Mig.	NA	Mig.	NA	Mig.	NA	New Habitat

(Table 26 continued on next page)

Table 26 (continued).

				DISTRIB results													
				Modeled IV						Future:Current Suitable Habitat							
				2010-2039		2040-2069		2070-2099		2010-2039		2040-2069		2070-2099		Change Class	
	FIA	Current	Model	PCM	GFDL	PCM	GFDL	PCM	GFDL	PCM	GFDL	PCM	GFDL	PCM	GFDL	PCM	GFDL
Common Name	IV	IV	Reliability	B1	A1FI	B1	A1FI	B1	A1FI	B1	A1FI	B1	A1FI	B1	A1FI	B1	A1FI
Osage-orange	0	13	Medium	14	43	20	106	48	189	1.08	3.31	1.54	8.15	3.69	14.54	New Habitat	New Habitat
Paper birch	1834	1773	High	1737	1453	1649	527	1550	406	0.98	0.82	0.93	0.3	0.87	0.23	No Change	Large Decrease
Peachleaf willow	9	7	Low	1	31	0	21	0	165	0.14	4.43	0	3	0	23.57	Large Decrease	Large Increase
Pignut hickory	0	0	High	0	2	0	55	1	165	NA	Mig.	NA	Mig.	Mig.	Mig.	New Habitat	New Habitat
Pin cherry	95	84	Medium	85	97	73	126	56	83	1.01	1.16	0.87	1.5	0.67	0.99	Decrease	No Change
Pin oak	0	2	Medium	2	2	2	40	5	108	1	1	1	20	2.5	54	New Habitat	New Habitat
Post oak	0	0	High	0	0	0	299	0	587	NA	NA	NA	Mig.	NA	Mig.	NA	New Habitat
Quaking aspen	6076	5942	High	4801	3927	4426	1703	3815	1374	0.81	0.66	0.75	0.29	0.64	0.23	Decrease	Large Decrease
Red maple	862	977	High	1292	1246	1436	1523	1739	1475	1.32	1.28	1.47	1.56	1.78	1.51	Increase	Increase
Red mulberry	0	8	Low	14	81	23	428	45	624	1.75	10.13	2.88	53.5	5.63	78	New Habitat	New Habitat
Red pine	507	557	Medium	556	595	567	735	589	726	1	1.07	1.02	1.32	1.06	1.3	No Change	Increase
River birch	2	1	Low	1	18	7	6	8	7	1	18	7	6	8	7	Increase	Increase
Rock elm	17	12	Low	10	8	10	37	11	52	0.83	0.67	0.83	3.08	0.92	4.33	No Change	Increase
Sassafras	0	0	High	0	2	0	86	1	161	NA	Mig.	NA	Mig.	Mig.	Mig.	New Habitat	New Habitat
Scarlet oak	0	0	High	0	2	0	18	1	77	NA	Mig.	NA	Mig.	Mig.	Mig.	New Habitat	New Habitat
Shagbark hickory	0	20	Medium	25	144	60	297	113	322	1.25	7.2	3	14.85	5.65	16.1	New Habitat	New Habitat
Shingle oak	0	0	Medium	0	1	0	34	0	50	NA	Mig.	NA	Mig.	NA	Mig.	NA	New Habitat
Silver maple	55	80	Medium	88	277	149	551	237	654	1.1	3.46	1.86	6.89	2.96	8.18	Large Increase	Large Increase
Slippery elm	36	51	Medium	85	325	126	723	209	811	1.67	6.37	2.47	14.18	4.1	15.9	Large Increase	Large Increase
Striped maple	6	14	High	9	17	12	32	16	33	0.64	1.21	0.86	2.29	1.14	2.36	No Change	No Change
Sugar maple	630	761	High	1169	1376	1289	1208	1519	971	1.54	1.81	1.69	1.59	2	1.28	Large Increase	Increase
Sugarberry	0	4	Medium	2	2	2	7	2	42	0.5	0.5	0.5	1.75	0.5	10.5	NA	New Habitat
Swamp white oak	4	1	Low	1	7	1	78	2	95	1	7	1	78	2	95	Increase	Large Increase
Sweet birch	0	1	High	1	0	0	28	1	32	1	0	0	28	1	32	NA	New Habitat
Sweetgum	0	0	High	0	0	0	33	0	58	NA	NA	NA	Mig.	NA	Mig.	NA	New Habitat
Tamarack	965	944	High	894	756	805	556	700	535	0.95	0.8	0.85	0.59	0.74	0.57	Decrease	Decrease
White ash	40	45	High	82	123	121	427	219	417	1.82	2.73	2.69	9.49	4.87	9.27	Large Increase	Large Increase
White oak	93	124	High	215	525	336	713	512	715	1.73	4.23	2.71	5.75	4.13	5.77	Large Increase	Large Increase
White spruce	297	316	Medium	243	185	212	138	199	169	0.77	0.59	0.67	0.44	0.63	0.54	Decrease	Decrease
Wild plum	3	3	Low	5	10	3	134	16	213	1.67	3.33	1	44.67	5.33	71	Increase	Increase
Yellow birch	95	126	High	170	149	179	84	269	79	1.35	1.18	1.42	0.67	2.14	0.63	Large Increase	Decrease
Yellow-poplar	0	0	High	0	0	0	5	0	48	NA	NA	NA	Mig.	NA	Mig.	NA	New Habitat

*Current importance values (Current IV) are based on modeled results, and FIA IV values are calculated based on FIA inventory data. Early-century, mid-century, and late-century importance values are average values for the indicated years. Future:Current Suitable Habitat is a ratio of projected importance value to current importance value. Species are assigned to change classes based on the comparison between end-of-century (2070-2099) and current figures for area-weighted importance value (Tables 24-25).

NA = not applicable, no suitable habitat projected.

Mig. = new migrant, new suitable habitat projected.

Table 27.—Modifying factors for the 74 tree species in the assessment area

	Model	Modifying Factors*		Adaptability Scores			
Common Name	**Reliability**	**Positive Traits**	**Negative Traits**	**DistFact**	**BioFact**	**Adapt**	**Adapt Class**
American basswood	Medium	COL	FTK	0.3	0.2	4.6	○
American beech	High	COL	INS FTK	-1.1	0	3.6	○
American elm	Medium	ESP	DISE INS	-0.8	0.3	4	○
American hornbeam	Medium	COL SES	FTK DRO	0.6	0.6	5.1	○
Balsam fir	High	COL	INS FTK DRO	-3	-0.4	2.7	—
Balsam poplar	High	FRG VRE	COL DRO	0.1	-0.6	4	○
Bigtooth aspen	High	FRG DISP	COL DRO FTK	1	0.2	5.1	○
Bitternut hickory	Low	DRO	COL	2.2	-0.8	5.6	+
Black ash	High		INS COL DISP DRO SES FTK ESP	-1.3	-3	1.7	—
Black cherry	High	DRO ESP	INS FTK COL	-1.6	-0.3	3	—
Black hickory	High		ESP COL	1	-2.3	4.1	○
Black locust	Low		COL INS	0	-0.6	3.8	○
Black oak	High	DRO ESP	INS DISE	0.5	0.4	4.9	○
Black spruce	High	COL ESP DISP	FTK INS DRO	-2.1	1.2	4.3	○
Black walnut	Medium	SES	COL DRO	0.4	-0.8	4	○
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	○
Chokecherry	Low		COL	0.2	-0.9	3.8	○
Eastern cottonwood	Low	SES	INS COL DISE FTK	0.2	-0.8	3.9	○
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 red cedar	Medium	DRO	FTK COL INS	0.6	-1.5	3.9	○
Eastern redbud	Medium			0.9	0	4.9	○
Eastern white pine	High	DISP	DRO FTK INS	-2	0.1	3.3	○
Flowering dogwood	High	COL		0.1	1	5	○
Green ash	Medium		INS FTK COL	-0.1	-0.3	4	○
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	○
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	○
Northern pin oak	Medium	DRO FTK	COL	2.5	-0.6	6	+
Northern red oak	High		INS	1.4	0.1	5.4	+
Northern white-cedar	High	COL	FTK	-0.7	0.5	4.2	○

(Table 27 continued on next page)

Table 27 (continued).

	Model	Modifying Factors*		Adaptability Scores			
Common Name	**Reliability**	**Positive Traits**	**Negative Traits**	**DistFact**	**BioFact**	**Adapt**	**Adapt Class**
Ohio buckeye	Low	COL	SES FTK	0.4	-1.9	3.5	○
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	○
Peachleaf willow	Low		COL	0.1	-1.7	3.4	○
Pignut hickory	High	ESP	INS DRO	0.2	0.4	4.7	○
Pin cherry	Medium	SES FRG FTK	COL	0.5	-0.7	4.2	○
Pin oak	Medium		FTK COL INS DISE	-0.7	-1.4	2.8	—
Post oak	High	DRO SES FTK	COL INS DISE	2.2	-0.6	5.7	+
Quaking aspen	High	SES FRG ESP	COL DRO FTK	0.6	0	4.7	○
Red maple	High	SES ESP ESP COL DISP		3	3	8.5	+
Red mulberry	Low	COL DISP	FTK	0.1	0.6	4.7	○
Red pine	Medium		INS COL DISP	0.9	-2.4	3.9	○
River birch	Low	DISP	FTK COL DRO	-0.5	-0.3	3.7	○
Rock elm	Low		ESP ESP SES	-0.2	-2.6	2.8	—
Sassafras	High		COL FTK	0.5	-0.6	4.2	○
Scarlet oak	High	VRE ESP ESP	INS DISE FTK	-0.4	0.7	4.6	○
Shagbark hickory	Medium		INS FTK	-0.2	0.4	4.4	○
Shingle oak	Medium	ESP	COL	1.3	-0.7	4.9	○
Silver maple	Medium	DISP SES COL	DRO FTK	0.1	1.6	5.6	+
Slippery elm	Medium	COL	FTK DISE	0	0.7	4.8	○
Striped maple	High	COL SES	DRO	1	0.3	5.1	○
Sugar maple	High	COL ESP		0.9	1.3	5.8	+
Sugarberry	Medium	COL SES	FTK	-0.2	0.6	4.6	○
Swamp white oak	Low			1	-0.3	4.9	○
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	○
Tamarack	High		FTK COL INS	-0.5	-1.2	3.1	—
White ash	High		INS FTK COL	-2	-0.5	2.7	—
White oak	High	ESP ESP SES FTK	INS DISE	1.7	1	6.1	+
White spruce	Medium		INS	0.1	-0.6	3.9	○
Wild plum	Low		COL	0.5	-1.3	3.9	○
Yellow birch	High	DISP	FTK INS DISE	-1.4	0	3.4	○
Yellow-poplar	High	SES DISP ESP	INP	0.1	1.3	5.3	+

*Modifying factors are key life-history or environmental factors that may cause a species to occupy more or less suitable habitat than the model results suggest (Matthews et al. 2011). Explanations for the modifying factor codes are displayed in Table 28. Adaptation factor scores below 3.2 are considered low (-), and scores above 5.3 are considered high (+).

Table 28.—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 or severity of insects that may attack the species
INP		Strong negative effects of invasive plants on the species, either through competition for nutrients or as a pathogen
SES	High ability to regenerate with seeds to maintain future populations	Low ability to regenerate with seeds to maintain future populations
VRE	Capable of vegetative reproduction through stump sprouts or cloning	

*These codes are used to describe positive or negative modifying factors in Table 27. 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.

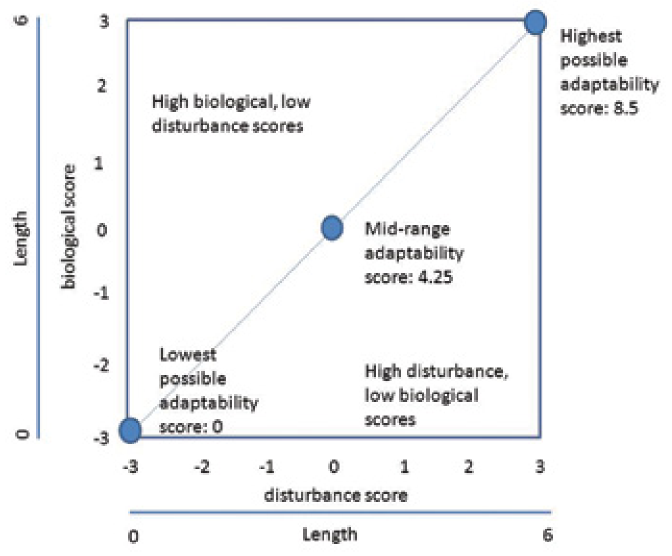

Figure 57.—Schematic showing how biological and disturbance modifying factors are translated into an overall adaptability score in the Tree Atlas model.

LANDIS-II

This section provides additional model outputs and methods for the model simulations developed for this assessment. More information is available online at the LANDIS-II Web site (www.landis-ii.org/), including detailed model descriptions and publications describing the LANDIS-II core model and extensions.

Biomass Projections

LANDIS-II outputs include biomass of individual species by age cohort (Table 29). For this assessment, we have combined values for separate age cohorts into a single biomass value by species.

Forest-type Classification

The forest-type maps presented in Chapter 5 (Fig. 38) rely on a simple classification scheme. To create these land cover maps, individual locations ("cells") in the LANDIS-II simulations were classified into six forest categories based on characteristic species composition. These classifications are based on the dominance of key indicator species (Table 30). The species assignment to groups is based on unique species within groups and a balance of high abundance species within groups. Certain species that do not contribute to the unique forest type dominance are subtracted from the dominance calculation. Species assignment adjustments were made based on matching the proportion of individual forest types found in regional FIA plots to the proportion of individual forest types found in LANDIS-II cells for the year 2000.

Management and Disturbance Scenarios

The simulations developed for this assessment were run with the Biomass Succession (v3.1), Base Fire (v3.0), and Base Wind (v2.0) extensions. Forest management was simulated by using the Biomass Harvest extension (v2.1), and output was delivered through the Biomass Output extension (v.2.0) (www.landis-ii.org/exts). A business-as-usual forest management scenario was developed for a variety of forest types, ownerships, and harvest methods through conversations with local forest management experts (Table 31).

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Table 29.—Projected aboveground biomass for 21 species assessed with the LANDIS-II model

			Current Climate		PCM B1		GFDL A1FI	
Species	Year 0 biomass (grams per square meter)	Year[a]	Biomass (grams per square meter)	Change from year 0[b] (%)	Biomass (grams per square meter)	Change relative to current climate biomass[c] (%)	Biomass (grams per square meter)	Change relative to current climate biomass[c] (%)
American basswood	67	40	122.53	184	194	59	174	42
		70	173	260	295	70	387	123
		100	227	341	538	137	754	232
American elm	11	40	18	156	29	63	26	48
		70	24	212	43	78	65	167
		100	29	257	64	119	133	354
Balsam fir	805	40	778	97	746	-4	674	-13
		70	1062	132	982	-8	533	-50
		100	1114	138	996	-11	263	-76
Bigtooth aspen	84	40	91	108	115	26	93	1
		70	135	160	190	41	141	4
		100	191	226	301	58	272	43
Black ash	137	40	238	174	265	11	227	-5
		70	250	182	278	12	177	-29
		100	248	181	270	9	116	-53
Black cherry	7	40	16	229	21	34	17	8
		70	28	400	41	47	38	35
		100	43	617	80	86	139	222
Black spruce	506	40	663	131	575	-13	566	-15
		70	651	129	536	-18	355	-45
		100	642	127	447	-30	210	-67
Bur oak	57	40	104	180	114	10	100	-3
		70	132	230	146	11	114	-14
		100	153	266	174	14	148	-3
Green ash	7	40	18	251	23	29	20	9
		70	22	303	28	27	26	18
		100	23	320	31	33	37	60
Eastern white pine	108	40	366	337	441	21	380	4
		70	681	628	820	20	675	-1
		100	1036	955	1288	24	1047	1
Jack pine	118	40	95	80	147	55	135	43
		70	98	83	146	50	106	8
		100	99	84	137	38	64	-36
Northern red oak	85	40	166	196	179	8	156	-6
		70	249	294	261	5	188	-25
		100	328	388	336	2	254	-23
Northern white-cedar	110	40	181	165	204	13	187	3
		70	192	175	212	11	147	-23
		100	203	185	222	9	110	-46
Paper birch	663	40	1628	246	1398	-14	1210	-26
		70	2558	386	2066	-19	904	-65
		100	2638	398	1879	-29	422	-84

(Table 29 continued on next page)

Table 29 (continued).

			Current Climate		PCM B1		GFDL A1FI	
Species	Year 0 biomass (grams per square meter)	Year[a]	Biomass (grams per square meter)	Change from year 0[b] (%)	Biomass (grams per square meter)	Change relative to current climate biomass[c] (%)	Biomass (grams per square meter)	Change relative to current climate biomass[c] (%)
Quaking aspen	2515	40	2440	97	2372	-3	2114	-13
		70	2198	87	2069	-6	1366	-38
		100	1811	72	1651	-9	1080	-40
Red maple	163	40	255	157	353	39	323	27
		70	287	177	464	61	592	106
		100	343	211	679	98	1010	194
Red pine	169	40	410	243	517	26	439	7
		70	649	385	814	26	500	-23
		100	858	509	1096	28	535	-38
Sugar maple	252	40	242	96	249	300	244	1
		70	204	81	213	4	215	5
		100	150	60	174	1600	219	46
White oak	2	40	3	137	4	15	3	1
		70	4	183	5	18	4	5
		100	5	236	7	36	9	59
White spruce	129	40	359	278	294	18	272	-24
		70	550	425	448	-19	236	-57
		100	662	512	475	-28	182	-72
Yellow birch	27	40	67	243	80	20	68	3
		70	97	352	117	22	81	-16
		100	127	462	166	31	87	-31

[a] Year represents the number of years from the year 2000 (e.g., 40 = year 2040).

[b] Percentage change from Year 0 is calculated as the change in biomass from year 2000 (100% equals no net change).

[c] Change relative to current climate biomass is calculated as the proportional change compared to the biomass under the Current Climate scenario for the same year.

Table 30.—Classification rules for creating the maps based on LANDIS-II outputs (Chapter 5, Fig. 38)

Forest type	Indicator species
Spruce-fir	Include black spruce, balsam fir, white spruce, and northern white-cedar Subtract sugar maple and jack pine
Oak association	Include northern red oak, white oak, and northern pin oak Subtract black spruce and white spruce
Jack pine	Include jack pine and red pine
Aspen-birch	Include quaking aspen, bigtooth aspen, and paper birch Subtract sugar maple and balsam fir
Red pine-white pine	Include red pine and white pine
Northern hardwoods	Include sugar maple, black cherry, northern red oak, and American basswood Subtract bigtooth aspen and quaking aspen

Table 31.—Business-as-usual (BAU) forest management scenario used in the LANDIS-II model for this assessment

Prescription	Landowner*	Proportion of landscape managed each 5 years	Rotation period (years)	Proportion of each stand harvested	Species planted
Aspen clearcut	DNR	8%	62	95%	
	Counties	8%	63		
	USFS	6%	89		
	PIF	9%	56		
Aspen clearcut/plant	DNR	1%	357	95%	white spruce
	Counties	1%	357		white pine
	USFS	1%	500		red pine
	PIF	2%	250		
Aspen clearcut PNIF	PNIF	4%	139	70%	
Black spruce clearcut	DNR	4%	135	80%	
	Counties	6%	89		
	USFS	4%	114		
	PIF	6%	89		
	PNIF	5%	111		
Jack pine clearcut	DNR	7%	70	80%	jack pine
	Counties	7%	70		red pine
	USFS	7%	70		
	PIF	13%	40		
	PNIF	8%	60		
Northern hardwoods patch	DNR	24%	21	75%	
	USFS	25%	20		
	PNIF	7%	75		
Northern hardwoods clearcut	Counties	4%	119	50%	
Northern hardwoods shelterwood	PNIF	3%	172	50%	
	PIF	7%	75		
Oak shelterwood	DNR	5%	111	25%	
	Counties	6%	89		
	USFS	4%	119		
	PIF	7%	75		
	PNIF	4%	119		
Red pine clearcut	DNR	4%	119	100%	red pine
	Counties	56%	89		white spruce
	USFS	4%	119		
	PIF	4%	119		
	PNIF	5%	100		
White pine clearcut	DNR	6%	83	50%	white pine
	Counties	7%	71		
	USFS	6%	83		
	PIF	8%	63		
	PNIF	7%	71		
Spruce fir clearcut	DNR	4%	125	50%	
	Counties	7%	70		
	USFS	6%	79		
	PIF	6%	79		
	PNIF	5%	100		

*Landowner categories are as follows: DNR = Minnesota Department of Natural Resources, USFS = U.S. Forest Service, PIF = private industrial forestland, PNIF = private nonindustrial forestland.

APPENDIX 5: VULNERABILITY AND CONFIDENCE DETERMINATION

METHODS

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 32). We sought to create a team of panelists who would be able to contribute a diversity of subject area expertise, management history, and organizational perspectives. Most panelists had extensive knowledge about the ecology, management, and climate change impacts on forests in northern Minnesota. This panel was assembled at an in-person workshop in Grand Rapids, Minnesota, in July 2012. Below, we describe the structured discussion process that the panel followed during the workshop and in subsequent conversations.

Forest Systems Assessed

The authors of this assessment opted to use the Native Plant Community (NPC) approach to classifying and describing forest ecosystems within

Table 32.—Participants in the July 2012 expert panel workshop

Name	Organization
Cheryl Adams	UPM-Kymmene
Kelly Barrett	Chippewa National Forest
Leslie Brandt*	U.S. Forest Service, Northern Research Station & Northern Institute of Applied Climate Science
Anthony D'Amato	University of Minnesota
Matthew Duveneck	Portland State University
Suzanne Hagell	Wisconsin Initiative on Climate Change Impacts
Stephen Handler*	U.S. Forest Service, Northern Research Station & Northern Institute of Applied Climate Science
Louis Iverson	U.S. Forest Service, Northern Research Station
Rosemary Johnson	Chippewa National Forest
Patty Johnson	Superior National Forest
Randy Kolka	U.S. Forest Service, Northern Research Station
Jason Kuiken	Chippewa National Forest
Mike Larson	Minnesota Deparment of Natural Resources
Casey McQuiston	Superior National Forest
Rebecca Montgomery	University of Minnesota
Steve Olson	Fond du Lac Forestry
Brian Palik	U.S. Forest Service, Northern Research Station
Emily Peters	University of Minnesota & Boreal Forest and Community Resilience Project
Jack Rajala	Rajala Companies
Peter Reich	University of Minnesota & Boreal Forest and Community Resilience Project
Rob Scheller	Portland State University
Clarence Turner	Minnesota Department of Natural Resources & Minnesota Forest Resources Council
Mark White	The Nature Conservancy
Kirk Wythers	University of Minnesota & Boreal Forest and Community Resilience Project

*Workshop facilitators

the assessment area (Chapter 1). We decided that we had neither the necessary precision of information nor the time to consider the individual NPC Classes, and instead we focused on the broader NPC Systems. The six forested NPC Systems present in the assessment area were the focus of the expert panel workshop.

For each NPC System, we extracted information related to the major system drivers, dominant species, and stressors that characterize that community from the *Field Guide to the Native Plant Communities of Minnesota: the Laurentian Mixed Forest Province* (Minnesota Department of Natural Resources 2003). The panel was asked to comment on and suggest modifications to the community descriptions, and those suggestions were incorporated into the descriptions.

After the expert panel workshop, we decided to consider two additional managed forest systems for this vulnerability assessment: managed aspen and red pine systems. The rationale was to complement the NPC Systems approach and to more explicitly consider these management-driven forest communities within the assessment area, which don't neatly fit the ecological community descriptions. We developed descriptions of drivers, dominant species, and stressors for these two systems based on published literature and conversations with a subset of the expert panel.

Potential Impacts

Potential impacts are the direct and indirect consequences of climate change on systems. Impacts are a function of a system's exposure to climate change and its sensitivity to any changes. Impacts could be beneficial or harmful to a particular forest or ecosystem type. To examine potential impacts, the panel was given several sources of background information on past and future climate change in the region (summarized in Chapters 3 and 4) and projected impacts on dominant tree species and forest productivity (summarized in Chapter 5). The panel was directed to focus on impacts to each community type from the present through the end of the century, but more weight was given to the end-of-century period. The panel assessed impacts by considering a range of climate futures bracketed by two scenarios: Hadley A1FI and PCM B1 (Box 8). Panelists were then led through a structured discussion process to consider this information for each forest community in the assessment.

Box 8: A Note on Future Climate Scenarios Used in this Assessment

The Hadley A1FI model/emissions scenario combination was originally chosen as the "high-end" scenario instead of GFDL A1FI. This scenario projects slightly higher temperatures and more summer precipitation than GFDL A1FI, but otherwise is fairly similar. We chose to replace the high-end scenario because the Hadley A1FI scenario produced extremely high results for northern Michigan, and the authors of the companion vulnerability assessment for that area were uncomfortable publishing an assessment with unreliable data. The Northern Institute of Applied Climate Science coordinated a discussion among all research teams conducting impact modeling for the Climate Change Response Framework and all groups decided it would be best to use GFDL A1FI as a high-end scenario instead. All results summarized in Chapter 6 were vetted with the expert panelists to ensure their vulnerability rankings were still consistent with GFDL projections.

Potential impacts on each community driver and stressor were summarized into a spreadsheet based on climate model projections, the published literature, and insights from the panelists. Impacts on drivers were considered positive or negative if they would alter system drivers in a way that would be more or less favorable for that 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 the results from Tree Atlas, LANDIS-II, and PnET-CN. They were asked to consider those results in addition to their knowledge of life-history traits and the ecology of those species. 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.

For each community type, panelists were each asked to identify which impacts they felt were most important to that system by using an individual worksheet (see example at the end of this appendix). Each panelist then determined an overall rating of potential impacts for each community type based on the summation of the impacts on drivers, stressors, and dominant species across a continuum from negative to positive.

Adaptive Capacity

Adaptive capacity is the ability of a species or ecosystem to accommodate or cope with potential climate change impacts with minimal disruption. Panelists discussed the adaptive capacity of each forest system based on their ecological knowledge and management experience with the community types in the assessment area. Adaptive capacity factors for each community type were delineated in a spreadsheet. Panelists were told to focus on community characteristics that would increase or decrease the adaptive capacity of that system. Factors that the panel considered included characteristics of dominant species within each community (e.g., dispersal ability, genetic diversity, range limits) and comprehensive community characteristics (e.g., functional and species diversity, tolerance to a variety of disturbances, distribution across the landscape). Rankings were based on a continuous spectrum, so a mid-range score would indicate strength in some areas and a deficit in others. The panelists were directed to base their considerations on the current condition of the system given past and current management regimes, with no consideration of potential adaptation actions that could take place in the future.

Vulnerability

Vulnerability is the susceptibility of a system to the adverse effects of climate change. It is a function of its potential impacts and the adaptive capacity of the system. After extensive group discussion, panelists individually evaluated the potential impacts and adaptive capacity of each community type to arrive at a vulnerability rating. Participants were provided with individual worksheets and asked to list which impacts they felt were most important to that system in addition to the major factors that would contribute to the adaptive capacity of that system.

Panelists were directed to mark their rating in two-dimensional space on the individual worksheet and on a large group poster (Fig. 58a). 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). The group compared and discussed individual ratings, with the goal of coming to a group determination through consensus. In many cases, the group determination was at or near the centroid of all individual determinations. Sometimes the group determination deviated from the centroid because further discussion convinced some group members to alter their original response. The group vulnerability determination was placed into one of five categories (low, low-moderate, moderate, moderate-high, and high) based on the discussion and consensus within the group, as well as the placement of the group determination on the figure. For example, if a vulnerability determination was on the border between low and moderate and the group agreed that it did not completely fall into one or the other category, it would receive a low-moderate determination.

Confidence

Panelists were also directed to give a confidence rating to each of their individual vulnerability determinations (Fig. 58b). 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.

After the expert panel workshop, this structured discussion was repeated for the two managed forest systems (managed aspen and red pine) in a webinar and conference call with a subset of the expert panel. Members of this smaller group were asked to describe potential climate change impacts, interactions, and adaptive capacity for these two systems. They also placed their rankings for vulnerability and confidence on the same figures used in the in-person workshop. The summary information related to drivers, dominant species, stressors, and adaptive capacity was vetted with all of the expert panelists to ensure that this information

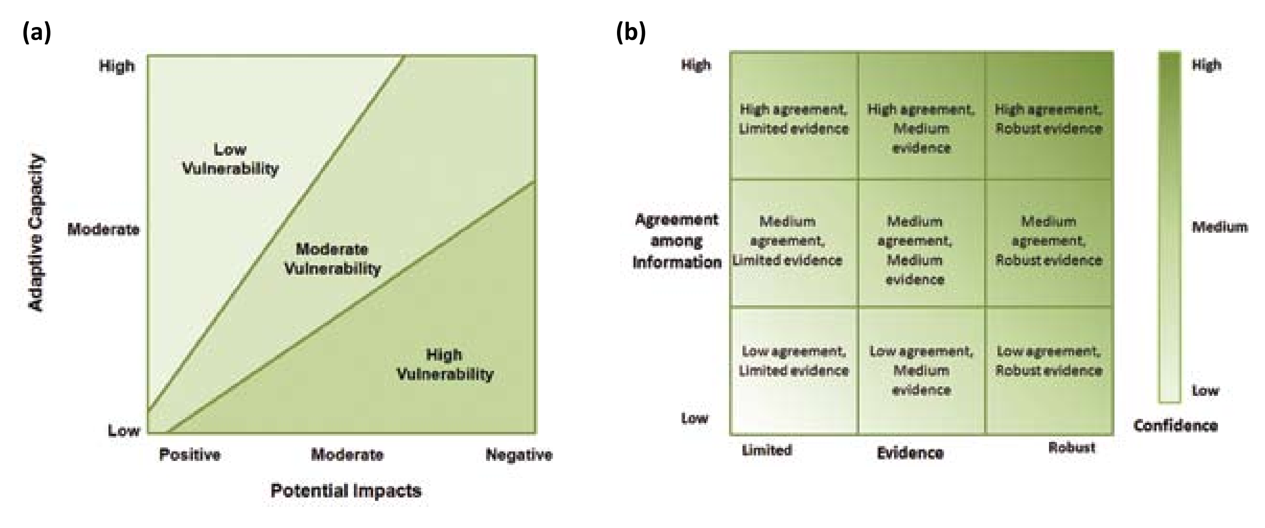

Figure 58.—Figure used for (a) vulnerability determination by expert panelists, based on Swanston and Janowiak (2012) and (b) confidence rating among expert panelists, adapted from Mastrandrea et al. (2010).

was adequately described and that the vulnerability and confidence determinations reflected the perspective of the entire group.

Forest System Determinations

Determinations of vulnerability and confidence were made for eight forested systems in the assessment area. The vulnerability determinations described above, along with information and ideas put forward during the group discussions, were collected and interpreted in order to develop the vulnerability summary descriptions presented in Chapter 6.

Vulnerability Statements

Recurring themes and patterns that transcended individual forest systems were identified and developed into the vulnerability statements (in boldface) and supporting text in Chapter 6. The lead author developed the statements and supporting text based on workshop notes and literature pertinent to each statement. An initial confidence determination (evidence and agreement) was assigned based on the lead author's interpretation of the amount of information available to support each statement and the extent to which the information agreed. Each statement and its supporting literature discussion were sent to the expert panel for review.

VULNERABILITY AND CONFIDENCE FIGURES

For reference, figures of individual and group determinations for all eight forest systems considered in this assessment are displayed (Figs. 59 through 66). 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. In some cases, the variance of vulnerability and confidence votes was due to a difference in expert opinion as well as the inherent difficulty of defining what is covered in the term "vulnerability."

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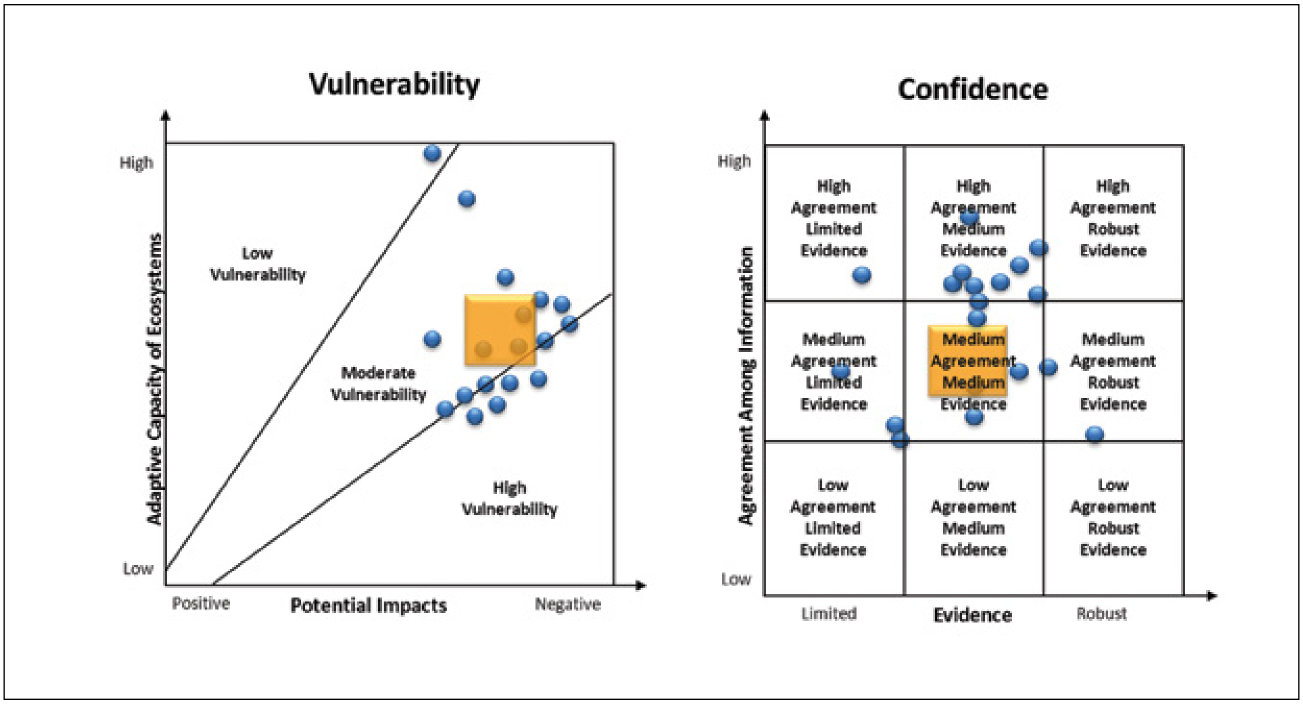


Figure 59.—Fire-Dependent Forests vulnerability and confidence determinations. Circles indicate individual determinations by each panelist and squares indicate the group determination after consensus was reached.

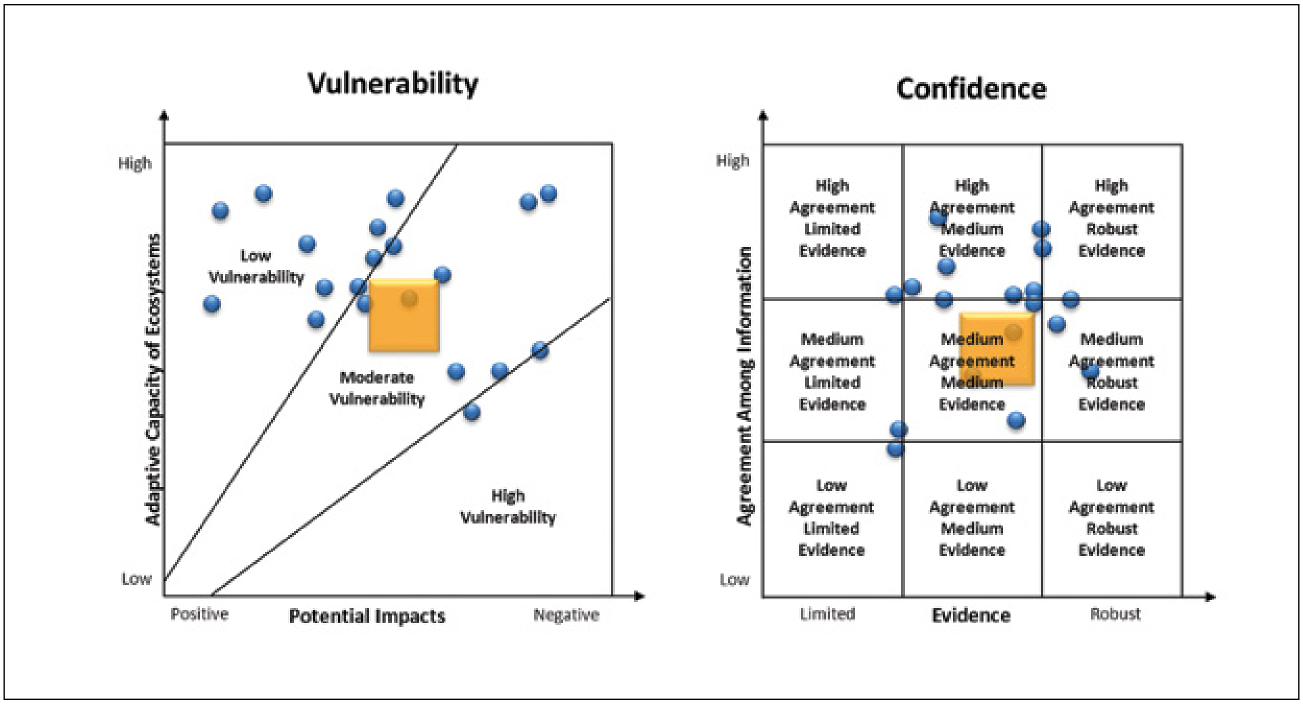


Figure 60.—Mesic Hardwood Forests vulnerability and confidence determinations. Circles indicate individual determinations by each panelist and squares indicate the group determination after consensus was reached.

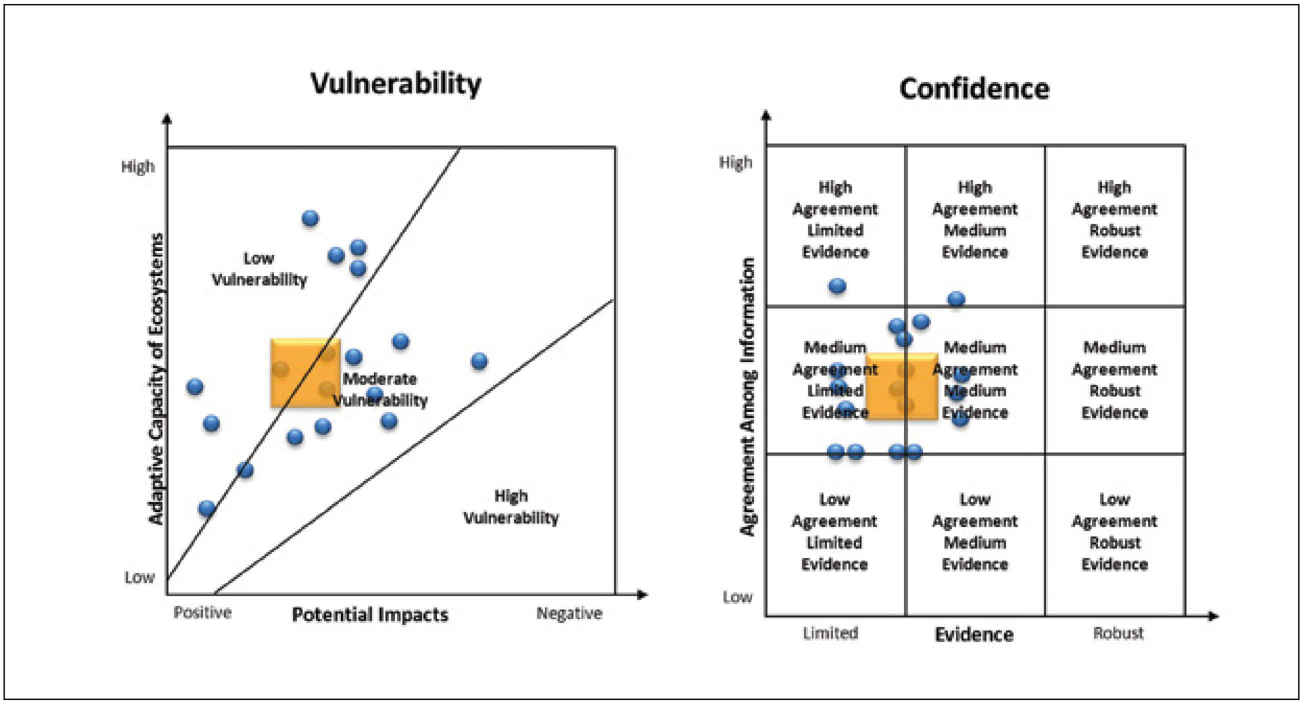


Figure 61.—Floodplain Forests vulnerability and confidence determinations. Circles indicate individual determinations by each panelist and squares indicate the group determination after consensus was reached.

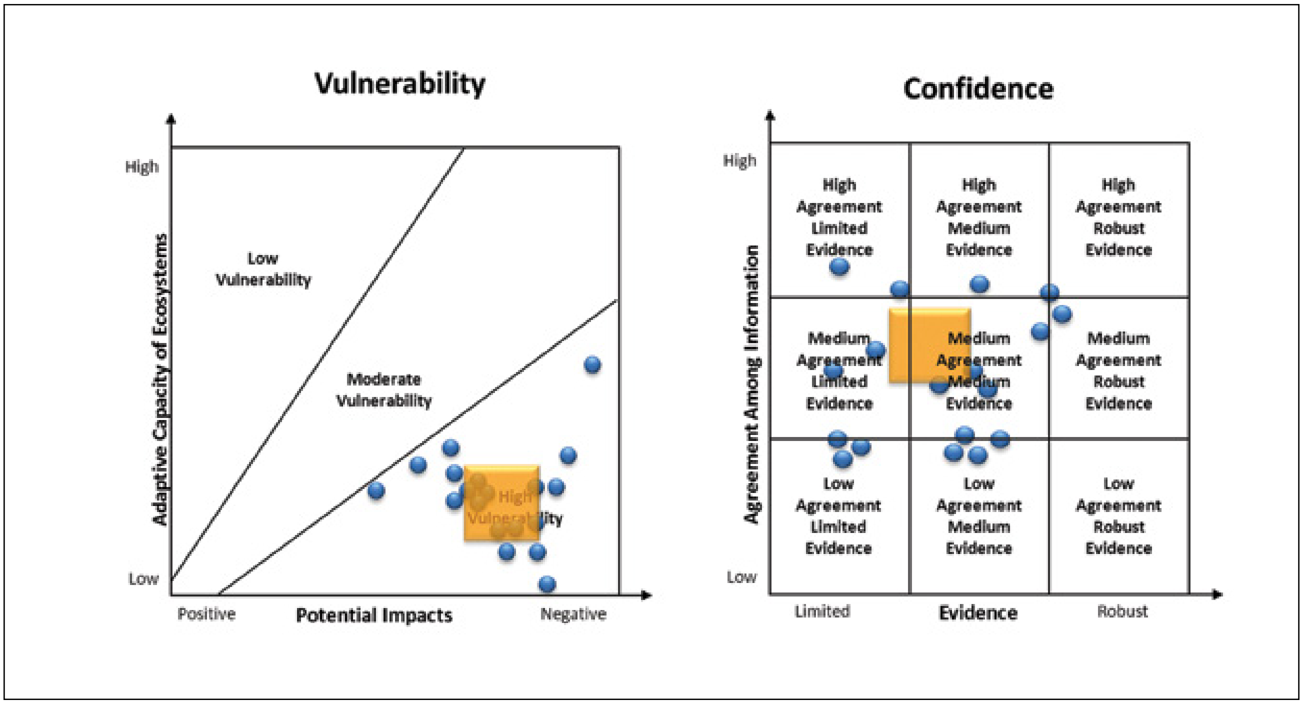


Figure 62.—Wet Forests vulnerability and confidence determinations. Circles indicate individual determinations by each panelist and squares indicate the group determination after consensus was reached.

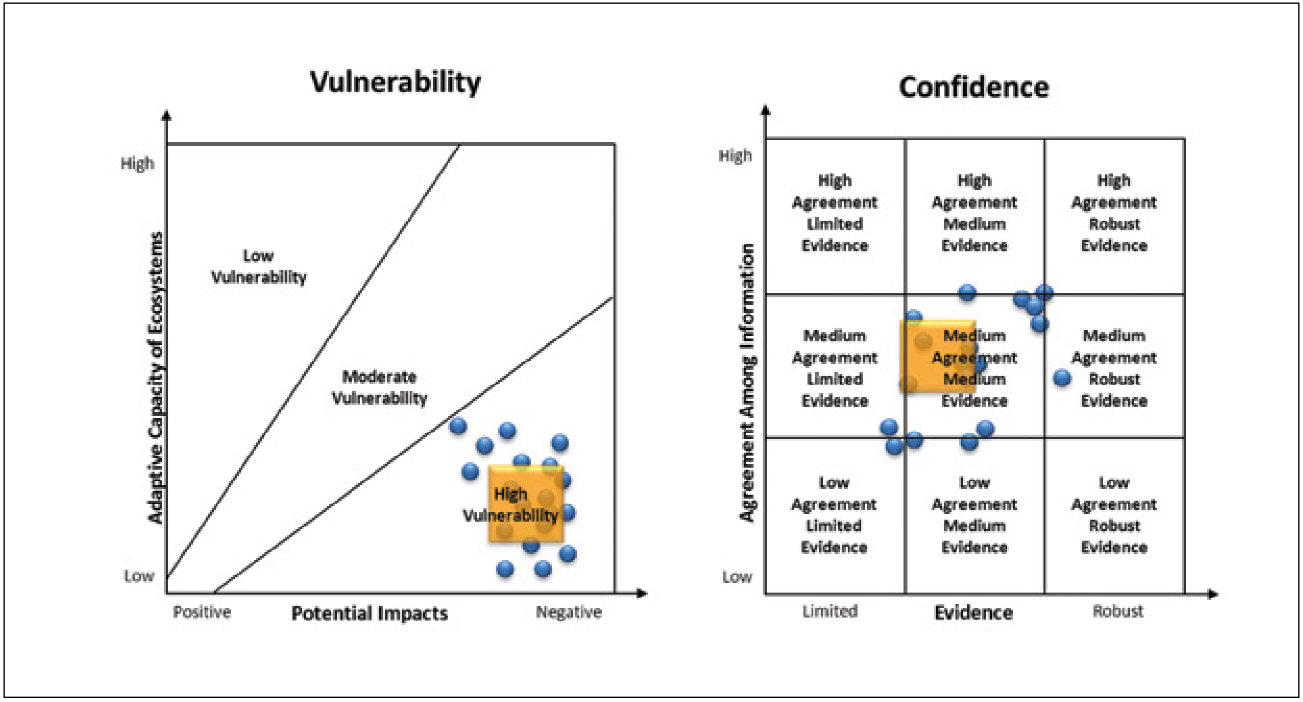


Figure 63.—Forested Rich Peatlands vulnerability and confidence determinations. Circles indicate individual determinations by each panelist and squares indicate the group determination after consensus was reached.

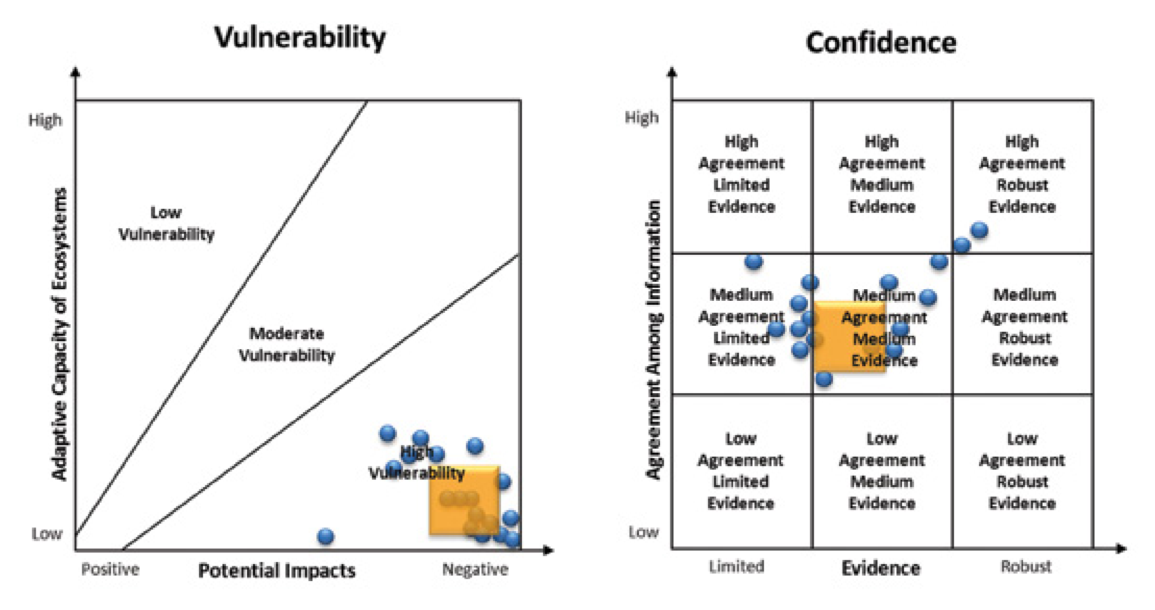


Figure 64.—Acid Peatlands vulnerability and confidence determinations. Circles indicate individual determinations by each panelist and squares indicate the group determination after consensus was reached.

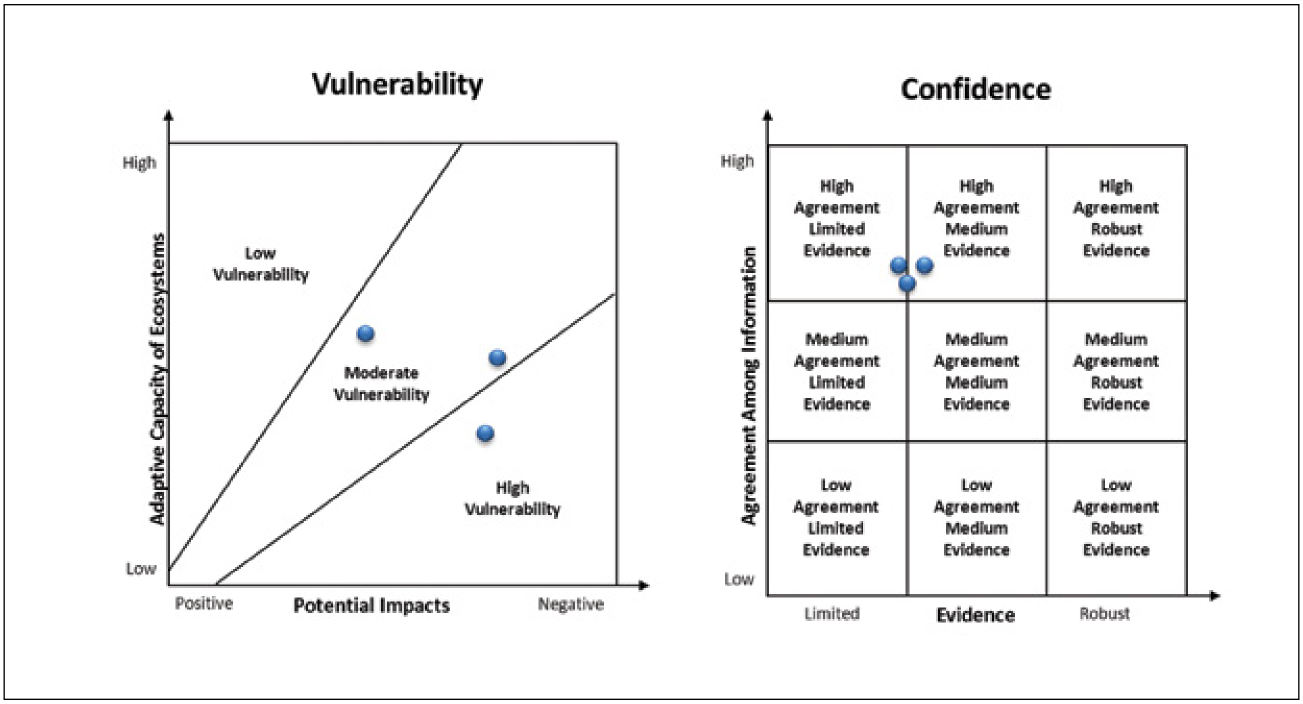


Figure 65.—Managed Aspen Forests vulnerability and confidence determinations. Circles indicate individual determinations. The group determination was reached through consensus with the remaining panelists.

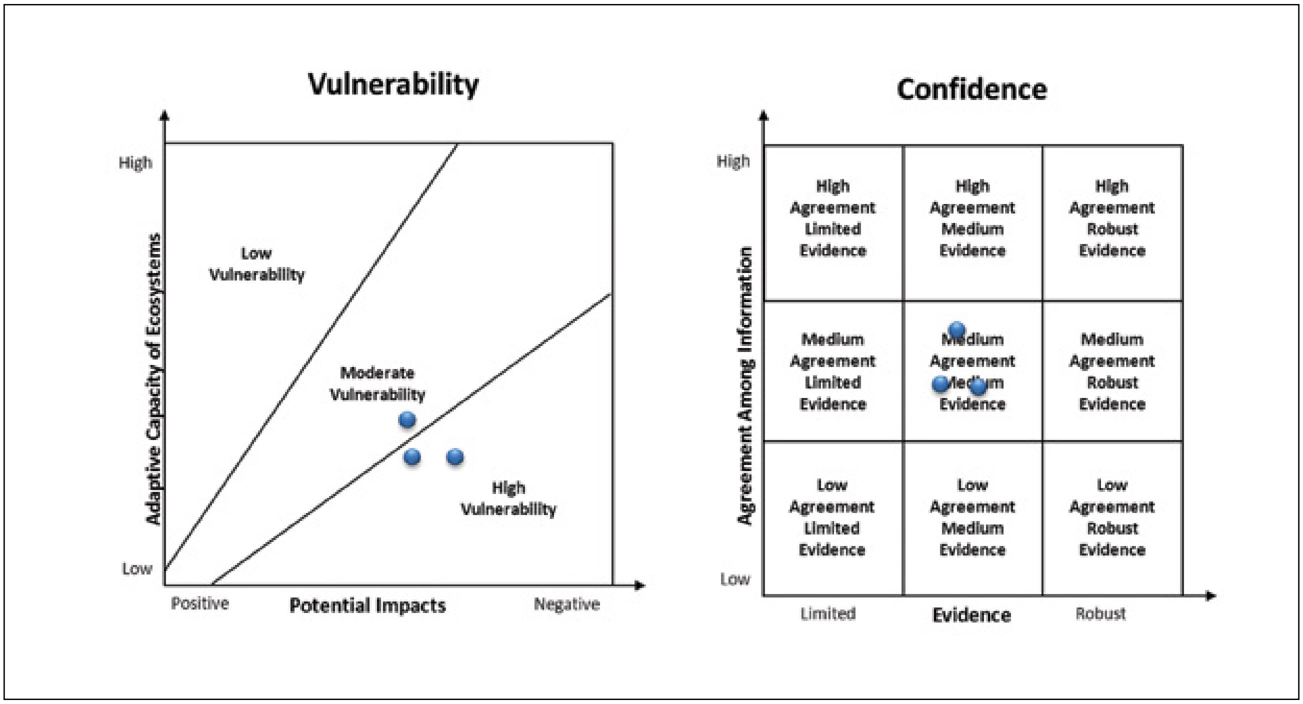


Figure 66.—Managed Red Pine Forests vulnerability and confidence determinations. Circles indicate individual determinations. The group determination was reached through consensus with the remaining panelists.

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

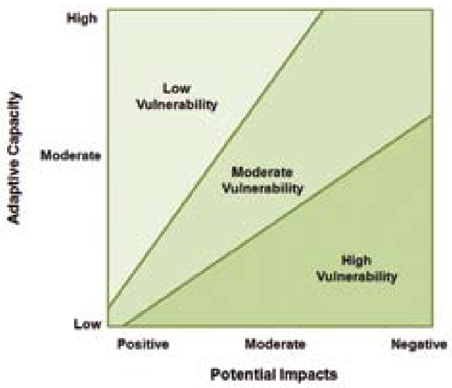
What do you think are the greatest <u>potential impacts</u> to the ecosystem?

What factors do you think contribute most to the <u>adaptive capacity</u> of the ecosystem?

(Continued on next page)

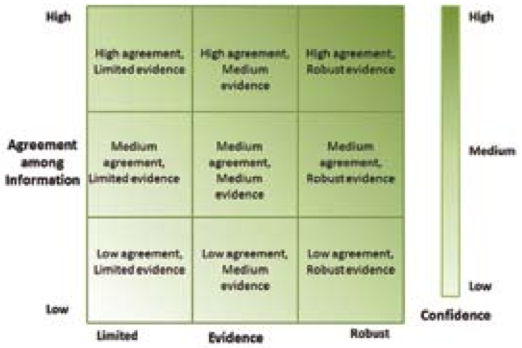
Vulnerability Determination

Use the handout for the vulnerability determination process and the notes that you have taken to plot your assessment of vulnerability on the figure below.



Confidence Rating

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



The ratings above are for the entire analysis area. Please note where you think potential impacts or adaptive capacity may vary substantially within the analysis area (e.g., forests in the eastern portion may be more prone to impact X).

APPENDIX 6. CONTRIBUTORS TO IMPLICATIONS CHAPTER

We relied on input from several subject-area experts from a variety of organizations to summarize the management implications of climate change in Chapter 7 (Table 33).

Table 33.—Contributors to implications chapter

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, LLC	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

Handler, Stephen; Duveneck, Matthew J.; Iverson, Louis; Peters, Emily; Scheller, Robert M.; Wythers, Kirk R.; Brandt, Leslie; Butler, Patricia; Janowiak, Maria; Shannon, P. Danielle; Swanston, Chris; Barrett, Kelly; Kolka, Randy; McQuiston, Casey; Palik, Brian; Reich, Peter B.; Turner, Clarence; White, Mark; Adams, Cheryl; D'Amato, Anthony; Hagell, Suzanne; Johnson, Patricia; Johnson, Rosemary; Larson, Mike; Matthews, Stephen; Montgomery, Rebecca; Olson, Steve; Peters, Matthew; Prasad, Anantha; Rajala, Jack; Daley, Jad; Davenport, Mae; Emery, Marla R.; Fehringer, David; Hoving, Christopher L.; Johnson, Gary; Johnson, Lucinda; Neitzel, David; Rissman, Adena; Rittenhouse, Chadwick; Ziel, Robert. 2014. **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.

Forests in northern Minnesota will be affected directly and indirectly by a changing climate over the next 100 years. This assessment evaluates the vulnerability of forest ecosystems in Minnesota's Laurentian Mixed Forest Province to a range of future climates. Information on current forest conditions, observed climate trends, projected climate changes, and impacts to forest ecosystems was considered in order to draw conclusions on climate change vulnerability. Wet Forests, Forested Rich Peatlands, and Acid Peatlands were determined to be the most vulnerable to projected changes in climate, whereas Floodplain Forests, Fire-Dependent Forests, and Mesic Hardwood Forests were determined to be less vulnerable. Projected changes in climate and the associated ecosystem impacts and vulnerabilities will have important implications for economically valuable timber species, forest-dependent wildlife and plants, recreation, and long-range planning.

KEY WORDS: climate change, vulnerability, adaptive capacity, forests, Climate Change Tree Atlas, LANDIS-II, PnET-CN, expert elicitation, climate projections, impacts

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