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New England and Northern New York Forest Ecosystem Vulnerability Assessment and Synthesis:

A Report from the New England Climate Change Response Framework Project

Forest Service | Northern Research Station | General Technical Report NRS-173 | January 2018

ABSTRACT

Forest ecosystems will face direct and indirect impacts from a changing climate over the 21st century. This assessment evaluates the vulnerability of forest ecosystems across the New England region (Connecticut, Maine, Massachusetts, New Hampshire, northern New York, Rhode Island, and Vermont) 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 natural resource professionals familiar with the forests of this region to assess ecosystem vulnerability through a formal consensus-based expert elicitation process.

Observed trends in climate over the historical record from 1901 through 2011 show that the mean annual temperature has increased across the region by 2.4 °F, with even greater warming during winter. Precipitation patterns also changed during this time, with a slight trend toward greater annual precipitation and a substantial increase in extreme precipitation events. Projected climate trends using downscaled global climate model data indicate a potential increase in mean annual temperature of 3 to 8 °F for the assessment area by 2100. Projections for precipitation indicate an increase in fall and winter precipitation, and spring and summer precipitation projections vary by scenario. We identified potential impacts on forests by incorporating these future climate projections into three forest impact models (DISTRIB, LINKAGES, and LANDIS PRO). Model projections suggest that many northern and boreal species, including balsam fir, red spruce, and black spruce, may fare worse under future conditions, but other species may benefit from projected changes in climate. Published literature on climate impacts related to wildfire, invasive species, and forest pests and diseases also contributed to the overall determination of climate change vulnerability.

We assessed vulnerability for eight forest communities in the assessment area. The assessment was conducted through a formal elicitation process with 20 scientists and resource managers from across the area, who considered vulnerability in terms of the potential impacts and the adaptive capacity for an individual community. Montane spruce-fir, low-elevation spruce-fir, and lowland mixed conifer forests were determined to be the most vulnerable communities. Central hardwoods, transition hardwoods, and pitch pine-scrub oak forests were perceived as having lower vulnerability 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 animals and plants, recreation, and long-term natural resource planning.

Cover Photo

Montane ecosystems, as seen from Mount Jefferson on the White Mountain National Forest. These ecosystems are particularly vulnerable to climate change. Photo by Toni Lyn Morelli, U.S. Geological Survey.

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PREFACE

This assessment is a fundamental component of the New England Climate Change Response Framework project. The Framework is a collaborative, cross-boundary approach among scientists, managers, and landowners to incorporate climate change considerations into natural resource management. Six Framework projects are currently underway, covering about 250 million acres in the U.S. Midwest and Northeast: Northwoods, Central Appalachians, Central Hardwoods, Mid-Atlantic, New England, and Urban. 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 on climate change and forest ecosystems. Its primary goal is to inform forest managers and natural resource professionals in New England and northern New York, in addition to other people who study, recreate, and live in these forests. As new scientific information arises, we may develop future versions to reflect that accumulated knowledge and understanding. Most importantly, this assessment does not make recommendations about how this information should be used.

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

The large list of authors reflects the highly collaborative nature of this assessment. The overall document structure and much of the language was a coordinated effort among Leslie Brandt, Patricia Butler-Leopold, Maria Janowiak, Stephen Handler, and Chris Swanston. Danielle Shannon conducted much of the data analysis and developed maps for Chapters 1, 2, and 3. Louis Iverson, Steve Matthews, Matthew Peters, and Anantha Prasad provided and interpreted Tree Atlas information for Chapter 4, and assisted with the data processing for the climate data presented in Chapter 3. Frank Thompson, Bill Dijak, and Jacob Fraser provided results and interpretation of the LINKAGES and LANDIS PRO models. All modeling teams coordinated their efforts impressively.

In addition to the authors listed, a number of people made valuable contributions to the assessment. We especially thank Colin Beier and Erika Rowland, who provided formal technical reviews of the assessment. Their thorough reviews greatly improved the quality of this assessment.

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EXECUTIVE SUMMARY

This assessment evaluates key ecosystem vulnerabilities for forest ecosystems in New England and northern New York (Fig. 1) across a range of future climate scenarios. This assessment was completed as part of the New England Climate Change Response Framework project, a collaborative approach among researchers, managers, and landowners to incorporate climate change considerations into forest management.

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

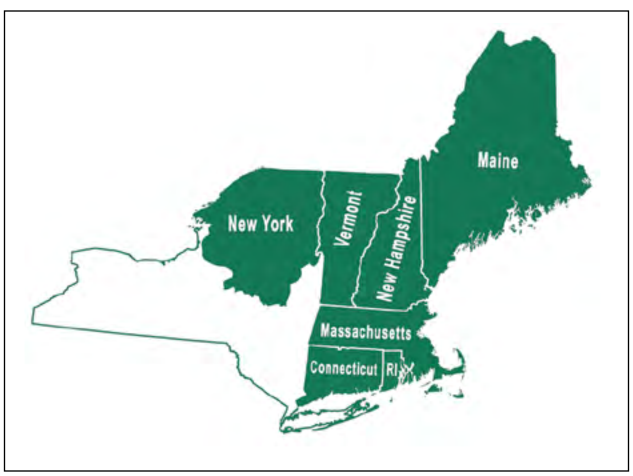

Figure 1.—The assessment area (green shaded area): the six New England states and northern New York.

CHAPTER 1: CURRENT FOREST CONDITIONS

This chapter describes the forests and related ecosystems of New England and northern New York and summarizes current threats and management trends. The information lays the foundation for understanding how shifts in climate may contribute to changes in forest ecosystems, and how climate may interact with other stressors on the landscape.

Main Points

- Of the nearly 53 million acres of land in the assessment area of New England and northern New York, about 40 million acres are forest. Maple/beech/birch and spruce/fir are the most abundant forest-type groups across the area. Private individuals and organizations own about 80 percent of the forest land.
- Historical land use and past management practices have tended to favor younger forests across the landscape and have often reduced species diversity and structural complexity.
- Current major stressors and threats to forest ecosystems in the assessment area include:
    - Fragmentation and land-use change
    - Fire regime shifts
    - Invasion by nonnative species
    - Forest diseases and insect pests
    - Overbrowsing
    - Extreme weather events.
- The forest products industry is a major contributor to the regional economy. Ninety percent of the forest land in the assessment area is classified as timberland, meaning that it is

considered suitable for wood production because forest harvesting is not prohibited. Across the assessment area, the amount of wood harvested each year is less than the amount of forest growth.

CHAPTER 2: OBSERVED CLIMATE CHANGE

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

Main Points

- Across the assessment area, the mean annual temperature increased by 2.4 °F (1.3 °C) between 1901 and 2011. Mean, minimum, and maximum temperatures increased across all seasons over the past century, with winter temperatures warming the most rapidly.
- Precipitation patterns have changed across the region, with a trend toward greater annual precipitation in the assessment area. The number of extreme precipitation events has increased. Snowfall has generally decreased across the assessment area.
- Climate change has caused substantial sea-level rise, with an increase of 12 inches across the northeastern United States and an even greater increase along the New England coastline observed since 1900.
- Climate change has also been indicated by trends showing reductions in lake ice, increased growing season length, and shifts in plant and animal phenology.

CHAPTER 3: PROJECTED CHANGES IN CLIMATE AND PHYSICAL PROCESSES

This chapter describes climate projections for the assessment area over the 21st century. Temperature and precipitation projections are derived from downscaled simulations of climate models. Published scientific literature provides the basis for describing possible trends in a range of climate-driven processes, such as extreme weather events and snowfall.

Main Points

- Temperatures are expected to continue to increase over the next century. A range of climate scenarios project warming in all seasons.
- Precipitation is projected to increase in winter and spring across a range of climate scenarios. Projections of summer and fall precipitation are more variable. Intense precipitation events are expected to continue to become more frequent.
- Winters will continue to become shorter and milder. 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 4: FUTURE CLIMATE CHANGE IMPACTS ON FORESTS

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

Main Points

- Boreal species such as balsam fir, red spruce, and black spruce are projected to have reductions in suitable habitat and biomass over the next century.

- Species with ranges that extend to the south such as red maple, northern red oak, black cherry, and American basswood may have increases in suitable habitat and biomass.
- Many currently common species are projected to decline under a hotter, drier future climate scenario, particularly in the southern portion of the assessment area.
- Forest productivity will be influenced by a combination of factors such as carbon dioxide fertilization, water and nutrient availability, succession, disturbance, and species migration.
- The model projections used in this assessment do not account for many other factors that may change under a changing climate, such as forest disturbance. Scientific literature was used to provide additional information on these factors, including:
    - Altered precipitation and hydrology
    - Drought stress
    - Wildfire frequency and severity
    - Altered nutrient cycling
    - Changes in invasive species, insect pests, and forest diseases
    - Interactions among these factors.

CHAPTER 5: FOREST ECOSYSTEM VULNERABILITIES

Forest ecosystems across New England and northern New York will face direct and indirect impacts from a changing climate over the 21st century. We assessed the vulnerability of major forest systems in the assessment area to climate change through the year 2100, focusing 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 provided for eight major forest systems (Table 1).

Main Points

Potential Impacts on Drivers and Stressors

- **Temperatures will increase (robust evidence, high agreement).** All global climate models agree that temperatures will increase with continued increases in atmospheric greenhouse gas concentrations.
- **Growing seasons will lengthen (robust evidence, high agreement).** There is strong agreement that projected temperature increases will lead to longer growing seasons in the assessment area.

Table 1.—Summary of vulnerability determination for the forest systems considered in this assessment evaluated through the end of the 21st century

Forest system	Potential impacts	Adaptive capacity	Vulnerability	Evidence	Agreement
Central hardwood-pine	Neutral-Positive	Moderate-High	Low	Medium	Medium-High
Low-elevation spruce-fir	Neutral-Negative	Moderate	Moderate-High	Medium	Medium
Lowland and riparian hardwood	Positive and Negative	Moderate-High	Moderate	Limited	Limited
Lowland mixed conifer	Neutral-Negative	Low-Moderate	Moderate-High	Limited-Medium	Medium
Montane spruce-fir	Neutral-Negative	Moderate	Moderate-High	Medium	Medium
Northern hardwood	Positive and Negative	Moderate-High	Low-Moderate	Medium	Medium
Pitch pine-scrub oak	Neutral-Positive	Moderate	Low	Medium	Medium
Transition hardwood	Positive and Negative	Moderate-High	Low-Moderate	Medium	Medium-High

- **Winter processes will change (robust evidence, high agreement).** There is strong evidence 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.
- **Sea levels will continue to rise (robust evidence, high agreement).** There is substantial evidence that ongoing sea-level rise will continue to affect low-lying coastal areas and increase potential impacts from flooding, saltwater intrusion, and storm surge.
- **The amount and timing of precipitation will change (robust evidence, high agreement).** There is strong agreement that precipitation patterns will change across the assessment area. Total precipitation is generally expected to increase during winter and spring, but summer and fall projections are more uncertain.
- **Intense precipitation events will continue to become more frequent (robust evidence, high agreement).** Climate models generally project that the number of heavy precipitation events will continue to increase in the assessment area. If they do increase, damage from flooding and soil erosion may also become more severe.
- **Soil moisture patterns will change in response to temperature and precipitation (medium evidence, high agreement).** Warmer temperatures and altered precipitation will interact to change soil moisture patterns throughout the year, but there is uncertainty about the direction and magnitude of the changes.
- **Forest vegetation may face increased risk of moisture deficit and drought during the growing season (medium evidence, medium agreement).** Studies show that climate change will affect soil moisture, but there is some disagreement among climate and impact models on how soil moisture and drought will change during the growing season.
- **Certain insect pests and pathogens will increase in occurrence or become more damaging (medium evidence, high agreement).** Evidence indicates that increases in temperature will lead to increased threats from insect pests and pathogens, but research to date has examined relatively few species.
- **Many invasive plants will increase in extent or abundance (medium evidence, high agreement).** Evidence indicates that increases in temperature, longer growing seasons, and more frequent disturbances will lead to increases in many invasive plant species.

Potential Impacts on Forests

- **Many northern and boreal tree species will face increasing stress from climate change (medium evidence, high agreement).** Ecosystem models agree that northern and boreal tree species will have 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 warm-adapted, temperate forest species.
- **Habitat will become more suitable for southern species (medium evidence, high agreement).** Ecosystem models agree that longer growing seasons and warmer temperatures will increase suitable habitat and biomass for many temperate species across the assessment area.
- **Forest composition will change across the landscape (medium evidence, high agreement).** Although few models have specifically examined how forest communities may change, model results from individual species and ecological principles suggest that recognized forest community assemblages will change.
- **Shifts in forest composition will take at least several decades to occur in the absence of major disturbance (medium evidence, medium agreement).** Although some models indicate major changes in habitat suitability, results from spatially dynamic forest landscape models indicate that a major shift in forest composition across the landscape may take 100 years or more in the absence of major disturbances.

- **Conditions affecting tree regeneration and recruitment will change (medium evidence, high agreement).** Seedlings are more vulnerable than mature trees to changes in temperature, moisture, and other seedbed and early growth requirements.
- **Forest productivity will increase during the next several decades in the absence of significant stressors (medium evidence, medium agreement).** Some studies have examined the impact of climate change on forest productivity within the assessment area, but they disagree on how multiple factors may interact to influence productivity. The diversity of forest conditions across the assessment area suggests that changes will be spatially variable.

Adaptive Capacity Factors

- **Low-diversity systems are at greater risk (medium evidence, high agreement).** Studies have consistently shown that high-diversity systems are more resilient to disturbance. Low-diversity systems are expected to be more vulnerable to climate change.
- **Tree species in isolated or fragmented landscapes will have reduced ability to migrate to new areas in response to climate change (limited evidence, high agreement).** The dispersal ability of individual tree species is reduced in fragmented landscapes, but the degree of landscape fragmentation in the future is an area of uncertainty.
- **Species or systems that are limited to particular environments will have less opportunity to migrate in response to climate change (limited evidence, high agreement).** Our current ecological understanding indicates that migration to new areas will be particularly difficult for tree species and forest communities with narrow habitat requirements.
- **Ecosystems that have greater tolerance to disturbance have less risk of declining on the landscape (medium evidence, high agreement).** Basic ecological theory and other evidence support the idea that systems adapted to more frequent disturbance will be at lower risk.

CHAPTER 6: MANAGEMENT IMPLICATIONS

This chapter summarizes the implications of potential climate change to forest management and planning in the assessment area. This chapter does not make recommendations as to how management should be adjusted to cope with these impacts, because impacts and responses will differ by ecosystem, ownership, and management objective.

Main Points

- Plants, animals, and people that depend on forests may face additional challenges as the climate shifts.
- Greater financial investments may be required to manage forests and infrastructure and to prepare for severe weather events.
- Management activities such as wildfire suppression or recreational activities such as snowmobiling and skiing 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

Forests are a prominent feature of the landscape across the six New England states (Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, and Vermont) and northern New York. Stretching from the coast of the Atlantic Ocean to the peaks of the Appalachian Mountains, this assessment area contains more than 50 million acres of land (Fig. 2), of which 40 million acres are forest. Increasingly, the effects of a changing climate are altering the forests of the Northeast, and many of these impacts are projected to continue and intensify in the future. Many of the important factors that influence forest composition and distribution are expected to change, including seasonal temperatures, precipitation timing and type, soil moisture patterns, natural disturbance severity and frequency, and pest and disease abundance. Future climatic changes and their associated impacts and vulnerabilities are anticipated to affect forests in expected and unexpected ways, which will unfold over the next several decades. Ecosystems are expected to respond to these changes in a variety of ways, often in reaction to increased stress.

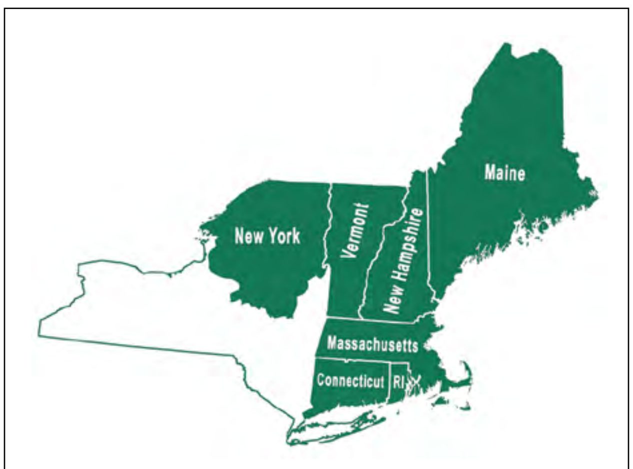

Figure 2.—The assessment area (green shaded area): the six New England states and northern New York.

Ongoing and future research will continue to provide more detailed information about specific impacts, but enough information is currently available to understand the anticipated vulnerabilities of regional forest ecosystems given climate variability and change. Numerous assessments describe the potential impacts of climate change on the forests of the Northeast (see the next three pages). In this document, we synthesize the available information to provide a more complete understanding of how forests in the assessment area are expected to respond to changing conditions in order to better inform management and conservation activities taking place in the region.

CONTEXT AND SCOPE

This assessment is a fundamental component of the New England 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 (www.forestadaptation.org). Six Framework projects are currently underway, covering approximately 250 million acres in the northeastern and midwestern United States: Northwoods, Central Appalachians, Central Hardwoods, Mid-Atlantic, New England, and Urban. Each regional project interweaves four components: science and management partnerships, vulnerability assessments, adaptation resources, and demonstration projects (Swanston et al. 2016).

We designed this assessment to highlight the best available scientific information on the topic of climate change and forest ecosystems. Its primary purpose is to inform natural resource managers in New England and northern New York, as well as other people who study, recreate, and live in these forests. As new scientific information arises, we may develop future assessments to reflect that accumulated knowledge and understanding. Most importantly, this assessment does not make recommendations about how this information should be used.

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

ASSESSMENT CHAPTERS

This assessment contains the following chapters:

Chapter 1: Current Forest Conditions describes existing conditions and provides background on the physical environment, ecological character, and broad socioeconomic dimensions of the assessment area.

Chapter 2: Observed Climate Change provides information on the past and current climate of the assessment area, as summarized from the interactive Climate Wizard database and published literature. This chapter also summarizes some relevant ecological indicators of observed climate change.

Chapter 3: Projected Changes in Climate and Physical Processes presents downscaled climate change projections for the assessment area, including future temperature and precipitation data. It also includes summaries of other climate-related trends that have been projected for the assessment area and the Northeast region.

Chapter 4: Future Climate Change Impacts on Forests summarizes ecosystem model results for the region and the assessment area. Three modeling approaches were used to model climate change impacts on forests: a species distribution model (Climate Change Tree Atlas) and two forest simulation models (LINKAGES and LANDIS PRO). This chapter also includes a literature review of other climate-related impacts on forests.

Chapter 5: Forest Ecosystem Vulnerabilities synthesizes the potential effects of climate change on the forested ecosystems of the assessment area and provides detailed vulnerability determinations for each of the eight major forest systems.

Chapter 6: Management Implications draws connections from the forest ecosystem vulnerability determinations to a wider network of related concerns shared by forest managers, including habitat for forest-dependent animals, forest management, recreation, and cultural resources.

RELEVANT CLIMATE CHANGE ASSESSMENTS

Global and National Assessments

Climate Science Special Report: Fourth National Climate Assessment, Vol. 1 (Wuebbles et al. 2017)

Forests (Joyce et al. 2014)

Climate Change Impacts in the United States: the Third National Climate Assessment (Melillo et al. 2014)

Climate Change 2013: the Physical Science Basis (Intergovernmental Panel on Climate Change 2013)

Climate Change in the Northeast—a Sourcebook: Draft Technical Input Report Prepared for the U.S. National Climate Assessment (Horton et al. 2012)

Effects of Climatic Variability and Change on Forest Ecosystems: a Comprehensive Science Synthesis for the U.S. Forest Sector (Vose et al. 2012)

Regional Assessments

Maine's Climate Future: 2015 Update (Fernandez et al. 2015)

Considering Vermont's Future in a Changing Climate: the First Vermont Climate Assessment (Galford et al. 2014)

Climate Change in Northern New Hampshire: Past, Present, and Future (Wake et al. 2014a)

Climate Change in Southern New Hampshire: Past, Present, and Future (Wake et al. 2014b)

Climate Change and Biodiversity in Maine: Vulnerability of Habitats and Priority Species (Whitman et al. 2014)

Regional Climate Trends and Scenarios for the U.S. National Climate Assessment. Part 1. Climate of the Northeast U.S. (Kunkel et al. 2013)

Implementing Climate Smart Conservation in Northeastern Upland Forests: a Report to the Wildlife Conservation Society and Northeastern Association of Fish and Wildlife Agencies (Manomet Center for Conservation Sciences and National Wildlife Federation 2013a)

The Vulnerabilities of Fish and Wildlife Habitats in the Northeast to Climate Change: a Report to the Northeastern Association of Fish and Wildlife Agencies and to the North Atlantic Landscape Conservation Cooperative (Manomet Center for Conservation Sciences and National Wildlife Federation 2013b)

The Vulnerabilities of Northeastern Fish and Wildlife Habitats to Sea Level Rise: a Report to the Northeastern Association of Fish and Wildlife Agencies and to the North Atlantic Landscape Conservation Cooperative (Manomet Center for Conservation Sciences and National Wildlife Federation 2013c)

Ecosystems and Wildlife Climate Change Adaptation Plan: Amendment to the New Hampshire Wildlife Action Plan (New Hampshire Fish and Game Department 2013)

Climate Change Adaptation Framework: Full Report (Tetra Tech 2013)

Climate Change and Biodiversity in Maine: a Climate Change Exposure Summary for Species and Key Habitats (revised) (Whitman et al. 2013)


A high-elevation ecosystem in northern New Hampshire. Photo by Todd Ontl, U.S. Forest Service.

Climate Change and Cold Water Fish Habitat in the Northeast—A Vulnerability Assessment: a Report to the Northeastern Association of Fish and Wildlife Agencies and to the North Atlantic Landscape Conservation Cooperative (Manomet Center for Conservation Sciences and National Wildlife Federation 2012)

Changing Climate, Changing Forests: the Impacts of Climate Change on Forests of the Northeastern United States and Eastern Canada (Rustad et al. 2012)

NEAFWA Regional Vulnerability Assessment Project—Report 2: the Habitat Vulnerability Model (Galbraith 2011a)

Report to the NEAFWA Vulnerability Assessment Expert Panel: Exposure Information (Galbraith 2011b)

Responding to Climate Change in New York State (New York State Energy Research and Development Authority 2011)

The Impacts of Climate Change on Connecticut Agriculture, Infrastructure, Natural Resources, and Public Health (Adaptation Subcommittee to the Governor's Steering Committee on Climate Change 2010)

NEAFWA Regional Vulnerability Assessment Project—Report 1: Forming the Expert Panel (Galbraith 2010)

Climate Change and Biodiversity in Maine: a Climate Change Exposure Summary for Participants of the Maine Climate Change Species Vulnerability Assessment (Manomet Center for Conservation Sciences 2010a)

Climate Change and Massachusetts Fish and Wildlife: Habitat Management (Volume 3) (Manomet Center for Conservation Sciences and Massachusetts Division of Fisheries and Wildlife (2010b)

Climate Change and Massachusetts Fish and Wildlife: Habitat and Species Vulnerability (Volume 2) (Manomet Center for Conservation Sciences and Massachusetts Division of Fisheries and Wildlife 2010a)

Climate Change and Massachusetts Fish and Wildlife: Introduction and Background (Volume 1) (Manomet Center for Conservation Sciences and Massachusetts Division of Fisheries and Wildlife 2010c)

Climate Change in the Champlain Basin: What Natural Resource Managers can Expect and Do (Stager and Thill 2010)

Maine's Climate Future: an Initial Assessment (Jacobson et al. 2009)

New Hampshire Climate Action Plan: a Plan for New Hampshire's Energy, Environmental and Economic Development Future (New Hampshire Department of Environmental Services 2009)

Confronting Climate Change in the U.S. Northeast: Science, Impacts, and Solutions (Frumhoff et al. 2007)

CHAPTER 1: CURRENT FOREST CONDITIONS

The current landscape of New England and northern New York is diverse, shaped by an array of environmental and social influences. Forest ecosystems are prominent across the area, providing benefits that include extensive vibrant fall colors, recreational opportunities, water quality protection, wildlife habitat, and forest-based products and livelihoods. This chapter describes the current condition of forests across the Northeast to provide context for how these forests may change in the future.

REGIONAL SETTING

This report focuses on forest ecosystems found across New England and northern New York within the northeastern United States. These forests are part of three ecological provinces, as delineated by the U.S. Forest Service (Cleland et al. 2007): Northeastern Mixed Forest (211), Adirondack–New England Mixed Forest (M211), and Eastern Broadleaf Forest (M221) (Fig. 3). Despite the diversity of the overall region, these three provinces each have similar traits such as climate, geology, soils, and vegetation that transcend political boundaries and distinguish them from other parts of the Northeast (McNab and Avers 1994, McNab et al. 2007).

- The Northeastern Mixed Forest Province has a climate that is moderated by proximity to the Atlantic Ocean and Great Lakes. Winters are generally long with continuous snow cover. Vegetation in this region generally reflects a transition between boreal conifer forests in colder and more northerly locations and the deciduous hardwood forests present to the south.

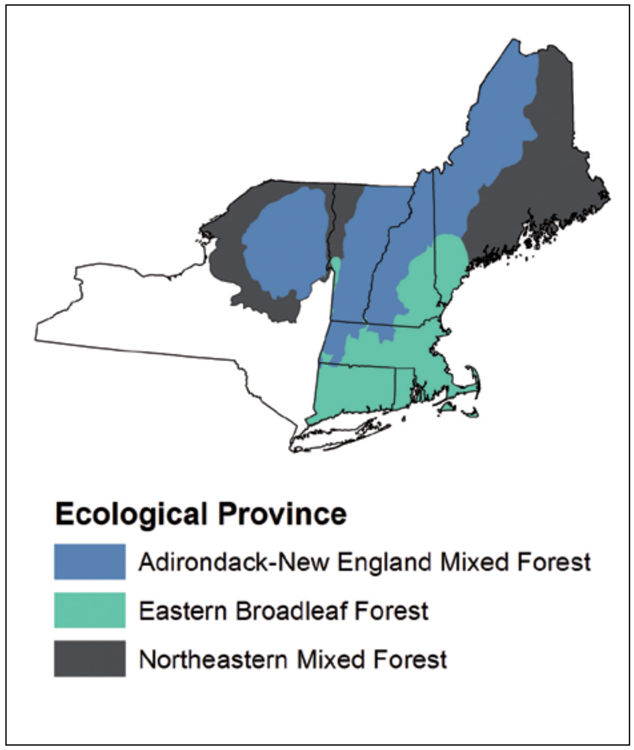

Figure 3.—Distribution of the three ecological provinces in the assessment area.

- The Adirondack–New England Mixed Forest Province is similar in many ways to the Northeastern Mixed Forest Province, although the region has a more continental climate that results in long, cold winters. Additionally, this area is mountainous (Fig. 4) and has topography, geology, and soils that reflect a combination of local bedrock and glacial features.
- The Eastern Broadleaf Forest Province is the most southerly area covered in this report. The topography and bedrock geology vary greatly in this area, from broad, hilly plateaus to the coastal zone along the Atlantic Ocean. This area has a warmer climate and longer growing season than the other ecological provinces.

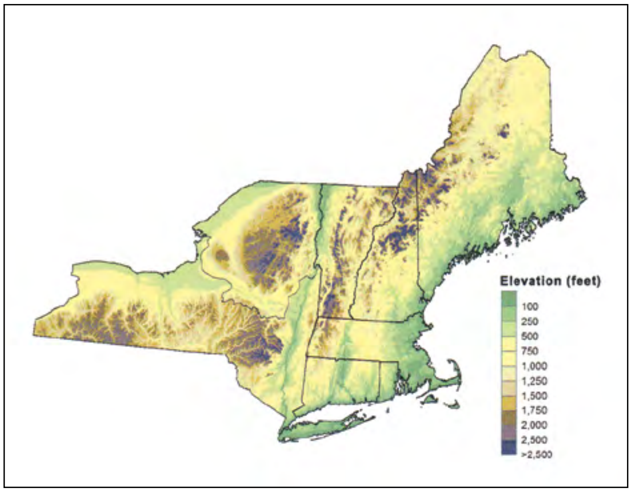

Figure 4.—Elevation (above mean sea level) of the Northeast.

The assessment area includes the six states of New England (Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, and Vermont), as well as northern New York. In many ways, the climate and forests of northern New York are more similar to the northern forests of New England than to areas of New York farther south. Therefore, the northern portion of New York—the Northeastern Mixed Forest (ecological province 211) and the Adirondack–New England Mixed Forest (ecological province M211)—is included in this report. This report summarizes broad-scale trends and conditions across the assessment area and the surrounding region, such as climate (Box 1), but it is important to note that the specific forest conditions at any particular place are a reflection of numerous environmental and social factors, both past and current.

Box 1: Climate in the Region

The climate in the assessment area is diverse, with large seasonal and spatial variation based on latitude, elevation, and proximity to the Atlantic Ocean or large inland water bodies (Kunkel et al. 2013). Winter is generally cold, with the jetstream bringing westerly, continental air and frigid temperatures to the region. Also affecting the area in important ways are several climatic phenomena such as extreme precipitation that leads to flooding, winter storms and nor'easters, ice storms, drought, and tropical cyclones (Kunkel et al. 2013).

Climate data from 1971 through 2000 provide a general picture of the contemporary climate (Table 2). Mean air temperature fluctuates by about 45 °F (25 °C) between winter and summer across the assessment area. July is the warmest month with a mean temperature of 67.2 °F (19.6 °C), and January is the coldest month with a mean temperature of 17.2 °F (–8.2 °C; Table 15 in Appendix 2). Temperatures tend to be higher in the southern and coastal parts of New England throughout the year, although differences are smaller during the warm season due to the moderating effect of the Atlantic Ocean. Precipitation is relatively constant throughout the year, with each season receiving 10 to 12 inches on average and precipitation tending to be greatest near the coast and at higher elevations (Table 15).

Table 2.—Average climate information for the assessment area, 1971 through 2000 (data source: Climate Wizard [2014])*

	Mean temperature (°F)	Mean minimum temperature (°F)	Mean maximum temperature (°F)	Mean precipitation (in)
Annual	43.1	32.5	53.7	45.2
Winter	20.1	10.0	30.2	10.1
Spring	41.3	30.3	52.4	11.1
Summer	64.9	53.5	76.3	11.9
Fall	46.1	36.2	56.1	12.0

*Additional data and maps are available in Appendix 2.

PAST CHANGES IN FOREST ECOSYSTEMS

Climatic changes occurring since the retreat of the glaciers about 10,000 years ago have influenced the migration and composition of northeastern forests. During the early Holocene (about 10,000 years ago), regional forests underwent dynamic transformations, including species migration and forest succession, in response to climatic changes. Most of the plant species present in New England today had migrated into the region by 8,000 years ago; American chestnut is among the most recent arrivals, about 3,000 years ago (Davis 1983, 1986). Throughout this time, species distributions continually changed across the landscape in response to climate, insect and disease outbreaks, and competition among species. Pollen records point to substantial changes in the abundance of different tree species even into the current millennium (Grimm and Jacobson 1992, Lindbladh et al. 2003). Please refer to Appendix 1 for common and scientific names of species mentioned in this report.

A variety of drivers continued to change forests until Euro-American settlement. In addition to climate, primary natural drivers of change in the regional forests included wind and ice storms, insects and diseases, beaver activity, and fires (Lorimer and White 2003). Intense wind events from tropical storms, hurricanes, and thunderstorms were the dominant natural disturbance events in many forest communities (Lorimer and White 2003). For example, the estimated return interval for severe hurricanes ranged from 85 to 400 years, with the highest frequency in the southeastern part of the region (Boose et al. 2001). Fire was locally important and most prevalent in pitch pine-scrub oak ecosystems, with average return intervals estimated at 20 years (Lorimer and White 2003, Parshall and Foster 2002). Presettlement land survey records and other historical sources suggest that fire rotation periods for northern hardwoods and other forest types were much less frequent, with return intervals that often exceeded 1,000 years (Lorimer and White 2003, Parshall and Foster 2002).

Native Americans also influenced the landscape across New England and northern New York in many ways, although uncertainty remains about the degree to which indigenous people affected plant communities at a regional scale (Fuller et al. 1998, Parshall and Foster 2002). Evidence for human-caused vegetation change is largely focused on southern New England, where many Native American people practiced subsistence agriculture (Fuller et al. 1998, Patterson and Sassaman 1988). Fire was used in river valleys and other low-elevation ecosystems largely dominated by oak and pine species to enhance conditions suitable for small-scale agriculture, increase mast production, and facilitate hunting (Abrams and Nowacki 2008, Fuller et al. 1998, Patterson and Sassaman 1988). Indigenous populations were also present in northern New England but did not practice agriculture, and burning was less advantageous to these people and not used as often as in the southern portion of the region (Patterson and Sassaman 1988).

Human activity over the past several hundred years has profoundly changed the regional forests (Foster et al. 1998). Euro-American settlement, land clearing for agriculture, and industrial logging began to greatly affect forests starting in the early 1700s and continuing through the mid-1800s (Foster et al. 1998, Fuller et al. 1998). In southern New England, which was more than 90 percent forested during presettlement periods, small woodlands covered less than 30 percent of the area in 1830 following agricultural conversion (Foster and O'Keefe 2000). Farmland was largely abandoned during the mid-to-late 1800s as agriculture expanded to more-fertile regions in the Midwest and populations shifted to cities in response to industrialization (Foster et al. 1998). Although northern New England experienced similar dynamics in more-fertile and settled areas, such as the Champlain Valley of Vermont and coastal Maine, much of its more remote and rugged portions remained forested and served as the center for important timber-producing operations beginning in the early 1800s through the 1900s (Whitney 1994). Today, forest is once again the dominant land cover type across the entire assessment area; however, the structure and composition of these areas have been strongly influenced and altered by this complex land-use legacy (Foster 1992, 2006).

LAND AND FOREST COVER

The northeastern United States is one of the most forested regions of the country. This report focuses on an assessment area spanning more than 52.8 million acres. Nearly two-thirds (34.4 million acres) of this land area is forest (Fig. 5, Table 3), according to the National Land Cover Dataset (NLCD) (Fry et al. 2011). Although dominated by forest (65 percent of land cover), the assessment area also contains substantial components of wetlands (10 percent) and developed land (8 percent). Additionally, agricultural lands (7 percent), water bodies (5 percent), and other shrubland, herbaceous cover, or barren lands (6 percent) complete the landscape (Fry et al. 2011).

The U.S. Forest Service Forest Inventory and Analysis (FIA) program provides similar estimates of land cover. Based on the FIA data, forest land covers 40.4 million acres (76 percent) of the total area (Table 4). The FIA estimate of forest land is higher than the NLCD estimate of forest because FIA captures many forested wetlands and other forest habitats that the NLCD may have classified as other land uses, such as wetlands, planted lands, or low-intensity developed lands.

Forest cover varies by state, largely reflecting the patterns of human settlement and development. Connecticut, Massachusetts, and Rhode Island have the lowest percentage of forest cover; however, these states are still heavily forested, with more than half of the land area being classified as forest (Table 4). Maine has the greatest proportion of forest land (85 percent) and the greatest acreage of forest land. As discussed earlier, the area covered by forest is substantially greater than during the 1700s and 1800s because diminishing farming activity allowed many areas to return to forest. During the past century, forest cover has increased substantially in New York and Maine, while forest cover has remained stable or has had smaller increases in other states (Shifley et al. 2012). In recent decades, land-use change for residential and commercial development and other uses has increased, placing new pressures on forest lands. One study found that deforestation in New England increased from

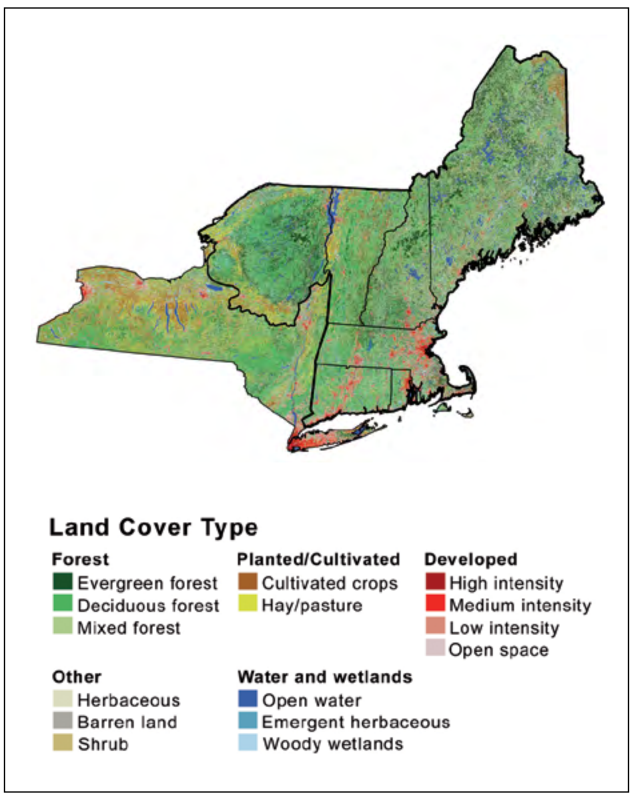

Figure 5.—Land cover in the Northeast based on the 2006 National Land Cover Dataset. Data source: Fry et al. (2011).

Table 3.—Land cover classifications within the assessment area based on the 2006 National Land Cover Dataset (data source: Fry et al. [2011])

Land cover class	Acres	Percent
Forest	34,416,515	65.2
Wetland	5,095,632	9.6
Developed	4,120,218	7.8
Agriculture	3,718,225	7.0
Water	2,397,736	4.5
Shrubland	2,344,330	4.4
Grassland	498,181	0.9
Barren land	222,541	0.4
Total	52,813,379	100

Table 4.—Forest cover by state for the assessment area (data source: U.S. Forest Service [2015])

	Forest land	Nonforest	Total	Percent forest cover
		Area (acres)		
Connecticut	1,799,342	1,392,234	**3,191,577**	56
Maine	17,636,080	3,140,719	**20,776,800**	85
Massachusetts	3,035,792	2,175,378	**5,211,169**	58
New Hampshire	4,783,477	1,144,583	**5,928,060**	81
New York*	8,228,567	2,778,457	**11,007,024**	75
Rhode Island	367,372	334,198	**701,570**	52
Vermont	4,514,171	1,659,368	**6,173,539**	73
Entire area	40,364,801	12,624,937	**52,989,738**	76

*Only the northern portion of New York is included in this report.

1985 to 2011, primarily as a result of residential development, and that there was not an increase in forest expansion elsewhere to counteract this effect (Olofsson et al. 2016). Rates of land-use change have slowed and there has been relatively little change in total forest acreage since 2007 (Butler et al. 2015, Morin et al. 2015), but the loss of forest cover remains an important issue in parts of the Northeast (Ducey et al. 2016, Foster et al. 2010).

FOREST COMPOSITION AND ABUNDANCE

Several different types of forest are found across the 40.4 million acres of forest land in the assessment area (Fig. 6, Table 5). The FIA program provides data to describe the forest-type groups present across the assessment area (Box 2) (U.S. Forest Service 2015). Maple/beech/birch (19.1 million acres) and spruce/fir (7.4 million acres) are the most abundant forest-type groups across the area (Table 5). Forest-type groups vary greatly across the region, with spruce/fir most abundant in Maine (Figs. 6, 7). Maple/beech/birch forests are most common in northern New York, Vermont, New Hampshire, and portions of Maine and Massachusetts. Oak/hickory, oak/pine, and white/red/jack pine forests are most common in the southern portion of the region (Figs. 6, 7). These forest-type groups store various amounts of carbon (Box 3).

FOREST SYSTEMS

Although the FIA-derived forest-type groups are useful for quantifying data about regional forests, forest communities are often described differently by regional and local conservation and management organizations (Box 2). In the rest of this document, a set of “forest systems” is generally used to describe the forests currently common across the region (Table 6). These systems can also be associated with terrestrial habitats and natural communities that have been described regionally (Anderson et al. 2013, Comer et al. 2003).

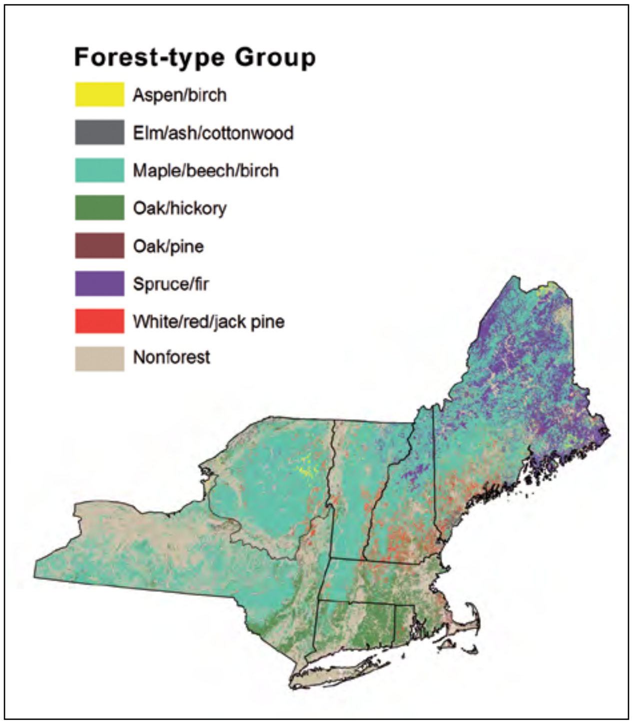

Figure 6.—Distribution of forest-type groups in the Northeast. Data source: Ruefenacht et al. (2013).

Table 5.—Forest land, by area and percentage of total forest land area, in the assessment area by U.S. Forest Service Forest Inventory and Analysis (FIA) forest-type group (data source: U.S. Forest Service [2015])

	Forest cover	
FIA forest-type group	**Acres**	**Percent**
Aspen/birch	3,052,102	7.6
Elm/ash/cottonwood	1,310,809	3.2
Maple/beech/birch	19,099,102	47.3
Oak/hickory	3,904,921	9.7
Oak/pine	1,473,585	3.7
Spruce/fir	7,406,580	18.3
White/red/jack pine	3,163,344	7.8
Other*	793,075	2.0
Nonstocked	161,283	0.4
Total forest land	**40,364,801**	**100.0**

*Other includes the exotic hardwoods, exotic softwoods, loblolly/shortleaf pine, oak/gum/cypress, other eastern softwoods, and other hardwoods forest-type groups.

Box 2: Forest Types Used in this Report

Different organizations describe forests in different ways based on their local forests and unique management needs. For example, each state natural resources agency defines the natural ecosystems, habitats, or communities in that state, and classifications will vary from state to state. This assessment uses two classification systems, which are used to convey different types of information. Although there are some general relationships between the two systems, they are organized differently enough that one cannot be substituted for the other.

One system was created by the U.S. Forest Service Forest Inventory and Analysis (FIA) program to characterize forests across the Nation. In this assessment, we describe acres, ownership category, and volume of timber using "forest-type groups" based on the FIA classification system (Woudenberg et al. 2010). The FIA system measures tree species composition on a set of systematic plots across the United States and uses that information to provide area estimates for each forest type, making it a good way to estimate what is currently on the landscape and the relative abundance of different forest types. In this report, FIA forest-type groups are used to provide quantitative data about regional forest conditions (Table 5). Additionally, forest-type groups have been mapped regionally and nationally (Fig. 6).

FIA forest-type groups are intentionally broad in order to characterize diverse forests across the Nation, but for this reason, they are less useful for describing local differences among similar forest ecosystems. For example, the spruce/fir FIA forest-type group combines several unique forest communities that correspond to different site conditions and are subject to different types

(continued on next page)

Box 2 (continued)

of natural disturbances and forest management activities. Therefore, spruce/fir is too broad for use at a regional or local level. Throughout this report, we also use a set of "forest systems" as the primary classification system whenever possible to better describe the forest ecosystems present in the region (Table 6 on pp. 18-19). We developed these categories based on the classification systems used by numerous forest management organizations in the assessment area, as well as regional descriptions of terrestrial habitats and natural communities (Anderson et al. 2013, Comer et al. 2003). We also used these forest systems to summarize forest vulnerability to climate change (Chapter 5).

Although these are different ways of categorizing forests, there are many similarities between the two systems. For example, the FIA maple/beech/birch forest-type group is largely synonymous with the northern hardwood forest system, and the FIA elm/ash/cottonwood forest-type group includes many forests similar to the lowland and riparian hardwood forest system. In this region, the FIA loblolly/shortleaf pine forest-type group is predominantly pitch pine forest.

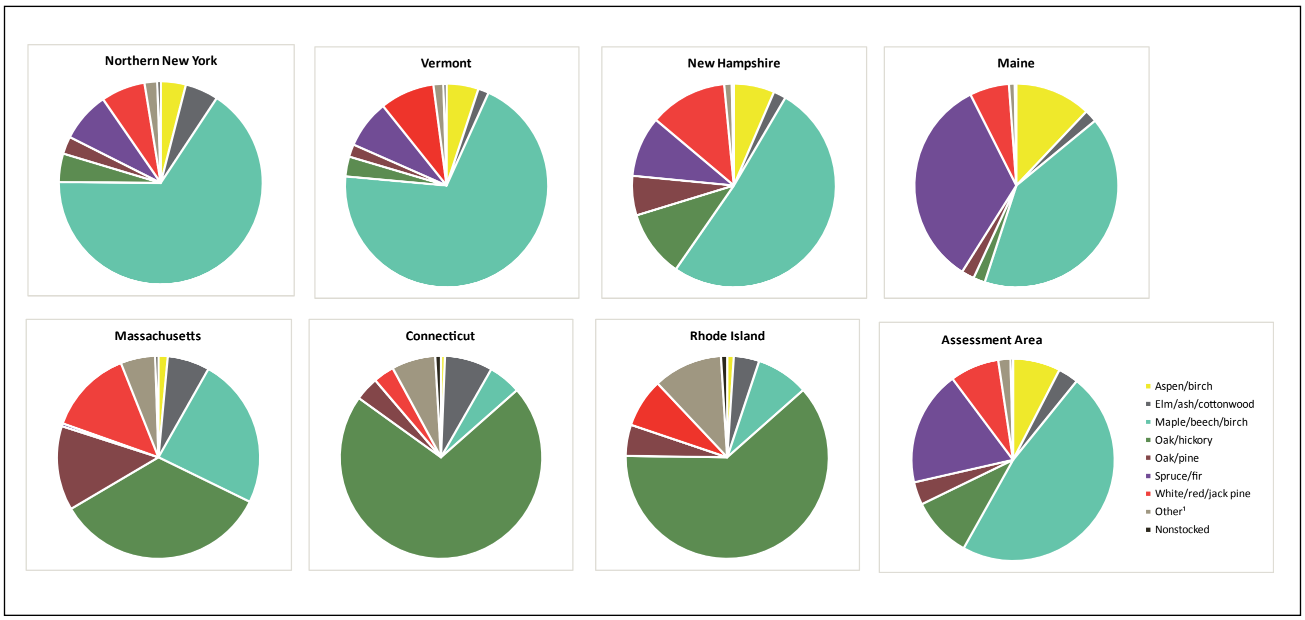

Figure 7.—Proportion of U.S. Forest Service Forest Inventory and Analysis forest-type groups by state and entire assessment area. Data source: U.S. Forest Service (2015).

[1]"Other" includes the exotic hardwoods, exotic softwoods, loblolly/shortleaf pine, oak/gum/cypress, other eastern softwoods, and other hardwoods forest-type groups.

Box 3: Forest Carbon

Forest ecosystems around the world play a valuable role as carbon sinks. The accumulated terrestrial carbon pool within forest soils, belowground biomass, dead wood, aboveground live biomass, and litter represents an enormous store of carbon (Birdsey 1996). Terrestrial carbon stocks in the region have generally been increasing for the past few decades (Shifley et al. 2012), and there is increased attention on the potential to manage forests to maximize and maintain this carbon pool (Malmsheimer et al. 2011). Carbon sequestration and storage in forest ecosystems depends on the health and function of those ecosystems resulting from human management, episodic disturbances, climate variability, and forest stressors.

Forest lands within the assessment area are estimated to hold about 2.7 billion metric tons of carbon. This is about one-fifth of the 13 billion metric tons of carbon stored in forests nationally, even though the region makes up a much smaller proportion of the Nation's forests (Shifley et al. 2012). Across the region, forests store about 66.6 metric tons per acre, although that number will vary widely depending on location, forest composition, and management history. The oak/pine and white/red/jack pine forest-type groups generally have the highest carbon stocks, storing nearly 80 metric tons per acre (Fig. 8). Aspen/birch forests generally have the lowest carbon stocks, with a regional average of 63.1 metric tons per acre. Spruce/fir and elm/ash/cottonwood forests have a higher proportion of carbon stored in soil organic matter.

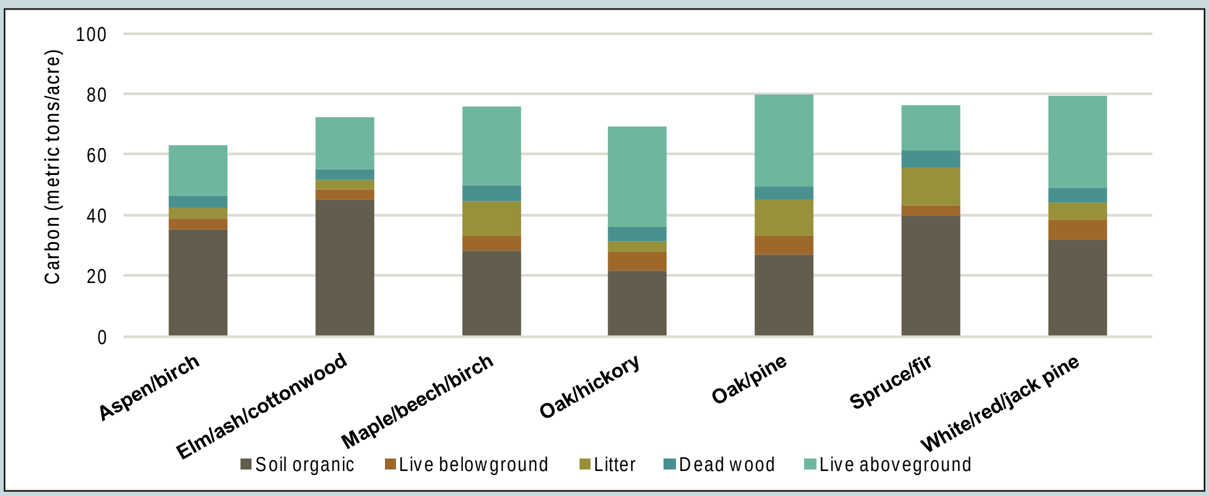

Figure 8.—Average carbon stocks per acre by forest-type group and carbon pool. Data source: U.S. Forest Service (2015).

Table 6.—Descriptions of the forest systems considered in this assessment*

Forest system	Description	Related terrestrial habitats (Anderson et al. 2013)
Central hardwood-pine	Central hardwood forests are found in dry to mesic conditions across a variety of sites in the southern portion of the assessment area. Dominant species in these forests include several oak species, especially red, white, black, or scarlet oak. Numerous hardwood species may be present as codominants based on the site conditions, including red maple, sassafras, or birch or hickory species. Pine species are more likely to be present In the warmer and drier conditions more common in the southernmost and coastal portions of the assessment area.	North Atlantic Coastal Plain Hardwood Forest Northeastern Interior Dry-Mesic Oak Forest Central Appalachian Dry Oak-Pine Forest Central Appalachian Pine-Oak Rocky Woodland Laurentian-Acadian Northern Pine-(Oak) Forest Northeastern Coastal and Interior Pine-Oak Forest
Low-elevation spruce-fir	Spruce-fir forests are dominated by boreal species that include red spruce, white spruce, and balsam fir. These systems are typically found at lower elevations in cold pockets, depressions, or valley bottoms. Sites typically have shallow acidic or nutrient-poor soils, and may be seasonally wet. Hardwood species, such as yellow birch and red maple, may also be present.	Acadian Low-Elevation Spruce-Fir Hardwood Forest Acadian Sub-boreal Spruce Flat
Lowland and riparian hardwood	This system encompasses a broad range of forested wetlands found in depressions and low-lying areas, along waterways, and in floodplains. These forests are heavily influenced by local hydrology, with plant communities that reflect the occurrence of flooding, erosion, groundwater seepage, or other dynamics. These forests are typically dominated by one or more of various hardwood species such as white ash, green ash, red maple, silver maple, swamp white oak, sycamore, American elm, or river birch.	Central Appalachian Stream and Riparian Glacial Marine and Lake Wet Clayplain Forest North Atlantic Coastal Plain Stream and River Northern Appalachian-Acadian Large River Floodplain North-Central Appalachian Large River Floodplain North-Central Interior and Appalachian Rich Swamp North-Central Interior Wet Flatwoods
Lowland mixed conifer	This system encompasses a broad range of forested wetlands with a conifer or mixed conifer-hardwood overstory. Forested wetlands typically have saturated soils, which may also be seasonally flooded. Many of these forests have acidic and nutrient-poor soils, which may be either organic or mineral. A greater variety of species may be present depending on local conditions, such as black spruce, red spruce, tamarack, balsam fir, eastern hemlock, and red maple. Northern or Atlantic white-cedar and black ash may also be present. Forested swamps occurring in areas with limestone or other calcareous substrate have less acidic soils. A greater variety of species is typically found in these forests compared to low-elevation spruce-fir forests.	North Atlantic Coastal Plain Basin Peat Swamp Laurentian-Acadian Alkaline Conifer-Hardwood Swamp North-Central Appalachian Acidic Swamp Northern Appalachian-Acadian Conifer-Hardwood Acidic Swamp

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Table 6 (continued).—Descriptions of the forest systems considered in this assessment

Forest system	Description	Related terrestrial habitats (Anderson et al. 2013)
Montane spruce-fir	Montane spruce-fir forests occur at higher elevations (generally above 1,500 feet) in the Appalachian Mountains. These forests are dominated by boreal species, particularly red spruce or balsam fir. Although spruce-fir forests are dominated by conifers, they may contain a number of associated northern hardwood species, such as yellow birch or sugar maple.	Acadian Low-Elevation Spruce-Fir Hardwood Forest Acadian Sub-boreal Spruce Flat
Northern hardwood	Northern hardwood forests are widely distributed over a variety of sites with dry-mesic to wet-mesic conditions and nutrient-poor to -rich soils. This forest type is generally found at low to moderate elevations. Species that are commonly dominant include sugar maple, yellow birch, American beech, eastern hemlock, and red spruce.	Laurentian-Acadian Northern Hardwood Forest Laurentian-Acadian Red Oak-Northern Hardwood Forest
Pitch pine-scrub oak	Pitch pine-scrub oak forests and barrens are found on xeric sites with deep, sandy soils. Pitch pine and scrub oak are the primary species. This is a fire-dependent system, and the species composition and structure of forests are heavily influenced by fire frequency. More frequent fires will promote pines. Oaks will have greater presence in areas with longer intervals between fires, or in areas where cold-air drainage creates conditions unsuitable for pine.	Northeastern Interior Pine Barrens North Atlantic Coastal Plain Pitch Pine Barrens
Transition hardwood	Transition hardwood forests reflect the transition between central hardwood forests in warmer and more southerly portions of New England and northern hardwood forests in northern New England. Northern species such as sugar maple, yellow birch, and American beech may be dominant or common in this forest type. In addition, numerous more southerly species can also be present or dominant, such as red maple, yellow-poplar, black cherry, sweet birch, and northern red oak. Eastern hemlock and eastern white pine may also be a component of this forest type.	Appalachian (Hemlock)-Northern Hardwood Forest Glacial Marine and Lake Mesic Clayplain Forest Laurentian-Acadian Pine-Hemlock-Hardwood Forest

*The list of characteristic species is not exhaustive, and composition may differ substantially from site to site across the assessment area.

MAJOR DRIVERS OF FOREST CHANGE

Agents of change within the assessment area include both natural and anthropogenic pressures. Past and current drivers of change are diverse and include fire suppression, severe weather events, pests and diseases, invasive species, acid deposition, fragmentation, and land-use change (Table 7). The impacts of particular threats and stressors are very dependent on local conditions and are not consistent across an area as large and diverse as New England and northern New York.

Table 7.—Major drivers of change to forest ecosystems in the assessment area

Driver of forest change	References
Atmospheric deposition of nitrates, sulfates, ozone, and other anthropogenic emissions impairs forest health and productivity. Acid deposition has caused red spruce to decline in high-elevation forests, particularly during the mid-1900s.	(Dietze and Moorcroft 2011, Groffman et al. 2012, Johnson and Siccama 1983)
Herbivory, particularly from white-tailed deer and moose, is considered a keystone driver through impacts on plant regeneration, structure, and species diversity, especially where deer density is high.	(Dobson and Blossey 2015, Rawinski 2016, Shipley and Spalinger, Waller and Alverson 1997)
Drought reduces plant growth, causes regeneration failure, and increases susceptibility to insect pests, diseases, and other environmental stressors. The potential for wildfire increases where drought causes tree dieback and mortality.	(Clark et al. 2016, Hayhoe et al. 2007, Millar and Stephenson 2015)
Soil erosion and reduced water quality from improperly designed or poorly maintained roads, trails, or log landings can increase the amount of silt and sediment transported and deposited by streams.	(Anderson and Lockaby 2010, Aust and Blinn 2004, Hornbeck et al. 1986)
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.	(Bohlen et al. 2004a, 2004b; Burtelow et al. 1998; Frelich et al. 2006)
Fragmentation associated with industrial and urban development has resulted in dispersal barriers that impede migration of species and exchange of genetic material, reduced forest patch size, and increased forest edge.	(Burchfield et al. 2006, Clark et al. 2009, Collinge 1996)
Invasive plants compete for resources and alter natural forest dynamics. Many invasive plant species are present. Problematic species include garlic mustard, buckthorn, nonnative honeysuckles, Asiatic bittersweet, Japanese barberry, and Japanese knotweed.	(Center for Invasive Species and Ecosystem Health 2016, Kurtz 2013)
Insect pests can cause reduced growth or mortality of target species. Pests of concern vary widely depending on the agents present in a geographic location and the susceptibility of the forest community based on species composition, age, health, and other factors. Problematic species include spruce budworm, balsam and hemlock woolly adelgids, emerald ash borer, Asian longhorned beetle, forest tent caterpillar, gypsy moth, and winter moth.	(Shifley et al. 2012, U.S. Forest Service 2016)
Forest pathogens increase the risk of individual tree mortality and species extinction or extirpation. Pathogens of concern vary widely depending on the agents present in a geographic location and the susceptibility of the forest community based on species composition, age, health, and other factors. Problematic pathogens and disease complexes include beech bark disease, Dutch elm disease, and chestnut blight.	(Shifley et al. 2012, U.S. Forest Service 2016)
Suppression of natural fire regimes has reduced structural and species diversity, allowed mesic hardwood encroachment on many sites, and limited suitable conditions for natural regeneration.	(Nowacki and Abrams 2008, Patterson 2006)

Disturbance Regimes

Wind, fire, insects, and diseases are still the primary natural disturbances influencing vegetation in much of the assessment area, although anthropogenic disturbances are also major drivers of forest composition (Schulte and Mladenoff 2005, White and Mladenoff 1994). Wind events can affect forest structure and composition on a broad spatial scale over time, although stand-replacing events are relatively rare (Lorimer and White 2003). The return intervals of stand-replacing wind events are about 1,000 to 7,500 years for northern hardwood forests and 575 to 2,800 years for spruce-fir dominated systems. Across most of the assessment area, small-scale blowdown events have been the primary natural disturbance agent. Windthrow events are highly variable in large part because the exposure of an individual site to extreme wind is strongly influenced by its geographic location and landscape position. Return intervals for windthrow events vary geographically and have not been consistent over the past 40 years (Coniglio and Stensrud 2004). Additionally, some tree species and age classes are more susceptible to windthrow, which affects both the spatial extent of windthrow and the degree of tree mortality from a single event (Rich et al. 2007).

Fire is an important disturbance regime across the region, although the role of fire varies among different forest systems. Fire occurrence has varied widely over time in response to climate, dominant vegetation, and human activities (Fuller et al. 1998, Parshall and Foster 2002). Before the arrival of the Europeans, fires were uncommon in the northern hardwood and hemlock forests that are more common across northern New England (Lorimer and White 2003, Parshall and Foster 2002). The mesic and wet forests of New England have often been referred to as “asbestos” forests because of the high levels of fire resistance (Bormann and Likens 1979, Lorimer and White 2003). In contrast, pollen records indicate that fire has long been more important in the pine- and oak-dominated forests that are more common in southern New England (Parshall and Foster 2002). These fire-dependent systems inherently benefit from the presence of fire (Cogbill et al. 2002, Lorimer and White 2003). Native Americans also used fire to influence at least some southern New England forests (Abrams and Nowacki 2008, Patterson and Sassaman 1988). Human activities have dramatically changed both forest composition and fire regimes in the Northeast during the past 300 years. Large-scale wildfires associated with logging and land-clearing dramatically affected some forests in the 1800s and early 1900s (Lorimer 1977, Ziegler 2000), leading to suppression efforts that have widely limited fire during the last century (Fuller et al. 1998, Nowacki and Abrams 2008). A relative lack of fire and disturbance has increased the abundance of mesic species such as red maple and beech (Cogbill et al. 2002, Fuller et al. 1998), and many of the forest communities present today are not fire-associated ecosystems (Nowacki and Abrams 2008, Pederson et al. 2014).

Pests and Diseases

Insect and disease outbreaks have also influenced the vegetation of the assessment area. Before European settlement, outbreaks were caused by native species, such as spruce budworm and forest tent caterpillar. Spruce budworm, a native defoliator of balsam fir and red, white, and black spruce has caused extensive damage to spruce-fir with an outbreak every 30 to 60 years (Fraver et al. 2007). More recently, insect and disease outbreaks have occurred at an increasing frequency because of introduction and establishment of nonnative insects and disease agents. For example, outbreaks of the nonnative gypsy moth have caused mortality in oak forests across the Northeast since the early 1900s, with severe regional impacts observed during outbreaks in the early 1980s (Elkinton and Liebhold 1990). Similarly, the introduced hemlock woolly adelgid, a scale-like insect, has caused complete mortality of eastern hemlock in portions of Connecticut and Massachusetts (Orwig et al. 2002). The exotic emerald ash borer and Asian longhorned beetle were introduced in parts of the assessment area in the mid-2000s (Shifley et al. 2012, U.S. Forest Service 2016). Beyond insect pests and forest diseases, earthworm introduction into previously glaciated regions of the Northeast has dramatically altered soil composition and structure, and organic matter decay rates and processes, making seedbed and germination conditions less favorable for some native plants (Bohlen et al. 2004, Hale et al. 2006).

Nonnative Plant Species

Nonnative plant species have become an increasing concern across the assessment area because of their potential to outcompete native species and affect species interactions that are important to ecosystem function. Some nonnative species can establish more rapidly than native species, in part because native diseases or pests are not adapted to compete against them (Ricciardi et al. 2013, Tu et al. 2001). This can lead to a decline of native species and, in combination with other stressors, can reduce biological diversity (Didham et al. 2005). Past and current changes in land use within the assessment area have made conditions more favorable for the introduction and spread of many nonnative invasive plant species. The presence of several common nonnative plant species, such as Japanese barberry, multiflora rose, and Asiatic bittersweet, was greatest along roads and in smaller, more fragmented parcels in southern New England; past land use had an even stronger influence than current land use, such that lands that were formerly residential lands or fields were more likely to have nonnative species currently (Lundgren et al. 2004). Similarly, another study looking across the six New England states found that housing patterns influenced the abundance and composition of different nonnative invasive species, largely by creating conditions favorable to the introduction and growth of these plants (Gavier-Pizarro et al. 2010). These issues are being addressed by the establishment of numerous cooperative weed management areas to control invasive plant species across political boundaries. Land management organizations in the assessment area have been actively combating the spread of nonnative invasive plants with integrated pest management tools that include prescribed fire, mechanical treatments, and herbicide application.

FOREST OWNERSHIP AND USE

Ownership

There are numerous types of forest landowners within the assessment area (Table 8), each with different approaches to forest management (Box 4). About one-fifth of the forest land in the assessment

Table 8.—Forest land ownership in the assessment area, by state (data source: U.S. Forest Service [2015])

	Forest cover - entire area		Forest cover by state (acres)						
Ownership	Acres	Percent	Connecticut	Maine	Massachusetts	New Hampshire	New York[1]	Rhode Island	Vermont
National Forest	1,297,962	3.2	–	58,221	–	793,384	–	–	446,357
Other federal[2]	410,199	1.0	14,320	127,579	81,133	62,366	80,584	–	44,217
State	5,275,821	13.1	303,690	883,817	592,223	209,368	2,858,097	60,661	367,964
County, municipal, and local	1,241,971	3.1	173,751	211,021	408,376	244,330	88,772	42,951	72,771
Private	32,138,848	79.8	1,307,581	16,355,442	1,954,060	3,474,029	5,201,114	263,760	3,582,863
Total	40,364,801	100	1,799,342	17,636,080	3,035,792	4,783,477	8,228,567	367,372	4,514,171

[1]Only the northern portion of New York (ecological provinces 211–Northeastern Mixed Forest and M211–Adirondack-New England Mixed Forest) is included in this report.

[2]Includes other federal agencies such as the National Park Service and Fish and Wildlife Service in the U.S. Department of the Interior, and the Department of Defense.

area is publicly owned, which includes federal, state, and local ownership. The U.S. Forest Service manages approximately 1.3 million acres, about 3 percent of the forest area, in the Green Mountain National Forest in Vermont and the White Mountain National Forest in New Hampshire and western Maine. About 1 percent of the forest area is owned by other federal agencies and includes such places as the Silvio O. Conte National Fish and Wildlife Refuge located in parts of Connecticut, Massachusetts, New Hampshire, and Vermont; the Appalachian National Scenic Trail, which starts in Maine and traverses all states in the assessment area except Rhode Island; and Marsh-Billings-Rockefeller National Historical Park in Vermont. Notable among state-owned lands is the Adirondack Forest Preserve in northern New York, which contains 2.6 million acres of forest interspersed within a patchwork of private lands (New York Department of Environmental Conservation 2016). Lands in the Adirondack Forest Preserve were afforded protection through the state constitution in the late 1800s to be “forever kept as wild forest lands.” The broader 6-million-acre Adirondack Park encompasses the Forest Preserve along with other public and private lands. About 3 percent of forest land in the assessment area is owned by local governments, and this ownership is most common in southern New England; about 10 percent of forest

Box 4: Owner Motivations for Land Management

Family forest owners were asked about their reasons for owning forest land as part of the National Woodland Owner Survey (Butler et al. 2016). The leading reasons that most families acquire or retain forest lands were related to beauty, protection of nature, privacy, family legacy, and hunting or other recreational activities (Butler et al. 2016). Fewer than 25 percent of families owned forest for the primary purposes of firewood production, timber production, or the collection of nontimber forest products. Family owners can enroll their lands in conservation easements or forest certification programs, such as the American Tree Farm System, which require forests to have written management plans. Engaged family forest owners often look to extension agents, conservation districts, and private consultants to provide technical assistance and other resources for managing forests.

Industrial forest landowners manage for timber products. Many industrial forest landowners voluntarily participate in third-party certification, but millions of acres of corporate land have been transferred to real estate investment trusts (REITs) and timberland investment management organizations (TIMOs) in recent decades (Bliss et al. 2009, Jin and Sader 2006). REITs and TIMOs are considered private (nonindustrial) forest landowners. They have been acquiring large areas of land and receiving much attention in the last 20 years. REITs own and operate income-producing real estate and timberland holdings, sometimes made public through trading of shares on a stock exchange. REITs are required to distribute at least 90 percent of taxable income to shareholders annually, which is an allowable deduction from corporate taxable income. TIMOs act as investment managers for institutional clients who therefore own the timberlands as investments or partnership shares (Fernholz et al. 2007). The goal is to maximize the growth of the timberland asset, and the TIMOs advise on management of the timberland. In contrast to corporate holdings, the risk of large investment losses is spread out among investors, as are the frequency and rate at which capital gains are taxed. The purchase of timberland by REITs and TIMOs raises concerns about parcelization, development, and high-yield management practices due to landholding objectives and timeframes (Bliss et al. 2009, Fernholz et al. 2007, Jin and Sader 2006).

Public (federal, state, and local) agencies and tribal organizations own extensive tracts of forest in the assessment area. These lands are often managed to provide a complex array of environmental benefits based on public or community needs, which may include wildlife habitat, water protection, nature preservation, timber production, recreation, cultural resources, and a variety of other uses (Shifley et al. 2012).

lands in Connecticut, Massachusetts, and Rhode Island are owned by local entities.

The majority of forest land, more than 30 million acres and about 80 percent of all forest, is privately held. This category reflects a diversity of landowner types, including industrial and corporate organizations in northern New England, conservation organizations, families, individuals, and tribes (Oswalt et al. 2014). Private ownership patterns are complex and change over time. For example, in recent decades a substantial amount of forest previously owned by the forest products industry has been sold to real estate investment trusts and timber investment management organizations (Box 4). Regionally, about one-quarter of privately owned land is currently held by corporate entities (Shifley et al. 2012).

Changes are also occurring among smaller private landowners, and these changes affect how forests are managed across the landscape (Box 4). Many parts of the Northeast are experiencing population growth, with development expanding into forested areas to support new primary and secondary homes and associated amenities (Ducey et al. 2016, Olofsson et al. 2016). Although the total area of forest land has been relatively stable in recent decades, the average size of forest parcels has decreased (Shifley et al. 2012). The size of forest ownerships affects many behaviors among family forest owners (Butler 2008, Butler et al. 2016). Family forest owners with larger parcels are more likely to engage in forest management, conservation easements, cost-share programs, and forest certification programs (Butler 2008). Smaller parcels are managed with less efficiency in terms of writing and executing management plans, and as parcel size decreases, public access and wildlife habitat can be threatened, for example by residential development of forest land (Shifley et al. 2012). Concern about the loss of forests and associated environmental benefits in the region has spurred greater action to protect lands through conservation easements and other activities (Foster et al. 2010, Meyer et al. 2014).

Forest Harvest and Products

Forests contribute to the Northeast's economically important wood products industry. For example, more than 750 million cubic feet of wood was harvested for commercial use across the region in 2006, which is nearly 5 percent of national production (Shifley et al. 2012). This material includes saw logs, veneer logs, pulpwood, fuelwood, and other wood products used by wood processing mills and other facilities in the region. Saw logs and pulpwood make up the majority of wood use, although some states—notably Vermont and New York—also produce a substantial amount of fuelwood (Shifley et al. 2012).

More than 36 million acres, or 90 percent, of the forest land in the region is classified as timberland, meaning that it is considered suitable for wood production because forest harvesting is not prohibited. Across the assessment area, the amount of wood harvested each year is less than the amount of forest growth (Fig. 9). This comparison of net annual forest growth to removals provides a relative indicator of pressure to use the timber resource (Butler et al. 2011, Shifley et al. 2012). The growth-to-removals ratio is based on FIA data and compares net growth (i.e., gross growth minus mortality) to removals from forest management for forested lands. Values greater than 1.0 indicate that net annual growth is greater than annual removals and that the timber resource is increasing across the landscape (Butler et al. 2011). The growth-to-removals ratio for the assessment area was 1.8 during the most recent inventory period. This means that forest growth was about 80 percent greater than removals, although this value varies by location and forest-type group (Fig. 9).

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

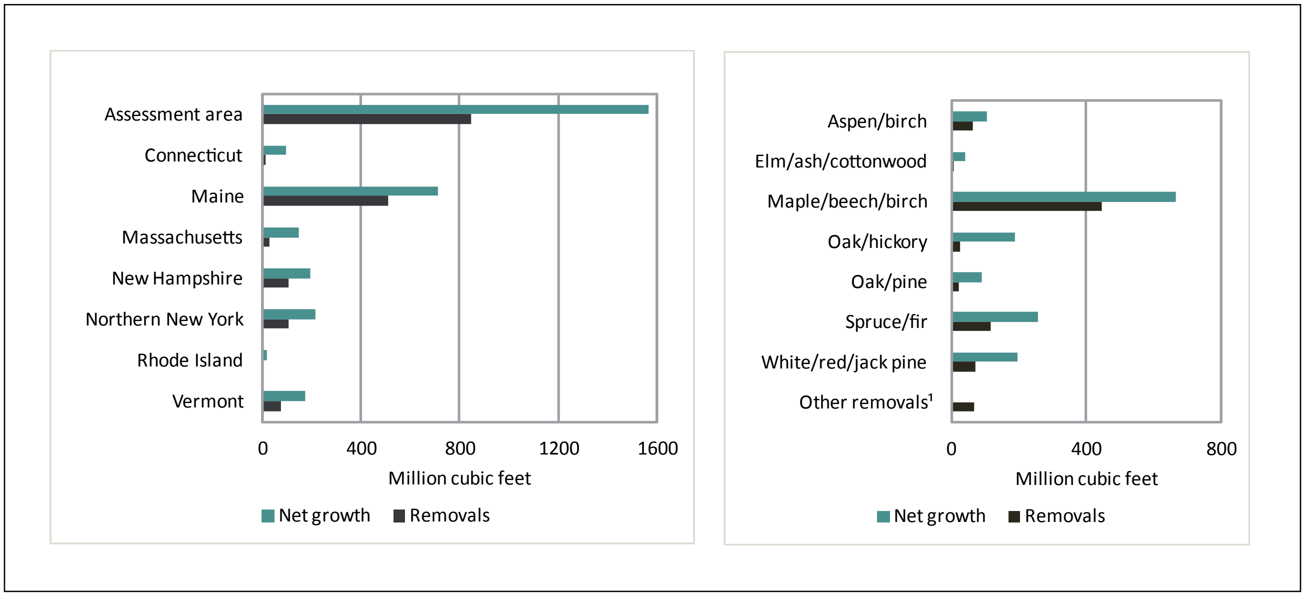

Figure 9.—Annual net growth and removals for individual states and the entire assessment area (left) and major forest-type groups (right) in the assessment area.

[1]"Other removals" refers to net growth and losses associated with changes in land use, such as conversion from forest to nonforest uses. Data source: U.S. Forest Service (2015).

oak/hickory had the highest growth-to-removals ratio (7.0), and most forest-type groups had ratios greater than the regional average. Removals from forest management and timber harvest in the assessment area were greatest in the most commercially important forest-type groups: maple/beech/birch (53 percent of total removals), spruce/fir (14 percent), and white/red/jack pine (9 percent).

Other removals—a category that includes loss of forest growth to conversion of land to other uses or to a protected (nontimberland) status—represented 8 percent of removals. Accounting for state size, Connecticut, Massachusetts, and Rhode Island had a higher volume of other removals (i.e., growing stock converted to nontimber or nonforest land uses) than the areas farther north. At the same time, these three states also had higher growth-to-removals ratios, which points to a lower level of forest utilization for wood products. Combined, the data provide evidence of both lower levels of forest harvest in southern New England and a higher rate of conversion to nontimber or nonforest land uses.

SUMMARY

Forests are a defining feature across the Northeast and 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, carbon storage, economic and cultural resources, and other values. The context presented in this chapter will be helpful for interpreting information in the chapters that follow. It may be particularly important to refer to this information when considering information on climate change impacts (Chapter 4), forest ecosystem vulnerability (Chapter 5), and connections with other aspects of natural resource management and planning (Chapter 6).

CHAPTER 2: OBSERVED CLIMATE CHANGE

As discussed in Chapter 1, climate is one of the principal factors that have determined the composition and extent of regional forest ecosystems over the past several thousand years. This chapter describes the climate trends in the assessment area that have been observed over the past century, including documented patterns of climate-related processes and extreme weather events. It also presents evidence that regional ecosystems are already exhibiting signals that they are responding to shifts in temperature and precipitation.

OBSERVED TRENDS IN TEMPERATURE AND PRECIPITATION

Temperature

The entire northeastern United States has experienced substantial changes in temperature and precipitation over the past 100 years (Kunkel et al. 2013). Although there is variation in annual mean (average) temperature from year to year, there is a long-term warming trend (Fig. 10) that is consistent with changes observed at state, continental, and global scales (Intergovernmental Panel on Climate Change [IPCC] 2013). Across the assessment area, the mean annual temperature increased by about 2.4 °F (1.3 °C) between 1901 and 2011 (Fig. 10) based on data from the Climate Wizard Custom tool (Box 5, Appendix 2).

Among individual seasons, the greatest temperature change during the 20th century was observed in winter, with an estimated increase in mean temperature of 3.5 °F (1.9 °C) and an increase in minimum (low) temperature of 4.2 °F (2.3 °C) across the assessment area. Warming has been pronounced throughout the winter; the greatest increases in mean, minimum, and maximum temperatures were observed in February (Fig. 11). Mean and minimum temperatures have increased over all seasons and months, whereas changes in maximum temperature have been more variable (Figs. 11, 12; Appendix 2). Observed temperature increases are spatially heterogeneous across the region. For example, temperatures at five weather stations across New Hampshire showed increases in minimum temperatures ranging from 0.4 °F (0.2 °C) to 2.9 °F (1.6 °C) during 1895 through 2012 (Wake et al. 2014a, 2014b). There are no clear trends in geographic variability across the region (Fig. 12), and notable increases or decreases in mapped data should be regarded with some skepticism because of the potential for localized anomalies or errors (Beier et al. 2012a).

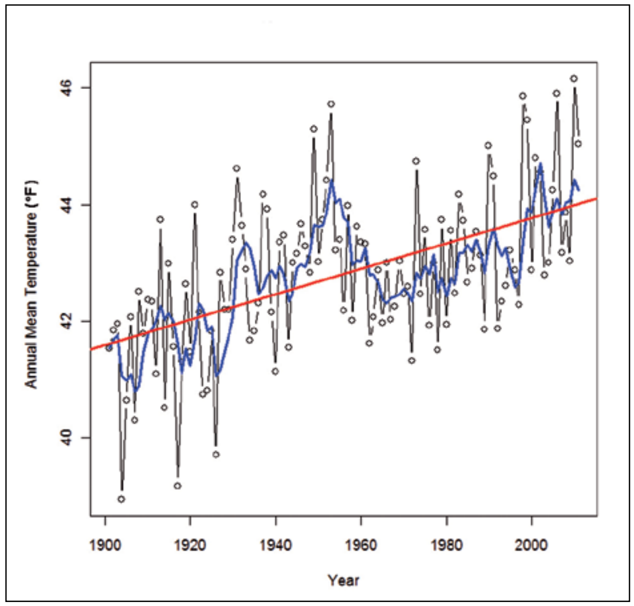

Figure 10.—Mean annual temperature across the assessment area, 1901 through 2011. Open circles represent the mean for each year. The blue line represents the rolling 5-year mean. The red regression line shows the trend across the entire time period (a rate of increase of 0.022 °F/year). Data source: Climate Wizard (2014).

Box 5: Where Are these Data from?

Weather stations in the Northeast have recorded measurements of temperature and precipitation for more than 100 years, providing a rich set of information to evaluate changes in climate over time. The Climate Wizard Custom Analysis Application was used to estimate the changes in temperature and precipitation across the assessment area (Climate Wizard 2014, Girvetz et al. 2009, Karl et al. 1996). This tool uses data from PRISM (Parameter-elevation Regressions on Independent Slopes Model) (Gibson et al. 2002, Karl et al. 1996), which converts measured point data from weather stations onto a continuous 2.5-mile grid over the entire United States. Temperature and precipitation data for the assessment area were used to derive long-term trends in annual, seasonal, and monthly values for the period 1901 through 2011. Additional details about the data presented in this chapter are available in Appendix 2.

Gridded historical climate products like the PRISM-based data used in this assessment can be helpful for understanding recent climatic changes at regional scales to support decisionmaking, but there are also some caveats that limit the ways that they should be used (Beier et al. 2012a, Bishop and Beier 2013). One major challenge is that data are interpolated (spatially estimated) in the areas between existing weather stations, which increases the uncertainty of the values in areas that have few weather stations. Additionally, the statistical methods used to develop these products are less robust at high elevations and in areas with complex topography and potentially overestimate or underestimate the change occurring in a particular location (Beier et al. 2012a). These limitations suggest that maps are best used to understand the overall trends that have been observed across the region (and which are supported by multiple lines of evidence) and are less appropriate for evaluating the amount of change in a specific location.

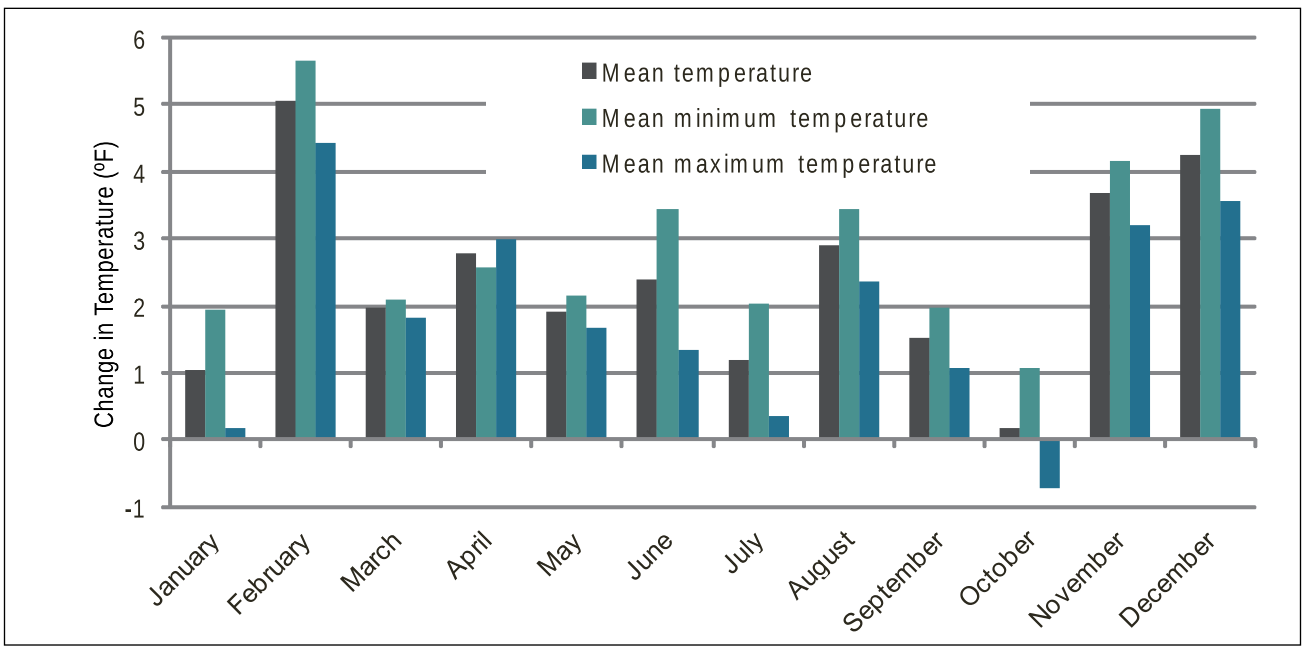

Figure 11.—Change in mean monthly temperature across the assessment area, 1901 through 2011. Data source: Climate Wizard (2014). Values are provided in Appendix 2.

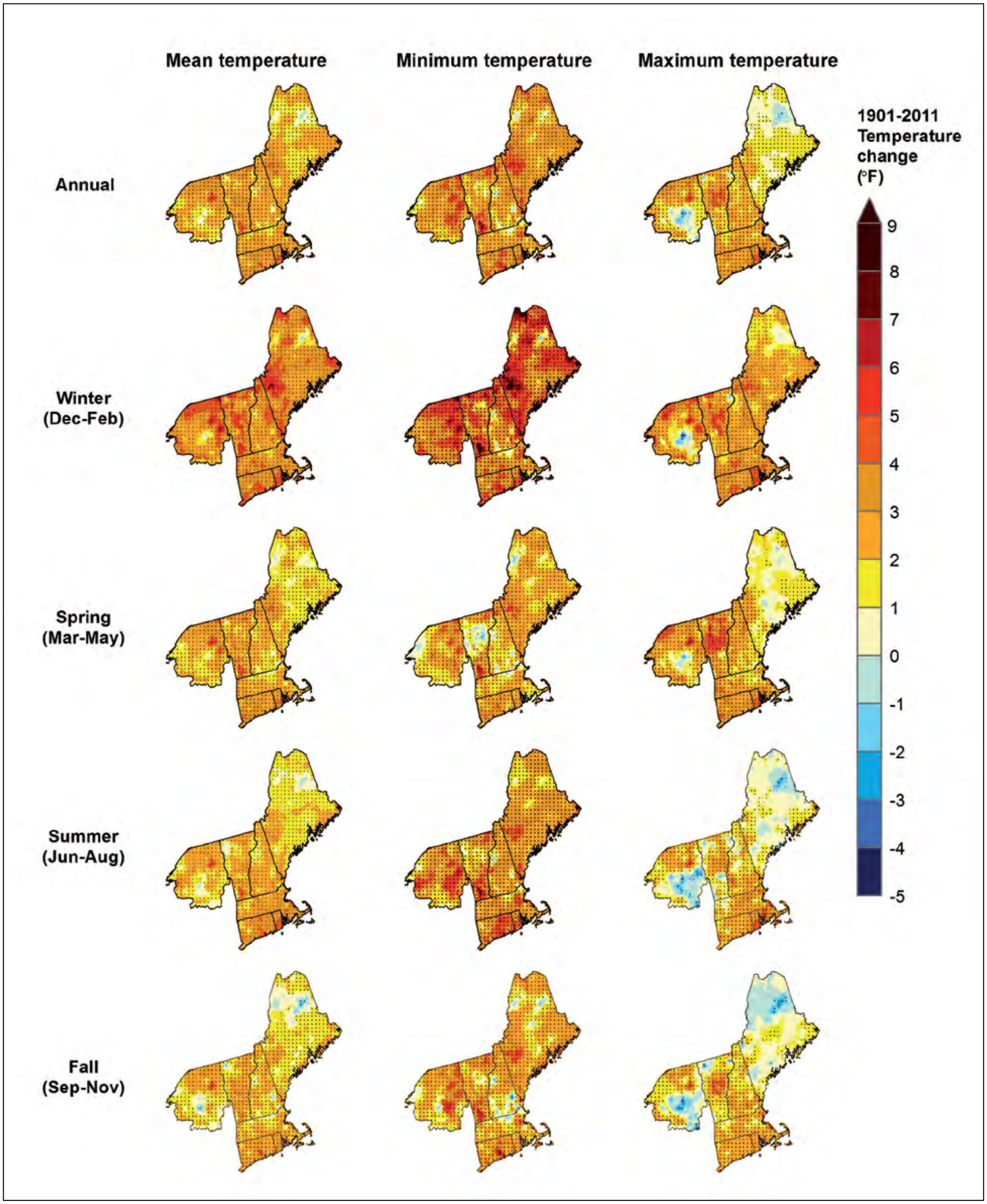

Figure 12.—Estimated change in annual and seasonal mean, minimum, and maximum temperature in the assessment area, 1901 through 2011. Stippling indicates there is less than 10-percent probability that the trend could have occurred by chance alone. Data source: Climate Wizard (2014). Additional information is available in Appendix 2.

The general trend toward increasing temperatures in the assessment area is similar to observations that have been reported elsewhere. The mean surface air temperature across the globe increased 1.5 °F (0.85 °C) over the last century (IPCC 2013). Average temperature across the United States warmed by 1.3 to 1.9 °F (0.7 to 1.1 °C) since 1895, with most of the increase occurring since 1970 (Melillo et al. 2014). Across the Northeast, temperatures rose an average of 0.16 °F (0.06 °C) per decade during 1885 through 2011, for a total increase of about 1.8 °F (1.0 °C) during that period (Kunkel et al. 2013).

Growing Season Length

Warmer temperatures have resulted in a longer freeze-free season and longer growing season across the region (Frumhoff et al. 2007, Kunkel et al. 2013). The freeze-free season, which is the period between the last occurrence of 32 °F in the spring and the first occurrence in the fall, was about 10 days longer in the Northeast during 1991 to 2010 compared to 1961 to 1990 (Kunkel et al. 2013). An examination of the end of season for forests (based on leaf senescence) from 1989 to 2008 found that the end of season is occurring later in the fall and that for much of the region, the delay in end of season is related to the number of cold-degree days (Dragoni and Rahman 2012). Increases in the growing season length and other climatic factors have caused noticeable changes in the timing of biological activities in the Northeast as well as across the world (Ellwood et al. 2013, Schwartz et al. 2006, Walther et al. 2002) (Box 6).

Box 6: Ecological Indicators of Climate Change

The timing of biological events, such as bird migration, wildlife breeding, and plant flowering and fruiting is determined by many variables, including seasonal temperature, food availability, and pollination mechanisms (Bradley et al. 1999). Numerous phenological changes have been observed across the region, such as the following:

Water

- Winter ice cover on lakes has declined by 2 or more weeks across much of the region (Beier et al. 2012b, Hodgkins et al. 2002).
- On rivers across New England, the timing of spring flows advanced by 1 to 2 weeks during the last three decades of the 20th century (Hodgkins et al. 2003).

Plants

- The green canopy duration of trees at Hubbard Brook Experimental Forest in New Hampshire increased about 10 days during a 14-year period (Richardson et al. 2006).
- The date of first flowering is 1 week earlier on average compared to Henry David Thoreau's records from the mid-1800s. Highbush blueberries and slender yellow woodsorrel are flowering several weeks earlier (Miller-Rushing and Primack 2009). Invasive and nonnative species have been better able to respond than native species (Willis et al. 2010).
- Comparison of the same clone of lilac across 72 sites in the Northeast showed a 4-day advancement since the 1960s (Wolfe et al. 2005).

Animals

- Migratory birds are arriving earlier and breeding earlier, with the ranges of some species shifting or contracting (Rahbeck et al. 2007, Waite and Strickland 2006, Zuckerberg et al. 2009) (Fig. 13).

Figure 13.—Nashville warbler, one of several northern bird species that have been observed as having a northward shift in southern range boundaries (Zuckerberg et al. 2009). Photo by Bill Thompson, used with permission.

Precipitation

Regional precipitation patterns have also changed over the past century (Kunkel et al. 2013, Spierre and Wake 2010). Although annual mean precipitation varies widely from year to year, there is a trend toward greater annual precipitation in the assessment area. Mean annual precipitation increased by 6.9 inches, or about 16 percent, across the assessment area from 1901 through 2011 (Figs. 14, 15). Precipitation patterns have also changed across seasons. Seasonally, the greatest increase was observed during the fall (3.0 inches), and the smallest increase during winter (0.6 inch) (Figs. 15, 16). It is important to note that monthly (Fig. 15) and seasonal averages combine data from across the assessment area, and that changes are geographically variable across the landscape (Fig. 16).

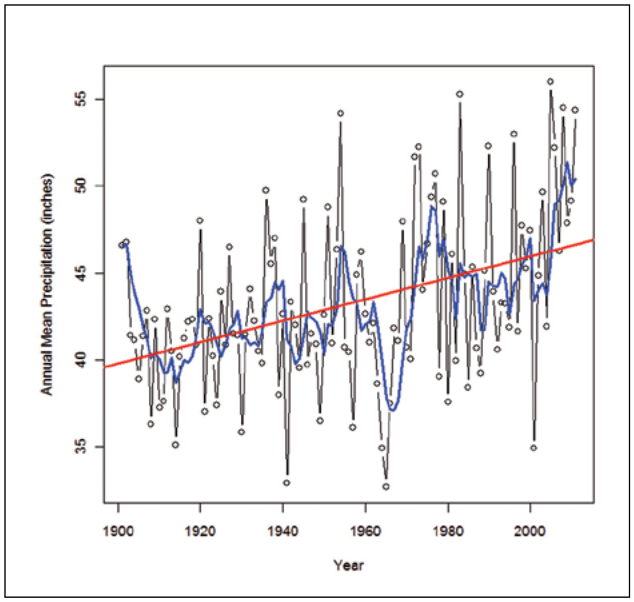

Figure 14.—Mean annual precipitation across the assessment area, 1901 to 2011. Open circles represent the mean for each year. The blue line represents the rolling 5-year mean. The red regression line shows the trend across the entire time period (a rate of increase of 0.062 inches/year). Data source: Climate Wizard (2014).

These observed changes in precipitation are consistent with observations reported elsewhere. Across the Northeast, annual precipitation increased 0.43 inch per decade between 1895 and 2011, which translates to a total increase of about 5 inches during that period (National Oceanic and Atmospheric Administration [NOAA] National Climatic Data Center 2014, Rahbek et al. 2007). Precipitation across the six New England states increased 0.56 inch per decade, or 6.6 inches total, from 1895 through 2011 (NOAA National Climatic Data Center 2014). Another study points to a precipitation increase of nearly 0.75 inch per decade across the Northeast, or about 4.3 inches total, from 1948 through 2007 (Spierre and Wake 2010).

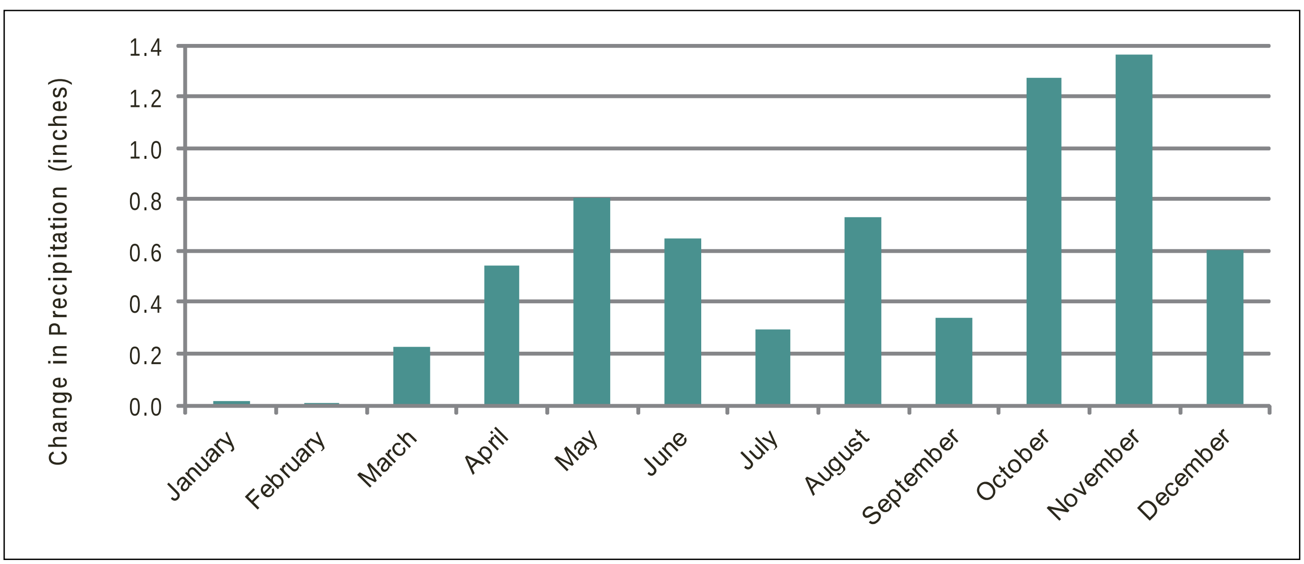

Figure 15.—Change in mean monthly precipitation across the assessment area, 1901 through 2011. Data source: Climate Wizard (2014).

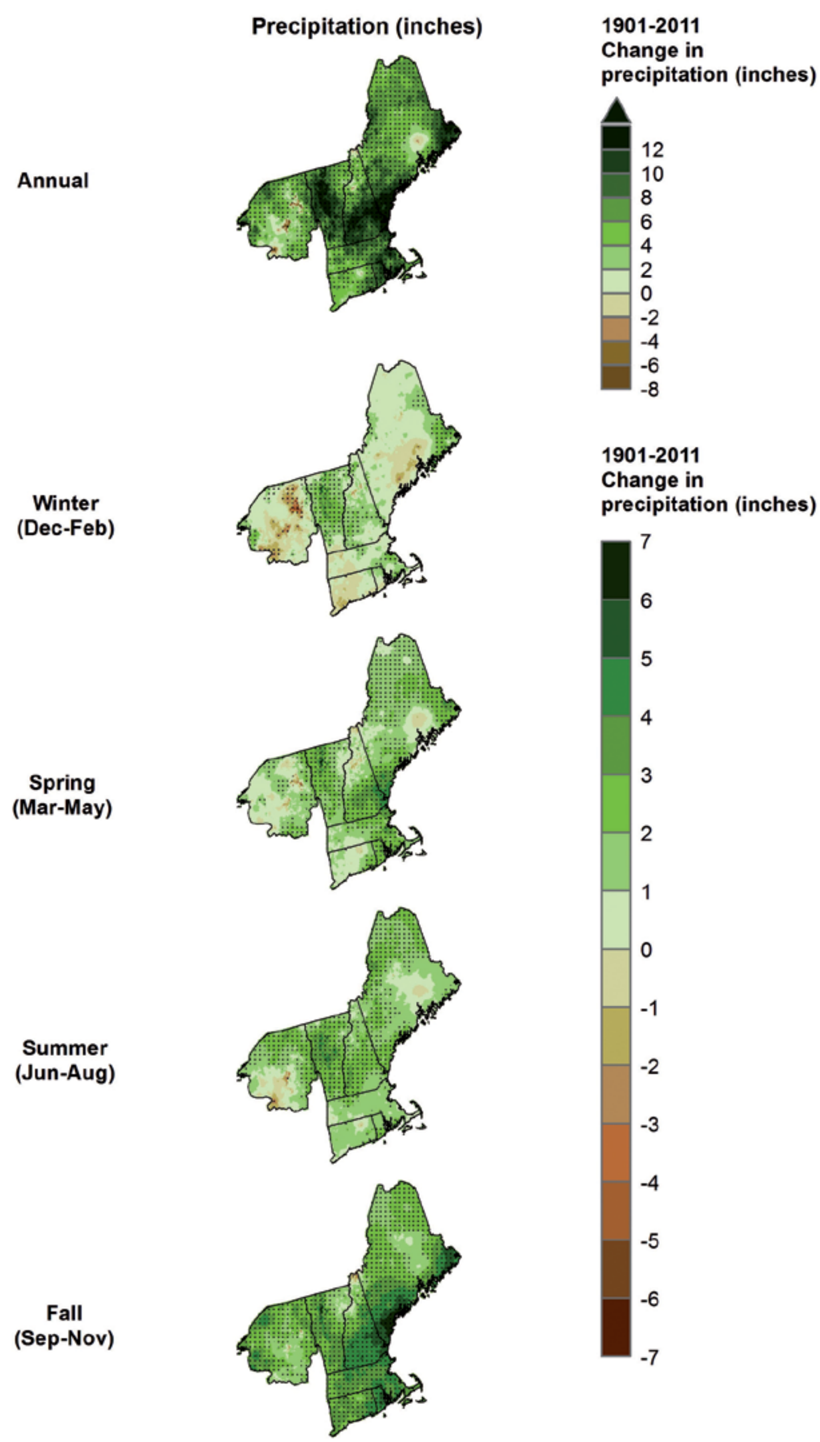

Figure 16.—Estimated change in annual and seasonal precipitation in the assessment area, 1901 through 2011. Stippling indicates there is less than 10-percent probability that the trend could have occurred by chance alone. Data source: Climate Wizard (2014). Additional information is available in Appendix 2.

Precipitation has generally increased across the assessment area, with high levels of variability from year to year (Hayhoe et al. 2007, Kunkel et al. 2013, NOAA National Climatic Data Center 2014, Waite and Strickland 2006) (Box 7). Additionally, the frequency of consecutive wet days has increased, while the number of consecutive dry days has decreased (Brown et al. 2010). The Northeast has generally had some of the greatest precipitation increases of any region in the United States, and the past four decades have been wetter than during the period from 1901 through 1960 (Melillo et al. 2014).

OBSERVED TRENDS IN EXTREME WEATHER EVENTS

Weather or climate extremes are defined as individual weather events or long-term patterns that are unusual in their occurrence or have destructive potential (Karl et al. 2008). These events can trigger catastrophic disturbances in forest ecosystems and can have significant socioeconomic impacts. There is evidence that extreme events are becoming more frequent and severe across the United States and globally, in part due to global climate change (Coumou and Rahmstorf 2012, IPCC 2012, Kunkel et al. 2008, Thibeault and Seth 2014). It is difficult to directly attribute the occurrence of a single event to climate change, although researchers are increasingly identifying changes in the underlying thermodynamic and biophysical relationships contributing to these events (Coumou and Rahmstorf 2012, Stott et al. 2010, Trenberth et al. 2015).

Temperature Extremes

Warmer mean temperatures are often correlated with higher extreme temperatures (Kling et al. 2003, Kunkel et al. 2008). The number of hot days and heat waves has increased across much of the United States (Kunkel et al. 2008, Melillo et al. 2014). In the Northeast, however, the occurrence of heat waves did not change during the 20th century (Kunkel et al. 2013). There were fewer intense heat waves from the late 1950s into the early 1980s than during periods earlier or later in the century. Some increases in the number of hot days and heat waves have been observed since the 1980s with moderately high heat wave index values occurring in 2001, 2002, 2010, and 2011 (Frumhoff et al. 2007, Kunkel et al. 2013).

Box 7: Drought

State-level data show particularly wet growing-season conditions since about 2005 in Maine, New Hampshire, and Vermont (NOAA National Climatic Data Center 2014), but in 2016, these states and the rest of the Northeast experienced the worst drought conditions since the 1960s. Droughts are among the greatest stressors on forest ecosystems, and can often lead to secondary effects of insect and disease outbreaks on stressed trees and increased fire risk. In North America and the United States, there has been a trend toward wetter conditions since 1950, and there is no detectable trend for increased drought based on the Palmer Drought Severity Index (Dai et al. 2004). Other studies of hydrologic trends over the last century generally observed little change or slight reductions in the duration and severity of droughts across the Northeast as a result of increased precipitation (Andreadis and Lettenmaier 2006, Peterson et al. 2013b). Regional data from the Northeast support this general pattern (NOAA National Centers for Environmental Information 2017, Peters et al. 2014). Between 1895 and 2014, there has been no change in drought incidence during the growing season (June through September), with the mid-1960s representing the most extreme droughts during the period of record (Kunkel et al. 2013, NOAA National Climatic Data Center 2014).

The number of extremely cold weather events appears to be decreasing. Minimum temperatures have increased more than maximum temperatures in many parts of the United States, including the Northeast (DeGaetano and Allen 2002, Peterson et al. 2008). These trends correspond to global and regional patterns of increasing occurrence of extreme hot weather and decreasing occurrence of extreme cold weather (Brown et al. 2010, Hansen et al. 2012).

Precipitation Extremes

Despite the high amount of variability in the number of extreme precipitation events that occur in any single year or decade, there is clear evidence that large precipitation events have become more frequent in the region over the past century (Kunkel et al. 1999, 2013; Melillo et al. 2014). Extreme precipitation events totaling more than 2 inches in 48 hours increased during the 1980s and 1990s (Frumhoff et al. 2007). Another study found that most weather stations in the Northeast had increases of 1- and 2-inch precipitation events from 1948 through 2007, and nearly 75 percent of stations also showed increases in 4-inch precipitation events during that period (Spierre and Wake 2010) (Fig. 17).

Another way to estimate the change in extreme precipitation events is to look at the 99th percentile of rainfall during a 24-hour period. Between 1948 and 2007, 86 percent of weather stations in the Northeast showed an increasing trend in the magnitude of the 99th percentile value. Across the Northeast, the heaviest 1 percent of daily precipitation events increased 71 percent between 1958 and 2012, the most of any region in the United States (Melillo et al. 2014). Similarly, recurrence intervals (such as a 50-year event) are also shorter than in the past (DeGaetano 2009).

Severe Storms

Numerous types of storms occur in the region as a result of its diverse climate, including thunderstorms, ice storms, tropical cyclones and hurricanes, and nor'easters (Kunkel et al. 2013). There is evidence of poleward movement among storm tracks in

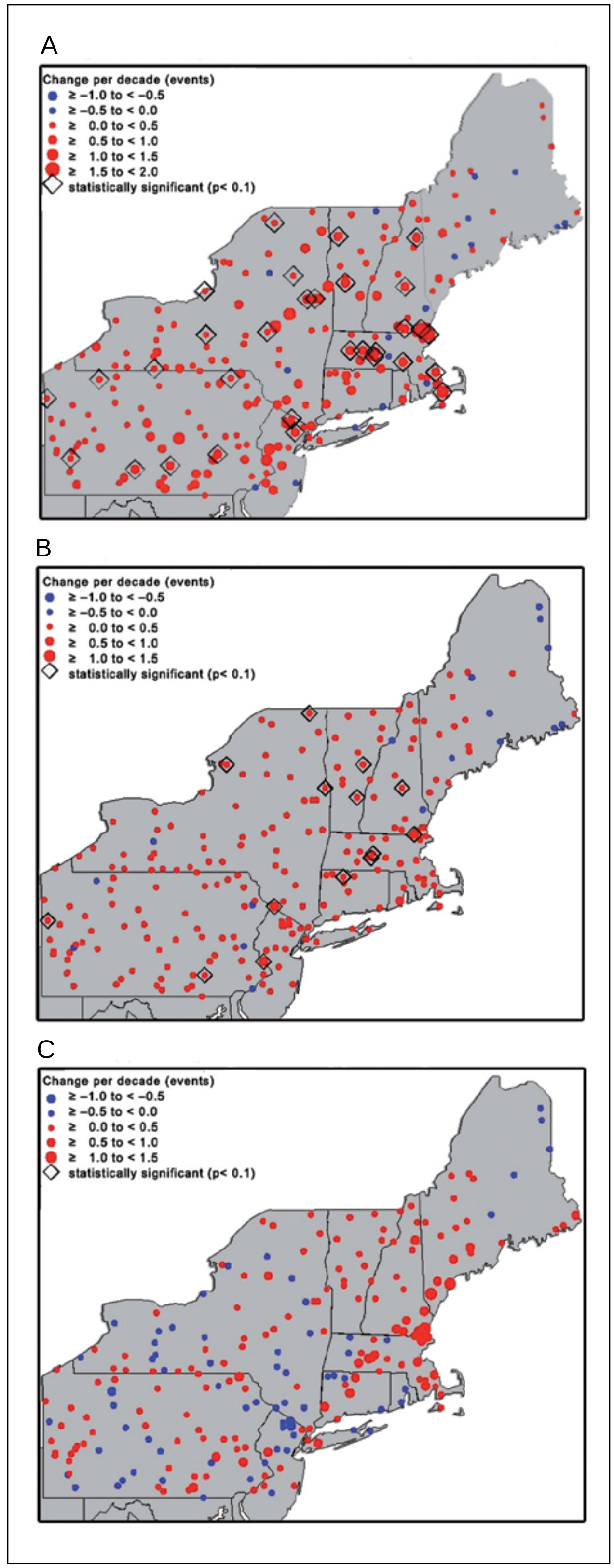

Figure 17.—Change in extreme precipitation events in the Northeast and Pennsylvania between 1948 and 2007: mean decadal change in (A) 1-inch events, (B) 2-inch events, and (C) 4-inch events (adapted from Spierre and Wake [2010], used with permission).

the North Atlantic since the middle of the 20th century, which may influence the pattern of storms (Huntington et al. 2009). The relative infrequency of extreme events and lack of consistent, long-term datasets create substantial challenges for detecting changes over time (Easterling et al. 2000, Kunkel et al. 2012) (Box 8). For example, a study of severe thunderstorm observations over the eastern United States identified an increase in thunderstorm frequency over the last 60 years, but it is difficult to assess whether those increases are biased by increased accuracy in storm reporting (Robinson et al. 2013). As a result, there has been a shift away from using observational data on thunderstorms to examining the environmental conditions associated with these events (Kunkel et al. 2012). Similarly, research on the frequency and intensity of tropical storms and hurricanes has turned up a variety of results (Box 9).

OBSERVED TRENDS IN SEA LEVEL

Climate change has caused substantial sea-level rise both globally and regionally. Sea-level rise is the result of numerous interacting dynamic forces within the oceans. As water temperatures increase, water expands and increases the volume of the

Box 8: Climate Variability

"… [O]ne of the brightest gems in the New England weather is the dazzling uncertainty of it. There is only one thing certain about it, you are certain there is going to be plenty of weather."
~Mark Twain

Although there is increasing and unequivocal evidence that the planet is warming and that the global climate is changing (IPCC 2007a, 2013), one of the challenges is distinguishing between the long-term trends that are attributable to climate change and those changes that are a result of natural climate variability. This can be particularly challenging in the northeastern United States because the regional climate generally has high levels of variability (Kunkel et al. 2013). Extreme events—including hurricanes, extreme wind, ice storms, and droughts—are influenced by changes in the Earth's climate, and many of these extreme events have increased in frequency or severity in recent decades (IPCC 2012). Although it is not possible to attribute a single event to climate change (Coumou and Rahmstorf 2012, Jacobson et al. 2009, Kunkel et al. 2012, Peterson et al. 2013b), new research is able to discern the relative contribution of climate change to a single event by looking at how an event is affected by known changes in the Earth's thermodynamic state (Herring et al. 2014, Trenberth et al. 2015).

Box 9: Tropical Storms and Hurricanes

Tropical cyclones and hurricanes moving up the Atlantic seaboard also affect the assessment area. From 1900 to 2010, coastal areas in New England were affected by as many as nine hurricanes and numerous tropical storms (Kunkel et al. 2013, Stoner et al. 2012). The assessment area has sustained intense rain, hail, wind, and flooding as a result of hurricanes, with the 1938 hurricane and recent hurricanes Irene and Sandy being particularly notable (Kunkel et al. 2013, Peterson et al. 2013b). Although not every hurricane formed in the Atlantic makes landfall or affects the assessment area, there is some evidence that the strength and frequency of hurricanes have been increasing since 1970, and that this increase is associated with warming sea surface temperatures (Holland and Webster 2007). Based on the average number of hurricanes from 1981 to 2010, the 2011 hurricane season was above average, and was the 12th such above-average season since 1995 (Blunden and Arndt 2012, Melillo et al. 2014). But there is no evidence of change in the frequency of hurricanes that make landfall (Holland and Webster 2007). Trends in severe weather frequency are difficult to attribute to changes in the climate (Kunkel et al. 2012, Peterson et al. 2013b) as recent advances in technology, population density, and social media have contributed to increases in storm reporting (Hayhoe et al. 2007, Miller-Rushing and Primack 2009, Peterson et al. 2013b, Robinson et al. 2013, Willis et al. 2010).

ocean. Melting glaciers and ice sheets further increase the amount of water going into the oceans. These changes cause additional changes to the circulation of the oceans as gradients (differences) in temperature and ocean salinity are altered.

Observations of sea-level rise show greater increases regionally compared to the global trend. Since 1900, the global average sea level rose 8 inches, whereas the increase was 12 inches across the northeastern United States and even more along the New England coastline (Horton et al. 2014). Between 1950 and 2009, observed increases in sea levels along the northeastern coast of North America were 3 to 4 times greater than the global average increase, with accelerating rates of increase in recent decades (Boon 2012, Holland and Webster 2007, Sallenger et al. 2012, Zuckerberg et al. 2009). The larger increase in the Northeast is a result of many complex factors including land subsidence and changes in oceanic currents (Horton et al. 2014). Sea levels are not constant across the world due to differences in water temperature and salinity, the shape of the Earth, and the Earth's rotation. Sea levels along the northeastern coast of North America were historically lower than elsewhere as a result of pressure gradients associated with the Atlantic Meridional Overturning Circulation (Boon 2012, Sallenger et al. 2012). In the Northeast, sea-level rise over the last century has increased the risk of erosion, damage from storm surges, flooding, and damage to infrastructure and coastal ecosystems.

OBSERVED HYDROLOGIC CHANGE

Snowfall and Snow Cover

Cold and snowy winters are characteristic of much of the region, particularly in the north. Cold-season precipitation has increased across much of the northeastern United States in recent decades, but warmer temperatures have resulted in a greater proportion of precipitation falling as rain rather than snow (Burakowski et al. 2008, Huntington et al. 2004). Total snowfall decreased in the region between 1965 and 2005. The largest decreases in snowfall occurred in December, with smaller decreases in February (Burakowski et al. 2008). Although snowfall amounts are quite variable from year to year, these results are similar to other observations of fewer heavy snowfall years across the Northeast during the last 30 years (Kunkel et al. 2013). The change in cold-season precipitation patterns also influences the timing and amount of streamflow (Box 10).

Snow cover is also changing. From 1948 through 1988, the average number of days with snow cover greater than 1.0 inch ranged from fewer than 50 days in coastal Connecticut and Rhode Island to more than 100 days in the Adirondack Mountains of New York and in the northern Appalachian Mountains, although there was large year-to-year variation (Leathers and Luff 1997). The number of snow-

Box 10: Streamflow

In New England, peak river flows typically occur in the spring when rain falls on snow or saturated soils (Hodgkins et al. 2003). Warmer temperatures, earlier snowmelt, and increases in winter and early spring rainfall have resulted in peak streamflows occurring earlier in the year (Huntington et al. 2009, Karl et al. 2008, Kunkel et al. 2013). Similarly, the winter/spring center of volume, which is when half of the spring volume of river flow has occurred, advanced across 27 streams in New England where long-term records were available (Hodgkins et al. 2003). The greatest changes were in northern and mountainous areas of New England, where the date has occurred 1 to 2 weeks earlier since the late 1960s. Average annual streamflow also increased on 22 of the 27 streams (Daly et al. 2008, Hodgkins and Dudley 2005, Karl et al. 2008, Walsh et al. 2014), which is similar to other observations of increased flows (Campbell et al. 2011). Higher peak flows can increase flood risk, and there is evidence that flood magnitude has increased across New England since the mid-1900s and particularly since 1970 (Collins 2009, Lins and Slack 1999, Peterson et al. 2013b, Richardson et al. 2006).

Extreme flooding at Hubbard Brook in central New Hampshire. Photo by Scott Bailey, U.S. Forest Service.

covered days decreased across the region between 1965 and 2005, particularly during December, January, and February (Burakowski et al. 2008). Reductions in snow cover appear to be related to increases in winter temperatures as well as the amount of precipitation falling as rain instead of snow (Burakowski et al. 2008, Hamburg et al. 2013, Huntington et al. 2004). The proportion of total precipitation falling as snow decreased at 50 percent of the observation locations in New England during the second half of the 20th century; these changes were predominantly due to decreasing snowfall, although some of the change was due to increasing rainfall at some locations (Huntington et al. 2004). None of the sites examined had a significant increase in the proportion of precipitation falling as snow (Huntington et al. 2004).

Lake and River Ice Cover

Warmer water temperatures and reduced ice cover often interact in a positive feedback cycle where warmer winter air and water temperatures reduce ice cover and increase the duration of open water conditions. The ensuing open water conditions allow the water to absorb more heat, further increasing water temperatures (Austin and Colman 2007). With increases in air temperatures, water temperatures also increase. The timing and extent of lake ice formation have been recorded for more than 100 years across the region, where records of fall ice-in and spring ice-out are used to determine the duration of ice cover (Hodgkins 2013). Ice-out is strongly related to air temperatures in the month or two preceding ice-out and serves as a useful indicator of climate change in winter and spring (Hodgkins 2013, Hodgkins et al. 2002, Magnuson et al. 2000). Ice-out dates advanced substantially between 1850 and 2000, with spring ice-out occurring 9 days earlier in more northerly and mountainous regions and 16 days earlier in southern New England (Hayhoe et al. 2007, Hodgkins et al. 2002). Similarly, earlier ice-out dates and reduced ice thickness were observed on the Piscataquis River in Maine between 1912 and 2001 (Huntington et al. 2003). Long-term records in the Adirondacks show that ice cover is forming later and leaving sooner, resulting in about 40 fewer days of lake ice cover in the 2000s than in the late 1800s (Beier et al. 2012b). These patterns correspond with trends that have been observed across the Great Lakes region, as well as the entire Northern Hemisphere (Jensen et al. 2007, Johnson and Stefan 2006, Kling et al. 2003, Magnuson et al. 2000).

CHAPTER 3: PROJECTED CHANGES IN CLIMATE AND PHYSICAL PROCESSES

Climate across the Northeast has changed over the past century, and it will continue to change in the future. This chapter describes climate projections for the assessment area over the 21st century, including projections related to patterns of extreme weather events and other climatic processes. Temperature and precipitation projections are derived from downscaled simulations of climate models. Information related to future weather extremes and other impacts is drawn from published research.

PROJECTED CHANGES IN TEMPERATURE AND PRECIPITATION

Projections of future climate show the potential for dramatic changes over this century. Temperature and precipitation are projected to change, with important seasonal variations and associated changes in snow and ice cover, growing season length, soil moisture, lake levels, and streamflow. In this chapter, we present climate projections using two climate scenarios, PCM B1 and GFDL A1FI (unless otherwise noted). These data are from a climate dataset where global data have been "downscaled" to provide regional data and a finer spatial scale (Hayhoe 2011). In this chapter, projected climate data for three 30-year periods in the 21st century (2010 through 2039, 2040 through 2069, and 2070 through 2099) are compared with the baseline historical data from 1971 through 2000 (presented in Chapter 1) to determine projected future change from current climatic conditions.

The PCM B1 and GFDL A1FI scenarios used in this assessment are just two of the many climate scenarios that are available for the Northeast (e.g., Karmalker and Bradley 2017, Lynch et al. 2016). The projections from individual models can vary widely, and these two scenarios can generally serve as "bookends" describing a broad range of potential future climatic conditions (Box 11, Appendix 3). Projected changes in temperature and precipitation for GFDL A1FI represent a greater degree of greenhouse gas emissions and projected climate warming than the PCM B1 scenario. When possible, the results from these two scenarios are compared with other datasets that are available for the region.

Temperature

Scientists agree with greater than 90-percent certainty that the global climate will get warmer during the 21st century (IPCC 2007a, 2013). This warming will translate into a wide-ranging set of changes to the climate system, globally as well as locally. The assessment area is projected to experience substantial warming during this century (Figs. 18-21, Box 11, Appendix 3). Although temperatures are projected to increase by 1 to 2 ºF (0.6 to 1.1 ºC) under both scenarios during the 2010 to 2039 period, the projections under the two future scenarios diverge mid-century, with the GFDL A1FI scenario projecting much larger temperature increases. By the end of the century, mean annual temperature (compared to the 1971 through 2000 baseline period) is projected to increase 2.6 ºF (1.4 ºC) under PCM B1 and 7.6 ºF (4.2 ºC) under GFDL A1FI (Fig. 18). There are few trends that describe geographic variations in projected temperature across the region (Figs. 19-21), and decreases or substantial increases in mapped data (i.e., differences in one or a small number of pixels) should be regarded with some skepticism because of the potential for localized anomalies or errors.

Box 11: Where Are these Data from?

In this chapter, we report downscaled climate projections for two scenarios of potential change. These scenarios combine general circulation models (GCMs; also called global climate models) that simulate physical processes on the Earth's surface and in the oceans and atmosphere with greenhouse gas emissions scenarios, which represent potential "storylines" of future climate forcing. The Geophysical Fluid Dynamics Laboratory (GFDL) climate 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 many models and lower than others. In contrast, the Parallel Climate Model (PCM) has lower sensitivity to greenhouse gas concentrations (Kopp et al. 2014, Washington et al. 2000).

These models are paired with different greenhouse gas emissions scenarios that were developed through the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (IPCC 2000, Kunkel et al. 2013). The A1FI scenario has the greatest increases in greenhouse gases by the end of the century and is closer to current trends in greenhouse gas emissions (Raupach et al. 2007), and the B1 scenario has the lowest level of greenhouse gas emissions. The IPCC created newer sets of climate scenarios for use in its Fifth Assessment Report (IPCC 2013). The newer datasets use Representative Concentration Pathways (RCPs) (Karmalkar and Bradley 2017, Knutti and Sedláček 2013, Meinshausen et al. 2011, Taylor et al. 2012). Although it is hard to compare the two sets of scenarios directly, there are many consistencies between the datasets (Knutti and Sedláček 2012). Projections for the greenhouse gas concentrations and global temperature are comparable between the A1FI emissions scenario and RCP 8.5, and between the B1 emissions scenario and RCP 4.5 (Sun et al. 2015).

This report uses two scenarios, GFDL A1FI and PCM B1 (unless otherwise noted), from a statistically downscaled climate dataset (Hayhoe 2011), which span a large range of possible futures. Both models and both scenarios were included in the IPCC Fourth Assessment Report (IPCC 2007b). Although the IPCC (2007b, 2013) and National Climate Assessment (Cook et al. 2016, Hayhoe et al. 2007, Kunkel et al. 2013, Melillo et al. 2014, Thibeault and Seth 2014a) reports present averages of multiple models, we instead selected two models that had relatively good skill at simulating climate in the eastern United States and that bracket a range of temperature and precipitation futures. This approach gives readers a better understanding of the range of projected changes in climate and provides a set of alternative scenarios that managers can use in planning and decisionmaking. It is important to note that actual emissions and temperature increases could be lower or higher than these projections. The actual future climate will be different from any of the developed scenarios, and therefore we encourage readers to consider the range of possible climate conditions over the coming decades rather than one particular scenario.

Using data from the GFDL A1FI and PCM B1 scenarios, we calculated the values for mean, minimum, and maximum temperature and mean precipitation for each season and the entire year for three 30-year periods (2010 through 2039, 2040 through 2069, and 2070 through 2099). We compared these projections for future periods with the baseline historical data from 1971 through 2000, presented in Chapter 1, to determine the projected future change from current climate conditions. Appendix 3 contains additional climate information.

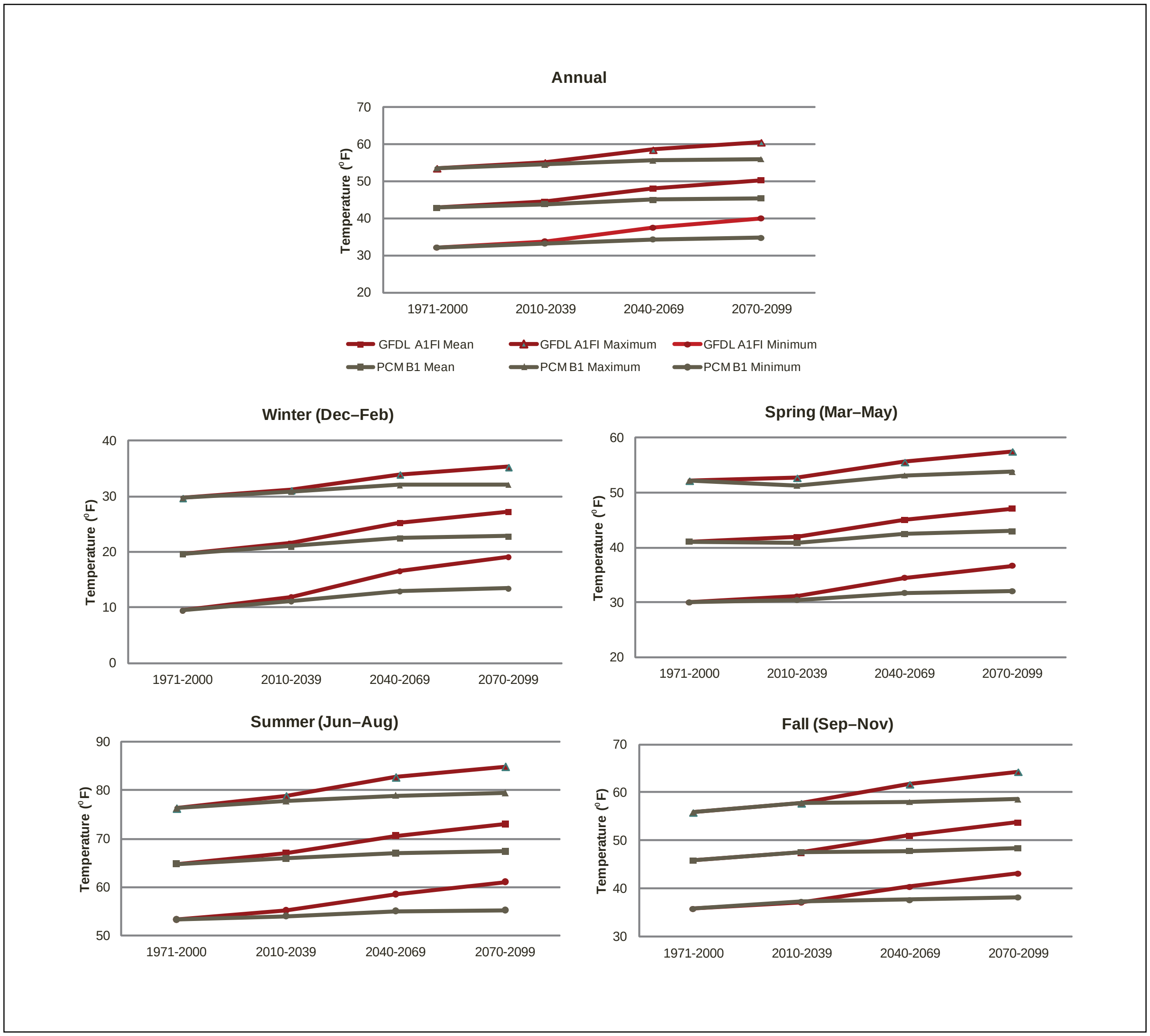

Figure 18.—Projected mean, minimum, and maximum temperature (°F) in the assessment area averaged over 30-year periods for the entire year and by season for two climate model-emissions scenario combinations. The 1971 to 2000 value is based on observed data from weather stations. Note that the panels have different Y-axis values. Data source: Climate Wizard (2014).

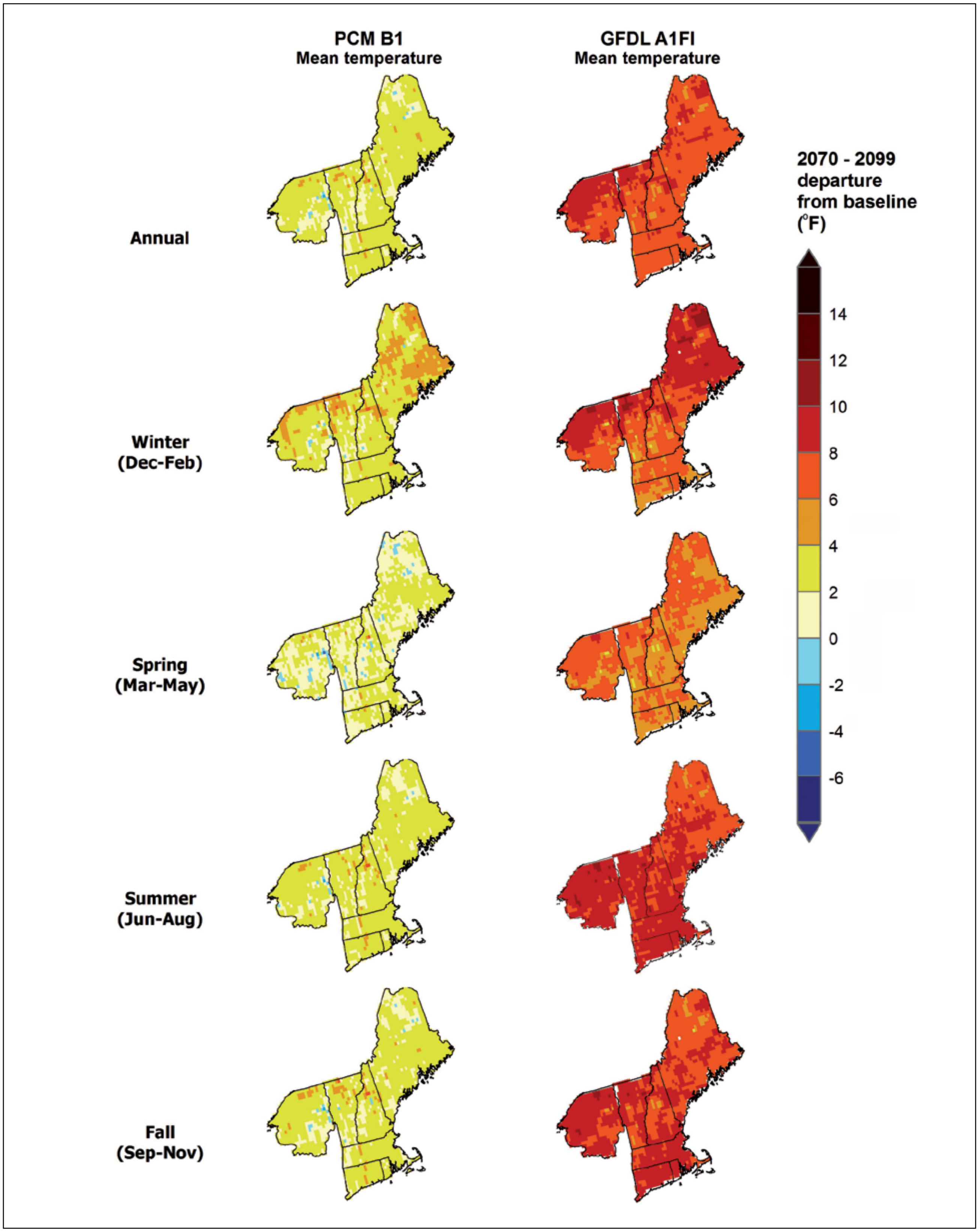

Figure 19.—Projected difference in mean daily mean temperature (°F) at the end of the century (2070 through 2099) compared to baseline (1971 through 2000) for two climate model-emissions scenario combinations.

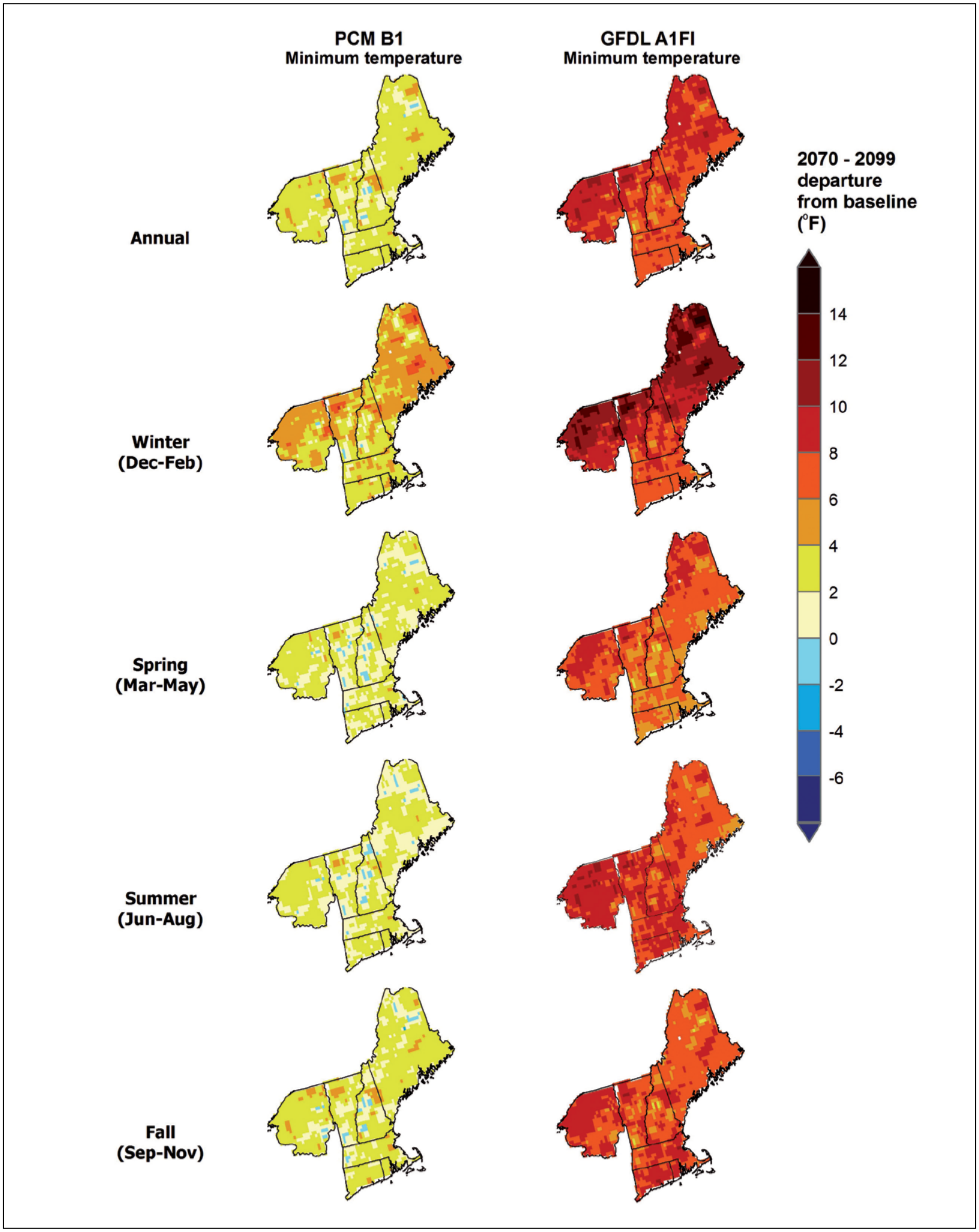

Figure 20.—Projected difference in mean daily minimum temperature (°F) at the end of the century (2070 through 2099) compared to baseline (1971 through 2000) for two climate model-emissions scenario combinations.

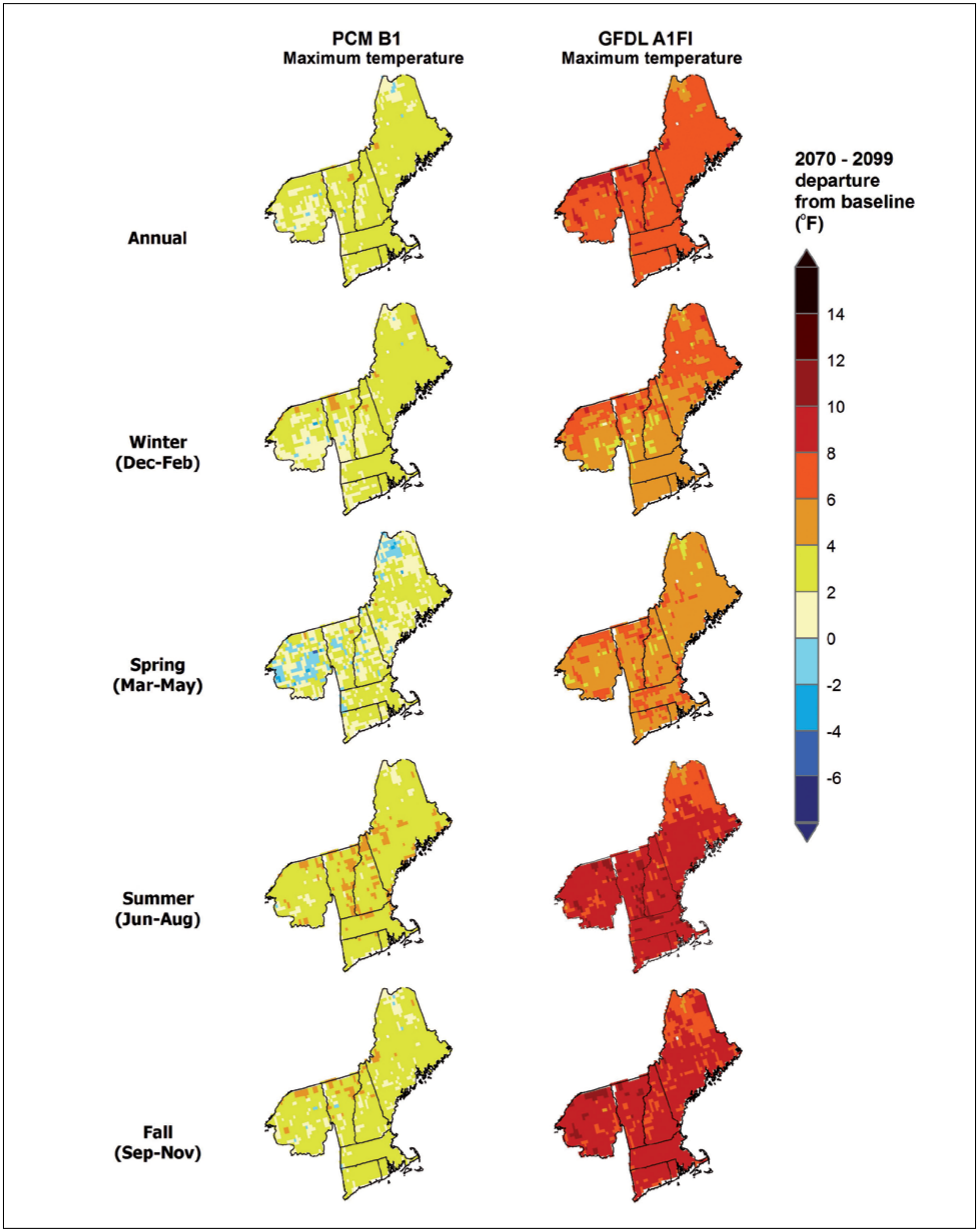

Figure 21.—Projected difference in mean daily maximum temperature (°F) at the end of the century (2070 through 2099) compared to baseline (1971 through 2000) for two climate model-emissions scenario combinations.

Although the two climate scenarios project different amounts of warming, they are in agreement that mean, minimum, and maximum temperature will increase in the assessment area during all seasons. The PCM B1 scenario projects much less warming than the GFDL A1FI scenario for the end of the century. The projected increase in mean temperature by the end of the 21st century is not equal across all seasons. The PCM B1 scenario projects relatively similar amounts of warming throughout the year, with increases of 1.9 to 3.2 °F (1.0 to 1.8 °C) during each season. In contrast, the GFDL A1FI scenario projects larger temperature increases than PCM B1, with all seasons projected to have temperature increases greater than 6.0 °F (3.4 °C). Under GFDL A1FI, the projected temperature increases vary across the seasons, with summer projected to have the most substantial warming with an increase of 8.3 °F (4.6 °C).

By the end of the century, the average annual minimum temperature is projected to increase across the assessment area by 2.7 ºF (1.5 °C) under PCM B1 and 8.0 °F (4.4 °C) under GFDL A1FI (Fig. 20). Winter minimum temperature is projected to increase the most under the GFDL A1FI scenario, warming 9.8 °F (5.5 °C) by the end of the century. Maximum annual temperature is projected to increase by 2.5 to 7.1 °F (1.4 to 3.9 °C) across the two scenarios by the end of the century. Summer maximum temperatures are projected to increase by 3.2 °F (1.8 °C) under PCM B1 and 8.7 °F (4.8 °C) under GFDL A1FI by the end of the century. Extreme temperatures are discussed in more detail later in this chapter.

These data are consistent with several other modeling efforts in the region. Although the temperature increases projected by individual climate models do differ, all models project that the future climate will be warmer and that the magnitude of future warming will be large compared to historical trends (Bryan et al. 2015, Center for Climatic Research 2017, Hayhoe et al. 2007, Kunkel et al. 2013, Lynch et al. 2016). Additionally, climate models from a variety of studies also demonstrate that higher greenhouse gas levels result in a greater degree of warming (Bryan et al. 2015, Center for Climatic Research 2017, Fan et al. 2014, Hayhoe et al. 2007, Karmalkar and Bradley 2017, Kunkel et al. 2013, Lynch et al. 2016).

Growing Season Length

The growing (i.e., freeze-free) season has expanded in the assessment area over the past century, and is expected to continue to expand into the future as a result of warmer temperatures. Although the change in growing season length was not modeled using the PCM B1 and GFDL A1FI scenarios, other modeling efforts project that the growing season length in the assessment area will increase by 20 to more than 50 days under a range of emissions scenarios (Center for Climatic Research 2017, Ning et al. 2015). The projected expansion of the growing season is a result of both earlier spring freeze-free dates and later fall freezes (Center for Climatic Research 2017). Other studies across the Northeast also project similar increases in growing season length throughout the 21st century (e.g., Hayhoe et al. 2007, Kunkel et al. 2013, Ning et al. 2015).

Precipitation

Climate change is expected to alter precipitation regimes and hydrologic conditions throughout the region. The two climate scenarios we chose for this assessment bracket the potential change in temperature across the assessment area. They also describe two markedly different scenarios of future precipitation for the assessment area (Figs. 22, 23). Other future projections of precipitation across the Northeast also differ substantially (Fan et al. 2014, Lynch et al. 2016). For this reason, it is important to keep in mind that other scenarios may project precipitation values outside of the range presented in this assessment.

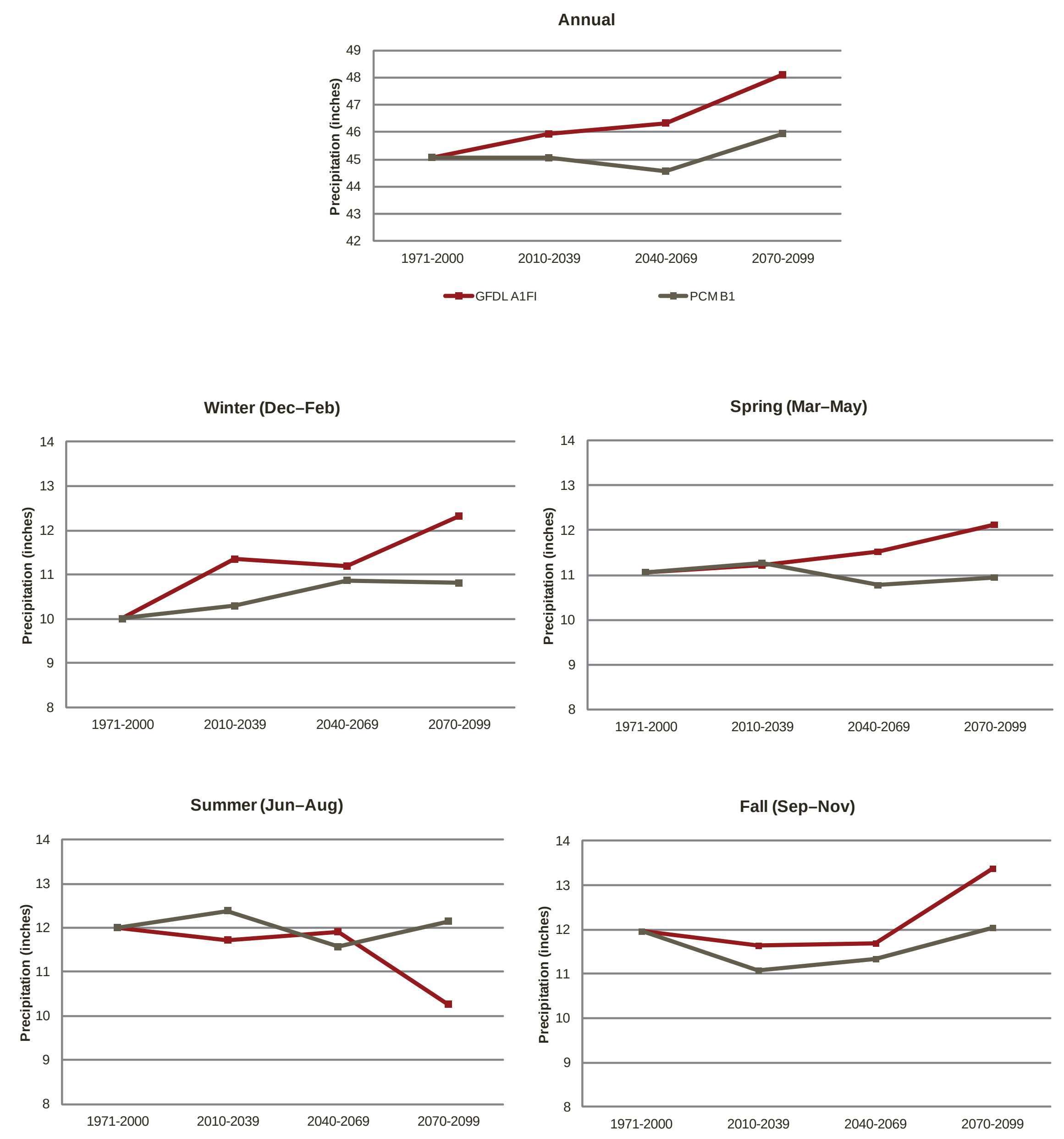

Figure 22.—Projected trends in mean precipitation in the assessment area averaged over 30-year periods for the entire year and by season for two climate model-emissions scenario combinations. The 1971 to 2000 value is based on observed data from weather stations.

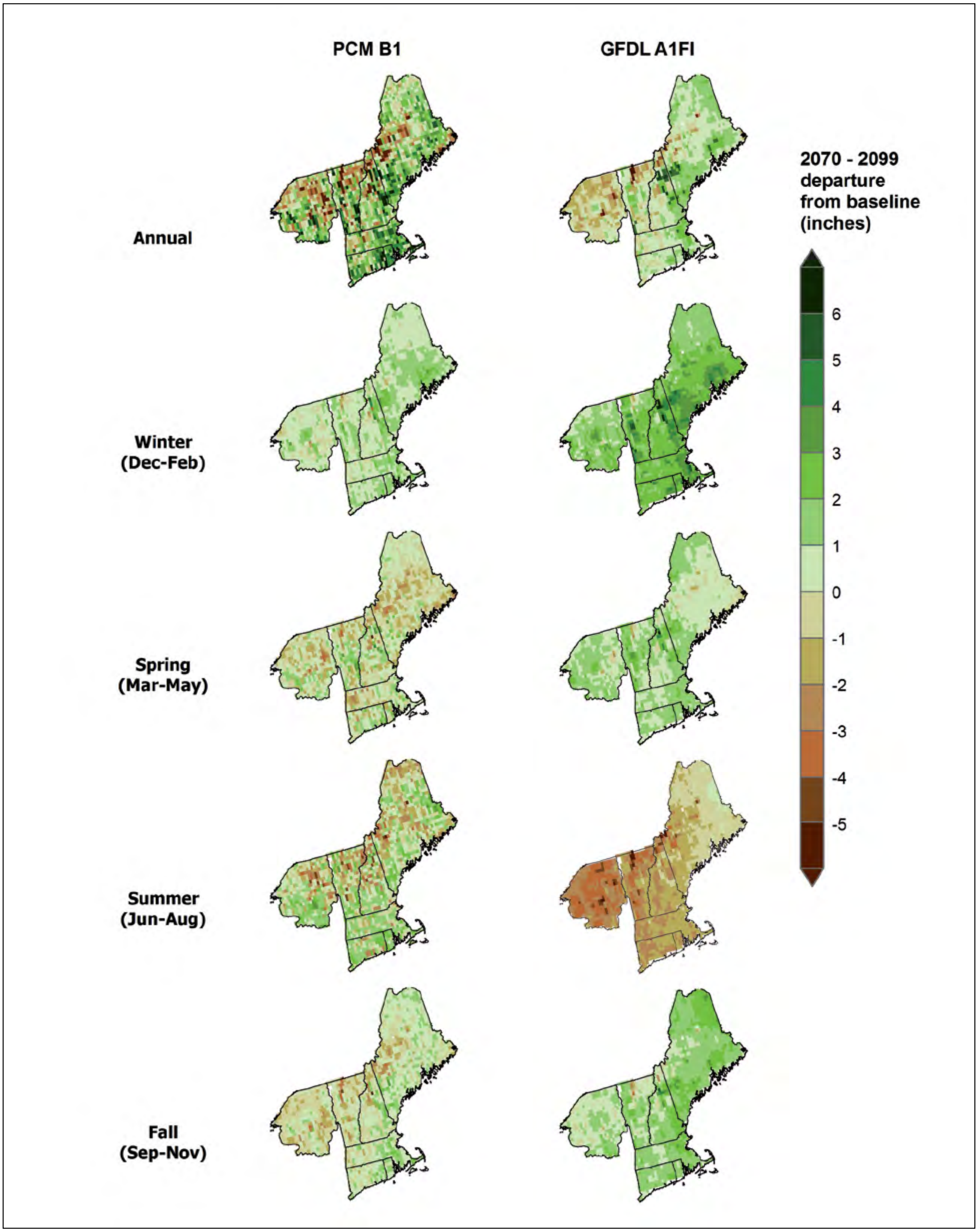

Figure 23.—Projected difference in mean precipitation at the end of the century (2070 through 2099) compared to baseline (1971 through 2000) for two climate model-emissions scenario combinations.

For the assessment area, mean annual precipitation is projected to increase by 0.9 inch (2.0 percent) under the PCM B1 scenario by the end of the 21st century (Fig. 23, Appendix 3) compared to the 1971 through 2000 baseline. In contrast, annual precipitation is projected to increase more substantially under the GFDL A1FI scenario, by an average of 3.0 inches (7 percent). Seasonal precipitation for the two scenarios generally follows the same trends, with small increases or decreases in precipitation by season over the 21st century. Winter precipitation is projected to increase the most of any season under both scenarios, increasing by 0.8 inch (8 percent) under PCM B1 and 2.3 inches (23 percent) under GFDL A1FI. Under the PCM B1 scenario, relatively little change is projected during the spring and fall at the end of the century. Summer precipitation under this scenario is projected to decrease slightly during mid-century, but then have an overall increase of 0.1 inch (1 percent) by the end of the century (compared to the 1971 to 2000 baseline). The GFDL A1FI scenario projects a much sharper pattern of altered seasonality in precipitation, with spring precipitation increasing 1.0 inch (9 percent) and summer precipitation declining by 1.7 inches (14 percent) by the end of the century.

One of the striking consistencies in the climate data presented here and in many other studies is that variability in projected precipitation is much greater than for temperature across virtually all climate modeling efforts (Fan et al. 2014, Hayhoe et al. 2007, Kunkel et al. 2013, Lynch et al. 2016, Thibeault and Seth 2014b). The data just presented are generally consistent with other projections for the region, although there are some differences. Similar to these results, several other modeling efforts indicate that annual precipitation is expected to increase in the assessment area and that the greatest precipitation increases will occur during the winter (Bryan et al. 2015, Hayhoe et al. 2007, Kunkel et al. 2013, Lynch et al. 2016). There is greater variability among projections of precipitation during other seasons, particularly summer. For example, one recent comparison of multiple climate models found that individual model projections for summer precipitation ranged from a decrease of 25 percent or more to an equivalent increase for the 2070 to 2099 period (Kunkel et al. 2013). Another recent study modeled future precipitation using multiple climate models and one high emissions scenario, and found a high degree of variation in projections of summer precipitation; summer precipitation showed a modest increase when the results from several models were averaged (Lynch et al. 2016). Although the total amount of summer precipitation may not change greatly, projected increases in extreme precipitation events suggest that the number of days without precipitation will correspondingly increase (Bryan et al. 2015).

PROJECTED CHANGES IN EXTREME WEATHER EVENTS

Extreme events such as heat waves, cold waves, windstorms, floods, and droughts are projected to become more frequent or severe as a result of climate change (IPCC 2012, Melillo et al. 2014). In general, there is less confidence in model projections of the magnitude and direction of change in extreme events over the next century compared with general temperature and precipitation changes (Bryan et al. 2015, Kunkel et al. 2012, Peterson et al. 2013b, Wuebbles et al. 2014). The stochastic nature of extreme events increases the difficulty of detecting changes in the frequency or intensity of events over time, but it is likely that the frequency of extreme weather events will increase across the Northeast (Brown et al. 2010, Bryan et al. 2015, Guilbert et al. 2015, Kunkel et al. 2013, Ning et al. 2015, Spierre and Wake 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 region point to an increasing frequency of hot days across the assessment area, particularly in the southern portions of the assessment area (Horton et al. 2014, Kunkel et al. 2013, Ning et al. 2015). Under a low emissions scenario, southern parts of New England are projected to have at least

15 more days per year with a maximum temperature exceeding 90 °F. Under a high emissions scenario, extremely hot days are projected to increase by 16 to 60 days per year over most of the assessment area, with the greatest increases in the southern coastal areas (Center for Climatic Research 2017, Ning et al. 2015). This increase in hot days is also expected to increase the frequency of heat waves lasting 3 days or more (Ning et al. 2015).

Extremely cold temperatures are projected to become less frequent as the climate warms, although they will not disappear completely. The frequency, intensity, and duration of cold-air outbreaks are expected to decrease (Horton et al. 2014). The number of days with a minimum temperature less than 10 °F is projected to decrease by 9 to 24 days per year (Kunkel et al. 2013). Another study indicates that number of days with a minimum temperature below 0 °F is also projected to decrease across the assessment area (Center for Climatic Research 2017). It is important to note, however, that the enhanced warming occurring in polar regions greatly influences weather patterns in the mid-latitudes and can lead to periods of extreme cold, even as the overall climate becomes warmer (Francis and Vavrus 2012, Vavrus et al. 2006).

Intense Precipitation

There is a clear trend toward more frequent and more extreme precipitation events in the assessment area, and this is expected to continue (Horton et al. 2014, Kunkel et al. 2013, Thibeault and Seth 2014a). One recent assessment projected that the entire Northeast will receive 21 percent more rainfall events greater than 1 inch by 2100, with larger events increasing by progressively larger amounts (Kunkel et al. 2013). Projections based on other climate data also indicate an increased frequency of large precipitation events. The occurrence of events producing more than 1 inch of rain is projected to increase by 12 or more days per decade by the end of the century, according to the Center for Climatic Research (2017). Coastal areas in southern and central New England are projected to have the greatest increases in heavy rainfall (Center for Climatic Research 2017). It is important to consider this trend in combination with the projected increases or decreases in mean precipitation over the 21st century, because a given increase or decrease in precipitation may not be distributed uniformly across a season or even a month. Additionally, climate change may increase the year-to-year variation of precipitation across the northern United States (Boer 2009, Thibeault and Seth 2014a). Therefore, the assessment area may experience more extremely wet and dry years in the future.

Extreme Storms and Wind

Beyond intense precipitation, extreme storm events (e.g., wind, hurricanes, ice storms) are expected to change as a result of a changing climate. The stochastic nature of extreme events increases the difficulty of both detecting changes in the frequency or intensity of events over time and attributing these alterations to climate change (Coumou and Rahmstorf 2012, Stott et al. 2010, Wuebbles et al. 2014). However, there is increasingly greater evidence for projected increases in many extreme weather events across the Northeast (Horton et al. 2014, Kunkel et al. 2013).

Ice storms are of particular concern in many parts of the region because of the potential impacts on infrastructure and ecosystems. Although future climate projections are generally available at relatively coarse spatial scales, some modeling work has investigated potential changes in ice storm risk in the northeastern United States and adjacent areas of Canada (Cheng et al. 2007, 2011). For example, one study projected an 8- to 40-percent increase in freezing rain events by the 2050s as compared to the past 40 years in south-central Canada, with the greatest projected increases in the northern portion of the area (Cheng et al. 2007). A more recent study by the same authors suggested that all of eastern Canada could experience more freezing rain events late this century during the coldest months (December through February), with greater increases in the north (Cheng et al. 2011).

PROJECTED CHANGES IN SEA LEVEL

Sea level is expected to continue to rise as temperatures warm across the globe. The complex dynamics that cause sea-level rise—including air and water temperature increases, freshwater inputs from melting ice, changes in salinity, and altered circulation patterns—make it difficult to project the magnitude of sea-level rise over the next century (Landerer et al. 2007, Sallenger et al. 2012, Yin et al. 2009). Results from a number of studies suggest that global sea level will rise between 1 and 4 feet in this century (Sallenger et al. 2012, Walsh et al. 2014, Yin et al. 2009). There is high variability among these estimates, however, and higher emissions scenarios lead to greater estimates of future sea-level rise (Kopp et al. 2014, Walsh et al. 2014). At the same time, even the best models cannot simulate the effects of rapid changes in ice sheet dynamics, so it is possible that the magnitude of future sea-level rise is being underestimated (Walsh et al. 2014).

PROJECTED CHANGES AFFECTING WATER AND SNOW COVER

Snowfall and Snow Cover

Warmer temperatures are expected to continue to have dramatic impacts on the winter season. The total amount of snowfall and the proportion of precipitation falling as snow decreased across the Northeast during the 20th century (Chapter 2), and these trends are expected to continue (Danco et al. 2016, Hayhoe et al. 2007, Ning and Bradley 2015). By the end of the 21st century, total snowfall is projected to decrease by 10 to 50 percent under a low emissions scenario and by 30 to 70 percent under a high emissions scenario (Center for Climatic Research 2017, Ning and Bradley 2015, Notaro et al. 2014). The most substantial loss of snow is expected to occur at the beginning of the winter season, which is December for most of the region and January for southern coastal New England (Notaro et al. 2014).

Similarly, the number of days with snow cover is projected to decrease and more southern parts of the region may lose a substantial portion of days with snow. One study projected decreases in the number of snow-covered days across the region and found decreases of as much as 30 days per year in northern New York, Vermont, New Hampshire, and Maine by the year 2100 (Hayhoe et al. 2007). A more recent study projected declines in snow depth of 40 percent or more across the region, with snow depth declining more than 80 percent in localized areas (Center for Climatic Research 2017, Notaro et al. 2014) (Fig. 24).

Soil Temperature and Frost

As increasing winter temperatures lead to a reduction in the depth and duration of snowpack, it is expected that the frequency of soil freeze-thaw events will increase. Across much of the Northeast, snow cover insulates the soil surface from changes in air temperature, thereby helping reduce both the number of freeze-thaw cycles and the depth to which frost penetrates the soil (Brown and DeGaetano 2011, Hardy et al. 2001). One study that manipulated snow depth at Hubbard Brook Experimental Forest in New Hampshire found that areas covered in deep snow were protected from extensive freezing while areas that were shoveled to reduce snow depth had substantial freezing (Hardy et al. 2001). Even when snow depth was not manipulated, soils froze early in the season before a late-arriving snowpack and remained frozen into April despite snowpack of more than 2 feet (Hardy et al. 2001). These results are consistent with projections of future soil temperature and frost, suggesting increased soil frost where snowpack is reduced (Brown and DeGaetano 2011). Conversely, areas of southern New England currently receive less snow and do not typically have the same dense snowpack that protects soils from frost; warming air temperatures may be more likely to warm soils in these areas (Brown and DeGaetano 2011).

Streamflow

The shifts in winter precipitation and temperature described earlier are expected to alter several hydrologic variables. Winter snow cover is an important factor for regulating streamflow throughout much of the year (Hodgkins et al. 2012).

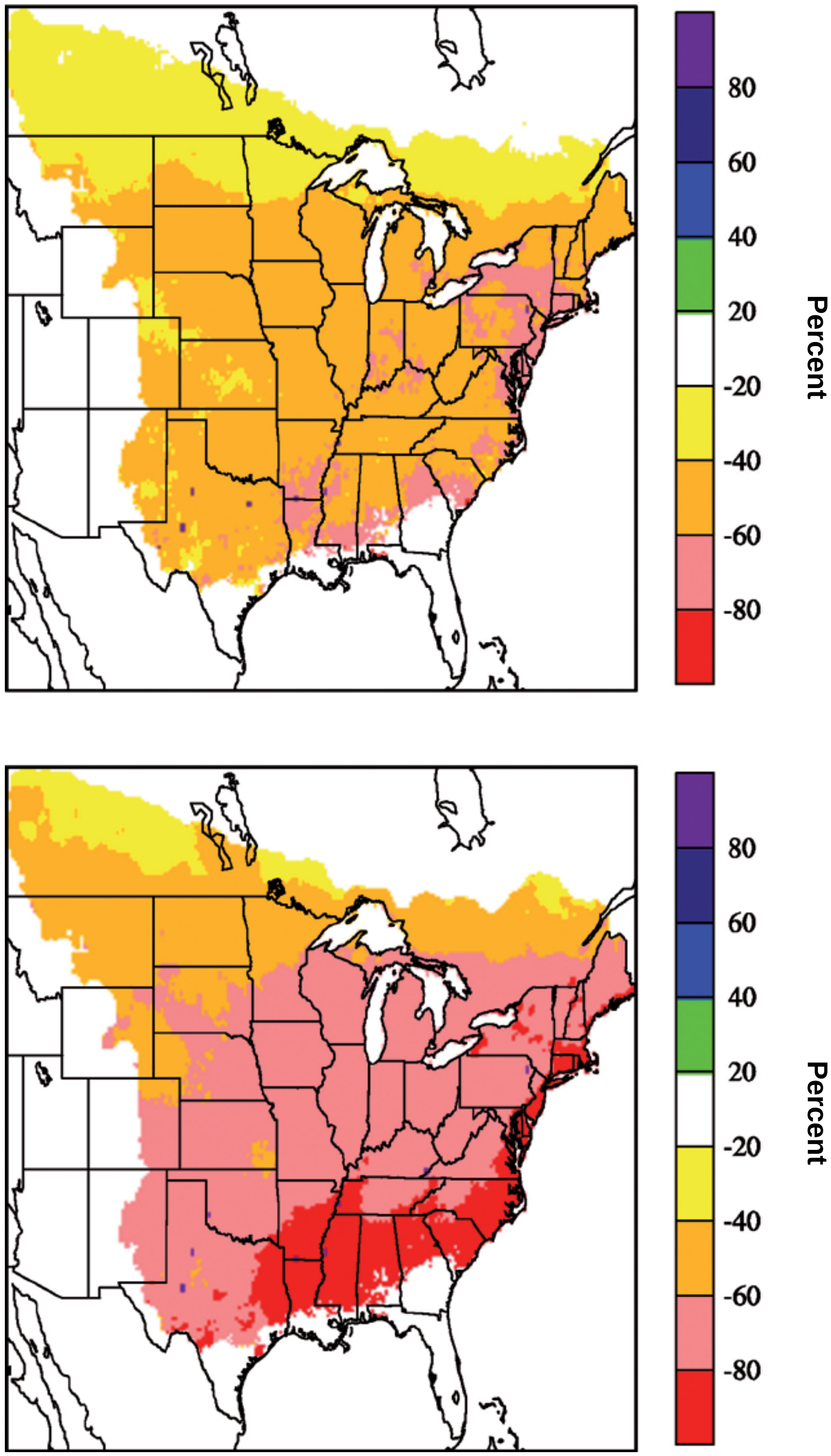

Figure 24.—Projected change (percent) in snow depth, based on nine global climate models from the Coupled Model Intercomparison Project Phase 3 (CMIP3), computed as the difference between 2081 to 2100 and 1981 to 2000. Results are shown for the B1 (top) and A2 (bottom) emissions scenarios from a daily, statistically downscaled climate product. The A2 emissions scenario projects greenhouse gas emissions similar to the A1FI scenario. Data source: Center for Climatic Research (2017).

Warmer temperatures can accelerate the hydrologic cycle by increasing cold-season rainfall and runoff (Cherkauer and Sinha 2010, Hayhoe et al. 2007). Changes in temperature and precipitation are expected to shift peak (winter/spring) streamflow earlier, with higher winter flows and lower spring flows (Campbell et al. 2011, Demaria et al. 2016, Hayhoe et al. 2007, Tu 2009). One study in the Northeast projected an advance in peak flows of 10 to more than 15 days by the end of the century, with greater shifts in the north due to the influence of snowmelt on streamflow (Hayhoe et al. 2007). Summer streamflows are generally projected to decrease; one study in eastern Massachusetts projected that streamflow during the summer months may be reduced by more than 50 percent for many watersheds (Tu 2009). Fall streamflow projections are variable and depend on the degree to which scenarios warm the climate and on interactions with vegetation (Campbell et al. 2011, Demaria et al. 2016, Hayhoe et al. 2007). There is also expected to be greater annual variation, with increases in both low- and high-flow events throughout the year (Campbell et al. 2011, Hayhoe et al. 2007).

Soil Moisture and Drought

Drought is a lack of water, and in forest ecosystems, drought is closely tied to the availability of soil water for maintaining stomatal conductance and plant function (Luce et al. 2016a, 2016b). It also mediates microbial activity, decomposition, and nutrient turnover. Changes in soil moisture are largely driven by the balance of temperature, precipitation, runoff, and evapotranspiration—that is, the combined amount of water lost through evaporation from plant surfaces, litter, and soils as well as through transpiration from plants. As temperatures increase, the atmosphere is able to hold larger quantities of water, which causes evaporation to increase. Plants also transpire more. Moisture stress may occur when increases in evaporation and transpiration are not offset by a corresponding increase in precipitation and soil moisture (Hayhoe et al. 2007, Vose et al. 2016).

There is an increased potential for reduced soil moisture and increased drought stress in the future (Luce et al. 2016b). Of the climate scenarios used in this assessment, the potential for more frequent droughts and moisture stress in the assessment area during the growing season appears to be higher under the GFDL A1FI scenario. Even under the milder PCM B1 scenario, however, warmer temperatures may lead to greater evaporative demand from the atmosphere and physiological stress if increases in precipitation do not correspond to temperature increases. Although precipitation projections have greater uncertainty than temperature projections, several modeling studies point to substantially higher temperatures with no more than relatively modest increases in growing season precipitation (Center for Climatic Research 2017, Hayhoe et al. 2007, Kunkel et al. 2013, Lynch et al. 2016).

Relatively few studies have projected future changes in soil moisture, making it difficult to make inferences about the effects of changes in future drought frequency or severity. One study using scenarios of future climate similar to those presented in this chapter projected that potential evapotranspiration, the evaporative demand from the atmosphere, would increase most during the spring and summer, which could reduce soil moisture toward the latter part of the growing season and increase the frequency of droughts lasting short durations of 1 to 3 months (Hayhoe et al. 2007). More-recent studies of future drought potential across North America and globally suggest that increased temperatures may increase evapotranspiration, reduce soil moisture, or increase drought risk in the northeastern United States through the next century (Berg et al. 2017, Jeong et al. 2014, Zhao and Dai 2016). Droughts are expected to occur more frequently in the future in areas where precipitation is not sufficient to compensate for increased temperatures during the growing season (Hayhoe et al. 2007, Luce et al. 2016a).

CHAPTER 4: FUTURE CLIMATE CHANGE IMPACTS ON FORESTS

Climate change is expected to have wide-ranging effects on forests in the Northeast. Some of these effects will be the direct effects of an altered climate, such as warmer temperatures and extreme storm events. Climate change will also lead to many indirect effects, including interactions with other disturbances that have the potential to severely change forest ecosystems across the region and worldwide. This chapter describes potential effects of climate change on forest ecosystems across New England and northern New York. It is organized into two sections. First, we present the results from three forest impact models to gather perspective on how forests are generally expected to change through the end of the century. In the second section, we provide a synthesis of existing literature on climate change and regional forest ecosystems to put the model results into context and present additional complexity that is not included in the models. This information provides a foundation to assess the potential vulnerability of forest ecosystems in the assessment area (Chapter 5).

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 relied on a combination of three forest impact models to describe these potential changes: the Climate Change Tree Atlas (DISTRIB), LINKAGES, and LANDIS PRO (Table 9). The Tree Atlas uses statistical techniques to model changes in suitable habitat for individual species over broad geographic areas. The LINKAGES model projects establishment and growth of trees based on climate, soils, and other site information. LANDIS PRO simulates changes in the abundance, density, and distribution of individual tree species. No single model offers a comprehensive projection of future impacts on forest ecosystems, but each tool is valuable for a particular purpose or set of questions (Iverson et al. 2017). Although each model produces different outputs (e.g., potential suitable habitat or realized landscape change), similarities in patterns across models suggest less uncertainty in projections than when patterns differ. Differences in patterns provide opportunities to better understand the nuances of ecological responses given the strengths and limitations of the models (Iverson et al. 2017).

All three models used the same downscaled climate projections from two combinations of general circulation models (GCMs) and emissions scenarios described in detail in Chapter 3: GFDL A1FI and PCM B1. Projected changes in temperature and precipitation for GFDL A1FI represent a greater degree of projected climate warming and change compared to PCM B1, allowing for comparisons across a range of potential future change. This consistency in the climate data used in each modeling approach allows the forest impact models to describe potential forest changes over the same range of future climates.

These model results are most useful for describing trends across large areas and over long time scales. These models are not designed to deliver spatially precise results for individual forest stands or a particular year in the future, despite the temptation to examine particular datapoints or locations on a map. Although the projections are not spatially exact, they indicate the relative abundances and spatial patterns across the assessment area. In this chapter, we

Table 9.—Overview of the three forest impact models used in this assessment

Feature	Tree Atlas	LINKAGES	LANDIS PRO
Summary	Suitable habitat distribution model (DISTRIB) + supplementary information (modifying factors)	Patch-level forest succession and ecosystem dynamics process model	Spatially dynamic forest landscape process model
Primary outputs for this assessment	Potential suitable habitat (area-weighted importance values) and modifying factors by species	Species establishment and growth by species (percentage change)	Basal area, and trees per acre by species
Model-scenario combinations		GFDL A1FI and PCM B1	
Assessment area		New England and northern New York assessment area delineated by three subregions (Fig. 25)	
Resolution	20-km (12-mile) grid	1/12 ha (0.2 acre) plots representing landforms in subsections	270-meter (886-foot) grid
Number of tree species evaluated	102	24	24
Control/baseline climate	1971 through 2000	1980 through 2009	n/a
Climate periods evaluated	2010 through 2039, 2040 through 2069, 2070 through 2099	1980 through 2009, 2080 through 2099	2009 through 2099
Simulation period	n/a	30 years	2009 through 2099
Competition, survival, and reproduction	No	Yes	Yes
Disturbances	No (but addressed through modifying factors)	No	Timber harvest only
Tree physiology feedbacks	No	Yes	No
Succession or ecosystem shifts	No	No	Yes
Biogeochemical feedbacks	No	Yes	No

n/a: not applicable

present simulations for the end of the 21st century across the entire assessment area. Model data for three subregions within the assessment area (Fig. 25) are used to describe geographic differences across the assessment area.

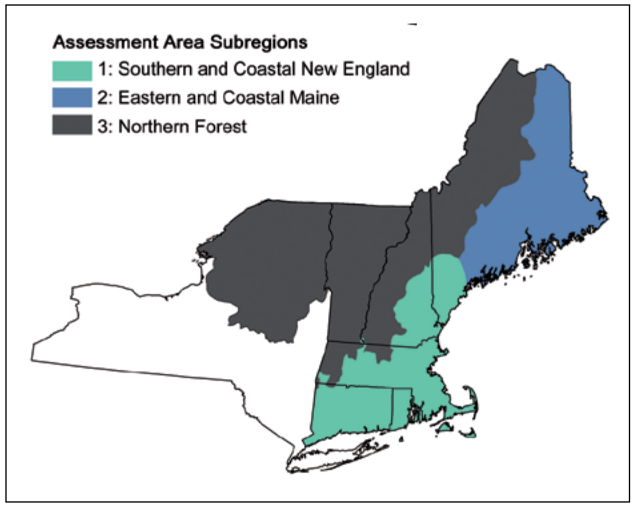

Figure 25.—Assessment area subregions based on ecological provinces and sections (Fig. 3) mapped by Cleland et al. (2007) and described by McNab et al. (2007).

Climate Change Tree Atlas

The Climate Change Tree Atlas (U.S. Forest Service n.d.) was used to evaluate potential changes in suitable habitat for tree species within the assessment area. The Tree Atlas does not model where species will occur in the future (i.e., occupied habitat), but rather projects where future habitat for individual tree species may be suitable in the future. As such, Tree Atlas projections should be interpreted not as expected species migration patterns, but instead as shifts in the distribution of favorable conditions for a given species to persist under future climatic conditions. The DISTRIB component of the Tree Atlas, a species distribution model, was used to examine the features that contribute to the current habitat of a tree species and then to project where similar habitat conditions are likely to occur in the future. Habitat suitability (measured in terms of importance value) was modeled for 134 eastern tree species (Iverson et al. 2008, 2010), 102 of which are currently present in the assessment area or are projected to have suitable habitat in the area by the end of this century. Most of these tree species are currently present in some part of the assessment area, and the remaining species may have newly suitable habitat in the future under one or both climate scenarios.

The projected change in potential suitable habitat for the 102 species was calculated for the years 2070 through 2099 using the PCM B1 and GFDL A1FI scenarios and compared to the present climate (Table 10). Species were categorized based on whether the results from the two climate-emissions scenarios projected an increase, decrease, or no change in suitable habitat compared to current climatic conditions. Further, some tree species that are currently not present in the assessment area are identified as having potential suitable habitat under future climate scenarios. Appendix 4 contains complete results from the DISTRIB model, including projections for three different periods (2010 through 2039, 2040 through 2069, and 2070 through 2099) and for each of the subregions.

The DISTRIB results indicate that climate change is likely to lead to changes in the suitable habitat of many common tree species; however, the ways in which tree species will actually respond to climate change are also influenced by life-history traits not included in the DISTRIB model. A set of "modifying factors" supplements the DISTRIB results and provides additional information about whether species may be expected to do better or worse than the future suitable habitat values would suggest (Matthews et al. 2011) (Table 11). These factors are based on a literature review of the life-history traits, known stressors, and other factors unique to individual species. Examples of modifying factors are drought tolerance, dispersal ability, shade tolerance, site specificity, and susceptibility to insect pests and diseases, all of which are highly related to the adaptive capacity of a species (Matthews et al. 2011).

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

Common Name	PCM B1	GFDL A1FI
Declines under Both Scenarios		
Balsam fir (–)	Small decrease	Large decrease
Balsam poplar	Small decrease	Large decrease
Black ash (–)	Small decrease	Small decrease
Black spruce	Large decrease	Large decrease
Mountain maple (+)	Small decrease	Large decrease
Northern white-cedar	Small decrease	Large decrease
Paper birch	Small decrease	Large decrease
Red spruce (–)	Small decrease	Large decrease
Tamarack (native) (–)	Small decrease	Small decrease
White spruce	Small decrease	Large decrease
Declines under High Emissions		
American beech	No change	Small decrease
American mountain-ash (–)	No change	Large decrease
Bigtooth aspen	No change	Small decrease
Black maple	No change	Small decrease
Butternut (–)	No change	Small decrease
Chokecherry	No change	Large decrease
Eastern hemlock (–)	No change	Small decrease
Eastern white pine	No change	Small decrease
Gray birch	No change	Small decrease
Pin cherry	No change	Small decrease
Quaking aspen	No change	Large decrease
Red maple (+)	No change	Small decrease
Striped maple	No change	Large decrease
Sugar maple (+)	No change	Small decrease
Yellow birch	No change	Large decrease
No Change under Both Scenarios		
American chestnut	No change	No change
Atlantic white-cedar (–)	No change	No change
Scrub oak	No change	No change
River birch	NA	No change
White ash (–)	Small increase	No change

Common Name	PCM B1	GFDL A1FI
Increases under Both Scenarios		
American elm	Small increase	Large increase
Black locust	Large increase	Large increase
Black oak	Small increase	Large increase
Black walnut	Small increase	Large increase
Black willow (–)	Small increase	Large increase
Chestnut oak (+)	Small increase	Large increase
Eastern cottonwood	Small increase	Large increase
Eastern redbud	Small increase	Small increase
Eastern redcedar	Large increase	Large increase
Flowering dogwood	Large increase	Large increase
Mockernut hickory (+)	Small increase	Large increase
Northern red oak (+)	Small increase	Small increase
Ohio buckeye	Small increase	Small increase
Pignut hickory	Small increase	Large increase
Pin oak (–)	Small increase	Large increase
Post oak (+)	Small increase	Small increase
Red mulberry	Large increase	Large increase
Sassafras	Large increase	Large increase
Scarlet oak	Small increase	Large increase
Shagbark hickory	Small increase	Large increase
Silver maple (+)	Small increase	Large increase
Slippery elm	Small increase	Large increase
Sourwood (+)	Small increase	Small increase
Sweet birch (–)	Small increase	Small increase
White oak (+)	Small increase	Large increase
Yellow-poplar (+)	Large increase	Large increase

Table 10 (continued).—Potential change in suitable habitat for tree species in the assessment area

Common Name	PCM B1	GFDL A1FI
Increases under High Emissions		
American basswood	No change	Large increase
American holly	No change	Large increase
American hornbeam	No change	Large increase
Bitternut hickory (+)	No change	Large increase
Black cherry (–)	No change	Small increase
Blackgum (+)	No change	Large increase
Boxelder (+)	No change	Large increase
Bur oak (+)	No change	Large increase
Eastern hophornbeam (+)	No change	Small increase
Green ash	No change	Large increase
Hackberry (+)	No change	Large increase
Honeylocust (+)	No change	Large increase
Jack pine	Small decrease	Small increase
Northern pin oak (+)	No change	Small increase
Pitch pine	No change	Small increase
Red pine	No change	Large increase
Serviceberry	No change	Small increase
Shellbark hickory	No change	Small increase
Swamp chestnut oak	No change	Small increase
Swamp white oak	No change	Small increase
Sycamore	No change	Large increase
Winged elm	No change	Small increase

Common Name	PCM B1	GFDL A1FI
New Suitable Habitat		
Bald cypress	New habitat	New habitat
Black hickory	NA	New habitat
Blackjack oak** (+)	NA	New habitat
Cedar elm	NA	New habitat
Cherrybark oak	New habitat	New habitat
Chinkapin oak**	NA	New habitat
Common persimmon (+)	New habitat	New habitat
Loblolly pine	New habitat	New habitat
Longleaf pine	New habitat	NA
Osage-orange (+)	NA	New habitat
Pawpaw	New habitat	New habitat
Pond pine (–)	New habitat	New habitat
Rock elm (–)	NA	New habitat
Sand pine (–)	New habitat	New habitat
Shingle oak	NA	New habitat
Shortleaf pine**	New habitat	New habitat
Shumard oak (+)	NA	New habitat
Southern red oak (+)	New habitat	New habitat
Sugarberry	NA	New habitat
Sweetbay**	New habitat	NA
Sweetgum**	New habitat	New habitat
Virginia pine	New habitat	New habitat
Water oak	NA	New habitat
Willow oak	NA	New habitat

*Species are grouped into change classes based on the proportional change between the year 2100 biomass under the PCM B1 and GFDL A1FI scenarios and the biomass under the current climate scenario in the year 2100. Large increases or decreases indicate that the proportional change under one or both climate change scenarios is greater than 50 percent.

“No change” indicates that biomass is within 20 percent of what is projected under the current climate scenario. Species with the highest and lowest modifying factor scores are marked with plus (+) and minus (–) signs, respectively.

See Appendix 4 for complete results for all species.

NA = No suitable habitat.

**Not observed in the Forest Inventory and Analysis data, but other data (e.g., State surveys) suggest species is present though rare.

Table 11.—Eastern tree species with the five highest and five lowest values for adaptive capacity based on Climate Change Tree Atlas modifying factors

Species	Modifying factors that affect rating
Highest adaptive capacity	
1. Red maple	high seedling establishment rate, wide range of habitats, shade-tolerant, high dispersal ability
2. Boxelder	high seedling establishment rate, shade-tolerant, high dispersal ability, wide range of temperature tolerances, drought-tolerant
3. Bur oak	drought-tolerant, fire-tolerant
4. Eastern hophornbeam	shade-tolerant, wide range of temperature tolerances, wide range of habitats
5. Osage-orange	wide range of habitats
Lowest adaptive capacity	
1. Black ash	susceptible to emerald ash borer, poor light competitor, limited dispersal ability, poor seedling establishment, fire-intolerant, dependent on specific hydrologic regime
2. Butternut	susceptible to butternut canker, drought-intolerant, fire-intolerant, poor light competitor
3. Balsam fir	susceptible to spruce budworm and other insect pests, fire-intolerant, drought-intolerant
4. White ash	susceptible to emerald ash borer, drought-intolerant, fire-intolerant
5. Eastern hemlock	susceptible to hemlock woolly adelgid, drought-intolerant

Decreases in Suitable Habitat

Ten species are projected to undergo large or small declines in suitable habitat under the range of climate scenarios, and declines are generally projected to be more severe under the GFDL A1FI scenario than under PCM B1 (Table 10). These reductions in suitable habitat do not imply that these trees will die or the species will be extirpated by the end of the century; rather, these results indicate that these species will be living outside of their ideal suitable habitat by the end of the century. As a result, trees living on marginal sites may have greater susceptibility to new or existing stressors such as drought, pests, diseases, or competition from other species including invasive species. Climate-related stress at these sites may also increase the risk of regeneration failure.

Many of the species projected to decline are common in the more northerly portions of the assessment area. These boreal or northern species are currently near the southern limit of their range in the assessment area and include balsam fir, red spruce, paper birch, white spruce, and black spruce. These species are currently common across the landscape and play an important role in many forests. The reduction of suitable habitat for these species is expected to affect ecologically important northern and high-elevation forests in the region.

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

There are also 15 species that are projected to decrease in suitable habitat under GFDL A1FI and undergo little change under PCM B1 (less than 20-percent increase or decrease from current abundance under PCM B1) (Table 10). This group also contains boreal species (quaking and bigtooth aspen) and species with negative modifying factors (eastern hemlock and butternut). In the case of eastern hemlock, the expansion of hemlock woolly adelgid is expected to have substantial near-term impacts on the species that are greater than the anticipated future effects from climate change. Similarly, butternut canker has already significantly reduced the abundance of butternut in the assessment area and will continue to be the dominant factor affecting habitat suitability in the near term. Overall habitat of both red maple and sugar maple is projected to decrease under the GFDL A1FI scenario and have very little change (less than 5 percent) under PCM B1. Both of these species have positive modifying factors that indicate the species may fare better than the model suggests. Red maple in particular has the most positive modifying factors among all 134 species that were assessed across the eastern United States. A formidable resilience to disturbances and a wide tolerance of soil types, moisture conditions, and pH levels give red maple an apparent advantage over other species; it is likely to do much better than modeled, and perhaps even flourish as some competitors decline (Table 11). The outlook for sugar maple is less clear. Sugar maple has some characteristics, such as high shade tolerance and fewer disease and insect pests relative to other species, that may allow it to fare better than the models suggest. At the same time, sugar maple appears to be especially sensitive to nutrient deficiencies caused by historical soil acidification in the region (Hallett et al. 2006, Sullivan et al. 2013).

No Change in Suitable Habitat

Five species, including white ash, scrub oak, and American chestnut, are projected to have less than a 20-percent change in suitable habitat under either of the scenarios (Table 10). These species are relatively uncommon in the region and generally present only in the southern half of the assessment area. American chestnut endures as a minor understory component, mostly as sprouts from old stumps and root systems, since the introduction of chestnut blight in the early 1900s (Anagnostakis 1995). Although white ash is projected to have a marginal increase (21 percent) in suitable habitat under PCM B1, no change is projected under the hotter and drier GFDL A1FI. Additionally, the emerald ash borer is likely to cause large declines for this species, so climate change model results may have limited value.

Increases in Suitable Habitat

Suitable habitat for 26 species is projected to increase under both models by the end of the century (Table 10). These species generally have more southerly distributions and few are currently widespread in the assessment area. The more common species with projected increases in suitable habitat under future climatic conditions include northern red oak, American elm, black oak, and white oak. Changes in climate are generally projected to extend the range of these species northward. Some of these species, including many oak and hickory species, are more tolerant of drought and fire. These biological traits could benefit the species and lead to even greater increases than the model results suggest. Of these species, several also have multiple positive modifying factors, which suggest that the biological characteristics (e.g., shade tolerance and seedling establishment) and response to various disturbances (e.g., insect pests, drought, and fire topkill) may allow the species to succeed even more than the model projections suggest. Species that are projected to increase under both climate scenarios and that have a high capacity to adapt to changing conditions include silver maple, white oak, chestnut oak, mockernut hickory, yellow-poplar, post oak, and sourwood.

Twenty-two species are projected to increase in suitable habitat under the GFDL A1FI scenario but with little change projected under PCM B1 (less than 20-percent increase or decrease from current abundance under PCM B1). These species, many of which are relatively infrequent in the assessment area—particularly farther north—include American basswood, boxelder, bitternut hickory, blackgum, bur oak, and sycamore. Several species in this category, including bitternut hickory and bur oak, have positive modifying factors, such as resistance to drought and fire topkill, which suggest that the species may be better able to take advantage of new conditions than the DISTRIB model would suggest.

New Suitable Habitat

The DISTRIB model also projects that newly suitable habitat will be available in the future under at least one of the climate scenarios for 24 species that are not currently present in the assessment area (Table 10). This does not necessarily mean that a given species will be able to migrate to newly available habitat and colonize successfully, but rather that conditions may be suitable for a species to occupy the site if it is established. These species are generally hardwood species associated with central and southern hardwood forests but also include bald cypress and six pine species (e.g., loblolly, shortleaf, Virginia). Many of these species have ranges that extend close to the assessment area, and some, such as blackjack oak, chinkapin oak, and shortleaf pine, are present in the southern edge of the assessment area but are relatively rare and therefore not recognized by the Tree Atlas as currently present on the landscape.

Other species that are not currently present in the assessment area would require long-distance migration, whether intentional or unintentional, in order to establish and occupy suitable habitat in the assessment area. Habitat fragmentation and the limited dispersal ability of seeds of some species could also hinder the northward movement of the more southerly species, despite the increase in habitat suitability (Ibáñez et al. 2008). Further, species are generally expected to migrate more slowly than their habitats will shift (Iverson et al. 2004a, 2004b). Of course, human-assisted migration is a possibility for some species or sites, and may be explored over the coming decades (Duveneck and Scheller 2015, Pedlar et al. 2012).

Geographic Trends

Projected changes are not uniform across the assessment area, and areas of suitable tree habitat are governed by latitude, elevation, soils, and other factors in addition to climate. The geographic and biological complexity of the assessment area varied across ecoregion subsections (Fig. 25). The DISTRIB model showed a greater number of tree species as having current or future suitable habitat in Southern and Coastal New England (97 species) compared to the Eastern and Coastal Maine (84 species) and Northern Forest (89 species) subregions. Species diversity is currently greatest in the Southern and Coastal New England subregion. This subregion is projected to remain the most diverse as many other species that are currently south of the assessment area but expected to have newly suitable habitat may move into the southern extent of the assessment area.

Decreases in present suitable habitat are projected to be greatest in Southern and Coastal New England. Species that are projected to decline in all subregions, such as balsam fir, red spruce, and paper birch, have the greatest projected decline at the southern extent of their ranges. Further, eastern white pine and quaking aspen are projected to sustain habitat decreases in Southern and Coastal New England at the end of the century, although suitable habitat generally did not change under PCM B1 and only a small decrease was observed under GFDL A1FI in other subregions and across the entire assessment area.

The habitat of five species is projected to increase in all three subregions: black oak, white oak, black willow, silver maple, and flowering dogwood. Southern and Coastal New England has the most species that are projected to increase, largely because it currently contains some species that are not present in measurable quantities in the other subregions, such as sassafras, bitternut hickory, and sycamore. Habitat suitability in both the Southern and Coastal New England and Northern

Forest subregions is projected to increase for several species that are not present in Eastern and Coastal Maine, including eastern redcedar, eastern cottonwood, yellow-poplar, and several oak and hickory species. The habitat for each of these species shows potential for increase in Eastern and Coastal Maine in the future.

Many species are also projected to have newly suitable habitat and may enter the assessment area by the end of the century. The greatest increases in potential new habitats for species occurs in Eastern and Coastal Maine. In that subregion, suitable habitat expands northward and eastward for 36 species, many of which are currently present elsewhere in New England. Twelve species are projected to have new habitat in all three subregions, although these species have new habitat in the Northern Forest subregion only under the more extreme GFDL A1FI scenario. Six species—common persimmon, loblolly pine, pawpaw, shortleaf pine, southern red oak, and sweetgum—have new habitat in Southern and Coastal New England under both climate scenarios and have new habitat in the other subregions under GFDL A1FI. Southern and Coastal New England is also projected under GFDL A1FI to be suitable for some species from much farther south, including bald cypress, pond pine, and sweetbay.

Outputs from DISTRIB can also be visualized spatially, and these results can provide greater context for interpreting the projected changes in suitable habitat. Maps of six species (red spruce, sugar maple, northern red oak, black cherry, chestnut oak, and pitch pine) provide examples of the potential changes in suitable habitat. These maps show that projected changes are not uniform across the assessment area, and that areas of suitable habitat are also related to projected climate change as well as local conditions (Fig. 26). Red spruce is projected to retain a large amount of suitable habitat in the assessment area under PCM B1, but suitable habitat decreases substantially under GFDL A1FI, contracting to the most northerly and highest elevation locations. Sugar maple is projected to have reduced suitable habitat under both climate scenarios, with a much greater reduction projected under GFDL A1FI. Areas of suitable habitat for northern red oak are projected to shift northward under both scenarios. Black cherry and chestnut oak, which are currently less abundant in the region, are expected to have increased habitat suitability in the future. Pitch pine habitat is projected to remain relatively stable, largely due to the unique soil and edaphic conditions associated with this species.

As mentioned earlier, DISTRIB results indicate only a change in suitable habitat, not necessarily that a given species will be able to migrate to newly available habitat. Additionally, these results do not incorporate the positive influence of modifying factors into the maps for sugar maple or white oak. 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 as an illustration of broad trends. Suitable habitat maps for all the species addressed in this assessment are available online through the Climate Change Tree Atlas Web site (www.nrs.fs.fed.us/atlas/tree; see also Appendix 4).

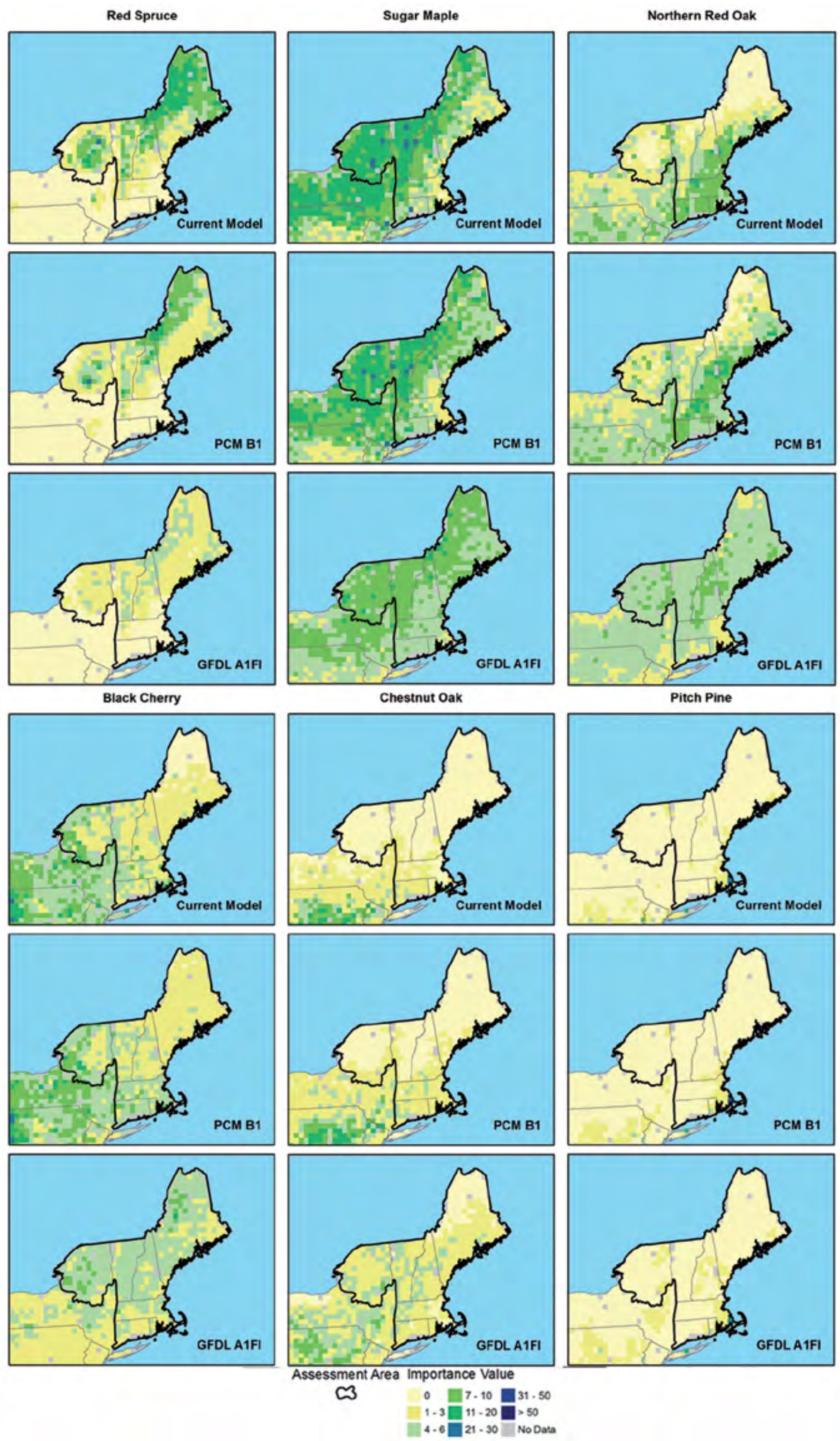

Figure 26.—Modeled importance values from the Climate Change Tree Atlas for six species in the assessment area. Maps show current importance values modeled from U.S. Forest Service Forest Inventory and Analysis data (top) and projected for the years 2070 through 2099 under the PCM B1 (middle) and GFDL A1FI (bottom) climate scenarios. Importance values can range from 0 to 100. An importance value of zero (light yellow) indicates that the species is not present currently (top), or will not have suitable habitat at the end of the century (middle, bottom).

LINKAGES

The LINKAGES model integrates soil, climate, and species attributes to simulate ecosystem-level changes in species establishment. Projections of species establishment probabilities produced by the model provide information about the likelihood that a particular species will establish and grow in a particular place assuming an adequate seed source, absent disturbance or competition from other species (Table 9). The maximum biomass reached by a species for the 30 years starting from bare ground was used as a measure of ability to establish from seed and grow under a climate at a particular site. The first 30 years was used because seedlings are most susceptible to climate warming, and stand dynamics for longer periods are more realistically addressed with the LANDIS PRO model. Results for years 2080 through 2099 under the PCM B1 and GFDL A1FI climate scenarios were compared to the current climate from 1990 through 2009.

Species establishment projections varied widely for the 24 species modeled by LINKAGES (Table 12). Across the entire assessment area, five species are projected to have substantially reduced species establishment at the end of the 21st century under climate change when compared to the current climate. Four northern conifer species—balsam fir, red spruce, northern white-cedar, and black spruce—are projected to have large declines under both climate change scenarios, with an almost total cessation of simulated establishment and growth (i.e., projected biomass values near zero) or extirpation under GFDL A1FI. Eastern hemlock is projected to undergo a similar outcome, although not as extreme. Four northern hardwood species (sugar maple, quaking aspen, yellow birch, and American beech) along with eastern white pine are projected under PCM B1 to have establishment similar to the current climate, but decreased establishment under the harsher GFDL A1FI scenario. Three hardwood species more common to transitional forests—red maple, northern red oak, and white ash—are not projected to have substantial changes in establishment.

Species common south of New England are generally expected to have an increased ability to establish in the assessment area under the two climate change scenarios. Black cherry and white oak are projected to have moderate increases under both scenarios, whereas pignut hickory and pitch pine have more substantial increases under GFDL A1FI. Shagbark hickory, yellow-poplar, and scarlet, black, and chestnut oak have large increases under both scenarios. Two species that are not currently present in the assessment area—loblolly and Virginia pine—were also modeled. For both species, the probability of establishment is projected to increase under climate change, although projected biomass values for the end of the century are relatively low and new habitat is located in the southern portion of New England.

Geographic Trends

Projected species establishment values are substantially different in Southern and Coastal New England compared to other parts of the assessment area (Fig. 27). Under PCM B1, individual species are generally projected to have larger decreases or less substantial increases in establishment than in other parts of the assessment area. More notably, the GFDL A1FI scenario projects especially severe impacts on establishment: Nearly all species are projected to have large decreases under GFDL A1FI. Some species, such as quaking aspen, balsam fir, red spruce, northern white-cedar, black spruce, and yellow birch, have no measurable established biomass in Southern and Coastal New England at the end of the century. These projected impacts are apparently related to modeled changes in regional precipitation. Under GFDL A1FI, the number of large (greater than 2 inches) rain events increases more substantially in Southern and Coastal New England, as does the time between rain events (i.e., days without precipitation). The result is a “boom and bust” cycle, in which most precipitation comes during large events and runs off the saturated soils, only to be followed by relatively long periods of no precipitation. Appendix 5 contains results from the LINKAGES model at year 2100 for each of the subregions and for the entire assessment area.

Table 12.—Projected change in biomass reached in 30 years of tree growth starting from bare ground projected by the LINKAGES model for 24 species in the assessment area under the current climate scenario and two climate model-emissions scenario combinations for the period 2070 through 2099

		Future climate			
	Current climate	PCM B1		GFDL A1FI	
Species	Biomass (metric tons/acre)	Biomass (metric tons/acre)	Change from current climate	Biomass (metric tons/acre)	Change from current climate
American beech	40.4	38.0	-6%	27.8	-31%
Balsam fir	11.9	5.5	-54%	0.3	-97%
Black cherry	30.8	40.3	31%	37.9	23%
Black oak	7.9	18.4	133%	30.8	290%
Black spruce	2.7	0.9	-67%	0.0	-100%
Chestnut oak	4.0	13.7	243%	34.0	753%
Eastern hemlock	20.0	11.2	-44%	3.4	-83%
Eastern white pine	32.3	29.1	-10%	13.5	-58%
Loblolly pine*	0.0	0.2	>1,000%	1.8	>1,000%
Northern red oak	48.3	52.7	9%	43.3	-10%
Northern white-cedar	8.2	3.9	-52%	0.2	-98%
Pignut hickory	11.4	22.7	99%	29.4	158%
Pitch pine	5.9	10.6	80%	12.6	114%
Quaking aspen	47.6	39.3	-17%	17.4	-63%
Red maple	42.2	45.0	7%	38.3	-9%
Red spruce	9.2	3.7	-60%	0.2	-98%
Scarlet oak	10.2	21.3	109%	29.3	187%
Shagbark hickory	5.8	13.7	136%	24.2	317%
Sugar maple	48.2	44.2	-8%	34.7	-28%
Virginia pine*	0.1	1.5	>1,000%	6.6	>1,000%
White ash	60.6	61.9	2%	50.5	-17%
White oak	30.5	43.1	41%	43.3	42%
Yellow birch	46.0	39.2	-15%	24.6	-47%
Yellow-poplar	15.5	39.3	154%	71.1	359%

*Species is not currently present in the assessment area. Increase in biomass represents new habitat.

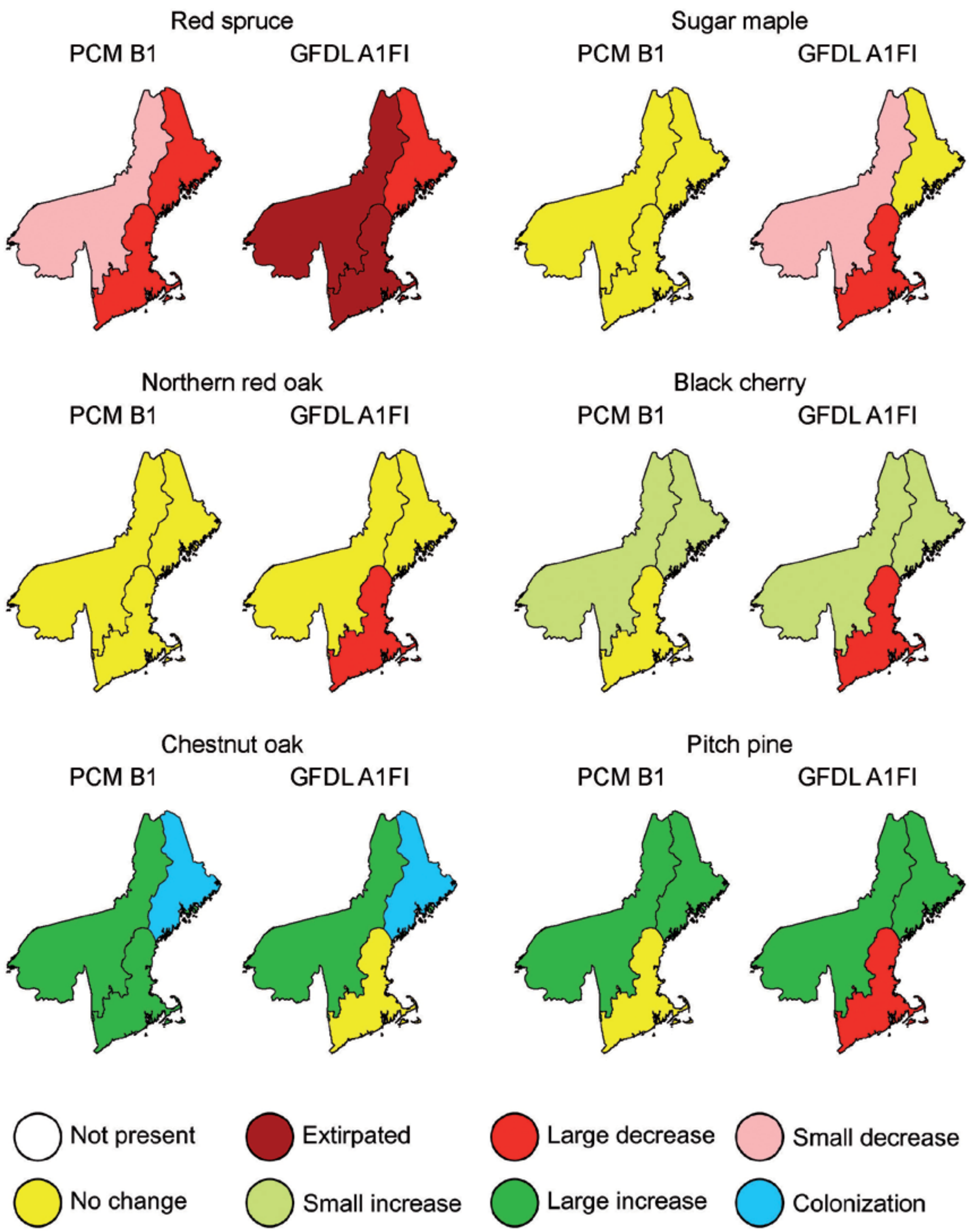

Figure 27.—Projections of relative amount and direction of change in biomass for six species in the assessment area using the LINKAGES model under the PCM B1 and GFDL A1FI climate scenarios, relative to the current climate scenario. Tree species growth values modeled by LINKAGES are presented as the biomass reached in 30 years of growth starting from bare ground in 2070 and ending in 2099. Appendix 5 contains maps of all modeled species.

LANDIS PRO

Forest landscape change was simulated using the LANDIS PRO model to project changes in tree abundance (basal area/acre) and density (trees/acre) for 24 tree species to the year 2100 and beyond (Wang et al. 2017) (Table 9). The LANDIS PRO model differs substantially from the Tree Atlas and LINKAGES because it simulates tree, stand, and landscape dynamics including succession and seed dispersal. LANDIS PRO can provide information about the projected composition and structure of an individual pixel for any point in time during the simulation. LANDIS PRO accounts for natural stand dynamics, including growth, mortality, competition, and succession, in addition to climate effects on establishment and growth. To incorporate the effects of climate on species establishment and early growth, we based the species establishment parameter in LANDIS PRO on the biomass values projected by LINKAGES under each climate scenario (Wang et al. 2017). We simulated landscape change out to the year 2300. Because trees are long-lived, nearer-term projections of forest change are more heavily influenced by the current forest conditions and management, and the effects of climate change become more pronounced over time as forests have time to respond (Duveneck et al. 2017, Thompson et al. 2011, Wang et al. 2017). This section describes the model projections of basal area and trees per acre by species for the year 2100; however, additional projections for 2040, 2070, and 2200 were also used to understand the long-term response of forests to climate change (Appendix 6). All LANDIS PRO simulation models integrate current levels of forest harvest based on data from the U.S. Forest Service Forest Inventory and Analysis program. These simulations do not include natural disturbances such as wind, fire, or insects, nor do they include effects from carbon dioxide (CO_2) fertilization or nitrogen deposition (Wang et al. 2017).

In this assessment, future forest composition and structure are reported as basal area and trees per acre for each tree species. Basal area is the area (square feet) of tree stems per unit area (acres). High basal area can be driven by many large-diameter trees, an even greater number of small-diameter trees, or a combination of the two. Therefore, trees per acre values are also included as another measure of abundance, regardless of tree size. A high basal area with a low number of trees per acre would indicate a higher relative proportion of larger and presumably older trees, and a low basal area with a high number of trees per acre would indicate a higher relative proportion of smaller and presumably younger trees.

Simulation results using the PCM B1 and GFDL A1FI climate scenarios were compared to simulations using a current climate scenario, which maintained the climate observed during 1960 to 2010 throughout the simulation. The current climate scenario is useful for understanding changes in tree species abundance and forest composition that occur as a result of natural succession and management, as opposed to changes driven by climate. Natural succession is important in the Northeast because many forests in the region are still recovering from past disturbances, such as land clearing (Chapter 1). As forests undergo succession, the tree species that are currently present in the region are generally expected to have increased basal area throughout the century under all climate scenarios (Duveneck et al. 2017, Wang et al. 2017).

Because of the existing strong influence of forest growth and succession over the next century, climate change has a relatively subtle influence on forests through 2100. Basal area is projected to increase under all three climate scenarios (current climate, PCM B1, GFDL A1FI). Climate-related changes for individual species are relatively small under the climate change scenarios (as compared to the current climate) for individual species (Table 13). In general, future basal area values for individual species under the PCM B1 and GDFL A1FI scenarios are within 20 percent of the values projected under the current climate scenario (Table 13). When basal area is summed across all species in the assessment area, total basal area is similar between PCM B1 and the current climate. This is plausible because the PCM B1 scenario projects rather mild changes in climate, allowing the trees to respond favorably to slightly

Table 13.—Basal area (BA) and trees per acre (TPA) projected by the LANDIS PRO model for 24 species in the assessment area at year 2100 under the current climate scenario and two climate model-emissions scenario combinations

		Basal area in year 2100					
		Current climate		PCM B1		GFDL A1FI	
Tree species	BA in 2000 (ft^2/acre)	BA in 2100 (ft^2/acre)	Change from 2000	BA in 2100 (ft^2/acre)	Change from current climate	BA in 2100 (ft^2/acre)	Change from current climate
American beech	6.2	11.5	85%	10.3	-10%	13.8	20%
Balsam fir	11.7	7.5	-36%	8.2	9%	9.7	29%
Black cherry	1.9	2.6	37%	2.5	-4%	3.0	15%
Black oak	1.2	1.4	17%	1.5	7%	1.4	0%
Black spruce	1.5	1.4	-7%	1.2	-14%	1.5	7%
Chestnut oak	0.3	0.6	100%	0.6	0%	0.6	0%
Eastern hemlock	9.8	9.1	-7%	8.6	-5%	10.1	11%
Eastern white pine	9.8	11.3	15%	10.6	-6%	13.3	18%
Loblolly pine	0.0	0.0	0%	0.0	0%	0.0	0%
Northern red oak	4.9	5.6	14%	5.3	-5%	6.3	13%
Northern white-cedar	4.1	4.4	7%	4.1	-7%	5.1	16%
Pignut hickory	0.3	0.7	133%	0.7	0%	0.7	0%
Pitch pine	0.2	0.2	0%	0.2	0%	0.2	0%
Quaking aspen	2.0	7.3	265%	7.0	-4%	7.9	8%
Red maple	16.2	15.6	-4%	15.4	-1%	16.8	8%
Red spruce	7.5	11.5	53%	9.1	-21%	11.8	3%
Scarlet oak	0.5	1.1	120%	1.1	0%	1.1	0%
Shagbark hickory	0.2	0.4	100%	0.4	0%	0.4	0%
Sugar maple	10.3	11.0	7%	10.1	-8%	12.5	14%
Virginia pine	0.0	0.0	0%	0.0	0%	0.0	0%
White ash	3.0	6.1	103%	5.5	-10%	7.3	20%
White oak	1.1	2.8	155%	2.8	0%	3.1	11%
Yellow birch	6.1	10.5	72%	9.0	-14%	12.3	18%
Yellow-poplar	0.1	0.1	0%	0.1	0%	0.1	0%

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Table 13 (continued).—Basal area (BA) and trees per acre (TPA) projected by the LANDIS PRO model for 24 species in the assessment area at year 2100 under the current climate scenario and two climate model-emissions scenario combinations

		Trees per acre in year 2100					
		Current climate		PCM B1		GFDL A1 FI	
Tree species	TPA in 2000	TPA in 2100	Change from 2000	TPA in 2100	Change from current climate	TPA in 2100	Change from current climate
American beech	71.1	26.4	-63%	24.4	-8%	34.8	32%
Balsam fir	237.6	15.4	-94%	21.8	42%	18.7	21%
Black cherry	7.4	6.3	-15%	6.0	-5%	9.3	48%
Black oak	1.8	2.2	22%	2.5	14%	1.9	-14%
Black spruce	11.3	12.2	8%	6.4	-48%	5.5	-55%
Chestnut oak	0.4	2.8	600%	3.9	39%	3.1	11%
Eastern hemlock	39.4	13.3	-66%	10.7	-20%	10.2	-23%
Eastern white pine	23.0	50.1	118%	40.0	-20%	65.4	31%
Loblolly pine	0.0	0.0	0%	0.0	0%	0.0	0%
Northern red oak	10.8	17.3	60%	15.7	-9%	20.6	19%
Northern white-cedar	26.2	45.7	74%	25.3	-45%	27.1	-41%
Pignut hickory	0.9	1.1	22%	1.2	9%	0.9	-18%
Pitch pine	0.3	0.3	0%	0.3	0%	0.3	0%
Quaking aspen	10.8	71.9	566%	68.9	-4%	78.2	9%
Red maple	107.2	25.9	-76%	25.7	-1%	34.9	35%
Red spruce	74.2	71.4	-4%	31.8	-55%	29.7	-58%
Scarlet oak	1.2	1.9	58%	2.1	11%	1.4	-26%
Shagbark hickory	0.6	0.8	33%	0.8	0%	0.9	13%
Sugar maple	42.2	20.4	-52%	20.1	-1%	25.8	26%
Virginia pine	0.0	0.0	0%	0.0	0%	0.0	0%
White ash	14.1	19.6	39%	16.3	-17%	28.1	43%
White oak	1.7	17.7	941%	17.2	-3%	18.1	2%
Yellow birch	36.9	46.8	27%	36.4	-22%	59.2	27%
Yellow-poplar	0.1	0.3	200%	0.3	0%	0.3	0%

longer growing seasons (Chapter 3). Projected basal area increases for all species are greater under GFDL A1FI, representing approximately 13 percent greater basal area than the current climate scenario (Fig. 28). This is plausible due to enhanced tree growth of the existing forest under warmer conditions and a longer growing season with adequate water. These changes are relatively consistent across all species projected by the LANDIS PRO model as well as by other regional forest landscape modeling (Duveneck et al. 2017).

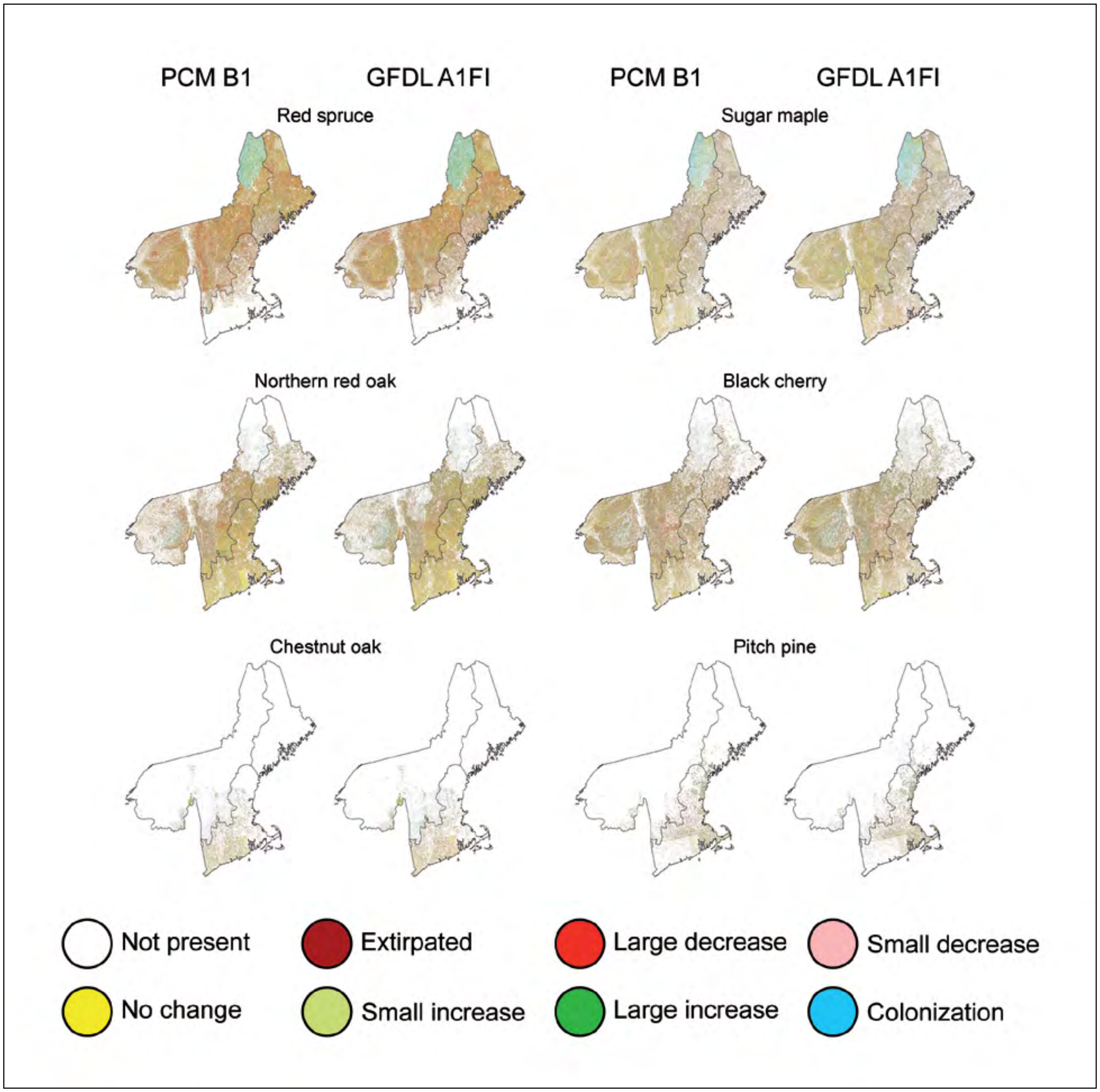


Figure 28.—Projections of relative amount and direction of change in basal area at year 2100 for six species in the assessment area using the LANDIS PRO model under the PCM B1 and GFDL A1FI climate scenarios, relative to the current climate scenario. Appendix 6 contains maps of all modeled species.

LANDIS PRO projects a greater response in trees per acre than in basal area because younger cohorts are more responsive to increased growing space due to harvest or mortality. Red spruce, northern white-cedar, and black spruce show the strongest reduction in the number of trees per acre as a result of a changing climate. The abundance of these species is projected to decrease at least 40 percent by 2100 under the PCM B1 and GFDL A1FI scenarios, compared to a scenario with no climate change. These reductions may be due to the natural mortality of mature trees combined with the future decreases in species establishment under climate warming that are projected by the LINKAGES model.The number of trees per acre for balsam fir is projected to be substantially reduced to less than 10 percent of the current value; this decline was seen in all three scenarios, including the current climate scenario (Table 13).

In contrast, climate change is projected to increase tree abundance for several other species by 2100. Yellow-poplar, which is at the northern extent of its range in the assessment area, is projected to undergo greater increases in the number of trees per acre under climate change compared to the current climate scenario (Table 13). Red maple, American beech, sugar maple, white ash, and black cherry are projected to be more abundant under the GFDL A1FI scenario compared to the current climate scenario. Chestnut oak is projected to have modest increases in both trees per acre and basal area under the two climate change scenarios, but these small increases are in addition to much more substantial increases that are modeled under the current climate scenario (Table 13).

Geographic Trends

LANDIS PRO results point to notable differences in how species and forests respond to climate change across the assessment area (Fig. 29). For some species, basal area or trees per acre are projected to increase in some areas while decreasing in others. In general, the number of trees per acre decreases for many tree species in Southern and Coastal New England while increasing in the Northern Forest. Responses in Eastern and Coastal Maine tend to be more neutral. For example, quaking aspen, sugar maple, and scarlet oak are projected to have small decreases in abundance in the Southern and Coastal New England subregion at the end of the century, while abundance is projected to increase in the Northern Forest region. Sugar maple abundance is also projected to increase in Eastern and Coastal Maine. This suggests that the climatic conditions may become less favorable for these species farther south, leading to increased mortality or reduced establishment of regeneration, while tree growth and regeneration can increase farther north as growing conditions become more suitable for these species. The northern conifer species, however, are generally projected to have reduced abundance in all subregions.

Discussion of Model Results

The three different models used in this assessment were selected because of the ability to model and represent different facets of potential forest change as a result of a changing climate (Iverson et al. 2017). The ability to compare results from different models helps us gain a deeper understanding of which parts of a forest ecosystem may be most responsive or vulnerable to change. However, the differences between the models, in terms of design, outputs, strengths, and weaknesses, also make direct comparisons among model results difficult. This section describes areas where the results from these different models point to similar or different future trends and provides context for how the results from multiple models can be integrated to better understand forest change.

Similarities

Despite the differences between the modeling approaches, the Tree Atlas, LINKAGES, and LANDIS show some strong similarities in forest change during the 21st century under a range of future climates (Iverson et al. 2017). All three models suggest that characteristic boreal species or northern species that are currently at their southern range limits will face increasing climate stress at the end of the century. All three models projected the greatest impacts on northern and boreal conifer

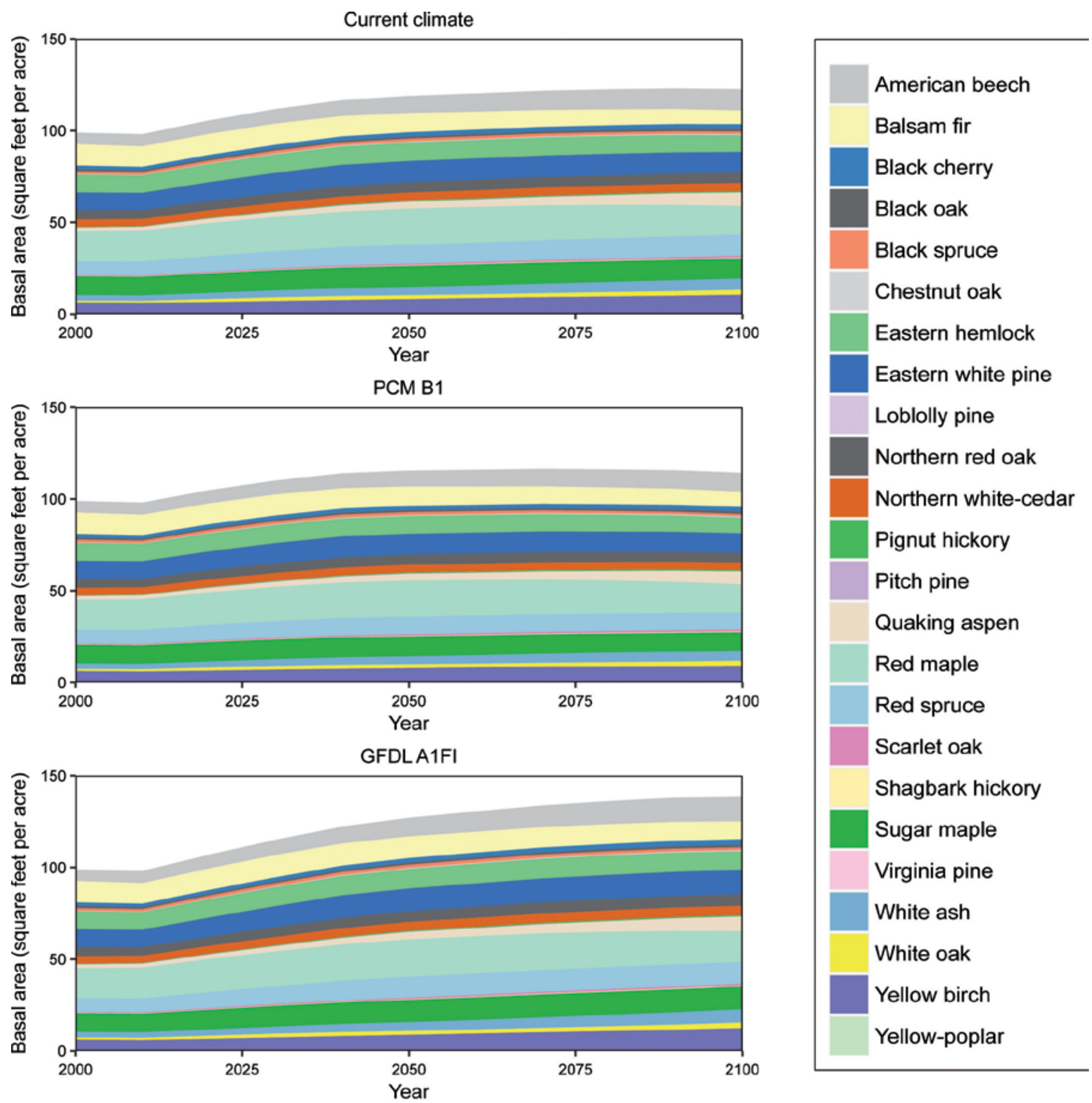


Figure 29.—Projected change in basal area for 24 species across the assessment area as modeled by LANDIS PRO. Appendix 6 contains values for individual species.

species, including black spruce, red spruce, and northern white-cedar, and to a somewhat lesser extent, eastern hemlock. These findings are similar to other modeling efforts looking at tree species responses to climate change in the Northeast, which have projected declines in boreal and northern forest communities relative to those more representative of warmer climates (e.g., Ollinger et al. 2008, Tang et al. 2012).

Additionally, all three models tend to agree that many species within the assessment area may fare better under the PCM B1 conditions than under GFDL A1FI. These results suggest that many temperate species currently present in the assessment area could tolerate a mild degree of warming with corresponding increases in growing season precipitation, as represented by the PCM B1 scenario, but may be pushed across temperature and other thresholds and suffer increased mortality or decline under more severe levels of climate change.

The models also agree that some species have the potential to increase under a range of climate futures, particularly with the greater change projected under the GFDL A1FI scenario (Iverson et al. 2017). Species projected to increase across all models are typically oaks (e.g., black, white, scarlet, chestnut) and hickories (e.g., pignut, shagbark). These species are currently common in the central hardwood forests located south of the assessment area and generally have characteristics that allow them to withstand hotter and drier conditions. Results from the DISTRIB component of the Tree Atlas and from LINKAGES point to increased suitability of site conditions for future tree growth for these species by the end of the century. The LANDIS PRO model, which includes tree growth, mortality, and succession in the simulations, also indicates that these species are likely to do better in the future. At the same time, the long-term nature of forest change is evident in LANDIS PRO, and many potentially future-adapted species are still relatively rare on the landscape at the end of the 21st century (Wang et al. 2017).

Differences

Although the three models indicate similar trends in tree species response to climate change, there are some differences in the projections for individual species among the three models. These are generally related to differences in how the models project change over time, rather than disagreement about how individual species are expected to respond in the future (Iverson et al. 2017). For example, chestnut oak is projected by the Tree Atlas to have increased future suitable habitat and is also associated with several positive modifying factors, such as high seedling establishment rates. The LINKAGES model also projects large increases in establishment of this species by the end of the century, particularly farther north in the assessment area. In the LANDIS model, which integrates LINKAGES results, notable increases in the number of chestnut oak trees per acre are not observed until 2100, and the basal area of chestnut oak does not show a distinct response to climate change until after 2100 (Fig. 28, Appendix 6).

The Tree Atlas and LINKAGES models provide information about future site suitability, with the Tree Atlas focusing on suitable habitat and LINKAGES, as used here, on potential species establishment. These models point to the potential for substantial changes in climatic and site conditions that may affect many tree species. These models tend to provide an early indication of forest changes that may first become evident in regeneration success or failure, although these changes may not be observed in forests for decades. In contrast, the LANDIS model simulates forest growth, competition, and succession over long time periods and instead suggests that much of the change in forests over the next 100 years will be due to succession and forest management. The LANDIS model results suggest that climate-related changes may take longer to manifest themselves because trees are long-lived and disperse slowly, although these model results do not include forest change from disturbance events (Wang et al. 2017).

Limitations

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

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

These factors result in forest ecosystem changes throughout the assessment area that may be independent of (or exacerbated by) effects from a changing climate. The potential for interactions among these factors adds layers of complexity and uncertainty. Despite these limitations, impact models are still the best tools available and can simulate a range of possible future outcomes. It is important to keep the preceding limitations in mind when weighing the results from different models and use them to inform an overall assessment. Future simulation modeling will broaden to incorporate more interacting factors into studies of climate change effects on forests. In the following section, we draw upon published literature to address other factors that may influence how forest ecosystems in the assessment area respond to climate change.

SUMMARY OF CURRENT SCIENTIFIC KNOWLEDGE

Climate change has the potential to alter the distribution, abundance, and productivity of forests and their associated species in several ways (Joyce et al. 2014, Vose et al. 2012). The results presented earlier provide us with important projections of suitable habitat and distribution of tree species across a range of climate futures, but these models do not account for all factors that may influence tree species and forest ecosystems under a changing climate. The effects of climate change on forests can broadly be divided into the direct effects of changing temperature, precipitation, and CO_2 levels on forests and the indirect effects of altered, new, and interacting stressors. For the most part, the model results just described primarily consider the direct effects from changes in temperature, precipitation, and other climate variables and their influence on competition. The remainder of this chapter summarizes the current state of scientific knowledge on additional direct and indirect effects of climate change on forests in the assessment area and throughout the Northeast.

Changes in Forest Productivity

One of the major implications of climate change is the potential for changes in forest productivity. Forest productivity describes the net growth rate of forests, which can be thought of as the total amount of biomass produced in a forest annually after taking into account losses from respiration and other causes. Forest productivity is an important way to assess the condition of a forest because it is the rate at which forests sequester carbon and produce forest products (e.g., timber). This section describes the potential effects of altered temperature and precipitation and nonclimatic factors such as CO_2 enrichment and ozone damage on forest productivity and carbon gain (Table 9). Other complex factors that also influence forest growth, such as amplified disturbance and intensified stressors, are discussed in subsequent sections.

Growing Season Length and Temperature

Warmer temperatures have increased the length of the growing season across the region (Chapter 2), and this trend is expected to continue (Chapter 3). Longer growing seasons extend the time available to plants for photosynthesis and can lead to enhanced forest growth (Loehle et al. 2016, McMahon et al. 2010, Ollinger et al. 2008). There is evidence both worldwide and regionally that increases in growing season length during the past century are partially responsible for observed increases in forest growth and carbon sequestration (Keenan et al. 2014, McMahon et al. 2010, Richardson et al. 2010, White et al. 1999). For example, one study of increased growing season length in northeastern forests found that a 1-percent increase in growing season length resulted in a 1.6-percent increase in net ecosystem productivity (McMahon et al. 2010, White et al. 1999). Projections of forest growth at four sites in the Northeast generally showed increases in productivity of up to 25 percent under scenarios of mild and moderate climate warming (Ollinger et al. 2008). Another study of forests across Massachusetts also projected increases in biomass from climate change due to the positive influence of warmer temperatures on photosynthesis (Thompson et al. 2011).

A high-elevation ecosystem in northern New Hampshire. Photo by Todd Ontl, U.S. Forest Service.

Temperature influences forest growth through effects on both photosynthesis and respiration. Plant respiration increases exponentially with increasing temperature, although plants are able to acclimate to different temperature regimes (Aber and Melillo 1991, Aber et al. 1995, Sendall et al. 2015). Some studies suggest that the increased respiration under warmer temperatures is offset by increases in growth, resulting in a net gain in productivity (Loehle et al. 2016, Richardson et al. 2010). Conversely, in one simulation of northeastern forests, growth rates declined when temperatures exceeded the optima for photosynthesis under a climate scenario with greater temperature increases; this effect was particularly strong in spruce-dominated forests because these forests have a lower temperature optimum for photosynthesis (Ollinger et al. 2008). Likewise, modeling of eastern white pine across its range suggests a future contraction of its range at the southern extent driven largely by temperature thresholds along with temperature interactions with moisture balance (Joyce and Rehfeldt 2013). The results of soil warming experiments indicate that warmer temperatures are likely to increase the amount of carbon lost from forests through soil respiration (Campbell et al. 2009, Melillo et al. 1995, Rustad et al. 2001), although the degree of soil respiration is related to the availability of soil moisture and nutrients.

As temperatures rise throughout the century, midsummer drought stress is projected to increase in regional forests (Campbell et al. 2009, Hayhoe et al. 2007). The warmer temperatures that cause growing seasons to shift earlier in the year also accelerate hydrologic cycles (Chapter 3). As peak streamflows move earlier into the year, there is an increased potential for late-summer soil moisture deficits (Chapter 3), which is further compounded by changes in the temporal distribution of rain throughout the year and increases in extreme precipitation events (Campbell et al. 2009, Hayhoe et al. 2007). The influence of increased evapotranspiration may be greater than the influence of decreasing summer precipitation on soil moisture (Campbell et al. 2009, Luce et al. 2016b). The effects of soil moisture and drought on forests are discussed later in this chapter.

Shorter winters and longer growing seasons may also affect other ecosystem processes, leading to negative impacts on productivity (Campbell et al. 2009). Shifts in the phenology of leaf emergence in response to warmer spring temperatures have the potential to increase the vulnerability of northeastern forests to late spring frosts when these events do occur. For example, early leaf emergence in response to warmer spring temperatures followed by frost reduced annual gross productivity 7 to 14 percent across large areas of northern hardwood forests in the Northeast during 2010 (Hufkens et al. 2012). Likewise, reduced snowpack can lead to frozen soils, affecting complex water, nutrient, and biotic dynamics. Where soils are exposed to extreme cold air temperatures, frozen soils may impede the infiltration of water into the soil and increase runoff (Hardy et al. 2001, Iwata et al. 2010). Deeper, more consistent frost has also been associated with increased export of nutrients, especially nitrogen and potassium, in stream water the following season (Fitzhugh et al. 2003, Mitchell et al. 1996). In winters when below-freezing air temperatures correspond with a lack of sufficient snow cover, increased depth and duration of soil freezing can lead to reductions in root biomass and rates of stem respiration (Reinmann and Templer 2016). 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). A smaller winter snowpack and greater depth and duration of soil freezing are also associated with declines in soil arthropod abundance and diversity in northern hardwood forests (Templer et al. 2012b).

Although climate change is expected to increase forest growth in many ways, it can be difficult to separate these trends from other changes that are occurring in forests. Previous land use in the region has resulted in second-growth forests that are young compared to pre-European settlement conditions (Foster et al. 1998, Thompson et al. 2011). Several modeling studies demonstrate that forests across the region are generally expected to accumulate carbon over the next several decades simply due to succession and forest maturation (Duveneck et al.

2017, Thompson et al. 2011, Wang et al. 2017). In the absence of severe disturbance, projected changes in forest productivity and biomass are generally driven by this successional change through mid-century, after which the effects of climate change on forest growth, whether positive or negative, become more apparent (Duveneck et al. 2017, Ollinger et al. 2008, Pan et al. 2009, Thompson et al. 2011, Wang et al. 2017). Additionally, land-use changes that result in conversion of forest to other land uses have the potential to decrease any carbon gained through either forest succession or growth from climate change (Puhlick et al. 2017, Thompson et al. 2011).

Carbon Dioxide Fertilization

One of the biggest uncertainties about the effects of climate change on forests may be the influence of CO_2 on plant productivity. Elevated CO_2 has a direct, positive effect on carbon uptake and can increase the water use efficiency of trees (Ainsworth and Rogers 2007, Hyvönen et al. 2007, Norby and Zak 2011). There is evidence that CO_2 fertilization has contributed to enhanced tree growth over the past two centuries (Cole et al. 2010, Franks et al. 2013, Loehle et al. 2016, Norby and Zak 2011) and has potentially offset some of the effects of drier growing seasons (Franks et al. 2013, Wang et al. 2006).

Modeling studies examining productivity in northeastern forests consistently project greater increases when the CO_2 fertilization effect is included in modeling (Aber et al. 1995, Ollinger et al. 2008, Pan et al. 2009). This effect is particularly strong for deciduous forests; the benefit of CO_2 was projected to be less in spruce forests because of the sensitivity of the northern forests to temperature increases (Aber et al. 1995, Ollinger et al. 2008). Often, the models suggest that CO_2 fertilization has a greater effect on forest productivity than does climate change (Aber et al. 1995, Ollinger et al. 2008, Pan et al. 2009). As discussed earlier, warmer temperatures and longer growing seasons can lead to increased evapotranspiration, respiration, and potential for drought stress (Hyvönen et al. 2007). Enhanced CO_2 can partially offset this effect by improving water use efficiency (Ollinger et al. 2008).

Although carbon dioxide enrichment experiments and models suggest net primary productivity will increase under elevated CO_2, several factors have the potential to limit the CO_2 fertilization effect. Other environmental change factors, including nutrient and water availability, ozone pollution, and tree species, age, and size, all influence the ability of trees to capitalize on CO_2 (Ainsworth and Long 2005, Norby and Zak 2011, Norby et al. 2005). For example, a future decrease in nitrogen availability may limit the otherwise positive effects of CO_2 enrichment (Templer et al. 2012a). Productivity increases under elevated CO_2 could be partially offset by reductions in productivity from warming-induced drought stress or the effects of future disturbances (Dieleman et al. 2012, Franks et al. 2013). Furthermore, climate change-related disturbance such as fire, insects, disease, and management could reduce forest productivity independent of CO_2 fertilization (Couture et al. 2015, Mohan et al. 2009).

Moreover, no CO_2 fertilization experiments have been undertaken in the Northeast (Ollinger et al. 2008), and observational studies elsewhere have generally not evaluated the effects of CO_2 fertilization beyond 600 ppm. These limitations make it difficult to predict how regional forests may respond under even higher levels of atmospheric CO_2, such as the 900-ppm levels projected under the A1FI emissions scenario for 2100.

Atmospheric Pollutants

Although warmer temperatures have the potential to increase enzymatic activity and nutrient cycling, interactions with atmospheric deposition will remain an important consideration. Anthropogenic emissions of nitrogen and sulfur increased during the past century, peaking in the 1970s. Although nitrogen and sulfur emissions have declined substantially since the Clean Air Act was enacted in 1970 to control pollution from coal-burning power plants (Clean Air Act of 1970, Strock et al. 2014), the effects on forests are long-lasting. Nitrogen and sulfur emissions undergo chemical transformations that produce nitrates and sulfates, which are eventually deposited on the ground (Elliott et al. 2013). Importantly, sulfur and nitrogen compounds are deposited at high concentrations in rain and snow in the eastern United States, particularly at high-elevation locations (Pardo et al. 2011). In forest ecosystems, hydrogen ions associated with nitrogen and sulfur deposition replace nutrient base cations of calcium, magnesium, and potassium, depleting these nutrients and allowing them to leach into drainage waters. At the same time, toxic cations of aluminum are mobilized, and the combined effects of nutrient depletion and increased toxicity have been proven to reduce the health and productivity of forests and streams through acidification (Aber et al. 1989, 1998; Elliott et al. 2013; Fernandez et al. 2003; Long et al. 2013; Schaberg et al. 2006).

Acid deposition has had dramatic effects on forest ecosystems in much of the assessment area (Likens et al. 1996), but it is less clear how these impacts will interact with the effects of a changing climate. Nitrogen saturation has been shown to reduce carbon allocation to plant roots and mycorrhizae and suppress organic matter decomposition (Frey et al. 2014, Pardo et al. 2011). Available evidence suggests that nitrogen and sulfur deposition has contributed to the increased susceptibility of forests to drought and insect attack, and is expected to contribute to reduced ability to withstand climatic changes (Friedland et al. 1984, McNulty and Boggs 2010, Pardo et al. 2011). At the same time, some research suggests that nitrogen deposition could be beneficial and help fuel forest growth in a future CO_2-rich world (Devaraju et al. 2016, Rustad et al. 2012, Thornton et al. 2007). Future rates of nitrogen deposition are unknown, but may continue to decrease in the future as an indirect outcome of reduced greenhouse gas emissions (Driscoll et al. 2014). The potential impacts of elevated nitrogen deposition in a changing climate remain unclear.

Ground-level ozone is a pervasive air pollutant that can damage plant tissue and decrease photosynthesis (Smith et al. 2012). Ozone levels are relatively low in the assessment area compared to other parts of the Northeast, although ozone injury was detected in sensitive species during most years and most states from 1994 through 2010 (Smith et al. 2012). Ozone affects stomatal control, causing reduced water use efficiency, and has also been linked to needle blights in white pine (Mohan et al. 2009). Studies suggest that ozone exposure can offset CO_2-induced gains in productivity and increase water stress (Karnosky et al. 2003, McLaughlin et al. 2007, Mohan et al. 2009). Ozone can also cause changes in leaf chemical composition and emission of volatile compounds, which have the potential to affect plant defense mechanisms or attractiveness to herbivores (Mohan et al. 2009). Ozone levels have been decreasing in recent decades, but it is possible that levels may increase with climate change as plants produce more volatile organic compounds, which then react with nitrogen oxides to produce ozone (Rustad et al. 2012).

Nutrient Cycling

As air temperatures warm and precipitation patterns change, the way nutrients are cycled between plants, soils, and the atmosphere may also change. Alterations in nutrient cycling have important implications for the productivity of forest ecosystems, which can be limited by nutrients such as phosphorus, nitrogen, calcium, magnesium, and potassium (Campbell et al. 2009, Templer et al. 2012a). The long-term effects of past and ongoing acid deposition in the region increase the complexity of connected nutrient cycles and their interactions, making predictions more difficult. Numerous factors, including changes in temperature, precipitation, soil moisture, acid deposition, and the interaction among these factors can impair nutrient cycling and the availability of nitrogen to trees and other vegetation (Campbell et al. 2009, Rennenberg et al. 2009). For example, increased nutrient leaching may occur where snowmelt, soil warming, and biological production of nutrients happen earlier in the spring while the onset of leaf-out, photosynthesis, and overstory plant nutrient uptake still happen later (Campbell et al. 2010, Groffman et al. 2012). Likewise, extremes in light environment, temperature, precipitation, pathogen attack, and herbivory can induce or amplify nutrient imbalances in sugar maple forests (St. Clair et al. 2008).

Decomposition of vegetation is a major component of most nutrient cycles and is largely carried out 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 et al. 2012, Finzi et al. 2006, Rustad et al. 2001). In studies that have examined the effects of extended dry periods followed by moisture pulses on nutrient cycling, moisture pulses led to a flush of mineral nitrogen, but this nutrient flush was not sufficient to compensate for the lack of microbial activity during dry periods (Borken and Matzner 2009). Thus, an increase in wet-dry cycles appears to lead to a reduction in nutrient availability for trees. These results suggest that the increasingly episodic precipitation regime in the assessment area may add further stress to forest ecosystems in the future.

Sea-level Rise

Forest ecosystems along coasts will be affected by climate change. Coastal ecosystems—including wetlands, salt marshes, estuaries, and forests—provide many benefits, including water filtration, nursery habitat for fish and other species, carbon storage, and recreation (Moser et al. 2014, Scavia et al. 2002). Additionally, coastal ecosystems help to buffer storm surges and waves and reduce impacts from flooding. As sea levels rise, land will become inundated by water, and areas that are currently farther inland or upland will be affected by warmer water temperatures, increased water salinity and acidity, and other changes in ecosystem dynamics (Moser et al. 2014). Further, coastal ecosystems play an important role in buffering the effects of extreme conditions along the coasts, and impacts on these systems can reduce their ability to protect against storm surges and flooding (Groffman et al. 2014).

Part of the extensive Atlantic Ocean coastline within the assessment area. Photo by Maria Janowiak, U.S. Forest Service.

Disturbance Frequency and Intensity

Climate change may increase the frequency and severity of disturbances, such as drought, catastrophic winds, ice storms, rainstorms, wildfires, and floods (Dale et al. 2001, Hanson and Weltzin 2000, Peterson 2000, Vose et al. 2012), although there are challenges in attributing changes in these events to a changing climate (Chapter 3). Changes in these various disturbance regimes, with their ability to fundamentally alter ecosystems, may have the most obvious and even drastic effects of climate change on northeastern forests. Some of these disturbances may also interact to increase system susceptibility to other disturbances; for example, tree mortality and increased downed wood caused by extreme wind events may increase wildfire risk.

Extreme Precipitation and Floods

One of the most striking effects of climate change is that the hydrologic cycle is intensified as a result of more energy in the atmosphere, resulting in a greater amount of precipitation falling in large events (Chapter 3). Extreme precipitation can have substantial effects on ecosystems, particularly when rainfall occurs as part of an extreme storm event. As one example, wind- and pressure-driven storm surges during hurricanes can result in flooding, especially when these events occur in conjunction with high tides (Frumhoff et al. 2007). This type of interaction occurred during the 1938 hurricane. Although nor'easters typically have less energy than hurricanes, these events may occur more frequently in the region and may be larger in duration and extent, leading to a greater overall effect on ecosystems.

Flooding can affect forest systems differently, depending on the frequency and duration of floods, and the soil, vegetation, and topographic complexity of the landscape. In mountainous areas, floods are generally brief and intense, with floodwaters funneling rapidly down steep slopes and into valley streams (Eisenbies et al. 2007, Swanson et al. 1998). These swift, fierce floods often damage trees by breaking stems and limbs, and scouring vegetation and soils. In lowland areas, floods are generally more gradual and last longer, with longer periods of soil saturation and less tree breakage. Flooding can increase erosion and transport of nutrients, contaminants, and pathogens (Groffman et al. 2014). Disturbances caused by floods, drought, scouring by ice, and river channeling often strongly influence tree species and forest diversity, especially in lowland and riparian forests (Vadas and Sanger 1997).

Increased extreme precipitation is expected to exacerbate runoff and soil erosion rates (Nearing et al. 2004), although most studies examining the effects of climate change on soil erosion have focused on agricultural settings, rather than forest ecosystems. Additional vegetative cover and root stabilization in forest systems may make forests less prone to soil erosion, but not all forest soils will be equally protected. Reductions in vegetative cover from climate-related impacts or disturbance events such as prolonged drought, wildfire, or increased tree mortality, could lead to greater susceptibility to erosion. Additionally, reduced snow cover and a shift of winter precipitation from snow to rain may make forest soils and streams particularly vulnerable to erosion during the late fall and early spring.

Wind Disturbance

Wind disturbances, including hurricanes, tornadoes, downbursts, gales, and intense windstorms, are a primary driver of vegetation patterns and succession in many regional forests, with both small-scale and stand-replacing wind events influencing tree species composition, forest structure, and landscape complexity (Xi and Peet 2011). These disturbance events have historically been an important component of the disturbance regime for northeastern forests (Boose et al. 1994). The effects of individual disturbances can vary greatly, occurring at different spatial scales and causing different types of damage to forests. The physical effects of a given wind event on forests will be influenced by numerous factors, such as storm severity, forest composition, stand age, soils, and topography (Foster and Boose 1992, Peterson 2000, Xi and Peet 2011). Impacts that are common across most wind disturbances include tree mortality, altered forest structure, and altered tree species composition and diversity (Xi and Peet 2011).

To date, the amount of evidence that climate change will alter atmospheric circulation patterns and processes, leading to increased risk of extreme storms, is somewhat limited (Intergovernmental Panel on Climate Change 2012, Kunkel et al. 2012, Ulbrich et al. 2009). No evidence is available to suggest that severe convective storms (e.g., thunderstorms, hailstorms) or extreme wind has increased in recent decades in the region (Bryan et al. 2015, Kunkel et al. 2012). Likewise, the infrequency of hurricanes makes it difficult to detect change or attribute changes to an altered climate (Kunkel et al. 2012). Looking to the future, there is some evidence that suggests wind events may increase in frequency or severity as the atmospheric conditions leading to high winds become more common (Del Genio et al. 2007; Peterson 2000; Trapp et al. 2007, 2011) and return intervals for severe wind events shorten (Frelich and Reich 2010). Although there is little information on localized wind events, there is greater evidence that the conditions leading to tropical storms and hurricanes may increase as a result of climate change (Chapter 3).

If wind disturbances do increase in a changing climate, forest ecosystem dynamics will also change. Under climate change, stand-replacing wind events could potentially act as a catalyst for more rapid ecosystem change than would occur through migration and competition alone. This may be particularly true where regeneration consists of novel species mixes or where other stressors, such as invasive species or overabundant herbivores, have greatly altered forest understory and regeneration conditions. Moreover, tree mortality as a result of future wind events may increase the risk of wildfire. Finally, postdisturbance management decisions, such as salvage logging, may also compound the severity of these events, creating novel regeneration environments.

Wind damage from less severe events can shift a system into smaller tree size-class distributions as larger trees suffer more bole breakage, leaving smaller trees as survivors (Peterson 2000). Evidence suggests that blowdowns disproportionately affect larger trees, shallow-rooted species, and thinned stands (Boucher et al. 2005, Dale et al. 2001). Sugar maple, sweet birch, and yellow birch are generally more wind resistant than black cherry, red maple, and yellow-poplar (Peterson et al. 2013a). Succession may be set back if sprouts of damaged trees reclaim the canopy, or altered altogether if understory species shift the composition toward late seral species (Peterson 2000), as was observed in many forests after the 1938 hurricane (Spurr 1956). More frequent or widespread blowdown events may release the understory and accelerate the transition to shade-tolerant species (Abrams and Scott 1989). This is especially the case in fire-dependent communities where shade-tolerant understories have developed in the absence of fire (Abrams and Nowacki 1992, Holzmueller et al. 2012). Events that create large openings may provide opportunities for regeneration of intermediate shade-tolerant species such as white oak, flowering dogwood, and various hickory species, especially in higher elevations (Abrams et al. 1998, Campbell et al. 2005). As with more severe events, local site conditions including forest composition, stand age, soils, and topography have a substantial influence on the specific effects of a particular disturbance event.

Ice Storms

Ice storms are especially prevalent in the eastern United States, and these storms can cause substantial damage to ecosystems and infrastructure (Changnon 2003, Irland 2000, Rustad and Campbell 2012). The most common cause of ice formation is when a winter warm front passes over much colder air. As rain falls from the warm layer through the layer at or below 32 °F, it becomes supercooled and able to freeze onto any surface it encounters. The Climatic Data Center’s Storm Data historical records document 18 major ice storms in the Northeast

A forest that has been subjected to ice storms and other disturbances. Photo by Maria Janowiak, U.S. Forest Service.

since the late 1800s, the most devastating of which occurred in 1998 (Irland 2000). The 1998 storm deposited up to 3.1 inches of freezing rain across nearly 24 million acres extending from south-central New England to northwestern New York and southern Quebec, paralyzed power grids, left much of the region without power, and caused more than $2.2 billion of damage (Irland 2000).

Some studies suggest that the frequency and severity of these storms will increase due to climate change (Castellano 2012; Cheng et al. 2007, 2011). In forests, the accumulation of ice on trees can have effects ranging from minor twig breakage to extensive crown damage. The decurrent growth habit (a wide crown with secondary trunks emerging from a main trunk) of many northern hardwoods makes them more vulnerable to ice damage than trees with a central leader (Turcotte et al. 2012). Species such as oaks, hickories, maples, and ashes are apparently highly susceptible to branch and stem breakage, whereas conical species such as spruce are less susceptible (Irland 2000, Turcotte et al. 2012). Within species, damage appears to be greater in older, taller individuals, with higher mortality in sawtimber size classes than in pole or sapling size classes (Turcotte et al. 2012). Residual trees can have reduced photosynthesis due to the loss of crown or decreased productivity as resources are used for closing the wound or protecting against pathogens. Damaged trees are also more susceptible to infection by pests and pathogens. Gap formation from branch and tree loss can alter light regimes, soil climate, and seedling establishment (Rustad and Campbell 2012). For example, the severe ice storm of 1998 affected canopy structure, regeneration, species composition, and nutrient cycling dynamics (Rhoads et al. 2002, Weeks et al. 2009) and influenced bird communities (Faccio 2003).

Wildfire

Climate change has the potential to affect patterns of wildfire disturbance in a number of ways, although the specific effects on eastern forests are complex, hard to predict, and likely to vary geographically, by forest community, and over time. Climate can directly affect the frequency, size, and severity of fires, as well as indirectly affect fire regimes through influence on vegetation structure and composition (Sommers et al. 2011). Fire can be a catalyst for change in vegetation in many ways, such as by prompting more rapid change than would be expected based only on the changes in temperature and moisture availability (Gillett et al. 2004). As with wind disturbances, the potential exists for novel successional pathways after wildfire if climatic conditions, seed sources, or management decisions favor different forest types.

The relationship between temperature, precipitation, and evapotranspiration will influence whether future conditions are suitable for wildfire. If temperature and evapotranspiration increases overwhelm modest precipitation increases, conditions supporting wildfire may become more frequent (Drever et al. 2009, Guyette et al. 2014). This may be particularly important during the spring and fall where wildfire conditions are more common. 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, Sommers et al. 2011). Drier conditions could also increase the frequency of wildfires in certain forest types of the Northeast, such as northern hardwoods, where fires have historically been rare. A change in vegetation, particularly an increase in oak systems over time, could increase the abundance of fire-associated forest types in the region (Mohan et al. 2009).

Relatively few studies have modeled how climate change will affect wildfire in regional forests. At global and national scales, models generally project an increase in wildfire probability, particularly for boreal forests, temperate coniferous forests, and temperate broadleaf forests (Bachelet et al. 2001, Moritz et al. 2012). One recent modeling effort suggests that wildfire risk may increase in the Northeast (Guyette et al. 2014), whereas another suggests that it is not likely to change substantially over the next century (Heilman et al. 2015, Tang et al. 2015). Projections for adjacent areas of Canada point to the potential for increased fire occurrence in the future, especially in lightning-caused fires (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).

It is likely that human activities and landscape may have a larger influence on wildfire activity than biophysical drivers across much of the assessment area. Land use and management decisions often determine whether a change in fire risk might translate to an actual increase in wildfire activity. But future policies, decisions, and actions regarding wildfire suppression and prescribed fire are unknown, adding to the uncertainty of potential effects of wildfire on forests in the assessment area.

Intensified Stressors

Moisture Stress and Drought

There is evidence for an increased risk of future moisture stress and drought in the assessment area (Chapter 3). Temperatures are expected to rise over the next century, and evapotranspiration in ecosystems is expected to increase as a result (Center for Climatic Research 2016, Hayhoe et al. 2007, Kunkel et al. 2013). Moisture stress and even drought can occur when increases in evapotranspiration are not offset by a corresponding increase in precipitation and soil moisture (Box 12). Within the assessment area, modeling results suggest a much greater potential for more frequent droughts and moisture stress during the growing season under the GFDL A1FI scenario, which projects much warmer temperatures and reduced summer precipitation (Chapter 3). Under the milder PCM B1 scenario, however, warmer temperatures may also lead to increased evapotranspiration and physiological stress if increases in precipitation do not correspond to temperature increases.

Box 12: What is 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 (Clark et al. 2016, Vose et al. 2016). Most simply, drought is a lack of water. A drought does not simply imply dry conditions, as certain ecosystems and forest communities are well adapted to dry conditions. Thus, a drought is when conditions are dry relative to long-term averages in a particular place.

Drought is described in several ways within the scientific literature, often as meteorological, hydrologic, or agricultural drought. Meteorological drought is a function of precipitation frequency, and hydrologic drought is a measure of how much water is available in a watershed. Agricultural drought takes into account changes in the amount of water that evaporates from the soil and is transpired by plants, as well as information about soil moisture and groundwater supply. All three indicators can be important in understanding the effects of climate change on water within forest ecosystems and determining whether systems are lacking sufficient water.

Additionally, because precipitation is more likely to occur during larger precipitation events, the number of consecutive days without precipitation is also expected to increase (Diffenbaugh et al. 2005).

One review of the consequences of precipitation variability on forests proposed that the typical state of soil moisture in a forest determines whether extreme precipitation events with longer intervals between events are likely to have positive or negative impacts on a system (Knapp et al. 2008). For example, xeric systems (adapted to dry conditions) would generally be less affected by dry periods because they are already limited by moisture stress, and larger precipitation events could recharge soil water levels, allowing for slightly longer periods of moisture. On the other end of the spectrum, hydric (i.e., wetland) systems are limited by anoxia rather than soil moisture, so longer dry periods between precipitation events would lower the water table, allowing oxygen to reach the roots of aquatic plants and increasing biomass productivity. Mesic systems (adapted to moderately moist conditions) would be the most affected by any increasing duration and severity of soil water stress because they are not well adapted to prolonged dry periods. This conceptual framework does not incorporate modifiers such as soil texture and root depth, but the general principles are useful.

Moisture availability is a critical dynamic for forests in the eastern United States, like other forests worldwide (Choat et al. 2012, Clark et al. 2016, Pederson et al. 2014, Vose et al. 2016). Early-season moisture is essential for seed germination and establishment. Although mature trees are better able to resist increases in temperature and reductions in available moisture, severe or sustained drought can increase tree mortality, open the forest canopy, alter forest growth and composition, and increase susceptibility to other stressors (Clark et al. 2016, Dale et al. 2001, Millers et al. 1989, Pederson et al. 2014). Drought stress has been linked to decline of oak and ash trees in the Northeast (Millers et al. 1989, Mohan et al. 2009). Further, drought-stressed trees are typically more vulnerable to insect pests and diseases (Dale et al. 2001, Millar and Stephenson 2015, Ryan and Vose 2012).

The potential effects of drought on forests will depend on many factors, including duration and severity of the drought and site-level characteristics of the forest. High stand density may compound susceptibility to moisture stress as high-density stands face increased competition for available moisture (D’Amato et al. 2011, Magruder et al. 2012). Tree species also respond differently to drought. For example, drought during the past century has been linked to dieback in sugar maple and some species of birch and ash (Auclair et al. 2010). Additionally, elevated atmospheric CO_2 reduces the rate of water loss from trees through evapotranspiration, but as discussed earlier in this chapter, it is unclear to what degree enhanced water use efficiency may be able to offset the combined effects of warmer temperatures and drier conditions (Ryan and Vose 2012).

There may be an increasing potential for exceptional drought events with unprecedented severity to occur in general, although evidence is lacking specifically for the Northeast. Where temperature-driven increases in moisture stress combine with extremely hot temperatures, the subsequent "hotter droughts" can emerge as novel stressors on ecosystems (Allen et al. 2015, Millar and Stephenson 2015). The effects of these disturbances can make forests more vulnerable to insect pests and pathogens, increase fire risk, or accelerate shifts to other forest types or nonforest vegetation (Millar and Stephenson 2015).

Invasive Plant Species

Nonnative invasive species are already a major threat to many forests in the assessment area. The invasion of nonnative plant species into new environments is related to both the species and environmental conditions in question. It is generally expected that many invasive plants will "disproportionately benefit" under climate change due to broad environmental tolerances, extended leaf phenology, more effective exploitation of changed environments, and more aggressive colonization of new areas (Dukes et al. 2009, Fridley 2012, Hellmann et al. 2008, Willis et al. 2010). Climatic factors that could influence the ability of a species to invade include warmer temperatures, earlier springs, and reduced snowpack (Hellmann et al. 2008, Ryan and Vose 2012). Across a variety of ecosystems and land uses, increases in CO_2 have been shown to have positive effects on growth for many plant species, including some of the most invasive weeds in the United States (Ziska 2003). Experiments with CO_2 fertilization on kudzu seedlings have indicated increased growth, increased competition with native species, and range expansion (Sasek and Strain 1988, 1989). Models have also projected that increased CO_2 emissions and subsequent warmer winter temperatures are likely to expand the northern ranges of bush honeysuckles, privet, and kudzu (Bradley et al. 2010).

Further, as discussed throughout this chapter, many potential effects of climate change are expected to increase stress and disturbance within forest ecosystems, thereby raising the potential for invasive species to exploit altered environments (Hellmann et al. 2008). Disturbances such as flooding, ice storms, and wildfire can open forest canopies, expose mineral soil, and reduce tree cover, providing greater opportunities for invasion (Ryan and Vose 2012). Once established, invasive plant species can also limit regeneration of native tree species through increased competition. Nonnative species may facilitate the invasion and establishment of other nonnative species. Evidence suggests that such an interaction occurs with European earthworms and buckthorn, which apparently have a co-facilitating relationship (Heimpel et al. 2010). Similarly, studies in northern Minnesota found that a combination of invasive earthworms and warming conditions could benefit nonnative understory plant species (Eisenbies et al. 2007).

Insect Pests and Forest Pathogens

The response of forest insect pests and pathogens to a warmer future will vary widely by modes of infection, transmission, survival, and tree response (Dukes et al. 2009). Pests and pathogens are generally expected to become more damaging in forest ecosystems as the climate changes, because they will be able to adapt more quickly to new climatic conditions, migrate more quickly to suitable habitat, and reproduce at faster rates than host tree species (Ryan and Vose 2012, Weed et al. 2013). Reviews examining forest pests and diseases in light of possible climate change impacts highlight the potential for interactions involving other stressors that heighten susceptibility to these agents (Sturrock et al. 2011, Trotter 2013, Weed et al. 2013). Threats from insect pests and forest disease outbreaks, including those of native species (e.g., forest tent caterpillar and spruce budworm), become more problematic when trees are stressed by factors such as drought (Babin-Fenske and Anand 2011, Gray 2008, Manion 1991).

Although the effect of climate on specific forest insects remains uncertain in many cases, information about some agents suggests the potential for negative impacts on forests in the assessment area. Research on the hemlock woolly adelgid indicates that its range is generally limited by cold winter temperatures with mortality occurring at temperatures below –20 °F (–29 °C) and that the ability of the insect to tolerate cold temperatures decreases as the winter progresses (Dukes et al. 2009, Paradis et al. 2008, Skinner et al. 2003). Less severe winters may increase insect survival and spread (Dukes et al. 2009, Paradis et al. 2008, Trotter 2013). Similarly, a warmer climate may also allow the balsam woolly adelgid to increase in the region (Kanoti 2006). Cold temperatures below about 0 °F (–18 °C) kill the southern pine beetle, and this species has been observed as expanding its range northward into the pinelands of New Jersey (Weed et al. 2013). The fungal pathogen *Armillaria* is already widespread, but could expand further or become more aggressive due to a longer active season, enhanced colonization under warmer and drier conditions, and increased stress on host trees, particularly in response to drought (Dukes et al. 2009, Kliejunas 2011, Sturrock et al. 2011). Although many forest insect pests are expected to have increased habitat in the region, populations of some species such as the native spruce budworm may be reduced under the warmer conditions expected in the future (De Grandpré and Pureswaran 2013, Pureswaran et al. 2015, Régnière et al. 2012).

Herbivory

As mentioned earlier, changes in snowfall amount and duration throughout the assessment area may change the wintertime foraging behavior for herbivores such as moose, white-tailed deer, and snowshoe hare. In particular, there is mounting evidence that climate change will influence both moose and white-tailed deer populations (Frelich et al. 2012, New Hampshire Fish and Game Department [FGD] 2013, Rempel 2011). Moose are expected to be negatively affected by numerous changes in the future, including heat stress from warmer temperatures and an increase in parasitism from winter ticks (Rempel 2011, Rodenhouse 2009).

In contrast, changes in climate may benefit deer in many parts of the region. Warmer winter temperatures and reduced snow depth are expected to reduce the energy requirements for deer and increase access to forage during winter months (New Hampshire FGD 2013, Wisconsin Initiative on Climate Change Impacts 2011). Where warmer temperatures and less severe winters enable deer populations to expand into areas currently dominated by moose, deer may spread brainworm—a common deer parasite that does not affect the species, but which causes mortality when spread to moose (Frelich et al. 2012).

Dynamics between moose and deer populations are tightly linked to forest composition, and any changes in the distribution or abundance of deer and moose will have a strong influence on forest composition in the future (Frelich et al. 2012, Rodenhouse 2009). The ability of either species to thrive will depend in part on the tree species that are available for browse. Research has found that deer browsing pressure may limit the ability of forest ecosystems to respond to climate change (Fisichelli et al. 2012). Northern white-cedar, in particular, has been negatively affected by excessive deer browsing within the assessment area (Boulfroy et al. 2012, Larouche and Ruel 2015), and expanded deer herbivory could affect recruitment of northern white-cedar, especially where snowpack and winter severity are reduced (Kenefic et al. 2015). Tree species that are anticipated to expand their ranges northward in the assessment area, such as many hardwood species, are browsed much more heavily than boreal fir and spruce species (Andreozzi et al. 2014). Deer herbivory may also favor species which are not preferred browse species, such as eastern hophornbeam and black cherry, or invasive species such as buckthorn or Japanese barberry.

Changes in Forest Composition

Trees and other plant species have responded to past climate change in a variety of ways. The ranges of tree species in eastern North America have shifted in response to climate since the last ice age (Davis 1983), and tree species are expected to shift in response to future climate change (Iverson et al. 2004a, Vose et al. 2012). Across the Midwest and Northeast, there is some evidence that tree species and other organisms may be moving northward (Fisichelli et al. 2014b, Parmesan and Yohe 2003, Woodall et al. 2009) and upward in elevation (Lee et al. 2005), with some species migrating at very high rates (Woodall et al. 2009). Evidence also suggests that ranges may be contracting as species retreat at the southern edge of their range in response to changed climatic conditions, without a corresponding expansion at the northern edge of their range (Murphy et al. 2010, Zhu et al. 2011). However, these changes are less visible at smaller spatial scales in New England, where cold-adapted conifer species are still recovering from historical declines (Foster and D'Amato 2015). Forest composition changes slowly due to the long-lived nature of trees (Davis 1989).

The modeling results presented earlier in this chapter describe projected changes, negative and positive, in future tree species distribution. In general, trees that are at the range boundary for the species are more likely to be influenced by climate change. Warmer temperatures are expected to be less favorable to species located at the southern extent of their range (Parmesan and Yohe 2003), and many species with northerly distributions are projected to undergo the greatest declines. Declines could occur in different life stages, depending on the species. For example, some species may suffer a decline in seedset or declines in successful germination or establishment, whereas others could find it difficult to grow into maturity (Ibáñez et al. 2007, 2008). Mature trees may initially fare better than young trees due to greater access to resources and a greater ability to resist heat and drought stress, but this may be a relatively short-term effect if the species as a whole is unable to grow into maturity and reproduce (Ibáñez et al. 2008).

Ecosystem models project that tree species currently near their northern range limits in the region may become more abundant and more widespread under a range of climate futures. As discussed earlier in this chapter, it is possible that some tree species that are not currently common or even present in New England or northern New York will establish in the region. However, it is expected that species establishment will substantially lag changes in climate (Dobrowski et al. 2013, Iverson and McKenzie 2013, Iverson et al. 2004a, Renwick and Rocca 2015). The northward expansion of tree species ranges is constrained by many factors, including seed dispersal dynamics and landscape fragmentation (Ibáñez et al. 2008, Scheller and Mladenoff 2008). Catastrophic disturbances, such as wildfire, could facilitate establishment of colonizing species from the south if environmental conditions promote germination and vigor of establishing seedlings, but also have the potential to reduce the ability of an area to maintain forest cover at any scale (Camill and Clark 2000). Assisted migration, the intentional movement of species to areas expected to provide suitable habitat, could also provide new sources for spread, thereby accelerating the rate of colonization (Duveneck and Scheller 2015, Iverson and McKenzie 2013, Pedlar et al. 2012).

Interactions

Although this chapter focuses on the potential effects of climate change on forests, there are substantial interactions between climate change and other changes occurring within the landscape of New England and northern New York. Climate change has the potential to alter an array of complex ecosystem processes and interactions, and the interactions among these impacts will be critically important in determining the resulting changes to forest ecosystems across the assessment area. Just as there are typically several interacting drivers for individual tree mortality (Dietze and Moorcroft 2011), overall ecosystem shifts will be influenced by multiple factors (Frelich and Reich 2010, Millar and Stephenson 2015). Although many of these potential interactions have been described in this chapter, many have not. Examples of additional community interactions that could alter forest ecosystems include changes in mycorrhizal associations, changes in synchrony among plants and pollinators, and changes in the relationships among hosts, predators, and parasites (Bartomeus et al. 2011, Trotter 2013). Across the landscape of New England and northern New York, factors related to land use and management affect how climate change will influence natural systems (Ordonez et al. 2014).

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

Likewise, there is increasing evidence for interactions among drought and insect pests or pathogens leading first to tree decline and mortality, and then sometimes to increased wildfire risk (Allen et al. 2010, Anderegg et al. 2015). Ultimately, ecosystems subjected to multiple interacting stressors may reach thresholds that fundamentally change ecosystem character and function (Manion 1991, Millar and Stephenson 2015). To date, much of the literature on this subject focuses on global and national analyses (Allen et al. 2010, 2015; Anderegg et al. 2015; Millar and Stephenson 2015).

SUMMARY

Models are useful for exploring potential future changes, but all models are simplified representations of reality and each has limitations. The Tree Atlas (DISTRIB), LINKAGES, and LANDIS PRO models suggest that conditions for some species will become less favorable during the 21st century, particularly farther south in the region and under the harsher climate of the GFDL A1FI scenario. Additionally, the Tree Atlas and LINKAGES tend to agree that the habitat for many species will remain stable or increase under the PCM B1 scenario and decrease under GFDL A1FI. These results support the idea that GFDL A1FI future climate is beyond the tolerance of many species, but that many currently present species could tolerate or would benefit from a mild degree of warming with a corresponding increase in growing season precipitation. All three models suggest that conditions in the Northeast will become more favorable for more-southerly species by the end of the century.

Generally, the changing climate tends to intensify the stressors that may already exist for many species and increases susceptibility to drought, pests, diseases, or competition from other species. It is the interaction among all these factors that will drive the response of forests to climate change. All of these factors need to be taken into account when evaluating the vulnerability of regional forests to climate change. The vulnerability of eight forest systems is described in the next chapter.

CHAPTER 5: FOREST ECOSYSTEM VULNERABILITIES

Climate change is expected to drive significant changes in fundamental ecosystem processes, alter the effects of current stressors, and influence species composition (Joyce et al. 2014, Rustad et al. 2012, Ryan and Vose 2012, Vose et al. 2016). This chapter describes the vulnerability of the forest ecosystems of New England and northern New York to climate change, drawing on the information presented in previous chapters. It is organized into two sections. First, we present an overall synthesis of the climate change vulnerability of the assessment area, organized according to drivers and stressors, ecosystem impacts, and factors that influence adaptive capacity. This synthesis is based on the current scientific consensus of published literature (Chapters 3 and 4). In the second section, we present individual vulnerability determinations for the eight forest systems that are currently common in this assessment area, as developed through an expert elicitation process (Brandt et al. 2016, 2017) (Appendix 7).

Vulnerability is the susceptibility of a system to the adverse effects of climate change (Glick et al. 2011, Intergovernmental Panel on Climate Change [IPCC] 2007a). It is a function of potential climate change impacts and the adaptive capacity of the system (Fig. 30). In this assessment, we consider a forest system to be vulnerable if it is at risk of a shift in composition that leads to a substantially different character for the system, or if the system is expected to suffer substantial declines in extent, health, or productivity. Although economic and social values affect the way a system is managed and therefore have some influence on the adaptive capacity of the system, the assessment of vulnerability presented in this chapter is based on the ability of forest ecosystems to persist given projected changes in climate without additional management interventions for adaptation. The ultimate decision of how to use this information—whether to conserve vulnerable systems, allow them to shift to an alternate state, or direct their transformation—will depend on the individual objectives and actions of land managers and stakeholders.

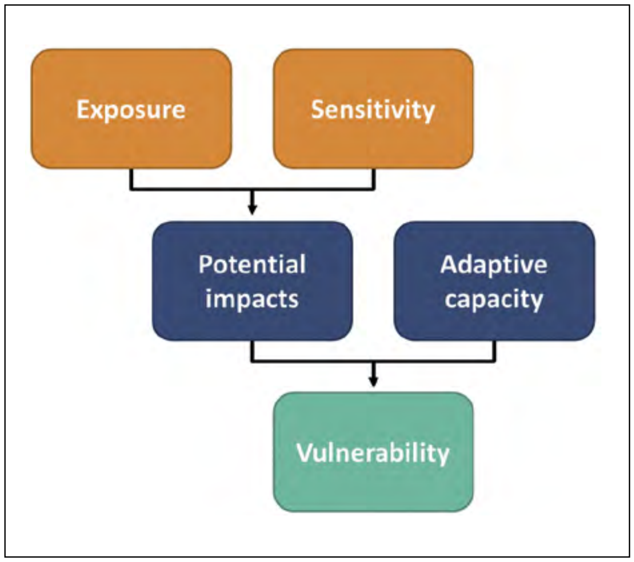


Figure 30.—Key components of vulnerability, illustrating the relationship among exposure, sensitivity, and adaptive capacity (adapted from Glick et al. [2011]).

Throughout this chapter, statements about potential impacts and adaptive capacity factors are qualified with a confidence statement, phrased according to definitions from the IPCC (Mastrandrea et al. 2010). Confidence was determined by gauging both the level of evidence and the level of agreement among information (Fig. 31). "Evidence" refers to the body of information available based on theory, data, models, expert judgment, and other sources. Evidence was considered robust when multiple observations or models, as well as an established

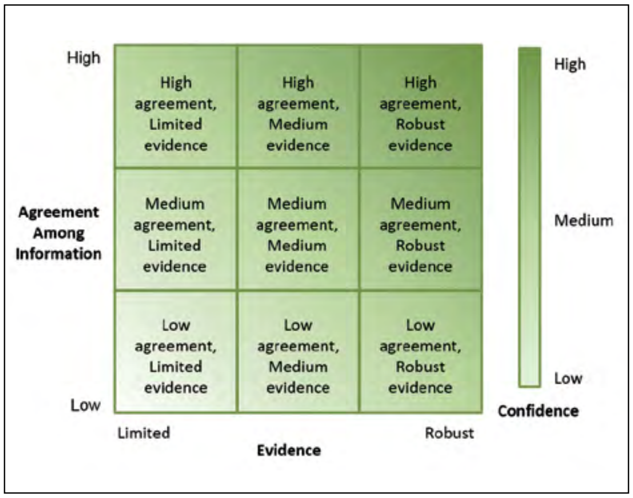


Figure 31.—Confidence determination diagram used in the assessment (adapted from Mastrandrea et al. [2010]).

theoretical understanding to support a statement, were available. "Agreement" refers to the agreement among the multiple lines of evidence. If theories, observations, and models tended to suggest similar outcomes, then agreement was high. Agreement does not refer to the level of agreement among the authors of this assessment.

SYNTHESIS OF CLIMATE CHANGE IMPACTS ON FOREST ECOSYSTEMS

Climate change will continue to cause wide-ranging direct and indirect impacts on ecosystems as a function of the degree to which a system is exposed to climatic changes and its sensitivity to these changes. Impacts could be beneficial to a system if the changes result in improved health or productivity, a greater area occupied by the system, or a tendency to maintain the current identity of the system. They could be negative if they disrupt the ecosystem by decreasing health and productivity, reducing the area occupied by the system, or causing a shift in composition that leads to a substantially different character for the system. The following summary includes the potential positive and negative impacts of climate change on the assessment area over the 21st century. This synthesis is based on the current scientific knowledge in published literature and described in more detail in the preceding chapters.

Potential Impacts on Drivers and Stressors

Many physical, chemical, and biological factors contribute to the current state of forest ecosystems in the assessment area. These factors include drivers, which are the most fundamental forces that shape a particular ecosystem, and stressors, which are agents that can reduce forest health or productivity or impair ecosystem functions. Some factors may be drivers in one situation and stressors in another. For example, forest pests and pathogens of species such as American chestnut, American beech, and American elm are initially stressors but may eventually become drivers after being present in the forest system for a long time. Similarly, some disturbances, such as flooding or fire, act as drivers in certain systems, but can cause additional stress on ecosystems if the timing or intensity of the disturbance changes.

Temperatures will increase (robust evidence, high agreement). *All global climate models agree 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 1). Temperatures across the assessment area have already increased (Chapter 2). Continued temperature increases are projected for the assessment area even under the most conservative future climate scenario (Chapter 3).

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

Evidence at both global and local scales indicates that growing seasons have been getting longer, and this trend is expected to become even more pronounced during this century (Chapters 2 and 3). Longer growing seasons have the potential to affect the timing and duration of ecosystem and plant physiological processes across the Northeast (Dragoni and Rahman 2012, Rustad et al. 2012).

Earlier springs and longer growing seasons are expected to cause shifts in phenology for plant species that rely on temperature as a cue for the timing of leaf-out, reproductive maturation, and other developmental processes (Schwartz et al. 2006, Walther et al. 2002), and some of these effects have already been observed (Dragoni and Rahman 2012, Hufkens et al. 2012, Richardson et al. 2006, Willis et al. 2010). Longer growing seasons may also result in greater growth and productivity of trees and other vegetation, but only if balanced by available water and nutrients (Chapter 4).

Winter processes will change (robust evidence, high agreement). *There is strong evidence 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.*

Climate models indicate that winter temperatures, particularly minimum temperatures, will increase more than temperatures in other seasons (Chapter 3). Projected temperature increases indicate that an increasing proportion of moisture will generally be delivered as rain rather than snow during the winter. Additionally, total snowfall, the duration of snow cover, and snow depth are expected to decrease across the assessment area by the end of the 21st century (Bryan et al. 2015, Ning and Bradley 2015, Notaro et al. 2014). The assessment area is also expected to experience complex changes in patterns of soil frost by the end of the century (Chapter 3). Decreases in snow cover and alteration of frozen soil conditions may affect a variety of ecosystem processes, including microbial activity, nutrient cycling, and the onset of the growing season (Campbell et al. 2010, Groffman et al. 2012).

Sea levels will continue to rise (robust evidence, high agreement). *There is substantial evidence that ongoing sea-level rise will continue to affect low-lying coastal areas and increase potential impacts from flooding, saltwater intrusion, and storm surge.*

Sea levels have risen approximately 1 foot along the coastline of the assessment area since 1900 (Boon 2012, Horton et al. 2014). All evidence points to a continuation of this trend due to the expansion of warming ocean waters and melting land ice flowing into the ocean (Church et al. 2008, Kopp et al. 2014). Although model projections differ, sea levels may rise another 2 feet or more during this century (Chapter 3). Coastal forests and ecosystems will be further threatened by inundation, more frequent coastal erosion, flooding, and saltwater intrusion (Kane et al. 2015, Manomet Center for Conservation Sciences and National Wildlife Federation [NWF] 2013c). Additionally, severe storms are more destructive with higher sea levels, causing increased damage from storm surges and flooding (Buonaiuto et al. 2010, Horton et al. 2014).

The amount and timing of precipitation will change (robust evidence, high agreement). *There is strong agreement that precipitation patterns will change across the assessment area. Total precipitation is generally expected to increase during winter and spring, but summer and fall projections are more uncertain.*

For the climate projections used in this assessment (Chapter 3) and other publications, there is greater uncertainty about projected changes in precipitation than for temperature across the assessment area (Bryan et al. 2015, Center for Climatic Research 2017, Kunkel et al. 2013). Although individual model projections for the assessment area differ, there is general agreement that total annual precipitation is projected to increase during the 21st century, largely due to more-intense precipitation events (Bryan et al. 2015, Hayhoe et al. 2007). Models also tend to agree that precipitation patterns between seasons may shift substantially (Kunkel et al. 2013). Precipitation increases are generally expected for winter and spring, whereas summer and fall precipitation projections are much more variable, ranging from very slight increases to moderate decreases (Bryan et al. 2015, Center for Climatic Research 2017, Kunkel et al. 2013). The two climate scenarios presented in this assessment reflect this range of potential outcomes (Chapter 3).

Intense precipitation events will continue to become more frequent (robust evidence, high agreement). *Climate models generally project that the number of heavy precipitation events will continue to increase in the assessment area. If they do increase, damage from flooding and soil erosion may also become more severe.*

Since the mid-20th century, heavy precipitation events have increased in number and severity in the Northeast more than in any other part of the United States (Brown et al. 2010, Horton et al. 2014, Walsh et al. 2014), and many models agree that this trend will continue during the 21st century (Center for Climatic Research 2017, Kunkel et al. 2013). Most heavy precipitation events in the assessment area currently occur during the warm season from May through September, although increases in intense rainfall are projected for all seasons (Bryan et al. 2015, Ning et al. 2015). Increases in extreme precipitation events are generally expected to be greatest under scenarios that project greater amounts of warming because of greater retention of water vapor in the atmosphere (Ning et al. 2015). Extreme precipitation events could lead to more frequent or severe flooding and an increase in soil erosion (Horton et al. 2014, Nearing et al. 2004). The risk from floods, erosion, and other related impacts will ultimately depend on local geologic and topographic conditions, current infrastructure, and land use, as well as future decisions about infrastructure and land use.

Soil moisture patterns will change in response to temperature and precipitation (medium evidence, high agreement). *Warmer temperatures and altered precipitation will interact to change soil moisture patterns throughout the year, but there is uncertainty about the direction and magnitude of the changes.*

Soil moisture is expected to change in response to warmer temperatures and seasonal changes in precipitation, although uncertainty remains regarding the specific amount, direction, and seasonality of precipitation changes (Huntington et al. 2009). Changes are likely to vary seasonally as well as geographically (Center for Climatic Research 2016). More intense and prolonged precipitation events would be expected to create wetter soil conditions, whereas increased temperatures and less frequent rainfall events would lead to drier soils (Bryan et al. 2015). Wetter conditions may become more frequent during parts of the year; however, soils may dry during the growing season as warmer temperatures drive increases in evaporation and transpiration that are not offset by corresponding increases in precipitation (Groffman et al. 2012, Hayhoe et al. 2007, Huntington et al. 2009). Locations where soils and landforms cannot retain the water from intense precipitation events may be more likely to have drier conditions during the growing season.

Forest vegetation may face increased risk of moisture deficit and drought during the growing season (medium evidence, medium agreement). *Studies show that climate change will affect soil moisture, but there is some disagreement among climate and impact models on how soil moisture and drought will change during the growing season.*

The uncertainty of future precipitation patterns makes it difficult to determine whether conditions may become dry enough to increase moisture stress for plants in the Northeast. Forests that are affected by moisture deficits and drought are more likely to have reduced tree vigor and increased tree mortality, both of which can affect forest composition and structure (Clark et al. 2016). Further, warmer temperatures can drive or exacerbate drought-induced mortality by disrupting plant physiology (Allen et al. 2015, McDowell et al. 2008). This “hotter drought” can also interact with other forest stressors to cause tree death and forest die-off (Allen et al. 2010, 2015; Millar and Stephenson 2015).

Certain insect pests and pathogens will increase in occurrence or become more damaging (medium evidence, high agreement). *Evidence indicates that increases in temperature will lead to increased threats from insect pests and pathogens, but research to date has examined relatively few species.*

A warming climate may allow some pests and pathogens to become a greater threat (Régnière et al. 2012, Sturrock et al. 2011, Trân et al. 2007). The loss of a historically cold climate and short growing season in the region may allow some insect pests and pathogens, such as hemlock woolly adelgid and southern pine beetle, to expand their ranges northward (Chapter 4). Forest pests and pathogens are generally able to respond rapidly to changes in climate. Forest impacts from insect pests and pathogens are generally more severe in ecosystems that are affected by drought and other stressors (Manion 1991, Weed et al. 2013). Basic information is often lacking on the climatic thresholds that trigger increased populations of many forest pests, and our ability to predict the mechanisms of infection, dispersal, and transmission for disease agents remains low (Régnière et al. 2012, Weed et al. 2013). Further, it is not possible to predict which new pests or pathogens will enter the assessment area during the 21st century.

Many invasive plants will increase in extent or abundance (medium evidence, high agreement). *Evidence indicates that increases in temperature, longer growing seasons, and more frequent disturbances will lead to increases in many invasive plant species.*

Many invasive species that currently threaten regional forests may benefit directly from projected climate change or benefit from the relatively slower adaptation response of native species (Rebbeck 2012). Increases in carbon dioxide have been shown to increase growth for many plant species, including some of the most invasive weeds in the United States (Ziska 2003). Warmer conditions may allow invasive plant species such as bush honeysuckles, privet, and kudzu to expand their ranges northward (Bradley et al. 2010, Dukes et al. 2009). Future increases in drought, fire, or flooding are likely to benefit invasive plants that are able to establish quickly and outcompete native vegetation on disturbed sites (Dukes et al. 2009). A lack of information about the climatic thresholds that apply to many invasive plants limits the ability to predict the mechanisms of introduction, dispersal rates and directions, and spread for specific agents. Additionally, it is not possible to predict all nonnative plant species that may enter the assessment area during the 21st century.

Potential Impacts on Forests

Shifts in drivers and stressors mentioned earlier are expected to alter forest ecosystems throughout the assessment area. Indirect impacts of climate change may be manifested through shifts in suitable habitat, species composition, or function of forest ecosystems.

Many northern and boreal tree species will face increasing stress from climate change (medium evidence, high agreement). *Ecosystem models agree that northern and boreal tree species will have 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 warm-adapted temperate forest species.*

Across northern latitudes, warmer temperatures are expected to become less favorable to tree species near the southern extent of their range (Gauthier et al. 2014, Iverson et al. 2008, Mohan et al. 2009). Results from climate impact models project a decline in suitable habitat and landscape-level biomass for northern species such as red spruce, paper birch, black spruce, and tamarack, as well as spruce-fir forest systems (Chapter 4). These northern species may persist in the assessment area through the 21st century, although with declining vigor (Mohan et al. 2009). Boreal and northern forest communities may persist in areas where climatic changes do not exceed thresholds for individual species. For example, topographic or hydrologic position may create favorable microclimates that are buffered from some changes (Morelli et al. 2016, Raney et al. 2016).

Habitat will become more suitable for southern species (medium evidence, high agreement). *Ecosystem models agree that longer growing seasons and warmer temperatures will increase suitable habitat for many temperate species across the assessment area.*

Model results project that tree species currently near their northern range limits in the assessment area may become more abundant and more widespread under a range of climate futures (Chapter 4). Species that are currently present and projected to increase in both suitable habitat and biomass in the assessment area include black cherry, chestnut oak, and yellow-poplar (Chapter 4). Results from the Climate Change Tree Atlas and, to a lesser extent, LANDIS PRO, project that habitat may become available for species not currently found in the assessment area by the end of the century (Chapter 4). The fragmentation of forests by other land uses and the dispersal limitations of individual species could hinder the northward movement of southern tree species, despite increases in habitat suitability. Most species can be expected to colonize new areas more slowly than their suitable habitats will shift (Iverson et al. 2004a, 2004b; Woodall et al. 2009). Pests and diseases such as emerald ash borer, beech bark disease, and Dutch elm disease are also expected to limit some species that are projected to increase according to tree species models.

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

Species will respond individually to climate change, and this may lead to new species assemblages (Davis et al. 2005, Root et al. 2003). The model results presented in Chapter 4 raise the possibility of large changes in tree species distribution across the assessment area. Evidence suggests that although dominant conifer species are currently expanding on the landscape, future climatic conditions will generally favor many hardwood species by the end of the century. Changes in distribution for individual species are expected to lead to shifts in forest assemblages from south to north (Iverson et al. 2008, Lenihan et al. 2008), and novel community types may emerge. Some studies have suggested that forest species may be prone to range contraction at southern limits and also less able to expand ranges northward into new areas at a pace that tracks changes in climate (Murphy et al. 2010, Treyger and Nowak 2011, Woodall et al. 2013, Zhu et al. 2011). Major shifts in overstory species composition may not be observable until well into this century because of the long timeframes associated with many ecosystem processes and responses to climate change (Chapter 4). These shifts, however, may become more apparent along ecotonal boundaries where boreal species reach the southern edge of their range (Fisichelli et al. 2014b, Legaard et al. 2015). Major stand-replacing disturbance events, forest management, and human activities all have the potential to strongly influence how forests change in response to changing climatic conditions (Duveneck et al. 2014, Millar and Stephenson 2015, Thompson et al. 2011). Additionally, nonnative species may be able to take advantage of shifting forest communities and unoccupied niches if native forest species are limited (Hellmann et al. 2008).

Shifts in forest composition will take at least several decades to occur in the absence of major disturbance (medium evidence, medium agreement). *Although some models indicate major changes in habitat suitability, results from spatially dynamic forest landscape models indicate that a major shift in forest composition across the landscape may take 100 years or more in the absence of major disturbances.*

Model results from the Tree Atlas and LINKAGES (Chapter 4) indicate substantial changes in habitat suitability or establishment probability for many species on the landscape, but do not account for seed source constraints, longevity of current species, or differences among age classes. Forest landscape models such as LANDIS PRO can incorporate spatial configurations of current forest ecosystems, seed dispersal, and potential interactions among native species and the invasion and establishment of nonnative plant species (Wang et al. 2014, 2015) (Chapter 4). In addition, forest landscape models can account for differences among age classes, and have generally found mature trees to be more tolerant of warming (He and Mladenoff 1999). Because mature trees are expected to remain on the landscape, and recruitment of new species is expected to be limited, major shifts in species composition are not likely to be observed by the middle of the century, except along ecotonal boundaries and in areas that undergo major stand-replacing disturbance events. However, climate change may increase the intensity, scope, or frequency of some stand-replacing events such as windstorms, ice storms, and insect outbreaks, possibly promoting rapid shifts in species composition where these events occur.

Conditions affecting tree regeneration and recruitment will change (medium evidence, high agreement). *Seedlings are more vulnerable than mature trees to changes in temperature, moisture, and other seedbed and early growth requirements.*

Evidence of climate change impacts on forest ecosystems is more likely to be seen in seedlings and early growth than in mature individuals (Fisichelli et al. 2014a, 2014b). Temperature and moisture requirements for seed dormancy and germination are often much more critical than habitat requirements of an adult tree (Kitajima and Fenner 2000). Projected changes in temperature, precipitation, growing season onset, and soil moisture may alter the duration or manifestation of germination conditions, and regeneration responses will be highly variable based on both environmental conditions and species characteristics. For example, regeneration failure in balsam fir populations has been attributed, at least partially, to climate change (Abrams et al. 2001). For species with high dispersal capabilities, these changes may result in redistribution on the landscape as seeds germinate only where conditions are favorable (Walck et al. 2011). Other species may fail to regenerate under altered future conditions, or may germinate without having optimal conditions for development. Warmer winters may promote the establishment of more southerly species, although warmer temperatures alone are unlikely to drive their establishment (Abrams 2003). Even after establishment, advance regeneration (i.e., saplings) is still more sensitive than mature trees to disturbances such as drought, heat stress, fire, flooding, and herbivory (Kitajima and Fenner 2000). Changes in tree regeneration and recruitment will have long-term effects on forest composition and structure.

Forest productivity will increase during the next several decades in the absence of significant stressors (medium evidence, medium agreement). *Some studies have examined the impact of climate change on forest productivity within the assessment area, but they disagree on how multiple factors may interact to influence productivity. The diversity of forest conditions across the assessment area suggests that changes will be spatially variable.*

Regional forests are still recovering from historical disturbance (Foster et al. 1998, Thompson et al. 2013), and continued forest recovery and succession following these disturbances are generally expected to be the dominant drivers of forest growth for the next several decades (Duveneck et al. 2017, Thompson et al. 2011, Wang et al. 2017) (Chapter 4). Changes in forest productivity are likely to be spatially variable. Projections of forest growth and carbon balance point to increased tree growth and ecosystem carbon sequestration under warmer temperatures and longer growing seasons where soil moisture is not limiting (Ollinger et al. 2008, Tang et al. 2014, Thompson et al. 2011). Further, many studies also point to the beneficial effects of carbon dioxide fertilization on forest productivity (Loehle et al. 2016, Ollinger et al. 2008, Tang et al. 2014, Thompson et al. 2011), although this effect can be dampened by nutrient and water limitations, ozone exposure, and tree age (Ainsworth and Long 2005, Dieleman et al. 2012, Franks et al. 2013). There is some evidence that deciduous forests will be better able to take advantage of warmer temperatures than coniferous forests in the region (Ollinger et al. 2008; Tang et al. 2012, 2014); however, one study found that modeled productivity was lower in southern New England as a result of moisture stress and increased soil respiration (Tang et al. 2014). Further, increasing disturbance, such as fires, windstorms, and pest outbreaks, and changes in land use could substantially reduce forest productivity, but are beyond the scope of most modeling efforts.

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, IPCC 2007a). It is strongly related to the concept of ecological resilience (Holling 1973, Stein et al. 2014). In this section, we summarize factors that could reduce or increase the adaptive capacity of forest systems within the assessment area. Higher adaptive capacity tends to reduce vulnerability to climate change, and lower adaptive capacity tends to increase vulnerability.

Low-diversity systems are at greater risk (medium evidence, high agreement). *Studies have consistently shown that high-diversity systems are more resilient to disturbance. Low-diversity systems are expected to be more vulnerable to climate change.*

In general, species-rich communities have exhibited greater resilience to extreme environmental conditions and greater potential to recover from disturbance than less diverse ecosystems (Isbell et al. 2015, Tilman et al. 2014). This makes less diverse ecosystems inherently more susceptible to future changes and stressors. Within an ecosystem, the range of potential responses of a system to environmental change is a critical component of ecosystem resilience (Elmqvist et al. 2003, Hooper et al. 2005). For example, mixed hardwood forests generally support a large number of tree species with many different traits and therefore have many possible future trajectories; in contrast, pitch pine-dominated forests 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 are more apt to have individuals that can withstand extreme events and adapt to changes over time (Reusch et al. 2005).

Tree species in isolated or fragmented landscapes will have reduced ability to migrate to new areas in response to climate change (limited evidence, high agreement). *The dispersal ability of individual tree species is reduced in fragmented landscapes, but the degree of landscape fragmentation in the future is an area of uncertainty.*

Habitat fragmentation can hinder the ability of tree species to move to more suitable habitat on the landscape; the degree to which fragmentation limits dispersal depends on the level of fragmentation, land cover and use, and the dispersal characteristics of individual species (Ibáñez et al. 2006, Iverson et al. 2004a). Modeling results indicate that average centers of suitable habitat for various tree species may shift 60 to 350 miles by the year 2100 under a high emissions scenario and between 30 and 250 miles under milder climate change scenarios (Iverson et al. 2004a). Based on gathered data for seedling distributions, it has been estimated that many northern tree species could possibly disperse seedlings northward at a rate of 60 miles per century (Woodall et al. 2009), and other evidence indicates that natural migration rates could be far slower for some species (McLachlan et al. 2005, Murphy et al. 2010). Fragmentation creates additional challenges by making the landscape less permeable to dispersal (Jump and Peñuelas 2005, Scheller and Mladenoff 2008). The potential for humans to assist in the migration of species to newly suitable areas (Pedlar et al. 2012, Schwartz et al. 2012) is beyond the scope of this assessment.

Species or systems that are limited to particular environments will have less opportunity to migrate in response to climate change (limited evidence, high agreement). *Our current ecological understanding indicates that migration to new areas will be particularly difficult for tree species and forest communities with narrow habitat requirements.*

Several species and forest types in the assessment area are confined to certain habitats on the landscape, whether through particular requirements for hydrologic regimes or soil types, or other reasons. Similar to species occurring only in fragmented landscapes, isolated species and systems face additional barriers to migration (Jump and Peñuelas 2005). Species restricted to riparian forests are not expected to migrate to upland areas because many species depend on seasonal flood dynamics for regeneration and a competitive advantage. Similarly, lowland conifer systems often contain a unique mix of species that are adapted to low pH values, peat soils, and particular water table regimes. These systems face greater challenges in migration than more widespread species with broad ecological tolerances. Even widespread species may have particular site requirements for optimal growth. For example, sugar maple does best on soils that are rich in nutrients such as calcium, so this species may not respond as predicted to new suitable habitat in the assessment area projected from temperature and precipitation patterns.

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

Disturbances such as wildfire, flooding, hurricanes, and pest outbreaks are expected to increase in the assessment area (Chapters 3 and 4). Northern hardwoods in particular are adapted to gap-phase disturbances, with stand-replacing events occurring over hundreds or thousands of years. Therefore, these systems may be less tolerant of more frequent widespread disturbances. Mesic systems can create conditions that could buffer against fire and drought to some extent, but these systems are not expected to do well if soil moisture declines significantly (Nowacki and Abrams 2008). Forest systems in the assessment area that are more tolerant of drought, flooding, or fire may be better able to withstand climate-driven disturbances. This principle is limited, however, because it is also possible for disturbance-adapted systems to be subjected to excessive disruption. For example, pitch pine systems might cover a greater extent under drier conditions with more frequent fire, but these systems might also convert to barrens or open grasslands if fire becomes too frequent or drought becomes too severe.

VULNERABILITY DETERMINATIONS FOR INDIVIDUAL FOREST SYSTEMS

Climate-induced shifts in drivers, stressors, and dominant tree species will result in different impacts to forest systems within the assessment area. Some communities may have greater resilience than others; some may be susceptible to relatively minor impacts. Therefore, it is helpful to consider these factors for individual forest systems.

We assessed the vulnerability of eight forest systems (described in Chapter 1) to climate change impacts, drawing on the information presented in previous chapters, as well as an expert panel assembled from a variety of organizations and disciplines across the assessment area. The 20 panelists evaluated anticipated climate trends for the assessment area and ecosystem model projections (Chapters 2, 3, and 4) and used their expertise to interpret the information. For each forest system, panelists considered the potential impacts and adaptive capacity to assign a vulnerability determination and a level of confidence in that determination using the confidence scale described earlier in this chapter. For a complete description of the methods used to determine vulnerability, see Appendix 7.

Vulnerability determinations for the forest systems ranged from low to moderately high based on the interaction between impacts and adaptive capacity (Table 14). These vulnerability determinations were associated with medium levels of confidence for most forest systems. Ratings of evidence were limited-medium or medium, generally reflecting unknown interactions among dominant tree species and potential stressors. The ratings of agreement among information sources also tended to be medium. Contrasting information related to future precipitation patterns was a major factor that limited the level of agreement. More importantly, there was reduced agreement where potential climate change impacts varied geographically across the assessment area (e.g., high elevations in the north vs. southern and coastal areas), especially for widely distributed forest systems. In some instances, use of broad forest systems for this assessment also limited agreement where species-level impacts and vulnerability varied widely within the forest system.

In the sections that follow, we summarize the climate-related impacts on drivers, stressors, and dominant tree species that were major contributors to the vulnerability determination for each forest system across the assessment area. In addition, we summarize the main factors contributing to the adaptive capacity of each system. Importantly, climate change impacts and the adaptive capacity of a forest system were evaluated across the entire assessment area. Because forest systems vary widely at a local level due to differences in elevation, climate, landform, soils, disturbance, past management, and numerous other factors, the vulnerability in a given location may be different—even markedly so—from the broad-scale information highlighted in this chapter. For this reason, the following summaries are best used as starting points for considering forest ecosystem vulnerability at finer spatial scales.

Table 14.—Summary of vulnerability determination for the forest systems considered in this assessment evaluated through the end of the 21st century

Forest system	Potential impacts	Adaptive capacity	Vulnerability	Evidence	Agreement
Central hardwood-pine	Neutral-Positive	Moderate-High	Low	Medium	Medium-High
Low-elevation spruce-fir	Neutral-Negative	Moderate	Moderate-High	Medium	Medium
Lowland and riparian hardwood	Positive and Negative	Moderate-High	Moderate	Limited	Limited
Lowland mixed conifer	Neutral-Negative	Low-Moderate	Moderate-High	Limited-Medium	Medium
Montane spruce-fir	Neutral-Negative	Moderate	Moderate-High	Medium	Medium
Northern hardwood	Positive and Negative	Moderate-High	Low-Moderate	Medium	Medium
Pitch pine-scrub oak	Neutral-Positive	Moderate	Low	Medium	Medium
Transition hardwood	Positive and Negative	Moderate-High	Low-Moderate	Medium	Medium-High

Central Hardwood-Pine

Low Vulnerability (medium evidence, medium-high agreement)

These forests support a diversity of tree species and occur over a wide range of habitats. Many species are tolerant of dry soil conditions and fire, although young trees may be sensitive to severe drought and fire. Several oak and hickory species are likely to benefit from projected changes in climate.

Neutral-Positive Potential Impacts

Drivers: The central hardwood-pine forest system is at the northern extent of its range in the region, occurring on a wide variety of dry-mesic sites and coarse, well-drained soils. These fire-adapted ecosystems are generally expected to be able to cope with increased risk of wildfire under warmer and drier conditions (Manomet Center for Conservation Sciences and Massachusetts Division of Fisheries and Wildlife [DFW] 2010a, Manomet Center for Conservation Sciences and NWF 2013b), although it is unclear whether fire occurrence will actually increase due to suppression by humans in this relatively densely populated region (Chapter 4).

Dominant Species: The many tree species found in these locations, including black, chestnut, scarlet, and white oak and pignut and shagbark hickory (Chapter 4), are generally expected to be able to persist on these sites into the future. These species may also potentially expand to new areas as conditions become suitable. At the same time, when extremely hot and dry conditions prevail, species establishment may be impaired for these trees in southern and coastal New England (Chapter 4).

Stressors: Climate change could amplify several stressors to central hardwood-pine forests. Insect pests, such as winter moth and southern pine beetle, are expected to cause more frequent and severe damage under climate change, and new pests present unknown risks. White-tailed deer populations may also increase with warmer winters, which may hinder regeneration as well as the expansion of this forest type. Invasive species such as buckthorn, honeysuckles, and garlic mustard can also hinder regeneration, and are poised to increase in the future.

Moderate-High Adaptive Capacity

Central hardwood forests are generally expected to fare better than other forest systems under climate change, in part because of an ability to thrive under relatively warm and dry conditions. These forests also contain a variety of oak and hickory species with diverse traits, including drought tolerance and varied reproductive strategies. This diversity may increase the number of ways in which the ecosystem can adjust to changing conditions while maintaining important ecosystem functions. This forest type, however, is often found in areas that have a high degree of historical or current human disturbance, and fragmentation, invasive species, or other threats that can reduce the adaptive capacity of certain locations. A history of fire suppression and reduced light reaching the forest floor has facilitated a shift to more mesic conditions and associated hardwood species (e.g., red and sugar maple, American beech, yellow-poplar). In many forests, regeneration of drought-tolerant oak and hickory trees is currently reduced due to fire suppression and competition from more shade-tolerant mesic species.

A central hardwood-pine forest in central Massachusetts. Photo by Anthony W. D'Amato, University of Vermont, used with permission.

A central hardwood-oak forest in southern New England, marked for forest harvest. Photo by Maria Janowiak, U.S. Forest Service.

Low-Elevation Spruce-Fir

Moderate-High Vulnerability (medium evidence, medium agreement)

The future climate is expected to be less suitable for the northern and boreal conifer species, while more favorable for many hardwood species that are a component of these forests. Heightened stress and changes in competitive relationships among tree species are likely to alter forest composition. Forest vulnerability is expected to vary widely across the assessment area, with forests in some locations undergoing substantial changes.

Neutral-Negative Potential Impacts

Drivers: The low-elevation spruce-fir forest system is widespread across the northern portion of the assessment area and will undergo varying levels of impacts. These forests may be particularly susceptible to warmer temperatures and longer growing seasons (Manomet Center for Conservation Sciences and NWF 2013b). Forest productivity may increase in areas that maintain adequate soil moisture, but substantially warmer and drier conditions could disrupt nutrient cycling, cause organic soils to break down, and increase stress. Warmer and drier conditions could also increase the likelihood of wildfire, which is currently rare in this forest type. Increases in extreme storm events may lead to greater tree mortality from disturbance.

Dominant Species: Red spruce, balsam fir, and other dominant species are projected to suffer substantial declines in suitable habitat, although these declines are most substantial under greater warming in the southern portion of the assessment area (Chapter 4). As a temperate conifer, red spruce may have a greater ability to adapt to a warmer climate than the boreal species black spruce and balsam fir due to its capacity for year-round photosynthesis and its greater phenotypic plasticity in response to temperature variations (Schaberg and DeHayes 2000). Impacts from climate change are projected to be less severe in the northern part of the assessment area, such as in Maine, allowing the dominant species to persist in some areas (Whitman et al. 2014). Species such as white pine or several northern hardwood species may become more competitive under future conditions (Chapter 4).

Stressors: Insect pests such as eastern spruce budworm and balsam woolly adelgid currently affect this system and are likely to respond to temperature changes. Warmer temperatures may allow balsam woolly adelgid to increase, while dampening the effects of the eastern spruce budworm in the assessment area (De Grandpré and Pureswaran 2013, Pureswaran et al. 2015, Régnière et al. 2012) (Chapter 4). Hemlock woolly adelgid may cause even greater mortality for hemlock under warmer conditions. Likewise, changes in herbivore populations may also have substantial effects on forest growth and composition. Although moose are generally projected to have reduced habitat suitability under warmer conditions, white-tailed deer populations may expand in some areas (Chapter 4).

Moderate Adaptive Capacity

Low-elevation spruce-fir forests are present across a variety of sites, representing varying levels of adaptive capacity. These forests tend to have relatively low diversity and be dominated by a relatively small number of northern boreal species; forests with lower species diversity may be more vulnerable. Past and current management often favors the hardwood component in these forests, and additional stress or disturbance may continue to shift forest composition toward hardwood species. This forest type also has some factors that increase adaptive capacity, such as the presence of multiple species that can regenerate prolifically when conditions allow, including red maple and balsam fir.

Spruce-fir forest in coastal Maine. Photo by Nicholas Fisichelli, Schoodic Institute at Acadia National Park, used with permission.

Dense spruce regeneration in lowland spruce-fir forest. Photo by Nicholas Fisichelli, Schoodic Institute at Acadia National Park, used with permission.

Red spruce and white pine regeneration in the forest understory. Photo by Maria Janowiak, U.S. Forest Service.

Lowland and Riparian Hardwood

Moderate Vulnerability (limited evidence, limited agreement)

Climate change is expected to alter the hydrologic regimes in riparian and lowland systems, and may amplify the effects of insect pests and invasive species. High diversity and the presence of southern species raise the adaptability of these forests. There is high uncertainty regarding future precipitation patterns and associated hydrologic change.

Positive and Negative Potential Impacts

Drivers: Climate change has the potential to substantially alter the hydrologic regimes in the lowland and riparian hardwood forest system. These hardwood forests are adapted to annual and seasonal water table fluctuations; however, more intense and variable precipitation events may present risks to this system through excessive flooding, inundation, streambank erosion, or prolonged droughts between heavy precipitation events. Extended droughts could cause significant damage to shallow-rooted species, but increased winter and spring precipitation may buffer summer droughts in low-lying areas on the landscape. Groundwater-fed systems may be less sensitive where cooler, wetter soil conditions can be maintained over time. There is substantial uncertainty about future precipitation patterns (Chapter 3), and impacts may be greater in areas that are subject to changes in water level, such as vernal pools, floodplain systems, and wetlands.

Dominant Species: This forest system contains many tree species that are tolerant of warmer temperatures, and the assessment area is in the central to northern portion of their range. Species such as American elm, silver maple, and eastern cottonwood are expected to gain suitable habitat across the assessment area under a range of climate futures. Species in these ecosystems that are expected to undergo decreased habitat suitability include balsam fir, paper birch, and northern white-cedar.

Stressors: There are many invasive plant species, insect pests, and forest diseases that have negative impacts on lowland and riparian hardwoods; many of these stressors are expected to increase through the direct and indirect effects of climate change. Invasive species such as Japanese stiltgrass and buckthorn are existing threats to these forests, and invasive species are expected to increase in abundance under climate change, particularly where forests are disturbed (Chapter 4). Likewise, insect pests such as hemlock woolly adelgid may also increase in response to warmer temperatures.

Moderate-High Adaptive Capacity

Many riparian and lowland forests can tolerate intermittent wet and dry conditions, including periodic floods and drought. Where these forests include a diverse array of tree species occupying a variety of microsites, there may be less risk of ecosystem transition under future conditions. Some of these forests are dominated by one or two canopy tree species (e.g., red maple or black ash), creating the potential for large alterations to ecosystem structure if these species are selectively affected by climate or other stressors.

Silver maple in a riparian forest. Photo by Anthony W. D'Amato, University of Vermont, used with permission.

Silver maple in a riparian forest. Photo by Anthony W. D'Amato, University of Vermont, used with permission.

Lowland Mixed Conifer

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

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

Neutral-Negative Potential Impacts

Drivers: The lowland mixed-conifer forest system functions in a relatively narrow window of hydrologic and soil conditions. These conditions are expected to be perturbed in a variety of ways, including through increased severe precipitation events and flooding, increased risk of drought, and changes in the water table or relative influence of precipitation versus groundwater. In general, drier conditions would be expected to have a greater negative impact than excess moisture. Organic soils could decompose more quickly under warmer and drier conditions. Drier conditions in peatland systems could also impair tree regeneration or shift tree species composition toward the few hardwood species found in these areas. Wetland communities may be affected by increased storm events because shallow-rooted trees on saturated soils may be more prone to windthrow.

Dominant Species: Most of the dominant tree species in this system, including balsam fir, red spruce, northern white-cedar, and black spruce, are expected to undergo significant declines in future habitat (Chapter 4). There are already concerns about sustainability of northern white-cedar in some parts of the assessment area, due to the negative effects from harvesting and deer browse (Chapter 4). Impacts from climate change are projected to be less severe in the northern part of the assessment area, such as in Maine, allowing the dominant species to persist in some areas (Whitman et al. 2014). Similarly, forests dominated by species with more southerly distributions, such as Atlantic white-cedar, may be less susceptible to changes in climate.

Stressors: Insect pests such as eastern spruce budworm and balsam woolly adelgid currently affect this system and are likely to respond to temperature changes. Warmer temperatures may allow balsam woolly adelgid to increase, while dampening the effects of eastern spruce budworm in the assessment area (Chapter 4). Changes in herbivory could have important effects on these ecosystems. Expanded deer herbivory could affect recruitment of northern white-cedar, especially where snowpack and winter severity are reduced.

Low-Moderate Adaptive Capacity

Although all forests will be uniquely affected by climate change, impacts on lowland mixed conifer forests are more likely to vary with site conditions (e.g., surface geology, hydrology, soils), dominant tree species, and local changes in climate. Nevertheless, these ecosystems, like other forested wetlands in the region, tend to have a very limited suite of tree species physiologically adapted to the moisture and nutrient conditions found in these areas, making them particularly vulnerable to the loss of a given species due to climate change and associated impacts.

Lowland spruce-fir forest in Downeast Maine. Photo by Nicholas Fisichelli, Schoodic Institute at Acadia National Park, used with permission.

Lowland conifer forest regeneration in autumn. Photo by Nicholas Fisichelli, Schoodic Institute at Acadia National Park, used with permission.

Northern white-cedar in a lowland mixed conifer forest. Photo by Maria Janowiak, U.S. Forest Service.

Montane Spruce-Fir

Moderate-High Vulnerability (medium evidence, medium agreement)

These cold-adapted forests are susceptible to warmer temperatures, increased disturbance, and declining habitat suitability for the dominant species. Interactions among these effects may exceed the ecological tolerances of the defining species in this system, particularly at lower elevations and more southerly locations. Ecosystems may persist in areas that remain relatively cool.

Neutral-Negative Potential Impacts

Drivers: The montane spruce-fir forest system is strongly associated with the coldest and most extreme climates in New England, making these ecosystems particularly susceptible to warmer temperatures and longer growing seasons (Cogbill and White 1991, Manomet Center for Conservation Sciences and NWF 2013b). Reductions in snowpack may decrease soil moisture availability in the spring or increase the probability of root damage during freeze-thaw events. Increases in extreme storm events may lead to greater tree mortality from disturbance.

Dominant Species: The dominant species, including balsam fir and red spruce, are projected to have substantial declines in suitable habitat, particularly under greater warming (Chapter 4). Montane spruce-fir forests are expected to be especially vulnerable at the southern extent of their range, where a temperature increase of 5 °F (–2.8 °C) could eliminate all habitat from Massachusetts (Manomet Center for Conservation Sciences and Massachusetts DFW 2010a). Impacts are projected to be less in the northern part of the assessment area, such as in Maine, where the dominant species are expected to persist in some areas (Whitman et al. 2014).

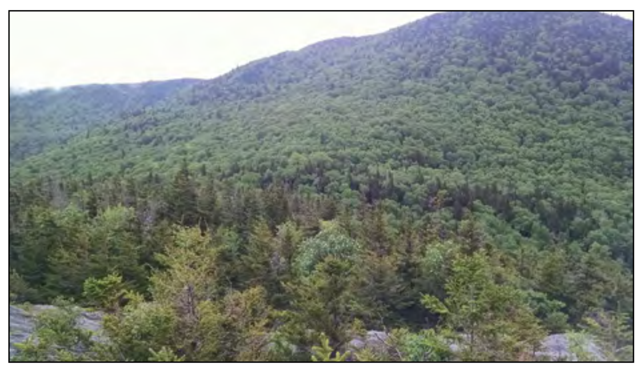
Stressors: Insect pests, such as eastern spruce budworm and balsam woolly adelgid, currently affect these ecosystems in many parts of the assessment area and are likely to respond to temperature changes. Warmer temperatures may allow balsam woolly adelgid to increase, while dampening the effects of eastern spruce budworm in the assessment area (Chapter 4). Likewise, changes in herbivore populations may also have substantial effects on forest growth and composition. Moose are generally projected to have reduced habitat suitability under warmer conditions, although higher elevations may provide cooler habitats where the species will persist for longer. White-tailed deer populations may expand in some areas, particularly at lower elevations.

Moderate Adaptive Capacity

Several factors contribute to a lower capacity for these forests to adapt to climate change, including relatively low species and genetic diversity and slow rates of recovery in response to disturbance. Additionally, the location at high latitudes and elevations presents little opportunity for this forest system to move to new habitats. This is particularly true in southern New England, where this forest system is highly fragmented and exists primarily on isolated mountaintops. At the same time, this system does have some adaptive capacity due to its ability to outcompete many other species, its capacity to persist on cold and nutrient-poor sites, and recent signs of its recovery from past stressors such as acid rain and logging that previously reduced its extent. This current rebound of the montane spruce-fir forest system (Foster and D’Amato 2015, Kosiba et al. 2013) on the landscape may increase its adaptive capacity in the coming decades.

Montane ecosystems, as seen from Mount Jefferson on the White Mountain National Forest. These ecosystems are particularly vulnerable to climate change. Photo by Toni Lyn Morelli, U.S. Geological Survey.

A montane spruce-fir forest. Photo by Anthony W. D'Amato, University of Vermont, used with permission.



A montane spruce-fir forest. Photo by Anthony W. D'Amato, University of Vermont, used with permission.

Northern Hardwood

Low-Moderate Vulnerability (medium evidence, medium agreement)

Climate change poses several threats to these forests, although the widespread and diverse nature of this system suggests that impacts will be highly variable across the region and dependent on local site conditions.

Positive and Negative Potential Impacts

Drivers: Climate change is expected to alter precipitation patterns and hydrology, leading to the potential for drier summer conditions (Chapters 3 and 4) for the northern hardwood forest system. Changes in soil temperature and moisture that increase risk of drought and alter nutrient availability or soil processes could have substantial effects on sugar maple and other dominant species (Groffman et al. 2012). Disturbance dynamics in these forests may also change, and increases in extreme weather events could lead to more frequent or widespread windthrow, affecting the gap-phase dynamics that foster regeneration of shade-tolerant species. The greatest changes in northern hardwood forests are expected to occur at lower elevations and latitudes.

Dominant Species: Many species common to these forests are projected to have a broad range of habitat changes under different climate scenarios (Chapter 4). Eastern hemlock, yellow birch, and quaking aspen, and to a lesser extent, sugar maple, have substantial projected declines in habitat suitability and biomass under the warmer and drier GFDL A1FI scenario than under the PCM B1 scenario, suggesting that greater changes in climate will lead to more-negative consequences. Red maple occurrence is not modeled to change substantially, but its current abundance, biological traits, and ability to respond to disturbance suggest that it may increase. Common associate species, such as American beech, American elm, and white ash, may not be able to increase as projected due to substantial impacts from insects and diseases. Some southerly-distributed hardwood species that are currently infrequent or absent in the assessment area are projected to gain suitable habitat, including white oak, sassafras, and yellow-poplar.

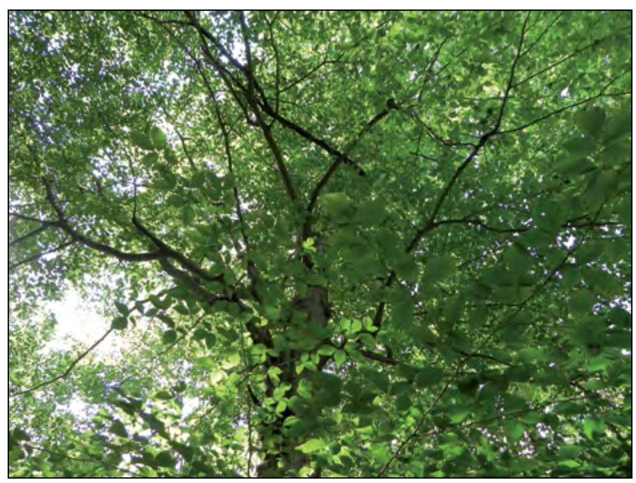
Stressors: Climate change may amplify several major stressors, including invasive plant species, herbivory by white-tailed deer, and forest pests such as the hemlock woolly adelgid. Confidence in the vulnerability of this system is somewhat lower due to the likelihood of different responses across the landscape as well as uncertainty about how climate change will interact with numerous other current threats to these ecosystems. Unanticipated interactions may also occur between multiple stressors, such as drought, invasive species, and forest pests and diseases. Overall, it is expected that these impacts may be greatest on currently marginal sites or on sites where soil conditions become substantially drier.

Moderate-High Adaptive Capacity

Northern hardwood forests are widespread across the region and occur on a variety of soils and landforms. These forests often contain many tree species, representing a broad mix of tolerances and reproductive strategies. In general, areas that are north-facing, at higher elevations, or farther north in the region are expected to undergo less change and may continue to support northern hardwoods in the future. In these areas, it is also possible that sites that are currently too wet or cold to support northern hardwoods may become suitable over time and be colonized by these species. At the same time, northern hardwood forests that are farther south may have a reduced capacity to cope with future conditions, particularly where past land use, land development, fragmentation, invasive species, or other factors have already impaired the system.


An old and unmanaged northern hardwood forest. Photo by Maria Janowiak, U.S. Forest Service.


A relict white pine growing above a northern hardwood forest. Photo by Maria Janowiak, U.S. Forest Service.


A large beech tree in a northern hardwood forest. Photo by Maria Janowiak, U.S. Forest Service.

Pitch Pine-Scrub Oak

Low Vulnerability (medium evidence, medium agreement)

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

Neutral-Positive Potential Impacts

Drivers: Warmer temperatures are generally not expected to have major effects on the pitch pine-scrub oak system because it is at the northern extent of its range in the region and occurs on particularly warm and dry sites (Manomet Center for Conservation Sciences and Massachusetts DFW 2010a, Manomet Center for Conservation Sciences and NWF 2013b, New Hampshire Fish and Game Department [FGD] 2013). Fire is the dominant natural disturbance in this system; increases in fire occurrence would generally be expected to favor pitch pine over more mesic oak and hardwood species that encroach in the absence of fire (Manomet Center for Conservation Sciences and Massachusetts DFW 2010a, Manomet Center for Conservation Sciences and NWF 2013b, New Hampshire FGD 2013). It is uncertain how climate change would affect the low-lying frost pockets common in this forest type, which generally support cold-hardy scrub oak. Over the long term, substantially warmer temperatures could reduce the occurrence of these unique microclimates (New Hampshire FGD 2013). Although pitch pine-scrub oak forests are generally expected to benefit under warmer and drier conditions, the close association of this forest system with sandy, nutrient-poor soils suggests that it may be unable to expand its extent appreciably.

Dominant Species: Considering the range of possible climate futures, scrub oak is projected to have little change in future habitat, and pitch pine habitat may increase slightly. Likewise, other oak species that are minor components of this forest system are generally expected to have similar or increased habitat and growth in the future.

Stressors: Insect pests and diseases affecting this forest type, such as red pine shoot blight, may become more damaging under a warmer climate. Additionally, species such as southern pine beetle have been observed expanding northward, and these movements are expected to continue due to higher temperatures (Weed et al. 2013). The continued shift toward mesic species in these forests may continue if fire suppression activities remain constant and broadleaf species such as red maple and black cherry increase under climate change.

Moderate Adaptive Capacity

This is a fire-dependent forest type that is generally expected to respond favorably to disturbance. Although the individual species common to this system are expected to fare better under warmer conditions, these ecosystems have low species diversity. Additionally, fire suppression has created denser forests in many locations, and it is unclear how human response to increased fire risk from climate change may alter future forest fire conditions. Further, some pitch pine-scrub oak forests may have reduced adaptive capacity where land use and development have increased forest fragmentation, fire suppression, or abundance of invasive species.

A southern New England forest containing pitch pine and oak trees. Photo by Maria Janowiak, U.S. Forest Service.

A forest containing pitch pine and scrub oak, marked for forest harvest. Photo by Anthony W. D'Amato, University of Vermont, used with permission.

Pitch pine trees in the forest overstory. Photo by Maria Janowiak, U.S. Forest Service.

Transition Hardwood

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

The transitional nature of this system suggests a variety of potential outcomes depending on the interaction of climate impacts and local conditions. Over the next several decades, change in these forests is expected to be driven primarily by a number of current stressors rather than climate change.

Positive and Negative Potential Impacts

Drivers: Longer growing seasons would be expected to increase productivity of the transition hardwood forest system where there is adequate moisture, but altered precipitation may increase the potential for drier summer conditions (Chapters 3 and 4). Further, changes in soil temperature, moisture, nutrient availability, freeze-thaw cycles, or belowground processes could have substantial effects on sugar maple and other dominant species. Disturbances that affect this forest system, such as blowdowns or ice storms, may become more frequent or severe. The widespread and diverse nature of this forest type suggests that impacts will be highly variable across the region and dependent on local site conditions, with systems in more southerly or warm locations expected to undergo greater impacts.

Dominant Species: Model projections vary by species but generally suggest decline under scenarios projecting greater climatic changes for many species common to these forests, such as eastern white pine and sugar maple (Chapter 4). Red maple occurrence is not modeled to change substantially, but its current abundance, biological traits, and ability to respond to disturbance suggest that it may increase. Species composition may change over time to reflect future conditions, and may ultimately make a transition to oak- and pine-dominated forests in some locations (Manomet Center for Conservation Sciences and Massachusetts DFW 2010a). At the same time, several species that are at the middle or northern edge of their range, such as black cherry and yellow-poplar, are present in lower abundances and may increase. This suggests the potential for changes in the relative abundance of different species within this system, altering the "character" of forest composition.

Stressors: Climate change may amplify several major stressors that are already affecting this forest system. Several pests, including beech bark disease, gypsy moth, and hemlock woolly adelgid, currently affect many forests, and there is a disproportionately large impact on forest systems where eastern hemlock is lost. Pests such as Asian longhorned beetle may present new risks as they expand. Invasive plants already affect many of these ecosystems and may increase due to warmer temperatures and exacerbated disturbance. Browsing by white-tailed deer may increase if populations expand under less severe winters.

Moderate-High Adaptive Capacity

These forests are found across a variety of landforms and local conditions and contain a mix of shade and moisture tolerances and reproductive strategies (e.g., seeding, sprouting). In general, areas that are north-facing, at higher elevations, or farther north in the region are expected to undergo less change compared to forests in warmer, drier, or more southerly locations (Manomet Center for Conservation Sciences and NWF 2013b, New Hampshire FGD 2013, Tetra Tech 2013). Likewise, forests containing a wide diversity of tree species as well as tree species that are expected to be better adapted to future conditions are likely to be able to respond more favorably to future conditions. In comparison with northern hardwoods, transition hardwood forests are more likely to be located in areas that have (or have had) higher levels of human disturbance; fragmentation, invasive species, or other stressors may have reduced the capacity of forests in some locations to cope with changing conditions (Manomet Center for Conservation Sciences and NWF 2013b). Adaptive capacity may also be reduced by ecosystem shifts toward more-mesic tree species and a lack of regeneration of oaks and other species tolerant of warmer and drier conditions.

A transition hardwood forest with coniferous and deciduous tree species. Photo by Anthony W. D'Amato, University of Vermont, used with permission.

A transition hardwood forest with a mix of deciduous tree species. Photo by Anthony W. D'Amato, University of Vermont, used with permission.

CHAPTER 6: MANAGEMENT IMPLICATIONS

The previous chapters of this assessment have described observed and anticipated climate trends, potential impacts to forest ecosystems, and the climate-related vulnerability of major forest systems in the assessment area. This chapter takes one additional step and summarizes some implications of these climate change impacts and vulnerabilities for a variety of topics important to natural resource managers working in forest ecosystems. 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 managers of public and private land. These topics, and the descriptions of climate change implications, are not comprehensive. Some topics have received less scientific attention or entail greater uncertainty. For some topics, we relied on input from subject-area experts to discuss climate change implications. Our goal is to provide a springboard for thinking about management implications of climate change and to connect managers to other relevant resources. When available, the "more information" sections provide links to key resources for managers to find more information about the impacts of climate change on that particular topic.

This chapter does not make recommendations as to how management should be adjusted to cope with climate impacts. We recognize that climate change will have varying implications for different forest systems, ownerships, and management objectives. Additionally, climate change is only one of many factors considered in making land management decisions. Therefore, we provide broad summaries rather than focusing on specific management issues. A separate document, *Forest Adaptation Resources*, has been developed to assist land managers in a decisionmaking process to adapt their natural resource management to projected impacts (Swanston et al. 2016).

NATURAL RESOURCE MANAGEMENT PLANNING

Until recently, climate change has not played a large role in natural resource planning. Many federal and state-level land management agencies are beginning to address the issue, however. For example, the recently updated U.S. Forest Service regulations for National Forest System Land Management Planning (also known as the 2012 Planning Rule) directly address the impacts and ramifications of climate change (36 CFR 219; U.S. Forest Service 2012). In fact, climate change was among the stated purposes for revising the rule (U.S. Forest Service 2012). When the Green Mountain National Forest in Vermont and the White Mountain National Forest in New Hampshire and western Maine revise their management plans in the future, they will be required to address climate change under this new rule. Similarly, the state-level management plans have not historically addressed climate change, but recent statewide forest strategies generally identify climate change as an issue that could influence the long-term sustainability of forests.

Incorporating climate change considerations into natural resource planning will always be a challenging endeavor. The uncertainties associated with planning over long time horizons are only compounded with climate change. Management plans for federal, state, and local agencies, as well as for private lands, are typically written to guide management for a 10- to 25-year period, and it may be difficult to address the potential long-term effects of climate change within a relatively short planning horizon. Management plans developed by Native American tribes look across longer timeframes, but still face the challenge of uncertainty about future conditions. Further, major storms or disturbance events are inherently unpredictable, and often force managers to deviate from planned analysis or treatment cycles. If climate change results in more frequent disturbances or unanticipated interactions among major stressors, it may be more difficult to adhere to the stated goals, objectives, and priorities in current plans. Future land management plans may have to incorporate adaptive management principles, include greater flexibility, or coordinate across land ownerships to address shifting conditions and priorities.

Private landowners, who own about 80 percent of the forest land in the assessment area, are also beginning to consider the implications of climate change for their planning and management. This may be out of a desire to anticipate the material risk posed to their forest land. For corporate or industrial owners, it may also be due to questions from outside funding, investment, and certification agencies regarding their "climate preparedness." In the near term, the biggest impacts are likely to come from changing pest and disease dynamics and increased risk from extreme events, such as heavy rainfall, storms, and more frequent drought conditions (Chapter 4). In the long term, adjustments may need to be made for suboptimal growing conditions induced by shifts in the climate envelope for commercially important tree species. For forest management in particular, climate change will present risks, such as more severe drought, increased pest pressure, and heavier precipitation events, as well as opportunities, such as longer growing seasons, potential for carbon dioxide fertilization, and the ability to grow entirely new species. Managers are increasingly thinking of climate change as a new lens through which to view management activities.

More Information

- More information on the U.S. Forest Service's 2012 Planning Rule can be found here: www.fs.usda.gov/planningrule
- State forest action plans have been prepared for all states in the assessment area. These statewide assessment and strategy documents include discussions of climate change. www.forestactionplans.org/regional-state
- The Forest Stewardship Program, which encourages private landowners to more actively manage their forest and related resources, offers guidance on including carbon sequestration and climate change resilience in Forest Stewardship Plans. www.fs.fed.us/cooperativeforestry/programs/loa/fsp.shtml
- The Climate Change Response Framework, led by the Northern Institute of Applied Climate Science, is a collaborative, cross-boundary effort working to incorporate climate change considerations into natural resource management. It provides an integrated set of tools, partnerships, and actions to support climate-informed conservation and forest management.
    - The Climate Change Response Framework Web site provides access to presentations, briefings, and other products that help integrate climate change into management planning and activities. The Web site highlights real-world adaptation demonstrations across public, tribal, and private lands. www.forestadaptation.org
    - *Forest Adaptation Resources: Climate Change Tools and Approaches for Land Managers, 2nd edition* provides concepts and tools for integrating climate change considerations into natural resource planning and management. www.nrs.fs.fed.us/pubs/52760

- An online adaptation workbook and associated Web site, workshops, and training sessions have given managers sound science and the tools to better and more proactively manage forests while taking climate vulnerability into consideration.
  www.adaptationworkbook.org

- The Climate Smart Land Network, led by Manomet, provides forest landowners and managers with direct access to experts on forests and climate, and the opportunity to learn from other forest landowners in the network. The Web site for the network has publicly available bulletins synthesizing a wide range of topics, as well as additional information about its services.
  www.climatesmartnetwork.org/
- The National Wildlife Federation has developed a guide to provide to conservation practitioners and natural resource managers guidance for conservation in a changing climate.
  www.nwf.org/What-We-Do/Energy-and-Climate/Climate-Smart-Conservation.aspx

HABITAT MANAGEMENT

Climate change is expected to have profound effects on forest ecosystems (Chapter 5), which will in turn lead to habitat changes for a variety of plant and animal species (Groffman et al. 2014; Manomet Center for Conservation Sciences and National Wildlife Federation [NWF] 2013b, 2013c; Staudinger et al. 2013). These changes mean that managers will increasingly need to consider the effects of climate change when managing wildlife habitats or working to conserve biodiversity (Mawdsley et al. 2009). Many organizations are beginning to address the effects of climate change by gaining a better understanding of which species and habitats are most vulnerable and identifying actions to maintain or improve critical habitats.

The complex effects of climate change on plant and animal species and their management is an area of active research. A short synthesis of some research is included in Appendix 8, but numerous climate change assessments have been developed for the Northeast as a whole and for individual states that provide a more thorough analysis of the subject. Many species are expected to respond to climatic changes by moving northward, upslope, or upstream, while others may adapt in place or be unable to cope with the changes (Staudinger et al. 2013). Climate change will affect species differently, such that some species may decline while others expand under future conditions. For example, although conditions in some areas of the region are currently favorable for moose (Wattles and DeStefano 2013), this cold-adapted species is considered to be highly vulnerable to climate change (Hoving et al. 2013, Whitman et al. 2013). Warmer temperatures can increase heat stress and infestations of winter tick, both of which are expected to cause moose populations to decline in the future (Dou et al. 2013, Murray et al. 2006, Musante et al. 2007). Future conditions are expected to make habitat conditions more suitable for white-tailed deer, which could further increase moose mortality due to spread of the brainworm parasite (Frelich et al. 2012, New Hampshire Fish and Game Department 2013, Rodenhouse et al. 2009).

It is hard to determine which species and habitats may be most vulnerable to climate change, but evidence and biological principles suggest some characteristics increase risk. For example, species with small geographic ranges, narrow physiological tolerance, fragmented distributions, or limited dispersal ability may be more restricted to certain


A dead hemlock tree that is providing benefits for wildlife. Photo by Maria Janowiak, U.S. Forest Service.

locations and less likely to move in response to changing conditions (Trani Griep and Manley 2012). Threatened and endangered species often face population declines due to a variety of nonclimatic factors, such as habitat loss, competition from invasive species, and disease, all of which can be exacerbated by climate-related stress. Some evidence suggests that aquatic systems and water-dependent habitats such as ephemeral ponds may be at higher risk because of changing hydrologic regimes, rising water temperatures, reduced oxygen levels, and altered nutrient cycling (Groffman et al. 2014, Staudinger et al. 2013, Trani Griep and Manley 2012). Coastal ecosystems are especially vulnerable to rising sea levels (Manomet Center for Conservation Sciences and NWF 2013c, Staudinger et al. 2013).

Many organizations are taking a deeper look into the effects of climate change on the habitats that they manage. For example, state agencies are working to incorporate climate change information into their state-level wildlife action plans. These plans identify wildlife species and associated habitats that are in greatest conservation need, many of which may be particularly vulnerable to climate change. There is also an increasing interest in strategies to support climate change adaptation (Mawdsley et al. 2009, Stein et al. 2014). Available strategies vary widely and include reducing nonclimate stressors, maintaining fundamental ecosystem processes and features, enhancing connectivity, protecting refugia, and relocating organisms (Mawdsley et al. 2009, Stein et al. 2014, Swanston et al. 2016). The selection of specific strategies and actions will depend on the needs and scope of a given project and location (Stein et al. 2014, Swanston et al. 2016).

More Information

- Many states have incorporated climate change information into their state wildlife action plans. The Northeast Climate Science Center developed a regional synthesis document to support the revision of these plans. The synthesis includes a summary of the current scientific knowledge of biological responses for wildlife species with a focus on Regional Species of Greatest Conservation Need.
  https://necsc.umass.edu/projects/integrating-climate-change-state-wildlife-action-plans
- The Climate Change Bird Atlas, developed by the U.S. Forest Service, is a companion to the Climate Change Tree Atlas, and uses information about climate change and effects on forest habitat to project changes in bird species distributions.
  www.nrs.fs.fed.us/atlas/bird
- The Massachusetts Wildlife Climate Action Tool is designed to inform and inspire local action to protect the Commonwealth's natural resources in a changing climate.
  www.climateactiontool.org
- The U.S. Forest Service Climate Change Resource Center provides topic pages that summarize how climate change may affect wildlife species and aquatic ecosystems.
  www.fs.usda.gov/ccrc/topics
- The Designing Sustainable Landscapes project has projected future habitat suitability for some regional forest wildlife under climate change.
  www.umass.edu/landeco/research/dsl/documents/dsl_documents.html
- NatureServe and Heritage Program collaborators have developed a Climate Change Vulnerability Index (CCVI) to provide a rapid, scientifically defensible assessment of species vulnerability to climate change for 60 species found in the North Atlantic Coastal Zone.
  http://northatlanticlcc.org/projects/CCVI-northeast-spp/CCVI-northeast-spp
- The National Wildlife Federation has developed a guide to provide to conservation practitioners and natural resource managers guidance for conservation in a changing climate.
  www.nwf.org/What-We-Do/Energy-and-Climate/Climate-Smart-Conservation.aspx

WILDERNESS MANAGEMENT

Land may gain wilderness status by federal or state designation. The Green Mountain and White Mountain National Forests contain several federally designated Wilderness areas, and New York designated and manages the Adirondack Forest Preserve. These areas play a special role in the regional landscape because of their remote and unmanaged character and their scenic, recreational, and ecological value. The federal Wilderness Act of 1964 was established to protect areas in their natural condition and to assure that an increasing human population, accompanied by expanding settlement and growing mechanization, does not modify all areas within the United States. U.S. Forest Service policy directs the agency to "manage the wilderness resource to ensure its character and values are dominant and enduring" (U.S. Forest Service 2007). Since the early 20th century, lands in New York's forest preserve have been required by Article 14 of the state constitution to be kept "forever wild". The potential for extensive ecosystem change resulting from climate change raises difficult questions about the future management of these and other wilderness areas.

Climate change is poised to affect wilderness areas in a number of ways. Weather and climate could influence recreational use; a shorter winter season may increase participation in some activities and areas. Although natural hazards and obstacles are inherently part of the wilderness experience, increased tree mortality from storms, drought, or insect or disease attack may pose increased risk to visitors, and extreme precipitation events may damage infrastructure. Wilderness areas also provide important benefits for wildlife species within the region. Some evidence suggests that climate change may have the greatest impacts on species that are confined to protected areas, largely because populations would not be able to migrate in response to changing range limits for species (Peters 1985). Additionally, species within protected areas may potentially face new competitors, predators, or diseases as many native and nonnative species move around on the landscape.

It is uncertain how climate-related impacts will influence management in wilderness areas because of differences in wilderness restrictions among different land management agencies and organizations. For example, federally designated Wilderness areas are legally required to be natural and untrammeled, and any changes to the management of these areas would require a thorough planning process to consider potential pros and cons.

More Information

- The Wildlife Conservation Society's Adirondack Communities and Conservation Program includes climate change in this boreal forest wilderness as an area of emphasis.
  http://programs.wcs.org/northamerica/wild-places/adirondacks/adirondack-climate-change.aspx
- The Wilderness.net Climate Change Toolbox provides information about climate change and wilderness, including management guidelines and strategies.
  www.wilderness.net/climate
- The U.S. 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/

A view of the Adirondack Mountains and lakes in northern New York. Photo by Maria Janowiak, U.S. Forest Service.

LAND CONSERVATION

Climate change has many important implications for land conservation planning in the assessment area, and climate change science can be used to help prioritize land conservation investments and help guide project design. For example, it may be important to identify parcels that have large carbon mitigation potential and prioritize these for land acquisition and conservation. This is particularly important in the Northeast, where human population densities and levels of forest fragmentation are relatively high and projected to increase further (Shifley and Moser 2016). Climate change trends and ecosystem models can also be used to identify lands that have long-term potential to provide refugia for at-risk species and habitats, enhance landscape connectivity, or protect water supplies. Planning for conservation of terrestrial habitat "strongholds" from climate change requires a close look at the landscape to identify those corridors and habitats that will be most resilient in the face of projected shifts (Anderson and Ferree 2010, Anderson et al. 2012). Integrating this kind of information into conservation planning and prioritization can help identify and protect areas that have unique potential for conservation.

When designing land conservation projects, there are important decisions to make about long-term ownership and management prescriptions attached to the conservation agreement (Rissman et al. 2015). In some cases, the best strategy may be to leave lands in private ownership, and to develop conservation easement terms that support adaptive management by the landowner to address climate shifts. In other cases, perhaps where complex restoration or species-specific management is needed, an appropriate conservation strategy may be to seek a public agency that can provide the necessary financial and technical resources. In either instance, the key principle is to use available climate information to assess potential effects of projected stressors on the property in the future, and then to integrate those considerations into project design. Private nonprofit organizations, government agencies, landowners, and entities that may provide funding will increasingly need research-based results on anticipated climate trends and impacts, including spatially explicit information on how these shifts will play out over the land. This science can enable effective use of funding, staff time, and other resources that are essential to advancing "climate-informed" conservation of forests in the region and shaping conservation efforts to promote a more resilient landscape.

More Information

- The Open Space Institute has developed the Resilient Landscapes Initiative to protect habitats that will serve as strongholds for plants and animals to adapt even as the climate changes. www.osiny.org/site/PageServer?pagename=Issues_Habitat
- The Nature Conservancy's Northeast Resilience Project has identified places that will be more resilient to climate change and serve as natural strongholds for diversity into the future. www.conservationgateway.org/ConservationByGeography/NorthAmerica/UnitedStates/edc/reportsdata/terrestrial/resilience/ne/Pages/default.aspx

FOREST PRODUCTS

The forest products industry is important to the local and regional economy of the assessment area (Chapter 1). Tree species and forest composition are projected to change over the 21st century (Chapters 4 and 5). Changes in forest composition across the landscape will be influenced by forest management, and in turn will influence forest management and the forest products industry (Moser et al. 2016). Several commercially important species such as quaking aspen are projected to suffer significant declines under a range of possible climate futures over the next century. Conversely, hardwood species such as white oak and yellow-poplar are projected to increase in the assessment area. Large potential shifts in commercial species availability may pose risks for the forest products sector if the shifts are rapid and the industry is unprepared. The forest products industry may benefit from awareness of anticipated climate trends and shifts in forest species. In many cases, forest managers can take actions to reduce potential risks associated with climate change or proactively encourage species and forest types anticipated to fare better under future conditions (Stein et al. 2014, Swanston and Janowiak 2016). 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.

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 throughout the century (Moser et al. 2016). 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 substantial changes over the past 100 years, and continued responsiveness can help the sector remain viable.

More Information

- The U.S. Forest Service 2010 Resources Planning Act Assessment includes future projections for forest products and other resources through the year 2060 and examines social, economic, land use, and climate change influences.
  www.fs.fed.us/research/rpa/
- The U.S. Forest Service's Northern Forest Futures Project uses the latest inventory data and scientific projections to understand how forests in the Midwest and Northeast will change as climate and other stressors change.
  www.nrs.fs.fed.us/futures/
- The Climate Change Tree Atlas, developed by the U.S. Forest Service, provides information on the projected suitable habitat for tree species under climate change.
  www.nrs.fs.fed.us/atlas/

A red pine plantation in central Vermont. Photo by Maria Janowiak, U.S. Forest Service.

FOREST HARVEST 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 may shorten the available time window for conventional forest management operations. Most management in lowland areas and on soils prone to compaction or erosion is accomplished during the winter. Climate change is projected to result in shorter seasons of frozen ground, more midwinter thaws, less snowpack, and more rain during winter months (Chapter 3). 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 entail 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 with coarse, sandy soils. Alternatively, summer dry periods and droughts could possibly extend operating windows in low-lying areas or clay soils. Extended or severe droughts could present problems in sandy areas, however, if it becomes necessary to install gravel over logging roads.

Projected changes in severe weather patterns could increase the need for salvage harvests. Harvesting green timber allows resource managers to strategically achieve desired objectives and outcomes. In contrast, salvage harvesting after a wind event or pest or disease outbreak generally arises from a more immediate need to remove hazardous fuels or clear affected forest areas. A salvage sale also does not garner as high a financial return as a green timber sale.

Winter landscape. Winters are becoming shorter and milder as temperatures warm. Photo by Maria Janowiak, U.S. Forest Service.

Analysis of timber harvest records in northern Wisconsin has identified some consequences of the changes in frozen ground condition (Geisler et al. 2016, Rittenhouse and Rissman 2015). Warmer winters can limit operability in forests with wet soils and shift harvest to upland forest types. Growing-season restrictions on harvest designed to curtail the spread of forest diseases can further reduce the annual harvest window. Additionally, ongoing stressors of overcapitalization, loan and insurance payments, and high fuel prices increased pressure on loggers to harvest year-round. Thus, climate change impacts on forestry operations have complex implications for timber production, loggers' livelihoods, water quality, and transportation systems.

INFRASTRUCTURE ON FOREST LAND

Changes in climate and extreme weather events are expected to affect infrastructure, such as roads, bridges, and culverts, on forest lands throughout the region. Many landowners and agencies are also responsible for managing water-related infrastructure such as dams, drainage ditches, and culverts. The current specifications for infrastructure are generally based on past climate patterns, and the current trend of intensifying precipitation has put additional strains on old and fragile infrastructure.

Heavy precipitation events, which are already increasing and projected to increase more in the future (Chapter 3), may overload existing infrastructure that has not been built to that capacity. For example, older road systems may be susceptible to increased rainfall events due to improper location or outdated building standards. Many of these aging structures are being replaced, with the expectation that new culverts will need to last up to 100 years into the future and be able to withstand heavier precipitation events. Replacing infrastructure often results in greater costs in order to upgrade to higher standards and capacity. Extreme events may also require more frequent maintenance of roads and other infrastructure, even if the structures are designed to appropriate specifications. Additionally, forest managers may find it necessary to take further precautions to prevent erosion when designing road networks or other infrastructure.

NONTIMBER FOREST PRODUCTS

Hundreds of nontimber forest products are used for food, medicine, craft materials, and other purposes across the assessment area, providing important cultural and economic benefits and contributing to food security for some populations (Baumflek et al. 2010, Robbins et al. 2008). Many of these products will be affected by climatic changes; each product will be uniquely affected based on the impacts of climate change on individual species of wild plants, fungi, and animals. For example, foraging for morels and other mushrooms is a passion for many people throughout the assessment area for their commercial value, medicinal properties, and culinary applications. Some evidence suggests that the relationship between the onset of the growing season and fungal phenology may lead to earlier or longer fruiting periods of morels and other edible fungi (Emery and Barron 2010, Gange et al. 2007, Kauserud et al. 2008). Similarly, climate change is expected to have impacts on tribal traditional food, such as the use of several berry species by tribal communities in the Northeast (Lynn et al. 2013, Saint Regis Mohawk Tribe 2013).

Maple syrup is a nontimber forest product that is largely synonymous with the forests of the Northeast. Maple syrup and sugar, made from boiling sugar maple sap, provided treasured sources of sweetness and a critical source of late winter nourishment well before the arrival of the first Europeans on the continent. Fur traders' records show that maple sugar was an important exchange good from the early days of settlement (Emery 2002). Today, gathering and boiling sugar maple sap continues to have profound cultural and economic importance in the region. Commercial production of maple syrup and related products provides millions of dollars of revenue in the assessment area, and this total does not include production of maple syrup that never enters the market. Gathering and boiling sap and sharing syrup knits together families and communities. Sap flow necessary for maple syrup production requires a combination of warm days and freezing nights that is highly seasonal. Climate records show such conditions now occur earlier than in the past and this trend is projected to continue; however, it is unclear whether the season will be shortened or sap yield reduced (Groffman et al. 2012, Matthews et al. 2017, Skinner et al. 2012). Maple producers report that their current ability to adapt to changing climatic conditions is largely related to the health of the forest and the ability of producers to adopt new technologies (Kuehn et al. 2016).

FIRE AND FUELS

Weather and climate are major drivers of fire behavior. Across the region, the fire season is controlled by a combination of day length, weather, and fuel conditions. Typically, short day lengths, cool temperatures, and wet fuels delay the onset of fire season until April or May. Although the summer months have the longest days and warmest temperatures, living vegetation requires extended dry periods of 2 weeks or more to increase the potential for fire ignition and spread. Live trees drop leaves and go dormant in the fall, but most forests become increasingly fire-prone around the same time that short days and cool temperatures return.

A prescribed fire in a pitch pine-scrub oak forest in the Montague Plains of western Massachusetts. Photo by Matthew Duveneck, Harvard Forest, used with permission.

Projected changes in climate could affect fire and fuels management in the assessment area. Climate change is generally expected to increase annual precipitation in the assessment area, but there is the potential for drier conditions during the growing season (Chapter 3). Drier conditions later in the growing season following wet springs could cause some tree mortality, increasing forest fuel loads and the potential for more-intense fires. High-intensity wildfire can result in species mortality, increases in invasive species, changes in soil dynamics (e.g., compaction, altered nutrient cycling, sterilization), or altered hydrology (e.g., increased runoff or erosion). Under intense fire weather conditions, wildfires could also become a hazard and safety risk to the public, firefighters, and infrastructure. More resources may be needed to reduce fuel loads to prevent these catastrophic wildfires, fight them when they do occur, and restore ecosystems after a catastrophic event.

Although some ecosystems may be negatively affected by wildfire, any increases in wildfire could also be beneficial in some areas. Increased fire potential could increase opportunities for restoring pitch pine-scrub oak forests, for example. Projected changes in climate could also affect the ability of public, tribal, and private land managers to apply prescribed fire in the assessment area. Wetter springs could make it more challenging to conduct prescribed burns in spring, shifting opportunities for dormant-season burning to the fall. On the other hand, 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 North Atlantic Fire Science Exchange provides fire science information to resource managers, landowners, and the public about the use, application, and effects of fire. http://www.firesciencenorthatlantic.org
- The U.S. 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/

CARBON SEQUESTRATION

Forests in the assessment area store a tremendous amount of carbon in live trees, dead trees and wood, the forest floor, and soils (Chapter 1). Climate change and associated impacts to forest ecosystems may change the ability of forests in the assessment area to store carbon. A longer growing season and carbon dioxide fertilization may lead to increased productivity and carbon storage in forests in the assessment area (Chapter 4). Several modeling studies suggest that forests are likely to continue to sequester additional carbon over the next several decades as relatively young forests continue to mature and forests benefit from slightly warmer conditions (Duveneck et al. 2017, Thompson et al. 2011, Wang et al. 2017). Over time, this increase could be offset by climate-related physical and biological disturbances (Gough et al. 2008, Hicke et al. 2011, Tang et al. 2014), leading to increases in carbon storage in some areas and decreases in others.

As forests change in response to climate change, patterns of carbon storage are likely to change on the landscape as well. Different forest types in the assessment area store different amounts of carbon (Chapter 1). On average, oak/pine and white/red/jack pine forests store the most carbon. Spruce/fir forests store slightly less carbon overall, but a much greater proportion of the carbon in this forest type is in soils. Regional modeling studies have examined the effects of species composition changes on landscape-scale carbon stocks, and they suggest that some forests may have increases in biomass and overall productivity, despite declines of some northern and boreal species (Duveneck et al. 2017; Tang et al. 2010, 2014). For example, one study projected that aboveground biomass would continue to increase over the next century, even though the contribution of biomass provided by different forest types would change as forest communities changed on the landscape. As long as forests are maintained as forests in the assessment area, a large-scale decline in carbon stocks is not expected. Additionally, forest management can be used to increase forest carbon stores and reduce carbon emissions (McKinley et al. 2011, Ryan et al. 2010).

More Information

- The U.S. Forest Service Climate Change Resource Center provides a summary of how climate change may affect the ability of forests to store carbon, including a video short course for land managers. More information can be found here:

  www.fs.usda.gov/ccrc/topics/carbon-land-mgmt
- A review report, *Considering Forest and Grassland Carbon in Land Management*, summarizes the key issues related to forest management and carbon.

  www.treesearch.fs.fed.us/pubs/54316

RECREATION

Forests are the centerpieces of outdoor recreation in the assessment area (Chapter 1). People throughout the Northeast enjoy a variety of recreational activities, including hunting, fishing, camping, wildlife watching, skiing, and snowboarding. People also explore trails on foot, bicycles, skis, snowshoes, horseback, and snowmobiles, and in 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 (Bowker and Askew 2013, Fisichelli et al. 2015). Forest-based recreation and tourism are strongly seasonal, and most visits to public lands are planned during times when the weather is most conducive to particular activities.

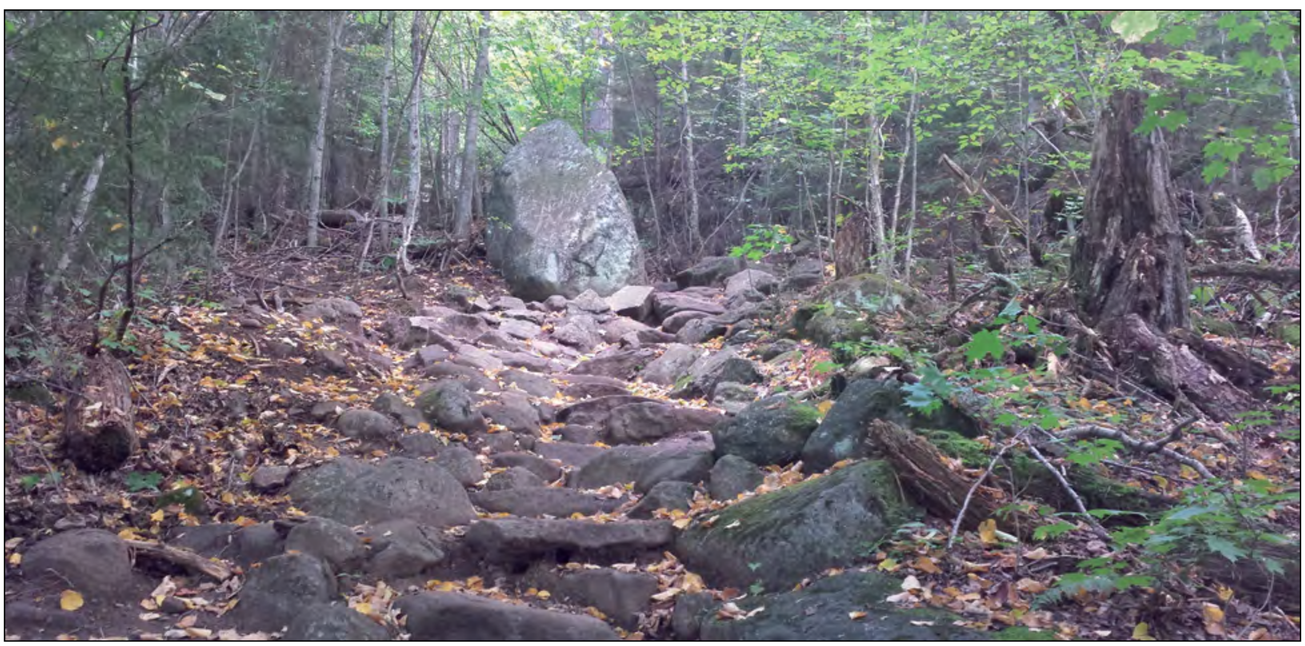
Projections indicate that seasonal shifts will continue toward shorter, milder winters and longer, hotter summers, which could reduce opportunities for popular winter-based recreation activities in the long term. Climate change has already caused reductions in the duration of lake ice in the assessment area (Chapter 3), and there may be fewer opportunities for activities such as ice fishing and pond hockey as conditions continue to change (Fairley et al. 2015). It is expected that much of the assessment area will have substantially less snow by the end of the century, which will create challenges to popular and economically important activities, such as snowmobiling and skiing in undeveloped areas, and downhill skiing (Bowker and Askew 2013, McBoyle et al. 2007, Scott et al. 2008). Because impacts on winter recreation activities will be closely tied to winter temperatures, southern parts of the assessment area are at greater risk in coming decades and will be less able to provide recreational opportunities such as downhill skiing (Dawson and Scott 2013, Scott et al. 2008). Recreationists may change the ways in which they participate in these activities, perhaps by changing the time or location of their participation, or switch to different activities that do not require snow (Dawson et al. 2013).

It is also expected that recreational activities during the spring, summer, and fall will shift in response to warmer and more variable climatic conditions. Some warm-weather forms of nature-based recreation such as mountain biking, motorized vehicle use, and fishing may benefit from extended seasons (Bowker and Askew 2013, Nicholls 2012). Conditions that are warmer, but not overly hot, could increase park use and participation in warm-weather activities (Bowker and Askew 2013, Fisichelli et al. 2015). Warmer spring and fall weather may increase the length of the recreation season; this could have implications for staffing, especially for recreation-related businesses that rely on student labor, which will be unavailable during the school year (Nicholls 2012). Regional increases in average temperatures and heat waves during summer months could shift visitor behavior, depending on the magnitude of changes, and visitor use is expected to decrease where hot weather becomes more frequent (Fisichelli et al. 2015, Nicholls 2012). Extreme weather events could also negatively affect recreation and tourism. For example, increased precipitation, severe storms, and associated flooding could damage infrastructure such as visitor centers, campsites, and trails.

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 coincide with the times when birds are migrating south in the fall, an event that is expected to shift to later in the year as temperatures warm (NWF 2013b). As mentioned earlier, climate change may also result in substantial changes in habitat availability and quality for wildlife and fish species. Big game species, such as moose, are expected to undergo greater stress as a result of climate change (NWF 2013a). Projected changes in water temperatures and fish species habitat may reduce opportunities for ice fishing and cold-water stream fishing but increase opportunities for warm-water lake fishing.

More Information

- The U.S. Forest Service Northern Forest Futures Project uses the latest inventory data and scientific projections to understand how recreational opportunities in the Midwest and Northeast will change as climate and other stressors change.
  www.nrs.fs.fed.us/futures/



A forest trail in the Adirondack Forest Preserve. Photo by Maria Janowiak, U.S. Forest Service.

ARCHAEOLOGICAL AND HISTORIC RESOURCES

Managing cultural resources may become more challenging as a result of the direct and indirect impacts of climate change. The remnants of past human activity, such as paintings, sculptures, and objects from everyday life, are present within the assessment area. These resources date to both prehistoric and historic time periods, and exist both above and below the ground surface. Climate change impacts on the physical environment have the potential to affect the character and condition of these cultural resources. For example, increases in extreme rain events and a more episodic precipitation regime may intensify erosion and weathering of cultural resources. Consequently, the physical integrity of historic structures could be undermined and subsurface resources threatened if the soil covering them is washed away. As precipitation increases, the risk of flooding also escalates; flooding would hasten the erosion process of sites on ridge slopes and on flood terraces. Floodwaters can further threaten the integrity of historic structures in low-lying areas by eroding the foundation, or adding moisture. The increased moisture can generate more mold and fungus growth, thereby hastening deterioration of wooden and other constructed features (Schiffer 1996).

FOREST-ASSOCIATED TOWNS AND CITIES

The ability of human communities to respond to environmental changes is directly related to their adaptive capacity—resources that can be leveraged by the community to monitor, anticipate, and proactively manage stressors and disturbances. Although models exist that 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 closely tied to the health and functioning of surrounding forests, whether for economic, cultural, recreational, or other reasons.

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

State and municipal agencies as well as private companies are also responsible for maintaining infrastructure in the assessment area, including roads, power lines, sewer lines, dams, drainage ditches, and culverts. Storms, extreme temperatures, longer growing seasons, and warmer winters can pose particular challenges for infrastructure. Extreme heat and longer growing seasons can result in rising costs associated with roadside and power line vegetation management. Extreme cold and freeze-thaw cycles can accelerate road deterioration. Intense rainfall could increase the potential for erosion on dirt and gravel roads common in forest landscapes, logging projects, gas development, and rural areas. Water resource infrastructure such as bridges, sewers, major culverts, low-water crossings, and dams may have to be redesigned and rebuilt to accommodate flows of increased duration and intensity. Projected increases in average temperature and summer heat waves can increase demand for cooling and place additional strain on electrical infrastructure.

If resource professionals, community leaders, and local organizations are to help communities adapt to changes, they must identify community vulnerabilities and sensitivities to climate-related impacts and also build community capacity to organize and engage community members and other resources (Moser et al. 2008). In the Northeast, much of the work done to date to assess the vulnerability of human communities and develop adaptation plans has focused on coastal communities and infrastructure (Olmstead et al. 2016, Woodruff and Stults 2016, Zimmerman and Faris 2010). When planning for climate change, decisionmakers can consider how ecological events or changes (e.g., floods, droughts, wildfire, windstorms, introduced species, outbreaks of insects or pathogens) will affect their communities and community members by asking several questions (Davenport et al. 2013). These include:

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

More Information

- The Resilience Alliance has created *Assessing Resilience in Social-Ecological Systems: Workbook for Practitioners 2.0*. www.resalliance.org/resilience-assessment
- The U.S. Department of Energy has examined current and potential future impacts of these climate trends on the U.S. energy sector. www.energy.gov/articles/climate-change-effects-our-energy
- The National Climate Assessment provides summaries of how climate change may affect different regions and sectors of the United States.
  - Urban systems and infrastructure: http://nca2014.globalchange.gov/report/sectors/urban
  - Rural communities: http://nca2014.globalchange.gov/highlights/regions/rural-communities
  - Indigenous peoples, lands, and resources: http://nca2014.globalchange.gov/report/sectors/indigenous-peoples

URBAN FORESTS

Climate change will also affect urban forests in the assessment area. Urban environments can pose additional stresses that trees do not encounter in natural environments, such as pollution from vehicle exhaust, confined root environments, and road salts. The altered vegetation structure and impervious surfaces in urban environments can also create microclimates different from those of the surrounding natural areas (Hall et al. 2016). Impervious surfaces can make urban environments more susceptible to flash floods, placing flood-intolerant species at risk. Responses of trees to disturbances such as drought may vary by land use within an urban area, so it is difficult to understand how the forest will respond as a whole (Fahey et al. 2013). All of these abiotic stressors can make urban forests more susceptible to nonnative species invasion, and insect and pathogen attack, especially because only a limited range of species and genotypes is typically planted in urban areas. Urban settings are also the most likely places for exotic insect pests to be introduced.

Projected changes in climate can pose both challenges and opportunities for the management of urban forests, and some cities have started assessing their vulnerability (Brandt et al. 2017, Ordóñez and Duinker 2015). Shifts in temperature and changes in extreme events may have effects on selection of species for planting (Yang 2009). Native species projected to decline under climate change are not expected to 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. 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 climatic conditions.

Large disturbance events may also become more frequent or intense in the future, necessitating informed decisions in response. For example, wind events or pest outbreaks may be more damaging to already stressed trees. If leaf-out dates advance earlier in the spring due to climate change, community forests may be increasingly susceptible to early-season frosts or snowstorms. 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 staffing and budgets.

More Information

- The U.S. 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
- Several urban areas have developed adaptation guides to help communities use urban forests to reduce climate change impacts and adapt urban forests to future conditions.
    - For urban forests in British Columbia: www.toolkit.bc.ca/Resource/Urban-Forests-Climate-Adaptation-Guide
    - For Toronto's urban forest: www.cleanairpartnership.org/pdf/climate_change_adaptation.pdf
- The Climate Change Response Framework is working with urban communities in the Midwest and Northeast to assess the vulnerability of urban forests to climate change and to identify and develop tools to aid adaptation of urban forests to climate change. www.forestadaptation.org/urban

A riparian forest containing hemlock, which is more susceptible to the hemlock woolly adelgid under warmer winter conditions. Photo by Todd Ontl, U.S. Forest Service.

HUMAN HEALTH

Climate change has important implications for the health of the people who live, work, or recreate in the forests of the assessment area. Climate change can influence a wide array of human health issues through complex interactions in the environment and the human body (Patz et al. 2011, Portier et al. 2013). Respiratory allergies and diseases may increase as longer growing seasons and changes in plant abundance lead to more pollen, or if warmer, moister conditions increase mold (Portier et al. 2013, Ziska et al. 2011). Extremely high temperatures can lead to heat stress, which can exacerbate cardiovascular disease or induce heat-related illness and death.

Vector-borne diseases, such as Lyme disease and West Nile virus, pose an ongoing risk to natural resource managers, local residents, and visitors alike, and this issue may become increasingly important over the 21st century. Vector-borne diseases are transmitted by arthropods such as ticks or mosquitoes and cycle back and forth between arthropod vectors and animal hosts—usually mammals or birds. Humans are typically infected incidentally when they are bitten instead of animal hosts. Climate is one of many key interacting variables that affect people's risk for vector-borne diseases (Portier et al. 2013). Changes in climate can influence vector-borne disease risk by affecting the abundance and distribution of ticks or mosquitoes, the percentage of vectors infected, the abundance and distribution of animal hosts, the presence of suitable habitat for these vectors, and the behaviors that bring humans into contact with infected vectors. Most arthropod vectors of disease are sensitive to physical conditions, such as levels of humidity, daily high and low temperatures, rainfall patterns, and winter snowpack. For example, blacklegged ticks (i.e., "deer ticks") are the vector for Lyme disease and several other diseases, and these ticks are most active on warm, humid days. They are most abundant in wooded or brushy habitats that contain abundant small mammals and deer. Projected expansion of mesic hardwoods with changing climatic conditions may increase the incidence of Lyme disease and other tick-borne diseases if humans frequently visit those habitats.

More Information

- The National Climate Assessment provides a summary of how climate change may affect human health. http://nca2014.globalchange.gov/report/sectors/human-health
- The Natural Resources Defense Council hosts an online Web viewer that provides state-level information about various threats to human health associated with climate change. www.nrdc.org/health/climate/
- The Centers for Disease Control and Prevention Climate and Health Program includes information on a variety of subjects. www.cdc.gov/climateandhealth/

SUMMARY

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

Confronting the challenge of climate change presents opportunities for managers and other decisionmakers to plan ahead, manage for resilient landscapes, and ensure that the benefits that forests provide are sustained into the future. Resources are available to help forest managers and planners incorporate climate change considerations into existing decisionmaking processes (Stein et al. 2014, Swanston et al. 2016), and more information on this subject is available at 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

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**).

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

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

climate change
a change in the state of the climate that can be identified (for example, 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.

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

downscaling
methods for obtaining high-resolution climate or climate change information from coarse-resolution general circulation models; 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 that characterize that larger region.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

hardwood
a dicotyledonous tree, usually broad-leaved and deciduous. Hardwoods can be split into soft hardwoods (for example, red maple, paper birch, quaking aspen, and American elm) and hard hardwoods (for example, 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
the 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 projections from general circulation models 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.

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

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

modifying factor
in the Climate Change Tree Atlas model, an environmental variable (for example, site conditions, interspecies competition, disturbance, dispersal ability) that influences the way a tree may respond to climate change.

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

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

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

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

precipitation
the process where water vapor condenses in the atmosphere to form water droplets that fall to the Earth as rain, sleet, snow, hail, etc.

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.

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

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

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

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

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

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

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

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

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

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

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.

stochastic
involving or containing a random variable or process.

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

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

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

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

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

topkill
death of aboveground tree stem and branches.

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

troposphere
the lowest part of the atmosphere from the surface to about 6 miles in altitude in mid-latitudes (ranging from 5.6 miles in high latitudes to 9.9 miles in the tropics on average) 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.

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

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APPENDIX 1: COMMON AND SCIENTIFIC NAMES OF SPECIES MENTIONED IN THIS REPORT

Plants and Fungi

Common name	Scientific name
American basswood	*Tilia americana*
American beech	*Fagus grandifolia*
American chestnut	*Castanea dentata*
American elm	*Ulmus americana*
American holly	*Ilex opaca*
American hornbeam (musclewood)	*Carpinus caroliniana*
American mountain-ash	*Sorbus americana*
Asiatic bittersweet (Oriental bittersweet)	*Celastrus orbiculatus*
Atlantic white-cedar	*Chamaecyparis thyoides*
bald cypress	*Taxodium distichum*
balsam fir	*Abies balsamea*
balsam poplar	*Populus balsamifera*
bigtooth aspen	*Populus grandidentata*
bitternut hickory	*Carya cordiformis*
black ash	*Fraxinus nigra*
black cherry	*Prunus serotina*
black hickory	*Carya texana*
black locust	*Robinia pseudoacacia*
black maple	*Acer nigrum*
black oak	*Quercus velutina*
black spruce	*Picea mariana*
black walnut	*Juglans nigra*
black willow	*Salix nigra*
blackgum	*Nyssa sylvatica*
blackjack oak	*Quercus marilandica*

Common name	Scientific name
boxelder	*Acer negundo*
buckthorn	*Rhamnus* spp.
bur oak	*Quercus macrocarpa*
bush honeysuckles	*Lonicera* spp.
butternut	*Juglans cinerea*
cedar elm	*Ulmus crassifolia*
cherrybark oak	*Quercus pagoda*
chestnut oak	*Quercus prinus*
chinkapin oak	*Quercus muehlenbergii*
chokecherry	*Prunus virginiana*
common persimmon	*Diospyros virginiana*
eastern cottonwood	*Populus deltoides*
eastern hemlock	*Tsuga canadensis*
eastern hophornbeam (ironwood)	*Ostrya virginiana*
eastern redbud	*Cercis canadensis*
eastern redcedar	*Juniperus virginiana*
eastern white pine	*Pinus strobus*
flowering dogwood	*Cornus florida*
garlic mustard	*Alliaria petiolata*
gray birch	*Betula populifolia*
green ash	*Fraxinus pennsylvanica*
hackberry	*Celtis occidentalis*
highbush blueberry	*Vaccinium corymbosum*
honeylocust	*Gleditsia triacanthos*
jack pine	*Pinus banksiana*
Japanese barberry	*Berberis thunbergii*

(continued on next page)

Common name	Scientific name
Japanese knotweed	*Polygonum cuspidatum*
Japanese stiltgrass	*Microstegium vimineum*
kudzu	*Pueraria lobata*
lilac	*Syringa* spp.
loblolly pine	*Pinus taeda*
longleaf pine	*Pinus palustris*
mockernut hickory	*Carya alba*
morel mushroom	*Morchella* spp.
mountain maple	*Acer spicatum*
northern pin oak	*Quercus ellipsoidalis*
northern red oak	*Quercus rubra*
northern white-cedar	*Thuja occidentalis*
Ohio buckeye	*Aesculus glabra*
Osage-orange	*Maclura pomifera*
paper birch (white birch)	*Betula papyrifera*
pawpaw	*Asimina triloba*
pignut hickory	*Carya glabra*
pin cherry	*Prunus pensylvanica*
pin oak	*Quercus palustris*
pitch pine	*Pinus rigida*
pond pine	*Pinus serotina*
post oak	*Quercus stellata*
privet	*Ligustrum vulgare*
quaking aspen	*Populus tremuloides*
red maple	*Acer rubrum*
red mulberry	*Morus rubra*
red pine	*Pinus resinosa*
red spruce	*Picea rubens*
river birch	*Betula nigra*
rock elm	*Ulmus thomasii*
sand pine	*Pinus clausa*
sassafras	*Sassafras albidum*

Common name	Scientific name
scarlet oak	*Quercus coccinea*
scrub oak (bear oak)	*Quercus ilicifolia*
serviceberry	*Amelanchier* Medik.
shagbark hickory	*Carya ovata*
shellbark hickory	*Carya laciniosa*
shingle oak	*Quercus imbricaria*
shortleaf pine	*Pinus echinata*
Shumard oak	*Quercus shumardii*
silver maple	*Acer saccharinum*
slender yellow woodsorrel	*Oxalis dillenii*
slippery elm	*Ulmus rubra*
sourwood	*Oxydendrum arboreum*
southern red oak	*Quercus falcata* var. *falcata*
striped maple	*Acer pensylvanicum*
sugar maple	*Acer saccharum*
sugarberry	*Celtis laevigata*
swamp chestnut oak	*Quercus michauxii*
swamp white oak	*Quercus bicolor*
sweet birch	*Betula lenta*
sweetbay	*Magnolia virginiana*
sweetgum	*Liquidambar styraciflua*
sycamore	*Platanus occidentalis*
tamarack	*Larix laricina*
Virginia pine	*Pinus virginiana*
water oak	*Quercus nigra*
white ash	*Fraxinus americana*
white oak	*Quercus alba*
white spruce	*Picea glauca*
willow oak	*Quercus phellos*
winged elm	*Ulmus alata*
yellow birch	*Betula alleghaniensis*
yellow-poplar (tuliptree)	*Liriodendron tulipifera*

Animals

Common name	Scientific name
American woodcock	*Scolopax minor*
Asian longhorned beetle	*Anoplophora glabripennis*
balsam woolly adelgid	*Adelges piceaea*
big brown bat	*Eptesicus fuscus*
black bear	*Ursus americanas*
black-legged tick	*Ixodes scapularis*
blackpoll warbler	*Setophaga striata*
brook trout	*Salvalinus fontinalis*
coyote	*Canis latrans*
dwarf wedgemussel	*Alasmidonta heterodon*
eastern box turtle	*Terrapene carolina carolina*
eastern cottontail	*Sylvilagus floridanus*
eastern pearlshell	*Margaritifera margaritifera*
emerald ash borer	*Agrilus planipennis*
European earthworm	*Dendrobaena octaedra, Lumbricus rebellus,* and *L. terrestris*
grouse	family Tetraonidae (order Galliformes)
gypsy moth	*Lymantria dispar*
hemlock woolly adelgid	*Adelges tsugae*
hoary bat	*Lasiurus cinereus*
map turtle	*Graptemys geographica*
moose	*Alces alces*
mosquito	family *Culicidae*
mussel	order Bivalvia
Nashville warbler	*Vermivora ruficapilla*
New England cottontail	*Sylvilagus transitionalis*
northern flying squirrel	*Glaucomys sabrinus*
northern long-eared bat (northern myotis)	*Myotis septentrionalis*
rainbow trout (coast rainbow trout)	*Oncorhynchus mykiss*
ruffed grouse	*Bonasus umbellus*
smallmouth bass	*Micropterus dolomieu*
snowshoe hare	*Lepus americanus*

Common name	Scientific name
southern flying squirrel	*Glaucomys volans*
southern pine beetle	*Dendroctonus frontalis*
spruce budworm	*Choristoneura fumiferana*
white-tailed deer	*Odocoileus virginianus*
wild turkey	*Meleagris gallopavo*
winter moth	*Operophtera brumata*
winter tick (moose tick)	*Dermacentor albipictus*
wood duck	*Aix sponsa*
wood turtle	*Glyptemys insculpta*

Pathogens, Viruses, and Other Diseases

Common name	Scientific name
beechbark disease	A complex of the scale insect *Cryptococcus fagisuga* and the fungus *Neonectria* spp.
brainworm	*Parelaphostrongylus tenuis*
butternut canker	*Sirococcus clavigignenti-juglandacearum*
chestnut blight	*Cryphonectria parasitica*
Dutch elm disease	*Ophiostoma ulmi*
Lyme disease	*Borrelia burgdorferi*
red pine shoot blight	*Diplodia pinea* or *Sirococcus conigenus*
West Nile virus	*Flavivirus* spp.
white-nose syndrome	*Pseudogymnoascus destructans*

APPENDIX 2: HISTORICAL CLIMATE DATA AND TREND ANALYSIS

HISTORICAL CLIMATE DATA

To examine historical trends in precipitation and temperature for the assessment area, we used the Climate Wizard Custom Analysis application (Climate Wizard 2014, Girvetz et al. 2009). Data for Climate Wizard are derived from PRISM (Parameter-elevation Regressions on Independent Slopes Model) (Gibson et al. 2002). The PRISM model interpolates historical data from the National Weather Service cooperative stations, the Midwest Climate Data Center, and the Historical Climate Network, among others. Data undergo strict quality control procedures to check for errors in station measurements. The PRISM model finds linear relationships between these station measurements and local elevation by using a digital elevation model (digital gridded version of a topographic map). Temperature and precipitation are then derived for each pixel on a continuous 2.5-mile grid across the conterminous United States. The closer a station is to a grid cell of interest in distance and elevation, and the more similar it is in its proximity to coasts or topographic features, the higher the weight of the station observations on the final, predicted value for that cell. More information on PRISM can be found at: www.prism.oregonstate.edu.

BASELINE CLIMATE CONDITIONS: 1971 TO 2000

Temperature and precipitation data were used to derive annual, seasonal, and monthly values for the 30-year average (also referred to as the “climate normal”) for 1971 through 2000 (Table 15; Figs. 32, 33).

OBSERVED CHANGES: 1901 TO 2011

Linear trend analysis for 1901 through 2011 was performed 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 Fourth Assessment Report and are considered an effective way to identify 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.

The developers of the Climate Wizard application advise users to interpret the linear trend maps in relation to the respective map of statistical confidence (Figs. 34, 35). In this case, statistical confidence is described using *p*-values from a t-test applied to the linear regression. A *p*-value can be interpreted as the probability of the slope being different from zero by chance alone. For this assessment, *p*-values of less than 0.10 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 15.—Mean annual, seasonal, and monthly temperature and precipitation for the assessment area from 1971 through 2000 (data source: Climate Wizard [2014])

	Mean temperature (°F)	Mean minimum temperature (°F)	Mean maximum temperature (°F)	Mean precipitation (inches)
Winter	**20.1**	**10.0**	**30.2**	**10.1**
December	23.3	14.3	32.4	3.7
January	17.2	6.9	27.4	3.7
February	19.8	8.9	30.6	2.8
Spring	**41.3**	**30.3**	**52.4**	**11.1**
March	29.5	19.1	39.9	3.6
April	41.2	30.6	51.9	3.7
May	53.3	41.4	65.3	3.9
Summer	**64.9**	**53.5**	**76.3**	**11.9**
June	62.2	50.6	73.9	4.0
July	67.2	55.8	78.6	4.0
August	65.4	54.2	76.6	4.0
Fall	**46.1**	**36.2**	**56.1**	**12.0**
September	57.0	45.9	68.0	4.0
October	46.0	35.5	56.5	3.9
November	35.5	27.0	43.9	4.1
Annual	**43.1**	**32.5**	**53.7**	**45.2**

A mosaic of northern hardwood forest and farmland in northern Vermont. Photo by Todd Ontl, U.S. Forest Service.

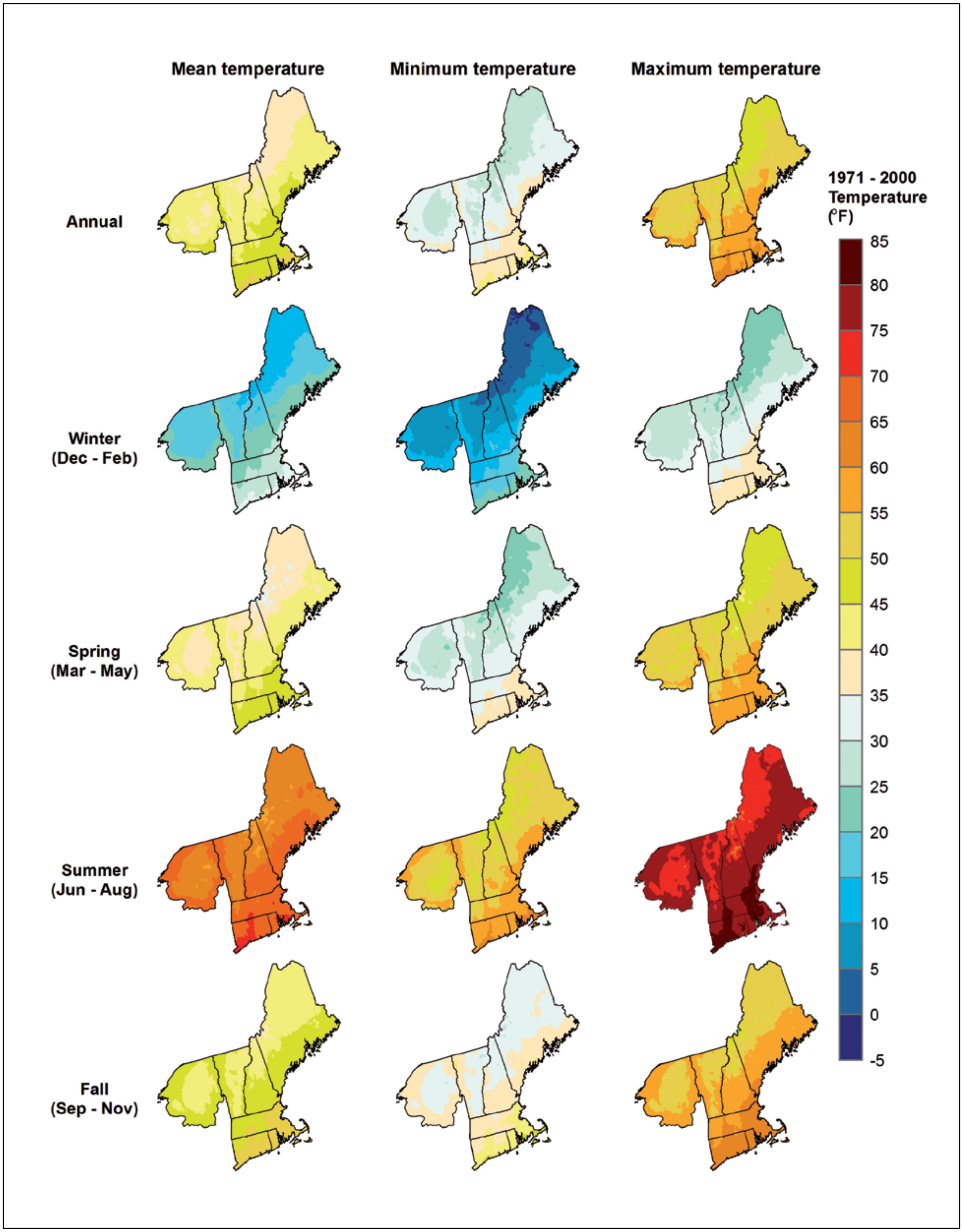

Figure 32.—Thirty-year annual and seasonal averages of mean, minimum, and maximum temperature across the assessment area, 1971 through 2000. Data source: Climate Wizard (2014).

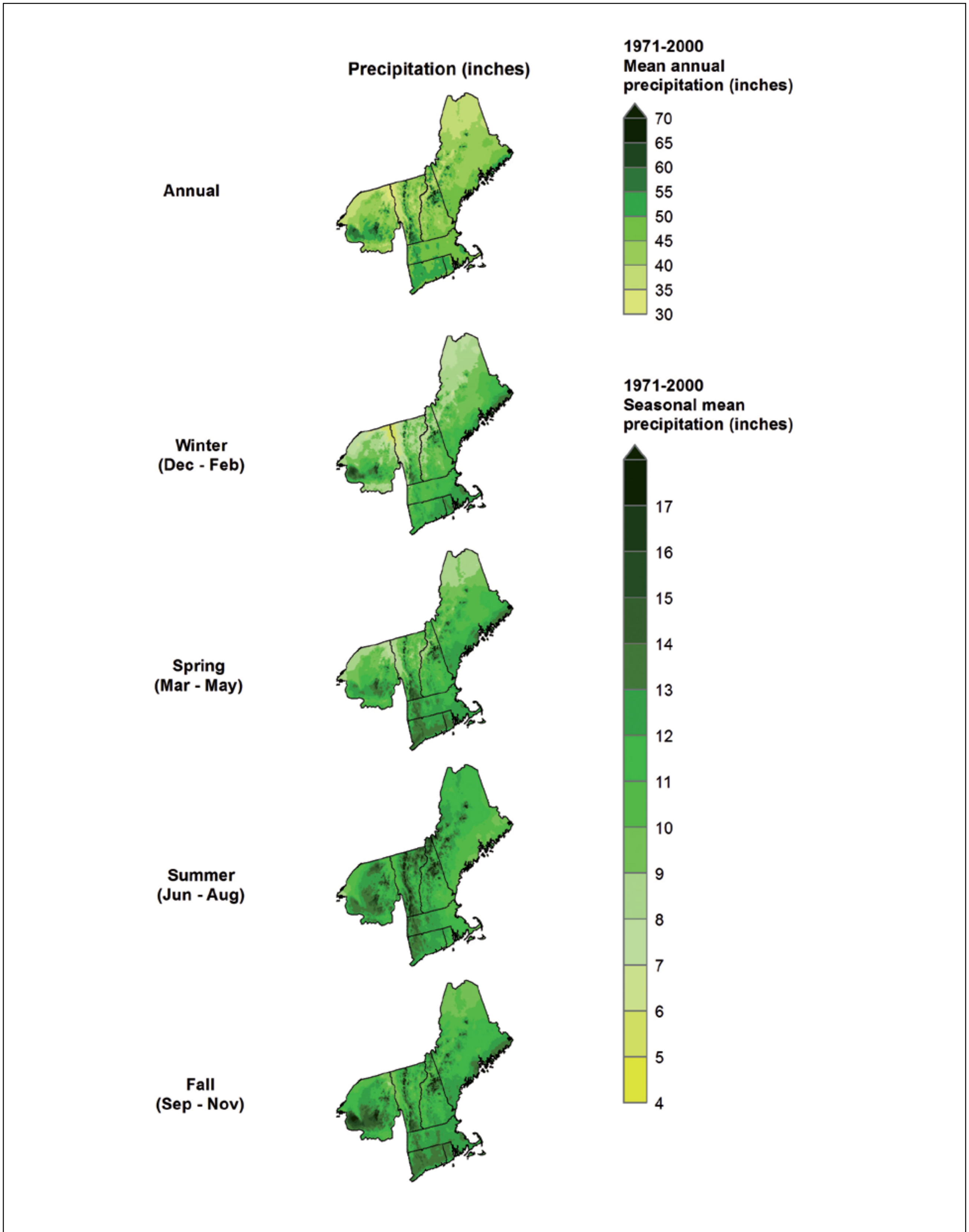

Figure 33.—Thirty-year averages of mean annual and seasonal precipitation across the assessment area. Data source: Climate Wizard (2014).

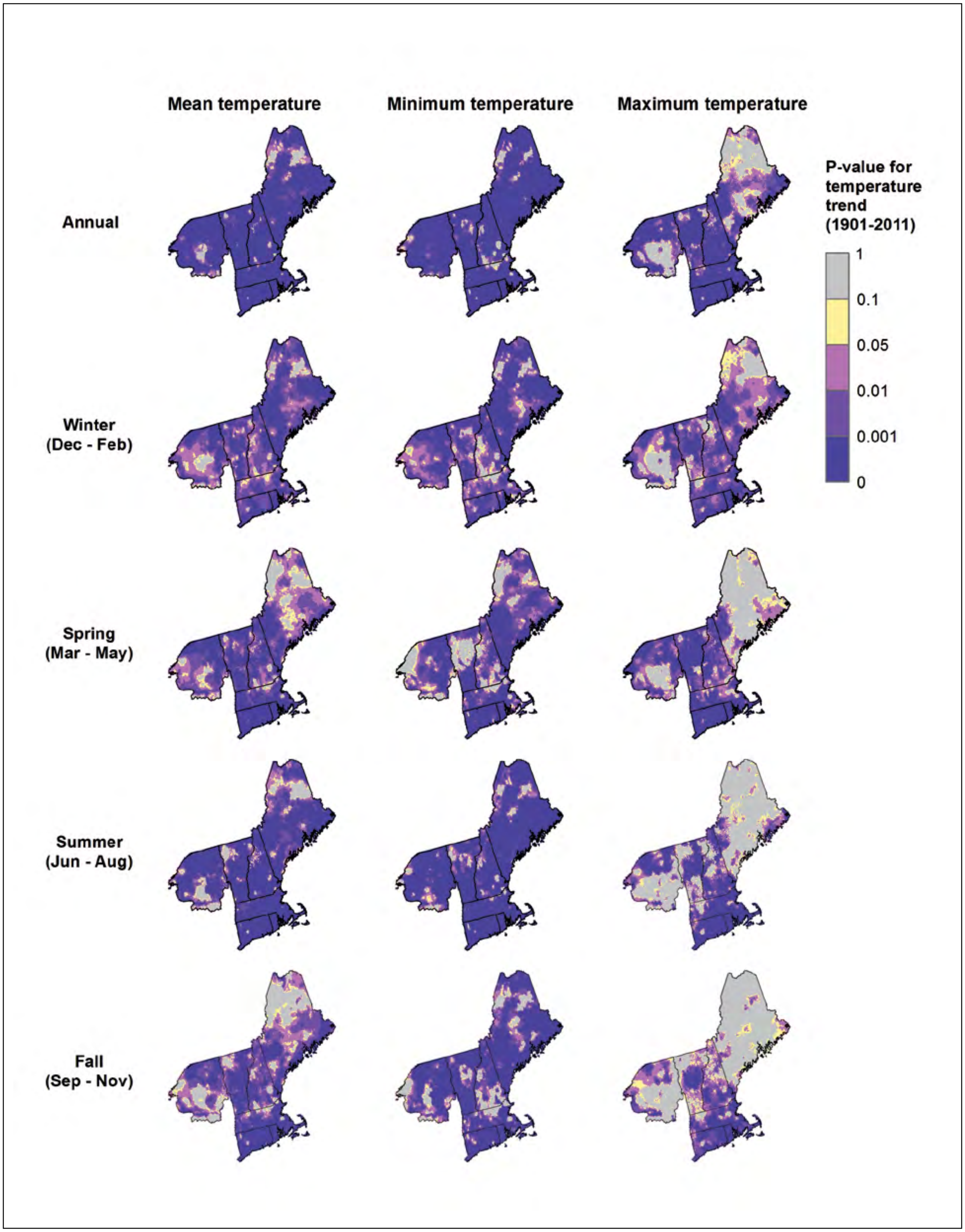

Figure 34.—Statistical confidence (*p*-values for the linear regression) for trends in temperature across the assessment area, 1901 through 2011. Gray values represent areas of low statistical confidence. Data source: Climate Wizard (2014).

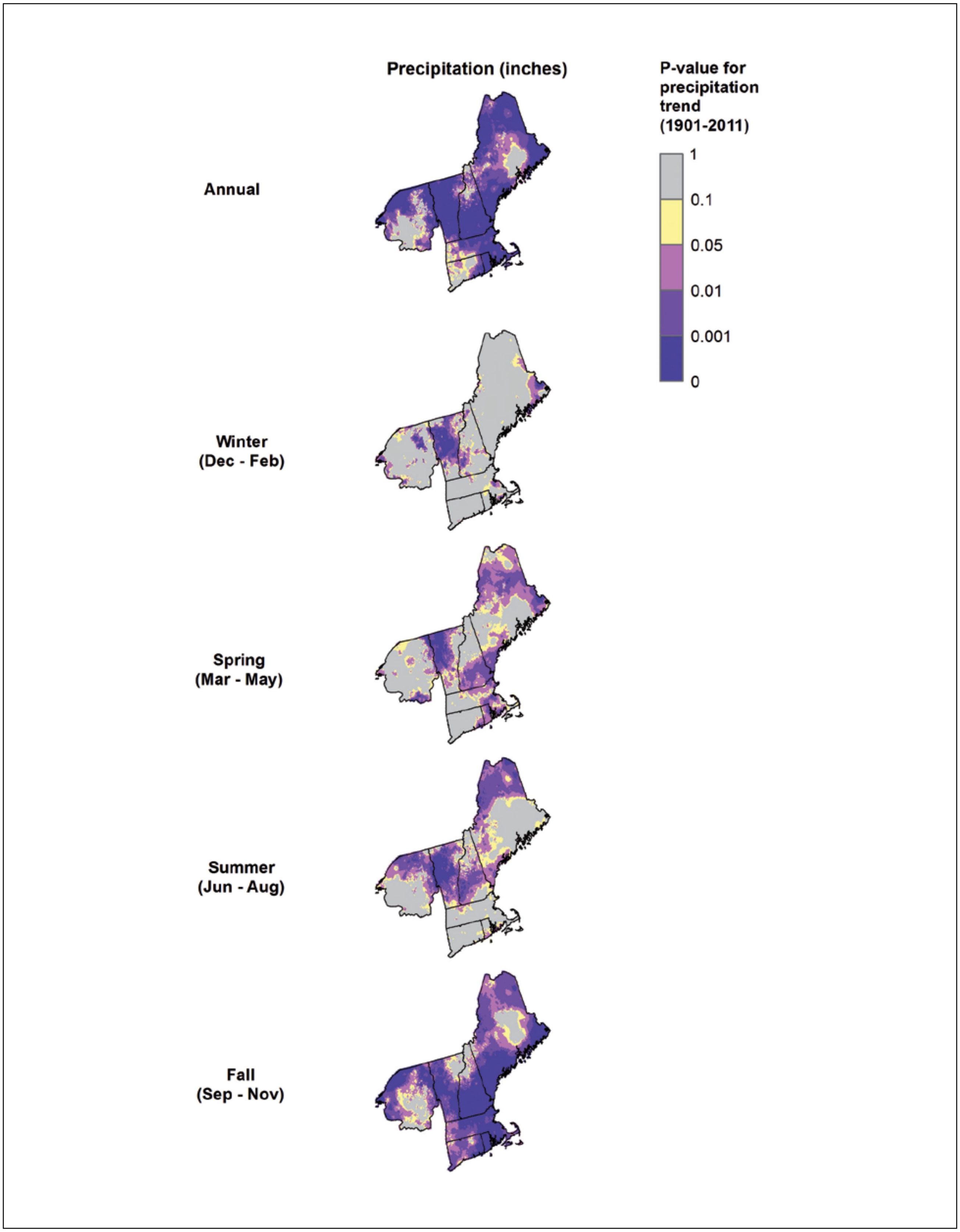

Figure 35.—Statistical confidence (*p*-values for the linear regression) for trends in precipitation across the assessment area, 1901 through 2011. Gray values represent areas of low statistical confidence. Data source: Climate Wizard (2014).

Because maps are developed from weather station observations that have been spatially interpolated, developers of the Climate Wizard tool and PRISM dataset 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). The comparison of a gridded PRISM dataset and another gridded climate product available in the Northeast showed localized biases in both products, signaling a need for caution when using these products (Beier et al. 2012, Bishop and Beier 2013). Several factors appear to contribute to the limitations of these products. Areas that have few weather stations lack data for interpolation and therefore have greater uncertainty. These issues are particularly pronounced at high elevations and in areas with complex topography, as well as along coasts (Beier et al. 2012). 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 certain location, it is best to refer to weather station data for the closest station in the Global Historical Climatology Network from the National Climatic Data Center (www.ncdc.noaa.gov/).

We selected the period 1901 through 2011 because it was sufficiently long to capture interdecadal and intradecadal variation in climate for the assessment area. 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.

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APPENDIX 3: ADDITIONAL CLIMATE PROJECTIONS

In this document, we primarily use statistically downscaled climate projections for two general circulation model (GCM)-emissions scenario combinations: GFDL A1FI and PCM B1. Both models and both scenarios were included in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (IPCC 2007). The latest version of the National Climate Assessment (in development) also draws on statistically downscaled data based on IPCC models and scenarios but uses the A2 scenario as an upper bound. The A2 scenario projects lower emissions compared to A1FI. The IPCC assessment includes about 20 other models, which are represented as a multi-model average in its reports. The National Climate Assessment takes a similar approach in using a multi-model average. For this assessment, we instead selected two models that had relatively good skill at simulating climate in the eastern United States and that bracketed a range of temperature and precipitation futures. This approach gives readers a better understanding of the range of projected changes in climate and provides a set of alternative scenarios that can be used by managers in planning and decisionmaking.

The National Oceanic and Atmospheric Administration's Geophysical Fluid Dynamics Laboratory model (GFDL) is considered moderately sensitive to changes in greenhouse gas concentrations (Delworth et al. 2006). In other words, any change in greenhouse gas concentration would lead to a change in temperature that is higher than some models and lower than others. The National Center for Atmospheric Research's Parallel Climate Model (PCM), in contrast, is considered to have low sensitivity to greenhouse gas concentrations (Washington et al. 2000). Together the GFDL A1FI and PCM B1 scenarios span a large range of possible futures. Although both projections are possible, the GFDL A1FI scenario is closer to current trends in greenhouse gas emissions (Raupach et al. 2007). It is important to note that actual emissions and temperature increases could be lower or higher than these projections.

This assessment relies on a statistically downscaled climate dataset (Hayhoe 2014). Daily mean, minimum, and maximum temperature and total daily precipitation were downscaled to an approximately 7.5-mile grid across the United States. This dataset uses a modified statistical asynchronous quantile regression method to downscale daily GCM output and historical climate data (Stoner et al. 2012). 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 et al. 2013). This is a different statistically downscaled dataset than used in the National Climate Assessment, which relies on a simpler “delta” approach (Kunkel et al. 2013). This dataset was chosen for several reasons. First, the dataset covers the entire United States, and thus allows a consistent dataset 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, Hayhoe et al. 2013). Third, the dataset includes daily values, which are needed for some impact models used in this report and provide the opportunity to examine questions related to growing season length, heavy precipitation events, and droughts. Fourth, the statistical technique used is more accurate at reproducing extreme values at daily time steps than simpler statistical downscaling methods (Hayhoe et al. 2013). Finally, the 7.5-mile resolution of the downscaled data is useful for informing land management decisions.

To show projected changes in temperature and precipitation, we calculated the average daily mean, minimum, and maximum temperature and mean precipitation for each month for three 30-year periods (2010 through 2039, 2040 through 2069, and 2070 through 2099). The use of 30-year periods reduces the influence of natural year-to-year variation that may bias calculations of change. The use of 30-year periods also allows for more direct comparison with the 1971 through 2000 historical data, highlighting longer-term trends over annual fluctuations. Monthly averages were used to calculate seasonal and annual values. We then subtracted the corresponding 1971 through 2000 average from these values to determine the departure from current climate conditions (Figs. 36 through 43, Tables 16, 17; Figs. 19, 20, 21, 23 in Chapter 3). Historical climate data used for the departure analysis were taken from Climate Wizard (Girvetz et al. 2009).

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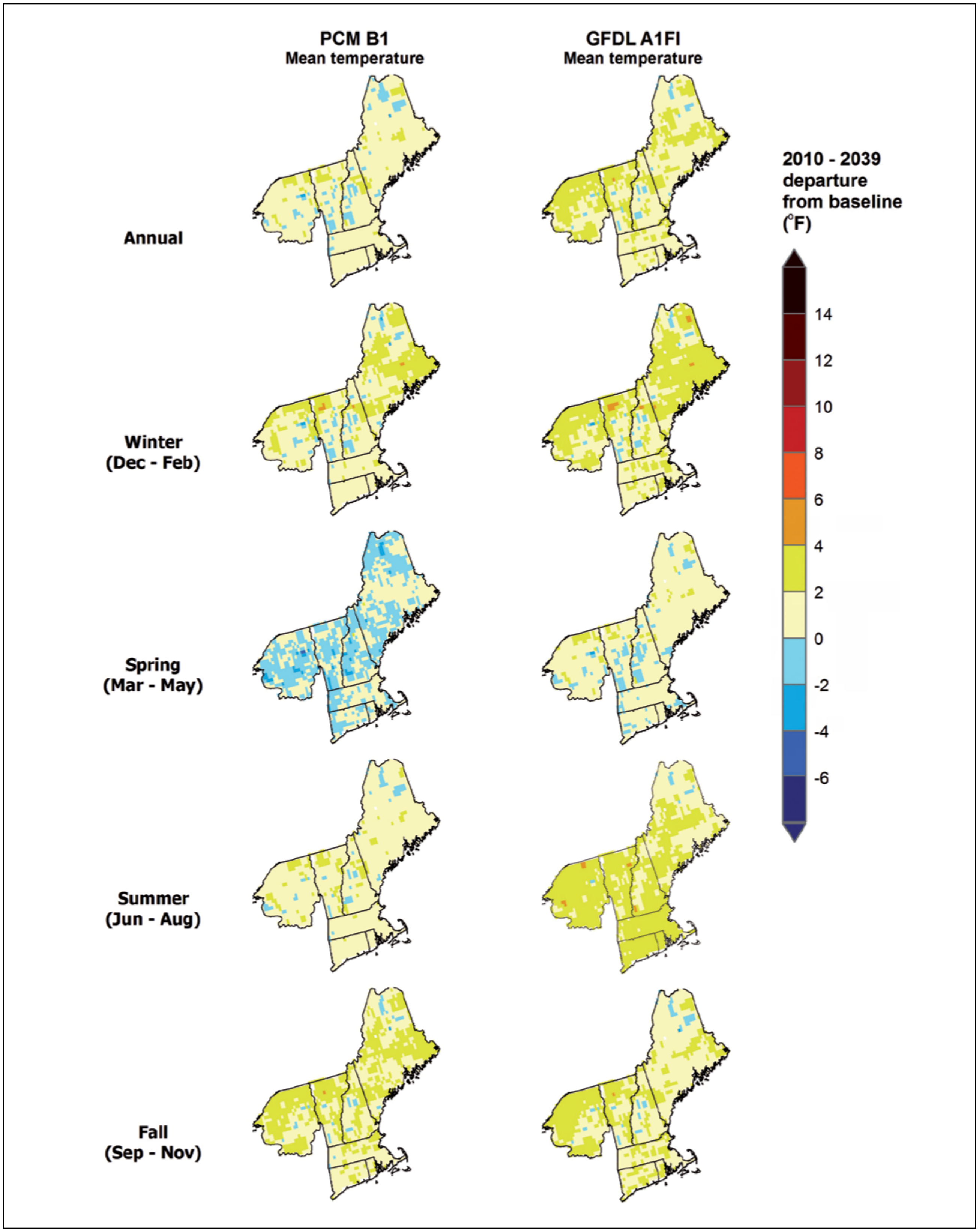

Figure 36.—Projected difference in mean daily mean temperature across the assessment area at the beginning of the century (2010 through 2039) compared to baseline (1971 through 2000) for two climate scenarios.

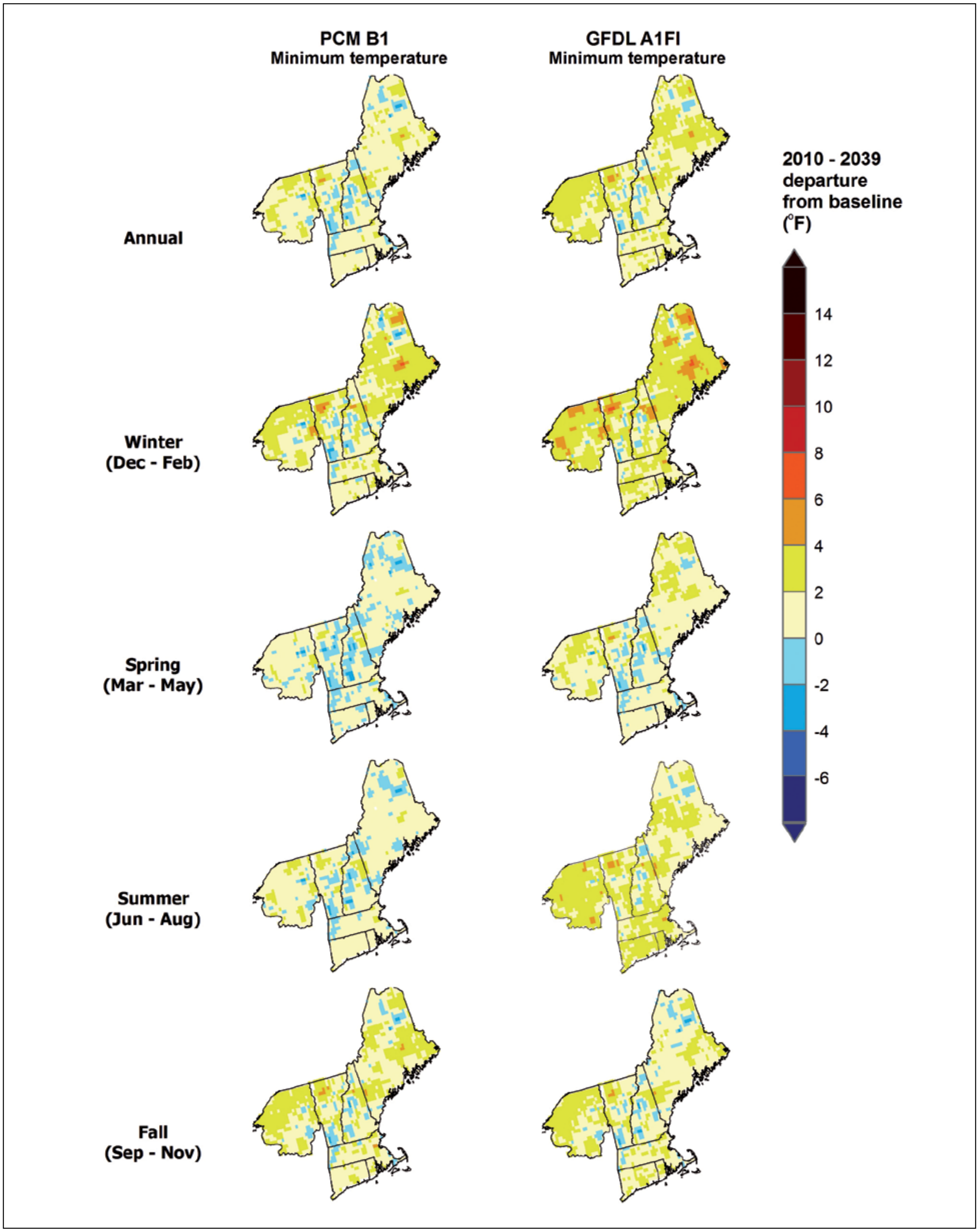

Figure 37.—Projected difference in mean daily minimum temperature across the assessment area at the beginning of the century (2010 through 2039) compared to baseline (1971 through 2000) for two climate scenarios.

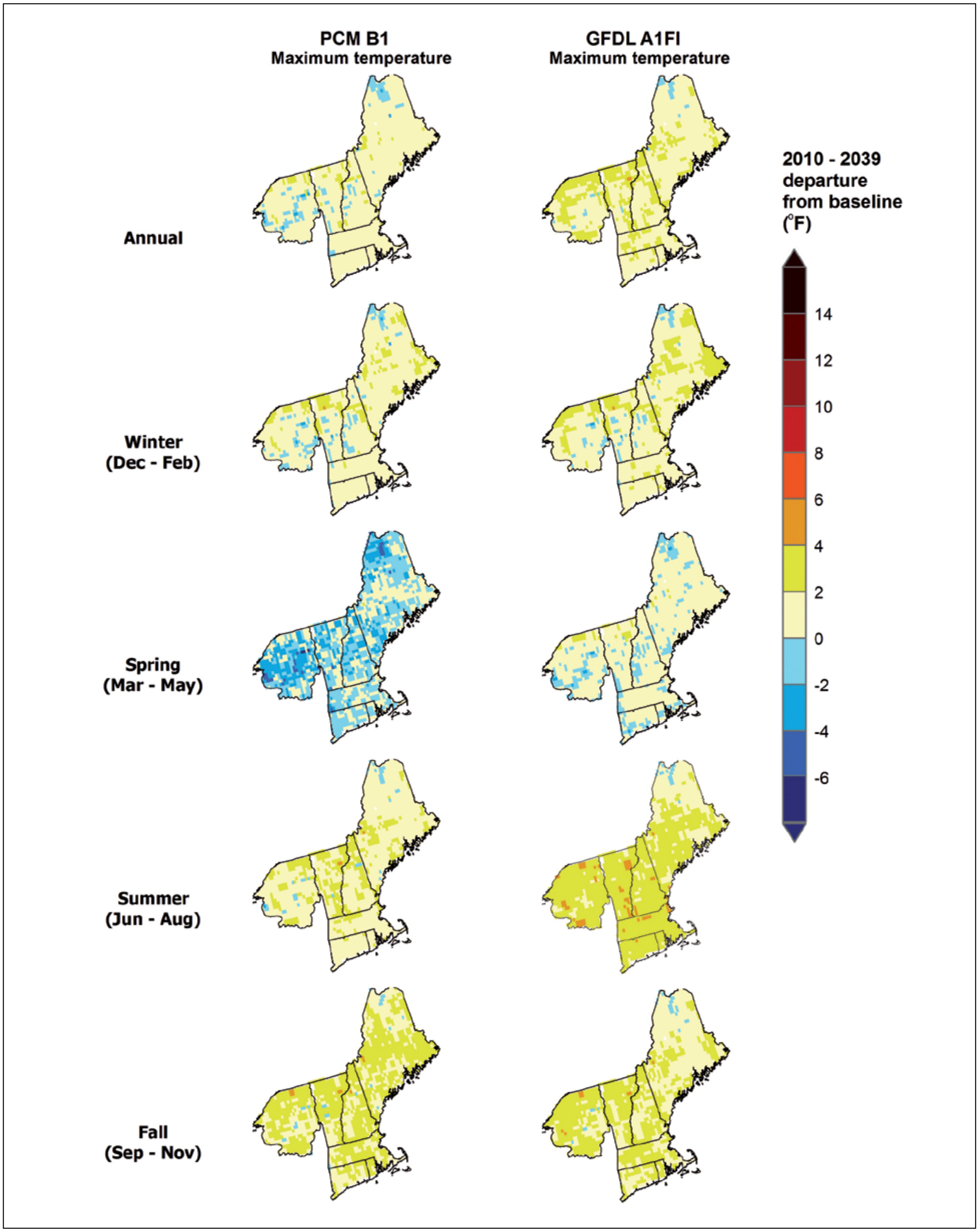

Figure 38.—Projected difference in mean daily maximum temperature across the assessment area at the beginning of the century (2010 through 2039) compared to baseline (1971 through 2000) for two climate scenarios.

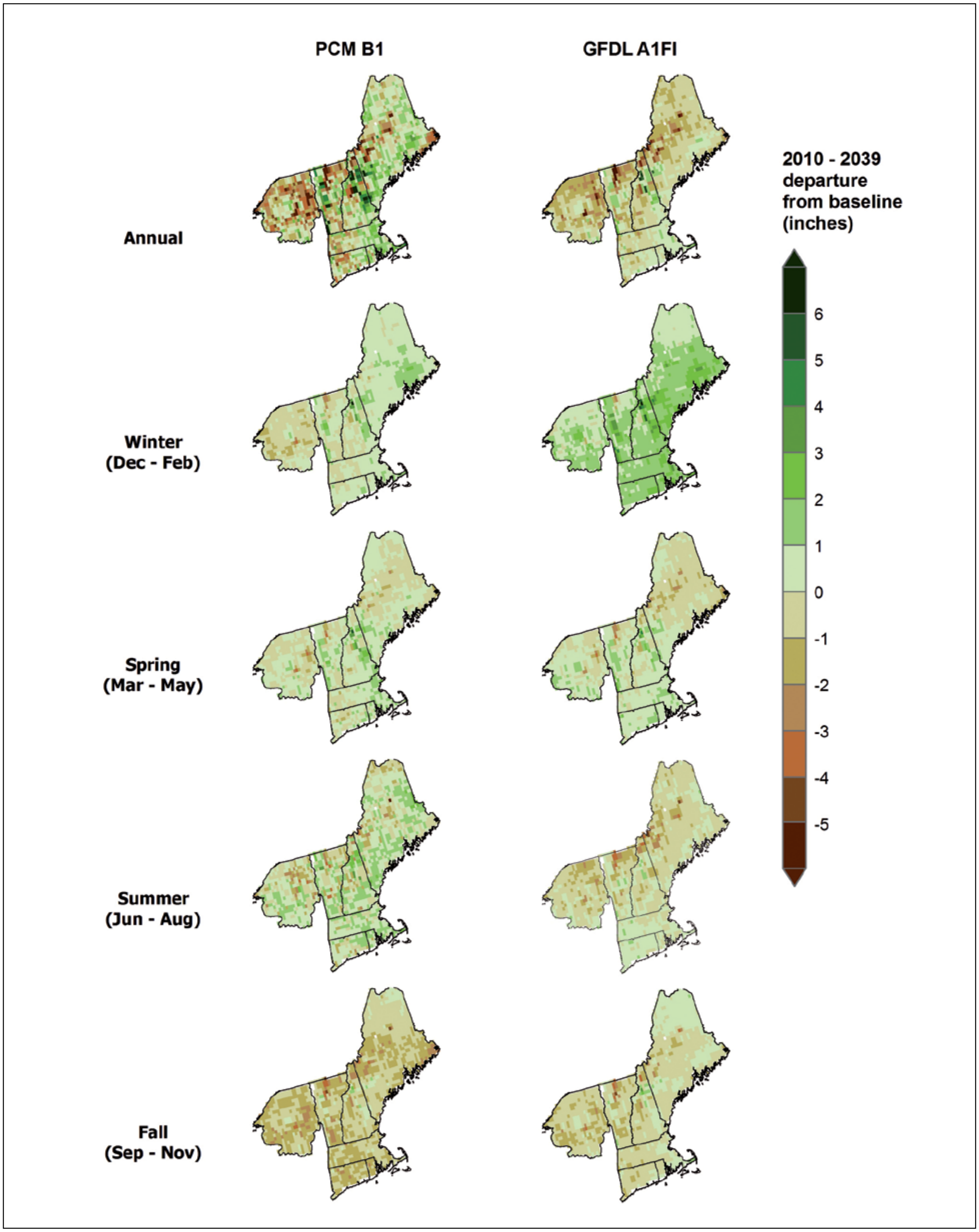

Figure 39.—Projected difference in precipitation across the assessment area at the beginning of the century (2010 through 2039) compared to baseline (1971 through 2000) for two climate scenarios.

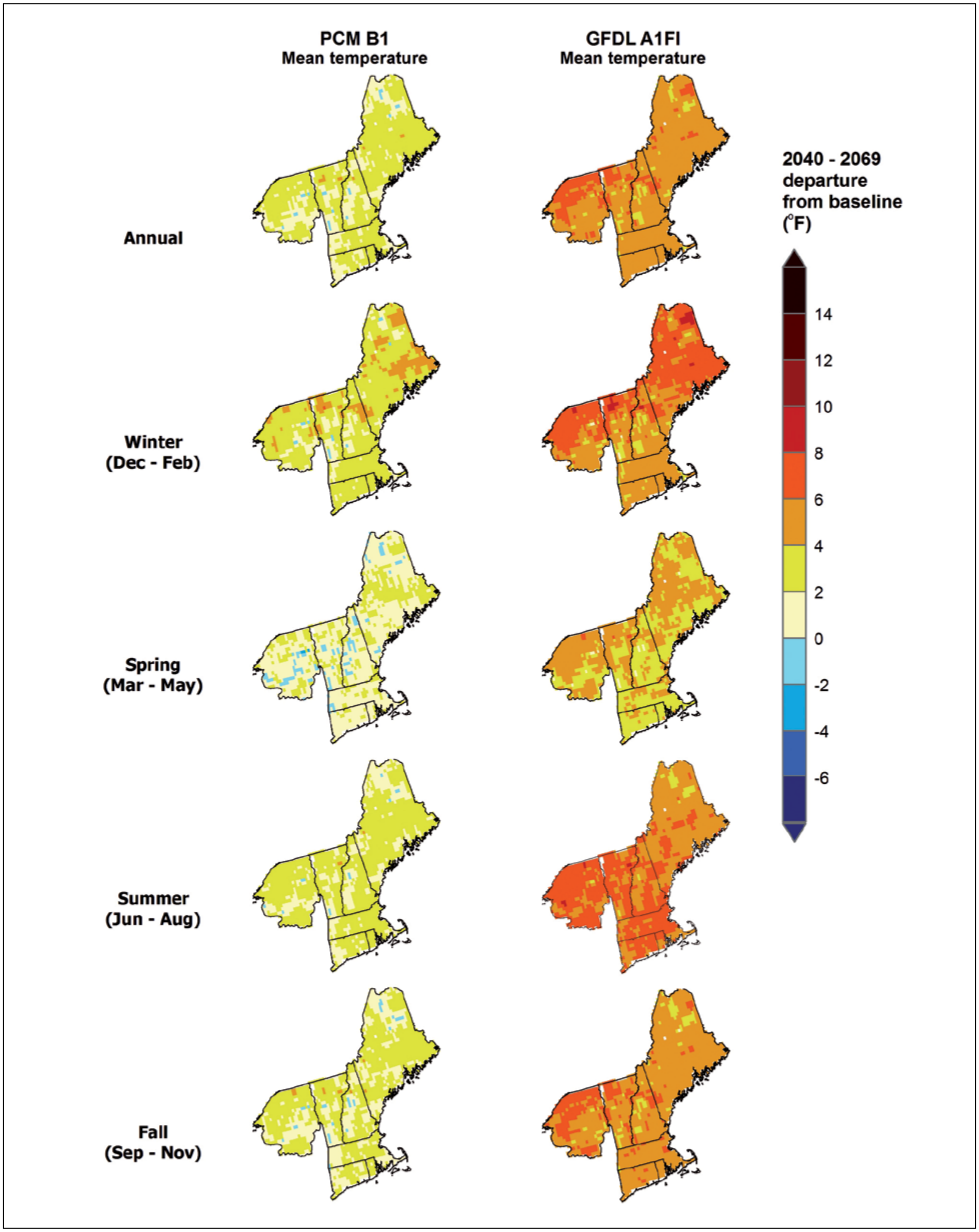

Figure 40.—Projected difference in mean daily mean temperature across the assessment area for the middle of the century (2040 through 2069) compared to baseline (1971 through 2000) for two climate scenarios.

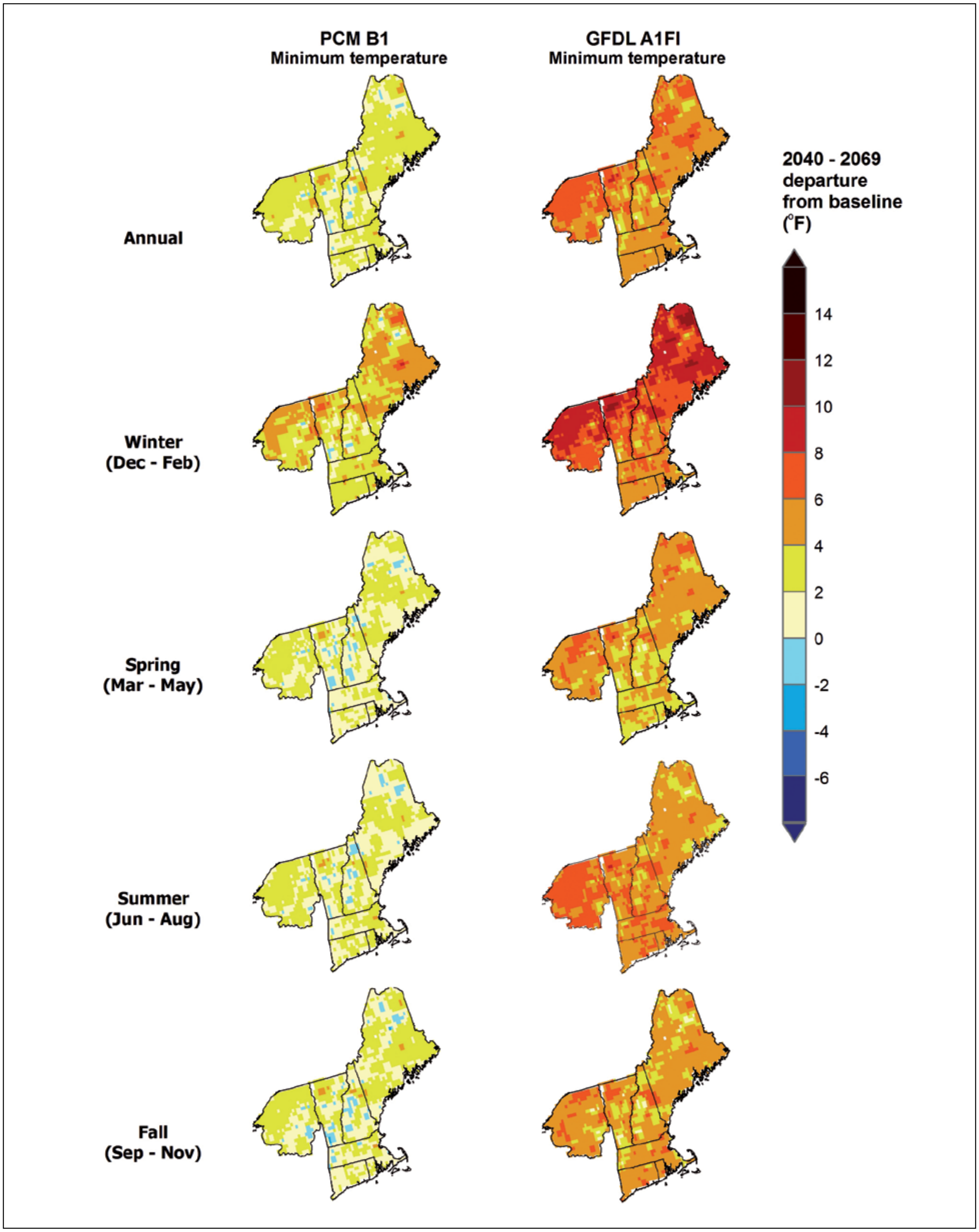

Figure 41.—Projected difference in mean daily minimum temperature across the assessment area for the middle of the century (2040 through 2069) compared to baseline (1971 through 2000) for two climate scenarios.

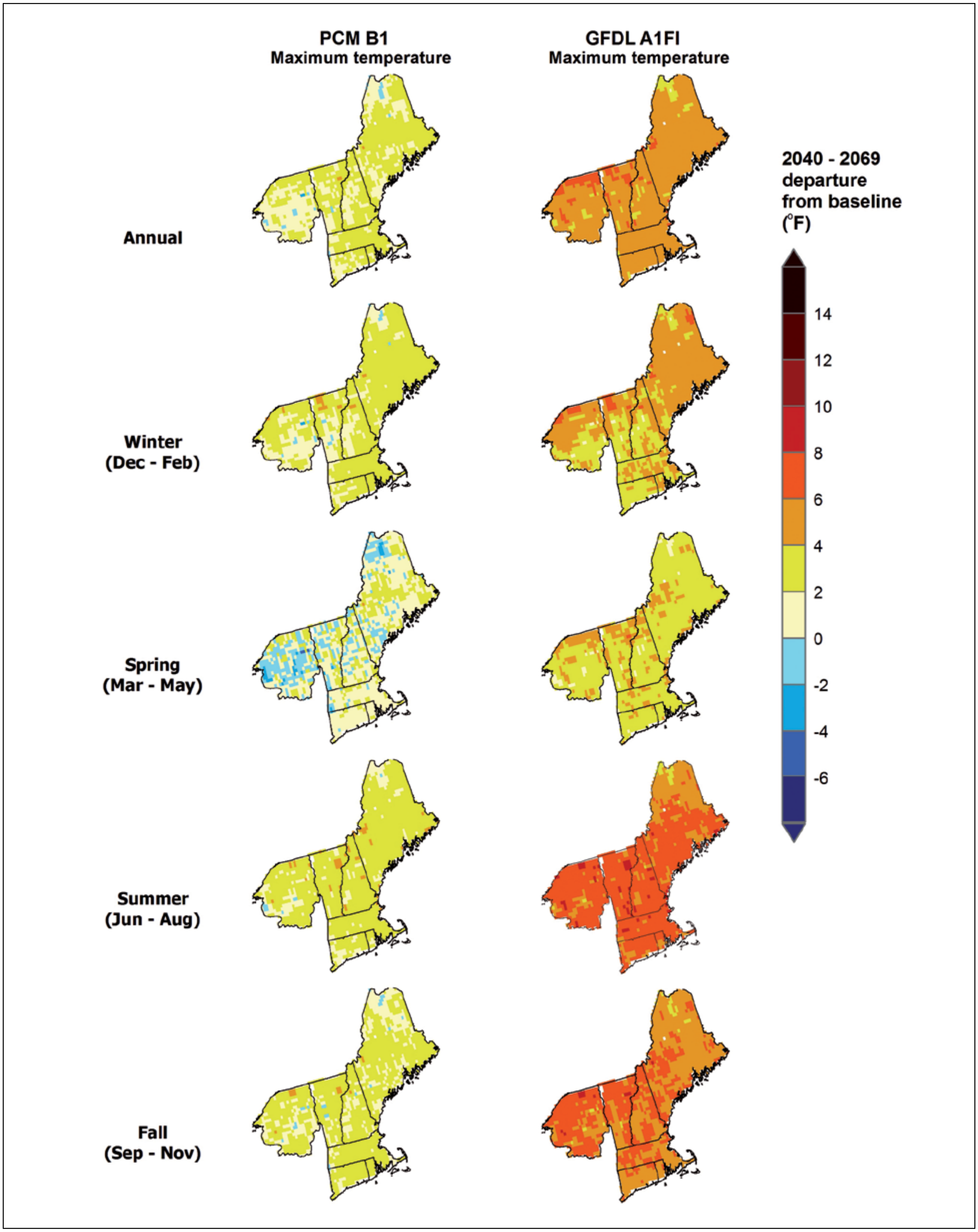

Figure 42.—Projected difference in mean daily maximum temperature across the assessment area for the middle of the century (2040 through 2069) compared to baseline (1971 through 2000) for two climate scenarios.

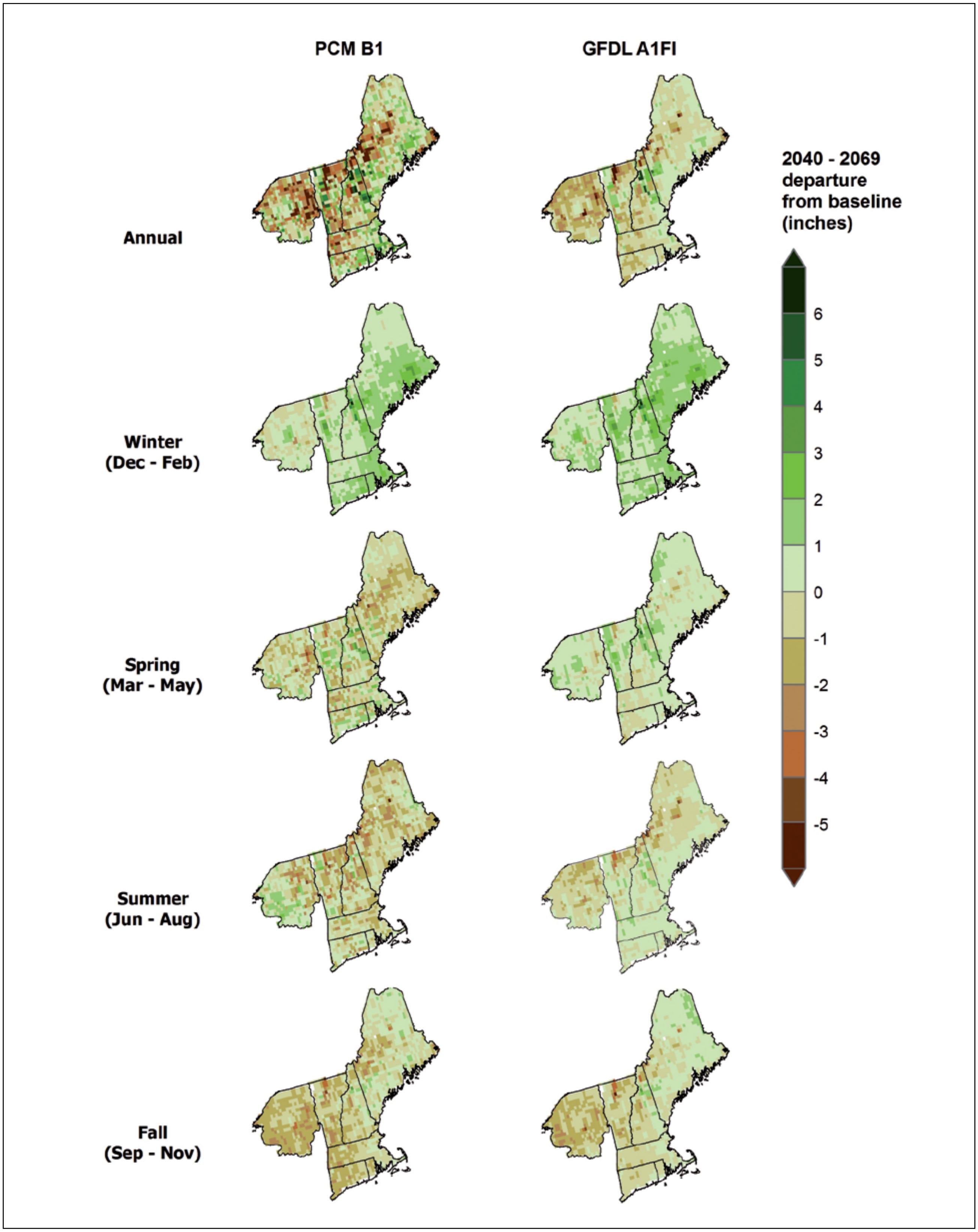

Figure 43.—Projected difference in precipitation across the assessment area for the middle of the century (2040 through 2069) compared to baseline (1971 through 2000) for two climate scenarios.

Table 16.—Projected change in mean daily mean, minimum, and maximum temperature under two future climate scenarios for the assessment area through the end of the century (°F)

		Baseline temperature (°F)	Temperature departure from baseline (°F)		
		1971-2000	2010-2039	2040-2069	2070-2099
Mean temperature					
Annual	PCM B1	42.8	1.1	2.2	2.6
	GFDL A1FI	42.8	1.8	5.3	7.6
Winter (Dec.-Feb.)	PCM B1	19.6	1.5	3.0	3.2
	GFDL A1FI	19.6	2.1	5.8	7.7
Spring (Mar.-May)	PCM B1	41.1	-0.1	1.5	1.9
	GFDL A1FI	41.1	0.9	4.1	6.1
Summer (June-Aug.)	PCM B1	64.8	1.2	2.3	2.6
	GFDL A1FI	64.8	2.3	5.9	8.3
Fall (Sept.-Nov.)	PCM B1	45.8	1.9	2.1	2.6
	GFDL A1FI	45.8	1.7	5.3	8.0
Minimum temperature					
Annual	PCM B1	32.1	1.2	2.3	2.7
	GFDL A1FI	32.1	1.8	5.5	8.0
Winter (Dec.-Feb.)	PCM B1	9.5	1.8	3.6	4.1
	GFDL A1FI	9.5	2.6	7.3	9.8
Spring (Mar.-May)	PCM B1	30.0	0.6	1.9	2.2
	GFDL A1FI	30.0	1.2	4.6	6.8
Summer (June-Aug.)	PCM B1	53.3	0.9	1.9	2.1
	GFDL A1FI	53.3	2.0	5.4	7.9
Fall (Sept.-Nov.)	PCM B1	35.8	1.6	2.0	2.5
	GFDL A1FI	35.8	1.5	4.7	7.5
Maximum temperature					
Annual	PCM B1	53.5	1.0	2.1	2.5
	GFDL A1FI	53.5	1.7	5.1	7.1
Winter (Dec.-Feb.)	PCM B1	29.8	1.2	2.4	2.5
	GFDL A1FI	29.8	1.5	4.4	5.7
Spring (Mar.-May)	PCM B1	52.2	-0.8	1.0	1.7
	GFDL A1FI	52.2	0.6	3.5	5.4
Summer (June-Aug.)	PCM B1	76.3	1.6	2.7	3.2
	GFDL A1FI	76.3	2.6	6.5	8.7
Fall (Sept.-Nov.)	PCM B1	55.9	2.1	2.3	2.8
	GFDL A1FI	55.9	2.0	5.9	8.6

Table 17.—Projected change in precipitation under two future climate scenarios for the assessment area through the end of the century

		Baseline precipitation (inches)	Precipitation departure from baseline (inches)		
		1971-2000	2010-2039	2040-2069	2070-2099
Annual	PCM B1	45.1	-0.2	-0.6	0.9
	GFDL A1FI	45.1	0.7	1.1	2.9
Winter (Dec.-Feb.)	PCM B1	10.0	0.3	0.8	0.8
	GFDL A1FI	10.0	1.3	1.2	2.3
Spring (Mar.-May)	PCM B1	11.1	0.2	-0.3	-0.1
	GFDL A1FI	11.1	0.1	0.4	1.0
Summer (June-Aug.)	PCM B1	12.0	0.3	-0.5	0.1
	GFDL A1FI	12.0	-0.3	-0.1	-1.8
Fall (Sept.-Nov.)	PCM B1	12.0	-0.9	-0.7	0.1
	GFDL A1FI	12.0	-0.4	-0.3	1.4

APPENDIX 4: SUPPLEMENTARY CLIMATE CHANGE TREE ATLAS RESULTS

This appendix contains additional model results and details from the Climate Change Tree Atlas, including the results of the DISTRIB model and additional modifying factors.

The DISTRIB model was used to simulate changes in suitable habitat during the 21st century for 102 tree species for this assessment, and model outputs for these species are provided in Table 18. More information about the modeling approach is available online through the Climate Change Tree Atlas Web site (www.nrs.fs.fed.us/atlas), 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).

For this assessment, current area-weighted importance values (IVs) were derived from U.S. Forest Service Forest Inventory and Analysis (FIA) data. Using the DISTRIB model, these were used to develop modeled current (1961-1990) IVs, as well as future IVs for three time periods (2010 through 2039, 2040 through 2069, 2070 through 2099) under the PCM B1 and GFDL A1FI climate scenarios. Across the eastern United States, 134 tree species were initially modeled. If a species never had an area-weighted IV greater than 3 (FIA, current modeled, or future) across the assessment area, it was deleted from the list because the species has either no current or no future suitable habitat in the region, or there were not enough data. This step resulted in the list of 102 tree species for which data are shown.

A set of rules was established to determine change classes for 2070 through 2099, which was used to create tables in Chapter 4. For most species, the following rules applied, based on the ratio of future IVs to current modeled IVs:

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

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

Special rules were created for rare species. A species was considered rare if it had a current modeled area-weighted IV that equaled less than 10 percent of the number of 12.5-mile by 12.5-mile pixels in the assessment area. The change classes are calculated differently for these species because their current infrequency tends to inflate the projected percentage change. The cutoff for the assessment area was 66 pixels, or 10 percent of the total number of pixels (657).

When a species was below the cutoff, “extirpated” was not used in this case due to low confidence, and the following rules applied:

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

Table 18.—Complete Climate Change Tree Atlas results for the 102 tree species in the assessment area

	Current IV			DISTRIB Results[a]													
				Modeled IV						Future:Current suitable habitat						Change class	
				2010-2039		2040-2069		2070-2099		2010-2039		2040-2069		2070-2099		2070-2090	
Common name	FIA	Modeled	Model reliability	PCM B1	GFDL A1FI	PCM B1	GFDL A1FI	PCM B1	GFDL A1FI	PCM B1	GFDL A1FI	PCM B1	GFDL A1FI	PCM B1	GFDL A1FI	PCM B1	GFDL A1FI
American basswood	255	311	Medium	254	413	287	529	301	637	0.82	1.33	0.92	1.70	0.97	2.05	No change	Large increase
American beech	3543	3659	High	3670	3333	3554	2609	3513	2086	1.00	0.91	0.97	0.71	0.96	0.57	No change	Small decrease
American chestnut	27	9	Medium	15	12	15	8	16	7	1.67	1.33	1.67	0.89	1.78	0.78	No change	No change
American elm	581	662	Medium	657	942	724	1344	823	1662	0.99	1.42	1.09	2.03	1.24	2.51	Small increase	Large increase
American holly	7	4	High	5	8	5	40	5	55	1.25	2.00	1.25	10.00	1.25	13.75	No change	Large increase
American hornbeam	188	248	Medium	250	286	273	470	291	546	1.01	1.15	1.10	1.90	1.17	2.20	No change	Large increase
American mountain-ash	77	33	Medium	43	22	28	5	21	2	1.30	0.67	0.85	0.15	0.64	0.06	No change	Large decrease
Atlantic white-cedar	31	36	Low	35	34	33	29	35	28	0.97	0.94	0.92	0.81	0.97	0.78	No change	No change
Bald cypress	0	24	Medium	25	40	24	53	41	91	1.04	1.67	1.00	2.21	1.71	3.79	New habitat	New habitat
Balsam fir	5334	5255	High	4501	3445	3713	1457	3313	1175	0.86	0.66	0.71	0.28	0.63	0.22	Small decrease	Large decrease
Balsam poplar	131	125	High	82	73	68	33	73	39	0.66	0.58	0.54	0.26	0.58	0.31	Small decrease	Large decrease
Bigtooth aspen	507	613	High	550	628	589	562	606	461	0.90	1.02	0.96	0.92	0.99	0.75	No change	Small decrease
Bitternut hickory	46	21	Low	36	116	36	280	54	420	1.71	5.52	1.71	13.33	2.57	20.00	No change	Large increase
Black ash	313	436	High	298	394	290	322	296	297	0.68	0.90	0.67	0.74	0.68	0.68	Small decrease	Small decrease
Black cherry	1355	1561	High	1630	1889	1752	2160	1807	2175	1.04	1.21	1.12	1.38	1.16	1.39	No change	Small increase
Black hickory	0	0	High	0	6	0	188	0	588	0.00	New	0.00	New	0.00	New	—	New habitat
Black locust	40	79	Low	101	234	143	508	182	768	1.28	2.96	1.81	6.43	2.30	9.72	Large increase	Large increase
Black maple	5	1	Low	1	1	1	1	1	0	1.00	1.00	1.00	1.00	1.00	0.00	No change	Small decrease
Black oak	473	563	High	654	964	803	1627	900	2059	1.16	1.71	1.43	2.89	1.60	3.66	Small increase	Large increase
Black spruce	475	537	High	345	294	266	30	222	5	0.64	0.55	0.50	0.06	0.41	0.01	Large decrease	Large decrease
Black walnut	9	31	Medium	40	204	99	587	138	801	1.29	6.58	3.19	18.94	4.45	25.84	Small increase	Large increase
Black willow	124	136	Low	135	243	153	448	181	623	0.99	1.79	1.13	3.29	1.33	4.58	Small increase	Large increase
Blackgum	37	62	High	107	130	139	336	165	500	1.73	2.10	2.24	5.42	2.66	8.07	No change	Large increase
Blackjack oak**	0	2	Medium	1	7	2	122	3	413	0.50	3.50	1.00	61.00	1.50	206.50	—	New habitat
Boxelder	49	99	Medium	77	235	84	350	104	543	0.78	2.37	0.85	3.54	1.05	5.49	No change	Large increase
Bur oak	12	32	Medium	13	100	14	217	21	397	0.41	3.13	0.44	6.78	0.66	12.41	No change	Large increase
Butternut	81	40	Low	50	50	46	32	48	21	1.25	1.25	1.15	0.80	1.20	0.53	No change	Small decrease
Cedar elm	0	1	Low	0	0	0	0	0	49	0.00	0.00	0.00	0.00	0.00	49.00	—	New habitat
Cherrybark oak	0	2	Medium	7	8	6	10	7	42	3.50	4.00	3.00	5.00	3.50	21.00	New habitat	New habitat
Chestnut oak	91	191	High	240	287	323	740	351	964	1.26	1.50	1.69	3.87	1.84	5.05	Small increase	Large increase
Chinkapin oak**	0	2	Medium	1	5	2	127	1	280	0.50	2.50	1.00	63.50	0.50	140.00	—	New habitat
Chokecherry	214	181	Low	174	170	167	88	180	65	0.96	0.94	0.92	0.49	0.99	0.36	No change	Large decrease
Common persimmon	0	0	Medium	0	48	1	338	8	797	0.00	New	—	New	New	New	New habitat	New habitat
Eastern cottonwood	51	78	Low	64	259	80	682	119	1057	0.82	3.32	1.03	8.74	1.53	13.55	Small increase	Large increase
Eastern hemlock	2804	2810	High	2891	2877	2909	2503	2957	2136	1.03	1.02	1.04	0.89	1.05	0.76	No change	Small decrease
Eastern hophornbeam	679	738	Medium	666	762	706	887	740	1053	0.90	1.03	0.96	1.20	1.00	1.43	No change	Small increase
Eastern redbud	1	1	Medium	1	31	14	302	24	615	1.00	31.00	14.00	302.00	24.00	615.00	Small increase	Small increase
Eastern redcedar	93	150	Medium	227	562	317	1593	399	2371	1.51	3.75	2.11	10.62	2.66	15.81	Large increase	Large increase
Eastern white pine	3608	3525	High	3303	3092	3273	2613	3254	2448	0.94	0.88	0.93	0.74	0.92	0.69	No change	Small decrease
Flowering dogwood	49	71	High	133	307	219	941	275	1372	1.87	4.32	3.09	13.25	3.87	19.32	Large increase	Large increase
Gray birch	649	603	Medium	584	566	555	483	555	475	0.97	0.94	0.92	0.80	0.92	0.79	No change	Small decrease
Green ash	70	108	Medium	75	101	79	142	96	300	0.69	0.94	0.73	1.32	0.89	2.78	No change	Large increase
Hackberry	4	16	Medium	9	166	19	614	43	952	0.56	10.38	1.19	38.38	2.69	59.50	No change	Large increase
Honeylocust	5	9	Low	9	107	12	449	20	742	1.00	11.89	1.33	49.89	2.22	82.44	No change	Large increase
Jack pine	14	111	High	37	136	41	142	50	163	0.33	1.23	0.37	1.28	0.45	1.47	Small decrease	Small increase
Loblolly pine	0	37	High	50	90	55	141	104	499	1.35	2.43	1.49	3.81	2.81	13.49	New habitat	New habitat
Longleaf pine	0	12	High	9	7	19	8	24	10	0.75	0.58	1.58	0.67	2.00	0.83	New habitat	—
Mockernut hickory	41	74	High	68	107	105	340	116	520	0.92	1.45	1.42	4.60	1.57	7.03	Small increase	Large increase
Mountain maple	294	281	High	223	188	176	38	153	18	0.79	0.67	0.63	0.14	0.54	0.06	Small decrease	Large decrease
Northern pin oak	3	13	Medium	2	58	5	45	6	60	0.15	4.46	0.39	3.46	0.46	4.62	No change	Small increase
Northern red oak	1618	1715	High	1961	2255	2127	2671	2267	2656	1.14	1.32	1.24	1.56	1.32	1.55	Small increase	Small increase
Northern white-cedar	1641	1726	High	1222	1193	1031	651	948	574	0.71	0.69	0.60	0.38	0.55	0.33	Small decrease	Large decrease
Ohio buckeye	1	0	Low	0	6	0	14	4	17	0.00	6.00	0.00	14.00	4.00	17.00	Small increase	Small increase
Osage-orange	0	8	Medium	8	15	7	59	9	94	1.00	1.88	0.88	7.38	1.13	11.75	—	New habitat
Paper birch	1902	1933	High	1653	1601	1469	773	1402	435	0.86	0.83	0.76	0.40	0.73	0.23	Small decrease	Large decrease
Pawpaw**	0	1	Low	2	20	15	72	14	169	2.00	20.00	15.00	72.00	14.00	169.00	New habitat	New habitat
Pignut hickory	170	217	High	251	351	308	731	349	981	1.16	1.62	1.42	3.37	1.61	4.52	Small increase	Large increase

(continued on next page)

Table 18 (continued).—Complete Climate Change Tree Atlas results for the 102 tree species in the assessment area

	Current IV			DISTRIB Results[a] Modeled IV						Future:Current suitable habitat						Change class	
				2010-2039		2040-2069		2070-2099		2010-2039		2040-2069		2070-2099		2070-2090	
Common name	FIA	Modeled	Model reliability	PCM B1	GFDL A1FI	PCM B1	GFDL A1FI	PCM B1	GFDL A1FI	PCM B1	GFDL A1FI	PCM B1	GFDL A1FI	PCM B1	GFDL A1FI	PCM B1	GFDL A1FI
Pin cherry	383	397	Medium	343	349	327	286	335	235	0.86	0.88	0.82	0.72	0.84	0.59	No change	Small decrease
Pin oak	3	12	Medium	16	80	31	241	55	346	1.33	6.67	2.58	20.08	4.58	28.83	Small increase	Large increase
Pitch pine	168	144	High	157	166	162	163	168	191	1.09	1.15	1.13	1.13	1.17	1.33	No change	Small increase
Pond pine	0	3	High	5	7	4	4	6	14	1.67	2.33	1.33	1.33	2.00	4.67	New habitat	New habitat
Post oak	1	2	High	1	45	10	624	15	1787	0.50	22.50	5.00	312.00	7.50	893.50	Small increase	Small increase
Quaking aspen	1278	1488	High	1249	1419	1249	967	1267	699	0.84	0.95	0.84	0.65	0.85	0.47	No change	Large decrease
Red maple	7631	7772	High	8003	7573	8121	6921	8126	5899	1.03	0.97	1.05	0.89	1.05	0.76	No change	Small decrease
Red mulberry	7	6		8	217	23	781	49	1163	1.33	36.17	3.83	130.17	8.17	193.83	Large increase	Large increase
Red pine	221	315	Medium	262	381	286	558	325	656	0.83	1.21	0.91	1.77	1.03	2.08	No change	Large increase
Red spruce	2750	2651	Low	2327	1606	1809	945	1692	915	0.88	0.61	0.68	0.36	0.64	0.35	Small decrease	Large decrease
River birch	1	7	Low	3	16	2	5	3	16	0.43	2.29	0.29	0.71	0.43	2.29	—	No change
Rock elm	0	0	Low	0	1	0	4	1	22	0.00	—	0.00	New	—	New	—	New habitat
Sand pine	0	11	Medium	27	24	21	27	23	32	2.46	2.18	1.91	2.46	2.09	2.91	New habitat	New habitat
Sassafras	56	103	High	143	208	208	569	236	880	1.39	2.02	2.02	5.52	2.29	8.54	Large increase	Large increase
Scarlet oak	217	208	High	300	345	351	634	377	846	1.44	1.66	1.69	3.05	1.81	4.07	Small increase	Large increase
Scrub oak	6	14	Low	10	14	12	17	13	16	0.71	1.00	0.86	1.21	0.93	1.14	No change	No change
Serviceberry	320	302	Medium	303	361	347	387	352	370	1.00	1.20	1.15	1.28	1.17	1.23	No change	Small increase
Shagbark hickory	110	128	Medium	158	274	195	511	225	651	1.23	2.14	1.52	3.99	1.76	5.09	Small increase	Large increase
Shellbark hickory	8	1	Low	2	9	2	87	3	161	2.00	9.00	2.00	87.00	3.00	161.00	No change	Small increase
Shingle oak	0	1	Medium	0	25	1	167	2	289	0.00	25.00	1.00	167.00	2.00	289.00	—	New habitat
Shortleaf pine**	0	5	High	4	8	16	107	14	384	0.80	1.60	3.20	21.40	2.80	76.80	New habitat	New habitat
Shumard oak	0	0	Low	0	0	0	0	0	23	0.00	0.00	0.00	0.00	0.00	New	—	New habitat
Silver maple	135	184	Medium	152	493	208	986	280	1372	0.83	2.68	1.13	5.36	1.52	7.46	Small increase	Large increase
Slippery elm	52	70	Medium	71	213	100	472	132	649	1.01	3.04	1.43	6.74	1.89	9.27	Small increase	Large increase
Sourwood	1	1	High	8	4	10	5	24	29	8.00	4.00	10.00	5.00	24.00	29.00	Small increase	Small increase
Southern red oak	0	0	High	3	3	11	82	11	261	New	New	New	New	New	New	New habitat	New habitat
Striped maple	1084	1056	High	1017	860	929	589	892	475	0.96	0.81	0.88	0.56	0.85	0.45	No change	Large decrease
Sugar maple	4620	4825	High	4768	4563	4624	3958	4628	3628	0.99	0.95	0.96	0.82	0.96	0.75	No change	Small decrease
Sugarberry	0	13	Medium	5	11	6	63	10	255	0.39	0.85	0.46	4.85	0.77	19.62	—	New habitat
Swamp chestnut oak	1	0	Medium	1	0	0	0	2	18	1.00	0.00	0.00	0.00	2.00	18.00	No change	Small increase
Swamp white oak	25	18	Low	21	39	24	74	29	115	1.17	2.17	1.33	4.11	1.61	6.39	No change	Small increase
Sweet birch	611	662	High	819	785	933	1073	957	1052	1.24	1.19	1.41	1.62	1.45	1.59	Small increase	Small increase
Sweetbay**	0	7	High	1	2	4	1	11	1	0.14	0.29	0.57	0.14	1.57	0.14	New habitat	—
Sweetgum**	0	32	High	91	182	115	422	198	938	2.84	5.69	3.59	13.19	6.19	29.31	New habitat	New habitat
Sycamore	9	13	Medium	16	41	24	210	37	360	1.23	3.15	1.85	16.15	2.85	27.69	No change	Large increase
Tamarack (native)	256	259	High	214	210	183	178	160	161	0.83	0.81	0.71	0.69	0.62	0.62	Small decrease	Small decrease
Virginia pine	0	13	High	27	17	41	109	44	246	2.08	1.31	3.15	8.39	3.39	18.92	New habitat	New habitat
Water oak	0	0	High	0	0	0	2	0	31	0.00	0.00	0.00	—	0.00	New	—	New habitat
White ash	2077	2135	High	2358	2403	2466	2515	2590	2538	1.10	1.13	1.16	1.18	1.21	1.19	Small increase	No change
White oak	404	564	High	666	1073	847	2112	961	2716	1.18	1.90	1.50	3.75	1.70	4.82	Small increase	Large increase
White spruce	491	524	Medium	379	384	300	229	286	185	0.72	0.73	0.57	0.44	0.55	0.35	Small decrease	Large decrease
Willow oak	0	7	Medium	5	3	5	24	5	77	0.71	0.43	0.71	3.43	0.71	11.00	—	New habitat
Winged elm	1	0	High	0	8	0	122	3	471	0.00	8.00	0.00	122.00	3.00	471.00	No change	Small increase
Yellow birch	2344	2314	High	2252	1919	2037	1101	1941	844	0.97	0.83	0.88	0.48	0.84	0.37	No change	Large decrease
Yellow-poplar	25	69	High	129	189	183	543	206	805	1.87	2.74	2.65	7.87	2.99	11.67	Large increase	Large increase

[a] Current importance values (Current IV) are based on modeled results. Modeled early-century, mid-century, and late-century importance values are average values for the indicated years. Future:Current suitable habitat is a ratio of projected importance value to current importance value. Species are assigned to change classes based on the comparison between end-of-century (2070 through 2099) and current figures for area-weighted importance value. Descriptions of the change classes are given later in this appendix. Data for the three subregions are available at www.fs.fed.us/nrs/atlas/products/#ra.

**Not observed in the Forest Inventory and Analysis data, but other data (e.g., State surveys) suggest species is present though rare.

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

MODIFYING FACTORS AND ADAPTABILITY SCORES

Modifying factors for the species modeled in the Tree Atlas (Table 19) were developed by using a literature-based scoring system to capture the potential adaptability of species to changes in climate that cannot be adequately captured by the DISTRIB model (Matthews et al. 2011). The Tree Atlas modelers used this approach to assess the capacity for each species to adapt and considered nine biological traits reflecting innate characteristics such as competition for light and edaphic specificity. Twelve disturbance characteristics addressed the general response of a species to events such as drought, insect pest outbreaks, and fire. This information distinguishes between species likely to be more tolerant (or sensitive) to environmental changes than the habitat models alone suggest.

Table 19.—Modifying factor and adaptability information for the 102 tree species in the assessment area modeled using the Climate Change Tree Atlas

		Modifying factors[1]		Adaptability scores[2]			
Common name	DISTRIB model reliability	Positive traits	Negative traits	DistFact	BioFact	Adapt	Adapt Class
American basswood	Medium	COL	FTK	0.31	0.16	4.6	o
American beech	High	COL	INS FTK	-1.14	0.03	3.6	o
American chestnut	Medium	COL	DISE FTK	0.13	0.30	4.5	o
American elm	Medium	ESP	DISE INS	-0.80	0.30	4.0	o
American holly	High	COL ESP	FTK	-0.10	0.47	4.5	o
American hornbeam	Medium	COL SES	FTK DRO	0.56	0.62	5.1	o
American mountain-ash	Medium	---	FTK COL ESP	-0.23	-1.62	3.1	—
Atlantic white-cedar	Low	DISP	FTK DRO ESP	-0.61	-1.21	3.0	—
Bald cypress	Medium	DISP	FTK	0.38	-1.02	3.9	o
Balsam fir	High	COL	INS FTK DRO	-3.00	-0.35	2.7	—
Balsam poplar	High	FRG VRE	COL DRO	0.13	-0.59	4.0	o
Bigtooth aspen	High	FRG DISP	COL DRO FTK	1.01	0.16	5.1	o
Bitternut hickory	Low	DRO	COL	2.17	-0.83	5.6	+
Black ash	High	---	INS COL DISP DRO SES FTK ESP	-1.31	-3.00	1.7	—
Black cherry	High	DRO ESP	INS FTK COL	-1.56	-0.32	3.0	—
Black hickory	High	---	ESP COL	1.04	-2.27	4.1	o
Black locust	Low	---	COL INS	0	-0.59	3.8	o
Black maple	Low	COL ESP	FTK	0.48	0.90	5.2	o
Black oak	High	DRO ESP	INS DISE	0.51	0.42	4.9	o
Black spruce	High	COL ESP DISP	FTK INS DRO	-2.14	1.24	4.3	o
Black walnut	Medium	SES	COL DRO	0.35	-0.83	4.0	o
Black willow	Low	---	COL FTK DRO	-0.31	-2.13	2.8	—
Blackgum	High	COL FTK	---	1.46	0.83	5.9	+
Blackjack oak**	Medium	DRO SES FRG VRE	COL FTK	1.56	0.21	5.6	+
Boxelder	Medium	SES DISP DRO COL SES	FTK	2.39	2.06	7.4	+
Bur oak	Medium	DRO FTK	---	2.77	-0.16	6.4	+

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Table 19 (continued).—Modifying factor and adaptability information for the 102 tree species in the assessment area modeled using the Climate Change Tree Atlas

		Modifying factors[1]		Adaptability scores[2]			
Common name	**DISTRIB model reliability**	**Positive traits**	**Negative traits**	**DistFact**	**BioFact**	**Adapt**	**Adapt Class**
Butternut	Low	---	FTK COL DRO DISE	-1.41	-1.27	2.3	—
Cedar elm	Low	---	DISE	-0.27	-1.17	3.3	○
Cherrybark oak	Medium	---	INS FTK	-0.51	0.06	3.9	○
Chestnut oak	High	SES VRE ESP FTK	INS DISE	1.39	1.29	6.1	+
Chinkapin oak**	Medium	SES	---	1.18	-0.66	4.8	○
Chokecherry	Low	---	COL	0.18	-0.86	3.8	○
Common persimmon	Medium	COL ESP	---	1.18	0.95	5.8	+
Eastern cottonwood	Low	SES	INS COL DISE FTK	0.22	-0.75	3.9	○
Eastern hemlock	High	COL	INS DRO	-1.34	-0.88	2.7	—
Eastern hophornbeam	Medium	COL ESP SES	---	1.72	1.29	6.4	+
Eastern redbud	Medium	---	---	0.90	-0.03	4.9	○
Eastern redcedar	Medium	DRO	FTK COL INS	0.56	-1.48	3.9	○
Eastern white pine	High	DISP	DRO FTK INS	-1.97	0.13	3.3	○
Flowering dogwood	High	COL	---	0.07	0.95	5.0	○
Gray birch	Medium	DISP ESP	FTK COL INS DISE	-1.14	0.03	3.6	○
Green ash	Medium	---	INS FTK COL	-0.13	-0.25	4.0	○
Hackberry	Medium	DRO	FTK	1.66	0.30	5.7	+
Honeylocust	Low	---	COL	1.91	-0.54	5.5	+
Jack pine	High	DRO	COL INS	1.87	-1.24	5.2	○
Loblolly pine	High	ESP	INS INP DRO COL	-0.51	-0.66	3.4	○
Longleaf pine	High	FTK	COL	0.96	-1.74	4.2	○
Mockernut hickory	High	---	FTK	1.69	-0.28	5.4	+
Mountain maple	High	COL VRE ESP	DRO FTK	0.80	1.48	5.9	+
Northern pin oak	Medium	DRO FTK	COL	2.52	-0.56	6.0	+
Northern red oak	High	---	INS	1.39	0.13	5.4	+
Northern white-cedar	High	COL	FTK	-0.70	0.49	4.2	○
Ohio buckeye	Low	COL	SES FTK	0.38	-1.92	3.5	○
Osage-orange	Medium	ESP ESP	---	2.32	0.33	6.3	+
Paper birch	High	FRG DISP ESP	FTK COL INS DRO	-1.72	0.18	3.4	○
Pawpaw**	Low	COL	DRO	-0.48	-0.32	3.7	○
Pignut hickory	High	ESP	INS DRO	0.22	0.40	4.7	○
Pin cherry	Medium	SES FRG FTK	COL	0.45	-0.68	4.2	○
Pin oak	Medium	---	FTK COL INS DISE	-0.65	-1.39	2.8	—
Pitch pine	High	---	COL INS	0.56	-1.79	3.8	○
Pond pine	High	---	DRO COL INS DISP	-1.06	-1.51	2.4	—
Post oak	High	DRO SES FTK	COL INS DISE	2.17	-0.59	5.7	+
Quaking aspen	High	SES FRG ESP	COL DRO FTK	0.56	0.01	4.7	○
Red maple	High	SES ESP ESP COL DISP	---	3.00	3.00	8.5	+

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Table 19 (continued).—Modifying factor and adaptability information for the 102 tree species in the assessment area modeled using the Climate Change Tree Atlas

		Modifying factors[1]		Adaptability scores[2]			
Common name	DISTRIB model reliability	Positive traits	Negative traits	DistFact	BioFact	Adapt	Adapt Class
Red mulberry	Low	COL DISP	FTK	0.07	0.59	4.7	○
Red pine	Medium	---	INS COL DISP	0.86	-2.42	3.9	○
Red spruce	High	ESP COL	FTK SES	-1.28	-0.62	2.9	—
River birch	Low	DISP	FTK COL DRO	-0.45	-0.32	3.7	○
Rock elm	Low	---	ESP ESP SES	-0.20	-2.61	2.8	—
Sand pine	Medium	---	DRO INS FTK	-1.09	-1.14	2.7	—
Sassafras	High	---	COL FTK	0.48	-0.64	4.2	○
Scarlet oak	High	VRE ESP ESP	INS DISE FTK	-0.35	0.71	4.6	○
Scrub oak	Low	FRG VRE	COL FTK	1.04	-0.81	4.6	○
Serviceberry	Medium	COL SES	DRO	-0.38	0.98	4.8	○
Shagbark hickory	Medium	---	INS FTK	-0.20	0.37	4.4	○
Shellbark hickory	Low	COL	FTK ESP	-0.48	-0.30	3.7	○
Shingle oak	Medium	ESP	COL	1.31	-0.74	4.9	○
Shortleaf pine**	High	ESP	COL INS DRO	0	-0.97	3.6	○
Shumard oak	Low	DRO SES	COL	2.45	-1.02	5.8	+
Silver maple	Medium	DISP SES COL	DRO FTK	0.13	1.63	5.6	+
Slippery elm	Medium	COL	FTK DISE	0.03	0.68	4.8	○
Sourwood	High	COL ESP	---	2.59	0.98	6.9	+
Southern red oak	High	SES	---	1.21	0.21	5.3	+
Striped maple	High	COL SES	DRO	0.96	0.25	5.1	○
Sugar maple	High	COL ESP	---	0.86	1.34	5.8	+
Sugarberry	Medium	COL SES	FTK	-0.17	0.64	4.6	○
Swamp chestnut oak	Medium	SES	COL INS	1.08	-0.81	4.6	○
Swamp white oak	Low	---	---	1.04	-0.30	4.9	○
Sweet birch	High	DISP	FTK COL INS DISE	-1.28	-0.32	3.2	—
Sweetbay**	High	FTK	INS	1.39	-0.47	5.1	○
Sweetgum**	High	VRE ESP	FTK COL DRO	-0.41	0.18	4.1	○
Sycamore	Medium	---	---	1.28	-0.90	4.8	○
Tamarack	High	---	FTK COL INS	-0.48	-1.24	3.1	—
Virginia pine	High	---	COL POL	0.10	-0.81	3.8	○
Water oak	High	SES	FTK COL	-0.17	-0.59	3.7	○
White ash	High	---	INS FTK COL	-2.01	-0.54	2.7	—
White oak	High	ESP ESP SES FTK	INS DISE	1.66	1.00	6.1	+
White spruce	Medium	---	INS	0.07	-0.62	3.9	○
Willow oak	Medium	SES SES	COL	0.63	-0.01	4.7	○
Winged elm	High	---	INS DISE	-0.58	-0.30	3.6	○
Yellow birch	High	DISP	FTK INS DISE	-1.38	-0.03	3.4	○
Yellow-poplar	High	SES DISP ESP	INP	0.13	1.26	5.3	+

[1]Modifying factor codes are described in Table 20.

[2]Adaptability scores are described in the appendix text. Scores of 3.2 and less are considered low (–), and scores of 5.3 and above are considered high (+). Scores between 3.2 and 5.3 are denoted by ○.

**Not observed in the Forest Inventory and Analysis data, but other data (e.g., State surveys) suggest species is present though rare.

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 (Matthews et al. 2011). 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 (Table 20).

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. 44). For this assessment, adaptability scores of 3.2 and less are considered low, and scores of 5.3 and greater are considered high (Table 20).

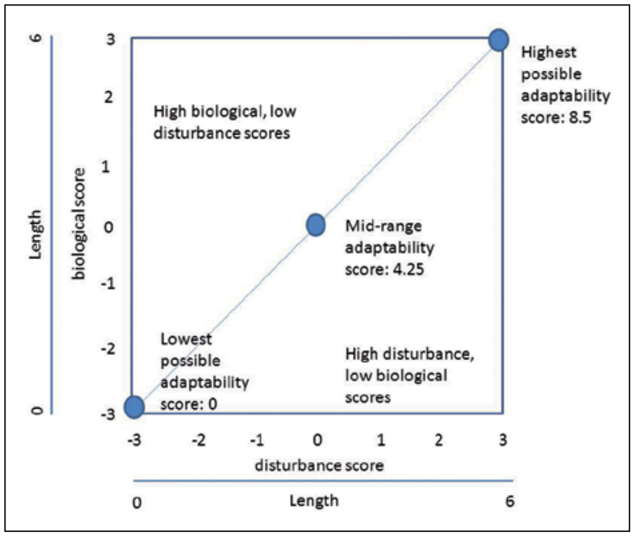

Figure 44.—Schematic showing how adaptability was determined for information for the 102 tree species in the assessment area modeled using the Climate Change Tree Atlas. Modifying factor codes are described in Table 20. Adaptability scores are described in the appendix text.

Table 20.—Description of Tree Atlas modifying factor codes*

Code	Description (if positive)	Description (if negative)
COL	Tolerant of shade or limited light conditions	Intolerant of shade or limited light conditions
DISE	---	Has a high number and/or severity of known pathogens that attack the species
DISP	High ability to effectively produce and distribute seeds	---
DRO	Drought-tolerant	Susceptible to drought
ESP	Wide range of soil tolerance	Narrow range of soil requirements
FRG	Regenerates well after fire	---
FTK	Resistant to fire topkill	Susceptible to fire topkill
INP	---	Strong negative effects of invasive plants on the species, either through competition for nutrients or as a pathogen
INS	---	Has a high number and/or severity of insects that may attack the species
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 describe positive or negative modifying factors used in Table 19. 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.

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.

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APPENDIX 5: SUPPLEMENTARY LINKAGES RESULTS

This appendix contains additional model details and results from the LINKAGES model, which was used to simulate changes in tree species establishment probability during the 21st century for 24 common tree species within the assessment area.

The LINKAGES model (version 3.0) (Dijak et al. 2016) is an ecosystem dynamics process model modified from earlier versions of LINKAGES (Pastor and Post 1985, Wullschleger et al. 2003). LINKAGES can model forest succession when initialized with tree plot data; however, here the model was initialized from bareground conditions and modeled the establishment and growth of individual tree species over 30 years. It also modeled ecosystem functions such as soil water balance, litter decomposition, nitrogen cycling, soil hydrology and evapotranspiration. Inputs to the model include climate variables (e.g., daily temperature, precipitation, wind speed, and solar radiation), soil characteristics (e.g., soil moisture capacity and rock, sand, and clay percentages for multiple soil layers), and biological traits for each tree species (e.g., growth rate and tolerance to cold and shade). Model results include number of stems, biomass, leaf litter, available nitrogen, humus, and organic matter. Similar to the Climate Change Tree Atlas, the LINKAGES model provides the unconstrained response in fundamental niche, or the habitat a species could occupy, to climate change. LANDIS PRO uses this fundamental niche information provided by LINKAGES and constrains the distribution through competition into the realized niche (the habitat that a species may actually occupy). Unlike the LANDIS PRO model, LINKAGES is not spatially dynamic, and does not simulate tree dispersal or any other spatial interaction among grid cells.

For this assessment, LINKAGES projected changes in forest distribution by using downscaled daily mean temperature and precipitation under GFDL A1FI and PCM B1 for the end of the century (2080 to 2099), and compared these projections with end-of-century projections under a current climate scenario (i.e., the climate during 1980 through 2009).

Future biomass projections for the 24 tree species are presented for the assessment area as a whole and by subregion (Table 21). Early growth potential (first 30 years) was also mapped for each species modeled by LINKAGES (Fig. 45). Change in early growth was calculated by dividing the modeled future biomass by the current climate biomass. Change was classified according to the following ratios:

Modeled:Current biomass	Class
<0.5	large decrease
0.5 to 0.8	small decrease
>0.8 to <1.2	no change
1.2 to 2.0	small increase
>2	large increase
current climate = 0 and future climate model = 0	not present
current climate >0 and future climate model = 0	extirpated

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Table 21.—Biomass reached in 30 years of tree growth starting from bare ground projected by the LINKAGES model for 24 species in the assessment area under the current climate scenario and two climate model-emissions scenario combinations for the period 2070 through 2099, by entire assessment area and subregion

	Current climate	PCM B1			GFDL A1FI		
Species	Biomass in 2100 (metric tons/acre)	Biomass in 2100 (metric tons/acre)	Change from current climate biomass in 2100	Change class	Biomass in 2100 (metric tons/acre)	Change from current climate biomass in 2100	Change class
Entire Assessment Area							
American beech	40.4	38.0	-6%	No change	27.8	-31%	Small decrease
Balsam fir	11.9	5.5	-54%	Large decrease	0.3	-97%	Large decrease
Black cherry	30.8	40.3	31%	Small increase	37.9	23%	Small increase
Black oak	7.9	18.4	133%	Large increase	30.8	290%	Large increase
Black spruce	2.7	0.9	-67%	Large decrease	0.0	-100%	Extirpated
Chestnut oak	4.0	13.7	243%	Large increase	34.1	753%	Large increase
Eastern hemlock	20.0	11.2	-44%	Small decrease	3.4	-83%	Large decrease
Eastern white pine	32.3	29.1	-10%	No change	13.5	-58%	Large decrease
Loblolly pine	0.0	0.2	>1,000%	New habitat	1.8	>1,000%	New habitat
Northern red oak	48.3	52.7	9%	No change	43.3	-10%	No change
Northern white-cedar	8.2	3.9	-52%	Large decrease	0.2	-98%	Large decrease
Pignut hickory	11.4	22.7	99%	Small increase	29.4	158%	Large increase
Pitch pine	5.9	10.6	80%	Small increase	12.6	114%	Large increase
Quaking aspen	47.6	39.3	-17%	No change	17.4	-63%	Large decrease
Red maple	42.2	45.0	7%	No change	38.3	-9%	No change
Red spruce	9.2	3.7	-60%	Large decrease	0.2	-98%	Large decrease
Scarlet oak	10.2	21.3	109%	Large increase	29.3	187%	Large increase
Shagbark hickory	5.8	13.7	136%	Large increase	24.2	317%	Large increase
Sugar maple	48.2	44.2	-8%	No change	34.7	-28%	Small decrease
Virginia pine	0.1	1.5	>1,000%	New habitat	6.6	>1,000%	New habitat
White ash	60.6	61.9	2%	No change	50.5	-17%	No change
White oak	30.5	43.1	41%	Small increase	43.3	42%	Small increase
Yellow birch	46.0	39.2	-15%	No change	24.6	-47%	Small decrease
Yellow-poplar	15.5	39.3	154%	Large increase	71.1	359%	Large increase

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Table 21 (continued).—Biomass reached in 30 years of tree growth starting from bare ground projected by the LINKAGES model for 24 species in the assessment area under the current climate scenario and two climate model-emissions scenario combinations for the period 2070 through 2099, by entire assessment area and subregion

	Current climate	PCM B1			GFDL A1FI		
Species	Biomass in 2100 (metric tons/acre)	Biomass in 2100 (metric tons/acre)	Change from current climate biomass in 2100	Change class	Biomass in 2100 (metric tons/acre)	Change from current climate biomass in 2100	Change class
Southern and Coastal New England							
American beech	22.3	21.6	-3%	No change	3.0	-87%	Large decrease
Balsam fir	0.7	0.2	-71%	Large decrease	0.0	-100%	Extirpated
Black cherry	26.3	30.6	16%	No change	6.1	-77%	Large decrease
Black oak	15.2	28.0	84%	Small increase	7.1	-53%	Large decrease
Black spruce	0.3	0.0	-100%	Extirpated	0.0	-100%	Extirpated
Chestnut oak	10.6	34.5	225%	Large increase	10.9	2%	No change
Eastern hemlock	1.3	1.1	-15%	No change	0.6	-54%	Large decrease
Eastern white pine	8.0	4.0	-50%	Small decrease	1.4	-83%	Large decrease
Loblolly pine	0.0	1.0	>1000%	New habitat	2.9	>1000	New habitat
Northern red oak	47.5	45.9	-3%	No change	15.9	-67%	Large decrease
Northern white-cedar	0.8	0.1	-88%	Large decrease	0.0	-100%	Extirpated
Pignut hickory	14.9	22.2	49%	Small increase	4.3	-71%	Large decrease
Pitch pine	9.8	11.1	13%	No change	2.4	-76%	Large decrease
Quaking aspen	31.6	15.2	-52%	Large decrease	0.0	-100%	Extirpated
Red maple	34.4	32.8	-5%	No change	8.3	-76%	Large decrease
Red spruce	0.6	0.2	-67%	Large decrease	0.0	-100%	Extirpated
Scarlet oak	17.5	27.9	59%	Small increase	6.8	-61%	Large decrease
Shagbark hickory	10.6	18.3	73%	Small increase	3.8	-64%	Large decrease
Sugar maple	36.2	31.9	-12%	No change	7.0	-81%	Large decrease
Virginia pine	0.4	4.7	>1000%	New habitat	3.9	875%	New habitat
White ash	47.6	45.5	-4%	No change	14.1	70%	Large decrease
White oak	43.7	44.0	1%	No change	22.4	-49%	Small decrease
Yellow birch	31.0	19.9	-36%	Small decrease	0.0	100%	Extirpated
Yellow-poplar	36.0	75.4	109%	Large increase	30.1	-16%	No change
Eastern and Coastal Maine							
American beech	54.6	53.6	-2%	No change	51.1	-6%	No change
Balsam fir	17.6	6.8	-61%	Large decrease	1.2	-93%	Large decrease
Black cherry	44.5	56.8	28%	Small increase	68.8	55%	Small increase
Black oak	5.3	22.2	319%	Large increase	51.6	874%	Large increase
Black spruce	4.4	0.6	-86%	Large decrease	0.1	-98%	Large decrease
Chestnut oak	0.0	8.7	>1,000%	New habitat	53.4	>1,000%	New habitat
Eastern hemlock	30.2	13.9	-54%	Large decrease	10.5	-65%	Large decrease
Eastern white pine	45.8	39.3	-14%	No change	35.2	-23%	Small decrease

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Table 21 (continued).—Biomass reached in 30 years of tree growth starting from bare ground projected by the LINKAGES model for 24 species in the assessment area under the current climate scenario and two climate model-emissions scenario combinations for the period 2070 through 2099, by entire assessment area and subregion

	Current climate	PCM B1			GFDL A1FI		
Species	Biomass in 2100 (metric tons/acre)	Biomass in 2100 (metric tons/acre)	Change from current climate biomass in 2100	Change class	Biomass in 2100 (metric tons/acre)	Change from current climate biomass in 2100	Change class
Loblolly pine	0.0	0.0	0%	—	1.1	>1,000%	New habitat
Northern red oak	60.9	63.4	4%	No change	64.0	5%	No change
Northern white-cedar	13.0	4.2	-68%	Large decrease	0.7	-95%	Large decrease
Pignut hickory	13.7	32.1	134%	Large increase	52.0	280%	Large increase
Pitch pine	6.1	14.6	139%	Large increase	21.7	256%	Large increase
Quaking aspen	57.3	56.7	-1%	No change	28.2	51%	Large decrease
Red maple	55.3	58.8	6%	No change	62.6	13%	No change
Red spruce	13.4	4.4	-67%	Large decrease	0.7	-95%	Large decrease
Scarlet oak	9.2	27.3	197%	Large increase	49.0	433%	Large increase
Shagbark hickory	4.0	17.7	343%	Large increase	43.8	995%	Large increase
Sugar maple	56.3	56.6	1%	No change	55.7	-1%	No change
Virginia pine	0.0	0.0	0%	—	12.9	>1,000%	New habitat
White ash	77.4	79.5	3%	No change	80.7	4%	No change
White oak	36.9	51.9	41%	Small increase	60.0	63%	Small increase
Yellow birch	54.0	53.7	-1%	No change	49.8	-8%	No change
Yellow-poplar	6.1	42.8	602%	Large increase	106.2	1,641%	Large increase
Northern Forest							
American beech	42.1	38.5	-9%	No change	28.6	-32%	Small decrease
Balsam fir	14.1	7.1	-50%	Small decrease	0.0	-100%	Extirpated
Black cherry	27.4	38.0	39%	Small increase	38.7	41%	Small increase
Black oak	6.1	13.4	120%	Large increase	32.1	426%	Large increase
Black spruce	2.9	1.3	-55%	Large decrease	0.0	-100%	Extirpated
Chestnut oak	2.9	7.7	166%	Large increase	35.8	1,134%	Large increase
Eastern hemlock	23.4	14.1	-40%	Small decrease	1.9	-92%	Large decrease
Eastern white pine	36.5	35.0	-4%	No change	10.1	-72%	Large decrease
Loblolly pine	0.0	0.0	0%	—	1.7	>1,000%	New habitat
Northern red oak	44.0	51.3	17%	No change	46.1	5%	No change
Northern white-cedar	9.3	5.2	-44%	Small decrease	0.1	-99%	Large decrease
Pignut hickory	9.3	19.4	109%	Large increase	30.6	229%	Large increase
Pitch pine	4.4	8.9	102%	Large increase	13.2	200%	Large increase
Quaking aspen	50.1	42.0	-16%	No change	20.0	60%	Large decrease
Red maple	40.4	44.6	10%	No change	40.8	1%	No change
Red spruce	10.9	4.7	-57%	Large decrease	0.0	-100%	Extirpated
Scarlet oak	7.8	16.6	113%	Large increase	30.6	292%	Large increase
Shagbark hickory	4.6	10.5	128%	Large increase	24.8	439%	Large increase
Sugar maple	49.8	44.4	-11%	No change	37.5	-25%	Small decrease
Virginia pine	0.0	0.8	>1,000%	New habitat	5.2	>1,000%	New habitat
White ash	59.3	61.6	4%	No change	53.4	-10%	No change
White oak	23.1	39.5	71%	Small increase	45.2	96%	Small increase
Yellow birch	48.7	41.2	-15%	No change	24.7	-49%	Small decrease
Yellow-poplar	11.1	24.2	118%	Large increase	73.9	566%	Large increase

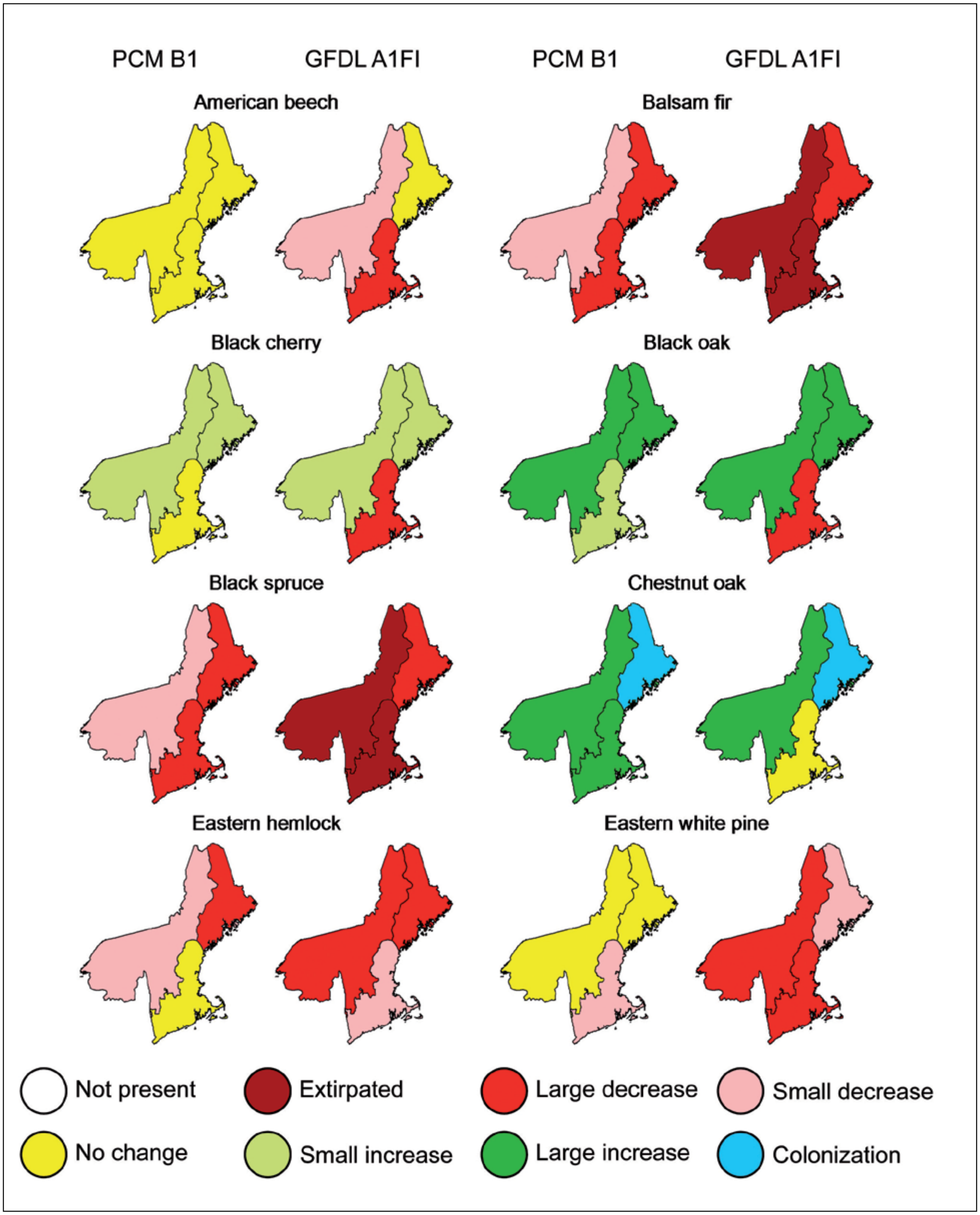

Figure 45.—Projections of relative amount and direction of change in biomass for 24 species in the assessment area using the LINKAGES model under the PCM B1 and GFDL A1FI climate scenarios, relative to the current climate scenario. Tree species growth values modeled by LINKAGES are presented as the biomass reached in 30 years of growth starting from bare ground in 2070 and ending in 2099.

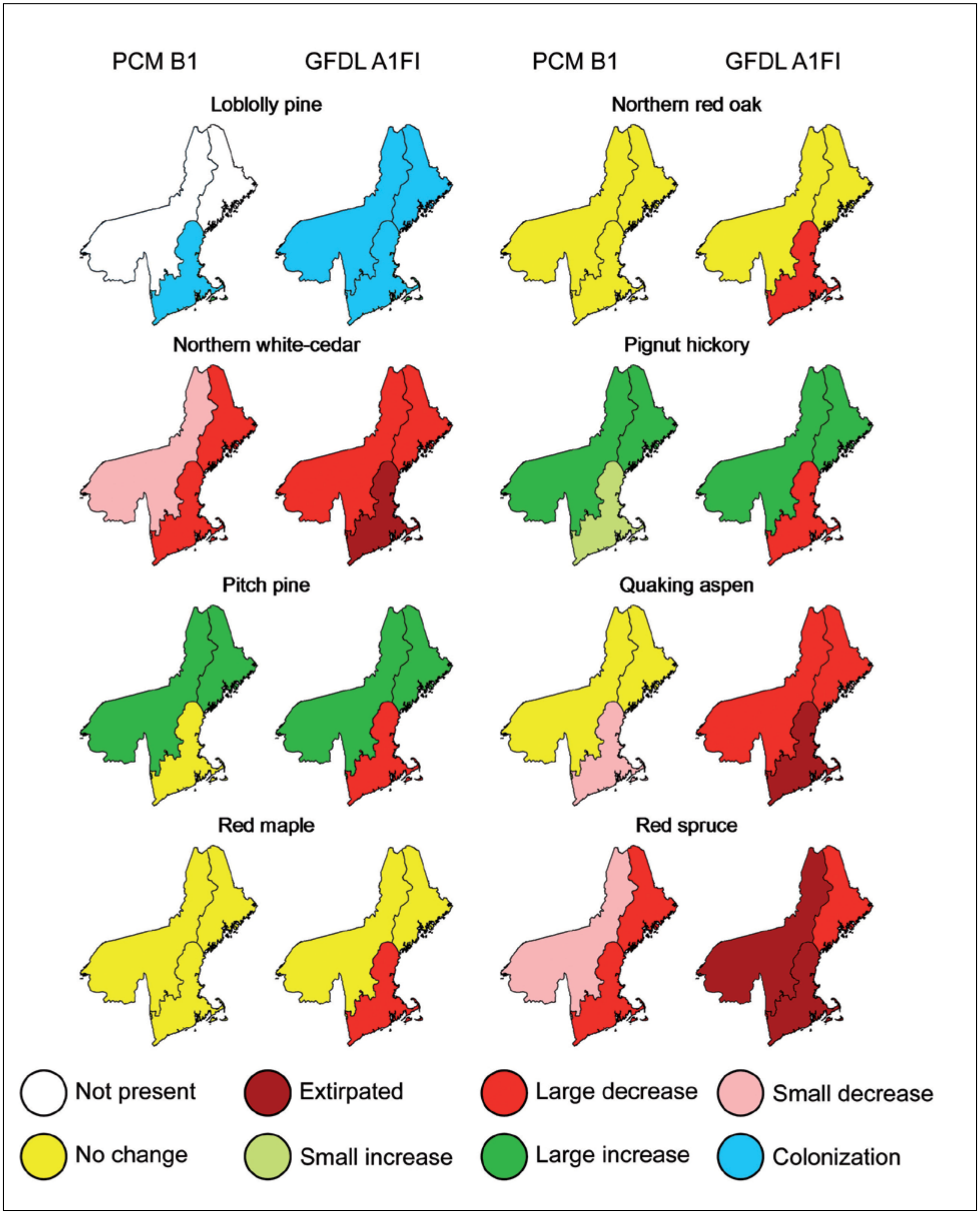

Figure 45 (continued).—Projections of relative amount and direction of change in biomass for 24 species in the assessment area using the LINKAGES model under the PCM B1 and GFDL A1FI climate scenarios, relative to the current climate scenario. Tree species growth values modeled by LINKAGES are presented as the biomass reached in 30 years of growth starting from bare ground in 2070 and ending in 2099.

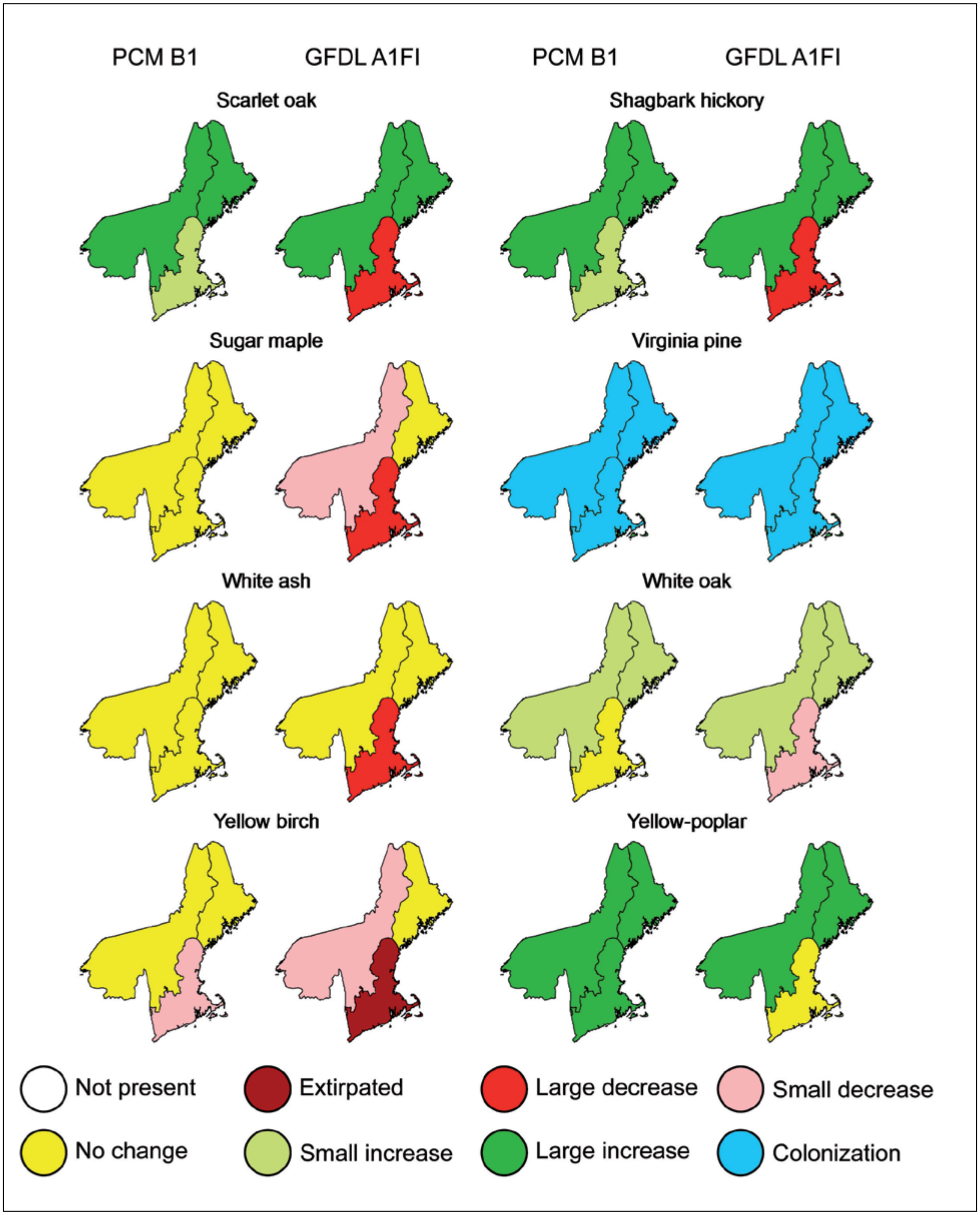

Figure 45 (continued).—Projections of relative amount and direction of change in biomass for 24 species in the assessment area using the LINKAGES model under the PCM B1 and GFDL A1FI climate scenarios, relative to the current climate scenario. Tree species growth values modeled by LINKAGES are presented as the biomass reached in 30 years of growth starting from bare ground in 2070 and ending in 2099.

APPENDIX 6: SUPPLEMENTARY LANDIS PRO RESULTS

This appendix contains additional model details and results from the LANDIS PRO model, which was used to simulate changes in tree abundance (basal area per acre) and density (trees per acre) through the year 2200 for 24 common tree species within the assessment area (Wang et al. 2017).

The LANDIS PRO model (Wang et al. 2014) is a spatially dynamic process model that simulates biological and ecosystem processes at the scale of individual species, stands, and landscapes. It is derived from the LANDIS model (Mladenoff 2004), but has been modified extensively from its original version. The LANDIS PRO model can simulate very large landscapes (millions of acres) at relatively fine spatial and temporal resolutions (typically 200 to 300 feet and 1- to 10-year time steps). One new feature of the model compared to previous versions is that inputs and outputs of tree species data include tree density and volume and are compatible with U.S. Forest Service Forest Inventory and Analysis (FIA) data. Thus, the model can be directly initialized, calibrated, and validated with FIA data. This compatibility ensures the starting simulation conditions reflect what is observed on the ground and allows the modelers to quantify the uncertainties inherent in the initial data.

The LANDIS PRO model stratifies the landscape into land types based on environmental characteristics. Within a land type, species establishment and resource availability are assumed to be similar. Basic inputs to the LANDIS PRO model include maps of species composition, land types, stands, management areas, and disturbance areas. In addition, species characteristics such as longevity, maturity, shade tolerance, average seed production, and maximum diameter at breast height are given as inputs into the model. A software program, Landscape Builder, is used to assign the number of trees by age cohort and species to each grid cell to generate the species composition map (Dijak 2013).

Species-level processes are simulated from known life-history traits and empirical equations and can include seedling germination and establishment, growth, vegetative reproduction, and tree mortality. Basic outputs in LANDIS PRO for a species or species cohort include biomass, age, and carbon. Stand-level processes include competition and succession. The model can simulate landscape-level processes including fire, wind, insect outbreaks, disease, invasive species, harvesting, silviculture, and fuels treatments, but only current forest harvest levels were a component of the simulations presented in this assessment.

Projections of future tree abundance and density for 24 tree species are shown for the assessment area as a whole for four time periods under three climate scenarios: a current climate scenario (in which the climatic conditions for 1980 through 2009 are used as the projected climate), PCM B1, and GFDL A1FI (Table 22). Relative amount and direction of change in projected tree abundance at year 2100 was also mapped for each species modeled by LANDIS PRO (Fig. 46). Estimated and projected abundance are graphed in Figure 47.

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Table 22.—Basal area (BA) and trees per acre (TPA) projected by the LANDIS PRO model for 24 species in the assessment area in the years 2040, 2070, 2100, and 2200 under the current climate scenario and two climate model-emissions scenario combinations

			Basal area							Trees per acre					
			Current climate		PCM B1		GFDL A1FI			Current climate		PCM B1		GFDL A1FI	
Tree species	BA in 2000 (ft²/acre)		BA (ft²/ acre)	Change from 2000	BA (ft²/ acre)	Change from current climate	BA (ft²/ acre)	Change from current climate	TPA in 2000	TPA	Change from 2000	TPA	Change from current climate	TPA	Change from current climate
American beech	6.2	2040	8.6	39%	8.1	-6%	9.2	7%	71.1	27.2	-62%	24.8	-9%	29.5	8%
		2070	10.5	69%	9.5	-10%	11.8	12%		23.1	-68%	20.3	-12%	27.3	18%
		2100	11.5	85%	10.3	-10%	13.8	20%		26.4	-63%	24.4	-8%	34.8	32%
		2200	11.7	89%	11.4	-3%	15.4	32%		42.7	-40%	38.9	-9%	53.1	24%
Balsam fir	11.7	2040	11.1	-5%	11.1	0%	12.1	9%	237.6	44.0	-81%	42.3	-4%	45.7	4%
		2070	9.2	-21%	9.5	3%	11.0	20%		21.9	-91%	23.8	9%	26.0	19%
		2100	7.5	-36%	8.2	9%	9.7	29%		15.4	-94%	21.8	42%	18.7	21%
		2200	2.2	-81%	2.4	9%	1.5	-32%		10.3	-96%	8.4	-18%	3.9	-62%
Black cherry	1.9	2040	2.2	16%	2.2	0%	2.3	5%	7.4	7.7	4%	7.4	-4%	8.2	6%
		2070	2.4	26%	2.3	-4%	2.6	8%		6.1	-18%	5.8	-5%	7.2	18%
		2100	2.6	37%	2.5	-4%	3.0	15%		6.3	-15%	6.0	-5%	9.3	48%
		2200	2.4	26%	2.7	13%	3.7	54%		6.9	-7%	7.8	13%	13.4	94%
Black oak	1.2	2040	1.1	-8%	1.1	0%	1.1	0%	1.8	3.0	67%	3.1	3%	3.0	0%
		2070	1.2	0%	1.2	0%	1.2	0%		2.1	17%	2.3	10%	2.0	-5%
		2100	1.4	17%	1.5	7%	1.4	0%		2.2	22%	2.5	14%	1.9	-14%
		2200	1.4	17%	1.6	14%	1.0	-29%		3.4	89%	4.2	24%	2.5	-26%
Black spruce	1.5	2040	1.6	7%	1.6	0%	1.7	6%	11.3	12.2	8%	10.9	-11%	12.3	1%
		2070	1.6	7%	1.5	-6%	1.8	13%		12.3	9%	8.5	-31%	10.0	-19%
		2100	1.4	-7%	1.2	-14%	1.5	7%		12.2	8%	6.4	-48%	5.5	-55%
		2200	0.8	-47%	0.5	-38%	0.3	-63%		8.6	-24%	3.1	-64%	0.6	-93%
Chestnut oak	0.3	2040	0.5	67%	0.5	0%	0.5	0%	0.4	2.4	500%	2.5	4%	2.4	0%
		2070	0.5	67%	0.5	0%	0.5	0%		1.8	350%	2.1	17%	1.9	6%
		2100	0.6	100%	0.6	0%	0.6	0%		2.8	600%	3.9	39%	3.1	11%
		2200	1.8	500%	2.2	22%	2.1	17%		5.3	1,225%	8.0	51%	8.0	51%
Eastern hemlock	9.8	2040	10.1	3%	9.8	-3%	10.6	5%	39.4	16.8	-57%	15.3	-9%	16.6	-1%
		2070	10.0	2%	9.5	-5%	10.8	8%		12.7	-68%	10.6	-17%	11.4	-10%
		2100	9.1	-7%	8.6	-5%	10.1	11%		13.3	-66%	10.7	-20%	10.2	-23%
		2200	4.3	-56%	3.5	-19%	3.6	-16%		17.2	-56%	10.0	-42%	7.7	-55%
Eastern white pine	9.8	2040	11.8	20%	11.6	-2%	12.4	5%	23.0	45.3	97%	43.0	-5%	46.3	2%
		2070	11.7	19%	11.3	-3%	13.0	11%		42.6	85%	36.3	-15%	44.0	3%
		2100	11.3	15%	10.6	-6%	13.3	18%		50.1	118%	40.0	-20%	65.4	31%
		2200	7.9	-19%	7.3	-8%	8.1	3%		39.6	72%	36.7	-7%	56.2	42%

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Table 22 (continued).—Basal area (BA) and trees per acre (TPA) projected by the LANDIS PRO model for 24 species in the assessment area in the years 2040, 2070, 2100, and 2200 under the current climate scenario and two climate model-emissions scenario combinations

			Basal area							Trees per acre					
			Current climate		PCM B1		GFDL A1FI			Current climate		PCM B1		GFDL A1FI	
Tree species	BA in 2000 (ft²/acre)		BA (ft²/ acre)	Change from 2000	BA (ft²/ acre)	Change from current climate	BA (ft²/ acre)	Change from current climate	TPA in 2000	TPA	Change from 2000	TPA	Change from current climate	TPA	Change from current climate
Loblolly pine	0.0	2040	0.0	0%	0.0	0%	0.0	0%	0.0	0.0	0%	0.0	0%	0.0	0%
		2070	0.0	0%	0.0	0%	0.0	0%		0.0	0%	0.0	0%	0.0	0%
		2100	0.0	0%	0.0	0%	0.0	0%		0.0	0%	0.0	0%	0.0	0%
		2200	0.0	0%	0.0	0%	0.0	0%		0.0	0%	0.0	0%	0.0	0%
Northern red oak	4.9	2040	5.4	10%	5.3	-2%	5.5	2%	10.8	14.5	34%	14.1	-3%	15.2	5%
		2070	5.7	16%	5.5	-4%	6.0	5%		14.2	31%	13.3	-6%	15.5	9%
		2100	5.6	14%	5.3	-5%	6.3	13%		17.3	60%	15.7	-9%	20.6	19%
		2200	7.8	59%	7.3	-6%	8.4	8%		21.3	97%	19.2	-10%	25.0	17%
Northern white-cedar	4.1	2040	4.3	5%	4.2	-2%	4.7	9%	26.2	36.2	38%	31.5	-13%	36.5	1%
		2070	4.4	7%	4.2	-5%	5.0	14%		41.2	57%	28.4	-31%	35.2	-15%
		2100	4.4	7%	4.1	-7%	5.1	16%		45.7	74%	25.3	-45%	27.1	-41%
		2200	3.2	-22%	2.1	-34%	2.0	-38%		41.0	56%	14.8	-64%	12.3	-70%
Pignut hickory	0.3	2040	0.5	67%	0.5	0%	0.5	0%	0.9	1.2	33%	1.2	0%	1.1	-8%
		2070	0.6	100%	0.6	0%	0.6	0%		1.1	22%	1.1	0%	1.0	-9%
		2100	0.7	133%	0.7	0%	0.7	0%		1.1	22%	1.2	9%	0.9	-18%
		2200	0.9	200%	0.9	0%	0.7	-22%		1.5	67%	1.6	7%	0.9	-40%
Pitch pine	0.2	2040	0.3	50%	0.3	0%	0.3	0%	0.3	1.9	533%	1.9	0%	1.8	-5%
		2070	0.2	0%	0.2	0%	0.2	0%		0.6	100%	0.7	17%	0.7	17%
		2100	0.2	0%	0.2	0%	0.2	0%		0.3	0%	0.3	0%	0.3	0%
		2200	0.0	-100%	0.0	0%	0.0	0%		0.1	-67%	0.1	0%	0.1	0%
Quaking aspen	2.0	2040	3.2	60%	3.2	0%	3.3	3%	10.8	29.0	169%	27.6	-5%	30.2	4%
		2070	4.5	125%	4.3	-4%	4.9	9%		41.5	284%	38.3	-8%	42.4	2%
		2100	7.3	265%	7.0	-4%	7.9	8%		71.9	566%	68.9	-4%	78.2	9%
		2200	23.6	1,080%	26.3	11%	19.2	-19%		179.6	1,563%	212.9	19%	163.1	-9%
Red maple	16.2	2040	19.3	19%	19.2	-1%	19.8	3%	107.2	60.9	-43%	60.1	-1%	63.6	4%
		2070	19.0	17%	18.9	-1%	20.0	5%		38.0	-65%	37.2	-2%	43.3	14%
		2100	15.6	-4%	15.4	-1%	16.8	8%		25.9	-76%	25.7	-1%	34.9	35%
		2200	3.5	-78%	3.6	3%	4.2	20%		10.1	-91%	10.5	4%	13.0	29%
Red spruce	7.5	2040	10.0	33%	9.5	-5%	10.7	7%	74.2	64.9	-13%	55.5	-14%	63.3	-2%
		2070	10.8	44%	9.6	-11%	11.9	10%		65.5	-12%	41.4	-37%	49.9	-24%
		2100	11.5	53%	9.1	-21%	11.8	3%		71.4	-4%	31.8	-55%	29.7	-58%
		2200	8.6	15%	4.8	-44%	4.4	-49%		47.1	-37%	13.3	-72%	5.0	-89%

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Table 22 (continued).—Basal area (BA) and trees per acre (TPA) projected by the LANDIS PRO model for 24 species in the assessment area in the years 2040, 2070, 2100, and 2200 under the current climate scenario and two climate model-emissions scenario combinations

			Basal area							Trees per acre					
			Current climate		PCM B1		GFDL A1FI			Current climate		PCM B1		GFDL A1FI	
Tree species	BA in 2000 (ft^2/acre)		BA (ft^2/acre)	Change from 2000	BA (ft^2/acre)	Change from current climate	BA (ft^2/acre)	Change from current climate	TPA in 2000	TPA	Change from 2000	TPA	Change from current climate	TPA	Change from current climate
Scarlet oak	0.5	2040	0.8	60%	0.8	0%	0.8	0%	1.2	1.9	58%	2.0	5%	1.9	0%
		2070	1.0	100%	1.0	0%	1.0	0%		1.5	25%	1.6	7%	1.4	-7%
		2100	1.1	120%	1.1	0%	1.1	0%		1.9	58%	2.1	11%	1.4	-26%
		2200	1.4	180%	1.5	7%	0.8	-43%		2.9	142%	3.6	24%	1.4	-52%
Shagbark hickory	0.2	2040	0.3	50%	0.3	0%	0.3	0%	0.6	0.8	33%	0.8	0%	0.8	0%
		2070	0.4	100%	0.4	0%	0.4	0%		0.7	17%	0.7	0%	0.7	0%
		2100	0.4	100%	0.4	0%	0.4	0%		0.8	33%	0.8	0%	0.9	13%
		2200	0.5	150%	0.5	0%	0.6	20%		1.0	67%	1.2	20%	1.2	20%
Sugar maple	10.3	2040	11.4	11%	10.9	-4%	11.8	4%	42.2	18.9	-55%	17.7	-6%	20.4	8%
		2070	11.6	13%	10.7	-8%	12.6	9%		15.2	-64%	14.4	-5%	18.5	22%
		2100	11.0	7%	10.1	-8%	12.5	14%		20.4	-52%	20.1	-2%	25.8	26%
		2200	12.9	25%	12.7	-2%	14.1	9%		38.2	-9%	37.6	-2%	44.5	16%
Virginia pine	0.0	2040	0.0	0%	0.0	0%	0.0	0%	0.0	0.0	0%	0.0	0%	0.0	0%
		2070	0.0	0%	0.0	0%	0.0	0%		0.0	0%	0.0	0%	0.0	0%
		2100	0.0	0%	0.0	0%	0.0	0%		0.0	0%	0.0	0%	0.0	0%
		2200	0.0	0%	0.0	0%	0.0	0%		0.0	0%	0.0	0%	0.0	0%
White ash	3.0	2040	4.2	40%	4.1	-2%	4.4	5%	14.1	13.4	-5%	12.7	-5%	14.3	7%
		2070	5.1	70%	4.8	-6%	5.7	12%		14.2	1%	12.7	-11%	16.8	18%
		2100	6.1	103%	5.5	-10%	7.3	20%		19.6	39%	16.3	-17%	28.1	43%
		2200	10.1	237%	8.5	-16%	15.3	51%		34.1	142%	26.5	-22%	66.0	94%
White oak	1.1	2040	2.2	100%	2.2	0%	2.2	0%	1.7	9.2	441%	9.2	0%	9.4	2%
		2070	2.2	100%	2.2	0%	2.3	5%		10.4	512%	10.3	-1%	10.8	4%
		2100	2.8	155%	2.8	0%	3.1	11%		17.7	941%	17.2	-3%	18.1	2%
		2200	5.2	373%	5.0	-4%	7.5	44%		21.2	1,147%	18.9	-11%	29.6	40%
Yellow birch	6.1	2040	7.6	25%	7.4	-3%	8.0	5%	36.9	30.6	-17%	28.5	-7%	31.9	4%
		2070	9.1	49%	8.5	-7%	10.1	11%		36.5	-1%	31.1	-15%	40.1	10%
		2100	10.5	72%	9.0	-14%	12.3	17%		46.8	27%	36.4	-22%	59.2	27%
		2200	18.0	195%	15.6	-13%	20.3	13%		72.4	96%	57.0	-21%	90.6	25%
Yellow-poplar	0.1	2040	0.1	0%	0.1	0%	0.1	0%	0.1	0.9	800%	0.9	0%	0.9	-2%
		2070	0.1	0%	0.1	0%	0.1	0%		0.4	300%	0.4	0%	0.4	0%
		2100	0.1	0%	0.1	0%	0.1	0%		0.3	200%	0.3	0%	0.3	0%
		2200	0.1	0%	0.1	0%	0.2	100%		0.5	400%	0.7	40%	1.2	140%

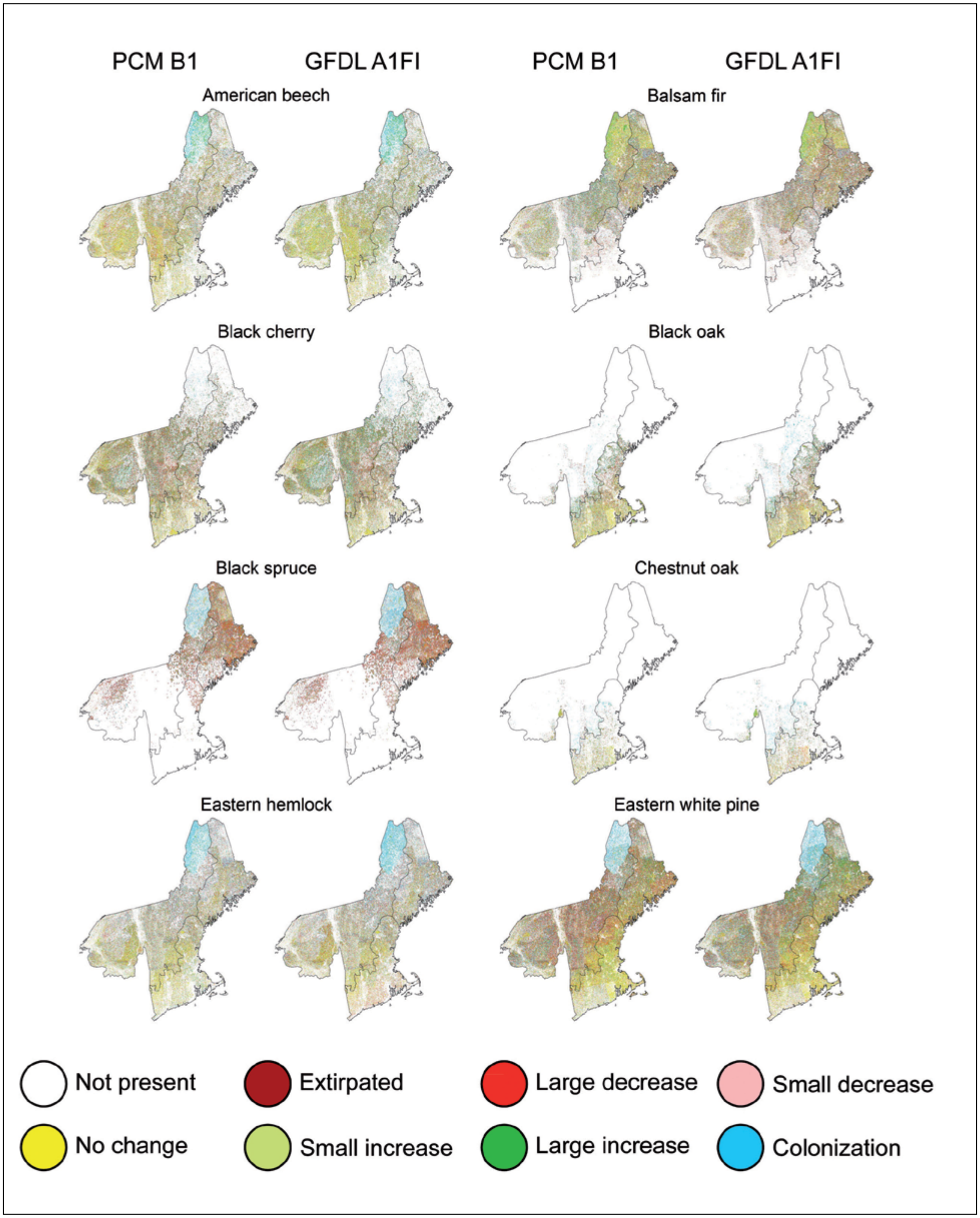

Figure 46.— Projections of relative amount and direction of change in basal area at year 2100 for 24 species in the assessment area using the LANDIS PRO model under the PCM B1 and GFDL A1FI climate scenarios, relative to the current climate scenario.

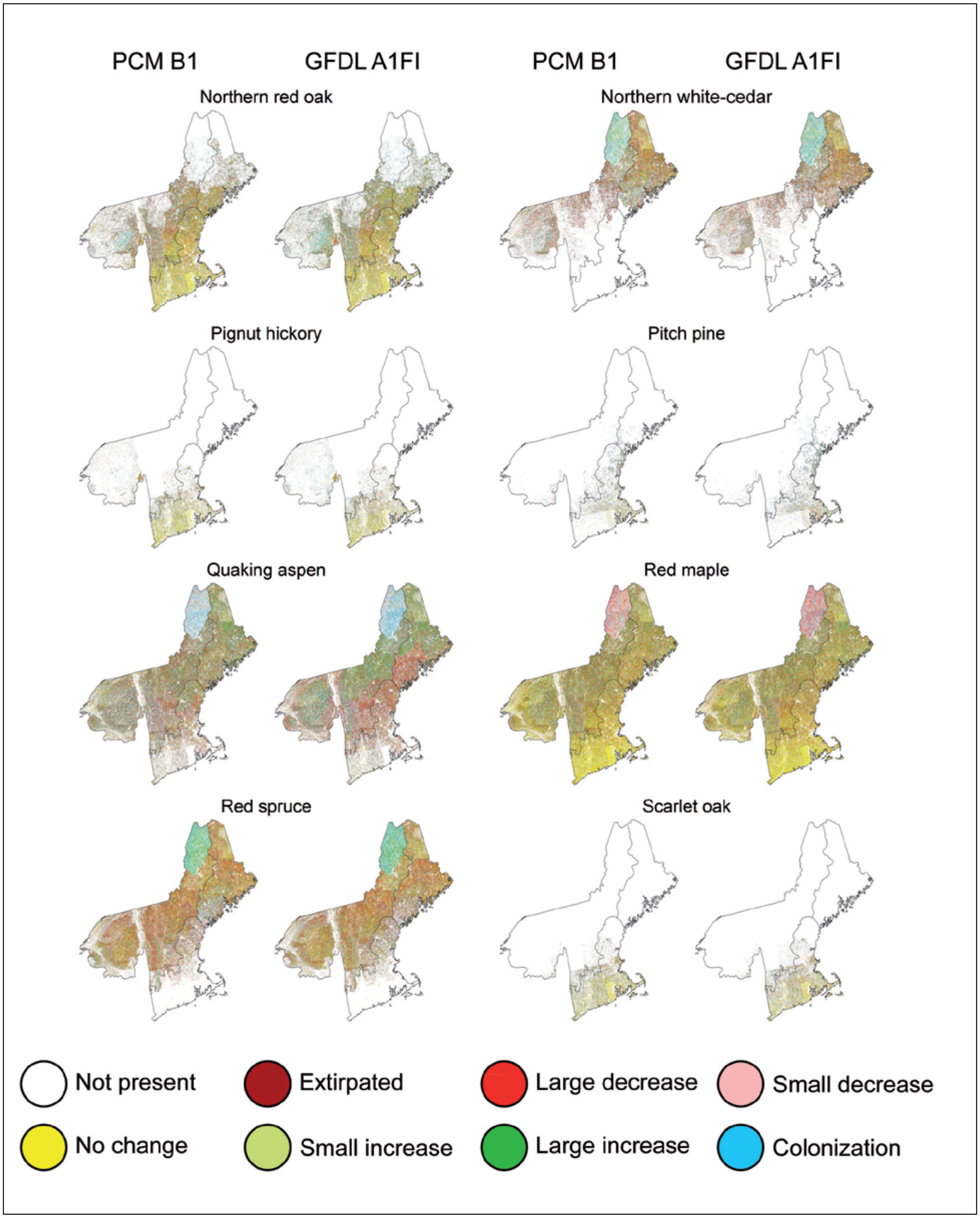

Figure 46 (continued).— Projections of relative amount and direction of change in basal area at year 2100 for 24 species in the assessment area using the LANDIS PRO model under the PCM B1 and GFDL A1FI climate scenarios, relative to the current climate scenario.

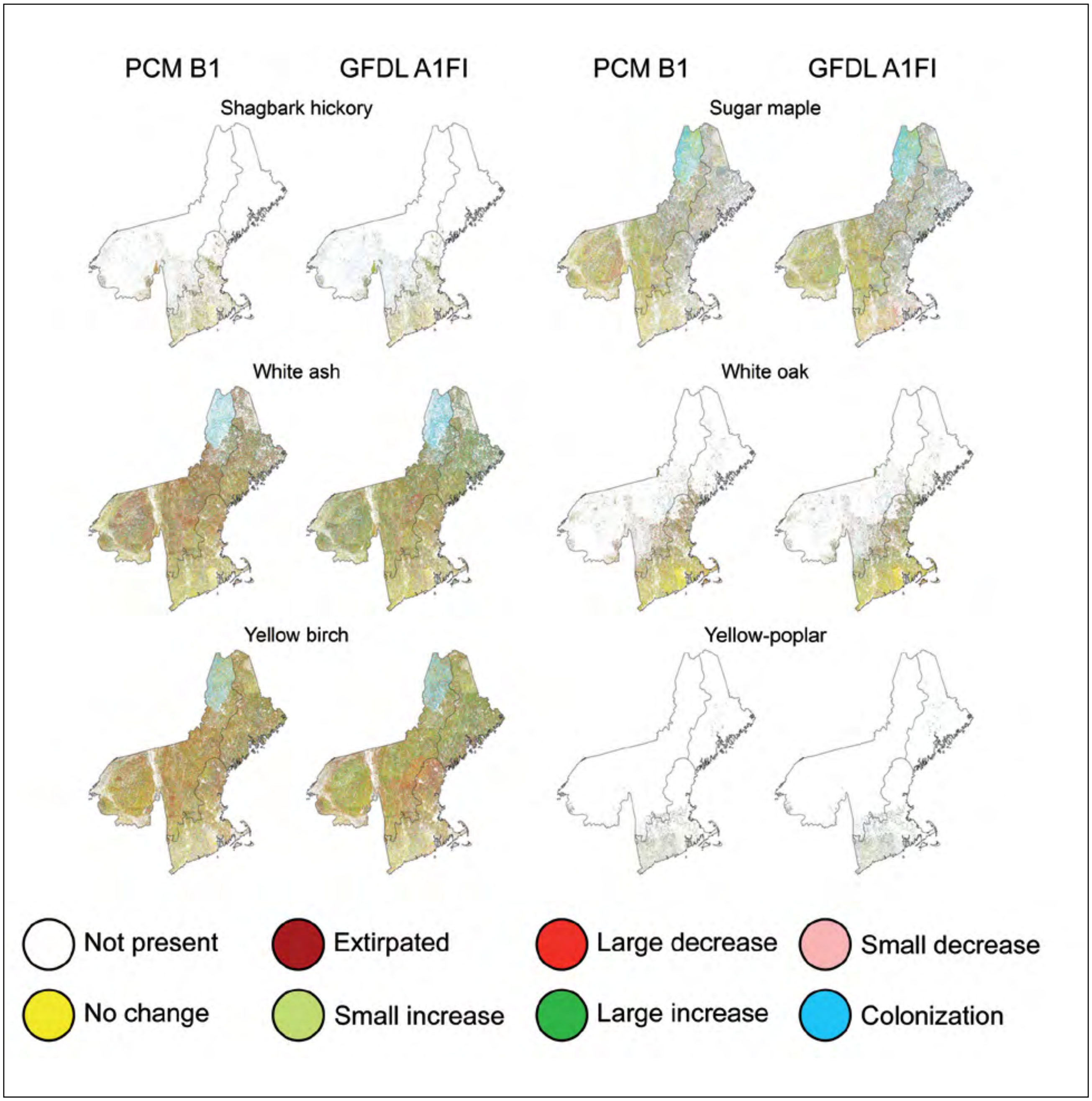

Figure 46 (continued).— Projections of relative amount and direction of change in basal area at year 2100 for 24 species in the assessment area using the LANDIS PRO model under the PCM B1 and GFDL A1FI climate scenarios, relative to the current climate scenario.

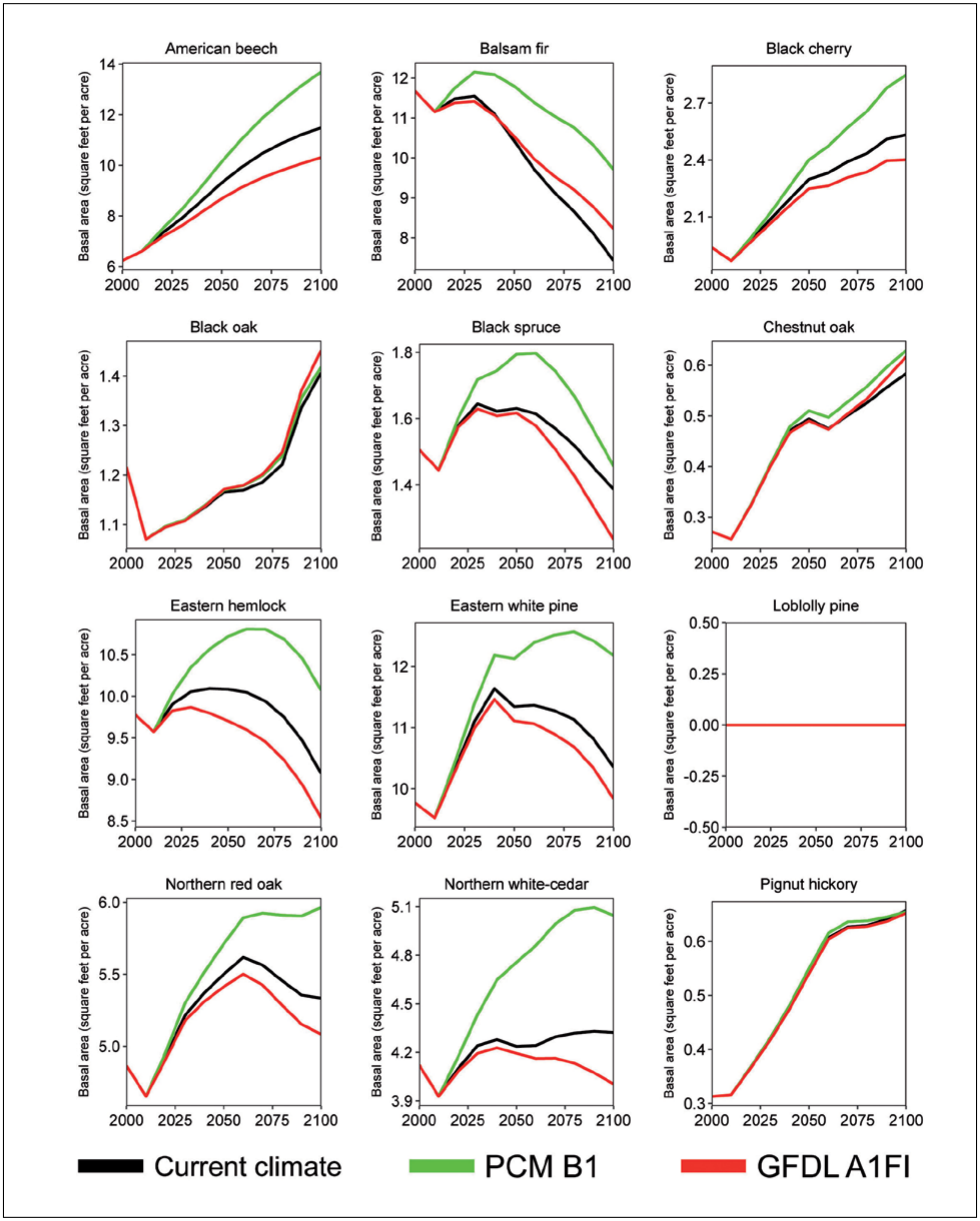

Figure 47.—Projected change in basal area for 24 species in the assessment area using the LANDIS PRO model under the current climate and two climate change scenarios. Note that the panels have different Y-axis values.

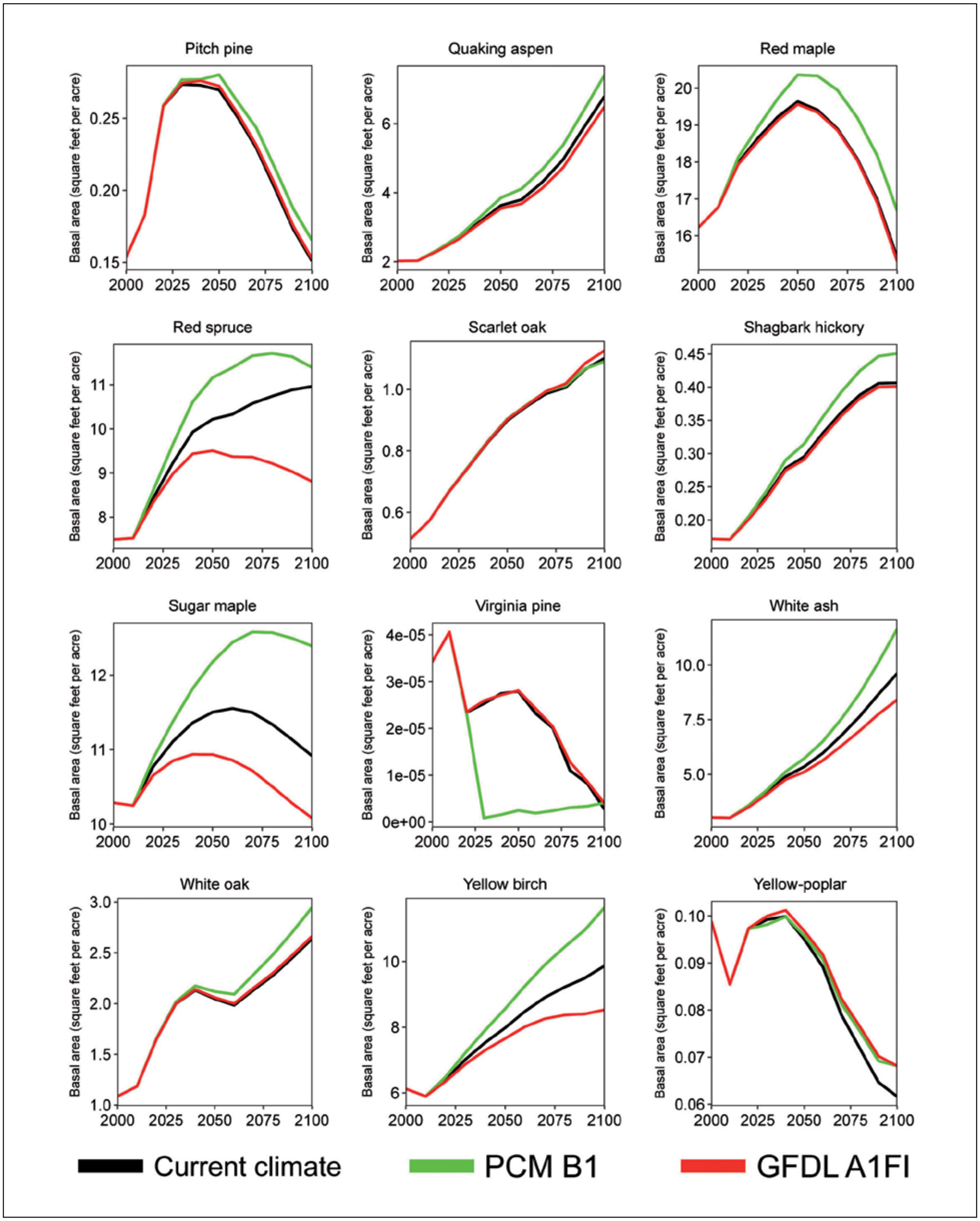

Figure 47 (continued).—Projected change in basal area for 24 species in the assessment area using the LANDIS PRO model under the current climate and two climate change scenarios. Note that the panels have different Y-axis values.

APPENDIX 7: VULNERABILITY AND CONFIDENCE DETERMINATION

EXPERT PANEL PROCESS

To assess vulnerabilities to climate change for each forest system, we elicited input from a panel of 20 experts from a variety of land management and research organizations across the assessment area (Table 23). We sought a team of panelists who would be able to contribute a diversity of subject area expertise, management history, and organizational perspectives. Most panelists had extensive knowledge about the ecology, management, and climate change impacts on forests in the assessment area. This panel was assembled at an in-person workshop in Burlington, Vermont, in December 2015. During that workshop, we used a structured discussion process to assess the vulnerability of eight forest types; the methodology is described in greater detail by Brandt et al. (2017).

Table 23.—Participants in the December 2015 expert panel workshop

Participant	Organization
Diane Burbank	Green Mountain National Forest
Patricia Butler*	Northern Institute of Applied Climate Science and Michigan Technological University
John Campbell	U.S. Forest Service, Northern Research Station
Charlie Cogbill	Independent scientist
Tony D’Amato	University of Vermont
Bill Dijak	U.S. Forest Service, Northern Research Station
Matt Duveneck	Harvard Forest
Marla Emery	U.S. Forest Service, Northern Research Station
Nick Fisichelli	National Park Service
Jane Foster	University of Vermont/Northeast Climate Science Center
Jennifer Hushaw	Manomet Center for Conservation Sciences
Louis Iverson	U.S. Forest Service, Northern Research Station
Maria Janowiak*	Northern Institute of Applied Climate Science and U.S. Forest Service
Laura Kenefic	U.S. Forest Service, Northern Research Station
Amanda Mahaffey	Forest Stewards Guild
Steve Matthews	Ohio State University
Toni Lyn Morelli	Northeast Climate Science Center
Nick Reo	Dartmouth College
Paul Schaberg	U.S. Forest Service, Northern Research Station
K. Rogers Simmons	White Mountain National Forest
Aaron Weiskittel	University of Maine
Sandy Wilmot	Vermont Agency of Natural Resources

* Workshop facilitators

FOREST SYSTEMS ASSESSED

The authors of this assessment used the forest ecosystem classification described in Chapter 1. For each forest type, we collected information related to the major system drivers, dominant species, and stressors that characterize that system from the relevant ecological literature. The panel was asked to comment on and suggest modifications to the descriptions of the forest systems, and those suggestions were incorporated into the descriptions.

POTENTIAL IMPACTS

To examine potential impacts, the panel was given several sources of background information on past and future climate change in the Northeast (summarized in Chapters 2 and 3) and projected impacts on dominant tree species and forest productivity (summarized in Chapter 4). The panel was directed to focus on impacts to each forest type from the present through the end of the century, but more weight was given to the end-of-century period. The panel assessed impacts by considering a range of climate futures bracketed by two scenarios: GFDL A1FI and PCM B1. Panelists were then led through a structured discussion process to consider this information for each of the eight forest systems in the assessment.

Potential impacts on community drivers and stressors were summarized based on climate model projections, the published literature, and insights from the panelists. Impacts on drivers were considered positive or negative if they would alter system drivers in a way that would be more or less favorable for that forest system. Impacts on stressors were considered negative if they increased the influence of that stressor or positive if they decreased the influence of that stressor on the forest system. 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 Tree Atlas, LINKAGES, and LANDIS PRO model results, and were asked to consider those results in addition to their knowledge of life-history traits and ecology of those species. The panel evaluated how much agreement existed within the available information, between climate scenarios, and across space and time. Finally, panelists were asked to consider the potential for interactions among anticipated climate trends, species impacts, and stressors. Input on these future ecosystem interactions relied primarily on the panelists' expertise and judgment because there are not many examples of published literature on complex interactions, nor are future interactions accurately represented by ecosystem models.

ADAPTIVE CAPACITY

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

VULNERABILITY

After extensive group discussion, each panelist evaluated the potential impacts and adaptive capacity of each forest system to arrive at a vulnerability rating. Participants were provided with individual worksheets and asked to list the 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. 48A). 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 (Brandt et al. 2017). Individual ratings were compared, discussed, and used to arrive at a group determination. In many cases, the group determination was at or near the centroid of all individual determinations. Sometimes the group determination deviated from the centroid because further discussion convinced some group members to alter their original response.

CONFIDENCE

Panelists were also directed to give a confidence rating to each of their individual vulnerability determinations (Fig. 48B). Panelists were asked to evaluate the amount of evidence they felt was available to support their vulnerability determination and the level of agreement among the available evidence (Mastrandrea et al. 2010). Panelists evaluated confidence individually and as a group, in a similar fashion to the vulnerability determination.

Vulnerability and Confidence Figures

For reference, figures of individual and group determinations for all eight forest systems considered in this assessment are displayed in Figures 49 through 56. 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.

Vulnerability Statements

Recurring themes and patterns that transcended individual forest systems were identified and developed into vulnerability statements (boldface text) and supporting text in Chapter 5. The coordinating 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 coordinating lead author's interpretation of the amount of information available to support each statement and the extent to which the information agreed. Each statement and its supporting literature discussion were sent to the expert panel for review. Panelists were asked to review each statement for accuracy, whether the confidence determination should be raised or lowered, if there was additional literature that was overlooked, and if there were any additional statements that needed to be made. Any changes that were suggested by a single panelist were brought forth for discussion. Changes to vulnerability statements required approval by the entire panel.

LITERATURE CITED

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Mastrandrea, M.D.; Field, C.B.; Stocker, T.F.; Edenhofer, O.; Ebi, K.L.; Frame, D.J.; Held, H.; Kriegler, E.; Mach, K.J.; Matschoss, P.R.; Plattner, G.-K.; Yohe, G.W.; Zwiers, F.W. 2010. **Guidance note for lead authors of the IPCC Fifth Assessment Report on consistent treatment of uncertainties.** Geneva, Switzerland: Intergovernmental Panel on Climate Change. Available at https://www.ipcc.ch/pdf/supporting-material/uncertainty-guidance-note.pdf (accessed July 11, 2017).

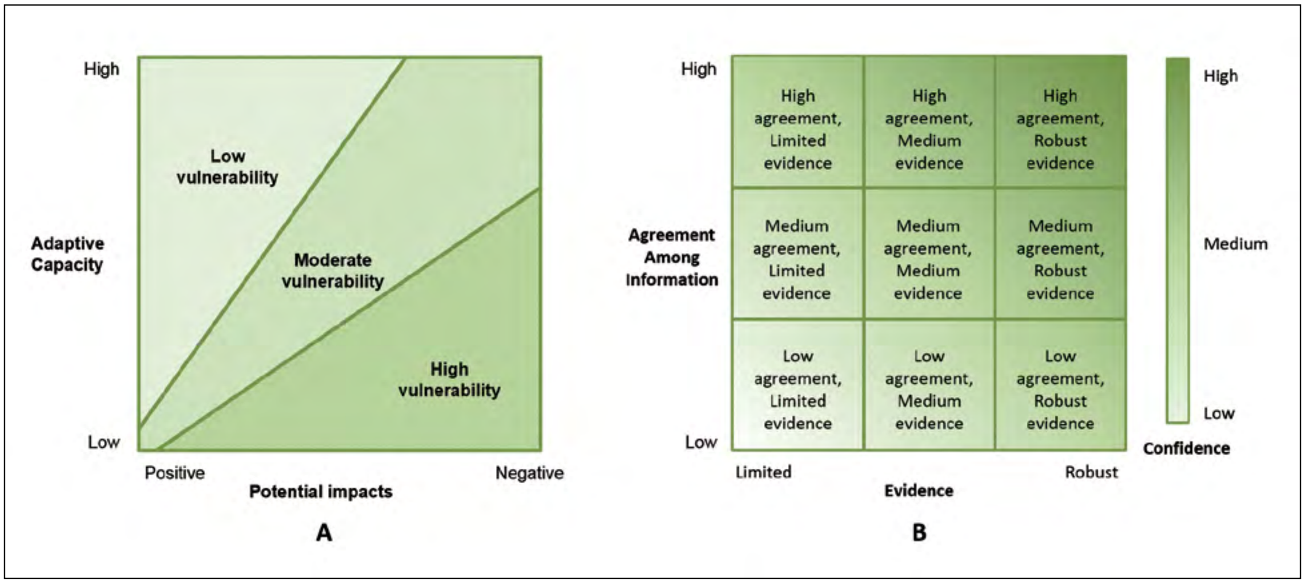

Figure 48.—Figure used for (A) vulnerability determination by expert panelists (described by Brandt et al. [2017]), and (B) confidence rating among expert panelists (adapted from Mastrandrea et al. [2010]).

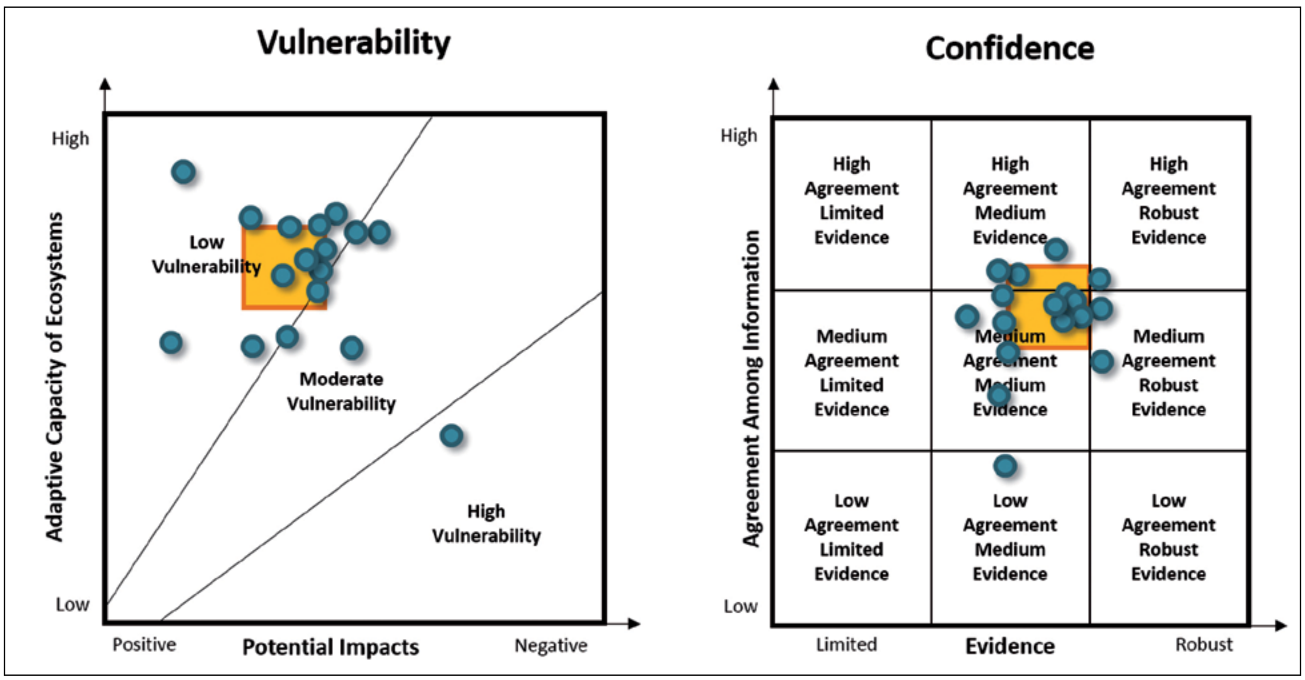

Figure 49.—Vulnerability and confidence determinations for the central hardwood-pine forest system. Circles indicate individual determinations by each panelist and squares indicate the group determination after consensus was reached.

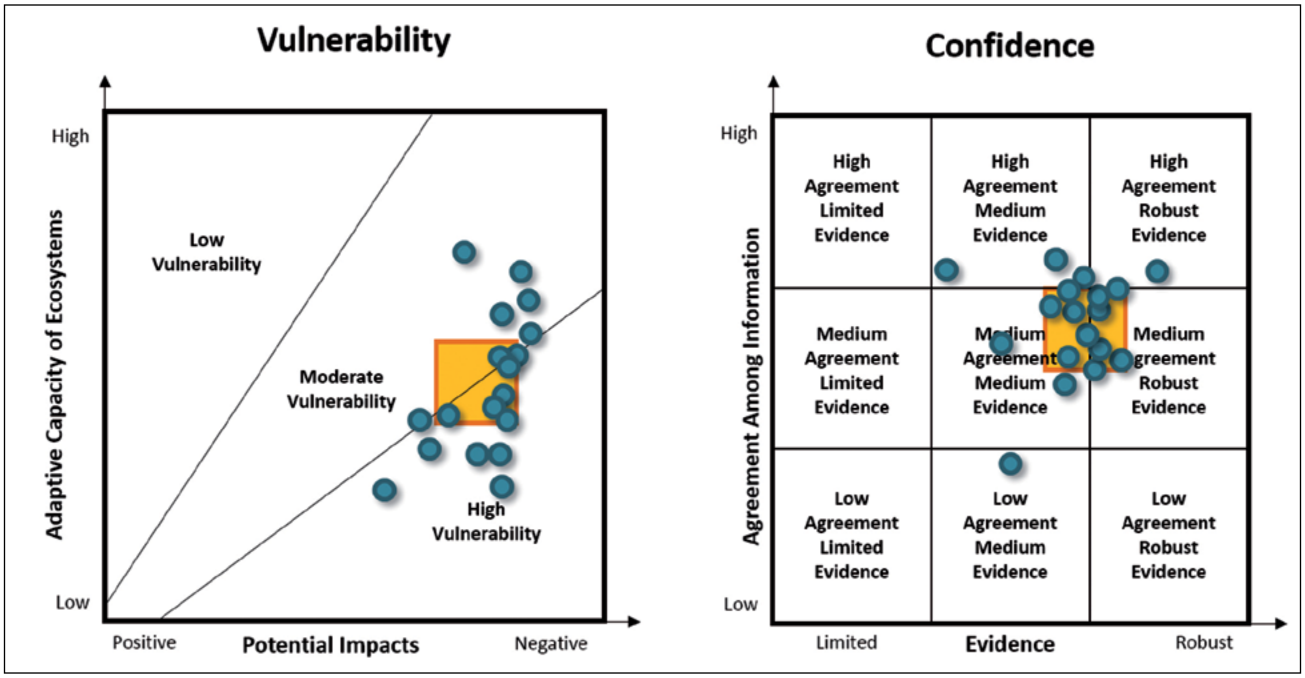

Figure 50.—Vulnerability and confidence determinations for the low-elevation spruce-fir forest system. Circles indicate individual determinations by each panelist and squares indicate the group determination after consensus was reached.

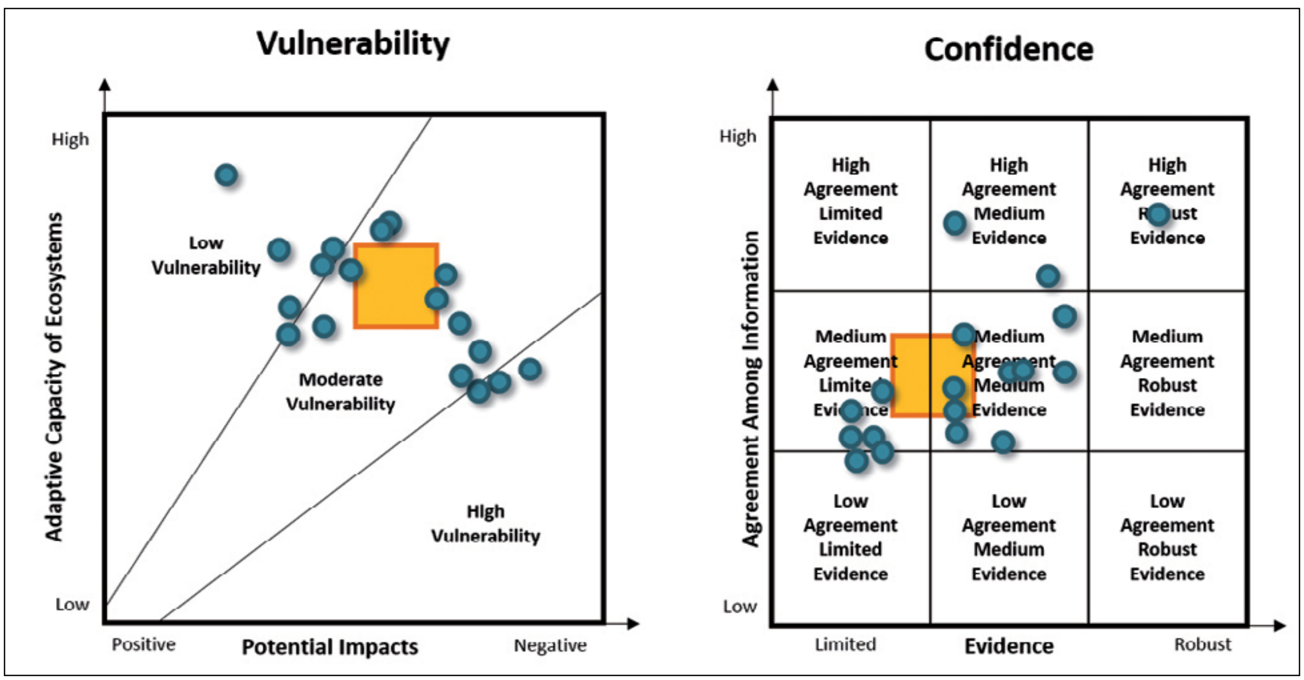

Figure 51.—Vulnerability and confidence determinations for the lowland and riparian hardwood forest system. Circles indicate individual determinations by each panelist and squares indicate the group determination after consensus was reached.

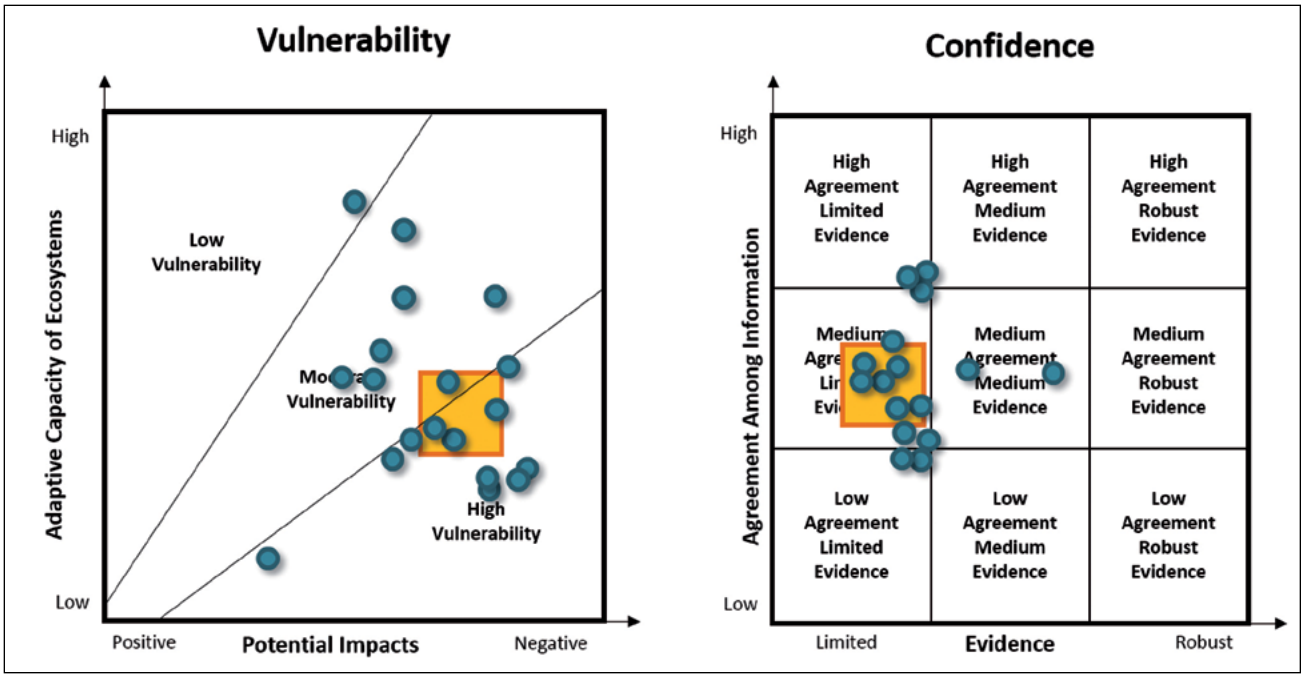

Figure 52.—Vulnerability and confidence determinations for the lowland mixed-conifer forest system. Circles indicate individual determinations by each panelist and squares indicate the group determination after consensus was reached.

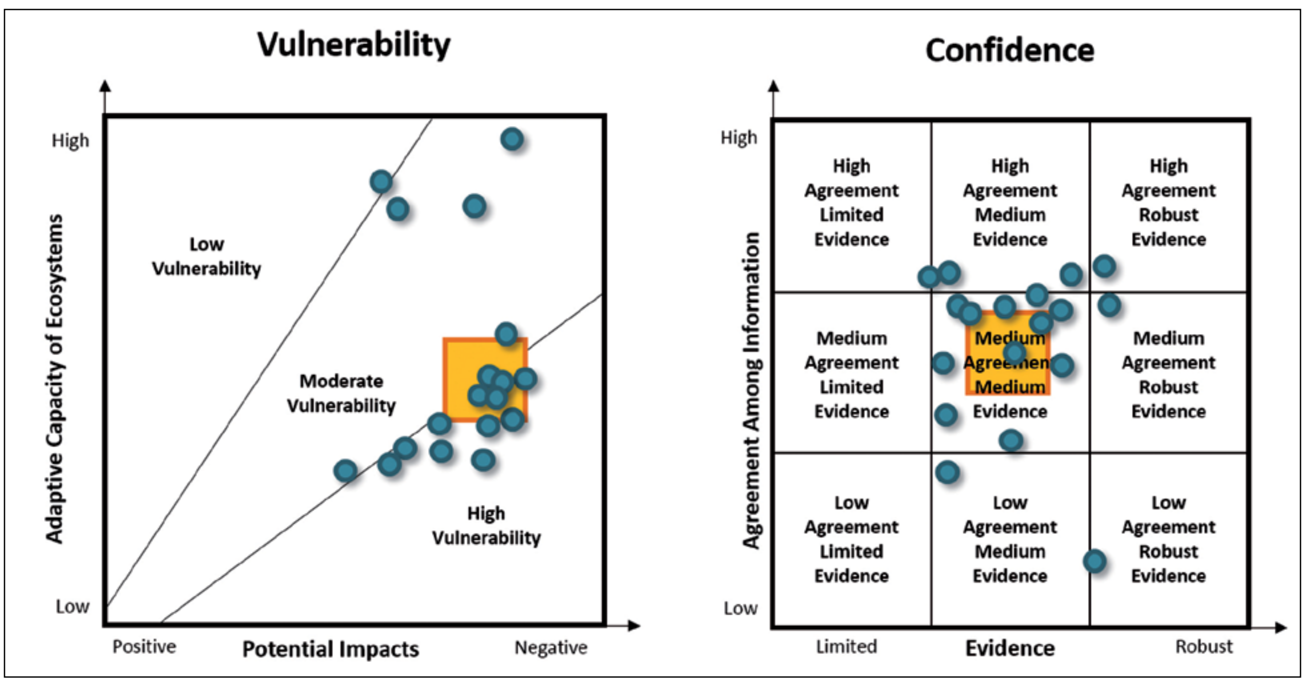

Figure 53.—Vulnerability and confidence determinations for the montane spruce-fir forest system. Circles indicate individual determinations by each panelist and squares indicate the group determination after consensus was reached.

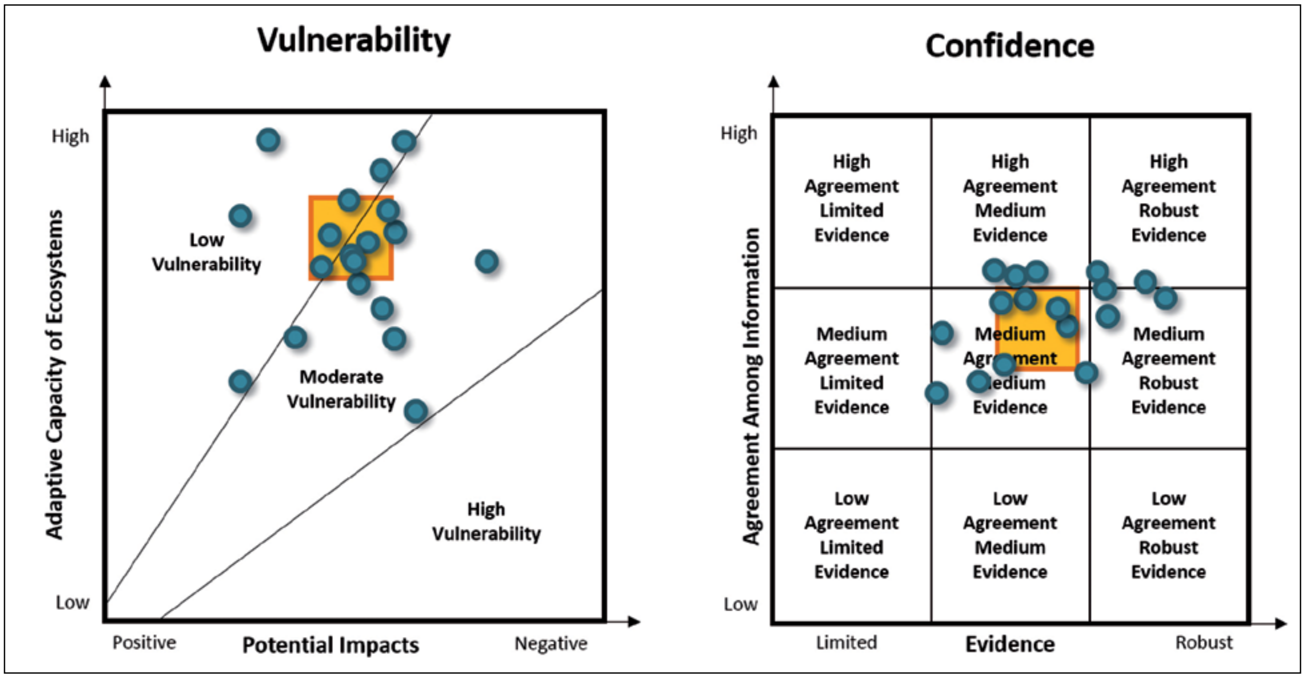

Figure 54.—Vulnerability and confidence determinations for the northern hardwood forest system. Circles indicate individual determinations by each panelist and squares indicate the group determination after consensus was reached.

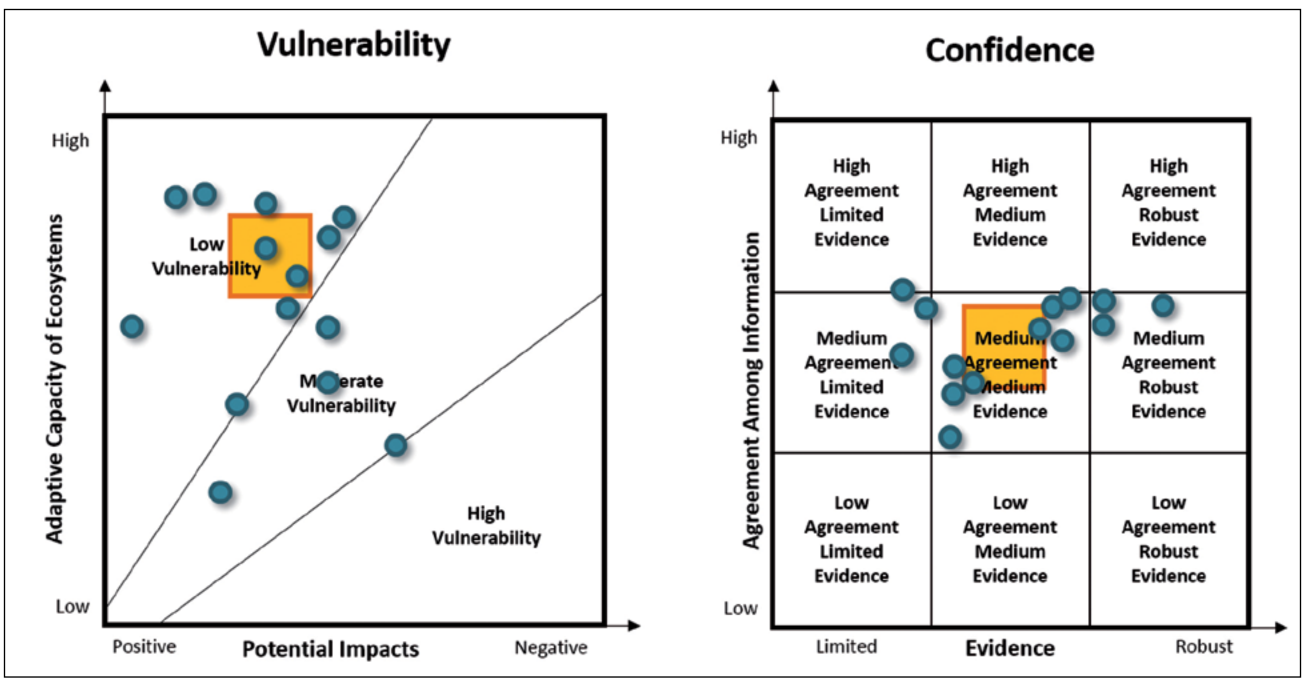

Figure 55.—Vulnerability and confidence determinations for the pitch pine-scrub oak forest system. Circles indicate individual determinations by each panelist and squares indicate the group determination after consensus was reached.

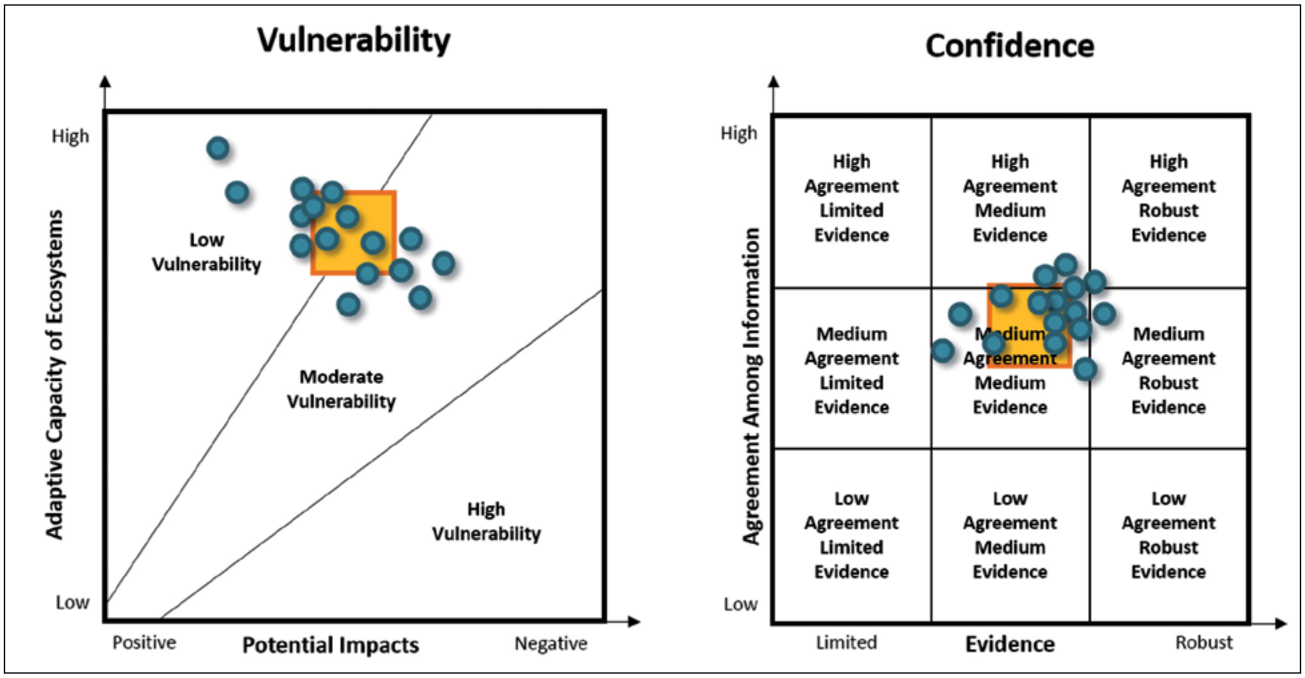

Figure 56.—Vulnerability and confidence determinations for the transition hardwood forest system. Circles indicate individual determinations by each panelist and squares indicate the group determination after consensus was reached.

APPENDIX 8: CLIMATE CHANGE IMPACTS ON BIODIVERSITY

Climate change will have profound effects on the species associated with forest ecosystems. Several detailed assessments have been developed to evaluate the vulnerability of species and habitats across the Northeast (see Introduction). This appendix provides a short review of some effects on wildlife, aquatic organisms, and plant species of concern in the assessment area.

WILDLIFE

Climate change is likely to have both direct and indirect impacts on wildlife populations and their habitats, and managers will increasingly need to consider these effects (Mawdsley et al. 2009). Changes to habitats discussed in Chapter 6 are likely to result in range expansion for some species and the reduction or complete loss of available suitable habitat for others. Wildlife populations may adapt to new conditions by shifting the timing of life cycle events, altering their physiology (e.g., developing tolerance to warmer and drier conditions), and changing their behavior (e.g., foraging for new food sources), or they may migrate to follow shifts in suitable habitat (Bellard et al. 2012). Species that are unable to adapt or have limited dispersal ability, particularly those that are already rare, may face the most substantial challenges in a changing climate.

Climate change is expected to shift the ranges of other boreal and subalpine specialists northward, which is expected to result in the fragmentation and loss of southern populations (Cheng et al. 2014). Snowshoe hares, for example, are likely to have mismatches between coat color and ground cover for longer as the number of snow-free days increases, leading to increased vulnerability to predators (Zimova et al. 2014). The moose is another cold-adapted species considered to be highly vulnerable to climate change in the Northeast (Hoving et al. 2013, Whitman et al. 2013) although conditions in some areas of the region, such as Massachusetts, are currently favorable for moose (Wattles and DeStefano 2013). Extreme infestations of winter tick, exacerbated by milder winters, can cause substantial mortality to moose (Musante et al. 2007), and increasing white-tailed deer populations can spread pathogens such as brainworm. Thermoregulatory stress associated with rising temperatures may also play an important role in moose population dynamics (Dou et al. 2013, Murray et al. 2006). The northern flying squirrel is an example of a species threatened by the northward shift of spruce-fir and northern hardwood ecosystems, which may reduce access to habitat and to the fungi and lichen that are important food sources for this squirrel species. Habitat and temperature changes are already allowing southern flying squirrels to expand northward; the subsequent decline of northern flying squirrels is associated with disease transmission and competition (Smith 2012).

Not all effects of climate change will be negative. The New England cottontail may benefit from decreased snow cover and forest disturbance in the Northeast. But indirect effects through changing relationships with other species such as predators and competitors are hard to predict. For example, if climate change affects eastern cottontails positively, there may be increased competition for New England cottontails (Fuller and Tur 2012). Milder winters may reduce the time that black bears spend in hibernation; increased bear activity combined with the potential for low food availability during winter months may increase the potential for human-bear conflict, as bears are more likely to visit urbanized areas in search of food during shortages (Baruch-Mordo et al. 2014, Obbard et al. 2014).

Generalist species such as the coyote may benefit from the greater food availability in milder winters (Knowlton and Gese 1995, O'Donoghue et al. 1997, Todd and Keith 1983, Windberg 1995). Likewise, milder winters may be advantageous to wild turkeys (Porter et al. 1983) and wood ducks (Oli et al. 2002). White-tailed deer are likely to benefit from milder winters and longer growing seasons (Mech et al. 1987, Post and Stenseth 1998).

With declines in bat populations due to white-nose syndrome, many managers are now thinking about how management might affect bat species. Bats may be particularly sensitive to climate change because many aspects of their ecology and life history are closely tied to temperature and precipitation, and many species in the assessment area have already suffered catastrophic declines as a result of white-nose syndrome. For example, the northern long-eared bat (northern myotis) is highly affected by white-nose disease while overwintering, but it is unclear whether climate change will increase overwintering stress (by decreasing access to insects or by causing bats to arouse more frequently from hibernation) or decrease overwintering stress (because a longer growing season may translate to a short hibernation time) (Rodenhouse et al. 2009). Hoary bats in the Northeast have been known to roost exclusively in eastern hemlock trees (Veilleux et al. 2009), which face increased risk of mortality from the hemlock woolly adelgid as a result of climate change (Paradis et al. 2008). On the other hand, increases in precipitation at the right time may bode well for insectivorous bat species (Moosman et al. 2012). Moreover, climate change may increase riparian habitat, which has been shown to be important for foraging by bats (e.g., hoary bats and big brown bats), in some areas of the Northeast in coming decades (Menzel et al. 2005).

Many bird species may be less vulnerable to climate change impacts than other taxonomic groups because they tend to have less habitat specificity, are able to disperse long distances, and are not as hindered by natural and anthropogenic obstacles on the landscape. American woodcocks are common in early successional forests and have already been found to be arriving earlier in Massachusetts and New York (Butler 2003) and breeding earlier in Maine (Wilson et al. 2000). However, bird species that are dependent on specific habitat types (e.g., high-elevation conifer forest) may be unable to meet their habitat requirements in a new location, or habitat shifts may introduce new competitors and predators (Matthews et al. 2011). Blackpoll warblers breed in the spruce-fir forests of the Northeast. As that habitat contracts northward and upslope, the species is likely to become less common. Some modeling studies have projected breeding populations of blackpoll warblers will be greatly reduced or extirpated from New York, Vermont, and New Hampshire by 2080, depending on the climate scenario used (Ralston and Kirchman 2013). Adequate snow cover and quality can also be important for overwinter survival in grouse (Whitaker and Stauffer 2003) and climate change might greatly reduce the proportion of the New England landscape that is capable of supporting ruffed grouse by 2080 (McGarigal et al. 2016). Other potential climate change impacts include changes in the timing of migration for some birds, or the resources (e.g., flowers, seeds, larvae) upon which they depend. Birds arriving either too early or too late could face suboptimal conditions (e.g., limited food resources or difficulty finding mates), resulting in adverse impacts to fitness and survival (Fraser et al. 2013).

Freshwater turtles will be affected by climate change in a variety of ways, mostly acting through effects on water temperature and flow. Wood turtles are particularly sensitive to flooding events (Jones and Sievert 2009). In contrast, map turtle hatchlings emerge later in the season with increasing temperatures and rain events, resulting in higher survival (Nagle et al. 2004). Population sex ratio determination is an important consideration in turtles, as it is driven by temperature. Thus, there is concern that populations will begin to be artificially skewed toward more females or more males, depending on the life history of the particular species and location of the population. Experimental manipulation has shown a lack of adaptive capacity to compensate for sex ratio bias resulting from warming nest temperatures, at least in some species (Refsnider et al. 2013). However, other studies have pointed out that the amount of atmospheric warming required to raise nest temperatures enough to affect sex ratio is not expected until late in the century, at least for eastern box turtles (Savva et al. 2010).

AQUATIC ORGANISMS

Aquatic organisms are expected to be affected by more-intense precipitation events, water quality changes, and other changes to the hydrology of the assessment area. Thermal habitat in cold-water lakes and streams may be further impaired as temperatures continue to warm. Altered precipitation patterns may influence streamflows, and more frequent and intense storms, rain-on-snow events, and other hydrologic changes may promote streambank and shoreline erosion, leading to increased turbidity and reduced water quality. These impacts may not occur equally across species or even across life stages of a given organism.

Warming water temperatures could influence activity levels, demand for food, growth rates, interspecific interactions, and the amount of suitable habitat available for freshwater fish. Cold-water and cool-water fish species, particularly populations inhabiting small, high-elevation streams that may encounter elevated water temperatures or drying of streambeds, are highly vulnerable to climate change impacts. Brook trout are sensitive to increased water temperatures, and riparian cover can locally buffer the effects of increasing temperatures (Argent and Kimmel 2013), potentially allowing for adaptive capacity in the species (Stitt et al. 2014). Competition for prey and thermal refugia typically constrains brook trout growth (Petty et al. 2014). Although cold-water species, such as brook and rainbow trout, may be adversely affected by impacts on their reproduction and exposure to more low-flow conditions in summer, evidence suggests that smallmouth bass and other warm-water species may show increased growth rates and northward expansion as temperatures rise (Groffman et al. 2014, Pease and Paukert 2014).

Freshwater mussels are already under threat from development, urbanization, and pollution. Many are nonmigratory with limited vertical movement and rely on flood events to make large distribution shifts (Furedi 2013). Increased flooding from climate change may decrease water quality as well as displace individuals from suitable habitat, while summer drought could slow or eliminate critical flows (Santos et al. 2015). For example, the dwarf wedgemussel is considered extremely vulnerable to climate change and especially increased flooding in the Northeast; populations are highly localized in areas within a narrow band of precipitation (Furedi 2013). Another species, the eastern pearlshell, is considered extremely vulnerable to climate change as it is found in cold, nutrient-poor, unpolluted streams and smaller rivers with moderate flow rates (Furedi 2013). Another study, however, found that it might have some capacity to adapt to increasing temperatures and shifting flows (Hastie et al. 2003). It may also be sensitive to sea-level rise. Cascading effects could result from shifts by its host species.

PLANT SPECIES OF CONCERN

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 specific combinations of environmental and habitat conditions, in many cases as relict populations from previous climatic conditions (Devall 2009). Threatened and endangered species often face population declines due to a variety of other factors, including habitat loss, competition from invasive species, and disease. As temperatures become warmer and the precipitation regime changes, already rare or declining species may therefore be among the first to undergo 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. 2006). In the absence of human intervention, rare or threatened species may face greater extinction risks. Alternatively, rare species that live in habitats that are buffered from climate shifts (i.e., refugia) may be able to persist. Vulnerability assessments for some states in the region, such as Massachusetts (Manomet and Massachusetts Division of Fisheries and Wildlife 2010) and Maine (Whitman et al. 2014), include consideration of rare or threatened plant species.

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Forest ecosystems will face direct and indirect impacts from a changing climate over the 21st century. This assessment evaluates the vulnerability of forest ecosystems across the New England region (Connecticut, Maine, Massachusetts, New Hampshire, northern New York, Rhode Island, and Vermont) 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 natural resource professionals familiar with the forests of this region to assess ecosystem vulnerability through a formal consensus-based expert elicitation process.

Observed trends in climate over the historical record from 1901 through 2011 show that the mean annual temperature has increased across the region by 2.4 °F, with even greater warming during winter. Precipitation patterns also changed during this time, with a slight trend toward greater annual precipitation and a substantial increase in extreme precipitation events. Projected climate trends using downscaled global climate model data indicate a potential increase in mean annual temperature of 3 to 8 °F for the assessment area by 2100. Projections for precipitation indicate an increase in fall and winter precipitation, and spring and summer precipitation projections vary by scenario. We identified potential impacts on forests by incorporating these future climate projections into three forest impact models (DISTRIB, LINKAGES, and LANDIS PRO). Model projections suggest that many northern and boreal species, including balsam fir, red spruce, and black spruce, may fare worse under future conditions, but other species may benefit from projected changes in climate. Published literature on climate impacts related to wildfire, invasive species, and forest pests and diseases also contributed to the overall determination of climate change vulnerability.

We assessed vulnerability for eight forest communities in the assessment area. The assessment was conducted through a formal elicitation process with 20 scientists and resource managers from across the area, who considered vulnerability in terms of the potential impacts and the adaptive capacity for an individual community. Montane spruce-fir, low-elevation spruce-fir, and lowland mixed conifer forests were determined to be the most vulnerable communities. Central hardwoods, transition hardwoods, and pitch pine-scrub oak forests were perceived as having lower vulnerability 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 animals and plants, recreation, and long-term natural resource planning.

KEY WORDS: Climate Change Tree Atlas, LINKAGES, LANDIS PRO, adaptive capacity, expert elicitation, climate projection, Connecticut, Maine, Massachusetts, New Hampshire, New York, Rhode Island, Vermont

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