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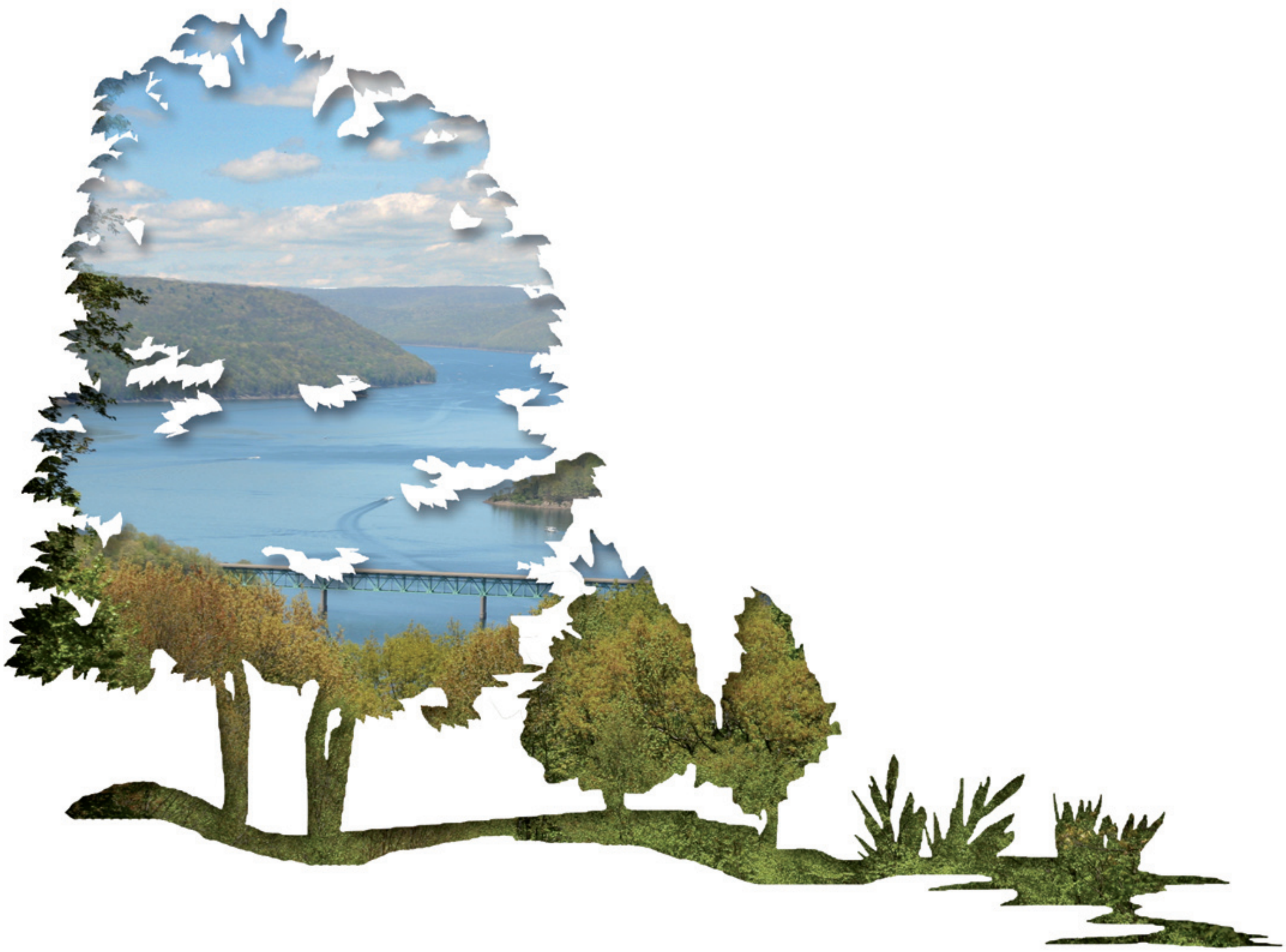
Mid-Atlantic Forest Ecosystem Vulnerability Assessment and Synthesis:

A Report from the Mid-Atlantic Climate Change Response Framework Project



Forest Service | Northern Research Station | General Technical Report NRS-181 | October 2018

Forest ecosystems will be affected directly and indirectly by a changing climate over the 21st century. This assessment evaluates the vulnerability of 11 forest ecosystems in the Mid-Atlantic region (Pennsylvania, New Jersey, Delaware, eastern Maryland, and southern New York) 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 forest impact models, which provided a range of potential tree responses to climate. Finally, we brought these results before two multidisciplinary panels of scientists and land managers familiar with the forests of this region to assess ecosystem vulnerability through a formal consensus-based expert elicitation process.

Each chapter of this assessment builds on the previous chapter. The description of the contemporary landscape presents major forest trends and stressors currently threatening forests in the Mid-Atlantic region and defines the forest communities being assessed. The background information in Chapter 2 summarizes climate data analysis and climate models. Analysis of climate records in Chapter 3 indicates that average temperatures and total precipitation in the region have increased. Downscaled climate models in Chapter 4 project potential increases in temperature in every season, but projections for precipitation indicate slight increases in winter and spring, and high variability in summer and fall projections, depending on the scenario. Potential impacts on forests in Chapter 5 were identified by incorporating the future climate projections into three forest impact models (DISTRIB, LINKAGES, and LANDIS PRO). These models project declines in growth and suitable habitat for many mesic species, including American beech, eastern hemlock, eastern white pine, red spruce, and sugar maple. Species that tolerate hotter, drier conditions are projected to persist or increase, including black oak, northern red oak, pignut hickory, sweetgum, and white oak. Climate impacts related to topics such as wildfire, invasive species, and forest pests were not included in the forest impact models, but were summarized from published literature.

In Chapter 6, we assessed vulnerability for 11 forest communities in the Mid-Atlantic region. Twenty-six science and management experts from across the region considered vulnerability in terms of the potential impacts on a forest ecosystem and the adaptive capacity of the ecosystem. The montane spruce-fir and lowland conifer forest communities were determined to be the most vulnerable ecosystems in the interior portion of the Mid-Atlantic region. Maritime and tidal swamp forest communities were determined to be the most vulnerable ecosystems in the coastal plain portion of the region. The woodland, glade, and barrens forest community was perceived as less vulnerable to projected changes in climate. Forest ecosystem vulnerabilities are expected to affect other forest-dependent topics such as wildlife management, timber production, and recreation. Information on these and other topics is summarized in Chapter 7.

Cover Photo

Allegheny Reservoir. This 25-mile-long lake touches nearly 100 miles of forested shoreline within the Allegheny National Forest boundaries, and provides both recreation opportunities and municipal water. Photo by USDA Forest Service, Eastern Region, via flickr.com.

Manuscript received for publication February 2018

Published by:

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

October 2018

For additional copies, contact:

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

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PREFACE

CONTEXT AND SCOPE

This assessment is a fundamental component of the Mid-Atlantic Climate Change Response Framework project led by the Northern Institute of Applied Climate Science. 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 in the Mid-Atlantic region, in addition to other people who study, recreate, and live in these forests. As new scientific information arises, we will develop future versions to reflect that accumulated knowledge and understanding. Most importantly, this assessment does not make recommendations about how this information should be used.

The scope of the assessment is terrestrial forest 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 were coordinated by 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, 3, and 4. Louis Iverson, Stephen Matthews, Matthew Peters, and Anantha Prasad provided and interpreted Climate Change Tree Atlas information for Chapter 5, and assisted with the data processing for the climate data presented in Chapter 4. Frank Thompson, William Dijak, and Jacob Fraser provided results and interpretation of the LINKAGES and LANDIS PRO models. All modeling teams coordinated their efforts impressively.

Among the many others who made valuable contributions to the assessment, Scott Pugh (USDA Forest Service, Forest Inventory and Analysis [FIA] program) provided technical and analytical support for querying FIA databases. We also thank Kathleen Walz (New Jersey Natural Heritage Program) for valuable contributions throughout the writing of this assessment. We also thank Margot Kaye (Penn State), Stephen Shifley (USDA Forest Service, Northern Research Station), and John Drake (State University of New York College of Environmental Science and Forestry), who provided formal technical reviews of the assessment. Their thorough reviews greatly improved the quality of this assessment.

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CONTENTS

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EXECUTIVE SUMMARY

This assessment evaluates key vulnerabilities for forest ecosystems in the Mid-Atlantic region across a range of future climate scenarios. This assessment was completed as part of the Mid-Atlantic 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 forest impact models that project 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 ecosystems within the assessment area through the end of this century. A final chapter summarizes the implications of these impacts and vulnerabilities for a variety of forest-related ecological, social, and economic topics across the region.

CHAPTER 1: THE CONTEMPORARY LANDSCAPE

Forests are a prominent feature of the landscape across the Mid-Atlantic region. Stretching from the Atlantic coast to the peaks of the Appalachian Mountains, our assessment area covers about 60 million acres and is approximately 50 percent forested (Fig. 1). This chapter describes the assessment area and purpose of this document. It also describes the forest communities assessed in later chapters and summarizes current forest threats and management trends. This information lays the foundation for understanding how shifts in climate may contribute to changes in forest ecosystems, and how climate may interact with other stressors on the landscape.

Main Points

- Of the nearly 60 million acres of land in the assessment area of the Mid-Atlantic region, about 32 million acres is forested. Private individuals, corporations, and conservation organizations own 74 percent of the forest land, and the remaining forest is owned by Federal, State, and municipal entities. Oak/hickory and maple/beech/birch are the most abundant forest-type groups across the area.

Figure 1.—The assessment area (shaded in green): eastern Maryland, southern New York, and the whole states of Pennsylvania, Delaware, and New Jersey.

- Historical land use and past management practices have resulted in second-growth forests that are young compared to pre-European settlement conditions.
- Current major stressors and threats to forest ecosystems in the Mid-Atlantic region include:
  - Fragmentation and land-use change (e.g., energy, agriculture, or residential development)
  - Shifts in natural disturbance regimes (e.g., shifts in fire regimes, drought frequency, or flood frequency)
  - Forest diseases and insect pests
  - Establishment of nonnative invasive plant species
  - Sea-level rise
  - Extreme weather events
  - Herbivory
- The forest products and forest-related recreation industries are major contributors to the regional economy, and an increasing amount of forest land is managed according to a sustainability certification standard.
- Net forest growth (gross growth minus mortality) is nearly three times as great as removals. Private forest lands, which include both industrial and nonindustrial ownerships, accumulate the most growing stock.
- Eleven forest communities are used to describe the forests in the Mid-Atlantic region. The descriptions of forest communities were based on macrogroups defined in the Northeast Terrestrial Habitat Classification System, but were revised as part of the expert elicitation process.

CHAPTER 2: CLIMATE CHANGE SCIENCE AND MODELING

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

Main Points

- Temperatures have increased at a global scale and across the United States over the past century. Climate scientists attribute this increase in temperature to increases in greenhouse gases resulting from human activities.
- Scientists use models, which are simplified representations of reality, to simulate future climates. In this assessment, general circulation models are used to project future climate and as inputs to forest impact models. The GFDL model developed by the National Oceanic and Atmospheric Administration is considered moderately sensitive to changes in greenhouse gas concentrations, and the PCM model developed by the National Center for Atmospheric Research is considered to have low sensitivity to greenhouse gas concentrations.
- General circulation models require estimates of future greenhouse gas concentrations. This assessment pairs the GFDL model with the most fossil-fuel intensive scenario developed by the Intergovernmental Panel on Climate Change [IPCC] Special Report on Emission Scenarios (A1FI) and pairs the PCM model with the least fossil-fuel intensive scenario (B1). These two model-scenario combinations represent the ends of a range of possible climate futures which are logical trajectories from the current climate.
- Climate projections for this assessment were statistically downscaled by using an asynchronous regional regression model. Daily mean, minimum, and maximum temperature and total daily precipitation were downscaled to an approximately 7.5-mile resolution grid across the United States.

- Downscaled climate projections from general circulation models provide important information about future climate, but forest impact models are required to explore how climate change may affect soil moisture, hydrology, forest composition, productivity, or interactions between these factors. In this assessment, we used one species distribution model, the Climate Change Tree Atlas, and two process models, LINKAGES and LANDIS PRO. These forest impact models operate at different spatial scales and provide different kinds of information.

CHAPTER 3: OBSERVED CLIMATE CHANGE

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

Main Points

- Temperature minimums (lows) and maximums (highs) have increased. Minimum temperatures have increased more than maximum temperatures in every season except spring, with the greatest increase in temperature during the winter.
- Precipitation patterns have changed across the region, with the most change occurring in fall (increase of 3.2 inches). The number of intense precipitation events has increased.
- Sea levels have risen in the Mid-Atlantic faster than global sea levels, about 12 inches since 1900 along the Atlantic coastline.
- Climate change is also indicated by observed changes in biological processes, such as growing season length, shifts in flowering phenology, and changes in wildlife emergence and migration.

CHAPTER 4: 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 increase over the next century, under a range of climate scenarios and 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.
- Localized soil moisture deficits are expected to become more frequent.
- The growing season length is expected to increase by up to 1 month.
- The number of hot days is expected to increase and the number of cold days is projected to decrease.
- Intense precipitation events are expected to become more frequent.
- Streamflow and flooding potential are expected to increase in the winter and spring, and decrease in the summer and fall.
- Sea level in the Mid-Atlantic is projected to rise by up to 7 feet by 2100, resulting in more flooding and storm surge.

CHAPTER 5: 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 Mid-Atlantic region.

Main Points

- Many mesic forest species, including American beech, eastern hemlock, eastern white pine, red spruce, and yellow birch, are among those projected to have reductions in suitable habitat, growth potential, and biomass under a high degree of warming over the next century.
- Many species are expected to lose regeneration potential over the next century, but mature individuals could continue to grow for much longer in the absence of other mortality factors.
- Many southern species—species with ranges extending largely south of the Mid-Atlantic region, including post oak, scarlet oak, and southern red oak—are projected to increase in suitable habitat and biomass within the Mid-Atlantic region.
- The forest impact models used in this assessment isolate the effects of climate change on tree species' growth and habitat, and do not account for many other factors that influence forests. Scientific literature was used to provide additional information on the effects of climate change on other factors such as:
  - Moisture stress
  - Acid deposition and carbon dioxide fertilization
  - Altered nutrient cycling
  - Invasive species, insect pests, and forest diseases
  - Herbivory on young regeneration
  - Interactions among these factors

CHAPTER 6: FOREST ECOSYSTEM VULNERABILITIES

This chapter focuses on the vulnerability of major forest ecosystems in the Mid-Atlantic region to climate change (Table 1). Detailed vulnerability determinations are provided for 11 forest ecosystems with an emphasis on dominant species, features that define a system (drivers), and features that disturb a system (stressors). The adaptive capacity of each forest ecosystem was also examined as a key component to overall vulnerability. 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 2007). We further rated the evidence used in assessing vulnerability as well as the level of agreement between sources of evidence. We consider a system to be vulnerable if it is at risk of a species composition change leading to a substantially different character for the forest system, or if the system is anticipated to suffer substantial declines in acreage, health, or productivity. General trends in climate change impacts and adaptive capacity factors for the Mid-Atlantic region are also captured in overarching synthesis statements.

Main Points

Potential Impacts of Climate Change on Ecosystem 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 Mid-Atlantic region.

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

Forest community	Potential impacts	Adaptive capacity	Vulnerability	Evidence	Agreement
Coastal Plain					
Maritime forest	Negative	Moderate-Low	High	Medium-Robust	Medium-High
Oak-pine-hardwood	Moderate-Positive	High	Moderate-Low	Medium	Medium-High
Pine-oak barrens	Moderate	Moderate	Moderate-Low	Medium-Robust	Medium-High
Swamp	Moderate	Moderate-High	Moderate-Low	Medium	Medium
Tidal swamp	Moderate-Negative	Moderate-Low	Moderate-High	Medium	Medium-High
Interior					
Central oak-pine	Moderate-Positive	Moderate-High	Moderate-Low	Medium	Medium-High
Lowland conifer	Negative	Moderate-Low	High	Medium	Medium
Lowland and riparian hardwood	Moderate	Moderate	Moderate	Medium-Limited	Medium
Montane spruce-fir	Negative	Low	High	Medium-Robust	High
Northern hardwood	Moderate-Negative	Moderate	Moderate-High	Medium-Robust	Medium-High
Woodland, glade, and barrens	Positive	Moderate-High	Low	Medium	Medium-High

- **The amount and timing of precipitation will change (robust evidence, high agreement).** There is strong agreement that precipitation patterns will change across the Mid-Atlantic region.
- **Intense precipitation events will continue to become more frequent (robust evidence, high agreement).** There is strong agreement among climate models that the number of heavy precipitation events will continue to increase in the Mid-Atlantic region. If they do increase, impacts from flooding and soil erosion may become more damaging.
- **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.
- **Soil moisture patterns will change in response to temperature and precipitation (medium evidence, high agreement).** Warmer temperatures and altered precipitation are expected to change soil moisture patterns throughout the year, but there is uncertainty about the direction and magnitude of the changes at specific locations.
- **Forest vegetation may face increased risk of physiological drought during the growing season (medium evidence, medium agreement).** Warmer temperatures can lead to decreased soil moisture even without an associated decrease in precipitation, resulting in a temporary inability for a tree to meet water demand.
- **Climate conditions will increase wildfire risk by the end of the century (medium evidence, medium agreement).** Some national and global studies suggest that conditions favorable for wildfire will increase, but few studies have specifically looked at wildfire risk in the Mid-Atlantic region. Wildfire risk will also depend on ignition, fire weather, ecosystem type, topography, fragmentation, and other regional characteristics.

- **Certain insect pests and pathogens will increase in occurrence or become more damaging (medium evidence, high agreement).** Evidence indicates that an increase in temperature, longer growing seasons, and more frequent disturbances 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 of Climate Change on Forest Communities

- **Northern and remnant boreal tree species will face increasing stress from climate change (medium evidence, high agreement).** Ecosystem models agree that these species may have reduced suitable habitat and biomass across the Mid-Atlantic region. These species may be less able than temperate forest species to take advantage of longer growing seasons and warmer temperatures.
- **Habitat will become more suitable for southern species (medium evidence, high agreement).** All three forest impact models project an increase in suitability and growth for southern species such as post oak, scarlet oak, and southern red oak compared to current climate conditions.
- **Forest composition will change across the landscape (medium evidence, high agreement).** Forest impact model results predict that habitat and biomass of individual tree species will change, and that tree species will respond uniquely. However, few studies have specifically examined how assemblages of species may change.
- **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; they are also expected to be more responsive to favorable conditions.
- **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 Mid-Atlantic region, but they disagree on how other factors such as species composition, stand age, disturbance, or pollution may interact to influence productivity. Changes are not expected to be consistent within a species, and the diversity of forest site conditions across the landscape suggests that changes will be spatially variable.

Adaptive Capacity Factors

- **Low-diversity forest communities are at greater risk (medium evidence, high agreement).** Studies have consistently shown that diverse systems are more resilient to disturbance, and low-diversity ecosystems are more vulnerable to change.
- **Most 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 most 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 may be impossible for tree species and forest communities with narrow habitat requirements.

- **Forest communities that have high tolerance to disturbance will be at lower risk of decline from shifting climate extremes (medium evidence, high agreement).** Basic ecological theory and other evidence suggest that communities adapted to disturbance will be at lower risk of declining on the landscape. However, some communities may tolerate only a narrow range of conditions related to a disturbance and may be susceptible to different, or more frequent and severe, disturbances.

CHAPTER 7: MANAGEMENT IMPLICATIONS

This chapter summarizes the implications of potential climate change impacts on important facets of forest management and planning in the Mid-Atlantic region, such as impacts on timber output, wildlife, or cultural resources. We point out key implications, ongoing research, and sources for more information on how climate change is expected to affect these topics. 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

- Climate change will present risks to forest management such as more disturbance, as well as opportunities such as longer growing seasons.
- Over the next century, climate change is expected to have profound effects on forest ecosystems, which will in turn lead to habitat changes for a variety of plant and animal species; management of forest-dependent plants and animals may face additional challenges as the climate shifts.
- Land conservation planning is expected to include more emphasis on climate adaptation strategies related to carbon mitigation, refugia for at-risk species and habitats, landscape connectivity for migration corridors, and water supply protection.
- Changes in climate and extreme weather events are expected to affect infrastructure such as roads, bridges, and culverts on forest lands throughout the region.
- The timing of activities, including timber removal, prescribed fire, and recreation, may need to be shifted as temperatures and precipitation patterns change.
- Responses to increased risk of wildfire may require more resources to reduce fuel loads, suppress fires after ignition, and manage ecosystems affected by wildfire.
- Climate change is expected to increase respiratory allergies and diseases, gastrointestinal illnesses, heat stress, and vector-borne diseases.

INTRODUCTION

CONTEXT

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

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

The Framework process is designed to work at multiple scales. The Mid-Atlantic Framework is coordinated across the region, but activities are generally conducted at the state or local level to allow for greater specificity. Other regional Framework projects are underway in the Central Appalachians, Central Hardwoods, New England, Northwoods, and Urban forests.

The Mid-Atlantic Framework is an expansion of the original northern Wisconsin effort, and has been supported in large part by the USDA Forest Service. Across the Mid-Atlantic region, the project is being guided by an array of partners with an interest in forest management, including:

- Northern Institute of Applied Climate Science
- USDA Forest Service, Eastern Region
- USDA Forest Service, Northern Research Station
- USDA Forest Service, Northeastern Area State & Private Forestry
- American Forests
- Center for Land Use and Sustainability
- Trust for Public Land
- The Nature Conservancy
- Natural Resources Conservation Service
- Northeast Climate Adaptation Science Center
- Pennsylvania Department of Conservation and Natural Resources
- Maryland Department of Natural Resources

This assessment is designed to provide detailed information for forest ecosystems across the Mid-Atlantic region. Several independent efforts related to climate change, natural ecosystems, and human well-being are also occurring at the state level. This assessment complements other assessments that have been created for the Mid-Atlantic region. The Framework project will also work to integrate the results and outcomes from other projects related to climate change and natural resource management.

This assessment bears some similarity to other synthesis documents about climate change science, such as the National Climate Assessment (https://nca2014.globalchange.gov/) and the Intergovernmental Panel on Climate Change reports (Working Group contributions to the Fifth Assessment at https://www.ipcc.ch/report/ar5/). Where appropriate, we refer to these larger-scale documents when discussing national and global changes. However, this assessment differs from these reports in many ways.

This assessment was not commissioned by any federal government agency, nor does it give advice or recommendations to any federal agency. It also does not evaluate policy options or provide input into federal priorities. Instead, this report was developed by the authors to fulfill a joint need of understanding local impacts of climate change on forests and assessing which tree species and forest ecosystems may be the most vulnerable in the Mid-Atlantic region. Although it was written to be a resource for forest managers, it is first and foremost a scientific document that represents the views of the authors.

SCOPE AND GOALS

The primary goal of this assessment is to summarize potential changes to the forest ecosystems of the Mid-Atlantic region under a range of possible future climates, and determine the vulnerability of forest ecosystems to these changes throughout the 21st century. Included is a synthesis of information about the current landscape as well as projections of climate and vegetation changes used to assess vulnerability. Uncertainties and gaps in understanding are discussed throughout the document.

This assessment covers about 60 million acres in eastern Maryland, Delaware, New Jersey, Pennsylvania, and much of New York (Fig. 1). The assessment area boundaries within these states are defined by six ecological provinces, according to the National Hierarchical Framework of Ecological Units: Northeastern Mixed Forest (211), Eastern Broadleaf Forest (221), Midwest Broadleaf Forest (222), Outer Coastal Plain Mixed Forest (232), Adirondack-New England Mixed Forest-Coniferous Forest-Alpine Meadow (M211), and Central Appalachian Broadleaf Forest-Coniferous Forest-Meadow (M221) (McNab and Avers 1994, McNab et al. 2007).

In addition to these state and ecological boundaries, we used county-level information that most closely represented the assessment area when ecoregional data were not available. We limited our selections to the counties that are most analogous to the assessment area.

Land ownership is fairly similar across the states or portions of states in the Mid-Atlantic region. Overall, more than 73 percent of forest land in the assessment area is owned by private individuals and organizations. State, county, and municipal lands compose the largest percentages of public forest land, followed by federal lands in National Forests, National Park Service land, and U.S. Department of Defense military installations. This assessment synthesizes information covering all forest lands in the assessment area in recognition of the area's dispersed patterns of forest composition and land ownership.

ASSESSMENT CHAPTERS

This assessment contains the following chapters:

Chapter 1: The Contemporary Landscape describes existing conditions, providing background on the physical environment, ecological character, and broad socioeconomic dimensions of the assessment area. It defines the 11 forest ecosystems we refer to in later chapters.

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

Chapter 3: Observed Climate Change provides information on the past and current climate of the assessment area, summarized from the interactive Climate Wizard database and published literature. This chapter also summarizes some relevant ecological indicators of observed climate change.

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

Chapter 5: Future Climate Change Impacts on Forests summarizes ecosystem model results that were prepared for this assessment. Three modeling approaches were used to simulate climate change impacts on forests: a species distribution model (DISTRIB of the 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 that the models did not consider.

Chapter 6: Forest Ecosystem Vulnerabilities synthesizes the potential effects of climate change on the forest ecosystems of the assessment area and provides detailed vulnerability determinations for 11 major forest ecosystems.

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

Red fox kits in Presque Isle State Park, Erie County, Pennsylvania. Photo by Greg Czarnecki, Pennsylvania Department of Conservation and Natural Resources, used with permission.

CHAPTER 1: THE CONTEMPORARY LANDSCAPE

The Mid-Atlantic region contains some of the most biologically diverse forests in North America. It is also home to almost 49 million people, most of whom reside in urban centers. Forests in the Mid-Atlantic region are primarily family-owned; state, federal, and industrial forest lands account for a relatively minor proportion of the forest land base. This chapter describes the current condition and major stressors of forests across the region to provide context for how these forests may change in the future.

REGIONAL SETTING

The assessment area is the Mid-Atlantic region, which is defined here by a combination of ecological and political boundaries and covers about 60 million acres in eastern Maryland, Delaware, New Jersey, Pennsylvania, and much of New York (Fig. 2). We hereafter use "assessment area" and "Mid-Atlantic region" interchangeably in this assessment. The Mid-Atlantic region overlaps six ecological provinces, according to the National Hierarchical Framework of Ecological Units: Northeastern Mixed Forest (211), Eastern Broadleaf Forest (221), Midwest Broadleaf Forest (222), Outer Coastal Plain Mixed Forest (232), Adirondack-New England Mixed Forest-Coniferous Forest-Alpine Meadow (M211), and Central Appalachian Broadleaf Forest-Coniferous Forest-Meadow (M221) (McNab and Avers 1994, McNab et al. 2007). New York north of the Catskill Mountains is included with the New England region in a separate assessment (Janowiak et al. 2018) because of the extensive northern forest communities that stretch from the Adirondack Mountains to Maine.

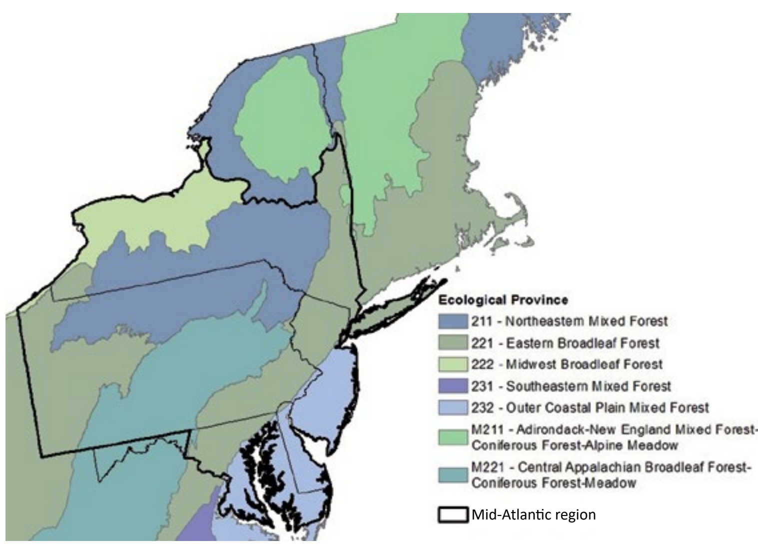


Figure 2.—Ecological provinces of the northeastern United States. The Mid-Atlantic region assessment area partly covers six ecological provinces and includes all or part of five states (Pennsylvania, Delaware, New Jersey, Maryland, and New York) (Cleland et al. 2007).

Ecological provinces are broad geographic areas that share similar coarse features, such as climate (Box 1), glacial history and soils, and vegetation types. The major physical and biological features of each ecological province in the Mid-Atlantic region are summarized next.

The Midwest Broadleaf Forest Province has a continental climate with warm to hot summers and frequent water deficits during the growing season. Lakes Ontario and Erie moderate temperatures throughout the year, and lake-effect precipitation is important in the fall and early winter. The topography is flat to hilly, with the lowest elevation close to Lake Erie, where characteristics of former glaciations are evident (Fig. 3).

Box 1: The Climate of the Mid-Atlantic Region

The current climate of the Mid-Atlantic region is strongly influenced by atmospheric circulation patterns, latitude, topography, and elevation (Fig. 3). In general, temperatures are warmer in the southern Mid-Atlantic, but they also increase as elevation drops from western mountainous terrain to the eastern coastal plain (Polsky et al. 2000). The Appalachian Mountains, which run from southwest to northeast, form a barrier to surface winds and contribute to different climatic conditions for the coastal versus inland areas (Kunkel et al. 2013b). The climate of the coastal areas is influenced by warm and humid easterly winds and by the Atlantic Ocean itself. In contrast, the climate of the inland area is influenced by a range of elevations, Lakes Ontario and Erie, and relatively dry westerly winds. Many climate extremes are observed in the Mid-Atlantic, including: extreme precipitation, flooding, winter storms (e.g., nor'easters), ice storms, drought, heat waves, tornadoes, tropical cyclones, and hurricanes (Kunkel et al. 2013a, McNab et al. 2007).

Based on the 1971 to 2000 climate average, the average annual temperature of the Mid-Atlantic region is 49 °F (10 °F) (Table 2). Mean winter temperature drops to 28 °F (-2 °C), and the coldest month is January, when the mean minimum temperature is 17 °F (-8 °C). Summer temperature averages 69 °F (21 °C), and the hottest month is July, when the mean maximum temperature reaches 82 °F (28 °C). Because of both geographic variation and daily variation, locations within the Mid-Atlantic region have experienced minimum and maximum temperatures that exceed these long-term regional averages. The freeze-free growing season is more than 200 days along the Atlantic coast, and becomes slightly shorter moving inland and upward in elevation. Annual precipitation averages 43.4 inches for the entire assessment area, but differs greatly from location to location (Appendix 3). Precipitation is most abundant in the higher elevations of the Catskill Mountains, where it can reach 70 inches per year. Precipitation is lowest over western New York, from Buffalo to Syracuse and south into Pennsylvania, where it can total 30 to 40 inches per year. Snowfall equivalents are included in these averages and follow a similar geographic pattern, with the high-elevation and lake-effect areas receiving a greater share of precipitation in the form of snow.

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

	Mean temperature (°F)	Mean minimum temperature (°F)	Mean maximum temperature (°F)	Mean total precipitation (inches)
Annual	49.2	38.8	59.5	43.4
Winter	28.5	19.8	37.3	9.1
Spring	47.6	36.4	58.7	11.1
Summer	69.0	57.8	80.2	12.1
Fall	51.6	41.3	61.9	11.1

[a]Additional data and maps are available in Appendix 2.

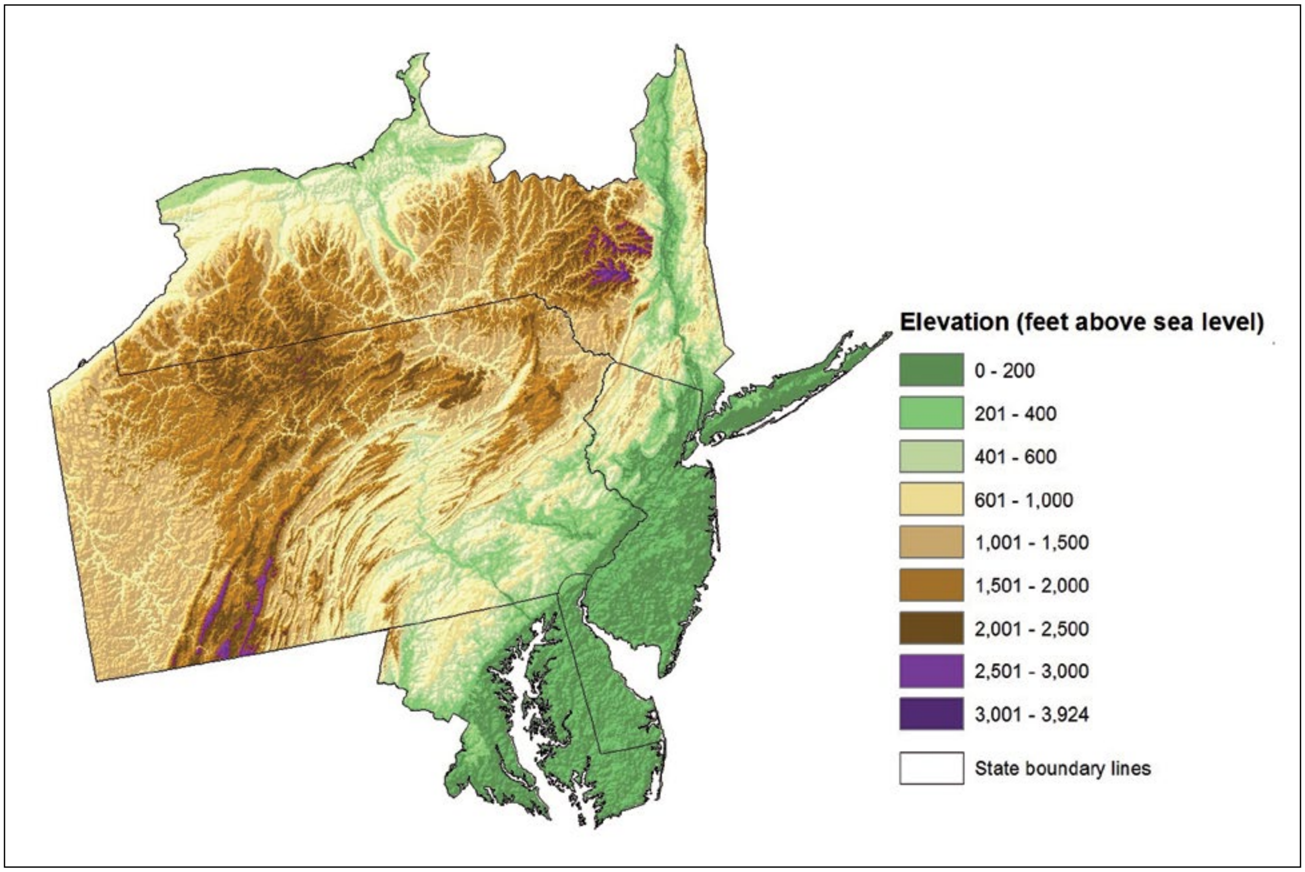


Figure 3.—Elevation zones within the Mid-Atlantic region. Data source: U.S. Geological Survey (1996).

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

The Eastern Broadleaf Forest Province has a warmer climate and longer growing season relative to the other provinces. The topography and bedrock geology vary greatly in this area, from broad, hilly plateaus in western Pennsylvania to the Atlantic coast in eastern New York. In western Pennsylvania, landscape features reflect a past glacial influence. This province generally has a warmer climate and longer growing season relative to the other provinces.

The Central Appalachian Broadleaf Forest-Coniferous Forest-Meadow Province has a temperate climate with cool summers and short, mild winters. Annual precipitation is abundant and is distributed relatively evenly throughout the year. This area is mountainous with a high degree of diversity in topography, geology, and soils.

The Outer Coastal Plain Mixed Forest Province has a distinct maritime climate with high humidity, mild winters, and warm summers. Precipitation is abundant and periods of drought are rare. The topography slopes down to the Atlantic Ocean, where elevation is near, at, or below sea level (Box 2).

The Adirondack-New England Mixed Forest-Coniferous Forest-Alpine Meadow Province is a tiny portion of the assessment area and is more similar

Box 2: The Coastal Plain

Starting east of the hills of the Piedmont, the coastal plain gently slopes toward the waters of the Atlantic Ocean (Fig. 3). The region is characterized by deep, sandy soils, with a high infiltration capacity (Markewich et al. 1990). Fed by abundant groundwater supplies, the plains are dissected by slow-moving rivers and streams bordered by extensive lowland forest swamps. The region's landscape and community types can be further subdivided based on soil characteristics (Brush et al. 1980, Collins and Anderson 1994). In addition to being low in nutrients and acidic, the coarsest sandy soils on the outer coastal plain have the highest percolation rates, leaving little moisture behind in the surface layer. These soils were not conducive to agriculture. The forests growing on them were harvested repeatedly for timber and charcoal before being left to regrow as large contiguous patches of scrubby pine-dominated forest; these forests are locally known as the "Pine Barrens" of New Jersey and Long Island (Forman 1979, Kurczewski and Boyle 2000). In contrast, the inner coastal plain has finer textured soils that are much more suitable to agriculture, resulting in a mosaic of farmland and forest land.

Sprawl and suburban development cover extensive areas of the coastal plain. Farmland was often the first land developed as major metropolitan areas grew. More recent trends point to an increase in the conversion of forest land to urban land uses in some locations (Hasse and Lathrop 2010). Development has threatened to destroy the character of the Pine Barrens of New Jersey and Long Island. These forests have been subject to special land-use planning regulations and open space protection, such as the Pine Barrens Protection Act (Central Pine Barrens Joint Planning and Policy Commission 2004, State of New Jersey 1980). Although these measures have prevented the loss of these unique ecosystems, the complex nature of the wildland-urban interface still creates challenges for wildfire management in these fire-prone systems (Jordan et al. 2003, La Puma et al. 2013).

The coastal plain shoreline is preceded by a long series of barrier islands, extensive tidal salt marshes, and shallow lagoons punctuated by several major larger riverine estuaries (Chesapeake, Delaware, Hudson). Major stretches of this barrier island coast are heavily developed with resort and vacation homes and serve as the summer playground for the entire Mid-Atlantic region and beyond. Sea-level rise associated with climate change has resulted in increased coastal flood risk from episodic storm surges, which affect both human and natural communities adjacent to the ocean and estuaries, especially those located on barrier islands and coastal bays (Chapter 4).

in many ways to the Northeastern Mixed Forest Province extending up through the Adirondacks in New England. Forests in this province are assessed in Janowiak et al. (2018).

Land and Forest Cover

The Mid-Atlantic region is dominated by extensive forests, but also contains other natural ecosystems, rich agricultural lands, major urban population centers, and industrial mining lands (Fig. 4). About half of the region is forested. Based on satellite imagery from the National Land Cover Dataset (NLCD), forests cover 49 percent of the land (Table 3) (Fry et al. 2011, Maryland Department of Natural Resources 2010). The remaining land is classified as agricultural (25 percent), developed (15 percent), wetland (6 percent), grassland/shrubland (3 percent), and inland water bodies (2 percent). Barren land (containing no vegetation) makes up less than one-half percent of the land. The most developed areas are located to take advantage of shipping ports on Lakes Erie and Ontario, the Atlantic Ocean, and numerous commercial waterways such as the Hudson and Delaware Rivers, in support of local industries including iron, glass, steel, shale oil, natural gas, and coal. Forests cover

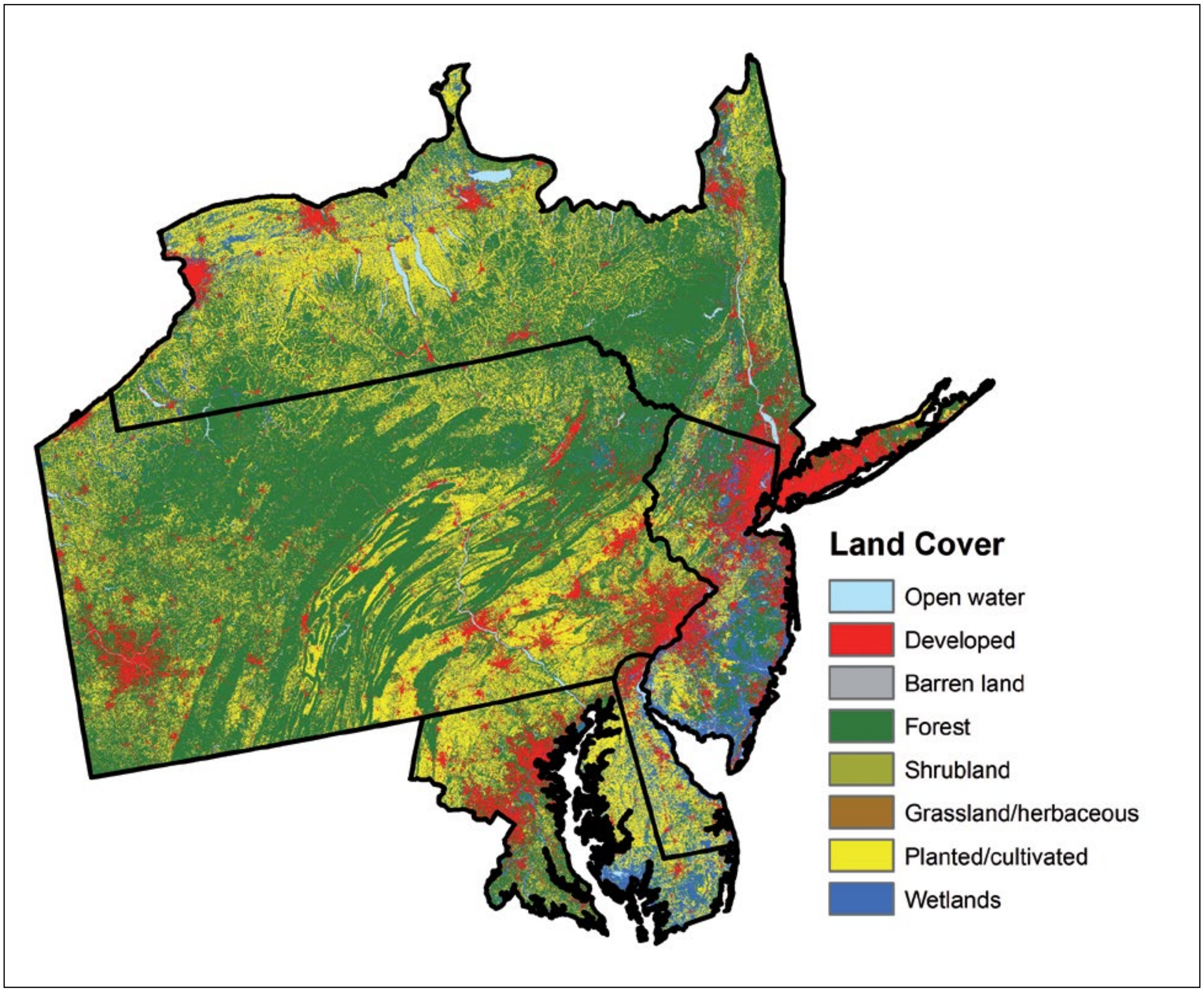


Figure 4.—Land cover classes in the Mid-Atlantic region based on the 2006 National Land Cover Dataset. Data source: Fry et al. (2011).

Table 3.—Land cover in the Mid-Atlantic region based on the 2006 National Land Cover Dataset (data source: Fry et al. [2011])

Land cover class	Acres	Percent
Forest	29,705,648	49.1
Agriculture	14,921,605	24.7
Developed	8,876,834	14.7
Wetland	3,802,152	6.3
Shrubland	1,665,798	2.8
Water	1,325,972	2.2
Barren land	229,377	0.4
Total	60,527,386	100

wide expanses in the interior, especially at higher elevations and on slopes. Agricultural lands occupy flat valley bottoms at lower elevations. Wetlands are scattered throughout the Mid-Atlantic region, occurring in geologic depressions, over clay soils, or in low-lying coastal plains subject to tidal flooding.

The USDA Forest Service Forest Inventory and Analysis (FIA) program provides another estimate of forest cover, which is based on inventories of forest plots. The FIA program estimates that forest land covers approximately 32 million acres, or 53 percent of the Mid-Atlantic region. The amount of forest land varies by state, reflecting regional land use patterns (Table 4) (USDA Forest Service 2018). The FIA estimate of forest land is somewhat higher than the NLCD estimate because FIA definitions of forest land include forested wetlands, plantations, and other land uses that NLCD would classify as woody wetlands or developed lands.

The oak/hickory forest-type group is the most common in the Mid-Atlantic region, covering 44 percent of the total forested area (Table 5). Most of the oak/hickory forest is concentrated in Pennsylvania and New York. Loblolly/shortleaf pine make up a larger proportion of forest in the coastal states than in Pennsylvania and New York (Fig. 5). Other common forest-type groups across the Mid-Atlantic region include maple/beech/birch (34 percent), elm/ash/cottonwood (5 percent), and oak/pine (3 percent). Differences among forest types can influence the amount of carbon stored aboveground and belowground (Box 3). Please refer to Appendix 1 for common and scientific names of species mentioned in this report.

Table 4.—Forest cover for the Mid-Atlantic region by state (data source: USDA Forest Service [2018])

State or portion of state within assessment area	Forest land	Nonforest	Total area	Percent forest cover
	Area (acres)			
Delaware	362,115	948,864	1,310,979	28
Eastern Maryland	1,845,666	3,472,053	5,317,719	35
New Jersey	2,001,608	2,861,626	4,863,234	41
Southern New York	10,719,923	9,340,737	20,060,660	53
Pennsylvania	16,999,249	12,015,025	29,014,274	59
Mid-Atlantic region	31,928,560	28,638,305	60,566,866	53

Table 5.—Forest land, by area and percentage of total forest land, in the assessment area by Forest Service Forest Inventory and Analysis (FIA) forest-type group (data source: USDA Forest Service [2018])

	Forest cover	
FIA forest-type group	Acres	Percent
Oak/hickory	14,177,242	44
Maple/beech/birch	10,749,040	34
Other[a]	1,548,688	5
Elm/ash/cottonwood	1,459,399	5
Oak/pine	1,084,204	3
Loblolly/shortleaf pine	960,043	3
White/red/jack pine	931,722	3
Aspen/birch	602,516	2
Nonstocked	337,329	1
Spruce/fir group	78,377	0
Total forest land	31,928,560	100

[a] "Other" includes Douglas-fir, exotic hardwoods, exotic softwoods, fir/spruce/hemlock, oak/gum/cypress, other eastern softwoods, and other hardwoods forest-type groups.

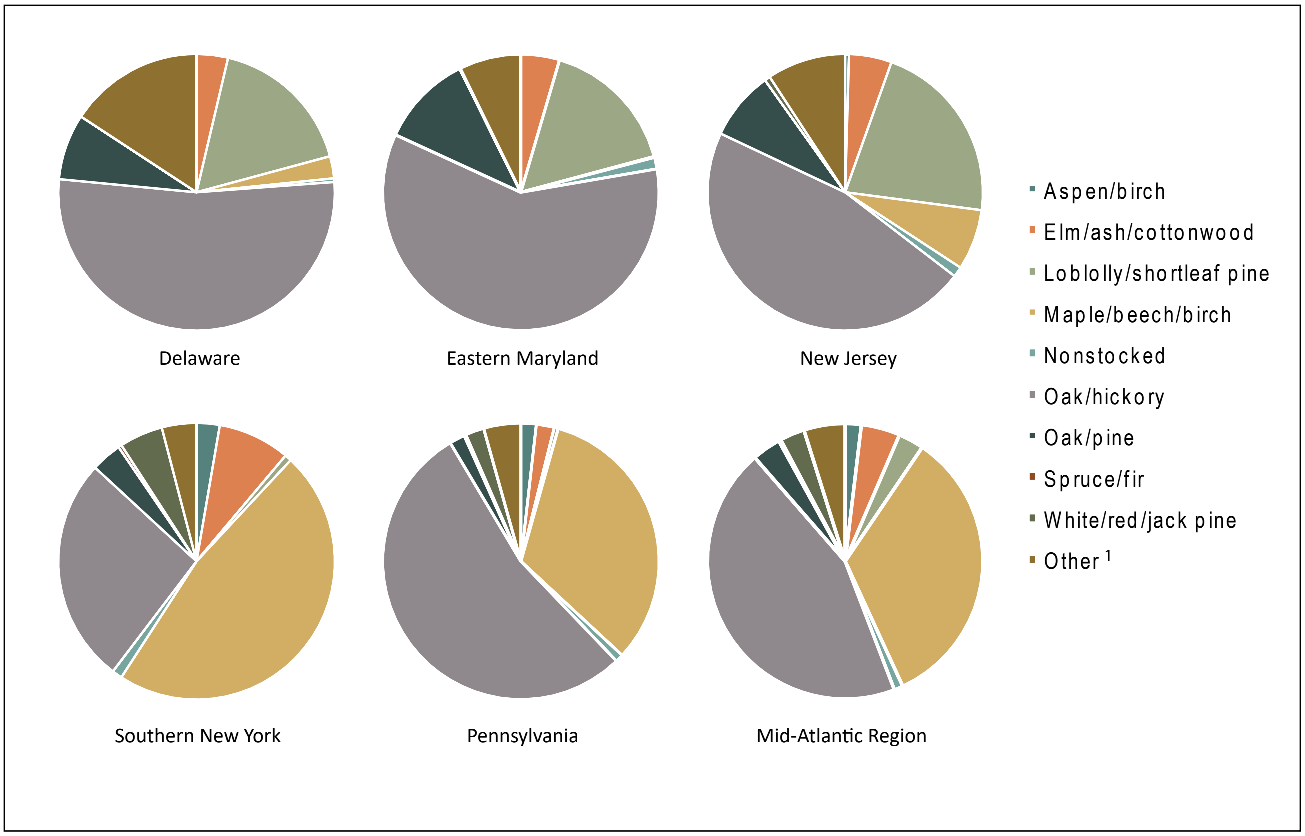


Figure 5.—Proportion of USDA Forest Service Forest Inventory and Analysis forest-type groups in the Mid-Atlantic region and for eastern Maryland, southern New York, and the whole states of Pennsylvania, Delaware, and New Jersey. Data source: USDA Forest Service (2018).

[1] "Other" includes Douglas-fir, exotic hardwoods, exotic softwoods, fir/spruce/hemlock, oak/gum/cypress, other eastern softwoods, and other hardwoods forest-type groups.

Fall colors in a northern hardwood forest, Pennsylvania. Photo by Greg Czarnecki, Pennsylvania Department of Conservation and Natural Resources, used with permission.

Box 3: Forest Carbon

Forests play a valuable role as carbon sinks. The accumulated terrestrial carbon pools within forest soils, belowground biomass, dead wood, aboveground live biomass, and litter represent an enormous store of carbon (Birdsey et al. 2006). Forest land in the Mid-Atlantic region is estimated to store more than 2.3 billion metric tons of carbon, an average of 73.4 metric tons of carbon per acre (USDA Forest Service 2018). Carbon density is lowest in the nonstocked forest-type group (46 metric tons per acre) and highest in the maple/beech/birch group (87 metric tons per acre) (Fig. 6). The most visible—and often most disturbed—carbon is in live aboveground vegetation (e.g., trees, stems, branches, leaves).

Carbon density on forest land also varies by ownership. The highest mean density of carbon on forest land is found on federal lands administered by the Forest Service (87.3 metric tons per acre), followed by the National Park Service and Fish and Wildlife Service (78.9 and 78.3 metric tons per acre, respectively), state lands (75.4 metric tons per acre) and county/municipal lands (73.1 metric tons per acre). Private lands store 72.6 metric tons of carbon per acre, a relatively low value that reflects less formal management compared to public lands (Mazza and Ralph 2010). However, most forest land in the Mid-Atlantic region is private land (Table 6), which stores a total of 1.7 billion metric tons of carbon compared to 1.5 billion metric tons of carbon on public lands.

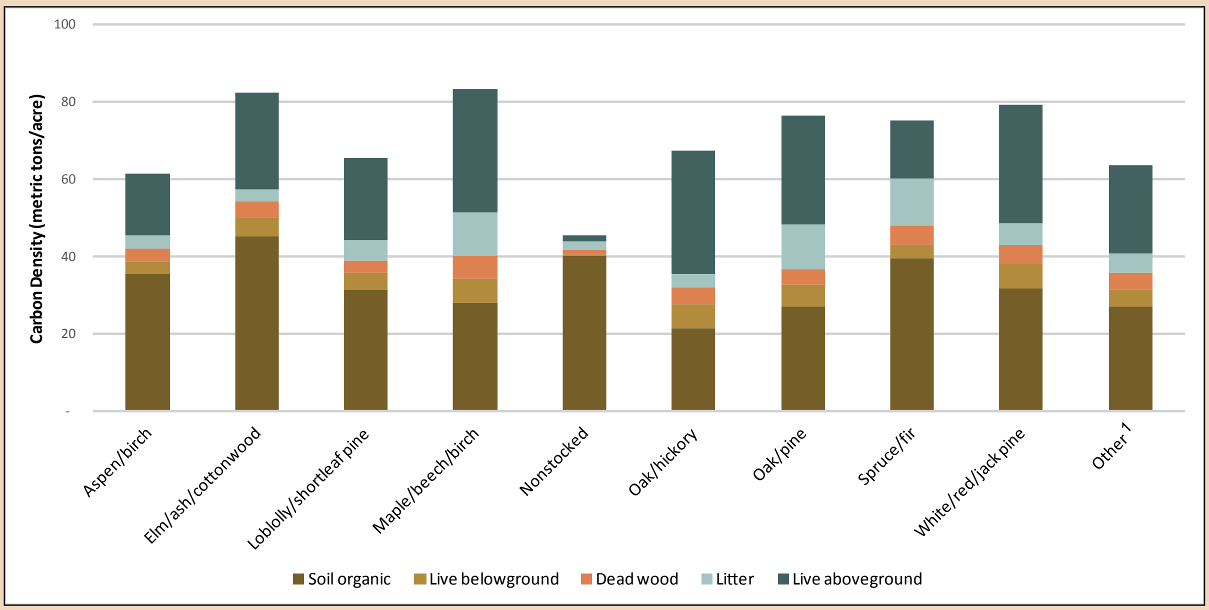


Figure 6.—Forest carbon density by forest-type group. Data source: USDA Forest Service (2018).

[1] "Other" includes Douglas-fir, exotic hardwoods, exotic softwoods, fir/spruce/hemlock, oak/gum/cypress, other eastern softwoods, and other hardwoods forest-type groups.

FOREST OWNERSHIP AND MANAGEMENT

There are numerous types of forest landowners within the Mid-Atlantic region (Fig. 7) that manage forest land for a variety of reasons (Box 4). About 73.5 percent of forest land is owned by three types of private landowners (Table 6) that reflect a diversity of landowner types: families, industrial and corporate organizations, and conservation organizations. A majority (60 percent) of private land in the Mid-Atlantic region is owned by private families, with corporate (10 percent) and nongovernmental/conservation organizations (4 percent) owning the rest. The remaining 26.5 percent of all forest land (8.4 million acres) in the Mid-Atlantic region is held in trust for the American public. State, county, and municipal lands compose the largest percentages of public forest land, followed by public lands in National Forest, National Park Service land, and U.S. Department of Defense military installations. The Allegheny National Forest in northwestern Pennsylvania encompasses 513,175 acres, and the Finger Lakes National Forest in New York encompasses 16,260 acres.

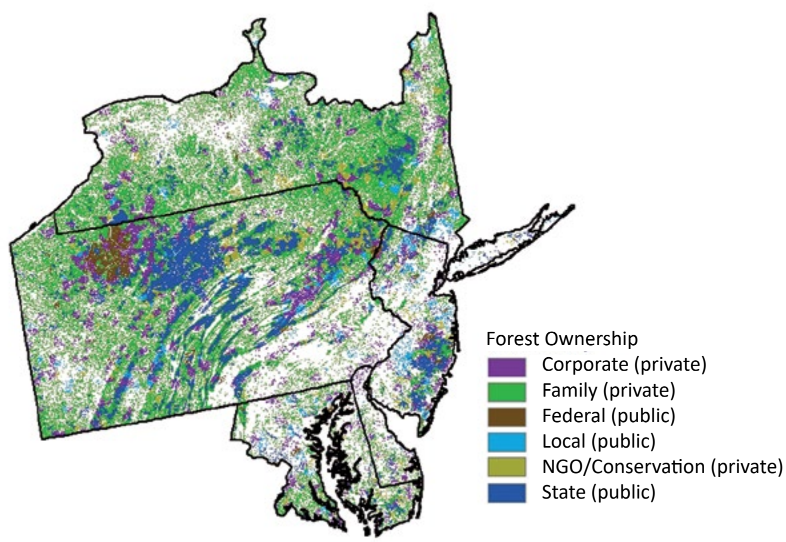


Figure 7.—Forest land ownership across the Mid-Atlantic region. “NGO” indicates nongovernmental organization. Data source: Hewes et al. (2017).

Table 6.—Forest land ownership for the Mid-Atlantic region and by state

	Forest cover - entire area		Forest cover by state (thousand acres)				
Ownership	**Thousand acres**	**Percent**	**Delaware**	**Eastern Maryland**	**New Jersey**	**Southern New York**	**Pennsylvania**
Private	23,482	73.5	279	1,386	971	8,885	11,961
State	6,093	19.1	67	259	626	1,263	3,879
County, municipal, and local	1,464	4.6	7	133	286	502	536
National Forest	516	1.6	-	-	-	14	502
Other federal	374	1.2	9	68	119	57	121
Total	31,929		362	1,846	2,002	10,720	16,999

Box 4: Forest Management and its Many Forms

Millions of nonindustrial private family forest owners hold 60 percent of the forest land in the Mid-Atlantic region. These families own woodlands for different reasons including privacy, scenery, protection of nature, a legacy for the next generation, and hunting and fishing (Butler 2008). Regardless of the primary objective, timber harvesting is also common and was reported by 46 percent of the family owners, who own 69 percent of family forest land (Butler 2008). Family owners invest various amounts of time in managing their woods. Family owners can enroll their lands in voluntary conservation easements, which permanently limit uses of the land in order to protect a conservation value, or enroll in certification programs such as American Tree Farm System, which promote forest products that originate from sustainably managed forests. American Tree Farm System currently certifies more than 1 million acres in Maryland, New Jersey, New York, and Pennsylvania (American Tree Farm System 2017). Family owners are provided technical assistance and other resources for managing forests by extension agents, conservation districts, and private consultants. Corporate and industrial forest owners hold 10 percent of the land and manage primarily for timber products or land value. Many corporate owners voluntarily participate in third-party certification such as the Forest Stewardship Council (Forest Stewardship Council n.d.) and the Sustainable Forestry Initiative (Sustainable Forestry Initiative 2017) (Table 7).

Public (federal, state, and county) agencies own 26.5 percent of forest land in the Mid-Atlantic region. These lands are often managed to provide a number of environmental benefits and ecosystem services, including wildlife habitat, water protection, soil conservation, nature preservation, timber production, recreation, cultural resources, and a variety of other uses (Maryland Department of Natural Resources 2010, Pennsylvania Department of Conservation and Natural Resources 2016, USDA Forest Service 2007). Federal land is managed by completing a process required by the National Environmental Policy Act of 1969 (NEPA). This process entails scoping, involving the public, identifying issues, using an interdisciplinary approach, gathering data, developing alternatives, estimating the effects of the alternatives, and documentation (Brandt and Schultz 2016).

Table 7.—Forest land enrolled in certification programs[1]

	Forest land enrolled in certification program (thousand acres)				
State	American Tree Farm System (ATFS)[2,5,6]	Forest Stewardship Council (FSC)[3]	Sustainable Forestry Initiative (SFI)[4]	Total area enrolled, by state	Percentage of forest land enrolled in a certification program
Delaware	17	1	10	29	8
Maryland	151	247	209	607	33
New Jersey	52	1	-	53	3
New York	564	1,560	1,472	3,596	34
Pennsylvania	331	2,416	105	2,852	17
Five-state total	1,114	4,225	1,797	7,136	22

[1] Data sources: [2]ATFS (2017); [3]FSC (n.d.); [4]SFI (2017); [5]G. Daly, New Jersey Tree Farm Program, pers. email, Jan. 6, 2016; [6]L.K. Yowell, Sussex County, Delaware, pers. email, Dec. 14, 2017.

Timber Harvest and Forest Products

Forests contribute to the Mid-Atlantic region's economically important wood products industry. More than 30.2 million acres, or 95 percent of the forest land in the Mid-Atlantic region, are classified as timberland by the FIA program and considered suitable for wood production (USDA Forest Service 2015). For example, more than 470.4 million cubic feet of industrial roundwood was produced across the Mid-Atlantic region per year on average from 2009 to 2013 (USDA Forest Service 2018). This material includes saw logs, veneer logs, pulpwood, fuelwood, and other wood products used by wood processing mills and other facilities within the Mid-Atlantic region. Across the five Mid-Atlantic states, saw logs and pulpwood make up nearly 77 percent of wood use, although some states—notably New York—also have substantial use of fuelwood (Shifley et al. 2012).

Across the Mid-Atlantic region, the amount of wood harvested each year is less than the amount of forest growth (Table 8). Comparison of net annual forest growth to removals provides a relative indicator of utilization pressure on the timber resource (Butler et al. 2015, Shifley et al. 2012). The growth-to-removals ratio is based on FIA data and provides one measure of sustainability by comparing 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. Across forest-type groups in the Mid-Atlantic region, the growth-to-removals ratio was 2.9, meaning that forest growth was nearly three times as great as removals. Private forest lands, which include both industrial and nonindustrial ownerships, are accumulating the most growing stock, and national forests the least; removals from Department of Defense forest land exceeded growth. Differences among ownerships in annual growth-to-removals ratios probably reflect different management goals and objectives and different intensities of active management (Box 4).

DEMOGRAPHIC CONDITIONS AND ECONOMIC SECTORS

Due to various methods of reporting, it is not always possible to summarize demographic and economic conditions for the assessment area as a whole. Much of this information is described next and summarized for entire states within the Mid-Atlantic region: New York, Pennsylvania, Delaware, New Jersey, and Maryland.

Table 8.—Annual net growth and removals of growing stock on forest land in the Mid-Atlantic region (data source: USDA Forest Service [2018])

Ownership	Annual net growth (million cubic feet)	Annual removals (million cubic feet)	Annual net growth:removals
Private	1,094	335	3.3
State	169	95	1.8
County, municipal, and local	58	22	2.6
National Forest	16	11	1.4
Other federal	12	4	2.8
Other[a]	2	2	0.8
Total	1,351	470	2.9

[a] "Other removals" refers to growth and losses associated with changes in land use, such as conversion from forest to nonforest uses.

Population Growth and Distribution

The Mid-Atlantic region is home to more than 48.5 million people, which accounts for 15 percent of the total U.S. population, and includes metropolitan areas with some of the highest population densities in the country (Headwaters Economics n.d.). Within the Mid-Atlantic region, most people (87 percent) reside in major urban areas such as New York City, Philadelphia, Washington, DC, Baltimore, and Pittsburgh. Included are some of the most populated cities in the Nation; New York ranks first and Philadelphia ranks fifth. With a combined population of 10 million residents, New York and Philadelphia alone account for one-fifth of the total population in the Mid-Atlantic region (Headwaters Economics n.d.).

Urban areas are highly developed centers of high-density infrastructure interspersed with natural areas and residential neighborhoods. These intensively developed areas are subject to conditions that are unique to the urban environments. For example, the urban heat island effect is responsible for hotter temperatures within the urban core, and impermeable surfaces create problems for storm sewers, roadways, and municipal water supplies (Kunkel et al. 2013b). Urban forests include all the street and yard trees, parks, woodlots, and undeveloped green spaces; by definition they are located close to infrastructure and people (Nowak et al. 2001). As urban areas continue to expand, increased resource use and development may cause further stress on these valuable resources.

Population growth within the Mid-Atlantic region has been modest since 1970 (16 percent) compared to the 58-percent increase in population at the national level during the same period. However, population growth rates differ appreciably among states within the Mid-Atlantic region, with the smallest states registering much higher densities. Population growth rates since 1970 were highest in Delaware (72 percent), Maryland (53 percent), and New Jersey (25 percent), whereas the rate of increase has been lowest in Pennsylvania and New York (8 percent each). Since 2000, Delaware continued to see a higher relative increase in population (18 percent) even as it represented the smallest absolute change of any of the five Mid-Atlantic States. Between 2000 and 2010, the rate of increase in residential land development was also greatest in Delaware (20 percent); increases in Maryland, New Jersey, New York, and Pennsylvania were below the 12-percent rate seen nationally (Headwaters Economics n.d.).

There are also many rural areas within the Mid-Atlantic region; the lowest population densities are located within the Allegheny Plateau of northern Pennsylvania, the Catskill Mountains of New York, and the Pine Barrens of New Jersey. These regions are heavily forested and contain large portions of public land.

Employment and Income

More than 29 million people, or 60 percent of the population in the five Mid-Atlantic states, work in full- or part-time jobs (Headwaters Economics n.d.). Unemployment rates in 2015 averaged 5.3 percent. Per capita income in 2015 was $56,000. This is nearly $8,000 greater than the national per capita income, but the cost of living is generally higher (Headwaters Economics n.d.).

Economic Sectors in the Mid-Atlantic Region

The five states of the Mid-Atlantic region together generated $3.2 trillion in gross domestic product in 2016 (Bureau of Economic Analysis 2017). Some of the economic sectors most important to the regional economy are manufacturing, construction, wholesale trade, retail trade, finance and insurance, real estate, and private services. Though representing a smaller contribution to the regional economy (less than 1 percent), several economic sectors directly influence land use and natural resources in the Mid-Atlantic region, including the forest products industry, agriculture, recreation, and resource extraction. These industries are especially important to the human communities located near forests and farms, and have the most potential to influence forests in the Mid-Atlantic region.

Forest Products Industry

The U.S. share of global wood products output has fallen steadily since the late 1990s, from 28 percent to 17 percent (Prestemon et al. 2015). A number of factors contributed to this decline, including reduced demand for writing paper and newsprint, a shrinking manufacturing sector, a slowdown in housing construction starts, and the rise in foreign production, particularly in China and Russia. More recently, signs of a recovering housing market and an emerging wood bioenergy market have resulted in modest gains since 2014 (Prestemon et al. 2015). The five states in the Mid-Atlantic region produced more than $22 billion of wood and paper products in 2013, representing 8.3 percent of total value for all wood and paper products shipped in the United States that year (Headwaters Economics n.d.). More than 82,000 people were employed in the forest products sector (i.e., forestry, logging, mills, paper and wood products) in the five Mid-Atlantic states in 2014, which is 45,000 fewer jobs than in 1998 (Headwaters Economics n.d.). Pennsylvania maintained the highest percentage of total private employment in the forest products sector during this time, starting at 1.2 percent in 1998 and falling to 0.8 percent by 2014.

Agriculture

Agricultural enterprises in the five Mid-Atlantic states generated $18.6 billion in gross income and spent $16.4 billion in production costs in 2015, resulting in a total realized net income of about $2 billion (Headwaters Economics n.d.). Across the Mid-Atlantic states, dairy products accounted for the greatest portion of farm income (29 percent), followed by chickens (12 percent) and corn (10 percent) (U.S. Department of Agriculture 2015). Dairy was the highest grossing agricultural product in both Pennsylvania and New York, while chickens generated the greatest revenue for Maryland and Delaware. The greenhouse and nursery industry earned the greatest revenues in New Jersey, although that state contributed the least to total agricultural earnings among the five states (6.8 percent). In 2015, there were 118,624 farms occupying 18.1 million acres in the five Mid-Atlantic States (or about 26 percent of the five-state area) (Headwaters Economics n.d.). Farm businesses employed a total of 169,479 workers, most of whom were located in Pennsylvania and New York. From 1970 to 2015, farm employment decreased by about 25 percent. The number of farms decreased, but farms became larger with fewer owners. Total farmland has declined slightly, but agricultural production has increased since mid-century, largely due to increased mechanization. Forest land is often converted to agricultural uses, such as cropland and pasture; pasture land continually reverts naturally to forest. Recently this shifting mosaic of forest and agricultural land has resulted in a net gain of forest land (Alig et al. 2010).

Recreation

The Mid-Atlantic region includes a variety of federal and state lands that provide ample opportunities for hunting, fishing, hiking, camping, nature viewing, biking, and skiing. The Allegheny National Forest, Delaware Water Gap National Recreation Area, New Jersey Pinelands National Reserve, Catskills Forest Preserve, Appalachian Trail (a 431-mile stretch), and hundreds of state and county parks and forests draw visitors and generate income for communities in the Mid-Atlantic region.

In fact, outdoor and forest recreation is a large driver of economic activity in the Mid-Atlantic region. Across the five Mid-Atlantic states, consumers spent $106.9 billion on equipment and travel-related expenditures for activities such as hunting, fishing, skiing, running, biking, and hiking (Table 9). Spending on outdoor recreation also supported 845,000 direct jobs in 2017 and generated $7.8 billion in local and state tax revenues (Outdoor Industry Association 2018).

Table 9.—Economic impact of outdoor recreation, by state (data source: Outdoor Industry Association [2018])

	Consumer spending ($ billion)	Wages and salaries ($ billion)	State and local tax revenue ($ million)	Direct jobs
Delaware	3.1	1.0	145	29,000
Maryland	14.0	4.4	951	109,000
New Jersey	18.9	5.9	1,200	143,000
New York	41.8	14.0	3,600	313,000
Pennsylvania	29.1	8.6	1,900	251,000
Total	106.9	33.9	7,796	845,000

Resource Extraction

Mining in the five Mid-Atlantic states generated $24.8 billion dollars in 2012 and included oil and gas extraction, coal mining, and metal and nonmetallic ore mining (Headwaters Economics n.d.). The mining industry is particularly strong in Pennsylvania, which employed five times as many workers as the other four states combined in 2014. Between 2002 and 2013, mining employment in Pennsylvania more than doubled, going from 16,037 to 33,228 employees. This dramatic increase was largely spurred by the Marcellus shale gas boom, which caused oil and gas extraction jobs to grow by more than 250 percent between 2007 and 2012, and placed Pennsylvania sixth highest in gas and oil extraction employment in the Nation (Cruz et al. 2014). In 2010, employment in gas and oil extraction surpassed that in coal mining, which has been a historically important and stable industry in Pennsylvania (Cruz et al. 2014). Outside of Pennsylvania, the greatest number of workers were employed in mining for nonmetallic minerals (e.g., gravel, granite, and other stone) among the various mining industries. These states have also restricted or prohibited the use of fracking technologies to extract gas and oil. Resource extraction is a major cause of forest land conversion in the Mid-Atlantic region. For example, shale-gas development continues to increase in forested areas, and is causing fragmentation and loss of core forest (Drohan et al. 2012).

FOREST COMMUNITIES OF THE MID-ATLANTIC REGION

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 5). In the rest of this document, a set of "forest communities" are typically used to describe the forests currently common across the region. These forest communities are generally based on macrogroups described by the Northeast Habitat Classification System (NETHCS), which provides a consistent classification system for aquatic and terrestrial ecosystems at a coarse scale across the Northeast (Anderson et al. 2013b).

The following descriptions of forest communities were based on NETHCS macrogroups (Table 10) and include information on ecological drivers and the dominant species as they actually occur within the boundaries of the Mid-Atlantic region. Even so, the actual species composition in any given location may differ depending on local site factors, such as landscape position, microclimate, hydrology, and disturbance regime. Thus Figure 8 is a coarse representation of the distribution of forest communities in the Mid-Atlantic region and cannot be quantified with accuracy. Five of the forest types are found only within the coastal plain. Appendix 5 explains the expert elicitation process for defining the forest communities in the Mid-Atlantic region.

Box 5: Forest Types Used in this Report

Different organizations describe forests using a variety of classification systems. This assessment uses two classification systems 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 Forest Service Forest Inventory and Analysis (FIA) program to characterize forests across the Nation. FIA data are used to present trends in forest cover, growth, and mortality for **forest-type groups**, which are defined by tree species composition (Woudenberg et al. 2010). Forest **types** are a classification of forest land based upon and named for the dominant tree species. Forest-type groups are a combination of forest types that share closely associated species or site requirements. The FIA system measures tree species composition on a set of systematic plots across the country and uses that information to provide area estimates for each forest-type group. However, it does not make any inferences about what vegetation was historically on the landscape and does not distinguish between naturally occurring and modified conditions. Something that is classified as "forest land" by FIA may have been historically a glade or woodland. Likewise, areas dominated by tree species that are not native to the area would still be assigned to a forest-type group based on dominant species.

The second system is forest communities, which are groupings of the Northeast Terrestrial Habitat Classification System (NETHCS), a product of collaboration among The Nature Conservancy, Association of Northeast Fish and Wildlife Agencies, NatureServe, the Natural Heritage Programs, and the U.S. Fish and Wildlife Service. NETHCS was created to describe wildlife habitat throughout the Mid-Atlantic and Northeast. Habitats are based on ecological cover types and incorporate other characteristics such as biogeographic region, dominant cover type, and disturbance regime. Although the final classification system describes 143 habitat systems, grouped into 35 "macrogroups," most of the forested communities in the assessment area are described by only 40 habitats representing 8 macrogroups (for a crosswalk between NETHCS and forest communities, see Table 10). We used these forested habitats and macrogroups to describe 11 forest communities that are assessed for vulnerability to climate change in Chapter 6. These forest communities are similar in scale to the macrogroups. However, in this assessment we considered forest communities in the coastal plain separately from those communities found outside the coastal plain, with little overlap between the two at a coarse scale.

Table 10.—Forest communities and Northeast Habitat Classification System (NETHCS) macrogroups

Forest community used in this assessment	Related NETHCS habitats	Common species by forest community
Maritime forest (coastal plain)	North Atlantic Coastal Plain Maritime Forest	pitch pine, Virginia pine, loblolly pine, shortleaf pine, scarlet oak, black oak, scrub oak, post oak, eastern redcedar, black cherry, American holly, sassafras, red maple
Oak-pine-hardwood (coastal plain)	North Atlantic Coastal Plain Hardwood Forest Southern Atlantic Coastal Plain Mesic Hardwood Forest	white oak, southern red oak, chestnut oak, black oak, scarlet oak, red maple, sassafras, gray birch, bigtooth and quaking aspen, hazelnut, pitch pine, Virginia pine, loblolly pine, shortleaf pine, sugar maple, American beech
Pine-oak barrens (coastal plain)	North Atlantic Coastal Plain Pitch Pine Barrens	pitch pine, scrub oak, scarlet oak, blackjack oak, chestnut oak, black oak, white oak, post oak
Swamp (coastal plain)	North Atlantic Coastal Plain Basin Peat Swamp North Atlantic Coastal Plain Basin Swamp and Wet Hardwood Forest North Atlantic Coastal Plain Pitch Pine Lowland Piedmont-Coastal Plain Large River Floodplain	red maple, sweetgum, blackgum, willow oak, green ash, pitch pine, Atlantic white-cedar, baldcypress, shagbark hickory, pin oak, swamp white oak, overcup oak In the south: loblolly pine
Tidal swamp (coastal plain)	North Atlantic Coastal Plain Tidal Swamp	baldcypress, pumpkin ash, red maple, green ash, blackgum, water tupelo, American elm, black willow, loblolly pine
Central oak-pine (interior)	Allegheny-Cumberland Dry Oak Forest and Woodland Central Appalachian Dry Oak-Pine Forest Central Appalachian Pine-Oak Rocky Woodland Northeastern Interior Dry-Mesic Oak Forest Northeastern Interior Pine Barrens Piedmont Hardpan Woodland and Forest Southern Appalachian Montane Pine Forest and Woodland	northern red oak, white oak, black oak, chestnut oak, scarlet oak, red maple, sassafras, pignut hickory, mockernut hickory On exposed ridges and outcrops: pitch pine, eastern white pine, Virginia pine
Lowland conifer (interior)	Laurentian-Acadian Alkaline Conifer-Hardwood Swamp High Allegheny Headwater Wetland North-Central Interior and Appalachian Rich Swamp North-Central Appalachian Acidic Swamp Northern Appalachian-Acadian Conifer-Hardwood Acidic Swamp	black spruce, tamarack, eastern hemlock, black ash, yellow birch, red maple At high elevations: red spruce, balsam fir
Lowland and riparian hardwood (interior)	Glacial Marine & Lake Wet Clayplain Forest North-Central Appalachian Large River Floodplain North-Central Interior Large River Floodplain North-Central Interior Wet Flatwoods Piedmont Upland Depression Swamp Piedmont-Coastal Plain Large River Floodplain	pin oak, swamp white oak, shagbark hickory, sweetgum, silver maple, sycamore, boxelder, American hornbeam (musclewood), blackgum, red maple, black ash, river birch, green ash, cottonwood (rare), bur oak (rare)
Montane spruce-fir (interior)	Acadian-Appalachian Montane Spruce-Fir-Hardwood Forest	eastern red spruce, balsam fir, yellow birch, paper birch, mountain maple, striped maple, mountain-ash
Northern hardwood (interior)	Appalachian (Hemlock)-Northern Hardwood Forest Laurentian-Acadian Northern Hardwood Forest Laurentian-Acadian Northern Pine-(Oak) Forest Laurentian-Acadian Pine-Hemlock-Hardwood Forest North-Central Interior Beech-Maple Forest South-Central Interior Mesophytic Forest Southern and Central Appalachian Cove Forest Southern Piedmont Mesic Forest	sugar maple, yellow birch, American beech, tulip tree, basswood, northern red oak, black walnut, black cherry, white pine, eastern hemlock On dry sites: white pine, red pine, northern red oak, bigtooth aspen, quaking aspen, paper birch
Woodland, glade, and barrens (interior)	Appalachian Shale Barrens Central Appalachian Alkaline Glade and Woodland Eastern Serpentine Woodland Great Lakes Alvar	eastern redcedar, sugar maple, northern red oak, white oak, pignut hickory, eastern redbud, hackberry On dry sites: pitch pine, Virginia pine, white oak

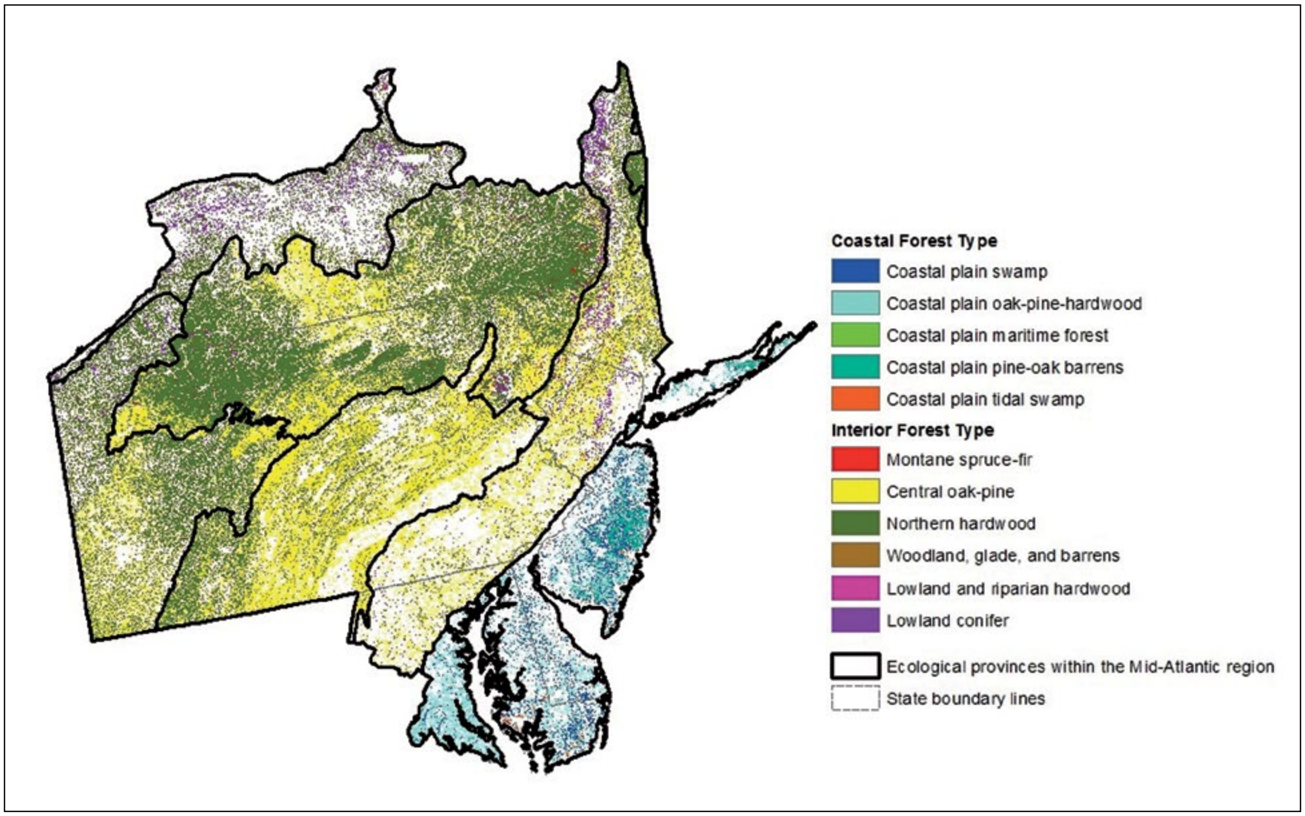


Figure 8.—Forest communities of the Mid-Atlantic region. These communities are aggregates of systems mapped by the Northeast Habitat Classification System (Anderson et al. 2013b).

Maritime Forest (Coastal Plain)

The maritime forest (coastal plain) community is a relatively uncommon mosaic of forest-shrubland that exists only near the Atlantic Ocean on barrier islands, bluffs, and sand dunes. In these locations, it is subject to unique maritime stresses including salt spray, high winds, dune shifting, sandblasting, and tidal overwash. Soils are coarse to fine sand with some organic material mixing into top layers. Forests have relatively few understory or canopy species. Stunted trees occur in various combinations of a few pine and oak species. Pine species can include pitch, Virginia, loblolly, and shortleaf. Oak species can include scarlet, black, scrub, and post. Other species may also find suitable microhabitat in upland or lowland depressions; these include eastern redcedar, black cherry, American holly, sassafras, and red maple. Among the primary natural disturbances are hurricanes and storm surge, which can result in shifting sand and uprooting of trees. This forest community is based on the North Atlantic Coastal Plain Maritime Forest NETHCS habitat.

Oak-Pine-Hardwood (Coastal Plain)

The coastal plain oak-pine-hardwood community occurs as small patches on flat to rolling hills and dunes. Soils are sandy outwash that is deep, generally coarse-textured, and variable in moisture and pH (ranging from dry to mesic and acidic to neutral). Relatively high rates of fine litter production and accumulation coupled with dry conditions foster periodic fire, which promotes several oak species, including white, southern red, chestnut, black, and scarlet. Dry sites in the southerly locations support pine species, including pitch, Virginia, loblolly, and shortleaf. Numerous hardwood species may be present as codominants in early successional sites, including red maple, sassafras, gray birch, bigtooth aspen, quaking aspen, and hazelnut. In more mesic areas, dominant species can be a mix of American beech and sugar maple within a mix of oaks and loblolly pine. Fire is an important natural disturbance in xeric pine- and oak-dominated sites and can be less frequent in mesic sites. Periodic outbreaks of southern pine beetle can temporarily influence the pine component. This forest community is based on the following NETHCS habitats:

- North Atlantic Coastal Plain Hardwood Forest
- Southern Atlantic Coastal Plain Mesic Hardwood Forest

Pine-Oak Barrens (Coastal Plain)

Coastal plain pine-oak barrens occur on dry, flat sites within the New Jersey portion of the Outer Coastal Plain Mixed Forest Province and the Long Island portion of the Eastern Broadleaf Forest (Fig. 2). Soils are low in nutrients, deep, and sandy. This forest community is adapted to dry conditions with frequent to occasional fire, and forest composition and structure vary with fire frequency and severity. Pitch pines dominate the canopy and occasionally mix with oaks (including scarlet, chestnut, black, white, and post) in stands with a longer fire return interval. Severe fire may eliminate associates which produce seed at a later age than pitch pine. Scrub oak stands may also occur without pine cover in low-lying areas where cold air drainage limits pine. The occurrence of oak generally decreases as fire frequency increases. In stands with very frequent fire—where fire returns in 10 years or less—dwarf pitch pine is the dominant cover. Although almost genetically identical to pitch pine, dwarf pitch pine result from frequent fire by developing serotinous cones and low stature, ranging from prostrate shrubs to a height of only 3 to 10 feet tall. This forest community is based on the North Atlantic Coastal Plain Pitch Pine Barrens NETHCS habitat.

Pitch pine-oak-heath woodland in the Central Long Island Pine Barrens, New York. Photo by Gregory J. Edinger, New York Natural Heritage Program, used with permission.

Swamp (Coastal Plain)

The coastal plain swamp type occurs mainly within the Outer Coastal Plain Mixed Forest Province (Fig. 2) in low-lying areas such as depressions and basins, as well as near streams and rivers. These forests are heavily influenced by local groundwater hydrology, with plant communities that reflect the presence of standing water for half the growing season or longer. The soils are mineral and acidic and can be covered by peat, sphagnum, or other organic material. Alluvial soils in large river floodplains are often redeposited by seasonal flooding. Common basin species include red maple, sweetgum, blackgum, willow oak, and green ash; loblolly pine may occur in locations south of the Delaware Bay. Baldcypress, shagbark hickory, and wet oaks (pin, swamp white, willow, and overcup) are often found on better drained soils within active floodplains. Atlantic white-cedar stands are found in acidic muck and peat-accumulating basins. Pitch pine lowlands are included here to reflect their occupation of saturated deep peats, but typically form a mosaic with upland pitch pine barrens. Fire is limited mainly to the pitch pine lowlands, where it helps to maintain a more open structure. This forest community is based on the following NETHCS habitats:

- North Atlantic Coastal Plain Basin Peat Swamp
- North Atlantic Coastal Plain Basin Swamp and Wet Hardwood Forest
- North Atlantic Coastal Plain Pitch Pine Lowland
- Piedmont-Coastal Plain Large River Floodplain

Coastal plain swamp in New Jersey. Photo by Rick Lathrop, Rutgers University, used with permission.

Tidal Swamp (Coastal Plain)

The coastal plain tidal swamp occurs as small patches mainly within the Outer Coastal Plain Mixed Forest Province (232). This hummock-and-hollow topography is situated in the uppermost portions of tidal rivers, which are predominantly freshwater with regular short-term flooding of saline water. Soils are poorly drained slightly acidic tidal muck consisting of variable amounts of silt, clay, and fine sands mixed with root-rich peats. Species richness is high and many communities are dominated by baldcypress, or by a mix of red maple and pumpkin ash or green ash. Other associates can include blackgum, water tupelo, American elm, and black willow. In higher salinity areas that are flooded irregularly (i.e., less than daily), loblolly pine can dominate and often transitions to tidal marshlands as salinity increases. Primary natural disturbances include hurricanes, drought, and fire. This forest community is based on the North Atlantic Coastal Plain Tidal Swamp NETHCS habitat.

Central Oak-Pine (Interior)

Oak and oak-pine forests cover more area than any other forest community in the Mid-Atlantic region. They occur as a variety of dry to mesic habitats forming large patch and matrix forests at various elevations. Soils are often acidic, and range from dry and nutrient-poor to mesic and enriched. Oaks are dominant, especially northern red, white, black, chestnut, or scarlet. Depending on site conditions, eastern white pine and numerous hardwood species may be present as codominants, including red maple, sassafras, pignut hickory, and mockernut hickory. American chestnut was once a common canopy tree before chestnut blight devastated the species a century ago. Pines (pitch, shortleaf, red, eastern white, Virginia) can outnumber oaks on exposed ridgetops and outcrops. Most oak-pine forests were extensively altered during harvesting that occurred between the mid-to-late 1800s and 1930s and thus are second growth (Whitney 1996). There is evidence that fire was a recurring natural disturbance prior to the early 19th century, but fire has been suppressed or excluded as part of wildfire prevention efforts since the 1930s (Lafon et al. 2017, Nowacki and Abrams 2008). Fire can have a large influence on species composition; appropriate fire regimes can promote oaks and pines on sites which would have a greater proportion of mesic species in the absence of fire. This forest community includes the following NETHCS habitats:

- Allegheny-Cumberland Dry Oak Forest and Woodland
- Central Appalachian Dry Oak-Pine Forest
- Central Appalachian Pine-Oak Rocky Woodland
- Northeastern Interior Dry-Mesic Oak Forest
- Northeastern Interior Pine Barrens
- Piedmont Hardpan Woodland and Forest
- Southern Appalachian Montane Pine Forest and Woodland

Lowland Conifer (Interior)

Lowland conifer forests occur over a range of low-lying areas that include glacial depressions, basin wetlands, and seepage areas. These forested wetlands typically have saturated soils throughout the year and may also be flooded seasonally. Many lowland sites are nutrient-rich alkaline wetlands associated with limestone; other sites are acidic and nutrient-poor. In both cases, soils are primarily mineral, though there may be peat development or organic muck accumulation in headwater wetlands and depressions. Depending on local site conditions, a variety of conifer species may be present, such as black spruce, tamarack, and eastern hemlock. Black ash, yellow birch, and red maple are common associates in many sites. Basins above 1,200 feet (e.g., northern Pennsylvania) are sometimes cool enough to support red spruce and balsam fir. Partially due to wet conditions and shallow rooting, the primary natural disturbance is gap formation from wind events. This forest community is based on the following NETHCS habitats:

- Laurentian-Acadian Alkaline Conifer-Hardwood Swamp
- High Allegheny Headwater Wetland
- North-Central Interior and Appalachian Rich Swamp
- North-Central Appalachian Acidic Swamp
- Northern Appalachian-Acadian Conifer-Hardwood Acidic Swamp

Lowland and Riparian Hardwood (Interior)

Lowland and riparian hardwood forests encompass a 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 seasonal flooding, ponding, erosion, groundwater seepage, or other local dynamics. Poorly drained or saturated soils can support silver maple, sycamore, boxelder, American hornbeam, blackgum, sweetgum, red maple, black ash, eastern hemlock, river birch, and green ash. Better drained soils may support a variety of hardwood species often dominated by pin oak, swamp white oak, shagbark hickory, and sweetgum. Microtopography and fluctuating moisture levels can create complexes of forest upland and wetland. Partially due to wet conditions and shallow rooting, the primary natural disturbance is gap formation from wind events. This forest community is based on the following NETHCS habitats:

- Glacial Marine & Lake Wet Clayplain Forest
- North-Central Appalachian Large River Floodplain
- North-Central Interior Large River Floodplain
- North-Central Interior Wet Flatwoods
- Piedmont Upland Depression Swamp
- Piedmont-Coastal Plain Large River Floodplain

Floodplain forest along the Hudson River near Bemis Heights in Saratoga County, New York. Photo by Gregory J. Edinger, New York Natural Heritage Program, used with permission.

Montane Spruce-Fir (Interior)

Within the Mid-Atlantic region, montane spruce-fir forests occur only in the Catskills of New York at the highest elevations (above 3,350 feet) where the growing season is shorter and summer temperatures are cooler than lower altitudes. The presence of cloud cover provides much of the forest's water supply, and positive feedbacks create a microclimate with plenty of water and cool temperatures (Cogbill and White 1991). These forests are dominated by populations of red spruce and balsam fir that are isolated from expansive spruce-fir forests to the north and remnant populations located farther south. Although spruce-fir forests are dominated by conifers, they may contain a number of associated northern hardwood species, such as yellow birch, paper birch, mountain maple, striped maple, and mountain ash. Soils are low to moderate fertility, acidic, and glaciated (Comer et al. 2003). The primary natural disturbance regime is gap formation from landslides or wind, snow, or ice damage. This forest community is based on the Acadian-Appalachian Montane Spruce-Fir-Hardwood Forest NETHCS habitat.

Montane spruce-fir forest on Hunter Mountain in the Catskill Mountains, New York. Photo by Troy W. Weldy, New York Natural Heritage Program, used with permission.

Northern Hardwood (Interior)

Northern hardwood forests are diverse and widely distributed across much of the Mid-Atlantic region. They occur as a variety of habitats forming a large and complex matrix on a range of sites from about 800 to 3,500 feet in elevation. Soils can vary greatly and can include conditions ranging from glaciated to unglaciated, shallow to deep, dry-mesic to wet-mesic, and nutrient-poor to nutrient-enriched. The highest elevations support sugar maple, yellow birch, and American beech, sometimes mixed with or dominated by eastern hemlock. Tulip tree, basswood, northern red oak, black walnut, black cherry, and white pine are often found on moist, well-drained sites where beech, sugar maple, red maple, white ash, gray birch, and sweet birch occur less frequently. Red pine, white pine, and northern red oak can dominate relatively dry sites at lower elevations, with associates of sugar maple, red maple, beech, aspen, sweet birch, and paper birch. Most northern hardwood forests are extensively altered and second growth, a result of the intensive harvesting that occurred between the mid-to-late 1800s and 1930s (Whitney 1996). The primary natural disturbance regime is gap formation from wind, tornadoes, snow, and ice damage, but occasional large-scale blowdown events can also affect large areas (Ruffner and Abrams 2003). This forest community is based on the following NETHCS habitats:

- Appalachian (Hemlock)-Northern Hardwood Forest
- Laurentian-Acadian Northern Hardwood Forest
- Laurentian-Acadian Northern Pine-(Oak) Forest
- Laurentian-Acadian Pine-Hemlock-Hardwood Forest
- North-Central Interior Beech-Maple Forest
- South-Central Interior Mesophytic Forest
- Southern and Central Appalachian Cove Forest
- Southern Piedmont Mesic Forest

Woodland, Glade, and Barrens (Interior)

"Woodland, glade, and barrens " describes several extreme habitats that occur on upper slopes and ridgetops and are associated with specific rock substrates. Soils are thin and xeric when they cover limestone, dolomite, serpentinite, basalt, or other calcareous or ultramafic rock, although sometimes vegetation grows on bare shale or limestone. These forests occupy the driest and most exposed sites in the Mid-Atlantic region. Some sites are maintained by fire, and others are protected from fire by lack of ground fuel or by a landscape barrier. Sugar maple, northern red and white oak, pignut hickory, eastern redbud, and hackberry can form an open, often stunted canopy on shale slopes, glades, and woodlands. Eastern redcedar can be common in the absence of fire. Pitch pine, Virginia pine, scrub oak, and white oak can occupy the driest areas. In addition to fire, drought is a primary natural disturbance that helps maintain the openness of this forest community. This forest community is based on the following NETHCS habitats:

- Appalachian Shale Barrens
- Central Appalachian Alkaline Glade and Woodland
- Eastern Serpentine Woodland
- Great Lakes Alvar (very rare)

DRIVERS OF CHANGE IN FOREST ECOSYSTEMS

The forest ecosystems of the Mid-Atlantic region have undergone significant changes during the past several thousand years. These changes were largely driven by periodic climate change and anthropogenic pressures on the natural resource base, which in turn have had major implications for fire occurrence and behavior, invasive species establishment, soil stability and structure, hydrology, and other drivers of species composition and structure.

Past Ecosystem Change

Paleoecological records of pollen and macrofossils have been collected from lakes and bogs throughout the eastern United States to determine long-term vegetation dynamics (Davis 1983, Williams et al. 2004). About 21,000 years ago glaciers in the Mid-Atlantic region carved out the Great Lakes and the Finger Lakes in New York and extended as far south as northern New Jersey and Long Island. Where glaciers were absent, tundra extended southward along the Appalachian Mountains. As the last glaciers retreated about 14,000 years ago, tree species migrated northward toward favorable habitat (Davis 1983, Williams et al. 2004). These dates are approximate to reflect some uncertainty in determining range limits and arrival dates from paleoecological data, especially when small or low-density populations may have existed (McLachlan et al. 2005).

In general, species moved at different rates into the Mid-Atlantic region from multiple locations including the Midwest, Deep South, or Atlantic Coast, depending on the suitability of climate, seed dispersal, and establishment success (Davis 1983). Oaks arrived relatively early, from 15,000 to 12,000 years ago. Eastern white pine and eastern hemlock arrived around 12,000 years ago, and elms and maples arrived 12,000 to 10,000 years ago (Williams et al. 2004). Some species arrived relatively recently in the Mid-Atlantic region, possibly delayed by the migration barrier presented by the Appalachian Mountains. For example, hickories and chestnut arrived only 8,000 to 5,000 years ago. This migration spanning thousands of years resulted in unique assemblages of species that are not common today, such as the spruce-pine forests that initially established in the Mid-Atlantic region (Jackson and Williams 2004, Williams et al. 2001).

Several broad periods of natural climate change occurred since the glaciers retreated, including Early Holocene Warming from 11,700 to 8,200 years ago, the Holocene Thermal Maximum from about 9,000 to 5,000 years ago, and the more recent Neoglacial Cooling (Nowacki and Abrams 2015). Within these broad periods, tree ring analysis provides some of the evidence for smaller periods of climate change that occurred over tens and hundreds of years, such as the wetter decades that occurred 700 to 800 years ago and the drier decades that occurred 450 to 550 years ago (Maxwell et al. 2011, 2012). These climatic cycles were major drivers of ecosystem change in the Mid-Atlantic region.

Other potential drivers, depending on various local factors, are coupled with Native American migration to the area around 11,500 years ago. A review of evidence from archaeology, ethnobotany, and palynology identified important influences of Native American land uses on eastern North American forests, indicating that human land use became an increasingly important driver of ecosystem change after the arrival of Native Americans in the region (Abrams and Nowacki 2008). Native American activities in some locations may have included fire, land clearing, and possible management of fruit and mast tree species. Fire and land clearing promoted the development of oak and pine forests, while unmodified areas promoted northern hardwoods and beech-maple forests.

There are few written records of forest conditions reflecting Native American land use prior to European settlement. But forest characteristics can be inferred from early land surveys conducted at the time of European settlement that recorded witness trees to delineate boundaries. These data can be used to reconstruct forest composition and structure, and infer fire history before European settlement (Table 11). Witness tree data can also provide key evidence of where fire was an important natural disturbance within the Northeast and Mid-Atlantic region. One recent study characterized witness tree species by fire tolerance. A predominantly fire-tolerant species was rated as a high pyrophilic percentage, whereas a predominantly fire-intolerant species was rated as a low pyrophilic percentage (Thomas-Van Gundy et al. 2015). Displaying past forest composition in these terms showed the transition from fire-tolerant oak-hickory forests in the southern portion of the region to fire-intolerant northern hardwoods to the north, demarcated by the tension zone line (Fig. 9) (Cogbill 2000). Fire-tolerant witness trees followed major river systems and the Atlantic coast, offering further evidence of the role of Native Americans and fire on the landscape (Thomas-Van Gundy et al. 2015).

European settlement of the Mid-Atlantic region began 400 years ago, and immediately became a new important driver of ecosystem change. The widespread logging and clearing for timber and agriculture resulted in dramatic changes to forests across the eastern United States. Before European settlement, forests in the northern part of the Mid-Atlantic region were dominated by American beech, sugar maple, and hemlock with small, localized pockets of fire-dependent oak, hickory, and American chestnut. Farther south, there is evidence of widespread fire-dependent oak, hickory, and American chestnut with smaller areas of pine. With the arrival of European settlers, fire increased across the region, largely due to slash burning and subsequent wildfires. Then, the implementation of fire suppression policies drastically reduced fire on the landscape to the longest fire return intervals in recent history (Brose et al. 2014). The current increase in mesic forests that has been observed in the absence of landscape burning (Abrams and Downs 1990, Abrams and Nowacki 1992, McEwan et al. 2011) is strong evidence for the role of fire in creating and maintaining the eastern oak ecosystems.

Table 11.—Forest composition estimates from witness trees in the Mid-Atlantic region

Location	Pre-European settlement forest composition	Reference
Southeastern New York	White oak (36%), black oak (15%), hickory (10%); more red maple in current forest	(Glitzenstein et al. 1990)
Eastern New Jersey, southeast New York	White oak, oak spp., American chestnut; pine (7%); Atlantic white-cedar/red maple swamps	(Loeb 1987)
Central and western New York	Central New York dominated by American beech (46%), maple (20%), hemlock (5%), black ash swamps, oak forests; western New York dominated by American beech (22%), sugar maple (20%), hemlock (19%)	(Marks et al. 1992)
Western New York	Allegheny Plateau – American beech (19%), sugar maple (12%), hemlock (11%); Till Plains – American beech (32%), sugar maple (18%), basswood (12%)	(Seischab 1990)
Western New York	American beech (37%), sugar maple (21%), hemlock (8%)	(Wang 2007)
Northern New Jersey	White oak (34%), black oak (18%), hickory (15%); more birch and maple in current forests	(Russell 1981)
Southwestern Pennsylvania	White oak (40%), hickory (9%), black oak (9%)	(Abrams and Downs 1990)
Southeastern Pennsylvania	Black oak (33%), white oak (17%), American chestnut (15%)	(Mikan et al. 1994)
Southeastern Pennsylvania	Uplands dominated by oaks, hickory, American chestnut; lowlands dominated by white oak, black oak, hickory	(Black and Abrams 2001a)
Southeastern Pennsylvania	Lowlands dominated by black oak (33%), white oak (29%), hickory (15-28%); uplands dominated by white oak (26%), black oak (24%), and American chestnut (18%)	(Black and Abrams 2001b)
Northwestern Pennsylvania	American beech (20%), hemlock (15%), white oak (14%) in areas of high Native American influence; American beech (49%), hemlock (20%), maple (9%) in areas of low Native American influence	(Black et al. 2006)
Northwestern Pennsylvania	White oak (21%), American beech (13%), sugar maple (9%) with oak and hickory more common on south-facing slopes, hemlock on north-facing slopes; more black cherry and red maple in current forests	(Whitney and DeCant 2003)
North-central Pennsylvania	American beech, hemlock, American chestnut on plateau tops; Allegheny Mountains dominated by white pine, maple, white oak, with differences found between landforms	(Abrams and Ruffner 1995)
Central Pennsylvania	Ridges dominated by oaks (42%), pines (27%), American chestnut (13%); coves dominated by oaks (33%), pines (27%), hemlock (17%); valley floors dominated by oaks (56%), pines (13%), hickory (12%); valley ravines dominated by oaks (25%), hickory (13%), walnut (10%); more maple, black cherry, and birch in current forests	(Nowacki and Abrams 1992)
Central Pennsylvania	Mountains dominated by pine (32%), chestnut oak (14%), white oak (12%); valleys dominated by white oak (43%), pine (11%), black oak (11%)	(Gonsalves 2011)
Northeastern United States	American beech (22%), oaks (17%), maples (11.3%), hemlock (10.9%), spruces (7.6%), birches (6.9%), pines (6.8%), chestnut (3.3%); more red maple, black cherry, aspen spp. in current forests	(Thompson et al. 2013)

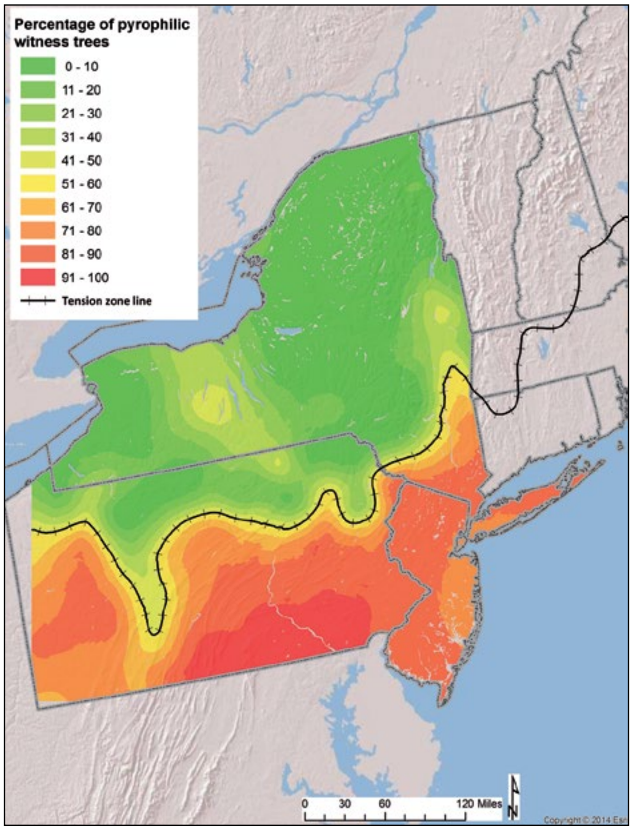


Figure 9.—Pyrophilic character of pre-European settlement forests in Pennsylvania, New York, and New Jersey based on witness tree data from land surveys during 1670 to 1890 (Thomas-Van Gundy et al. 2015).

Primary Agents of Change

Agents of change within the Mid-Atlantic region include both natural and anthropogenic disturbances (Table 12). Natural disturbances, such as wind, wildfire, storms and severe weather, and native pests and diseases, have shaped contemporary forests, and forests have adapted in response to patterns of disturbance (Gutschick and BassiriRad 2003). Anthropogenic disturbances have altered forests more recently and include deforestation, fragmentation, large-scale surface mining, acid deposition, and the introduction of exotic plants and pests. Disturbances can disrupt ecosystem services, carbon storage, timber production, and primary productivity (Thom and Seidl 2016). On the other hand, disturbances can improve species richness, habitat quality, and overall diversity.

Natural Disturbances and Disturbance Regimes

Natural disturbances have regularly influenced the structure, composition, function, and spatial-temporal dynamics of forest ecosystems (Seidl et al. 2011). Small-scale disturbances are often caused by wind, drought, ice, snow, flooding, landslides, insect outbreaks, intermediate-intensity fires, and pathogens (Anderson et al. 2013b, NatureServe 2017). Large-scale disturbances, which can affect entire stands and swaths of forest across the landscape, include tornadoes, hurricanes, wildfire, flooding along major rivers, and catastrophic insect and pathogen outbreaks.

Forest systems have distinct disturbance regimes, characterized in part by the soils, landforms, and vegetation (McNab et al. 2007). The disruption of natural disturbance regimes has included harvesting and fire suppression as well as hydrologic disruption in riparian and lowland forests. Natural regeneration and succession of forest ecosystems are strongly tied to disturbance regimes, so in many cases alteration of disturbance regimes has resulted in regeneration failure for those disturbance-adapted species and reduced landscape diversity (Abrams and Nowacki 1992, Nowacki and Abrams 2008, Patterson 2005). Conversely, other species may benefit from the altered disturbance regime, particularly fire-sensitive, shade-tolerant trees, especially red maple.

Fragmentation and Land-use Change

Residential and urban development has led to the fragmentation of forests across the Mid-Atlantic region, resulting in a patchwork of public and private parcels of natural, agricultural, and developed lands (Riitters 2011). As mentioned earlier, about 40 percent of the Mid-Atlantic region is now agricultural or developed land (Jin et al. 2013). The Mid-Atlantic region encompasses the major metropolitan areas of New York City, Baltimore, and Washington, DC, which compose the core of the urbanized region stretching along the Mid-Atlantic coast (Short 2007). The most vulnerable lands are

Table 12.—Major drivers of change to forest ecosystems in the Mid-Atlantic region

Driver of forest change	References
Atmospheric deposition of nitrates, sulfates, ozone, and other anthropogenic emissions negatively affects forest productivity and resilience.	(Driscoll et al. 2016, Pan et al. 2004, Thomas et al. 2010)
Herbivory, particularly from white-tailed deer, is considered a keystone driver through impacts on plant regeneration, structure, and species diversity, especially where deer density is high.	(Comisky et al. 2005, Horsley et al. 2003, Knight et al. 2009, Rawinski 2016, Redding 1995)
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 plant mortality and thus fuels for fire from dried plant materials.	(Brose et al. 2013, Clark et al. 2016, Luce et al. 2016, Vose et al. 2016)
Energy development for wind energy and shale-gas installations alter ecosystem structure through vegetation clearing, soil disturbance, increased erosion potential, fragmentation, and direct impacts on forest wildlife species.	(Cruz et al. 2014, Drohan et al. 2012, Johnson et al. 2010)
Soil erosion from improperly designed or poorly maintained roads, trails, or log landings can increase the amount of siltation and sedimentation transported and deposited by streams and result in reduced water quality.	(Eisenbies et al. 2007, Ezer et al. 2014, Pennsylvania Department of Environmental Protection 2012)
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.	(Drohan et al. 2012, Irwin and Bockstael 2007, Jantz et al. 2005, Riitters 2011)
Invasive plants compete for resources and alter natural forest dynamics. A large number of invasive plant species are present, including garlic mustard, ailanthus, stiltgrass, and nonnative honeysuckles and buckthorns.	(Hoffberg and Mauricio 2016, Kurtz 2013)
Insect pests can cause reduced growth or mortality of target species. Pests of concern vary widely based on susceptibility of trees at a particular site, depending on tree age, density, health, and other factors. Problematic insect species include budworm, hemlock woolly adelgid, emerald ash borer, Asian longhorned beetle, and forest tent caterpillar.	(Krist et al. 2007, USDA Forest Service n.d.b)
Forest pathogens increase the risk of tree mortality and species extinction or extirpation. Pathogens of concern vary widely based on susceptibility of trees at a particular site, depending on tree age, density, health, and other factors. Diseases include beech bark disease, Dutch elm disease, elm yellows, and chestnut blight.	(Krist et al. 2007, USDA Forest Service n.d.b)
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.	(Clark et al. 2016, La Puma et al. 2013, Nowacki and Abrams 2008, Patterson 2006)

those on the fringes of these cities and major towns, and in rural areas where second homes contribute to sprawling development (Irwin and Bockstael 2007, Jantz et al. 2005, USDA Forest Service 2011). In other areas, industrial land-use change drives fragmentation. For example, installation of natural gas well pads in Pennsylvania disturbs 3 to 5 acres of land per well pad over Marcellus shale (Drohan et al. 2012, Johnson et al. 2010). Forest lands across the Mid-Atlantic region are often heavily dissected by roads, trails, and utility lines that serve and connect residential, business, and industrial complexes.

Parcelization is also a concern as the number of forest landowners is increasing and the size of parcels is decreasing (Widmann et al. 2015). For example, more than 70 percent of forest land in Pennsylvania is in private ownership, with 70 percent of family forest owners owning 9 acres or less (Albright et al. 2017). Large natural features, such as the Chesapeake Bay and its tributaries, exert a strong attractive force on new development, resulting in continued forest fragmentation (Boesch and Greer 2003, Irwin and Bockstael 2007). Fragmentation of natural landscapes increases edges along forest boundaries and reduces the amount of interior forest (Drohan et al. 2012, Irwin and Bockstael 2007). Reduced connectivity creates isolated populations that are unable to exchange genetic information, leading to reduced biological and genetic diversity (Riitters 2011). Fragmentation has also led to the physical loss of wetlands and wildlife habitat, increased exposure to disturbances, and the spread of invasive species.

Insect Pests and Forest Diseases

Insect and disease outbreaks regularly influence the structure and health of forest ecosystems in the Mid-Atlantic region. Native insects and pathogens are responsible for natural cycles of mortality and reduced productivity in healthy ecosystems (Stolte et al. 2012). Under certain conditions, a native pest population may increase dramatically, overwhelming host trees and causing widespread mortality. Large-scale population dynamics are captured in annual surveys that observe damage from common insect pests, and the level of damage varies from year to year (Man 2012). For example, the eastern tent caterpillar regularly defoliates black cherry in the Mid-Atlantic region, and fall cankerworm defoliates hardwoods. Defoliation by the forest tent caterpillar is known for interannual fluctuations and hotspots, such as a severe outbreak in New York in 2005, the same year defoliation in Pennsylvania was reduced from 2004. Recent outbreaks of another native species, the southern pine beetle, have occurred in the New Jersey Pine Barrens and in Long Island, New York, and warrant monitoring and management of this pest (Natural Resources Conservation Service 2013).

International trade and the inadvertent transport of nonnative species from countries around the world have amplified exposure to new diseases and impacts on tree species of the Mid-Atlantic region. Dutch elm disease, chestnut blight, and beech bark disease are particularly devastating and have reduced or eliminated keystone species from their native habitats (Stolte et al. 2012). Gypsy moth is another serious pest and has caused substantial losses of white oak, red oak, basswood, and sweetgum

Gypsy moth caterpillars. During the larval stage, gypsy moths eat for 7 weeks, stripping plants and trees of their leaves. Photo by Greg Czarnecki, Pennsylvania Department of Conservation and Natural Resources, used with permission.

(Stolte et al. 2012). The hemlock woolly adelgid continues to threaten eastern hemlock with needle loss, followed by branch dieback and eventual death (Jonas et al. 2012). Beech bark disease has resulted in mortality of beech trees across millions of acres in New England and the Mid-Atlantic region, and has yet to invade the bulk of the American beech range in the Midwest (Morin et al. 2007). Furthermore, where heavy mortality has resulted in newly opened gaps, beech sprouts and seedlings have often become dense to the detriment of advance regeneration of beech or other species (Giencke et al. 2014, Houston 1994). The emerald ash borer has caused mortality in all ash species, including white ash, black ash, and green ash, resulting in the loss of more than 50 million trees between 2002 and 2009, and mortality is expected to increase as the beetle spreads (Kovacs et al. 2010, Morin et al. 2016). The Asian longhorned beetle was confirmed in central New Jersey and Long Island, and its potential to spread to adjacent states could result in mortality to many species including maples, buckeyes, birches, willows, and elms (State of New Jersey 2015, Townsend Peterson and Scachetti-Pereira 2004).

Nonnative and Invasive Plants

Nonnative plant species are a risk to forest ecosystems when they become invasive. These species affect forest ecosystems through direct competition for resources, alteration of fire or hydrologic conditions, disruption of natural succession and pollination, and other cascading influences (Frelich et al. 2012, Tu et al. 2001). Invasive plant species can be introduced into native ecosystems by the transport of seed on vehicles or equipment, on the soles of shoes, in manure from domestic or wild animals, or via dissemination by wind and water. Major shipments from international origins are often the source of new exotic species, such as Amur honeysuckle and reed canarygrass. The Forest Service's FIA program has monitored 25 invasive species in the eastern United States since 2007 (Fig. 10) (Kurtz 2013). The density of invasive species was found to be highest in the Piedmont stretching from western Maryland to eastern New York, where five to seven invasive species were found in most of the plots. Another study using FIA data found more species and abundance in

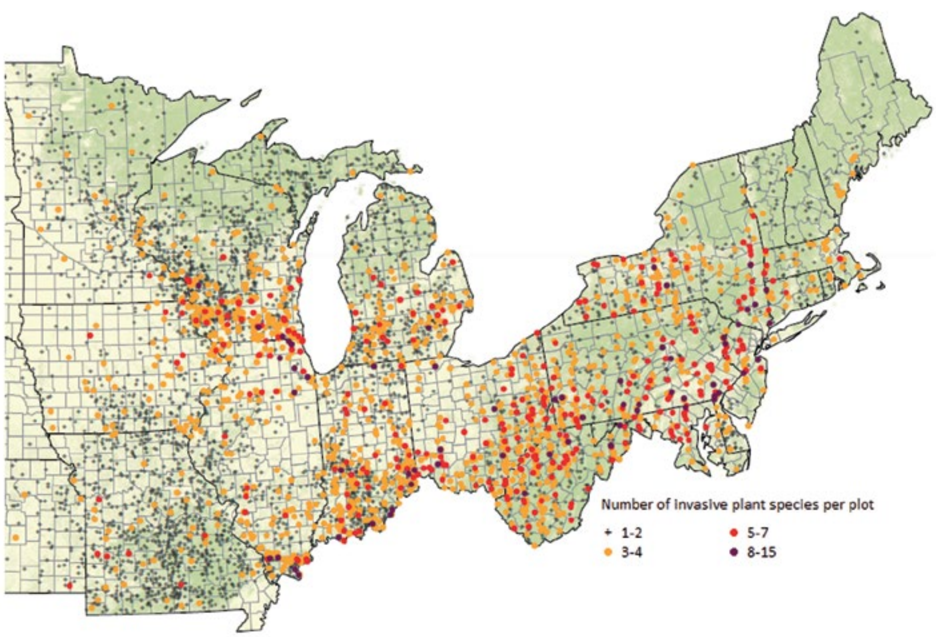


Figure 10.—Abundance of 25 invasive plant species monitored by the USDA Forest Service Forest Inventory and Analysis program from 2005 through 2010 (Kurtz 2013). Plot locations are approximate.

fragmented forest landscapes, including areas of the Mid-Atlantic region (Iannone et al. 2015). Glossy buckthorn, bush honeysuckles, autumn olive, crown vetch, Japanese knotweed, Japanese stiltgrass, garlic mustard, ailanthus, mile-a-minute, and multiflora rose are among the most problematic invasive species in the Mid-Atlantic region (Grafton 2003). In some cases, exotic species may be present, but limited by current climate conditions in the Mid-Atlantic region. For example, kudzu and other southerly invasive species are currently being limited by fall and winter minimum temperatures and have the potential to become more problematic as the climate warms (Bradley et al. 2010, Hoffberg and Mauricio 2016). Another study found that nonnative climbing vines on trees are increasing in abundance and number of species, and that vines are greatest in fragmented areas near forest edges (Matthews et al. 2016).

Fire on the Landscape

Fire regimes have shifted in the Mid-Atlantic region during the past several hundred years, and these shifts influence the composition of forest communities found here. Both natural and human-caused fire has been a driver of eastern forests for thousands of years, although the return interval, intensity, and extent are largely dependent on human activity, landscape position, and environmental factors (Abrams 1992, Nowacki and Abrams 2008, Thomas-Van Gundy and Nowacki 2013). For many fire-dependent communities in the eastern United States, there are few quantitative data describing historical fire regime attributes such as frequency, severity, and seasonality, or how these varied through time (Marschall et al. 2016). Studies in the Mid-Atlantic region are especially sparse compared to the eastern United States, but soil charcoal and fire scars in oak and pine forests indicate that fire return increased due to land clearing during European settlement, with the exact timing depending on the stand and location (Brose et al. 2014). After the peak logging stopped in the early 1900s, fire suppression efforts nearly eliminated the occurrence of fire, even in drought years (Brose et al. 2013). By the 1950s, fire exclusion across the Mid-Atlantic region began to favor red maple, sugar maple, American beech, and black cherry (Brose and Van Lear 1999, Nowacki and Abrams 2008, Schuler and Gillespie 2000, Wright and Bailey 1982). Oaks continue to be replaced by other hardwood species, especially red maple, in the absence of fire (Brose et al. 2008). For example, forests dominated by mesic hardwoods on the Allegheny Plateau in Pennsylvania and New York are largely characterized by a low incidence of wildfires, and infrequent fuels management, compared to pine- and oak-dominated forests.

The historical role of fire in the development and maintenance of oak forests has been well established in the literature (Brose et al. 2014). Efforts to restore oaks by using prescribed fire have successfully promoted advance regeneration, but require other methods (e.g., thinning or herbicide) to promote growth into larger oaks and hickories, especially on mesic sites (Brose et al. 2012, Hutchinson et al. 2012).

Prescribed fire at the Buckaloons Recreation Area, Allegheny National Forest, Pennsylvania. Controlled fires are used to promote warm season grassland. Photo by Kathleen Creek, Allegheny National Forest.

In comparison, pine-dominated and oak-pine forests throughout the Mid-Atlantic tend to be the most wildfire prone, and are typically the focus of fire management activities on the coastal plain. There is evidence that shifting fire regimes in the coastal plain were subject to similar drivers, but with overall shorter fire return intervals (Clark et al. 2013, 2015). Fire-tolerant pines or oaks dominate the overstory and ericaceous shrubs are common in the understory. The dominant tree in the coastal plain is pitch pine. This species has fire-adapted traits such as serotinous cones, which require fire to open and release seeds. It also has the ability to produce new shoots from the trunk and branches after fire (Ledig and Little 1979).

Forest-dependent Wildlife

The Mid-Atlantic region is remarkably diverse in both habitats and species. In the western part of the region are large, unbroken tracts of deciduous forests bisected by cold-water streams that are home to native brook trout. To the east are coastal forests such as the New Jersey Pine Barrens, home to the colorful Pine Barrens tree frog. Due to its central location on the Atlantic flyway, the entire Mid-Atlantic region is critically important for migratory songbirds, waterfowl, shorebirds, and raptors. Thus, the region is the focus of many connectivity and conservation projects.

Perhaps no wildlife species has had a greater impact on the Mid-Atlantic forest than white-tailed deer (Rawinski 2008). Populations of this keystone species are relatively high today compared to the near-extirpation of deer during the early European-settlement period (Horsley et al. 2003). In some parts of the Mid-Atlantic region, native vegetation dynamics have been dramatically altered by deer, leading to a less diverse forest with limited tree regeneration and an understory dominated by deer-resistant species, including invasive species such as Japanese stiltgrass and garlic mustard (Rawinski 2008). Although the ecological impacts of deer are complex, deer overabundance has been most detrimental to forest health and sustainability (Rawinski 2008).

Other species are suffering habitat loss in the Mid-Atlantic region and are listed among the many species of high conservation concern. For example, the golden-winged warbler is a Neotropical migrant that prefers early successional forests created by fire, timber harvesting, or reversion of abandoned farmland to forest. But the species has been declining due to habitat replacement by aging forests, hybridization, and other causes. From 1966 through 2012, annual declines in golden-winged warbler populations ranged from 5.3 percent in New York to nearly 10 percent in New Jersey (Sauer et al. 2014). Although this species is often featured in efforts to publicize the need for early successional habitat, there are many other species that also depend on early successional habitat and face similar challenges as forests continue to age in large, continuous tracts.

CHAPTER SUMMARY

The Mid-Atlantic region of Pennsylvania, New York, New Jersey, Delaware, and Maryland supports a mosaic of forest ecosystems. These forests supply important benefits to the people of the area, including wood products and recreation opportunities. Changes in climate, weather extremes, and fire regime; habitat fragmentation; species invasions; insect pests and diseases; and other alterations to the landscape continually shape forest ecosystems. For this assessment, forest communities are broadly based on the Northeast Terrestrial Habitat Classification System but modified according to the ecological drivers and dominant species present within the Mid-Atlantic region. Ecosystem vulnerability for each of the 11 major forest communities that we defined is discussed in Chapter 6.

CHAPTER 2: CLIMATE CHANGE SCIENCE AND MODELING

This chapter provides a brief background on climate change science, climate simulation models, and models that project the impacts of changes in climate on tree species and ecosystems. Throughout the chapter, boxes list resources for more information on each topic. A more detailed scientific review of climate change science, trends, and modeling can be found in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (IPCC 2014), and the Fourth National Climate Assessment (U.S. Global Climate Research Program [USGCRP] 2017).

CLIMATE CHANGE

Climate is not the same thing as weather. Weather is a set of the meteorological conditions for a given point in time in one particular place (such as the temperature at 3:00 p.m. on May 1 in Annville, PA). Climate, in contrast, is the long-term average (30 years or more) of meteorological conditions and patterns for a geographic area. This climate average is calculated from individual measurements taken at multiple locations across a geographic area, and at different points through time. The IPCC (2007: 30) defines climate change as "a change in the state of the climate that can be identified (e.g. using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer." A key finding of the IPCC in its Fourth Assessment Report (IPCC 2007) was that "warming of the climate system is unequivocal." This was the first assessment report in which the IPCC considered the evidence strong enough to make such a statement, and the Fifth Assessment Report repeated it. Current observations of higher global surface, air, and ocean temperatures and thousands of long-term (since 1950 or earlier) datasets from all continents and oceans contributed to these conclusions. These datasets show significant changes in snow, ice, and frozen ground; hydrology; coastal processes; and terrestrial, marine, and biological systems. The IPCC's Fifth Assessment Report contains the most recent and comprehensive evidence of global changes. Selected global and national assessments are listed in Box 6.

The Warming Trend

The Earth is warming, and the rate of warming is increasing (IPCC 2014). Measurements from weather stations across the globe indicate that warming of the global mean temperature is unprecedented since the 1950s, and that the period from 1983 through 2012 was the warmest 30-year period in 800 years for the Northern Hemisphere (IPCC 2014). In the contiguous United States, 2012 ranked as the warmest year on record during the 1985 to 2015 base period, and 2016 ranked second (National Oceanic and Atmospheric Administration [NOAA] 2017c). Temperatures in the United States have risen by an average of 0.5 °F (0.3 °C) per decade since the 1970s, a total of 2.3 °F (1.3 °C) between 1970 and 2016 (NOAA 2017c).

Average annual global temperature increases since 1970 are just one aspect of a more complex and wide-ranging set of climatic changes. For example, the frequency of cold days, cold nights, and frosts since the 1950s has decreased over many regions of the world while the frequency of hot days, hot nights, heat waves, and heavy precipitation has increased (IPCC 2014). Global rises in sea level,

Box 6: Global and National Assessments

Intergovernmental Panel on Climate Change

The Intergovernmental Panel on Climate Change (IPCC; www.ipcc.ch) is the leading international body for the assessment of climate change. It was established by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) in 1988 to provide the world with a clear scientific view on the current state of knowledge in climate change and its potential environmental and socioeconomic impacts. These reports are available for download at the Web addresses that follow. Please note that Web addresses are current as of the publication date of this assessment but are subject to change.

Climate Change 2014: Synthesis Report and Working Group contributions to the Fifth Assessment Report. www.ipcc.ch/report/ar5/

Climate Change 2007: Synthesis Report. www.ipcc.ch/publications_and_data/ar4/syr/en/contents.html

U.S. Global Change Research Program

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

Synthesis and Assessment Products https://www.globalchange.gov/browse/reports

decreasing extent of snow and ice, and shrinking of arctic ice sheets have all been observed during the past 50 years, and are consistent with a warming climate (IPCC 2014).

Average temperature increases of 2.3 °F may seem small, but even small increases can result in substantial changes in the severity of storms, the nature and timing of precipitation, droughts, heat waves, ocean temperature and volume, and snow and ice—all of which affect humans and ecosystems. Temperature increases above 3.6 °F (2.0 °C) are likely to cause major societal and environmental disruptions through the rest of the century and beyond (Richardson et al. 2009). The International Scientific Congress on Climate Change concluded that "recent observations show that societies and ecosystems are highly vulnerable to even modest levels of climate change, with poor nations and communities, ecosystem services, and biodiversity particularly at risk" (Richardson et al. 2009: 6).

Based on available evidence, 97 percent of the climate science community attributes increases in temperature and changes in precipitation and extreme weather events to human activities (Anderegg et al. 2010, Cook et al. 2013, Doran and Zimmerman 2009, Stott et al. 2010). Scientists have been able to attribute these changes to human causes by using climate model simulations of the past, both with and without human-induced changes in the atmosphere, and then comparing those simulations to observational data. Overall, these studies have shown a clear human "fingerprint" on recent changes in temperature, precipitation, and other climate variables due to changes in greenhouse gases and particulate matter in the air (Stott et al. 2010). The Paris Agreement was ratified in 2016 by parties of the United Nations Framework Convention on Climate Change with the goal of limiting global temperature rise in this century to 3.6 °F above preindustrial levels, and of striving further to limit global temperature rise to 2.7 °F (1.5 °C) from preindustrial levels (United Nations 2016).

The Greenhouse Effect

The greenhouse effect is the process by which certain gases in the atmosphere absorb and re-emit energy that would otherwise be lost into space. The greenhouse effect is necessary for human survival; without it, Earth would have an average temperature of about 0 °F (-18 °C) and be covered in ice, rather than a comfortable 59 °F (15 °C). Several greenhouse gases occurring naturally in the atmosphere contribute to the greenhouse effect; these include carbon dioxide, methane, nitrous oxide, and water vapor. Water vapor is the most abundant greenhouse gas; it resides in the atmosphere on the order of days as it responds to changes in temperature and other factors. Carbon dioxide, methane, nitrous oxide, and other greenhouse gases reside in the atmosphere for decades to centuries. Thus, these other long-lived gases are of primary concern with respect to long-term warming.

Human Influences on Greenhouse Gases

Humans have increased the concentrations of carbon dioxide, methane, nitrous oxide, and halocarbons in the atmosphere since the beginning of the industrial era. More carbon dioxide has been released by humans into the atmosphere than any other greenhouse gas, and it is currently the largest contributor to the greenhouse gas effect (NOAA n.d.a). Global carbon dioxide levels increased at a rate of 3.3 parts per million (ppm) in 2016, surpassing 400 ppm in December 2015, the highest recorded values to date (Dlugokencky and Tans 2016) (Fig. 11). By comparison, preindustrial carbon

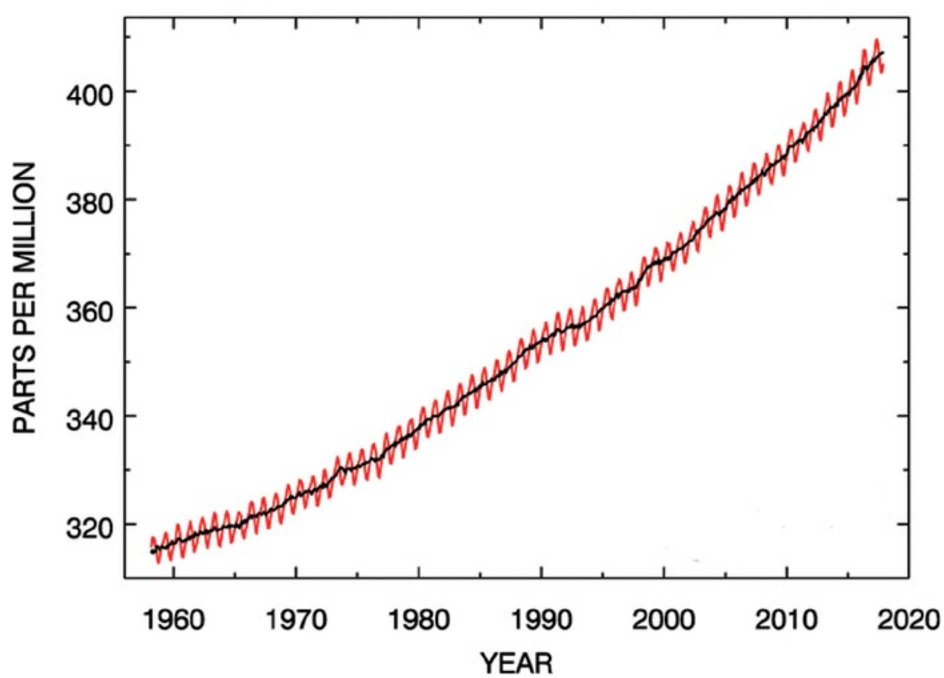


Figure 11.—Atmospheric carbon dioxide (CO_2) at Mauna Loa Observatory in Hawaii (NOAA 2017b). These concentrations are similar to the global average. The full record of CO_2 data (red curve), measured as the mole fraction in dry air, on Mauna Loa constitute the longest record of direct measurements of CO_2 in the atmosphere. The black curve represents the seasonally corrected data.

dioxide levels were around 280 ppm (IPCC 2007). Fossil fuel combustion and industrial processes have accounted for an estimated 78 percent of the anthropogenic increase in carbon dioxide from 1970 to 2010 (IPCC 2014). The remaining 22 percent of human-induced emissions comes primarily from deforestation of land for conversion to agriculture, which releases carbon dioxide when forests burn or decompose (IPCC 2014, van der Werf et al. 2009). However, increases in fossil fuel emissions during the past decade have reduced the contribution from land-use changes to the total carbon emissions (IPCC 2014, Le Quéré et al. 2009).

Methane accounted for roughly 11 percent of global greenhouse gas emissions in 2010 (IPCC 2014). Concentrations of this gas have also been increasing as a result of human activities, including agricultural production of livestock and increases in rice production (IPCC 2013). Livestock production contributes to methane emissions primarily from fermentation in the guts of cattle and other ruminants. Rice production requires wet conditions that are also ideal for microbial methane production. Other sources of methane include biomass burning, microbial-induced methane emissions from landfills, fossil fuel production, and leakage of natural gas during extraction and distribution.

Nitrous oxide accounts for about 6 percent of global greenhouse gas emissions (IPCC 2014). The primary human source of nitrous oxide is agriculture. The use of fertilizer causes emissions from soil as microbes break down nitrogen-containing products. This is especially dramatic in areas where tropical forests were converted to agricultural lands, because tropical areas have high rates of biological turnover and decomposition due to warmer, wetter conditions (Meurer et al. 2016). Other human-caused sources of nitrous oxide include nylon production and combustion of fossil fuels.

Humans have also reduced stratospheric ozone, which protects us from ultraviolet radiation, in the atmosphere through the use of chlorofluorocarbons (CFCs) once used widely in refrigeration, air conditioning, and other applications. Restrictions against the use of CFCs under the Montreal Protocol led to a decline in CFC emissions, and reductions in ozone have subsequently slowed. After CFCs were banned, another class of halocarbons, hydrofluorocarbons (HFCs, also known as F-gases), largely replaced CFCs in refrigeration and air conditioning. HFCs do not deplete stratospheric ozone, but many are powerful greenhouse gases. Currently HFCs account for 2 percent of greenhouse gas emissions (IPCC 2014).

CLIMATE MODELS

Scientists use models, which are simplified representations of reality, to simulate future climates. Models can be theoretical, mathematical, conceptual, or physical. General circulation models (GCMs, also called global climate models) combine complex mathematical formulas representing physical processes in the ocean, atmosphere, and land surface within large computer simulations. In this assessment, GCMs are used to project future climate conditions, which are in turn used as inputs to forest impact models.

General Circulation Models

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

Although climate models use highly sophisticated computers, requirements on computing power mean that projections are limited to relatively coarse spatial scales. Instead of simulating climate for every single point on Earth, modelers divide the land surface, ocean, and atmosphere into a three-dimensional grid (Fig. 12). Each cell within the grid is treated as an individual unit, and is able to interact with adjacent cells. Although each GCM is slightly different, the size of each cell in the grid is usually between 2 and 3° latitude and longitude, which is about the size of Pennsylvania. These horizontal grids are stacked in interconnected vertical layers that simulate ocean depth or atmospheric thickness at increments usually ranging from 650 to 3,280 feet.

Several research groups from the United States and abroad have developed GCMs that have been used in climate projections for the IPCC reports and elsewhere (Box 7). These models have been developed by internationally renowned climate research centers such as NOAA's Geophysical Fluid Dynamics Laboratory (GFDL CM2) (Delworth et al. 2006), the United Kingdom's Hadley Centre (HadCM3) (Pope et al. 2000), and the National Center for Atmospheric Research (PCM) (Washington et al. 2000). These models use slightly different grid sizes and ways of quantitatively representing physical processes. They also differ in sensitivity to changes in greenhouse gas concentrations, which means that some models may project higher increases in temperature than others under the same greenhouse gas concentrations (Winkler et al. 2012).

Like all models, GCMs have strengths and weaknesses (Box 8). In general, they are useful and reliable tools because they are based on well-understood physical processes and have been selected in part for their ability to accurately simulate past climate. Simulations with GCMs can be run for past climate, and output from these simulations generally correspond well with proxy-based estimates of ancient climates

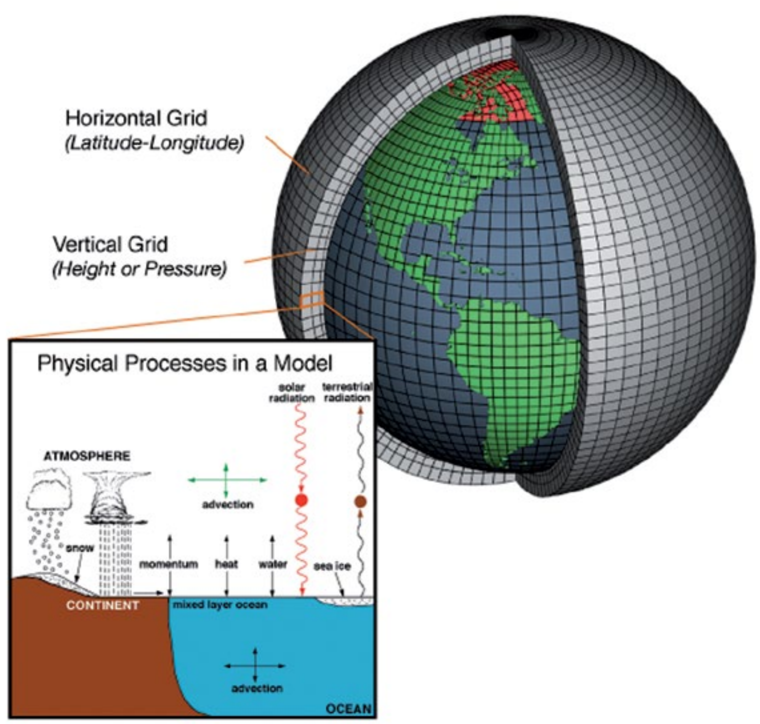


Figure 12.—Schematic describing climate models, which are systems of differential equations based on the fundamental laws of physics, fluid motion, and chemistry (NOAA 2017b). The planet is divided into a three-dimensional grid that is used to apply basic equations; atmospheric models calculate winds, heat transfer, radiation, relative humidity, and surface hydrology within each grid and evaluate interactions with neighboring points.

Box 7: More Resources on Climate Models and Emissions Scenarios

USDA Forest Service

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

Climate Data
https://www.fs.usda.gov/ccrc/library/climate-data

U.S. Global Change Research Program

Climate Models: an Assessment of Strengths and Limitations
https://www.globalchange.gov/browse/reports/sap-31-climate-models-assessment-strengths-and-limitations

Intergovernmental Panel on Climate Change

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

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

Box 8: Models Limitations and Uncertainty

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

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

Model results are not considered standalone components of this vulnerability assessment because there are many assumptions made about the processes simulated by general circulation models (GCMs) and forest impact models, future greenhouse gas concentrations, and the grid scale and number of inputs that a model can reliably handle. At the global scale, precipitation projections usually have much more variability among GCMs than temperature, and this variability is present in downscaled projections. Complex topography and elevational gradients can support a diversity in microclimates that many models cannot capture. Therefore, model results are interpreted by local experts to identify regional caveats and limitations of each model, and are considered with additional knowledge and experience in the forest ecosystems being assessed.

Models can be useful, but they are inherently incomplete. We integrated fundamentally different types of impact models into our assessment of forest vulnerability to climate change. These models operate at different spatial scales and provide different kinds of information. The DISTRIB model component of the Climate Change Tree Atlas projects the amount of available suitable habitat for a species. The LINKAGES model projects species establishment and growth. The LANDIS PRO model projects changes in basal area and abundance by species. There are similarities between some inputs into these models—downscaled climate models and scenarios, simulation time periods, and many of the same species—but because of the fundamental differences in their architecture, their results are not directly comparable. Their value lies in their ability to provide insights into how various interrelated forest components may respond to climate change under a range of possible future climates.

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

and actual historical measurements of recent climates. Projections by GCMs are not perfect, however. Sources of error in model output include incomplete scientific understanding of some climate processes and the fact that some influential climate processes occur at spatial scales that are too small to be modeled with current computing power. Technological advances in the computing industry along with scientific advances in our understanding of Earth's physical processes may lead to continued improvements in GCM projections.

Emissions Scenarios

General circulation models require significant amounts of information to project future climates. Some of this information, such as future greenhouse gas concentrations, is not known and must be estimated. Although human populations, economies, and technological developments will certainly affect future greenhouse gas concentrations, these developments cannot be completely foreseen. One common approach for dealing with uncertainty about future greenhouse gas concentrations is to develop storylines (narratives) about how the future may unfold and calculate the potential greenhouse gas concentrations for each storyline. The IPCC Special Report on Emission Scenarios (SRES) created six standard emissions scenarios that have served as a widely accepted set of such storylines for the third and fourth IPCC global climate assessments (Fig. 13) (Burkett et al. 2014, IPCC 2000). The IPCC's fifth assessment uses a new and different set of

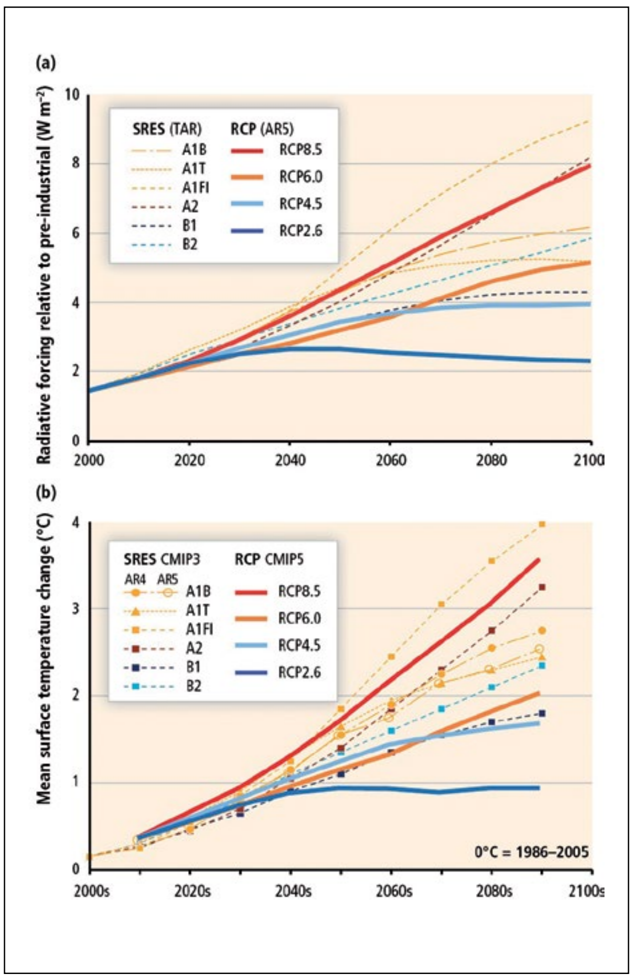


Figure 13.—(a) Projected radiative forcing (RF,W m^{-2}) and (b) global mean surface temperature change (°C) over the 21st century using the Special Report on Emissions Scenarios (SRES) and Representative Concentration Pathway (RCP) scenarios. RF for the RCPs are taken from their published CO_2-equivalent (Meinshausen et al., 2011), and RF for SRES are from the Third Assessment Report Appendix II (Table II.3.11). For RF derived from the Coupled Model Intercomparison Project Phase 5 (CMIP5) models, see WGI (Section 12.3; Tables AII.6.9, 6.10). The ensemble total effective RF at 2100 for CMIP5 concentration-driven projections are 2.2, 3.8, 4.8, and 7.6 W m^{-2} for RCP2.6, RCP4.5, RCP6.0, and RCP8.5, respectively. The SRES RF are shifted upward by 0.12 W m^{-2} to match the RCPs at year 2000 because the climate change over the 21st century is driven primarily by the changes in RF and the offset is due primarily to improvements in model physics including the aerosol RF. For more details and comparison with pre-SRES scenarios, see WGI AR5 Chapter 1 (Figure 1-15). Temperature changes are decadal averages (e.g., 2020s = 2016–2025) based on the model ensemble mean CMIP5 data for the RCPs (colored lines). The same analysis is applied to CMIP3 SRES A1B (yellow circles). See WGI AR5 Chapters 11, 12; Table AII.7.5. The colored squares show the temperature change for all six SRES scenarios based on a simple climate model tuned to the CMIP3 models (WGI AR4 Figure 10.26). The difference between the yellow circles and yellow squares reflects differences between the simple model and analysis of the CMIP3 model ensemble in parallel with the CMIP5 data. Figure courtesy of Burkett et al. (2014: 179); caption reused intact as requested (Burkett et al. 2014).

storylines called Representative Concentration Pathways (RCPs), which are largely consistent with these and other scenarios in the literature, such as the Shared Socio-Economic Pathways (Fig. 13) (IPCC 2014, Knutti and Sedláček 2013, Kriegler et al. 2017, van Vuuren et al. 2011). Notably, they differ from the SRES scenarios in that they are not emissions scenarios; rather they are radiative forcing scenarios. The Fourth National Climate Assessment also uses RCPs (Fig. 13) (USGCRP 2017). The A1FI scenario is roughly comparable to the RCP 8.5 emissions storyline from the fifth IPCC assessment, which represents the upper range of potential emissions; the B1 scenario is roughly comparable to the RCP 4.5 storyline, which represents a commitment to sustainability and conservation (Kriegler et al. 2017, Meinshausen et al. 2011, USGCRP 2017).

The use of different emissions scenarios in GCMs results in different projections of climate, depending on the model and scenario combination. The A1FI scenario, which is used in this assessment, is the most fossil-fuel intensive, and thus projects the highest future greenhouse gas concentrations. On the opposite end of the spectrum is the B1 scenario, the other scenario used in this assessment. It represents a future where the use of alternative energies decreases our reliance on fossil fuels and greenhouse gas concentrations increase the least.

Although these scenarios were designed to describe a range of future emissions during the coming decades, it is important to note that global emissions in the future are likely to differ from the developed scenarios, whether SRESs or RCPs. Emissions scenarios quantify the effects of alternative demographic, technological, or environmental developments on atmospheric greenhouse gas concentrations. None of the current scenarios in this assessment includes any changes in national or international policies, such as the Kyoto Protocol or the Paris Agreement, directed specifically at climate change. However, some of the scenarios that include a reduction in greenhouse gases through other means, such as advances in technology, demonstrate the possible effects of reduced emissions. It is highly unlikely that future greenhouse gas emissions will be less than described by the B1 scenario even if national or international policies were implemented immediately. In fact, global emissions are currently near the top end of the original SRES scenarios, more closely tracking the greenhouse gas emissions of the A1FI scenario (Le Quéré et al. 2009, Raupach et al. 2007).

Downscaling

As mentioned previously, GCMs simulate climate conditions for relatively large areas on a relatively coarse scale. To better examine the future climate of areas within the Mid-Atlantic region, a smaller grid scale is needed. One method of improving the resolution uses statistical downscaling, a technique that establishes statistical relationships between GCM model outputs and on-the-ground measurements (Hayhoe et al. 2007, Stoner et al. 2012a). First, a statistical relationship is developed between GCM output for a past "training period," and observed climate variables of interest (e.g., temperature, precipitation). The historical relationship between GCM output and monthly or daily climate variables at the regional scale can then be tested by using an independent historical "evaluation period" to confirm the relationship is robust. Finally, the historical relationship between GCM output and observed climate variables is used to downscale both historical and future GCM simulations to the same scale as the initial observations. The grid resolution for the downscaled climate projections can range anywhere from 50 km (i.e, each cell represents 31 square miles) to 800 m (a cell represents 0.5 square mile).

Statistical downscaling has several advantages and disadvantages (Daniels et al. 2012). It is a relatively simple and inexpensive way to produce smaller-scale projections using GCMs. One limitation is that downscaling assumes that past relationships between large-scale weather systems and local climate will remain consistent under future change. Another limitation is that downscaling depends on local climatological data. If there are too few weather stations in the area of interest, estimates of future climate may reflect some weather station bias for that area. Finally, local influences on climate that occur at finer scales (such as land cover type or topography) cannot be addressed by statistical downscaling, adding to uncertainty when downscaling climate projections.

Another approach, dynamical downscaling, uses a regional climate model (RCM) embedded within a GCM to simulate physical processes through mathematical representations on a grid (Daniels et al. 2012; Jones et al. 1995, 1997). RCMs operate on a finer resolution than GCMs, typically ranging from 15.5 to 31.0 miles, but can be finer than 6.2 miles. Thus, they can more realistically simulate the effects of topography, land cover, lakes, and regional circulation patterns that operate on smaller scales. However, dynamical downscaling requires even more computational power than statistical downscaling. Another approach, probabilistic downscaling, uses a high-resolution grid to predict the time-varying probability density function for each point in the grid (Nelson Institute Center for Climatic Research 2018). Thus, the probability method can provide more realistic projections of climate extremes. Because of limitations with these other approaches at the start of this assessment, we use statistically downscaled data in this report.

Downscaled General Circulation Models Used in this Assessment

We report statistically downscaled climate projections for two model-emissions scenario combinations: GFDL A1FI and PCM B1 (unless otherwise noted). Both models and both scenarios were included in the IPCC Fourth Assessment Report (IPCC 2007). The Third National Climate Assessment (Melillo et al. 2014) also draws on statistically downscaled data based on IPCC models and scenarios but uses the A2 scenario as an upper bound (Fig. 13). The IPCC Assessment includes several other models, which are represented as a multi-model average in its reports. For this assessment, we instead selected two models that simulated climate in the eastern United States with low error and that bracketed a range of temperature and precipitation futures (Hayhoe 2014). This approach attempts to give readers a range of alternative scenarios that can be used by managers in planning and decisionmaking. Working with a range of plausible futures helps managers avoid placing false confidence in a single scenario given uncertainty in projecting future climate. We note, however, that the two models selected here represent the range of possible futures in terms of average annual and seasonal temperature and precipitation trends. These models do not necessarily represent the bracketed range in terms of other metrics such as daily maximums and minimums, or extremes. Therefore, readers should exercise caution when interpreting trends.

The GFDL general circulation model developed by NOAA is considered moderately sensitive to changes in greenhouse gas concentrations (Delworth et al. 2006). In other words, an increase in greenhouse gas concentrations in GFDL would lead to a projected change in temperature that is greater compared to less-sensitive models and smaller than more-sensitive models. The A1FI scenario is the highest greenhouse gas emissions scenario used in the 2007 IPCC assessment (IPCC 2000). Therefore, the GFDL A1FI scenario represents a higher-end projection for future temperature increases. The PCM model, in contrast, is considered to have low sensitivity to greenhouse gas concentrations. The B1 scenario is the lowest greenhouse gas emissions scenario used in the 2007 IPCC assessment, and is lower than the likely trajectory for greenhouse gas emissions for the coming decades (Washington et al. 2000). Therefore, the PCM B1 combination represents a lower-end projection of future climate change. Together, the GFDL A1FI and PCM B1 scenarios span a large range of possible futures. Although both projections are possible, carbon emissions over the past 15 to 20 years have been more consistent with the A1FI scenario (Raupach et al. 2007, USGCRP 2017). No likelihood has been attached to any of the emissions scenarios, however, and it is possible that actual emissions and temperature increases could be lower or higher than these projections (IPCC 2013).

Climate projections for this assessment were statistically downscaled by using an asynchronous regional regression model (Hayhoe 2014, Stoner et al. 2012a). Daily mean, minimum, and maximum temperature and total daily precipitation were downscaled to an approximately 7.5-mile resolution grid across the United States. Asynchronous quantile regression used historical gridded meteorological data from 1960 through 1999 at 1/8º resolution (6.2 to 9.3 miles, depending on latitude) (Maurer et al. 2002). In addition to the gridded data set, weather station data from the Global Historical Climatology Network were used to train the downscaling model. Weather stations were required to have at least two decades of continuous daily observations in order to robustly sample from the range of natural climate variability and to avoid overfitting model results (Hayhoe 2010).

These climate projections (GFDL A1FI and PCM B1) were chosen for several reasons. First, they cover the entire United States, and thus a consistent data set can be used in this and other regional vulnerability assessments being conducted simultaneously. Second, they included downscaled projections for the A1FI emissions scenario, which tracks more closely with recent trends (last two decades) in global greenhouse gas emissions (Peters et al. 2012, Raupach et al. 2007, USGCRP 2017). Third, the availability of data at daily timesteps was advantageous because it was needed for some impact models used in this report. Fourth, the quantile regression method is more accurate at reproducing extreme values at daily timesteps than simpler statistical downscaling methods (Hayhoe 2010). Finally, the 7.5-mile grid scale resolution was considered useful for informing land management decisions.

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

The downscaled future climate projections were also used in each of the forest impact models described next. This consistency in future climate data allows for more effective comparison across different model results. These models generally require monthly precipitation and temperature values as inputs. They also operate on grid scales that may be larger or smaller than the grid scale of the downscaled data set, and grid scales were adjusted accordingly.

FOREST IMPACT MODELS

Downscaled climate projections from GCMs provide important information about future climate. Although some downscaled climate models attempt to simulate soil moisture, hydrology, forest composition, productivity, or interactions between these factors, they generally do not perform as well as impact models that have been designed specifically to simulate these processes (Fig. 14). Impact models use downscaled GCM projections as inputs, as well as information about tree species and soil types. Several different models are used to simulate impacts on species and forest ecosystems. These models generally fall into one of two main categories: species distribution models (SDMs) and

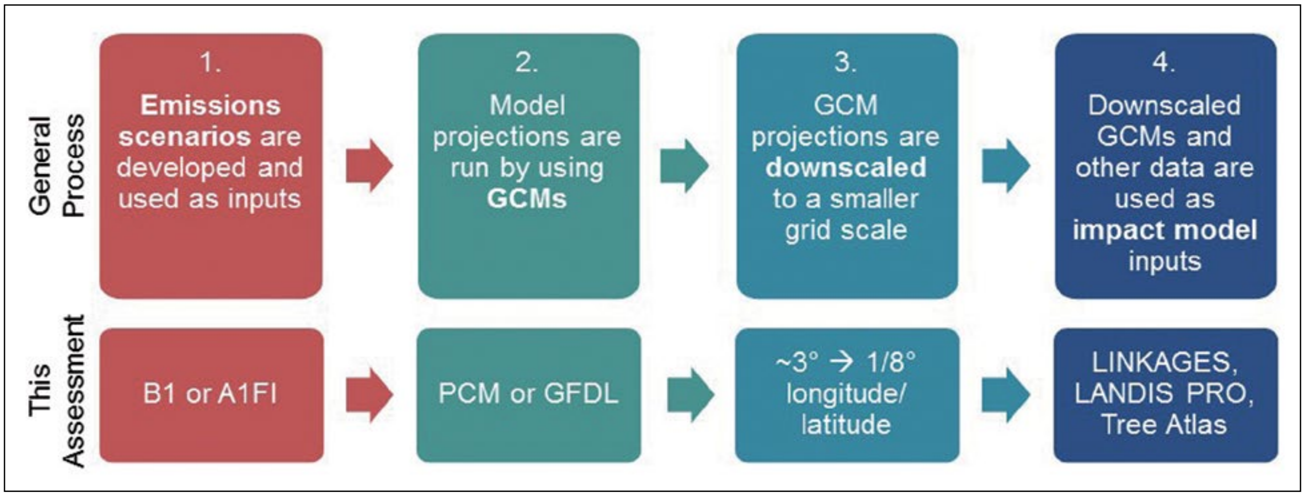


Figure 14.—Steps in the development of forest impact models using projections from general circulation models (GCMs) and specific steps taken in this assessment.

process models. In this assessment, we used one species distribution model, the Climate Change Tree Atlas (USDA Forest Service n.d.a), and two process models, LINKAGES, version 3.0 (Dijak et al. 2016) and LANDIS PRO (Wang et al. 2013, 2015). These models operate at different spatial scales and provide different kinds of information. We chose them because they have been used to assess climate change impacts on ecosystems in our geographic area of interest, and have stood up to rigorous peer review in scientific literature (Brandt et al. 2017, Dijak et al. 2016, Iverson et al. 2016).

Models for Assessing Forest Change

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

In contrast to SDMs, process models such as LANDIS PRO and LINKAGES simulate ecosystem and tree species dynamics based on mathematical representations of physical and biological processes. LANDIS PRO can simulate change in tree species dispersal, succession, and biomass over space and time. Because these models simulate spatial and temporal dynamics of a variety of complex processes and operate at a finer pixel size, they typically require more computational power than SDMs. Therefore, fewer species can be modeled by these two models compared to SDMs. Process models also have several assumptions and uncertainties that should be considered when results are applied to management decisions. Process models rely on empirical and theoretical relationships that are specified by the modeler. Any uncertainties in these relationships can be compounded over time and space, leading to potential biases.

Although useful for projecting future changes, both process models and SDMs share some important limitations. They assume that species will not adapt evolutionarily to changes in climate. This assumption may be true for species with long generation times (such as trees), but some short-lived species may be able to adapt even while climate is rapidly changing. Both types of models may also magnify the uncertainty inherent in their input data. Data on the current distribution of trees, site characteristics, and downscaled GCM projections are estimates that add to uncertainty. No single model can include all possible variables, and there are “unknown unknowns”; thus, there are important inputs that may be overlooked for individual models. In this assessment, competition from understory vegetation, herbivory, and pest outbreaks are a few of the processes not included in the impact models.

View of a northern hardwoods forest at Hawk Mountain in southeastern Pennyslvania. Photo by Greg Czarnecki, Pennsylvania Department of Conservation and Natural Resources, used with permission.

Given these limitations, it is important for all model results to pass through a filter of local expertise to ensure that results match with reality on the ground. Chapter 6 and Appendix 5 explain the expert elicitation process for determining the vulnerability of forest ecosystems based on local expertise and model synthesis.

Climate Change Tree Atlas

The Climate Change Tree Atlas incorporates a diverse set of information about potential shifts in the distribution of tree species habitat in the eastern United States during the 21st century (USDA Forest Service n.d.a). The species distribution model DISTRIB measures relative abundance, referred to as the "importance value," for 134 eastern tree species. The model then projects future importance values and suitable habitat for individual tree species by using downscaled GCM data readjusted to a 12.4-mile grid of the eastern United States (USDA Forest Service n.d.a).

The DISTRIB model uses inputs of tree abundance, climate, and environmental attributes to simulate current and future species habitat. Current tree abundance is estimated from the Forest Service's Forest Inventory and Analysis (FIA) data plots (Miles et al. 2006). Future climates are simulated from downscaled climate data created by the Climate Science Center at Texas Tech University (Hayhoe 2014) for two GCMs (GFDL and PCM) and two emissions scenarios (A1FI and B1) (see Chapter 4 for maps of downscaled climate data for the assessment area). Thirty-eight predictor variables describe 4 land uses, percent fragmentation, 7 climate variables, 5 elevation variables, 9 soil classes, and 12 soil properties obtained from various agencies and data clearinghouses (Table 13) (Iverson et al. 2008a, Riitters et al. 2002). The reliability of individual species models is evaluated through the calculation of a model reliability score, which is based on statistically quantified measures of fitness (Matthews et al. 2011). The strengths and limitations of the Tree Atlas should be considered when results are being interpreted. Importantly, DISTRIB projects where the habitat suitability may change for a particular species, but does not project where the species may actually occur at a given future time. The actual rate of migration into the new suitable habitat may be influenced by large time lags, dispersal and establishment limitations, and availability of refugia. Each tree species is further evaluated for additional factors not accounted for in the statistical models (Matthews et al. 2011). These modifying factors (Appendix 4) are supplementary information on life-history characteristics such as dispersal ability or fire tolerance as well as information on sensitivity to disturbances such as pests and diseases that have had negative effects on the species. This supplementary information allows us to identify situations where an individual species may do better or worse than DISTRIB model projections suggest.

The FIA data plots are nonbiased and extensive across the assessment area, but are spatially sparse at the standard 12.4-mile resolution. Species that are currently rare on the landscape are often undersampled in the FIA data, and consequently have lower model reliability. Likewise, species that are currently abundant on the landscape usually have higher model reliability. The methods assume the species are in equilibrium with the environment, and do not account for species that rapidly change distributions (e.g., invasive species). The models do not account for biological or disturbance factors (e.g., competition or fire) that affect species abundance. Thus, the modifying factors are provided as a supplement to the model output to help address these deficiencies.

Results from the DISTRIB model are provided in Chapter 5. They are also available from the online Climate Change Tree Atlas (https://www.fs.fed.us/nrs/atlas/products).

Table 13.—Parameters used to predict current and future tree species habitat with the DISTRIB model (Iverson et al. 2008a)

Climate (°C, mm)	• Mean annual temperature • Mean January temperature • Mean July temperature • Mean May through September temperature	• Annual precipitation • Mean May through September precipitation • Mean difference between July and January temperature
Elevation (m)	• Elevation coefficient of variation • Minimum elevation • Maximum elevation	• Average elevation • Range of elevation
Soil class (%)	• Alfisol • Aridisol • Entisol • Histosol • Inceptisol	• Mollisol • Spodosol • Ultisol • Vertisol
Soil property	• Soil bulk density (g/cm^3) • Potential soil productivity (m^3/ha timber) • Percent clay (<0.002 mm size) • Soil erodibility factor • Soil permeability rate (cm/h) • Percent soil passing sieve no. 10 (coarse)	• Soil pH • Depth to bedrock (cm) • Percent soil passing sieve no. 200 (fine) • Soil slope (%) of a soil component • Organic matter content (% by weight) • Total available water capacity (cm)
Land use and fragmentation (%)	• Cropland • Nonforest land • Forest land	• Water • Fragmentation index (Riitters et al. 2002)

LINKAGES

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. But as used here, it is initialized from bare ground so that it models tree establishment and growth of individual tree species from 0 to 30 years. It also models ecosystem functions such as soil-water balance, litter decomposition, nitrogen cycling, soil hydrology, and evapotranspiration. Inputs to the model are 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). A full list of model inputs is presented in Table 14. Outputs from the model include number of stems, biomass, leaf litter, available nitrogen, humus, and organic matter, as well as hydrologic variables such as runoff. LINKAGES projections, like Tree Atlas projections, estimate the unconstrained response in potential fundamental niche, or the habitat a species could occupy, to climate change. LANDIS PRO utilizes this fundamental niche information provided by LINKAGES and constrains each species' distribution through tree competition into the

Table 14.—Parameters used in the LINKAGES model[a]

Location	• Latitude, longitude	
Climate (daily)	• Total daily precipitation • Daily minimum temperature • Daily maximum temperature	• Daily total solar radiation • Mean monthly wind speed
Soil	• Field capacity for 12 soil layers • Wilting point for 12 soil layers • Hydrological coefficients for 12 soil layers (based on percent sand and clay)	• Organic matter (Mg/ha) • Nitrogen (Mg/ha) • Percent rock for 12 soil layers
Tree species	• Total annual degree day maximum and minimum (Virginia Tech and USDA Forest Service 2018) • Height and diameter growth equation coefficients (Miles et al. 2006) • Typical maximum mortality age (Loehle 1988) • Frost tolerance (Virginia Tech and USDA Forest Service 2018) • Shade tolerance • Drought tolerance • Nitrogen equation coefficients (Natural Resources Conservation Service 2014, Post and Pastor 1996) • Sprout stump number and minimum and maximum diameter	• Mineral or organic seedbed • Maximum seeding rate • Crown area coefficients • Root:shoot ratio by species • Leaf litter quality class • Foliage retention time • Leaf weight per unit crown area

[a] From Post and Pastor (1996) unless noted otherwise.

realized niche (the habitat that a species may actually occupy). Unlike the LANDIS PRO model (described next), LINKAGES is not spatially dynamic, and does not simulate tree dispersal or any other spatial interaction among grid cells. Simulations are done at yearly timesteps on multiple 0.2-acre circular plots, which correspond to the average gap size when a tree dies and falls over. Typically, the model is run for a specified number of plots in an area of interest, and results are averaged to determine relative species biomass across the landscape over time.

For this assessment, LINKAGES simulates changes in tree species establishment probability during the 21st century for 24 common tree species within the Mid-Atlantic region. The model projects changes in tree species distributions by using downscaled daily mean temperature and precipitation under GFDL A1FI and PCM B1 for the end of the century (2070 to 2099), and compares these projections with those under a current climate scenario (i.e., the climate during 1980 through 2009) at the end of the century. One hundred and fifty-six 0.2-acre virtual plots were located at the geographic center of a subsection and parameterized in LINKAGES; this number represents 1 plot for each of 6 landforms in 26 ecological subsections. Ecological processes are modeled stochastically, so each of the 156 plots was replicated 30 times and results were averaged. Section-level estimates were derived from the area-weighted average of landforms in a subsection and the weighted average of subsections in a section. Therefore, some heterogeneity in species establishment and growth can be masked by this averaging because the results represent the average of the entire subsection.

LANDIS PRO

The LANDIS PRO model (Wang et al. 2014) is a spatially dynamic process model that simulates species-, stand-, and landscape-level processes. 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 at 1- to 10-year timesteps). One new feature of the LANDIS PRO model compared to previous versions is that inputs and outputs of tree species data include tree density and volume and are compatible with 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 best known on the ground and allows the modelers to quantify the uncertainties inherent in the initial data (Wang et al. 2014).

Basic inputs to the LANDIS PRO model include maps of species composition, land types, stands, management areas, and disturbance areas (Table 15). 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 generate the species composition map (Dijak 2013). Landscape Builder uses the FIA unit map, national forest type map, national forest size class map, the National Land Cover Dataset (MRLC 2011), and landform maps to assign the number of trees by age cohort and species to each grid cell. Landform maps specify the slope, aspect, and landscape position to replicate the complex topography of the assessment area (Fig. 15).

The model simulates processes at three levels: the species, stand, and landscape. At the species level, LANDIS PRO simulates seedling germination and establishment, growth, vegetative reproduction, and tree mortality. At the stand level, the model simulates competition and succession. At the landscape level, the model is capable of simulating disturbances (e.g., fire, wind, and disease), harvesting, and silviculture treatments. However, only the harvest levels were a component of simulations in this assessment. The LANDIS PRO model stratifies the landscape into land types based on topography, climate, soil, and other environmental characteristics. Within a land

Table 15.—Parameters used in the LANDIS PRO model

Initial forest conditions	• Land type map • Species map (imputed from FIA)	
Species biological traits	• Reproductive age • Longevity age • Maximum seed dispersal distance • Seed dispersal shape • Shade tolerance	• Maximum stand density index (SDI) • Maximum d.b.h. • Maximum number of germinating seeds • Species growth rate • Species stump sprout age (if applicable)
Species physiological response to climate change[a]	• Species establishment probability by land type	• Maximum growing space capacity by land type
Harvest	• Harvest method • Percentage of management unit to harvest • Minimum basal area to initiate harvest • Management unit map	• Desired postharvest basal area • Rule for ranking harvest priority • Species priority ranking for harvest • Stand map

[a] From the LINKAGES model

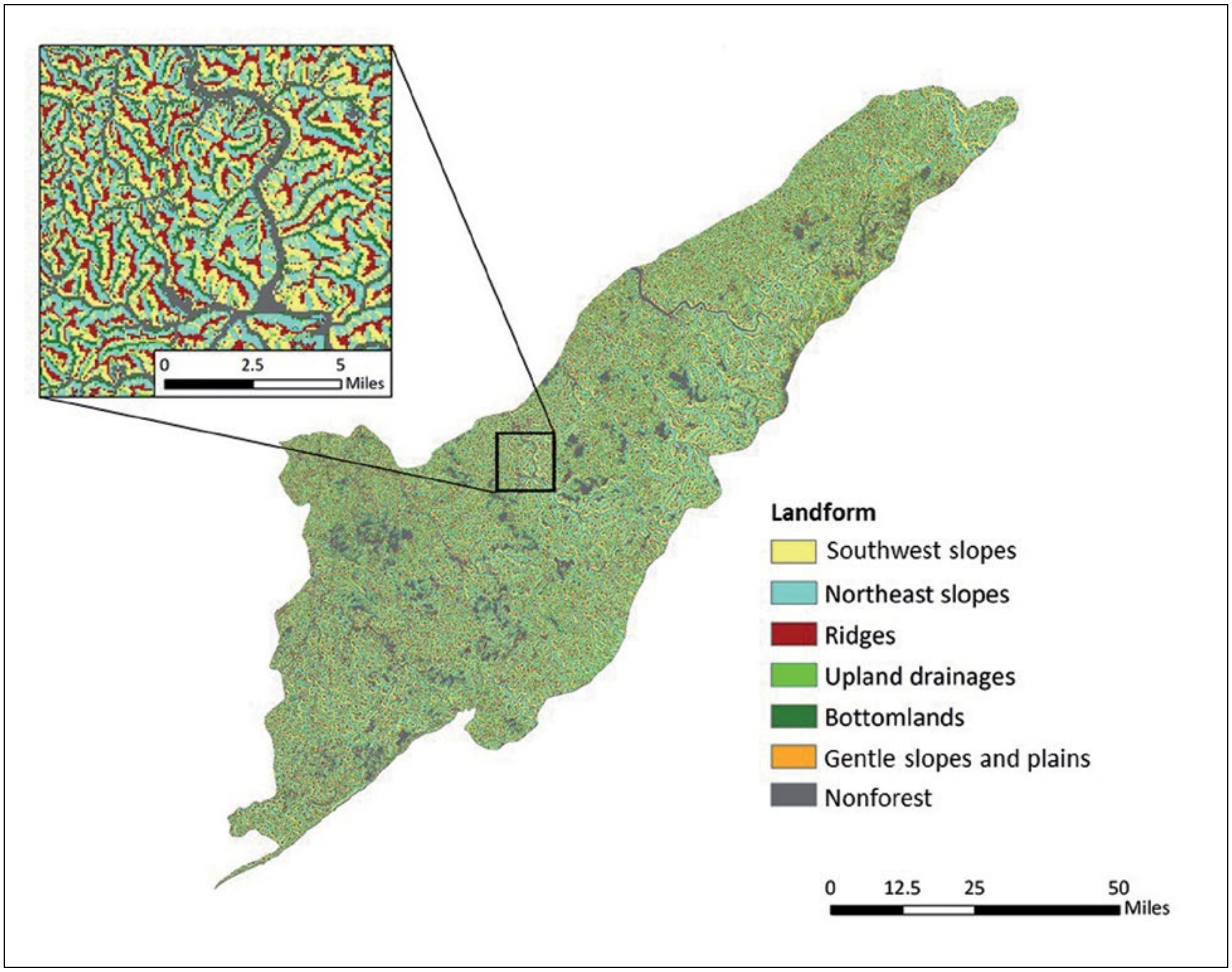


Figure 15.—Example landform map used in landscape initialization in the LANDIS PRO model (Dijak et al. 2016).

type, species establishment and resource availability are assumed to be similar. Combined with anthropogenic and natural disturbances, these land type-specific processes allow the model to simulate landscape heterogeneity over time and space.

Basic outputs in LANDIS PRO for a species or species cohort include aboveground biomass, age, and distribution. Disturbance and harvest history can also be summarized. The spatially dynamic nature of the model and its fine spatial resolution are unique advantages of LANDIS PRO compared to LINKAGES and statistically based models such as DISTRIB. Disadvantages of LANDIS PRO are that it is too computationally intensive to be run for a large number of species (in contrast to DISTRIB) and does not account for ecosystem processes such as nitrogen cycling or decomposition (in contrast to LINKAGES).

For this assessment, LANDIS PRO simulates changes in basal area and trees per acre on 866-foot grid cells during the 21st century for 20 dominant tree species across the Mid-Atlantic region. Species establishment probabilities generated by LINKAGES are then used by LANDIS PRO to incorporate climate change effects into the LANDIS PRO forest landscape simulation.

There are important strengths and limitations to LANDIS PRO that should be considered when results are being interpreted. This model assumes that historical successional dynamics are held constant into the future. It is also assumed that the resource availability by land type accurately reflects the effects of landscape heterogeneity at 866-foot resolution. Additionally, only harvest was included in simulations for this assessment; fire, wind, insect outbreaks, disease, invasive species, and fuels treatments were not included but are important landscape processes.

CHAPTER SUMMARY

Temperatures have been increasing across the world in recent decades largely due to increases in greenhouse gases from human activities. Even if dramatic changes are made to help curtail greenhouse gas emissions, the existing greenhouse gases are expected to persist in our atmosphere for decades to come. Scientists can model how these increases in greenhouse gases may affect global temperature and precipitation patterns by using GCMs. These large-scale climate models can be downscaled and incorporated into other types of models that project changes in forest composition and ecosystem processes to inform local decisions. Although there are inherent uncertainties in what the future holds, all of these types of models can help frame a range of possible futures. This information can be most useful in combination with the local expertise of researchers and managers to provide important insights about the potential effects of climate change on forest ecosystems.

Red maple-hardwood swamp at West Mountain near the Appalachian Trail. Photo by Aissa L. Feldmann, New York Natural Heritage Program, used with permission.

CHAPTER 3: OBSERVED CLIMATE CHANGE

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

OBSERVED TRENDS IN TEMPERATURE AND PRECIPITATION

The Mid-Atlantic region has experienced changes in temperature and precipitation patterns from 1901 through 2011, and the rate of change appears to be increasing. Long-term trends in annual, seasonal, and monthly temperature (mean, minimum, and maximum) and total precipitation over these 111 years were examined for the assessment area by using the Climate Wizard Custom tool (Box 9 and Appendix 2). Observed changes in other ecological indicators (e.g., streamflow and flooding) are often described on a statewide basis because finer resolution data were not available, unless otherwise indicated.

Temperature

Substantial changes in temperature have occurred throughout the northeastern United States during the past 100 years (Kunkel et al. 2013b). Although the annual mean (average) temperature varies from year to year, there is a long-term warming trend (Fig. 16) that is consistent with changes at the state, continental, and global scales (Intergovernmental Panel on Climate Change [IPCC] 2014, U.S. Global Change Research Program [USGCRP] 2017). The trend for the 111-year period shows the Mid-Atlantic region has warmed at a rate of 0.016 °F (0.009 °C) per year, or 1.8 °F (1.0 °C) during the entire record. The coolest average temperatures on record were observed in the early part of the century, warmer temperatures followed in the 1940s and 1950s, and a cold period characterized the 1960s and 1970s. The transition into the 21st century is punctuated by the warmest year on record (2012) and a series of warmer-than-average temperatures (National Oceanic and Atmospheric Administration [NOAA] 2018).

Wetland in Lebanon County, Pennsylvania. Photo by Greg Czarnecki, Pennsylvania Department of Conservation and Natural Resources, used with permission.

Box 9: Where Are these Data from?

Weather stations in the region 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). This tool uses high-quality data from PRISM (Parameter-elevation Regressions on Independent Slopes Model), which converts monthly measured point data from about 8,000 weather stations onto a continuous 2.5-mile grid over the entire United States (Gibson et al. 2002, Karl et al. 1996). 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 to 2011. Additional details about the data presented in this chapter are available in Appendix 2.

Accompanying tables and figures present the change over the 111-year period estimated from the slope of the linear trend. In the following text, trends which have moderate to high probability ($p < 0.10$) that they did not occur by chance are highlighted over less certain trends (for *p*-values, see Appendix 2). We also evaluated trends beginning in 1970, but did not find changes in the sign (i.e., positive or negative) of these trends (data not shown). However, the rate of warming has increased dramatically since the 1970s (Tebaldi et al. 2012), roughly three times faster than the 20th-century trend (Climate Wizard 2014, Ellwood et al. 2013).

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. 2012, 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 coastal areas and potentially overestimate or underestimate the change occurring in a particular location (Beier et al. 2012, Bishop and Beier 2013). 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.

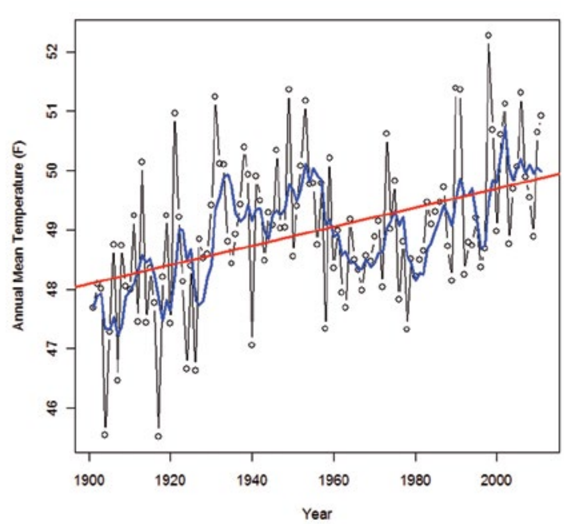


Figure 16.—Annual mean temperature in the assessment area, 1901 through 2011. The blue line represents the rolling 5-year mean. The red regression line shows the trend across the entire time period (a rate of increase of 0.016 °F or 0.01 °C per year). Data source: Climate Wizard (2014).

Both temperature minimums (lows) and maximums (highs) have increased. Minimum temperatures have increased more than maximum temperatures in every season except spring (Fig. 17, Table 16). The

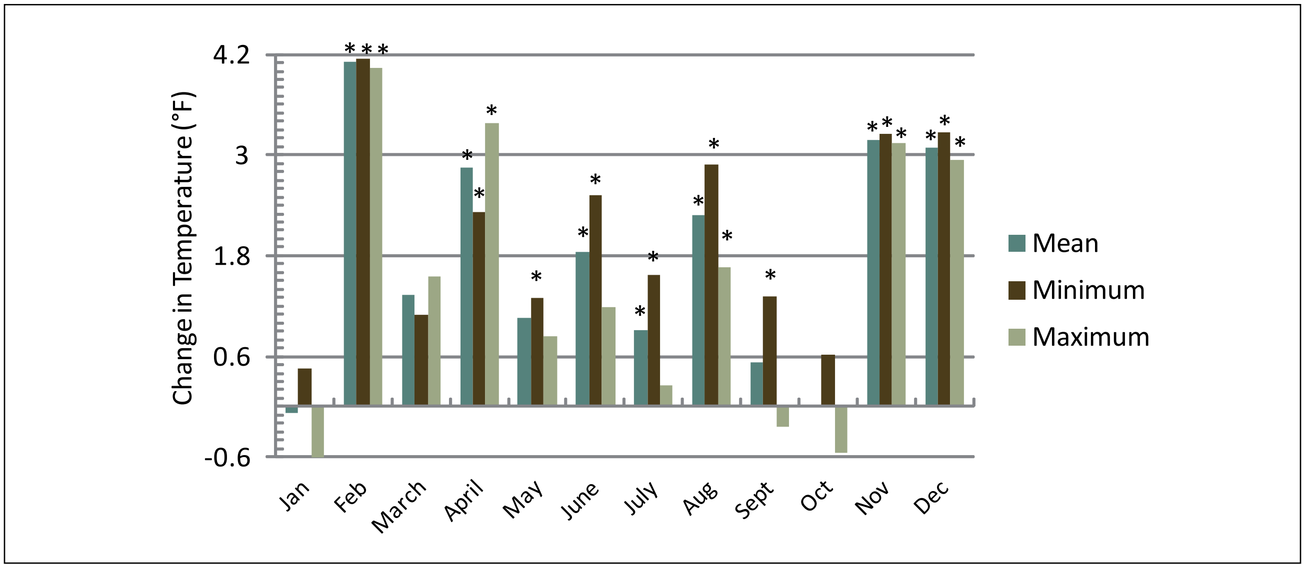


Figure 17.—Change in monthly mean, minimum, and maximum temperatures in the assessment area, 1901 through 2011. Asterisks indicate there is less than 10-percent probability that the trend could have occurred by chance alone. Data source: Climate Wizard (2014).

Table 16.— Mean annual, seasonal, and monthly temperatures, and change[a], in the assessment area, 1901 through 2011 (data source: Climate Wizard [2014])

Month or season	Mean temperature (°F)[a]	Mean temperature change (°F)	Mean minimum (°F)	Mean minimum change (°F)	Mean maximum (°F)	Mean maximum change (°F)
January	26.5	-0.1	17.8	0.5	35.1	-0.6
February	27.4	**4.1**	18.0	**4.2**	36.8	**4.0**
March	36.4	1.3	26.3	1.1	46.4	1.6
April	47.4	**2.8**	36.1	**2.3**	58.7	**3.4**
May	57.9	1.1	46.0	**1.3**	69.8	0.8
June	66.6	**1.8**	55.0	**2.5**	78.1	1.2
July	71.0	**0.9**	59.6	**1.6**	82.4	0.3
August	69.3	**2.3**	58.1	**2.9**	80.6	**1.7**
September	62.7	0.5	51.4	1.3	73.9	-0.2
October	51.7	0.0	40.6	0.6	62.8	-0.6
November	40.9	**3.2**	31.8	3.3	50.0	**3.1**
December	30.2	**3.1**	22.1	**3.3**	38.3	**2.9**
Winter	28.0	**2.4**	19.3	**2.6**	36.7	**2.2**
Spring	47.2	**1.8**	36.1	**1.6**	58.3	**1.9**
Summer	69.0	**1.7**	57.6	**2.3**	80.4	**1.0**
Fall	51.8	**1.3**	41.3	**1.7**	62.2	0.8
Annual	49.0	**1.8**	38.6	**2.1**	59.4	**1.5**

[a] Values in boldface indicate less than 10-percent probability that the trend was due to chance alone.

greatest change in temperature has occurred during the winter, with an increase in minimum temperature of 2.6 °F (1.5 °C) and in maximum temperature of 2.2 °F (1.2 °C) (Table 16). Mean, minimum, and maximum temperatures have all increased the most in February, each by more than 4 °F (2.2 °C). November and December minimum and maximum temperatures also warmed considerably, whereas January temperatures changed very little. February, April, August, November, and December are notable months because mean, minimum, and maximum temperatures all increased significantly in those months.

Within the assessment area, there are local differences in the magnitude and direction of observed temperature changes (Fig. 18). Mean temperatures have warmed more along the

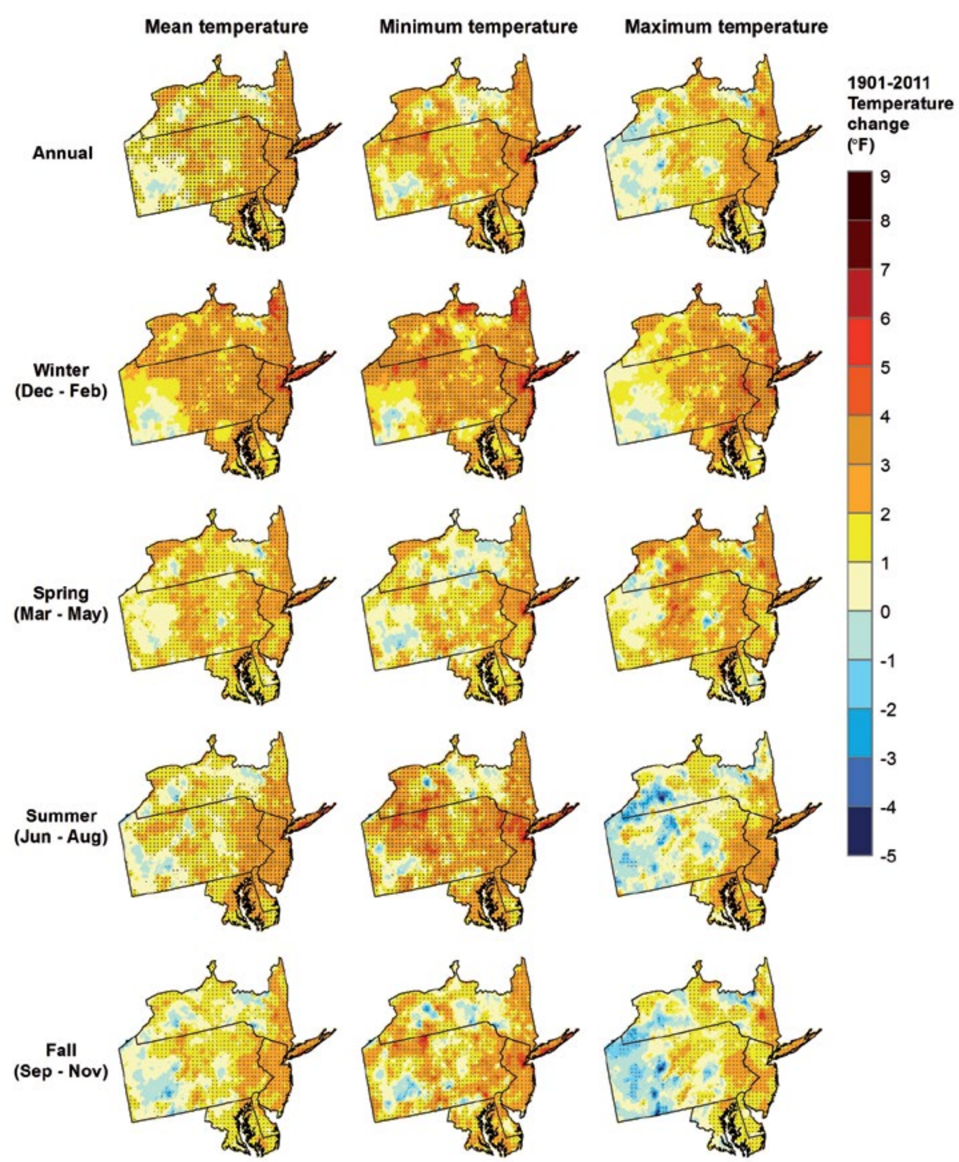


Figure 18.—Change in annual and seasonal mean, minimum, and maximum temperature (°F) in the assessment area, 1901 through 2011. Stippling indicates there is less than 10-percent probability that the trend could have occurred by chance alone. Data source: Climate Wizard (2014).

Atlantic coast than in areas inland to the north and west. For example, New Jersey and Long Island winter temperatures have warmed by up to 6.0 °F (3.3 °C) while relatively little change has occurred in southwestern Pennsylvania. Summer and fall temperatures indicate warmer maximum temperatures for the coastal section, and significant cooling near Lake Erie. Notable increases or decreases in mapped data should be regarded with caution because of the potential for localized anomalies or errors inherent in a particular observational data product, such as the PRISM data presented here (Box 9) (Beier et al. 2012).

The general trend toward increasing temperatures in the Mid-Atlantic region is similar to observations that have been reported elsewhere. The mean surface air temperature across the globe increased 1.5 °F (0.85 °C) during the last century (IPCC 2013). Average temperatures across the United States warmed by 1.8 °F (1 °C) since 1895, with rapid warming occurring since 1979 (USGCRP 2017). The rate of warming has increased and temperatures in the United States have risen by an average of 0.5 °F (0.3 °C) per decade since the 1970s, a total of 2.3 °F (1.3 °C) above the 20th-century average during the 1970-2016 period (NOAA 2018).

Precipitation

From 1901 to 2011, mean annual precipitation increased by 4.5 inches, or about 10 percent across the assessment area (Table 17) (Climate Wizard 2014). The time series of annual precipitation for the assessment area displays a consistent upward trend despite a high degree of year-to-year variability (Fig. 19). During the entire record, there are six years with greater than 50 inches of precipitation, and five of them occurred since 1971. The three wettest years on record occurred during the past 10 years.

Table 17.—Mean annual, seasonal, and monthly precipitation, and change[a], in the assessment area, 1901 through 2011 (data source: Climate Wizard [2014])

Month or season	Mean precipitation (inches)	Mean precipitation change (inches)
January	3.0	-0.1
February	2.6	-0.1
March	3.4	0.3
April	3.6	0.2
May	3.8	0.6
June	4.0	0.2
July	4.1	-0.1
August	4.0	-0.1
September	3.7	**1.3**
October	3.3	0.6
November	3.2	**1.3**
December	3.2	0.3
Winter	8.8	0.1
Spring	10.7	1.1
Summer	12.1	0.0
Fall	10.3	**3.2**
Annual	41.9	**4.5**

[a] Values in boldface indicate there is less than 10-percent probability that the trend was due to chance alone.

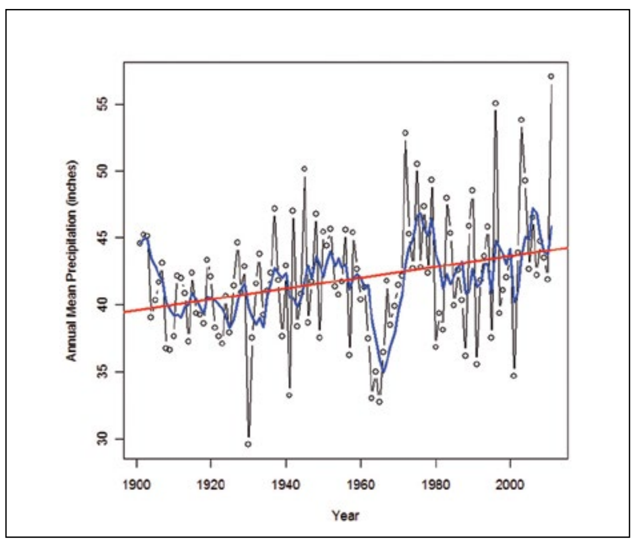


Figure 19.—Annual precipitation in the assessment area, 1901 through 2011. The blue line represents the rolling 5-year mean. The red regression line shows the trend across the entire time period (a rate of increase of 0.04 inch per year). Data source: Climate Wizard (2014).

The apparent trend in the assessment area is that fall has been getting wetter, whereas winter, spring, and summer are changing too little to establish a significant trend (Table 17). The largest absolute increase in measured precipitation from 1901 through 2011 occurred in fall (3.2 inches). Trends in individual months from 1901 through 2011 indicate that September and November precipitation increased by 1.3 inches each (Fig. 20). It is important to note that monthly (Fig. 20) and seasonal averages combine data from across the assessment area, and that changes are geographically variable across the landscape (Fig. 21). For example, summer precipitation has increased in the northwestern and northeastern parts of the region, but has decreased in some southern areas, suggesting increased potential for summer moisture deficits.

Observed increases in precipitation are consistent with observations reported elsewhere. Across the Northeast, annual precipitation increased 5 inches between 1901 and 2011 (NOAA 2018). Similarly, another study of the Northeast (including most of the Mid-Atlantic region) points to an increase of nearly 0.75 inch of precipitation per decade, or about 4.3 inches total, during 1948 through 2007 (Spierre and Wake 2010). This study also found larger increases in summer and fall than in spring and winter. The trend in increased fall precipitation was also observed in the adjacent Central Appalachians region (Butler et al. 2015). The northeastern United States has generally had some of the greatest precipitation increases of any region in the country, and the past four decades have been wetter than during the period from 1901 to 1960 (Melillo et al. 2014, Pederson et al. 2012) (Box 10).

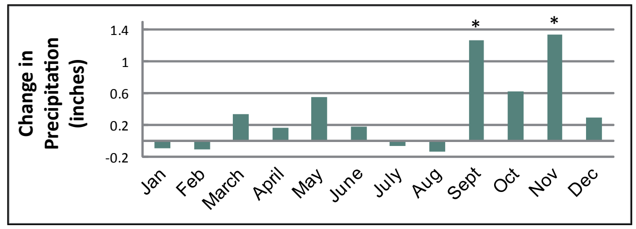


Figure 20.—Change in annual monthly precipitation within the assessment area, 1901 through 2011. Asterisks indicate there is less than 10-percent probability that the trend could have occurred by chance alone. Data source: Climate Wizard (2014).

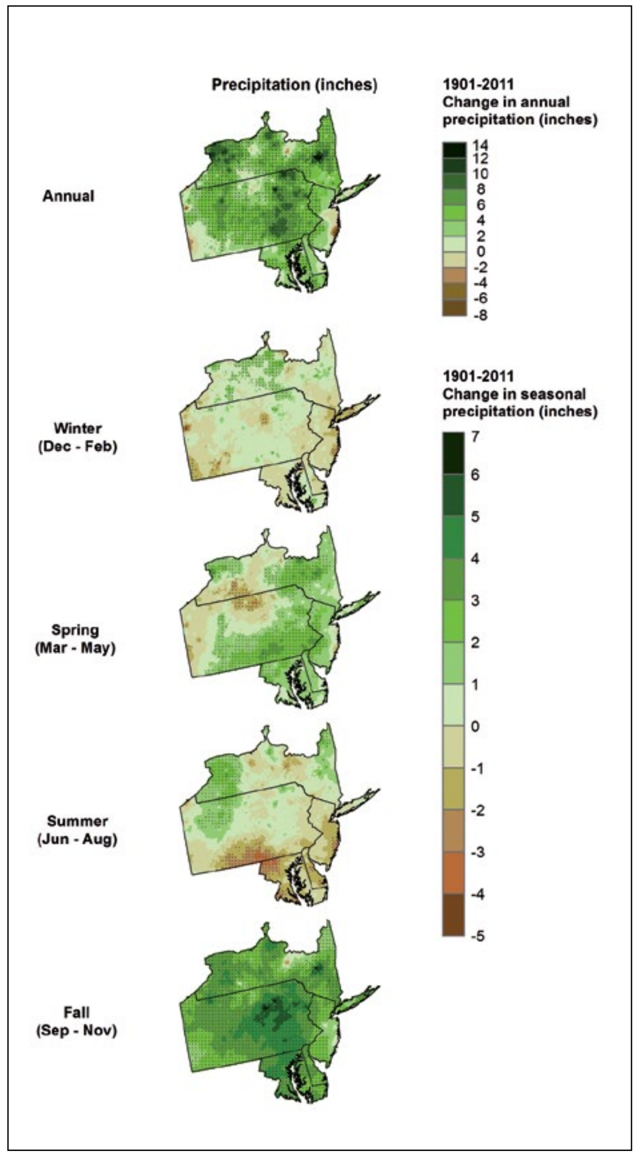


Figure 21.—Change in annual and seasonal precipitation in the assessment area, 1901 through 2011. Stippling indicates there is less than 10-percent probability that the trend could have occurred by chance alone. Data source: Climate Wizard (2014).

Box 10: Climate Changes in the 21st Century

In this chapter, we present changes in climate over the entire historical record for which spatially interpolated data trends are available for the assessment area (1901 through 2011). Looking across the entire record is helpful in detecting long-term changes, but it can also obscure shorter trends. In fact, the long-term trend is made up of shorter periods of warming and cooling, depending on the time period analyzed.

Annual average temperature and precipitation can be explored within the entire climate record (1895 through 2016) through the Climate at a Glance tools from the National Centers for Environmental Information (NOAA 2018). Analysis of historical data shows temperatures above and below the long-term average for the Northeast, which includes the entire Mid-Atlantic region and New England (NOAA 2018) (Fig. 22). Eight of the last 16 years have ranked among the highest recorded temperatures in history: 2012 (the hottest year on record), 2006, 2016, 2010, 2011, 2001, 2002, and 2005. The other seven hottest years were, in descending order, 1998, 1990, 1999, 1953, 1949, 1991, 1931, and 1921. The record coldest years all occurred before the 21st century, with the 15 coldest occurring before 1978.

Precipitation is much more variable, but has broken some records during the 21st century. The wettest year on record occurred in 2011 for the Northeast on average, as well as for the individual states of Pennsylvania, New York, and New Jersey. Four other years in this century have ranked among the 10 wettest: 2003 (Maryland's record wettest year), 2008, 2005, and 2006. Only 1 year, 2001, ranked among the 10 driest years (NOAA 2018).

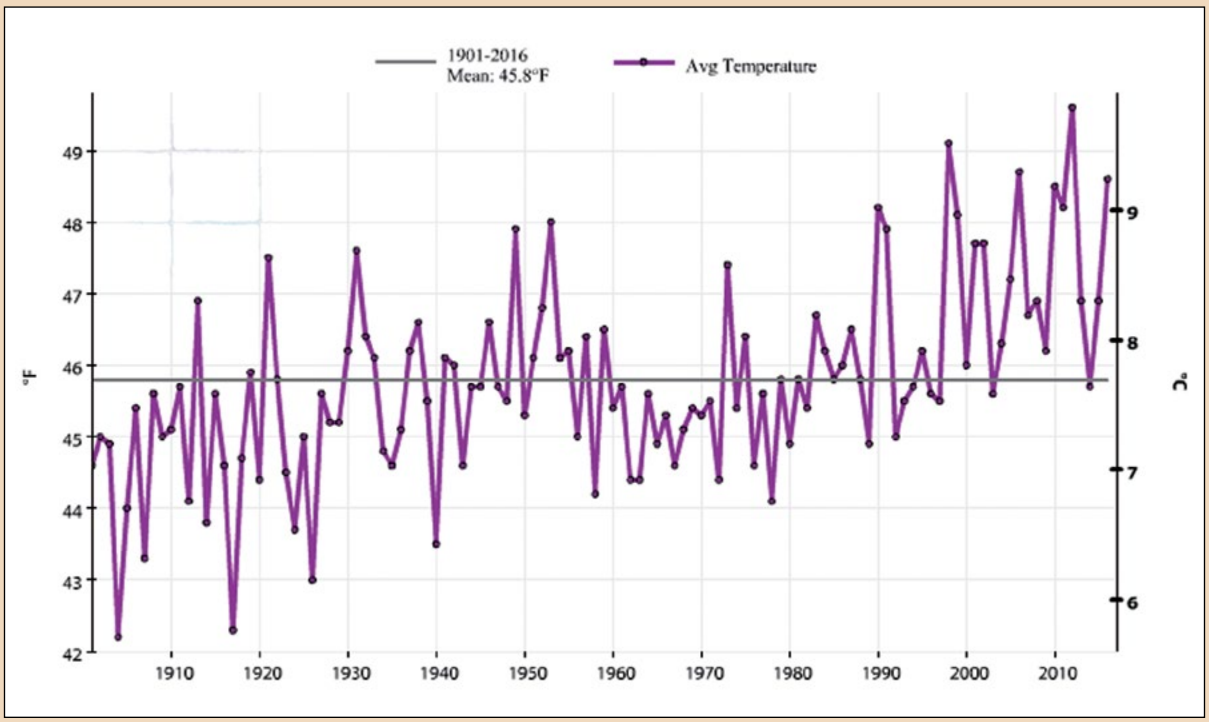


Figure 22.—Annual mean temperature in the northeastern United States, which includes the Mid-Atlantic region and New England. Data source: NOAA (2018).

HISTORICAL TRENDS IN EXTREMES

Although it can be very instructive to examine long-term trends in mean temperature and precipitation, climate extremes can have a greater impact on forest ecosystems and the human communities that depend on them. Extreme weather events include droughts, floods, heavy precipitation events, heat waves, cold spells, tropical and extratropical storms, and coastal sea-level storm surges (Box 11). Weather or climate extremes are defined as individual weather events or patterns that are unusual in their occurrence or have destructive potential (Climate Change Science Program 2008). These events can trigger catastrophic disturbances in forest ecosystems (USGCRP 2016). In addition, the distribution of individual species or forest types is often controlled by particular climatic extremes, for example, winter minimum temperatures. The effects of extreme events may differ depending on existing conditions, timing, and the ecology of individual organisms and processes. For example, a 100 °F (38 °C) day in the New Jersey Pine Barrens may have different consequences from a 100 °F day in the Finger Lakes region. Similarly, record hot temperatures in spring may have different effects on ecosystem processes than record hot temperatures in summer. Scientists agree that climate change has increased the probability of several kinds of extreme weather events, although it is not possible to predict the timing of future extreme events or to directly attribute one particular event to climate change (Coumou and Rahmstorf 2012).

Box 11: Sea-level Rise

Climate change has caused sea-level rise both globally and regionally. Sea-level rise is the result of numerous interacting dynamics within the oceans. As water temperatures increase, water expands and increases the volume of the ocean. Melting glaciers and ice sheets further increase the amount of water going into the oceans (DeConto and Pollard 2016). These changes cause additional changes to the circulation of the oceans as gradients in temperature and ocean salinity are altered.

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 (Sallenger et al. 2012). Sea levels along the northeastern coast of North America are generally higher than in other places, partly due to local influences of ocean circulation (Boon 2012, Sallenger et al. 2012). Global sea levels have risen about 8 inches over the past century, and the rate of rise has been increasing in recent decades (Melillo et al. 2014). The amount of increase has been greater in the northeastern United States, with an overall increase of about 12 inches since 1900 along the Atlantic coast (Horton et al. 2014, Melillo et al. 2014). The accelerated sea-level rise in the Northeast is a result of many complex factors including development, land subsidence from groundwater withdrawal, and changes in oceanic currents (Horton et al. 2014). The Atlantic coast is considered a hotspot of accelerated sea level rise, and has experienced three to four times the global rate during the second half of the 20th century (IPCC 2007, Kunkel et al. 2013b, McCabe et al. 2001, Sallenger et al. 2012, USDA Forest Service 2007). In the Northeast, sea-level rise has increased the risk of erosion, damage from storm surges, flooding, and damage to infrastructure and coastal ecosystems (Boesch et al. 2013, USDA Forest Service 2007). Increased salinity of surface and groundwater threatens natural habitat and human systems in the coastal plain.

Extreme Temperatures

Extreme temperatures can influence forest ecosystems in a variety of ways. Some tree species are limited by hot temperatures during the growing season, and others are limited by cold winter temperatures. Extreme temperatures may also be associated with disturbance events such as drought, wildfire, ice storms, and flooding. Globally and across the Northeast, the number of warm days and nights has increased and the number of cold days and nights has decreased since the 1960s (Alexander 2016, Brown et al. 2010, Griffiths and Bradley 2007, IPCC 2013). Furthermore, both the hottest and coldest temperatures have been increasing, so that the coldest temperatures are not as cold and the warmest temperatures are warmer than historical averages (NOAA n.d.c). Minimum temperature extremes have been much above normal in recent decades, more so than maximum temperature extremes, which have also been increasing. Extreme maximum temperatures, defined as temperatures much above normal or extreme conditions that fall in the upper 10th percentile, were calculated for the Northeast for the period 1910 through 2016 (NOAA n.d.c) (Fig. 23). Within a single year, the difference between the highest maximum temperature for

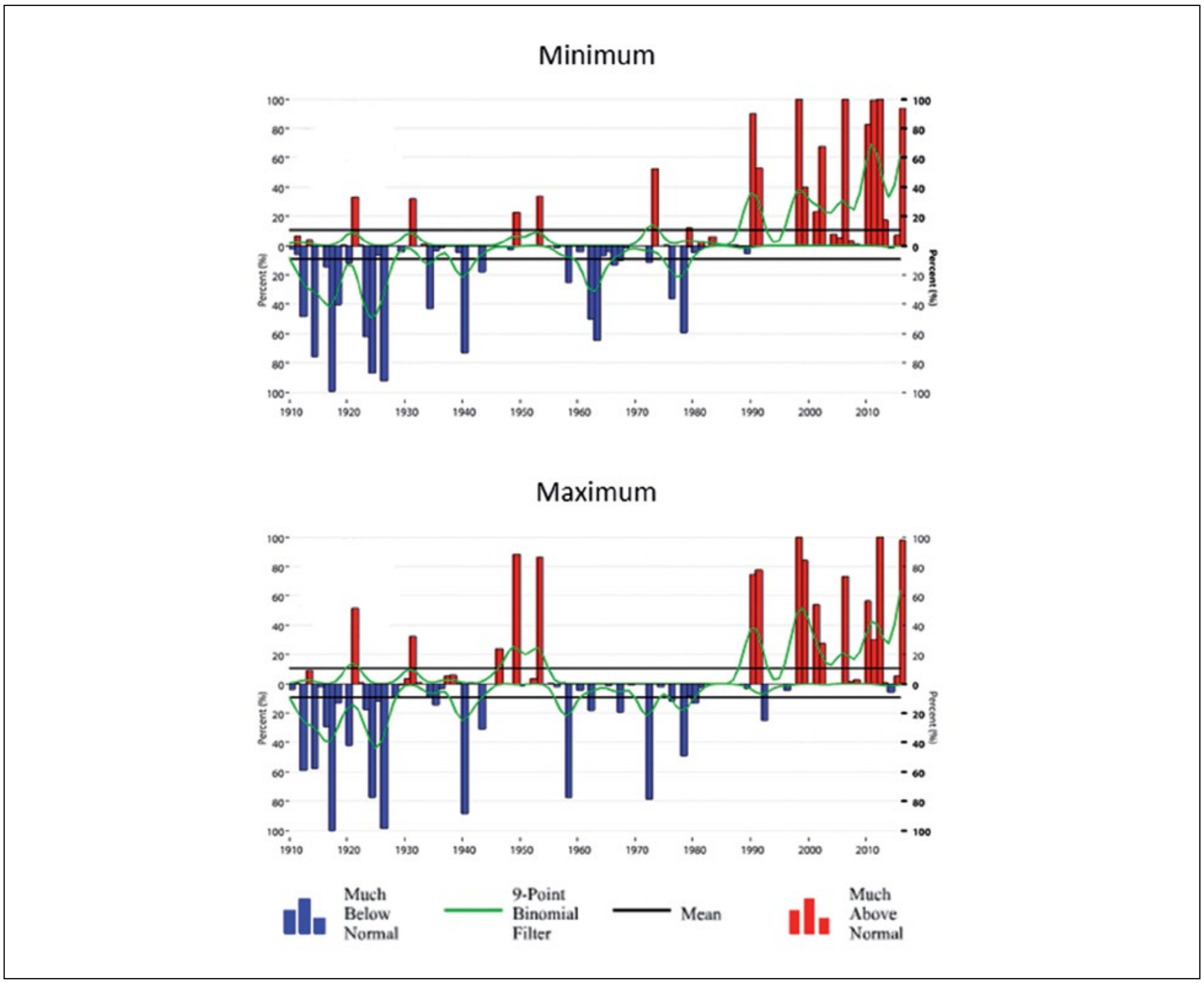


Figure 23.—Extreme temperatures (expressed as the percentage above or below normal) for the northeastern United States. Data source: NOAA (n.d.c).

summer and the lowest minimum temperature for winter has been decreasing (Griffiths and Bradley 2007), resulting in decreased range of extreme temperatures (Alexander et al. 2006). Since the 1960s, the number of warm nights (where minimum temperatures exceeded the 90th percentile) increased along the Mid-Atlantic coast, and decreased farther inland (Griffiths and Bradley 2007). The largest increases in daily maximum and minimum temperatures in the United States have occurred in the coldest months. These trends correspond to global patterns of increasing occurrence of extreme hot weather and decreasing occurrence of extreme cool weather (Hansen et al. 2012, Robeson et al. 2014).

Intense Precipitation

The Mid-Atlantic region is located in one of the wetter regions of the country, and many areas have been experiencing increases in total precipitation during the last century (Fig. 21). Despite high 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 during the past century (Kunkel et al. 1999, 2013b; Melillo et al. 2014). One study found that most weather stations in the Northeast had increases of 1- and 2-inch precipitation events during 1948 through 2007 (Spierre and Wake 2010). Another study found increases in the number of extreme 2-day precipitation events over the United States from 1900 through 2014 (Melillo et al. 2014).

A common way to estimate the change in extreme precipitation events is to look at the 99th percentile of rainfall during a 24-hour period, which averaged 1.04 inches in the Northeast during 1948 through 2007 (Spierre and Wake 2010). Analysis of this 50-year time series shows that the top 1 percent of 24-hour events is delivering more precipitation. Another study found that the heaviest 1 percent of daily precipitation events increased by 71 percent in the Northeast between 1958 and 2012, the most of any region in the United States (Melillo et al. 2014).

Similarly, recurrence intervals are becoming shorter across the Northeast (i.e., a 50-year rain event may occur every 40 years) (DeGaetano 2009). A study of the eastern United States found that the heavy precipitation events (relative to a local weather station's largest recorded storm) are occurring 55 percent more frequently in the Mid-Atlantic region; heavy precipitation events that used to occur every 12 months are now occurring every 7.7 months (Madsen and Willcox 2012).

Severe Thunderstorms and Tornadoes

Numerous types of storms frequently occur within the region as a result of its diverse climate, including thunderstorms, ice storms, tropical storms, and hurricanes (Box 12), and nor'easters originating from mid-latitude westerly winds (Dolan et al. 1988, Kunkel et al. 2013a). Strong thunderstorms occur most frequently from June to August within the assessment area (Changnon 2003b), and there is a general expansion northward and eastward as the season progresses (Robinson et al. 2013). Thunderstorm frequency is generally greatest in the southern parts of the assessment area, averaging 30 to 35 days per year in the Chesapeake Bay region and southeastern Pennsylvania, compared to only 20 to 25 days in southern New York (Changnon 2003b, Changnon 2011). A study of severe thunderstorm observations over the eastern United States identified an increase in thunderstorm frequency during the last 60 years; however, it is uncertain if those increases are biased by increased accuracy in storm reporting (Robinson et al. 2013). There is no evidence that the frequency of nor'easters, which occur often from October through April, has changed during the last century (Brooks 2013, Brooks et al. 2014).

Tornadoes also affect the assessment area. They occur less frequently than thunderstorms, but

Box 12: Coastal Storms and Hurricanes

Hurricanes and other warm-water tropical storms are a major cause of damage in coastal areas, whereas smaller "extratropical" storms often produce waves that are responsible for coastal erosion on a regular basis (Dolan et al. 1988). Hurricane activity in the Atlantic Ocean typically occurs June through November (National Oceanic and Atmospheric Administration n.d.b). Although not every hurricane or storm formed in the Atlantic makes landfall, associated winds or storm surge can damage coastal areas. In fact, hurricanes that do not make landfall can be more damaging to coastal ecosystems because of the lack of rain to help dilute intruded saltwater. Technology for observing hurricanes has improved over recent decades with the increased use of satellites, and observations are probably biased over the long-term climate record, as they are for tornadoes.

There is also some debate about whether increases in hurricane frequency are attributable to climate change or to natural variability. However, evidence suggests that Atlantic hurricane frequency has increased over the period since high-quality satellite data became available (1981 to 2010) (Bell et al. 2012, Melillo et al. 2014). One study divided the hurricane record into three distinct periods and found that each period contained 50 percent more hurricanes than the previous period (Webster et al. 2005). Other evidence indicates 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). Additionally, there is some evidence that storm tracks have shifted poleward, suggesting that tropical cyclones are maintaining their strength farther north (Kossin et al. 2014). Long-term records from tide gauges may also describe the storm surge resulting from tropical cyclones without the need to direct observe cyclones themselves, thereby reducing potential bias in observation. One study used tide gauges to develop a surge index and found an increase in large surge events, with twice as many large events occurring in warm years than in cold years (Grinsted et al. 2012). Another study linked increased storm surge with increased flood risk in New York City, and found that the return interval for a 7.4-foot flood has decreased from 500 years to less than 25 years (Reed et al. 2015).

locations where they occur often suffer severe localized damage. Based on a 30-year average from 1985 to 2014, Pennsylvania experienced the most tornadoes per year (15), followed by New York (10), Maryland (8), New Jersey (3), and Delaware (1) (National Weather Service Storm Prediction Center 2016). Tornado outbreaks occur when six or more tornados occur in quick succession; most tornado-related damage occurs during these outbreaks (Tippett et al. 2016). One recent study found that the number of outbreak tornadoes increased by about 15 percent from 1973 to 2010, while the number of non-outbreak tornadoes decreased by 20 percent (Fuhrmann et al. 2014). The same study found that the number of outbreaks is increasing. This shift in tornado behavior was found to be statistically significant, but could also be biased due to increased technology and reporting success, such as the introduction of Doppler Radar technology in the 1980s and an enhanced Fujita scale that includes more damage indicators (Fuhrmann et al. 2014, Widen et al. 2015). Other studies also report no change in overall tornado frequency and fewer tornado days, but a higher number of tornadoes on days that they do occur (Brooks et al. 2014, Elsner et al. 2015).

PHYSICAL PROCESSES

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

Streamflow and Flooding

Several studies have identified close relationships between climate and streamflow in the Mid-Atlantic region (Neff et al. 2000, Schulte et al. 2016). A nationwide study of streamflow during 1944 to 1993 demonstrated that baseflow and median streamflow have increased at many streams in the Midwest and Mid-Atlantic region (Lins and Slack 1999). More recent studies have confirmed increased annual streamflow from 1961 through 1990, at least partially due to increased storm frequency (Groisman et al. 2004, Schulte et al. 2016). Changes in streamflow are driven by increased precipitation, as well as changes in land cover and land use (DeWalle et al. 2000, Groisman et al. 2004). After accounting for these factors, however, streams in the eastern United States still exhibited increased discharge during the past several decades, which is attributed to climate change (Patterson et al. 2013, Wang and Hejazi 2011).

Flood occurrence is driven partially by weather-related factors, such as the timing of spring snowmelt, heavy rainfall, and storm surge resulting from hurricanes and tropical storms (Fig. 24). Flood occurrence also depends on soil saturation, soil temperature, and drainage capabilities. Floods can develop slowly as the water table rises, or quickly if large amounts of rainfall rapidly exceed moisture thresholds. Although snowpack in the Mid-Atlantic region is generally short-lived, melting can contribute substantial volume to winter and spring peak flow and flooding (Eisenbies et al. 2007, Kochenderfer et al. 2007). Areas with steep and narrow terrain are more prone to flash flooding of the smaller rivers, streams, and tributaries (Eisenbies et al. 2007). Although many small floods originate from small, unmonitored watersheds and go unreported, major regional floods are typically recorded by stream gauge measurements (Mohamoud and Parmar 2006). In Maryland, 57 major floods were recorded from 1860 to 2004, with at least 13 of them associated with hurricanes (Joyce and Scott 2005). The Delaware River Basin, which stretches between Delaware, New Jersey, Pennsylvania, and New York, has experienced 10 major floods from 1903 to 2011, about 1 every 15 years (Delaware River Basin Commission 2015). The City of Pittsburgh, at the confluence that forms the Ohio River, reports 20 major floods since 1861. Damage from floods has been increasing in recent decades due to larger flood events (Villarini et al. 2011, 2014). Hurricanes contribute to flooding across the eastern United States (Box 12), causing severe flooding hundreds of miles inland, and moderate flooding farther inland (Fig. 24).

Freeze-free and Growing Season Length

Growing season length is often estimated as the period between the last spring freeze and first autumn freeze (climatological growing season), but can also be estimated through the study of plant phenology, which represents the biological growing season (Linderholm 2006). A large body of research using observations from the last 50 to 110 years concurs that the frost-free season has lengthened by 10 to 20 days at global, hemispheric, and national scales, primarily due to an earlier onset of spring (Christidis et al. 2007; Easterling 2002; Griffiths and Bradley 2007; Linderholm 2006; Schwartz et al. 2006, 2013). Regional studies of weather stations in the northeastern United States provide evidence of similar trends in the freeze-free season: an increase

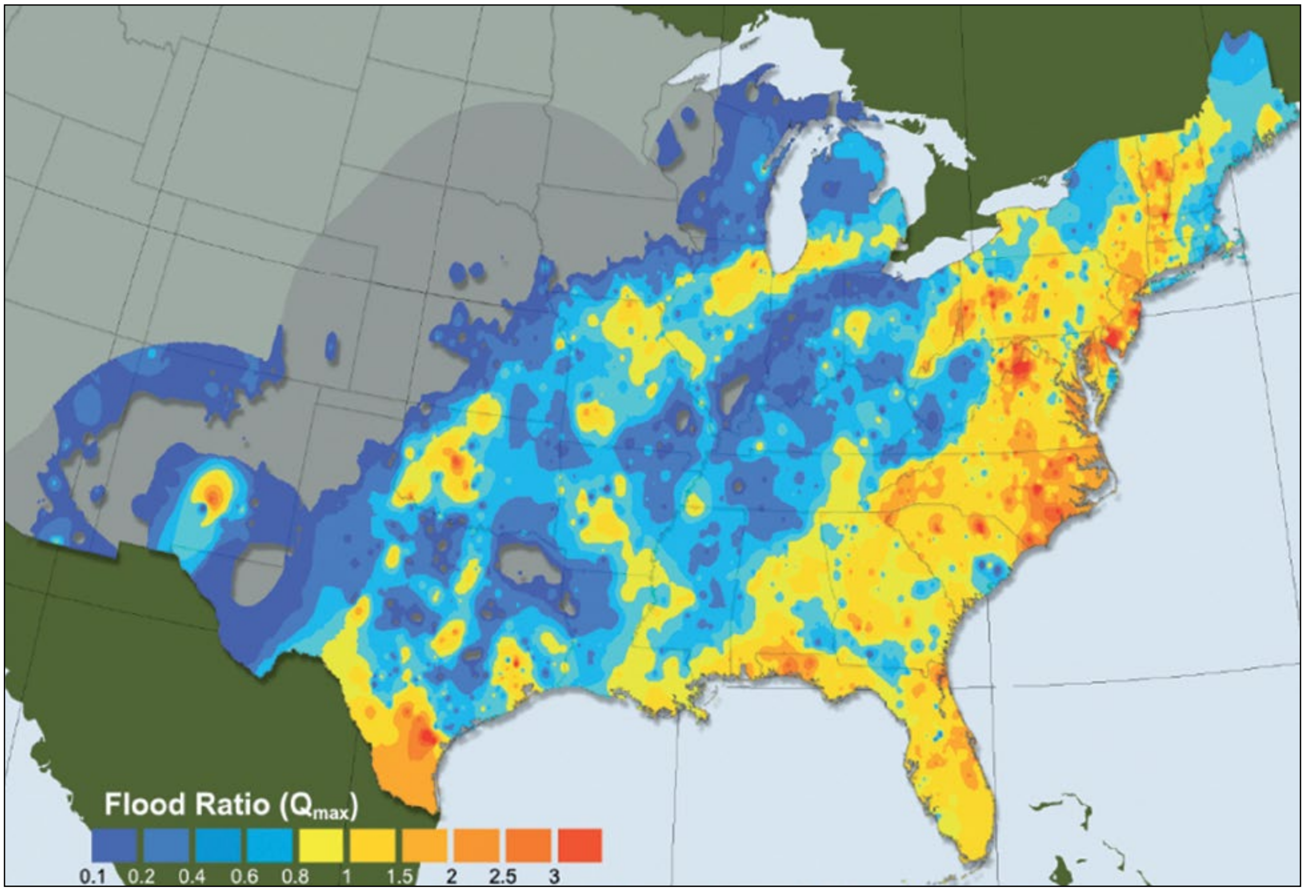


Figure 24.—Composite map of floods associated with hurricanes that made landfall from 1981 through 2011, based on stream gauge data. The flood ratio (Q) indicates the magnitude of departure from the 10-year flood peak; values larger (smaller) than 1 indicate floods were larger (smaller) than the 10-year flood peak. Figure adapted from data compiled by Villarini et al. (2014) and presented here from U.S. Global Change Research Program (2016).

of 0.7 days per decade during 1915 to 2003, and 2.5 days per decade from 1970 to 2000 (Brown et al. 2010, Frumhoff et al. 2007).

There is also phenological evidence from remote sensing and satellite imagery that deciduous forests in the eastern United States are retaining leaves later in the fall, especially for forests at lower elevations (Elmore et al. 2012). This delay is associated with a decrease in the number of cold days occurring after the summer maximum temperature and subsequent delay in leaf senescence (Dragoni and Rahman 2012). Another study using remote sensing across the northern hemisphere found no significant trend in the start of season, but did find that the end of season occurred later, and the total growing season lengthened by about 9 days from 1981 through 2008 (Jeong et al. 2011). Increases in the growing season length are causing some noticeable changes in the timing of biological activities, such as bird migration (Box 13).

Snow and Winter Storms

Warmer temperatures have caused precipitation to increasingly fall as rain in winter (Feng and Hu 2007). Although precipitation has increased across the eastern United States, warmer average winter temperatures have caused a smaller proportion to fall as snow (Kunkel et al. 2009). In the Mid-Atlantic region, several studies indicate a strong downward trend in snowfall. A study using long-

Box 13: Ecological Indicators of Change

The timing of biological events (phenology), 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). Increases in the growing season length and other climatic changes have caused noticeable changes in the timing of biological activities across the world (Walther et al. 2002). Likewise, numerous phenological changes have been observed across the region:

- The snowshoe hare, whose coat turns white during the winter to camouflage it in the snow, has been declining throughout the Appalachian Mountains (Maryland Department of Natural Resources 2016). Increased predation during the winter is a result of a mismatch between the animal's white winter fur and its surroundings due to a longer snow-free season (Mills et al. 2013; Zimova et al. 2014, 2016). The range of snowshoe hare has contracted to the coldest regions of Pennsylvania that still have persistent snowpack (Diefenbach et al. 2016, Gigliotti 2016). This range contraction northward is primarily attributed to a reduction in snow cover duration in the southern historical range (Pauli 2016).

Snowshoe hare in Elk County, Pennsylvania. Photo by Hal Korber, Pennsylvania Game Commission, used with permission.

- Ten species of native bees in the Northeast have been emerging an average of 10 days earlier over the last 130 years, with much of the change linked to warming trends since 1970. Bee-pollinated plants are also blooming earlier, suggesting that these generalist bee species are keeping pace with changes in plant phenology (Bartomeus et al. 2011).
- The purple martin, a long-distance migratory songbird that overwinters in the assessment area, has been declining across North America and Canada (Nebel et al. 2010). Population declines are linked to an increasing mismatch between spring arrival date and timing of food availability (Fraser et al. 2013). A recent study tracking spring migration from the Amazon basin to two breeding sites in Pennsylvania and Virginia found that purple martins were unable to depart earlier, migrate faster, or claim breeding sites earlier in response to earlier green-up and insect emergence.
- One hundred native plant species were monitored in a 100-mile radius near Washington, DC, and 86 percent showed earlier flowering times (Abu-Asab et al. 2001). Two species of cherry, *Prunus serrulata* and *P. yedoensis*, are blooming 6 and 7 days earlier, respectively, than they did in 1970. This plant is featured during Washington, DC's Cherry Blossom Festival, which relies on predicting peak-flowering season to meet tourist expectations.

term snowfall totals from 1930 through 2007 found a trend of decreasing snow in the Mid-Atlantic region, especially along the coast (Kunkel et al. 2009). Another study observed a decrease of 1.5 snow days in the Northeast between 1970 and 2000 (Hayhoe et al. 2007). Regional trends indicate that although snowfall is highly variable from year to year, the most recent 30 years have had fewer heavy snowfall years, but with more intense snowfalls when they do occur (Feng and Hu 2007). One exception to the decreasing trends is in the lee of Lakes Erie and Ontario, where warmer lake surface temperatures have fueled increases in lake-effect snowfall during the past 50 years (Burnett et al. 2003).

Lake and River Ice

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 a century across the region. Ice-out, which is the date in spring when ice cover leaves a lake, 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 and Dudley 2006, Magnuson et al. 2000). A study of selected U.S. lakes analyzed ice-out dates for three inland lakes in New York and found earlier ice-out dates for all of them (U.S. Environmental Protection Agency 2015). Lake Otsego in central New York has records of lake ice dating back to 1894 and analysis shows that the lake has thawed earlier by 11 days during the 165-year period. Across the Midwest and Northeast, records beginning in the 1850s have shown that ice on inland lakes is also thawing earlier in the spring and forming later in the fall (Benson et al. 2012). Annual ice cover on Lake Ontario declined by 88 percent between 1973 and 2010 while ice cover on Lake Erie declined by half (Wang et al. 2012). The combined effect of these trends is a longer ice-free period for lakes across the region and the assessment area.

CHAPTER SUMMARY

Temperatures have been warming faster since the 1970s, with 15 of the 16 warmest years on record occurring during the 21st century. There are significant geographic patterns that show less warming in some parts of the region (e.g., southwestern Pennsylvania) than warming observed along the Atlantic coast. Most of the change in precipitation totals is attributed to large increases in precipitation in the fall. Precipitation changes during other seasons were smaller and varied geographically. The hottest days are getting hotter and the number of hot days is increasing. The coldest days are also getting warmer and the number of cold days is decreasing. Heavy precipitation events have become more frequent and intense. Characteristic winter conditions such as snowfall and lake ice have been diminishing with warmer temperatures. In addition, the growing season has lengthened. Other ecological indicators are beginning to reflect these changes as well, as shown by novel mismatches between animals and their food and habitat. These trends are generally consistent with regional, national, and global observations related to anthropogenic climate change.

CHAPTER 4: PROJECTED CHANGES IN CLIMATE AND PHYSICAL PROCESSES

In Chapter 3, we examined how climate has changed in the Mid-Atlantic region during the past century. This chapter examines how climate is expected to change during the 21st century, including changes in extreme weather events and other climate-related processes. General circulation models, also called global climate models (GCMs), are used to project future change at coarse spatial scales and then downscaled in order to be relevant at scales where land management decisions are made. These downscaled data can then be incorporated into forest species distribution models and process models (results are presented in Chapter 5). Chapter 2 more fully describes the models, data sources, and methods used to generate these downscaled projections, as well as the inherent uncertainty in making long-term projections. In Chapter 4, we focus on two climate scenarios for the assessment area, chosen to bracket a range of plausible changes in average annual and seasonal temperatures and precipitation totals. We note, however, that the two models selected here do not necessarily represent the bracketed range in terms of other metrics such as daily maximums and minimums, or extremes. Therefore, readers should exercise caution when interpreting future trends. Information related to future weather extremes and physical processes is drawn from published research.

PROJECTED TRENDS IN TEMPERATURE AND PRECIPITATION

Projected changes in temperature and precipitation within the Mid-Atlantic region were examined by using a statistically downscaled climate dataset (Chapter 2). Daily mean, minimum, and maximum temperature and total daily precipitation were downscaled to an approximately 7.5-mile grid across the United States. To show projected changes in temperature and precipitation, we calculated the average mean, minimum, and maximum temperatures and precipitation for each month for three 30-year time periods through the end of this century (2010 through 2039, 2040 through 2069, and 2070 through 2099) (Stoner et al. 2012b). The use of 30-year periods reduces the influence of natural year-to-year variation that may bias calculations of change and allows for more direct comparison with the 1971 through 2000 baseline (see Chapter 2 and Appendix 2) from which changes are calculated (Girvetz et al. 2009). For all climate projections, two GCM-emissions scenario combinations are reported: GFDL A1FI and PCM B1. The A1FI scenario used in this assessment is the most fossil-fuel intensive, and thus projects the highest future greenhouse gas concentrations; GCM simulations using the A1FI scenario project the highest future warming. On the other end of the spectrum, the B1 scenario used in this assessment represents a future where alternative energy sources decrease our reliance on fossil fuels and greenhouse gas concentrations increase the least. GCM simulations using the B1 scenario project the lowest increase in global temperature. The GFDL A1FI model-scenario combination consistently projects greater changes in future temperature and precipitation than the PCM B1 model-scenario combination (hereafter referred to simply as GFDL A1FI and PCM B1). Because the future may be different from any of the developed scenarios, it is important to consider the range of possible climate conditions during the coming decades rather than one particular scenario.

The PCM B1 and GFDL A1FI scenarios used in this assessment are just two of many climate scenarios that are available. The projections from alternative scenarios can vary widely, but these two scenarios serve as "bookends" for a broad range of potential future climate conditions (Chapter 2). Projected changes in temperature and precipitation for GFDL A1FI represent a greater level 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

The Mid-Atlantic region is projected to experience substantial climate warming during the 21st century, especially under the GFDL A1FI scenario (Fig. 25). Early-century (2010 through 2039) annual average temperature is projected to increase by 0.9 °F (0.5 °C) for PCM B1 and 1.9 °F (1.1 °C) for GFDL A1FI (Fig. 25, Table 18). Projections of temperature diverge substantially over time, resulting in increasingly larger differences between the two scenarios. By the end of the century, these differences result in a projected temperature increase that is 5.4 °F (3.0 °C) larger for GFDL A1FI than for PCM B1. Compared to the 1971 through 2000 baseline climate, the average annual temperature at the end of the century is projected to increase by 2.2 °F (1.2 °C) for PCM B1 and by 7.6 °F (4.3 °C) for GFDL A1FI (Table 18). Seasonal changes follow this pattern, with less change projected during the early century period, and more change projected at the end of the century, especially for GFDL A1FI. See Appendix 3 for projected changes in mean, minimum, and maximum temperatures during the early, mid-, and late century for all four seasons.

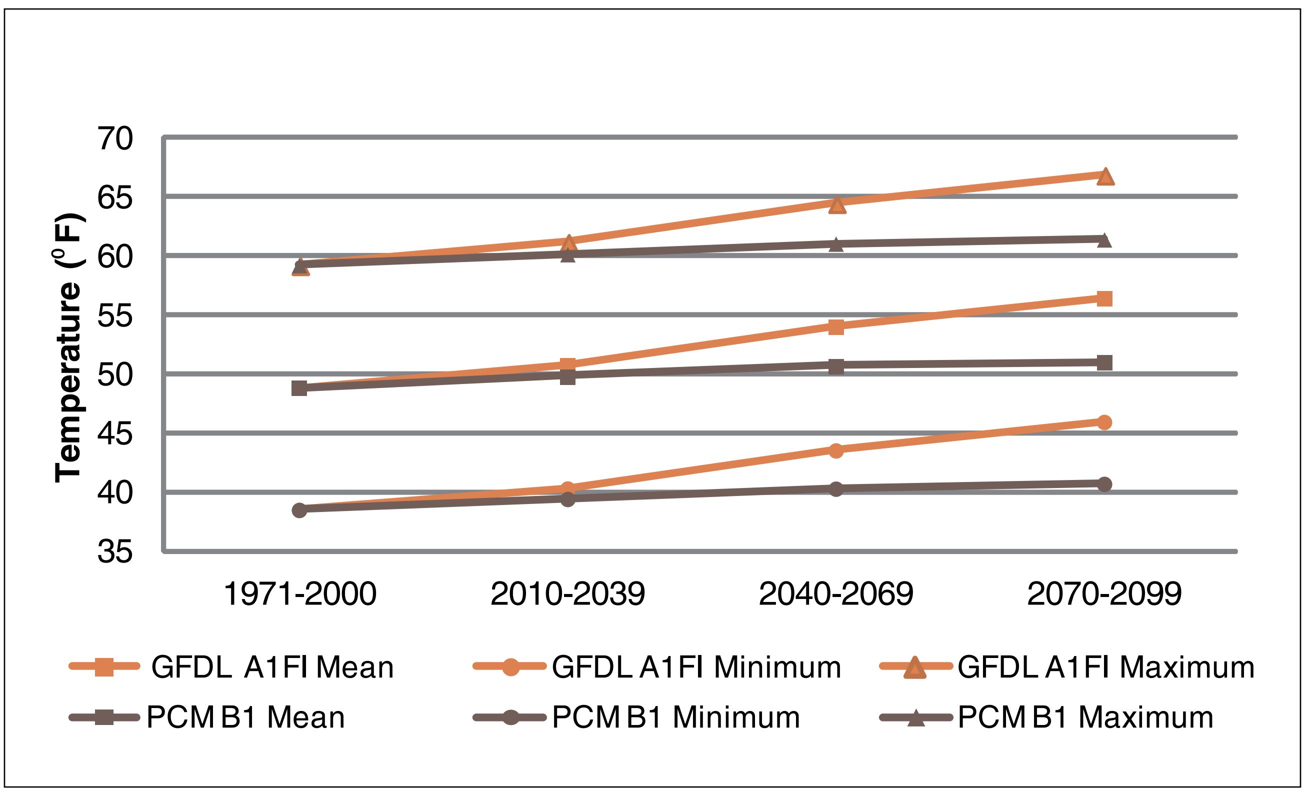


Figure 25.—Projected annual mean, minimum, and maximum temperature (°F) in the assessment area averaged over 30-year periods for two climate-model emissions scenario combinations (Climate Wizard 2014). The 1971 through 2000 value is based on observed data from weather stations. See Appendix 3 for projected changes by season.

Table 18.—Projected change in mean daily mean, minimum, and maximum temperature in the assessment area averaged over 30-year periods compared to baseline temperature

	Baseline		Departure from baseline		
	(1971-2000)[a]	Scenario	2010-2039	2040-2069	2070-2099
Mean temperature (°F)					
Annual	48.9	PCM B1	0.9	1.8	2.2
		GFDL A1FI	1.9	5.2	7.6
Winter (Dec-Feb)	28.2	PCM B1	1.0	2.3	2.4
		GFDL A1FI	1.7	4.4	5.9
Spring (Mar-May)	47.3	PCM B1	0.1	1.3	1.9
		GFDL A1FI	0.7	4.0	6.6
Summer (Jun-Aug)	68.8	PCM B1	1.1	1.8	2.3
		GFDL A1FI	3.0	6.6	9.2
Fall (Sep-Nov)	51.3	PCM B1	1.6	1.8	2.2
		GFDL A1FI	2.2	5.5	8.6
Minimum temperature (°F)					
Annual	38.5	PCM B1	1.0	1.8	2.2
		GFDL A1FI	1.9	5.1	7.5
Winter (Dec-Feb)	19.4	PCM B1	1.1	2.6	2.9
		GFDL A1FI	1.9	5.0	6.7
Spring (Mar-May)	36.2	PCM B1	0.6	1.7	2.1
		GFDL A1FI	1.0	4.3	6.6
Summer (Jun-Aug)	57.5	PCM B1	0.9	1.8	2.0
		GFDL A1FI	2.6	6.1	8.6
Fall (Sep-Nov)	41.0	PCM B1	1.3	1.3	2.0
		GFDL A1FI	2.0	4.9	8.1
Maximum temperature (°F)					
Annual	59.3	PCM B1	0.9	1.8	2.1
		GFDL A1FI	2.0	5.2	7.6
Winter (Dec-Feb)	36.9	PCM B1	0.9	2.0	1.9
		GFDL A1FI	1.5	3.8	5.1
Spring (Mar-May)	58.5	PCM B1	-0.5	1.0	1.8
		GFDL A1FI	0.5	3.8	6.5
Summer (Jun-Aug)	80.1	PCM B1	1.3	1.9	2.6
		GFDL A1FI	3.4	7.2	9.8
Fall (Sep-Nov)	61.6	PCM B1	1.9	2.2	2.3
		GFDL A1FI	2.4	6.1	9.2

[a] The 1971 through 2000 value is based on observed data from weather stations.

Although the two climate scenarios project different amounts of warming, they are largely in agreement that mean, minimum, and maximum temperatures will increase throughout the assessment area both annually and in all seasons. During the past century, minimum temperatures have warmed more than maximum temperatures in winter, summer, and fall (Chapter 3). For both scenarios, this trend is expected to shift slightly during the 21st century, so that minimum temperatures are projected to warm more than maximum temperatures in both winter and spring, but maximum temperatures are projected to increase more than minimum temperatures in summer and fall. The amount of change varies considerably among scenarios. Under PCM B1, minimum and maximum temperatures are projected to increase by 1.8 to 2.9 °F (1.0 to 1.6 °C) for winter, spring, summer, and fall between 2070 and 2099. Under GFDL A1FI, however, changes in minimum and maximum temperatures during this period are projected to increase by 5.1 to 9.8 °F (2.9 to 5.6 °C), with the highest temperature increases projected for summer and fall.

Projected changes in temperature are expected to vary geographically across the assessment area (Figs. 26 through 28). As described in Chapter 3, climate of the Mid-Atlantic region is influenced by latitude, elevation, and proximity to large bodies of water. However, uncertainties introduced in historical data can be compounded in downscaled future climate models, which are not very sensitive to regional landscape features (Box 14) (Horton et al. 2011, Polsky et al. 2000). Thus, mapped data should be at best considered representative of large-scale trends because of the potential for localized anomalies or errors associated with landscape topography and water bodies (Beier et al. 2012).

These data are consistent with several other modeling efforts in the region and globally. Although the temperature increases projected for individual climate models do differ, a vast array of models developed across the globe project a warmer future climate and a greater magnitude of warming than historical trends (IPCC 2014, Nelson Institute Center for Climatic Research 2018, U.S. Global Change Research Program [USGCRP] 2017). The Intergovernmental Panel on Climate Change (IPCC) created another set of climate scenarios for use in its Fifth Assessment Report (IPCC 2013). The newer datasets use Representative Concentration Pathways (RCPs) (Knutti and Sedláček 2013, Meinshausen et al. 2011, Taylor et al. 2012). The greenhouse gas concentration and global temperature projections are roughly comparable between the A1FI emissions scenario and RCP 8.5 and between the B1 emissions scenario and RCP 4.5 (Sun et al. 2015). Global mean temperatures for 2081 to 2100, relative to a 1985 to 2005 climate normal, were projected to warm by 2.0 to 4.7 °F (1.1 to 2.6 °C) under RCP 4.5 and by 4.7 to 8.6 °F (2.6 to 4.8 °C) under RCP 8.5 (IPCC 2013). However, differences in the periods chosen to represent climate normals, as well as differences between the scenarios and RCPs, prevent direct comparison (Chapter 2).

Entrance to a 120-acre tract of old-growth hemlock in Pennsylvania. Hemlock is a species vulnerable to climate change. Photo by Greg Czarnecki, Pennsylvania Department of Conservation and Natural Resources, used with permission.

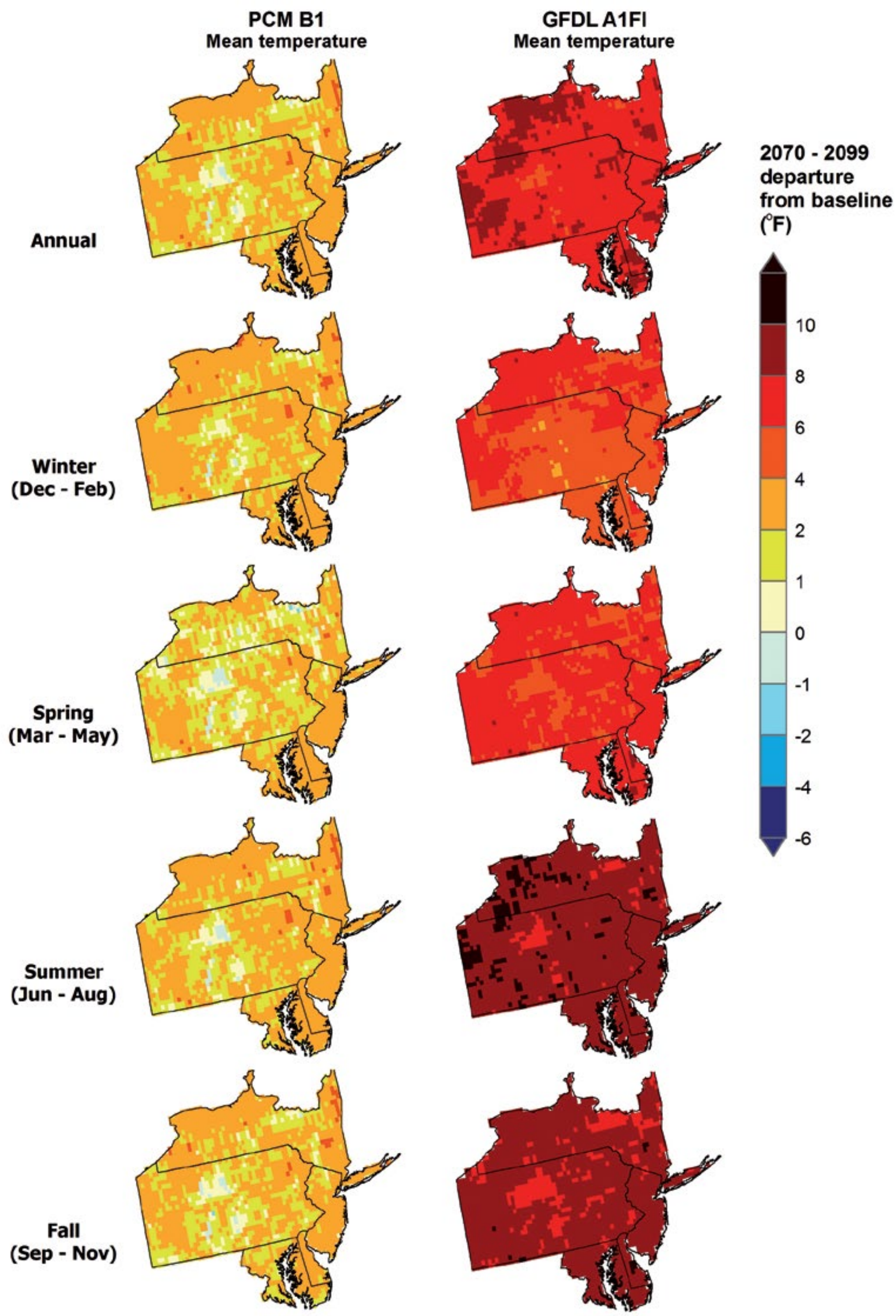


Figure 26.—Projected difference in mean daily mean temperature (°F) at the end of the century (2070 through 2099) compared to baseline (1971 through 2000) for two climate model-emissions scenario combinations. See Appendix 3 for maps of projected changes in early- and mid-century mean daily mean temperature.

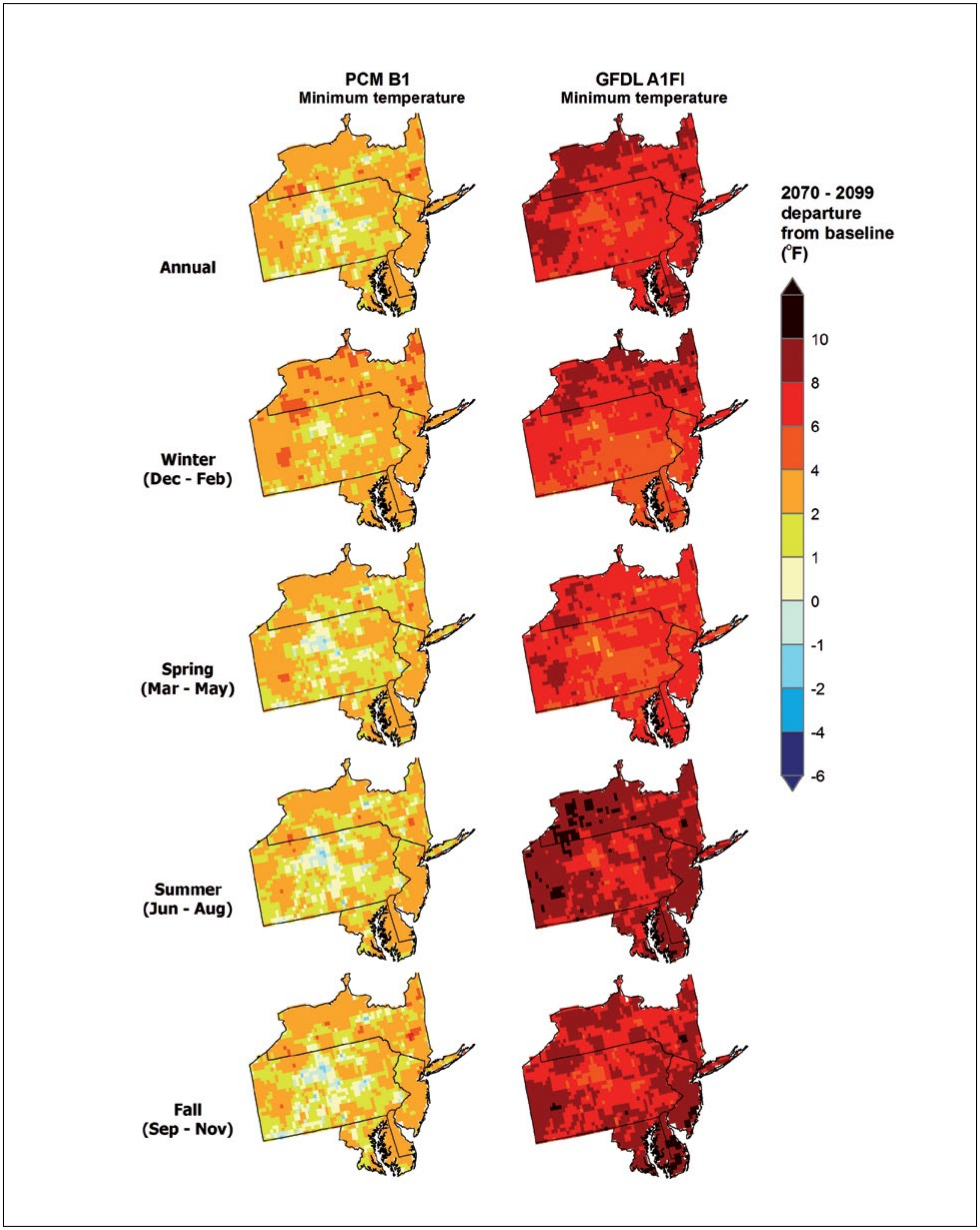


Figure 27.—Projected difference in mean daily minimum temperature (°F) at the end of the century (2070 through 2099) compared to baseline (1971 through 2000) for two climate model-emissions scenario combinations. See Appendix 3 for maps of projected changes in early- and mid-century mean daily minimum temperature.

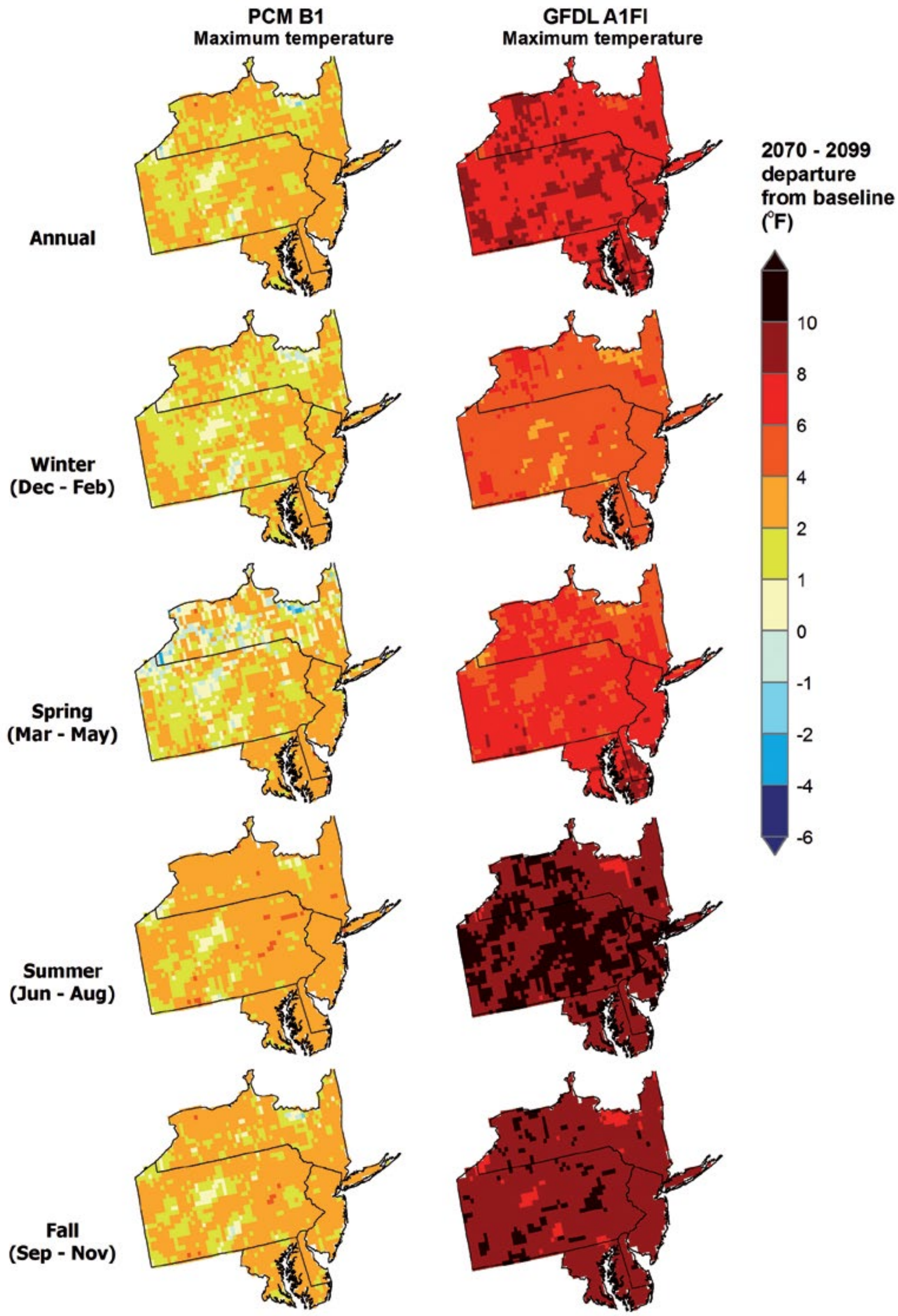


Figure 28.—Projected difference in mean daily maximum temperature (°F) at the end of the century (2070 through 2099) compared to baseline (1971 through 2000) for two climate model-emissions scenario combinations. See Appendix 3 for maps of projected changes in early- and mid-century mean daily maximum temperature.

Box 14: Climate Modeling in Complex Topography

Areas of complex topography contain some of the highest biological diversity in the world (Hoekstra et al. 2010). Landscape patterns of ridges, valleys, plains, and water features can influence precipitation through rainshadow effects, temperature through cold air pooling, and other fine-scale processes that create a complex suite of ecological niches with various temperature and moisture regimes (Anderson and Ferree 2010). Terrain amplifies disparities between the climate at a site and the broad climate trends for any given region (Daly et al. 2010), yet there is often a paucity of weather stations in high elevations (Daly et al. 2002). Modeling precipitation patterns in coastal areas is particularly complicated owing to the complexity of evaporation, atmospheric circulation, rainshadow effects, and orographic lifting of moisture to higher elevations (Daly et al. 2002). Large water bodies are also associated with temperature gradients that extend from coastal to inland areas (Daly et al. 2008).

Although few studies have investigated finer scale modeling of coastal plains and mountain ranges in the eastern United States, there have been some studies that may shed light on how downscaled climate models may be overestimating or underestimating temperature and precipitation trends at various elevations and landscape positions. A study examining climate data and trend maps in the Northeast detected strong bias in both montane and coastal areas (Beier et al. 2012). For example, data from a single weather station showed a warming trend in the Adirondack Mountains, whereas statistical interpolation of those data onto a gridded historical climate map produced cooling trends. This discrepancy was attributed to a processing error associated with that single station, resulting in a bias in the mapped data. An example of bias in Long Island, NY, is attributed to different methods of dealing with the boundary between land and water (Beier et al. 2012). A study in the Oregon Cascades, which is prone to cold-air pooling similar to the Catskill Mountains, found that temperatures in sheltered valley bottoms are somewhat buffered from changes projected for the whole study area (Daly et al. 2010).

These studies suggest inaccurate modeling in areas with complex topography and rapid elevation change. Regional climate models for the Mid-Atlantic region have not performed as well as in areas of relative homogeneity (e.g., upper Midwest), and some correction may be necessary to account for elevation, slope, aspect, and relative exposure or isolation from the elements. Finer resolution modeling would help identify biases in the data based on these factors, but resolution will vary with the complexity of topography, and is still likely to produce some bias. Though relatively coarse, the resolution of data used in this assessment can provide a broad foundation of plausible future climates from which to consider the caveats mentioned.

Precipitation

Due to the highly variable nature of precipitation and complexity in modeling it, projections of precipitation are more variable between models and generally carry with them a higher level of uncertainty than projections of temperature (Bryan et al. 2015, Kunkel et al. 2013b, Winkler et al. 2012). 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. 29, 30). 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.

Within the assessment area, annual precipitation is projected to increase by 2.1 inches for PCM B1 and 2.6 inches for GFDL A1FI at the end of the century (Table 19). Although the projections for the end of the century are discussed throughout this assessment, the precipitation regime is dynamic and these patterns may be slightly different in the early and middle periods of the 21st century. For example, although precipitation is expected to increase for GFDL A1FI in winter and spring at the end of the century, the amount of increase is reduced during the middle part of the century (Table 19). The seasonal precipitation trends for summer and fall exhibit even more departure from the baseline between the two scenarios (Appendix 3). For example, PCM B1 projects summer precipitation to increase steadily through the end of the 21st century, while GFDL A1FI projects summer precipitation to steadily decrease.

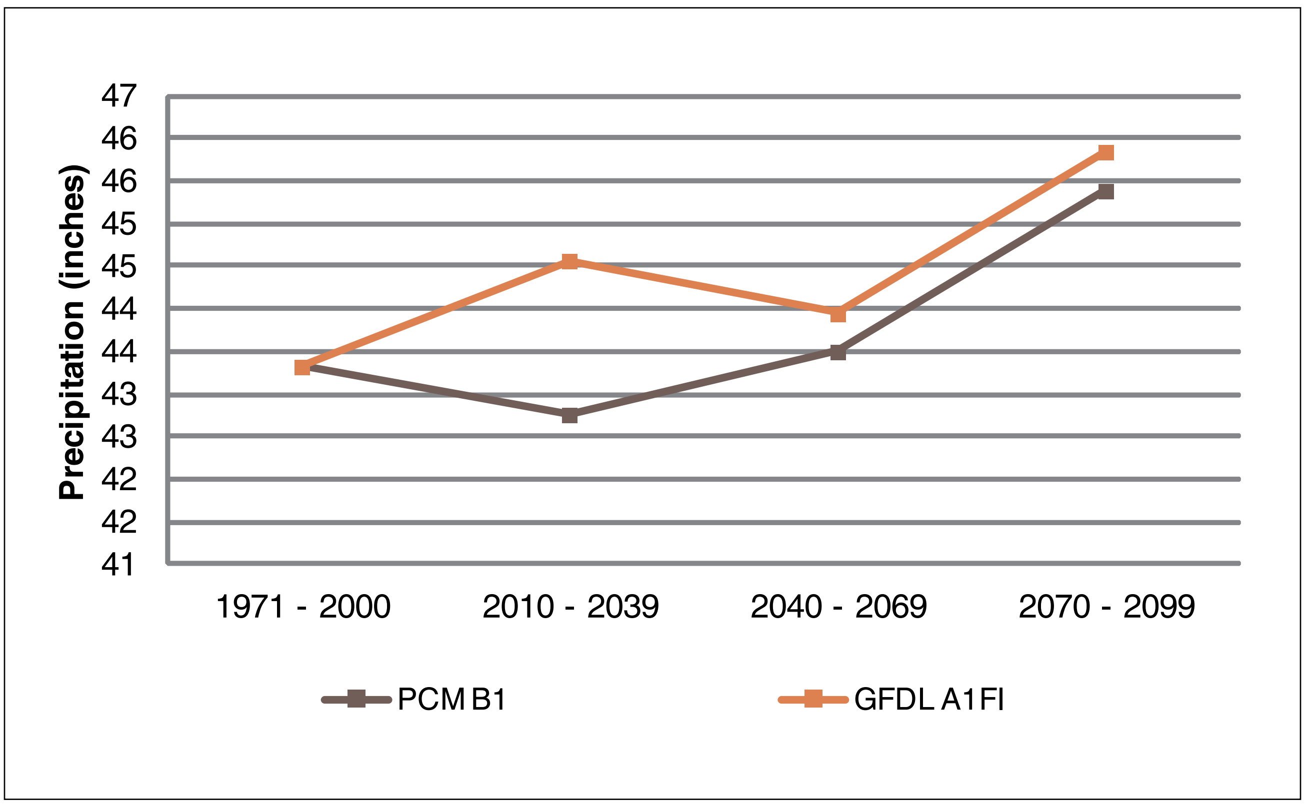


Figure 29.—Projected trends in mean annual precipitation in the assessment area averaged over 30-year periods for two climate model-emissions scenario combinations. The 1971 through 2000 value is based on observed data from weather stations. See Appendix 3 for projected changes by season.

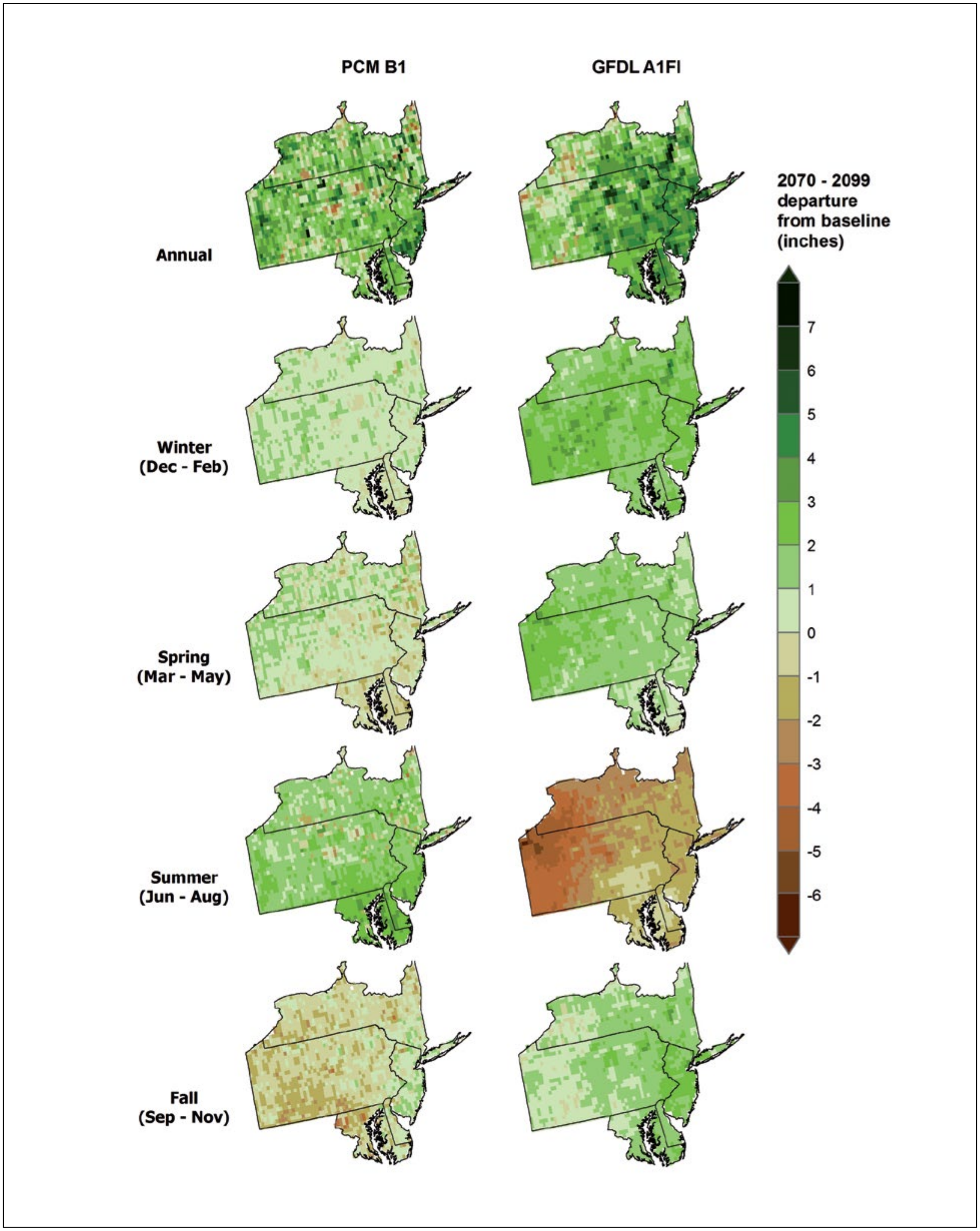


Figure 30.—Projected difference in mean precipitation (inches) at the end of the century (2070 through 2099) compared to baseline (1971 through 2000) for two climate model-emissions scenario combinations. See Appendix 3 for maps of projected changes in early- and mid-century mean precipitation.

Table 19.—Projected change in annual precipitation in the assessment area averaged over 30-year periods compared to baseline precipitation

	Baseline precipitation (inches), 1971-2000[a]	Scenario	Departure from baseline (inches)		
			2010-2039	2040-2069	2070-2099
Annual	43.3	PCM B1	-0.5	0.2	2.1
		GFDL A1FI	1.3	0.7	2.6
Winter (Dec-Feb)	9.0	PCM B1	0.0	0.7	0.6
		GFDL A1FI	1.1	1.1	2.1
Spring (Mar-May)	11.1	PCM B1	0.3	0.4	0.3
		GFDL A1FI	0.8	0.4	1.5
Summer (Jun-Aug)	12.1	PCM B1	0.3	1.1	1.6
		GFDL A1FI	0.1	-0.4	-2.3
Fall (Sep-Nov)	11.1	PCM B1	-1.2	-1.9	-0.5
		GFDL A1FI	-0.6	-0.4	1.3

[a] The 1971 through 2000 value is based on observed data from weather stations.

It is more important, however, to consider changes by season than by mean annual total, as the timing of increases or decreases has the most implications for forest ecosystems. During the end of the century (2070 through 2099), winter precipitation is projected to be 0.6 to 2.1 inches more than the baseline climate (1971 through 2000). Summer precipitation projections are more variable and are expected to change by -2.3 to 1.6 inches during the end of the century. Relative to the baseline climate, winter, spring, and fall precipitation is projected to remain about the same under PCM B1, but increase under GFDL A1FI by 23 percent in winter, 14 percent in spring, and 12 percent in fall. In summer, precipitation is projected to increase by 13 percent under PCM B1 and decrease by 19 percent under GFDL A1FI (Table 19).

Changes in precipitation are also projected to vary across the assessment area (Fig. 30). In winter and spring, changes for PCM B1 are slight (< 2 inches) and vary in direction (increasing or decreasing) across the landscape. Summer projections show many areas with increasing precipitation under PCM B1 and many areas with decreasing precipitation under GFDL A1FI (Fig. 30). Under GFDL A1FI, precipitation is projected to increase most in winter, followed by spring and fall across large portions of the assessment area, with annual totals increasing by 1 to 5 inches. In terms of growing season (spring, summer, and fall), it is notable that a summer increase is followed by a fall decrease for PCM B1. Under GFDL A1FI, this sign change occurs earlier in the season, with a spring increase followed by a significant summer decrease. Within the bracket of least to greatest amount of projected change, these patterns suggest a moisture deficit sometime during the growing season, with low confidence to predict the timing of precipitation decreases in summer or fall.

These data are consistent with a number of recent modeling efforts for the Northeast that consistently present greater variability in projected precipitation than in temperature (Fan et al. 2014, Hayhoe et al. 2007, Kunkel et al. 2013b, Lynch et al. 2016, Thibeault and Seth 2014b). Models generally detected precipitation increases in all seasons except for summer, despite an overall increase in total annual precipitation. Models generally disagreed on whether future summer precipitation may increase or decrease. A recent comparison of multiple climate models found projections for summer precipitation that ranged from a 25-percent or greater decrease to an equivalent increase for the 2070 to 2099 period (Kunkel et al. 2013b). Another recent study found a high degree of variation among multiple climate models and an overall modest increase in summer precipitation when the results were averaged (Lynch et al. 2016). The newest set of climate scenarios in the IPCC Fifth Assessment Report project similar precipitation changes except for summer; summer precipitation in the Mid-Atlantic region is projected to increase by 10 percent under RCP 8.5 (Walsh et al. 2014). It is also an important consideration that climate change may increase the year-to-year variation of precipitation across the Northeast (Boer 2009, Thibeault and Seth 2014a).

PROJECTED TRENDS IN EXTREMES

Although it is instructive to examine long-term means of climate and weather data, in many circumstances extreme events can have a greater impact on forest ecosystems. Weather or climate extremes are defined as individual weather events or short-term patterns that are unusual in their occurrence or have destructive potential (Climate Change Science Program 2008). Extreme events are stochastic by nature, and usually occur at fine spatial scales (i.e., a particular place). Thus, extreme events are difficult to predict and they are obscured in long-term or large-scale averages. Moreover, it is not possible to directly attribute the occurrence of a single extreme event to climate change (Coumou and Rahmstorf 2012, Stott et al. 2010).

Despite these limitations, many lines of evidence indicate that some extreme events have become more frequent and severe across the United States and globally, in part due to global climate change (Buckley and Huey 2016, Coumou and Rahmstorf 2012, IPCC 2012). Several studies have projected increases in some weather and climate extremes in the Mid-Atlantic region and the Northeast (Brown et al. 2010, Bryan et al. 2015, Griffiths and Bradley 2007, Kunkel et al. 2013b, Ning et al. 2015). Sea-level rise is expected to exacerbate flooding and storm-related damage in coastal areas (Box 15). Extreme events such as floods, droughts, heat waves, cold waves, and windstorms can trigger catastrophic disturbances in forest ecosystems and entail significant socioeconomic impacts.

Extreme Temperatures

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 (Ning et al. 2015). Studies of extreme temperatures often define hot days as days hotter than 90 °F (32 °C) and cold days as days colder than 32 °F (0 °C). Climate studies from across the Midwest and Northeast consistently project 20 to 30 more hot days per year by the end of the century (Diffenbaugh et al. 2005, Ebi and Meehl 2007, Gutowski et al. 2008, IPCC 2014, Meehl and Tebaldi 2004, Ning et al. 2015, Winkler et al. 2012). Another climate study projected hot days through 2070 under the A2 scenario to increase by 30 to 40 days across much of the Mid-Atlantic region, and by more than 60 days per year in the coastal areas of New Jersey, Maryland, and Delaware (Horton et al. 2014). By 2090, models predict increases of 75 to 90 days per year in those southern coastal areas (Nelson Institute Center for Climatic Research 2018). Days above 100 °F (38 °C) are projected to increase mainly in southeastern Pennsylvania (by 7 to 21 days per year), and New Jersey, Maryland, and Delaware (by 21 to 28 days per year) (Nelson Institute Center for Climatic Research 2018). The frequency of multiday heat waves is also projected to increase by 4 to 6 days throughout the region (Ning et al. 2012).

Box 15: Projected Sea-level Rise

The Mid-Atlantic region is home to large populations of people in high-density cities located along the Atlantic coast. The accelerated sea-level rise observed in the Northeast is a result of many complex factors including development, land subsidence from groundwater withdrawal, and changes in oceanic currents (Chapter 3; Box 11) (Horton et al. 2014). The dynamic processes that drive sea-level rise— fresh-water inputs from melting ice, warming air and water temperatures, increasing water volume, changing salinity, and altered circulation patterns—introduce uncertainty in projecting the magnitude of sea-level rise over the next century (Landerer et al. 2007, Sallenger et al. 2012, Yin et al. 2009). Including the addition of water from the Greenland and Antarctica ice sheets, global sea level is projected to rise an additional 0.8 to 2.6 feet by 2100 under a low emissions scenario and by 1.6 to 4.3 feet under a higher emissions scenario (Girvetz et al. 2009, USGCRP 2017). Results from several regional studies in the Northeast estimate additional sea-level rise due to changes in the Gulf Stream and in ocean circulation, with no consensus on the timing or magnitude (Rahmstorf et al. 2007; Sallenger et al. 2012; Schwartz et al. 2013; Walsh et al. 2014; Yin et al. 2009; L. Yowell, email, Dec. 14, 2017). One study in the Mid-Atlantic region discussed the influence of bedrock geology on the rate of sea-level rise; sea level on the sandy coastal plain is expected to rise 3.6 inches more than on adjacent areas underlain by bedrock (Miller et al. 2013).

Higher emissions scenarios generally project greater sea-level rise (Pennsylvania Department of Conservation and Natural Resources 2016, Walsh et al. 2014). At the same time, even the best models cannot simulate the effects of rapid changes in ice sheet dynamics, which makes it likely that estimates of future sea-level rise are underestimated (Maryland Department of Natural Resources 2010, Walsh et al. 2014). While methods to forecast sea-level rise continue to improve, one set of studies has focused on using flooding statistics to detect acceleration in both sea-level rise and flooding extent (Ezer and Atkinson 2014, Ezer and Corlett 2012). The area of land exposed to inundation is also projected to increase: 14.5 percent more land in Washington, DC, 11.4 percent in Delaware, and 10.2 percent in Pennsylvania. One study of the Atlantic coast found that a sea-level rise of 2.6 feet would result in 7 to 20 percent more storm surge inundation (Maloney and Preston 2014). Increases in sea-level rise directly and immediately influence storm surge and erosion potential of low-lying areas. Natural habitats and developed areas will continue to be increasingly exposed to sea-level rise and storms (Chapter 7).

Studies from across the region also project the annual frequency of cold days and cold nights to decrease by 12 to 15 days by the end of the century (Diffenbaugh et al. 2005, Gutowski et al. 2008, IPCC 2012). One study observed that the ratio of extreme record highs to record lows has been increasing since the 1970s, and extreme record high temperatures may outpace record low temperatures by 50 to 1 by the end of the century (Meehl et al. 2009). These trends are consistent with studies covering the entire Midwest and Northeast regions, which project that the assessment area could experience 22 to 26 fewer days below 32 °F and 9 to 10 fewer days below 0 °F (-18 °C) by the middle of the 21st century (Kunkel et al. 2013b, Ning et al. 2012, Peterson et al. 2013b). 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). During the growing season, these cold air outbreaks can be damaging to vegetation that has already been stimulated by warm temperatures to develop buds, leaves, or fruit (Ault et al. 2013).

Intense Precipitation

There is a clear trend toward more heavy precipitation events in the assessment area, and this is expected to continue (Gutowski et al. 2008, Kunkel et al. 2008, Ning et al. 2012, Thibeault and Seth 2014a). Rainfall from these high-intensity events represents a larger proportion of the total annual and seasonal rainfall, meaning that the precipitation regime is becoming more episodic. Downscaled projections for the Northeast estimate up to 30-percent increases in heavy precipitation events (i.e., days exceeding 1 inch) (Kunkel et al. 2013b). One recent study projected that the Mid-Atlantic region may receive 1 to 4 more days per year of precipitation events exceeding 0.4 inch with greater intensities during the 2050 through 2099 period relative to the 1950 to 1999 period (Ning et al. 2015). Another modeling effort classified precipitation totals, and projected the number of days with 1 inch or more precipitation to increase by 21 days per decade across much of the Mid-Atlantic region (Nelson Institute Center for Climatic Research 2018). Although simulations consistently project a continued increase in extreme events, the magnitude of change is more uncertain, reflecting the high spatial and temporal variability in these events.

It is important to consider this trend in combination with the projected changes in total precipitation during the 21st century. A given increase or decrease in precipitation is unlikely to be distributed evenly across a season or even a month. Large-scale modeling efforts have also suggested that climate change may increase the year-to-year variability of precipitation across the Midwest and Northeast (Boer 2009, Thibeault and Seth 2014a). Further,

Dam on Laurel Lake, Pine Grove Furnace State Park, Pennsylvania. Photo by Greg Czarnecki, Pennsylvania Department of Conservation and Natural Resources, used with permission.

ecological systems are not all equally capable of holding moisture that comes in the form of extreme events. Areas dominated by very coarse or very fine-textured or shallow soils may not have the water holding capacity to retain moisture received during intense rainstorms. More episodic rainfall could result in increased risk of moisture stress between rainfall events or higher rates of runoff during rainfall events. Landscape position may also influence the ability of a particular location to retain moisture from extreme events; for example, steep slopes shed runoff faster than flatter surfaces.

Severe Weather: Thunderstorms, Hurricanes, and Tornadoes

Several studies concluded that projected changes in temperature and precipitation may lead to more frequent days with conditions that are favorable for severe storms and tornadoes, increasing the probability that a storm may occur (Brooks 2013, Diffenbaugh et al. 2013, Lee 2012, Trapp et al. 2007). These studies suggest that climate change may influence storm characteristics, although the nature of change is uncertain. A synthesis report on extreme weather events stated that “there is low confidence in projections of small spatial-scale phenomena such as tornadoes and hail because competing physical processes may affect future trends and because current climate models do not simulate such phenomena” (IPCC 2012: 13). As the sophistication of global and regional climate models increases, our understanding of how patterns in hail and tornadoes may change in the future may increase as well.

Increases in thunderstorm frequency were projected within the assessment area for both mid-range (A1B) and higher (A2) emissions scenarios (Trapp et al. 2007, 2009). Models suggest that the nature of hurricanes may also change (Gutowski et al. 2008). One study estimated that for every 1.8 °F (1 °C) increase in tropical sea surface temperature, hurricane wind speeds may increase up to 8 percent, and core rainfall rates may increase by 6 to 18 percent (Gutowski et al. 2008). Another study found that although tropical storm frequency is projected to decrease under three downscaled model ensembles, both tropical storm intensity and hurricane intensity are projected to increase (Knutson et al. 2013). Orographic effects of tropical storms and hurricanes in the mountainous sections of the assessment area also have the potential to increase precipitation and subsequent flooding of river channels (Sturdevant-Rees et al. 2001).

PHYSICAL PROCESSES

Across the globe, increases in temperature are projected to intensify the hydrologic cycle, leading to greater evaporative losses and more heavy precipitation events (IPCC 2014). Changes in runoff and streamflow can contribute to changing watershed dynamics and risk associated with flooding and erosion. At the same time, increases in temperature are projected to lengthen the growing season, a time when vegetation requires adequate moisture for growth and regeneration.

Growing Season Length

The assessment area has experienced an expansion of the growing (i.e., freeze-free) season during the past century, and these changes are expected to continue 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 models project an increase in the growing season length at the end of the century (2081 to 2100) of 21 to 35 days under a low emissions scenario (B1) and by 42 to 50 or more days under a high emissions scenario (A2) (Nelson Institute Center for Climatic Research 2018). The projected expansion of the growing season is a result of nearly equal shifts toward earlier spring freeze-free dates and later fall freezes. Other studies across the Northeast also project similar increases in growing season length throughout the 21st century (Hayhoe et al. 2007, Kunkel et al. 2013b).

In addition to a longer growing season from spring through fall, winters are projected to become milder, with increased risk of warm spells. Winter temperature variability is expected to alter plant phenology, which is another measure of growing season length. Earlier bud break and leaf onset can increase the risk of frost damage during subsequent spring frost events, which are expected to remain the same or increase due to increasing variability in daily temperature (Augspurger 2013, Pagter and Arora 2013, Rigby and Porporato 2008). However, the occurrence and timing of future frost events may depend on tree physiology and interactions with atmospheric moisture, temperature, wind speed, cloud cover, and air pollution (Hufkens et al. 2012; Inouye 2000, 2008).

Snow and Freezing Rain

Warmer temperatures are expected to continue to have dramatic impacts on the winter season. Total snowfall and the proportion of precipitation falling as snow decreased across the region during the 20th century (Chapter 3), and these trends are expected to continue (Hayhoe et al. 2007, Ning et al. 2015). Although the change in snowfall was not modeled using the PCM B1 and GFDL A1FI scenarios, other models project a decrease in total snowfall by the end of the 21st century (2081 to 2100) of 30 to 50 percent under a low (B1) emissions scenario and by more than 50 percent under a high (A2) emissions scenario (Nelson Institute Center for Climatic Research 2018). In the coastal region of southern New Jersey, Delaware, and Maryland, total snowfall is projected to decline even more (50 to 70 percent under B1 and more than 70 percent under A2). The most substantial decrease in snow is expected to occur at the beginning of winter, in December and January (Notaro et al. 2014).

Similarly, the number of days with snowpack is projected to decrease across the Mid-Atlantic region, largely due to earlier melting of snow accumulations (Brown and Mote 2009, Hay et al. 2011). Changes in snow cover and duration may be observed sooner in mountainous regions and maritime environments (Brown and Mote 2009). Days with measurable snowpack are expected to be fewer by 30 to 50 percent across the region under the B1 scenario, with 50 to 70 percent fewer days along the coastal areas (Nelson Institute Center for Climatic Research 2018). Under the A2 scenario, days with snowpack are projected to decrease by 50 to 70 percent, except for the coastal plain, where they are projected to decrease by more than 70 percent. Some studies suggest that the frequency and severity of freezing rain may increase as the boundary between snowfall and rainfall moves northward with warming temperatures (Cheng et al. 2007, 2011).

Streamflow

Projected changes in temperature and precipitation are expected to alter streamflow in the Mid-Atlantic region (Hayhoe et al. 2007, Neff et al. 2000). One study in the Mid-Atlantic region projected increased streamflow under a range of climate models due to reduced snowpack (Neff et al. 2000). A more recent 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 as more water evaporates due to higher temperatures (Neff et al. 2000). Fall streamflow projections are variable based on the degree to which scenarios warm the climate and interactions with vegetation (Campbell et al. 2011, 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, Demaria et al. 2015). Researchers projected heavy peak streamflows to increase by 19 days during the period 2028 to 2082 under two climate scenarios (Demaria et al. 2015). Similarly, low streamflows are generally projected to be lower, particularly during the fall and under scenarios projecting greater warming (Demaria et al. 2015, Hayhoe et al. 2007).

Soil Moisture and Drought

In forest ecosystems, drought is a deficit of soil moisture available to plants and other organisms. Soil moisture is necessary for maintaining stomatal conductance and plant function; it also mediates microbial activity, decomposition, and nutrient turnover (Luce et al. 2016). Changes in soil moisture are largely driven by the balance of temperature, precipitation, runoff, and evapotranspiration; this balance equals the total amount of water added to or lost from the system (Box 16). Moisture stress can occur when increases in temperature and evaporation are not offset by a corresponding increase in precipitation (Clark et al. 2016, Hayhoe et al. 2007).

Within the climate scenarios used in this assessment, the potential for more frequent droughts and moisture stress during the growing season appears to be highest under the GFDL A1FI scenario. Even under the milder PCM B1 scenario, however, warmer temperatures may also lead to greater evaporative demand of the atmosphere and physiological stress if increases in precipitation do not correspond to temperature increases. Although precipitation projections have greater uncertainty than temperature projections, a number of modeling studies point to substantially higher temperatures with no more than relatively modest increases in growing season precipitation (Hayhoe et al. 2007,

Box 16: What is Drought?

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 occurs when conditions are dry relative to long-term averages in a particular place, often causing moisture stress on plants adapted to that 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.

In the United States as well as throughout North America, 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 region as a result of increased precipitation in the eastern United States (Andreadis and Lettenmaier 2006, Peterson et al. 2013b). Regional data from the Northeast support this general pattern (Peters et al. 2014). Between 1895 and 2014, there have been periods of drought; the mid-1960s represent the most extreme droughts during the period of record. Over the entire period, however, there has been no trend toward increasing drought incidence during the growing season (June through September) (Dobrowski 2011, Kunkel et al. 2013b, National Oceanic and Atmospheric Administration [NOAA] 2018). State-level data show increasingly wet conditions in New York and Pennsylvania over the last century, and decreasing moisture in Maryland, New Jersey, and Delaware (NOAA 2018). However, in 2016 and early 2017, many of these states along with the rest of the Northeast experienced the worst drought conditions since the 1960s (NOAA 2017a).

The effects of drought on vegetation vary with timing, length, and severity of drought, the water holding capacity of soil, a species' tolerance to drought, and whether other stressors are present. The effects of drought and moisture deficit on forests are discussed in Chapter 5.

Kunkel et al. 2013b, Lynch et al. 2016, Nelson Institute Center for Climatic Research 2018). Model projections may differ because different model-scenario combinations project opposite trends. Many models generally agree on an increase in precipitation (and also soil moisture) in the Mid-Atlantic region during the winter and spring. However, models disagree on the direction and magnitude of change in the summer and fall, depending on the model scenario (Lynch et al. 2016).

Modeling soil moisture, especially in areas of complex topography, is complicated by the spatial and temporal variability in precipitation during the growing season. Many climate models cannot simulate the fine-scale local climate processes involving interactions of temperature and precipitation which result in changes in the hydrologic properties of soil (Ashfaq et al. 2010). The Variable Infiltration Capacity model simulated seasonal soil saturation across the United States during 2071 through 2100 and projected summer and fall decreases in soil moisture; within the Mid-Atlantic region, it projected the greatest decrease (10 to 15 percent) in Pennsylvania (Ashfaq et al. 2010). A more recent study mapped the Hadley Centre Climate Model (A2 scenario) and the Keetch-Byram drought index on a grid for the 2041 to 2070 period in the Mid-Atlantic region and projected large increases in drought potential during summer and fall (Liu et al. 2013). Even without substantial decreases in precipitation, higher temperatures are expected to drive increases in evapotranspiration and overall moisture loss from the soil and vegetation (Naz et al. 2016). These results suggest that the Mid-Atlantic region may experience more short-duration (1 to 3 months) warm-season droughts, but that the number of longer duration or severe droughts may not change significantly (Huntington et al. 2009). Changes in temperature, precipitation, and soil moisture are likely to be highly variable within the Mid-Atlantic region, depending on landscape position, site characteristics, variability in weather events, and degree of climate change (Singh et al. 2014).

CHAPTER SUMMARY

Projected trends in annual, seasonal, and monthly temperature and total precipitation indicate that the climate will continue to change through the end of this century. Temperatures are projected to increase in all seasons, and extreme warming is projected under the GFDL A1FI scenario at the end of the century. Future average temperature increases range from 1 to 8 °F with even higher potential increases in summer and fall. Precipitation patterns will also change and, combined with warmer temperatures, suggest a potential moisture deficit during a longer growing season. Changes in temperature and precipitation are also expected to destabilize long-term atmospheric patterns and result in more intense storms and subsequently more frequent flooding. The heightened uncertainty in projected summer and fall precipitation totals, and the ratio of precipitation events to dry spells, could have important consequences for tree growth, seedling establishment, and other forest processes that depend on adequate soil moisture. In the next chapter, we examine the ecological implications of these anticipated changes on forest ecosystems.

CHAPTER 5: FUTURE CLIMATE CHANGE IMPACTS ON FORESTS

Climate change is expected to have wide-ranging effects on forests in the Mid-Atlantic region. Some of these effects will be the direct effects of an altered climate, such as warmer temperatures and extreme precipitation. Climate change may also lead to many indirect effects, including interactions with other disturbances, which have the potential to severely change forest ecosystems. This chapter describes potential changes in forest ecosystems from the direct and indirect effects of climate change. The chapter is organized into two sections. First we present the results of three forest impact models to gather perspective on how individual tree species 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 6).

MODELED PROJECTIONS OF FOREST CHANGE

Forest ecosystems in the assessment area may respond to climate change in a variety of ways. Potential changes include shifts in the spatial distribution, abundance, and productivity of tree species. For this assessment, we 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 20). The Tree Atlas' DISTRIB model uses statistical techniques to model changes in suitable habitat for individual species over broad geographic areas. The LINKAGES model predicts establishment and growth of trees based on climate, soils, and other site information. The LANDIS PRO model 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. 2016). Although each model has different inputs and 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 provide opportunities to better understand the nuances of ecological responses given the strengths and limitations of each model (Iverson et al. 2016).

All three models used the same downscaled climate projections from two combinations of general circulation models (GCMs) and emissions scenarios: GFDL A1FI and PCM B1 (Chapters 2 and 4). Projected changes in temperature and precipitation for GFDL A1FI represent a greater degree of projected climate warming and change compared to PCM B1, so comparisons can be made 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. A single simulation for each climate-model scenario was completed for each forest impact model.

Table 20.—Overview of the three forest impact models used in this assessment (see Chapter 2 for detailed descriptions of each model)

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	Area-weighted importance values and modifying factors by species	Species establishment and growth maps (percentage change)	Basal area and trees per acre by species
Model-scenario combinations	GFDL A1FI and PCM B1 (see Chapter 2)		
Assessment area	Mid-Atlantic assessment area and six subregions		
Resolution	20-km (12-mile) grid	0.8-ha (0.2-acre) plots representing landforms in subsections	270-m (886-foot) grid
Number of species evaluated	112	24	24
Control/baseline climate	1971 through 2000	1980 through 2009	1980 through 2009
Climate periods evaluated	2010 through 2039, 2040 through 2069, 2070 through 2099	1980 through 2009, 2070 through 2099	2009 through 2099
Simulation period	n/a	30 years	2009 through 2099
Competition, survival, and reproduction	No (but addressed through modifying factors)	Yes	Yes
Disturbances	No (but addressed through modifying factors)	No	Timber harvest
Tree physiology feedbacks	No	Yes	No
Succession or ecosystem shifts	No	No	Yes
Biogeochemical feedbacks	No	Yes	No

The forest impact model results are most useful for describing trends across large areas and over long timescales. These models are not designed to deliver precise results for individual forest stands or a particular year in the future, despite the temptation to examine particular moments or locations on a map. In this chapter, we present simulations for the end of the 21st century across the entire Mid-Atlantic region. Model results are presented for each model separately, and areas of agreement and disagreement between models are discussed. Model data for six subregions (Fig. 31) are also provided and describe some geographic differences across the assessment area; these subregions are based on the ecological provinces described in Chapter 1. For a few species, maps are provided to illustrate changes in the relative abundances and distributions of tree species in the Mid-Atlantic region. Data for intermediate time periods and geographic subregions are provided in Appendix 4.

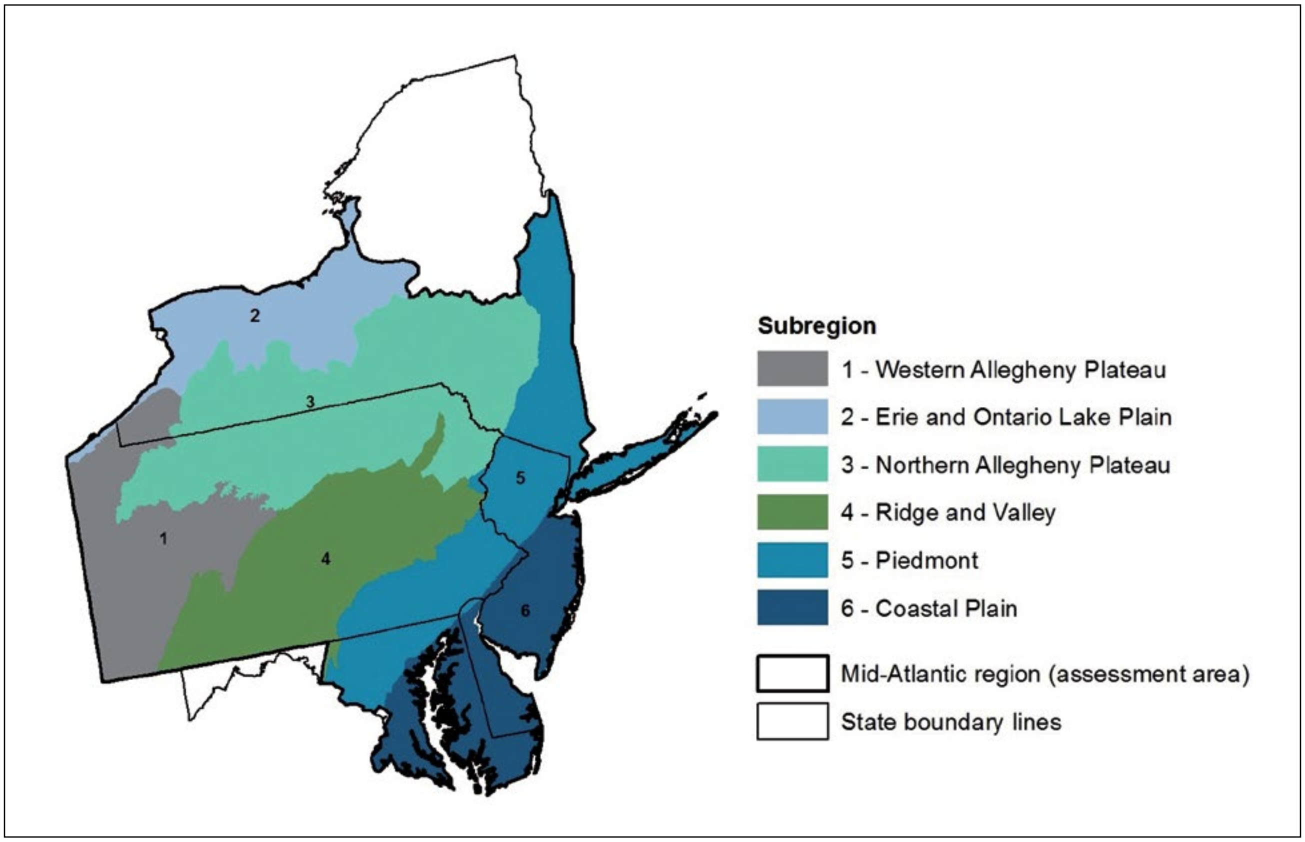


Figure 31.—Assessment area subregions based on ecological provinces and sections (Fig. 2) mapped by Cleland et al. (2007) and described by McNab et al. (2007).

In general, there are only minor differences in model projections between the Mid-Atlantic region as a whole, and the individual subregions. However, the coastal plain subregion is notable for projections that differ considerably from those presented here for the overall region; these differences are attributed to unique climate in the coastal plain (see Chapters 3 and 4). Therefore, the model results presented here for the region best reflect the interior subregions (subregions 1-5). For the coastal plain expert panel to assess vulnerability, we used the model results only for the coastal subregion. For the interior expert panel, we used the results for the whole Mid-Atlantic region.

Climate Change Tree Atlas

The Climate Change Tree Atlas (USDA Forest Service n.d.a) was used to evaluate potential changes in suitable habitat for tree species within the assessment area. The Tree Atlas does not model where species may occur in the future, but rather projects where suitable habitat for individual tree species may be present. As such, Tree Atlas projections should be interpreted not as expected species migration patterns, but as shifts in the distribution of favorable habitat conditions for a given species. A species distribution model called DISTRIB, which is a component of the Tree Atlas, 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 (USDA Forest Service n.d.a). Habitat suitability (measured in terms of a species' importance value) was modeled for 134 eastern tree species, 112 of which are currently present in the Mid-Atlantic region or are projected to have suitable habitat in the region during the 21st century under one or both climate scenarios.

The projected changes in potential suitable habitat were calculated for the years 2070 through 2099 for the GFDL A1FI and PCM B1 scenarios and compared to suitable habitat under the present climate (Table 21). Species were categorized based on whether the results from the two climate scenarios projected an increase, decrease, or no change in suitable habitat compared to current climate conditions. Model results were considered mixed if an increase was projected under one scenario while a decrease was projected under the other scenario. Several tree species that are currently not present in the assessment area were identified as having potential new suitable habitat in the future under one or both scenarios. The DISTRIB model projects future habitat for each species individually, and the model reliability varies for each species. Model reliability is generally higher for common species than for rare species because forest inventories tend to undersample rare species (Iverson et al. 2008a). Table 30 (Appendix 4) contains the full set of results from the DISTRIB model, including model reliability and projections for three time periods (2010 through 2039, 2040 through 2069, and 2070 through 2099) and six subregions within the Mid-Atlantic region. Table 31 (Appendix 4) summarizes model results at the end of the century for the region and the six subregions. Results for each subregion are available in Tables 32-37 (Appendix 4).

Table 21.—Potential change[a] in suitable habitat projected by the DISTRIB model for tree species in the Mid-Atlantic region

Common name	PCM B1	GFDL A1FI
Declines under Both Scenarios		
American beech	Small decrease	Large decrease
American mountain-ash (-)	Large decrease	Large decrease
Balsam fir (-)	Large decrease	Large decrease
Balsam poplar	Small decrease	Small decrease
Black ash (-)	Large decrease	Large decrease
Black maple	Small decrease	Large decrease
Black spruce	Small decrease	Large decrease
Chokecherry	Small decrease	Large decrease
Eastern hemlock (-)	Small decrease	Large decrease
Eastern white pine (-)	Small decrease	Large decrease
Gray birch	Small decrease	Small decrease
Jack pine	Large decrease	Large decrease
Mountain maple (+)	Small decrease	Large decrease
Northern white-cedar	Large decrease	Large decrease
Paper birch	Large decrease	Large decrease
Pin cherry	Small decrease	Large decrease
Quaking aspen	Small decrease	Large decrease
Red pine	Small decrease	Large decrease
Red spruce (-)	Small decrease	Small decrease
Tamarack (native) (-)	Small decrease	Small decrease
White spruce	Small decrease	Small decrease

Common name	PCM B1	GFDL A1FI
Increases under Both Scenarios		
Black walnut	Small increase	Small increase
Blackgum (+)	Small increase	Small increase
Chinkapin oak	Small increase	Large increase
Eastern redcedar	Small increase	Large increase
Flowering dogwood	Small increase	Large increase
Hackberry (+)	Small increase	Large increase
Loblolly pine	Small increase	Large increase
Persimmon (+)	Large increase	Large increase
Pin oak (-)	Small increase	Large increase
Pond pine (-)	Large increase	Large increase
Post oak (+)	Large increase	Large increase
Sassafras	Small increase	Small increase
Scarlet oak	Small increase	Small increase
Scrub oak (bear oak)	Small increase	Small increase
Shagbark hickory	Small increase	Large increase
Southern red oak	Small increase	Large increase
Swamp tupelo (-)	Large increase	Small increase
Sweetgum	Small increase	Large increase
Sycamore	Small increase	Large increase
Winged elm	Large increase	Large increase

(continued on next page)

Table 21 (continued).—Potential change[a] in suitable habitat projected by the DISTRIB model for tree species in the Mid-Atlantic region

Common name	PCM B1	GFDL A1FI
Increases under High Emissions		
American elm	No change	Small increase
Baldcypress	No change	Small increase
Bitternut hickory (+)	No change	Large increase
Black oak	No change	Large increase
Black willow (-)	No change	Large increase
Blackjack oak (+)	No change	Large increase
Boxelder (+)	No change	Small increase
Bur oak (+)	No change	Large increase
Cherrybark oak	No change	Large increase
Eastern cottonwood	No change	Large increase
Eastern redbud	No change	Large increase
Green ash	No change	Large increase
Honeylocust	No change	Large increase
Mockernut hickory	No change	Large increase
Northern catalpa	No change	Small increase
Osage-orange (+)	No change	Small increase
Pignut hickory	No change	Small increase
Red mulberry	No change	Large increase
Rock elm (-)	No change	Large increase
Shellbark hickory	No change	Large increase
Shingle oak	No change	Large increase
Shortleaf pine	No change	Large increase
Slippery elm	No change	Small increase
Water oak (+)	No change	Large increase
White oak	No change	Small increase
Willow oak	No change	Small increase
New Suitable Habitat		
Black hickory	New habitat	New habitat
Cedar elm (-)	NA	New habitat
Laurel oak**	New habitat	New habitat
Longleaf pine**	New habitat	New habitat
Ohio buckeye**	New habitat	New habitat
Overcup oak**	New habitat	New habitat
Redbay** (+)	New habitat	NA
Shumard oak** (+)	NA	New habitat
Slash pine	New habitat	New habitat
Sugarberry**	New habitat	New habitat
Turkey oak (+)	New habitat	New habitat
Water hickory	NA	New habitat

Common name	PCM B1	GFDL A1FI
Declines under High Emissions		
American basswood	No change	Small decrease
American holly	No change	Small decrease
Atlantic white-cedar (-)	No change	Small decrease
Bigtooth aspen	No change	Large decrease
Black cherry (-)	No change	Large decrease
Butternut (-)	No change	Large decrease
Red maple (+)	No change	Large decrease
Serviceberry	No change	Small decrease
Striped maple	No change	Large decrease
Sugar maple (+)	No change	Small decrease
Sweet birch (-)	No change	Large decrease
White ash (-)	No change	Small decrease
Yellow birch	No change	Large decrease
No Change under Both Scenarios		
American chestnut	No change	No change
American hornbeam	No change	No change
Black locust	No change	No change
Chestnut oak (+)	No change	No change
Eastern hophornbeam (+)	No change	No change
Northern red oak	No change	No change
Pawpaw	No change	No change
Pitch pine	No change	No change
River birch	No change	No change
Swamp chestnut oak	No change	No change
Swamp white oak	No change	No change
Sweetbay	No change	No change
Virginia pine	No change	No change
Water tupelo (-)	No change	No change
Yellow buckeye (-)	No change	No change
Mixed Results		
Cucumber tree	Small increase	Small decrease
Silver maple (+)	Small decrease	Large increase
Sourwood (+)	Small increase	No change
Table Mountain pine (+)	Small decrease	No change
Tulip tree	Small increase	Small decrease

[a] Species are grouped according to change classes (e.g., increase, no change) based on the proportional change in the area-weighted importance value for the end of century (2070 through 2099) for two climate-emissions scenarios. Species with the 20 highest or 20 lowest modifying factor scores are marked with plus (+) and minus (-) signs, respectively. Appendix 4 contains descriptions of change classes and complete results for all species.

**Not observed in the Forest Inventory and Analysis data, but other data suggest species is present, but rare.

The DISTRIB results indicate that climate change is likely to lead to changes in the suitable habitat of many common tree species. At the same time, the ways in which tree species may actually respond to climate change are also influenced by life-history traits (e.g., dispersal mechanism, fire tolerance) not included in the DISTRIB model. Thus, 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 (Table 22) (Matthews et al. 2011). For example, although suitable habitat for red maple is projected to remain roughly the same under the milder climate scenario (PCM B1) and decrease under the harsher climate scenario (Table 21), red maple can take advantage of a wide range of habitat conditions and can disperse easily, suggesting that it may be able to compensate for potential loss of suitable habitat. Modifying factors are based on a literature review of the life-history traits, known stressors, and other factors unique to individual species. Other 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). See Appendix 4 for a detailed description of modifying factors and adaptability scores for each tree species.

Decreases in Suitable Habitat

For the Mid-Atlantic region, 21 species are projected to undergo large or small declines in suitable habitat for both climate scenarios at the end of the 21st century (2070 through 2099), and declines are generally projected to be more severe under GFDL A1FI than PCM B1 (Table 21). These reductions in suitable habitat do not imply that mature trees will die within this century or that the species will be extirpated; rather, these results indicate that these species may be living under declining habitat conditions. As a result, trees living on already marginal sites may have greater susceptibility

Table 22.—Tree species with the five highest and five lowest values for adaptive capacity based on Climate Change Tree Atlas modifying factors

Species	Factors that affect rating
Highest adaptive capacity	
1. Red maple	high probability of seedling establishment, wide range of habitats and soils, shade tolerant, high dispersal ability
2. Boxelder	high probability of seedling establishment, high dispersal ability, drought tolerant, shade tolerant, wide range of temperature tolerances
3. Sourwood	good light competitor, wide range of habitats
4. Bur oak	drought tolerant, fire tolerant
5. Eastern hophornbeam	shade tolerant, wide range of habitats, wide range of temperature tolerances
Lowest adaptive capacity	
1. Black ash	emerald ash borer susceptibility, shade intolerant, low dispersal ability, drought intolerant, poor seedling establishment, fire intolerant, narrow range of soils
2. Pecan	fire intolerant, susceptible to insect pests, shade intolerant
3. Water tupelo	drought intolerant, fire intolerant, shade intolerant, narrow range of suitable habitats
4. Butternut	fire intolerant, shade intolerant, drought intolerant, susceptible to butternut canker
5. Pond pine	drought intolerant, shade intolerant, susceptible to southern pine beetle and other insect pests, low dispersal ability

to stressors (e.g., drought, pests, diseases, or competition from other species including invasives), or be at greater risk of regeneration failure.

American beech, eastern hemlock, eastern white pine, and quaking aspen are currently abundant within the assessment area, but suitable habitats for these species are projected to decline for both scenarios, especially under GFDL A1FI. Many of the species projected to decline under both scenarios are currently near the southern limit of their range in the Mid-Atlantic region or exist as disjunct populations in areas of glacial refugia. Red spruce, northern white-cedar, and balsam fir are glacial relicts that are currently limited to cool environments found at higher elevations, and the majority of these species' ranges is much farther north (Hessl et al. 2011, Potter et al. 2010). Red spruce and balsam fir also have highly negative modifying factors (Table 39 in Appendix 4), suggesting that there are life-history traits or disturbance stressors that may cause these species to lose even more suitable habitat than the model results indicate. Eastern hemlock and red spruce are currently suffering attacks by hemlock woolly adelgid and spruce budworm. Balsam fir and red spruce are rated very low in adaptability (Table 39) to climate change due to their susceptibility to fire topkill and a number of other disturbances, but fir can regenerate successfully in a wider range of site conditions (Day et al. 2014).

Other species are not as geographically limited or climate restricted, and therefore occupy a wider range of sites and conditions throughout the assessment area. Red pine, pin cherry, gray birch, paper birch, and black ash are projected to decrease substantially, but their current distributions may allow species movement into suitable refugia. Black ash also has highly negative modifying factors; black ash is shade intolerant and susceptible to drought, and the emerald ash borer is expected to cause high rates of mortality for all ash species in the region. Gray birch, paper birch, and pin cherry have some positive and some negative modifying factors (Table 39).

For 13 species, DISTRIB projected no change in suitable habitat under PCM B1 and a decrease under GFDL A1FI. Red maple, black cherry, white ash, and sugar maple are currently the most abundant species in the Mid-Atlantic, but all are projected to experience decreases in suitable habitat for GFDL A1FI. Red maple and sugar maple have high adaptability scores, suggesting they may do better than the models suggest, whereas white ash and black cherry have low adaptability scores. Other common species projected to lose suitable habitat under the high emissions scenario include sweet birch, striped maple, serviceberry, yellow birch, bigtooth aspen, American basswood, American holly, and butternut.

Atlantic white-cedar is limited to a narrow coastal band (within 100 miles) along the Atlantic Ocean. Projected decreases in suitable habitat may be catastrophic for these highly localized populations, as they are unlikely to find alternate refugia within the assessment area. A negative modifying factor for Atlantic white-cedar is its narrow range of soil requirements, often limited to acidic muck bordering tidal marsh lands; as sea-level rise continues to encroach beyond current tidal habitats, salt intolerance is likely to have a more immediate impact on this species.

No Change in Suitable Habitat

The DISTRIB model projected "no change" (i.e., less than 20 percent change) in suitable habitat for 15 species under both scenarios (Table 21). Northern red oak and chestnut oak are currently abundant and widespread across the region and their habitats are not projected to decrease or increase substantially. Chestnut oak has one of the highest adaptability scores and it is expected to do better than projected, partly because of its successful seed dispersal and establishment potential, ability to resprout, and resistance to fire topkill. Eastern hophornbeam, American hornbeam, pitch pine, and Virginia pine are somewhat less common on the landscape. American chestnut, swamp white oak, pawpaw, and yellow buckeye are considered relatively rare on the landscape. Eastern hophornbeam has positive modifying factors, including drought tolerance, shade tolerance, and regeneration success. Yellow buckeye has several negative modifying factors, including specific habitat requirements and susceptibility to fire and drought, suggesting this species may fare worse than projected.

Increases in Suitable Habitat

Suitable habitats for 20 species are projected to increase under both models by the end of the century (Table 21). Some of these species are already common in the assessment area: sassafras, blackgum, sweetgum, flowering dogwood, scarlet oak, black walnut, eastern redcedar, loblolly pine, scrub oak, shagbark hickory, sycamore, pin oak, southern red oak, and hackberry. Other species are considered rare but are projected to gain suitable habitat: persimmon, post oak, chinkapin oak, pond pine, swamp tupelo, and winged elm.

Some of the species projected to increase have positive modifying factors that could help them occupy newly available habitat; these are blackgum, southern red oak, hackberry, persimmon, and post oak. Pin oak, pond pine, and swamp tupelo have negative modifying factors, which suggest that they may face additional stresses that could reduce their ability to take advantage of new suitable habitat.

The assessment area is currently at the northern range limit for some species, including loblolly pine, post oak, southern red oak, and sweetgum. These species' ranges can potentially shift northward as the distribution of suitable habitat potentially moves northward. Because many of the species projected to lose suitable habitat through the end of the century are already established, forests in the assessment area may undergo changes, even increases, in species richness as species respond differently on the landscape.

Red maple-sweetgum swamp at Magnolia Swamp, New York. Photo by David M. Hunt, New York Natural Heritage Program, used with permission.

For 26 species, DISTRIB projected that suitable habitat will not change under PCM B1 but will increase under GFDL A1FI. White oak, black oak, and American elm are relatively common across the assessment area and have positive modifying factors such as drought tolerance or fire tolerance. Pignut hickory, and mockernut hickory are also relatively abundant in the assessment area, but these species are close to the northern extent of their range and DISTRIB results suggest that suitable habitat may move northeast in the future. The remaining species are relatively infrequent and in some cases limited to specific habitats. For example, slippery elm, boxelder, black willow, green ash, eastern cottonwood, and water oak are typically associated with moist, rich soils of lower slopes, floodplains, and bottomlands or occasionally grow on limestone formations.

Mixed Results in Suitable Habitat

For five species, the Tree Atlas model projected different responses for the two scenarios (Table 21). Mixed results for tulip tree and cucumber tree reflect projected habitat increases under a slightly warmer climate (PCM B1) but projected habitat decreases under a much warmer and drier climate (GFDL A1FI). The positive modifying factors associated with tulip tree, including its ability to disperse and regenerate successfully on a wide range of sites, suggest that it may do better than the model projected. Suitable habitat for sourwood is expected to increase under PCM B1, but persist under GFDL A1FI. Suitable habitat for silver maple is projected to decrease under PCM B1, but increase under GFDL A1FI. A positive modifying factor associated with sourwood and silver maple is shade tolerance. Table Mountain pine is projected to decrease under PCM B1 and not change under GFDL A1FI but has a positive modifying factor associated with drought tolerance.

New Suitable Habitat

The DISTRIB model projected gains in newly suitable habitat for 12 species (Table 21) that are currently not present at detectable levels (i.e., in FIA inventory) in the assessment area. Black hickory, laurel oak, longleaf pine, Ohio buckeye, overcup oak, slash pine, sugarberry, and turkey oak are projected to gain new suitable habitat within the Mid-Atlantic region under both climate scenarios. Cedar elm, Shumard oak, and water hickory are projected to gain new habitat only under GFDL A1FI. Redbay is projected to gain new suitable habitat only under PCM B1. Many of these species have ranges that extend close to the assessment area, and some, such as laurel oak, overcup oak, redbay, slash pine, sugarberry, and turkey oak, are actually present in the southern edge of the assessment area. But these species are relatively rare and therefore not recognized by the Tree Atlas as currently on the landscape.

Other species that are not currently present in the Mid-Atlantic region would require long-distance migration, whether natural or assisted, to establish and occupy suitable habitat in the assessment area. Habitat fragmentation and the limited dispersal ability of seeds could hinder the movement of species, despite the increase in habitat suitability (Ibáñez et al. 2008). Most species are expected to migrate more slowly than their habitats can shift (Iverson et al. 2004a, 2004b).

Geographic Trends

Projected changes are not uniform across the assessment area, and areas of suitable tree habitat are governed by soils, salinity, moisture gradients, elevation, and other factors in addition to climate. The geographic and biological complexity of the Mid-Atlantic region warranted a closer look at the six subregions within the broader assessment area (see Figure 31 for a map). Appendix 4 shows complete model results by subregion. About half of the species modeled were detected in all six subregions. Among the species projected to have suitable habitat across four or more subregions, distinct differences in climate, landform, and other characteristics often result in a variety of projected change classes between sections for a single species. The Piedmont (subregion 5) contains the most species (107), and the Western Allegheny Plateau (subregion 1) has the fewest species (83). This is not a complete reflection of species richness or diversity, however, because some additional rare species may be present but not at levels abundant enough to be detected by FIA inventories and subsequently modeled.

Nine species were currently present or modeled only in the Piedmont or Coastal Plain subregion, or both subregions: American holly, bluejack oak, laurel oak, longleaf pine, redbay, slash pine, turkey oak, water hickory, and water locust. Of 31 species showing significant geographic trends (Appendix 4), 13 species exhibit noticeable differences in modeled species response in the Coastal Plain compared to inland areas. For example, habitat for scarlet oak and blackgum is projected to increase in every subregion except the Coastal Plain, where habitat is projected to decrease. Conversely, eastern hemlock is projected to decline in every subregion except the Coastal Plain, where habitat is projected to increase but remain rare.

Outputs from DISTRIB can also be visualized as maps, such as those available online through the Climate Change Tree Atlas Web site (https://www.nrs.fs.fed.us/atlas), and these maps can provide greater context for interpreting the projected changes in suitable habitat. It is important to note that these maps detect relative change on a more detailed pixel by pixel (20 km × 20 km [12.5 miles × 12.5 miles]) basis rather than averaged by subregion within the assessment area (Table 20). For this assessment, maps for six species—black cherry, chestnut oak, northern red oak, pitch pine, red spruce, and sugar maple—were clipped to the shape of the Mid-Atlantic region (Fig. 32). These species were chosen to represent several species that are important for their abundance, economic value, or keystone species status. The maps highlight geographic trends in suitable habitat under two climate scenarios to show that projected changes are not uniform across the region, and that areas of suitable habitat are related to both climate change and local conditions.

Suitable habitat for chestnut oak and northern red oak is currently widespread and was not projected to change considerably overall under both scenarios, although some areas show potential habitat loss under GFDL A1FI (Fig. 32). Suitable habitat for black cherry and sugar maple was not projected to change considerably under PCM B1 but was projected to decrease under GFDL A1FI; for black cherry the loss of habitat is evident across much of the assessment area and the remaining suitable habitat is largely concentrated in the New York portion (Fig. 32). Pitch pine is currently important only in the coastal plain and its habitat is projected to remain steady under both climate scenarios, with suitable habitat potentially increasing in central Pennsylvania and New York, although it is not likely to migrate on its own (Fig. 32). Red spruce is a keystone species currently limited to the cooler temperatures and moister conditions that occur above 3,000 feet in the Catskill Mountains of New York. The DISTRIB model projected, with high reliability, suitable habitat for red spruce to decrease under PCM B1 and to be extirpated from the Mid-Atlantic region under the high emissions scenario (Fig. 32). As temperatures continue to warm, local populations may be unable to migrate northward because these populations are already positioned at the highest elevations.

These maps should be interpreted carefully. As mentioned earlier, DISTRIB results indicate only a change in the amount and geographic distribution of suitable habitat, not necessarily that a given species

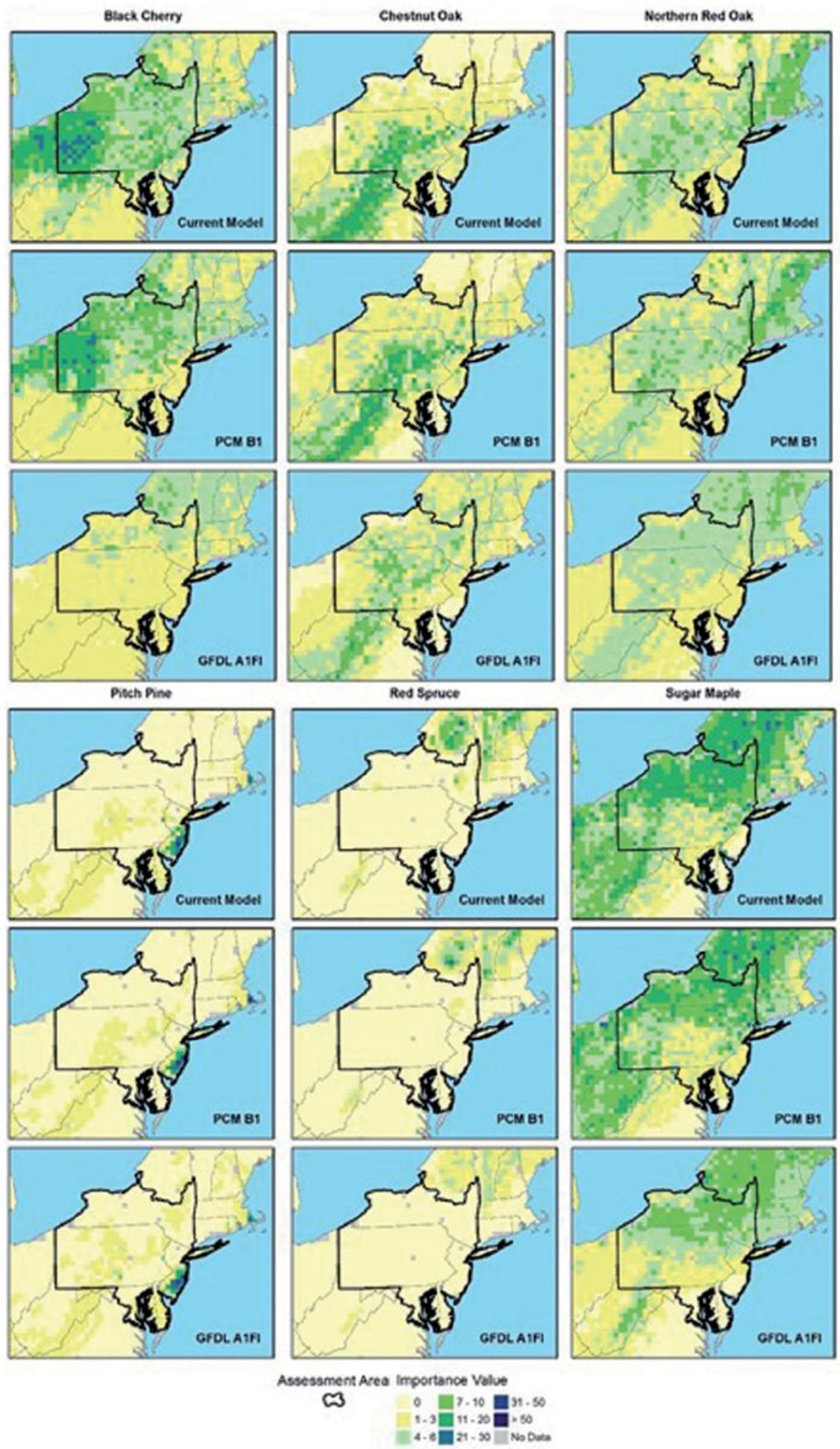


Figure 32.—Modeled importance values for six tree species. Maps show current importance values modeled by DISTRIB, using USDA Forest Service Forest Inventory and Analysis data (top) and projected for the end of the century (2070 through 2099) under PCM B1 (middle) and GFDL A1FI (bottom) climate model-emissions scenarios. Importance values can range from 0 to 100, with 0 indicating that the species is not present.

will be able to migrate to newly available habitat. Additionally, these results do not incorporate the influence of modifying factors (positive for sugar maple, northern red oak, and chestnut oak; negative for pitch pine, black cherry, and red spruce). As is the case for interpreting any spatial model outputs, local knowledge of soils, landforms, microclimate, and other factors is necessary to determine whether particular sites may indeed be suitable habitat for a given species in the future. These maps serve only as an illustration of broad patterns. Suitable habitat maps for all the species considered in this assessment are available online through the Climate Change Tree Atlas Web site (https://www.nrs.fs.fed.us/atlas/tree; see also Appendix 4).

LINKAGES

The LINKAGES model integrates soil, climate, and species attributes to simulate changes in tree species growth potential and total biomass production at the landscape scale under future climate scenarios (Table 20). This information was used to parameterize the LANDIS model described in the following section. Growth potential represents a species' ability to establish from seed and grow from bare ground at a particular site, assuming the presence of an adequate seed source and the absence of disturbance and competition from other species. Species growth is measured by the maximum biomass reached by a species at year 30. This 30-year timespan is used because young regeneration is most susceptible to climate warming. Forest stand dynamics are more realistically addressed during longer periods by using the LANDIS PRO model.

For this assessment, the LINKAGES model was used to predict tree growth potential for 24 species within the Mid-Atlantic region and for 6 subregions (Fig. 31). Estimates were derived from the weighted average of 0.2-acre plots within 6 to 8 landforms in 47 subsections. Absolute and percent changes in biomass were calculated by comparing the period 2070 through 2099 under the PCM B1 and GFDL A1FI climate scenarios to the current climate during 1980 through 2009 (Table 23). Change classes were calculated by dividing the modeled future biomass by the current climate biomass (see Appendix 4 for more change class methods).

The LINKAGES model projected growth potential to decrease under both climate scenarios for seven species: yellow birch, quaking aspen, pitch pine, balsam fir, northern white-cedar, red spruce, and black spruce. With the exception of pitch pine, growth potential for these species was projected to reach zero (extirpation of species) under GFDL A1FI, suggesting that the higher emissions scenario may prevent tree regeneration and advanced growth in the Mid-Atlantic region. LINKAGES projected a large decrease in growth potential for pitch pine under GFDL A1FI.

Eleven species exhibited no change under PCM B1, and decreases under GFDL A1FI. These decreases under GFDL A1FI were moderate for white ash, northern red oak, red maple, black cherry, scarlet oak, black oak, and pignut hickory. Sugar maple, eastern white pine, and eastern hemlock were projected to decline to a larger degree. These results are indicative of seedling sensitivity to soil moisture in the LINKAGES model, and suggest additional challenges to tree regeneration under GFDL A1FI.

Loblolly pine was the only species modeled to increase under both scenarios, with great increases under GFDL A1FI. LINKAGES projected no change (i.e., less than 20 percent change) in growth potential for chestnut oak and white oak. Growth potential for shagbark hickory and Virginia pine is projected to increase under PCM B1, but decrease under GFDL A1FI, suggesting that a small degree of climate change may benefit these species but that too much change may be detrimental. Tulip tree was projected to increase slightly (21 percent) under PCM B1, but not change from current levels under GFDL A1FI (14 percent).

Table 23.—Change in tree species growth potential measured in maximum biomass reached in 30 years starting from bare ground as projected by the LINKAGES model in the Mid-Atlantic region under a current climate scenario (1980-2009) and two climate model-emissions scenarios at the end of the century (2070-2099)

	Current climate	Future climate					
		PCM B1			GFDL A1FI		
Species	Biomass (metric tons/acre)	Biomass (metric tons/acre)	Change (%)	Change class	Biomass (metric tons/acre)	Change (%)	Change class
Decreases under Both Scenarios							
Balsam fir	2.74	0.89	-67	Large decrease	0.00	-100	Extirpated
Black spruce[a]	0.27	0.04	-86	Large decrease	0.00	-100	Extirpated
Northern white-cedar	2.38	0.49	-79	Large decrease	0.00	-100	Extirpated
Pitch pine	35.88	27.42	-24	Decrease	7.86	-78	Large decrease
Quaking aspen	86.96	55.20	-37	Decrease	0.00	-100	Extirpated
Red spruce	1.89	0.78	-59	Large decrease	0.00	-100	Extirpated
Yellow birch	96.74	61.54	-36	Decrease	0.03	-100	Extirpated
Decreases under High Emissions							
American beech	96.30	87.36	-9	No change	14.99	-84	Large decrease
Black cherry	106.58	114.52	7	No change	71.47	-33	Decrease
Black oak	88.74	101.42	14	No change	60.13	-32	Decrease
Eastern hemlock	19.05	17.34	-9	No change	0.93	-95	Extirpated
Eastern white pine	50.47	53.26	6	No change	3.69	-93	Large decrease
Northern red oak	147.06	136.18	-7	No change	83.25	-43	Decrease
Pignut hickory	85.62	98.38	15	No change	60.09	-30	Decrease
Red maple	131.36	135.82	3	No change	89.96	-32	Decrease
Scarlet oak	91.38	99.62	9	No change	58.49	-36	Decrease
Sugar maple	123.80	107.84	-13	No change	28.89	-77	Large decrease
White ash	159.45	166.85	5	No change	93.01	-42	Decrease
Increases under Both Scenarios							
Loblolly pine	42.84	55.62	30	Increase	87.13	103	Large increase
No Change under Both Scenarios							
Chestnut oak	84.95	101.08	19	No change	71.39	-16	No change
White oak	130.63	124.12	-5	No change	116.08	-11	No change
Mixed Results							
Shagbark hickory	60.82	83.28	37	Increase	18.96	-69	Large decrease
Tulip tree	182.12	220.43	21	Increase	207.85	14	No change
Virginia pine	12.34	29.42	138	Large increase	6.01	-51	Decrease

[a] A species with a biomass value ≥1.0 could exist at very low levels or not at all.

Large increases in biomass are projected for some species that are currently absent from the region or have very limited distributions. For example, loblolly pine is currently uncommon east of the Ridge and Valley subregion (Fig. 31). LINKAGES projected a large increase in biomass for this species under GFDL A1FI partly because the modest increase in biomass more than doubled its presence on the landscape, increasing its biomass to levels comparable to black cherry and scarlet oak under current climate. Conversely, LINKAGES projected large decreases in biomass under both scenarios for balsam fir, northern white-cedar, red spruce, and black spruce partly because these species currently have low biomass in the region and even a small reduction in biomass resulted in large declines on the landscape. To account for these relationships, change percentages and change classes should always be compared to the absolute biomass values for the current climate at year 2100 and for each climate scenario.

Geographic Trends

In addition to LINKAGES model results for the entire Mid-Atlantic region, model results are provided for six subregions to explore how trends may differ from one subregion to another (Appendix 4). Sixteen species exhibit important subregional responses under PCM B1: black cherry, black oak, chestnut oak, eastern hemlock, eastern white pine, northern red oak, pignut hickory, pitch pine, red maple, scarlet oak, sugar maple, tulip tree, Virginia pine, white ash, white oak, and yellow birch. Many species also exhibit important subregional responses under GFDL A1FI. Projected species establishment values are substantially different in the Coastal Plain compared to other subregions in the assessment area.

Model results for the entire region show no detectable change for black cherry under PCM B1, and a decrease in growth potential under GFDL A1FI (Table 23); however, when results are explored at the subregional level, we see some geographic variation (Fig. 33). Under PCM B1, black cherry is projected to increase in three subregions and decrease in two subregions. However, the subregions projected to increase under PCM B1 are projected to decrease under GFDL A1FI, especially in the Coastal Plain. This discrepancy suggests that black cherry may benefit from a small amount of warming projected by PCM B1 but that the large amount of warming projected by GFDL A1FI may exceed this species' ecological limits. Chestnut oak is not projected to change under either scenario across the entire region, yet it also shows a mixture of increases and decreases when viewed on a subregional level (Fig. 33).

LINKAGES results indicate only potential growth. Projected changes in biomass do not represent actual current or future distributions and do not predict that a given species will be able to colonize newly available habitat. We focused on establishment and growth of young trees, but mature trees could persist on a site for hundreds of years. Furthermore, LINKAGES is not spatially dynamic and does not simulate tree dispersal or any other spatial interaction, such as competition. This spatial interaction is examined by using LINKAGES results as input in the LANDIS PRO model. As is the case for interpreting any spatial model outputs, local knowledge of soils, landforms, and other factors is necessary to determine whether particular sites may indeed be suitable habitat for a given species in the future. These maps serve only as an illustration of broad trends.

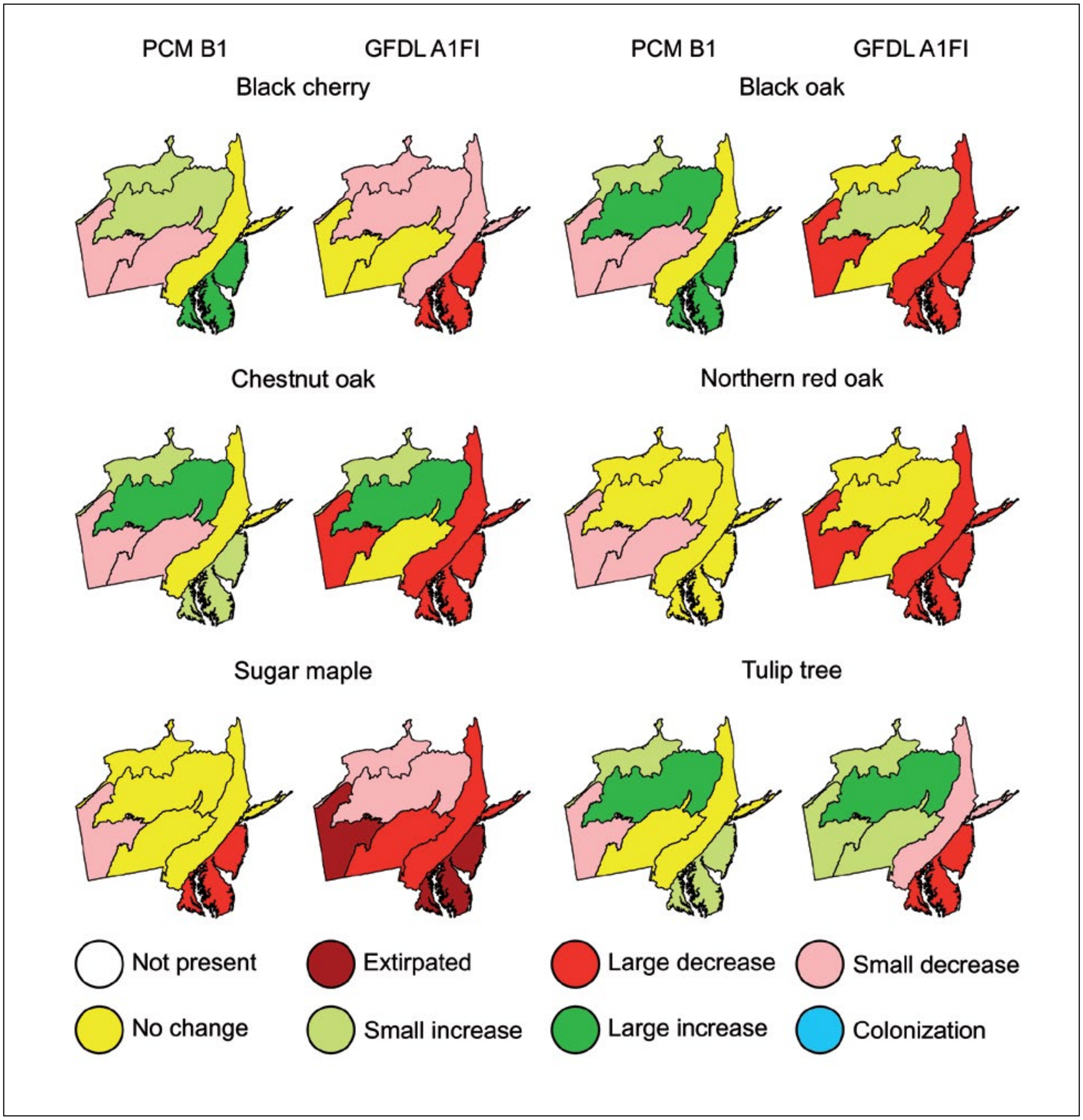


Figure 33.—Change in growth potential projected by the LINKAGES model for six tree species under two climate model-emissions scenario combinations at the end of the century (2070 through 2099) relative to a current climate scenario (1980 through 2009). Appendix 4 contains maps of all modeled species.

LANDIS PRO

Forest landscape change was simulated by using the LANDIS PRO model to project changes in tree abundance (basal area per acre) and density (trees per acre) for 24 tree species through the year 2100 and beyond (Wang et al. 2017). The LANDIS PRO model differs substantially from the Climate Change Tree Atlas and LINKAGES because it simulates tree, stand, and landscape dynamics over time and can provide a prediction about the composition and structure of an individual pixel or larger area for any point in time during the simulation. 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 (Wang et al. 2017). LANDIS PRO accounts for natural stand dynamics, including growth, mortality, competition, and succession, in addition to climate effects on establishment and growth. Because trees are long-lived, near-term projections of forest change are more heavily influenced by the current forest conditions and management; the effects of climate change become increasingly pronounced over the long term (Duveneck et al. 2016, Iverson et al. 2016, Wang et al. 2017).

Although the current climate is expected to change during the 21st century (Chapter 4), a current climate scenario—which holds current climate steady through 2100—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 forests for this region as areas continue to recover from historical land clearing and timber harvest (Chapter 1). Because many forests in the region are still recovering from past disturbances, the basal area of most tree species is generally expected to increase throughout the century under all climate scenarios as forests undergo succession. All LANDIS PRO model results reflect current levels of forest harvest (based on FIA data), but do not include natural disturbances such as wind, fire, or insects. Forest harvest was simulated within management units (private industrial, nonindustrial, and public forest lands) in order to capture harvest variation across the region. Further details and methods were published by Wang et al. (2017).

The remainder of this section describes the LANDIS PRO model projections of basal area and trees per acre by species for the year 2100 (Table 24). The number of trees and basal area per acre are most informative in combination. For a given number of trees per acre, basal area increases with larger tree diameters. Thus, a high basal area with a relatively low number of trees can indicate a forest composed of trees that are relatively older and large in diameter. Conversely, a low basal area with a high number of trees per acre can indicate a forest composed of trees that are relatively younger and smaller in diameter. Change classes were calculated by dividing the modeled future basal area by the current climate basal area, and modeled trees per acre by the current climate trees per acre (Appendix 4). When model results are interpreted, it is important to compare the absolute values (which represent abundance) to the change percentages and change classes. Additional projections in 2040 and 2070, as well as 2200, were also used to understand the long-term response of forests to climate change (Appendix 4).

Results from the PCM B1 and GFDL A1FI scenarios were compared to a current climate scenario, which maintained the climate observed during 1960 to 2010 through the end of the century. Under current climate, changes from 2000 to 2100 are attributed to succession and management (Fig. 34). Decreases represented tree removal due to harvest or natural mortality without recruitment. Under the current climate scenario, LANDIS PRO projected both basal area and trees per acre to decrease for black spruce, northern white-cedar, and balsam fir (Table 24). Increases under the current climate

Table 24.—Change in basal area (BA) and trees per acre (TPA) projected by the LANDIS PRO model under a current climate scenario and two future climate model-emissions scenarios in the year 2100 for 24 species in the Mid-Atlantic region (see Appendix 4 for explanations for the change classes)

		Current climate			PCM B1			GFDL A1FI		
Tree species	BA in 2000 (ft²/ acre)	BA in 2100 (ft²/ acre)	Change from 2000	Current change class	BA in 2100 (ft²/ acre)	Change from current climate	PCM change class	BA in 2100 (ft²/ acre)	Change from current climate	GFDL change class
American beech	3.49	6.49	+86%	Increase	6.01	-7%	No change	7.46	+15%	No change
Balsam fir	0.06	0.05	-25%	Decrease	0.04	-7%	No change	0.05	+9%	No change
Black cherry	7.90	9.14	+16%	No change	9.02	-1%	No change	9.63	+5%	No change
Black oak	2.16	2.37	+10%	No change	2.38	+1%	No change	2.52	+6%	No change
Black spruce*	0.00	0.00	-46%	Large decrease	0.00	-30%	Decrease	0.00	+5%	No change
Chestnut oak	4.67	5.73	+23%	Increase	5.94	+4%	No change	7.25	+26%	Increase
Eastern hemlock	5.30	4.72	-11%	No change	4.48	-5%	No change	5.09	+8%	No change
Eastern white pine	3.38	2.86	-15%	No change	2.63	-8%	No change	2.84	-1%	No change
Loblolly pine	1.32	1.17	-11%	No change	1.18	+1%	No change	1.45	+24%	Increase
Northern red oak	6.54	5.33	-18%	No change	5.18	-3%	No change	5.81	+9%	No change
Northern white-cedar	0.04	0.03	-39%	Decrease	0.02	-24%	Decrease	0.03	+2%	No change
Pignut hickory	0.81	1.30	+60%	Increase	1.24	-4%	No change	1.42	+9%	No change
Pitch pine	1.84	2.83	+54%	Increase	2.90	+2%	No change	3.47	+23%	Increase
Quaking aspen	0.88	4.31	+391%	Large increase	3.77	-13%	No change	3.52	-18%	No change
Red maple	16.50	23.61	+43%	Increase	23.61	+0%	No change	24.94	+6%	No change
Red spruce	0.24	0.23	-5%	No change	0.21	-9%	No change	0.25	+8%	No change
Scarlet oak	1.41	2.39	+70%	Increase	2.40	+0%	No change	2.50	+5%	No change
Shagbark hickory	0.35	0.92	+163%	Large increase	0.88	-4%	No change	1.07	+17%	No change
Sugar maple	7.11	8.67	+22%	Increase	8.08	-7%	No change	9.24	+7%	No change
Tulip tree	3.38	2.92	-14%	No change	2.94	+1%	No change	3.47	+19%	No change
Virginia pine	0.49	0.71	+45%	Increase	0.72	+1%	No change	0.81	+14%	No change
White ash	4.16	7.60	+83%	Increase	7.11	-6%	No change	8.93	+18%	No change
White oak	3.33	5.89	+77%	Increase	5.52	-6%	No change	7.10	+21%	Increase
Yellow birch	0.84	1.90	+125%	Large increase	1.69	-11%	No change	1.93	+2%	No change

*Species is present but rare; the zero value is the result of rounding to two decimal places.

(continued on next page)

Table 24 (continued).—Change in basal area (BA) and trees per acre (TPA) projected by the LANDIS PRO model under a current climate scenario and two future climate model-emissions scenarios in the year 2100 for 24 species in the Mid-Atlantic region (see Appendix 4 for explanations for the change classes)

		Current climate			PCM B1			GFDL A1FI		
Tree species	TPA in 2000	TPA in 2100	Change from 2000	Current change class	TPA in 2100	Change from current climate	PCM change class	TPA in 2100	Change from current climate	GFDL change class
American beech	25.9	18.3	-29%	Decrease	16.1	-12%	No change	14.1	-23%	Decrease
Balsam fir	0.5	0.1	-87%	Large decrease	0.0	-54%	Large decrease	0.0	-47%	Large decrease
Black cherry	24.0	18.8	-21%	Decrease	18.6	-1%	No change	21.4	+14%	No change
Black oak	3.0	3.5	+18%	No change	3.8	+9%	No change	3.4	-2%	No change
Black spruce*	0.0	0.0	-67%	Large decrease	0.0	-62%	Large decrease	0.0	-41%	Large decrease
Chestnut oak	9.3	24.5	+165%	Large increase	32.2	+32%	Increase	41.2	+68%	Increase
Eastern hemlock	17.1	5.1	-70%	Large decrease	5.2	+2%	No change	2.8	-46%	Large decrease
Eastern white pine	9.0	8.8	-2%	No change	7.7	-12%	No change	3.6	-59%	Large decrease
Loblolly pine	3.8	3.3	-14%	No change	3.5	+9%	No change	3.2	-1%	No change
Northern red oak	10.3	8.9	-14%	No change	8.3	-7%	No change	12.3	+38%	Increase
Northern white-cedar	0.8	0.2	-77%	Large decrease	0.1	-68%	Large decrease	0.1	-68%	Large decrease
Pignut hickory	2.8	2.7	-4%	No change	2.7	+2%	No change	2.6	-2%	No change
Pitch pine	7.3	4.4	-40%	Decrease	4.0	-8%	No change	4.1	-7%	No change
Quaking aspen	2.4	35.3	+1,354%	Large increase	27.0	-23%	Decrease	9.9	-72%	Large decrease
Red maple	74.5	42.6	-43%	Large decrease	44.1	+3%	No change	52.9	+24%	Increase
Red spruce	1.7	0.4	-73%	Large decrease	0.2	-48%	Large decrease	0.2	-50%	Large decrease
Scarlet oak	3.0	3.7	+22%	Increase	4.1	+11%	No change	3.0	-20%	No change
Shagbark hickory	1.3	2.9	+113%	Large increase	3.0	+6%	No change	3.4	+20%	No change
Sugar maple	29.6	26.6	-10%	No change	24.1	-10%	No change	18.1	-32%	Decrease
Tulip tree	4.2	13.8	+230%	Large increase	14.8	+7%	No change	20.4	+48%	Increase
Virginia pine	1.1	1.1	+1%	No change	1.1	+0%	No change	0.9	-21%	Decrease
White ash	16.4	25.9	+58%	Increase	24.1	-7%	No change	32.2	+24%	Increase
White oak	7.2	32.5	+353%	Large increase	29.7	-9%	No change	42.7	+31%	Increase
Yellow birch	3.7	6.5	+74%	Increase	5.2	-19%	No change	2.6	-60%	Large decrease

*Species is present but rare; the zero value is the result of rounding to one decimal place.

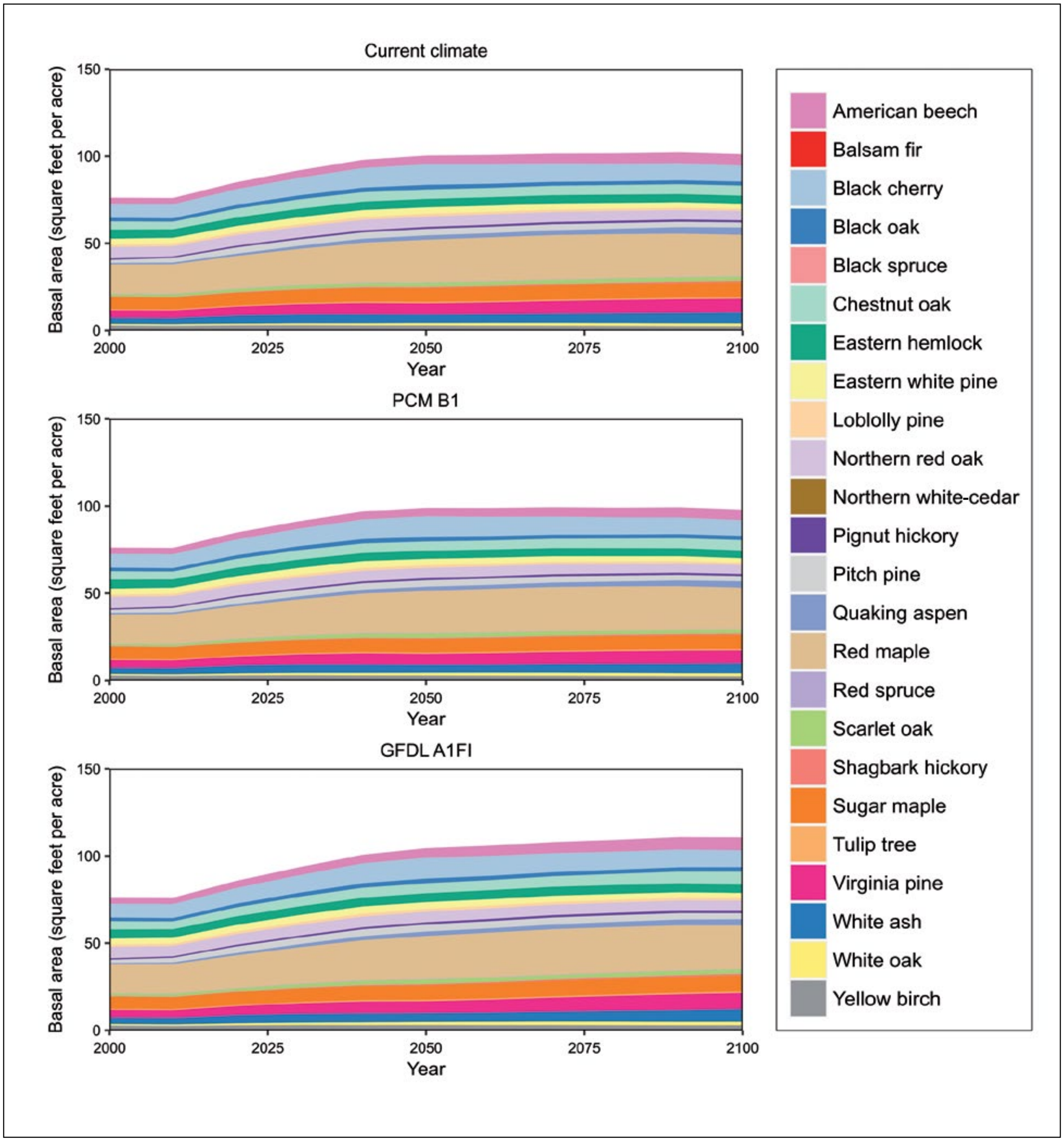


Figure 34.—Change in basal area projected by the LANDIS PRO model for 24 tree species in the assessment area.

scenario represented pioneer species such as quaking aspen capturing new growing space, or long-lived shade-tolerant species such as sugar maple regenerating and growing under existing canopies. Increases were projected in both trees per acre and basal area for chestnut oak, quaking aspen, scarlet oak, shagbark hickory, white ash, white oak, and yellow birch. Pitch pine is projected to increase in basal area, but decrease in the number of trees per acre. Black cherry is projected to change little in basal area, but decrease in the number of trees per acre. Trees per acre was projected to increase for tulip tree whereas basal area changed little, suggesting that this species may be able to take advantage of reduced competition as other species decline. Eastern white pine, loblolly pine, northern red oak, pignut hickory, sugar maple, and Virginia pine are projected to change little in the number of trees per acre, and change little or increase slightly in overall basal area.

Because of the strong influence of forest growth and succession during the 21st century, climate change is expected to have a relatively subtle influence on forest composition between now and 2100. There was no change in basal area projected under both scenarios for most of the species modeled, and the remaining six species were projected to increase or decrease moderately under only one scenario (Table 24). Most of those (chestnut oak, loblolly pine, pitch pine, and white oak) were projected to increase under GFDL A1FI. Black spruce and northern white-cedar were projected to decrease under PCM B1 but not change under GFDL A1FI.

The number of trees per acre is also an important measure of abundance and was projected to stay the same under both climate scenarios for black cherry, black oak, loblolly pine, pignut hickory, pitch pine, scarlet oak, and shagbark hickory (Table 24). Combined with the information on basal area, black cherry, black oak, and pignut hickory were not expected to change much in the number of trees per acre and basal area under both scenarios. The number of trees per acre was also projected to stay the same under both climate scenarios for loblolly pine and pitch pine, but those species increased in basal area under GFDL A1FI, suggesting that conditions under the higher emissions scenario may not impede regeneration while the remaining trees continue to accrue biomass. Five species were projected to decrease substantially (see Appendix 4 for classification methods) in trees per acre under both scenarios: balsam fir, black spruce, northern white-cedar, quaking aspen, and red spruce. Balsam fir, black spruce, northern white-cedar, and red spruce were also projected to decrease due to succession or management under the current climate scenario, suggesting that climate change will exacerbate the decline of these species. Chestnut oak was projected to increase in trees per acre under both GFDL A1FI and PCM B1, and due to succession under the current climate scenario. Chestnut oak basal area was also projected to increase under the current climate scenario, with no change projected under PCM B1 and an increase under GFDL A1FI, suggesting that climate change may further promote an increasing trend on the landscape.

Geographic Trends

LANDIS PRO results point to notable differences in how species and forests respond to climate change across the Mid-Atlantic region. LANDIS PRO can provide information about the projected composition and structure of an individual pixel for any point in time during the simulation (Fig. 35). For some species, basal area is projected to increase in some areas while decreasing in others. For example, although chestnut oak is projected to increase on average for the Mid-Atlantic region, these increases are largely concentrated in the Northern Allegheny Plateau and Catskill Mountains (subregion 3), while the Hudson Valley and Piedmont (subregion 5) and the Coastal Plain (subregion 6) showed much more mixed responses for both climate scenarios. For many species, the Northern Allegheny Plateau (the large subregion in the middle of the Mid-Atlantic region) is a hotspot of activity, showing a fine-scale mixture of increases, decreases, and no change

Table 25.—Comparison of change classes for the end of century (2070 through 2099) period under two climate model-emissions scenarios for the 24 tree species in the Mid-Atlantic region modeled by all three forest impact models

	LINKAGES growth potential		Tree Atlas (DISTRIB) suitable habitat		LANDIS PRO trees per acre		LANDIS PRO basal area	
	PCM B1	GFDL A1FI	PCM B1	GFDL A1FI	PCM B1	GFDL A1FI	PCM B1	GFDL A1FI
American beech	No change	Large decrease	Decrease	Large decrease	No change	Decrease	No change	No change
Balsam fir	Large decrease	Extirpated	Large decrease	Large decrease	Large Decrease	Large Decrease	No change	No change
Black cherry	No change	Decrease	No change	Large decrease	No change	No change	No change	No change
Black oak	No change	Decrease	No change	Large increase	No change	No change	No change	No change
Black spruce	Large decrease	Extirpated	Decrease	Large decrease	Large Decrease	Large Decrease	Decrease	No change
Chestnut oak	No change	No change	No change	No change	Increase	Increase	No change	Increase
Eastern hemlock	No change	Large decrease	Decrease	Large decrease	No change	Large Decrease	No change	No change
Eastern white pine	No change	Large decrease	Decrease	Large decrease	No change	Large Decrease	No change	No change
Loblolly pine	Increase	Large increase	Increase	Large increase	No change	No change	No change	Increase
Northern red oak	No change	Decrease	No change	No change	No change	Increase	No change	No change
Northern white-cedar	Large decrease	Extirpated	Large decrease	Large decrease	Large Decrease	Large Decrease	Decrease	No change
Pignut hickory	No change	Decrease	No change	Increase	No change	No change	No change	No change
Pitch pine	Decrease	Large decrease	No change	No change	No change	No change	No change	Increase
Quaking aspen	Decrease	Extirpated	Decrease	Large decrease	Decrease	Large Decrease	No change	No change
Red maple	No change	Decrease	No change	Large decrease	No change	Increase	No change	No change
Red spruce	Large decrease	Extirpated	Decrease	Decrease	Large Decrease	Large Decrease	No change	No change
Scarlet oak	No change	Decrease	Increase	Increase	No change	No change	No change	No change
Shagbark hickory	Increase	Large decrease	Increase	Large increase	No change	No change	No change	No change
Sugar maple	No change	Large decrease	No change	Decrease	No change	Decrease	No change	No change
Tulip tree	Increase	No change	Increase	Decrease	No change	Increase	No change	No change
Virginia pine	Large increase	Decrease	No change	No change	No change	Decrease	No change	No change
White ash	No change	Decrease	No change	Decrease	No change	Increase	No change	No change
White oak	No change	No change	No change	Increase	No change	Increase	No change	Increase
Yellow birch	Decrease	Extirpated	No change	Large decrease	No change	Large Decrease	No change	No change

so that the whole region looks gray. Additionally, maps for some species, such as chestnut oak, have a noticeable cutoff in data in the Northern Allegheny Plateau; this cutoff is the result of using statewide FIA data. Chestnut oak does not actually stop at the state line, but the higher abundance in Pennsylvania was reflected in the FIA data up to the state line. The scarcity of chestnut oak in New York reflects a much lower abundance in the New York FIA dataset. Additionally, the maps indicate abrupt transitions between change classes that are evident at the subregional lines, which are based on ecological provinces. The abrupt transitions are the result of using a particular soil for each subsection. In the hierarchy of ecological units, subsections are aggregated by section, which are aggregated by provinces. Provinces are areas of distinct soils, climate, and geological features, and these features seem to set the stage for how tree species respond to changes in climate.

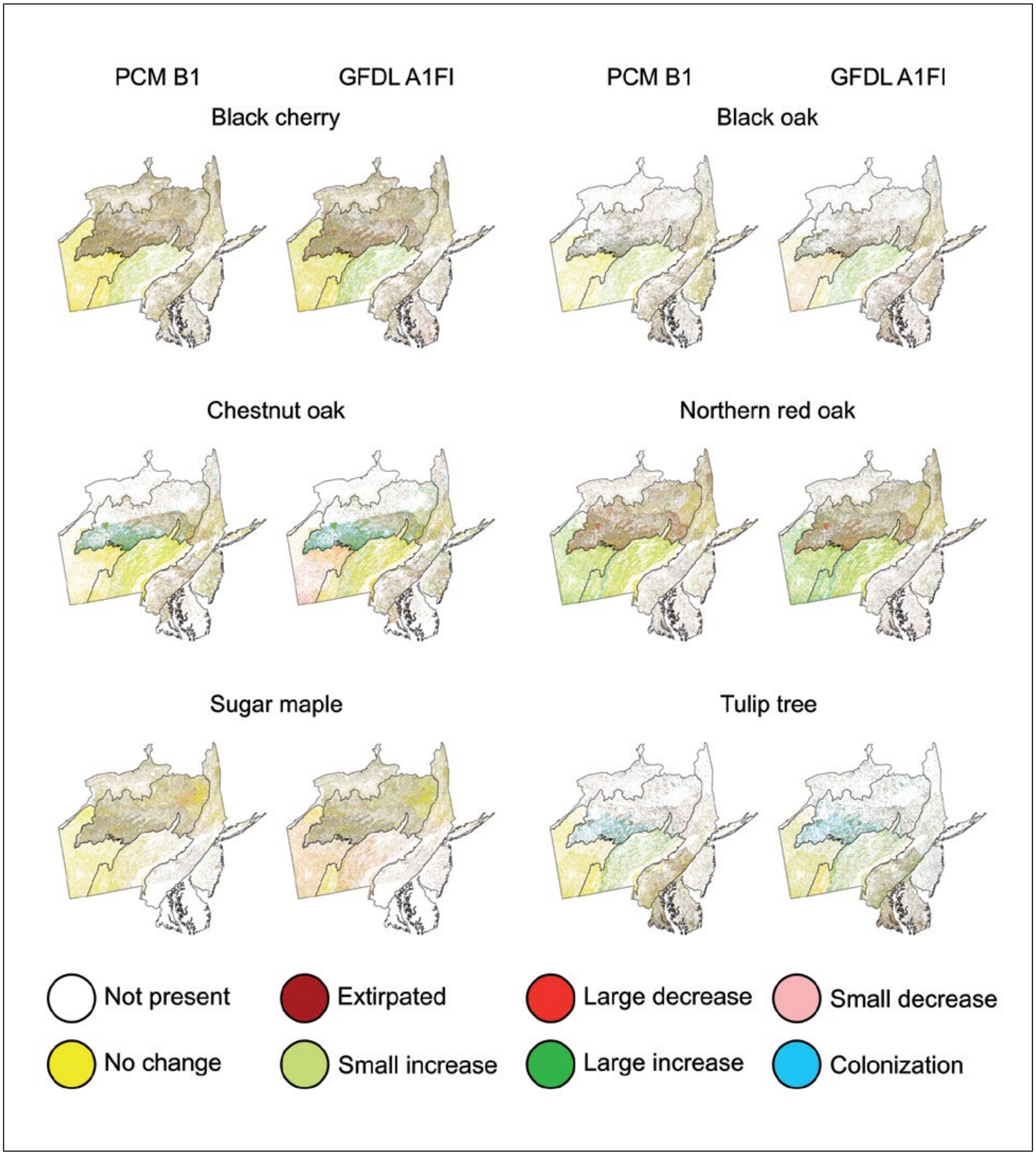


Figure 35.—Change in basal area projected by the LANDIS PRO model for six tree species under two climate model-emissions scenario combinations at year 2100 relative to a current climate scenario (1980 through 2009). Appendix 4 contains values for all modeled species.

DISCUSSION OF MODEL RESULTS

The three different models used in this assessment represent different facets of potential forest change in response to a changing climate. Therefore, the ability to make comparisons between the different models gives us a deeper understanding of which parts of a forest ecosystem may be most responsive or vulnerable to change (i.e., habitat and tree establishment, growth, and density) (Iverson et al. 2016). At the same time, however, the differences between the models, in terms of design, outputs, strengths, and weaknesses, prevent direct comparisons among model results (Iverson et al. 2016). This section describes areas of agreement and disagreement between the results and provides context for how the results from multiple models can be integrated to better understand forest change. A comparison using a suite of metrics among the three models for this and other regions has recently been published (Iverson et al. 2016).

Areas of Agreement

The DISTRIB model used by the Tree Atlas was able to characterize habitat for 112 species in the Mid-Atlantic region, and the LINKAGES and LANDIS PRO models simulated 24 species. Therefore, only 24 species can be compared across all three models (Table 25 and Appendix 4). The changes in trees per acre from the LANDIS PRO model generally agree with LINKAGES and the Tree Atlas DISTRIB model. But climate-related changes in basal area were not evident by the end of the century, suggesting that mature trees may persist in even unsuitable habitat, in the absence of nonclimatic mortality factors. Where DISTRIB and LINKAGES results agree with LANDIS PRO estimates of trees per acre, there is higher confidence that results can suggest changes in tree establishment and growth.

All three models suggest that conditions at the end of the century will become less favorable for balsam fir, black spruce, eastern hemlock, northern white-cedar, quaking aspen, red spruce, and yellow birch, especially under the scenario of greater climate change (GFDL A1FI). At the same time, all three models suggest that conditions will remain favorable or become more favorable for black oak, chestnut oak, loblolly pine, and white oak, especially under GFDL A1FI. Additionally, the models tend to agree that many species that remain stable for PCM B1 are projected to increase or decrease under GFDL A1FI, and many species that are projected to decrease under PCM B1 are projected to decline further under GFDL A1FI. These results support the idea that the GFDL A1FI scenario represents a future climate that is beyond the tolerance of many species. These results also suggest that many temperate species currently present in the assessment area could tolerate a mild degree of warming with corresponding increase in growing season precipitation, as represented by the PCM B1 scenario.

The LANDIS PRO model simulates the pace at which forests are changing due to succession and management, with and without the benefits and drawbacks of climate change. These forests are often still responding to the significant human intervention during the past 300 years, and have substantial inertia in their species assemblages and growth patterns. However, model results generally do not incorporate large-scale disturbance events, including temperature and precipitation extremes, wind and ice storms, pests and diseases, and fire. Individual disturbances, and especially interactions between them, may result in rapid changes to existing forests and their long-term trajectories and response to climate change.

Disagreements

There do not appear to be any major discrepancies between results for individual species when the three models are compared, although there are some differences that can be explained by the differences between the model outputs. DISTRIB and LINKAGES both project suitable habitat, but key differences in LANDIS PRO are due to the added components of succession and dispersal. Although DISTRIB and LINKAGES projected small to large decreases for black cherry habitat in the Mid-Atlantic region, LANDIS PRO projected no change in basal area because black cherry trees are expected to persist where individuals are already established. In other words, although the amount of suitable habitat may decline, affecting a species' ability to establish and grow past sapling stage, mature trees are likely to persist or even thrive in the absence of herbivory, competition, or other stressors. LANDIS PRO results emphasize that changes in habitat and species establishment largely complement changes in the number of trees per acre within the next century, but that changes in overstory composition and basal area are likely to take much longer in the absence of severe disturbance.

The LANDIS PRO model projected no change in basal area for most species, but predicted more changes in trees per acre, particularly under GFDL A1FI. This result suggests that climate changes during the next century may have a more obvious impact on tree regeneration and recruitment, and that without other large-scale disturbances, changes in overall biomass may take longer. There were also several cases where model results disagreed on the direction of change. For example, under GFDL A1FI, LINKAGES projected a small decrease for scarlet oak, whereas Tree Atlas projected an increase for scarlet oak, suggesting that despite retaining suitable habitat, this species may face future challenges with regeneration and early growth.

Limitations

The three different models used in this assessment were selected because each model represents a different mechanism of potential forest change as a result of a changing climate (Iverson et al. 2016). 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. Examples of factors that are not considered in these models are:

- Land management and policy responses to climate change or impacts to forests
- Land-use change or forest fragmentation
- Future changes in forest industry, including products and markets
- Changes in phenology and potential timing mismatches for key ecosystem processes
- Genetic adaptation or phenotypic plasticity leading to diverse responses within a population
- Responses of understory vegetation, soil micro-organisms, or soil mycorrhizal associations
- Changes in nutrient cycling due to changes in nitrogen deposition
- 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
- Future herbivory pressure, particularly from white-tailed deer
- Interactions among all these factors

Most of these factors could drive large changes in forest ecosystems throughout the assessment area, and 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. To inform an overall assessment, it is important to keep the preceding limitations in mind when the results from different models are weighed. 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.

Aftermath of a rain storm that damaged a section of the Appalachian Trail in Pennsylvania. Such extreme events are not well modeled in climate projections. Photo by Patricia Leopold, Northern Institute of Applied Climate Science and Michigan Tech, used with permission.

SUMMARY OF CURRENT SCIENTIFIC KNOWLEDGE ON POTENTIAL FOREST IMPACTS ASSOCIATED WITH CLIMATE CHANGE

The results presented earlier provide us with important projections of tree species distributions and forest response across a range of future climates, but these models do not account for all factors that may influence tree species and forest communities in a changing climate. Climate change has the potential to alter the distribution, abundance, and productivity of forests and their associated species in a variety of ways (Joyce et al. 2014, Vose et al. 2012). These impacts can be coarsely divided into the **direct** effects of changing climate variables (e.g., temperature, precipitation, and carbon dioxide levels) on forests and the **indirect** effects of altered, new, and interacting stressors. For the most part, models such as the ones just described consider direct effects from changes in climate variables, but we recognize that the indirect effects of stressors can have important effects that models may not capture. It is also important to note that some of the impacts may in fact be positive or beneficial to native forest ecosystems. The remainder of this chapter summarizes the current state of scientific knowledge about additional direct and indirect effects of climate change on forests in the assessment area. The following information focuses on biological and atmospheric drivers of change rather than anthropogenic drivers of change (e.g., forest management), which can also have a major influence on forest change. Chapter 7 highlights climate change effects on topics such as forest management, human communities, and development.

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 losses from respiration and other causes are taken into account. It is an important way to assess the condition of a forest because it is related to the rate at which forests can sequester carbon and produce timber. This section describes the potential effects of altered temperature and precipitation and nonclimatic factors such as carbon dioxide enrichment and ozone on forest productivity and carbon gain. Other complex factors that may also influence forest growth—such as enhanced 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 3), and this trend is expected to continue (Chapter 4). There is evidence both worldwide and regionally that longer growing seasons during the past century have increased the time available to plants for photosynthesis and are partly responsible for observed increases in forest growth and carbon sequestration (Keenan et al. 2013, 2014; White et al. 1999). One study of increased growing season length in the eastern United States found that carbon uptake advanced in the spring and extended later in the fall (Keenan et al. 2014). Projections of forest growth at four sites in the Northeast generally showed increases of up to 25 percent in productivity under scenarios of mild and moderate climate warming (Ollinger et al. 2008). Another study found that a 1-percent increase in growing season length resulted in a 1.6-percent increase in net ecosystem productivity (White et al. 1999).

Temperature influences forest growth through effects on both photosynthesis and respiration. Plant respiration increases with increasing temperature, although plants are able to become acclimated 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). One study of forests across the Mid-Atlantic attributed a modest average increase in productivity of 4 percent due to the positive influence of warmer temperatures on photosynthesis (Pan et al. 2009). Another study focused on the New Jersey Pine Barrens projected increases in biomass for black oak, chestnut oak, pitch pine, and white oak (Scheller et al. 2012), all of which were projected to increase in biomass by the LANDIS PRO model. However, most plants have specific ecological thresholds for survival and reproduction within a specific range of minimum and maximum temperatures. Variability of temperatures within a single year is likely to continue to limit individuals as temperatures exceed those thresholds (Jackson et al. 2009). For example, the New Jersey study projected decreases in species establishment probability, suggesting that established individuals may benefit from climate change, but that regeneration may begin to fail. The New Jersey study also projected decreases in biomass for Atlantic white-cedar and swamp tupelo (Scheller et al. 2012). Another simulation of forests in the Northeast predicted slower growth rates when temperatures under A1FI exceeded the optima for photosynthesis, especially in spruce-dominated forests, which have a lower optimum temperature for photosynthesis (Ollinger et al. 2008).

As temperatures rise during the next 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 lengthen also accelerate hydrologic cycles (Chapter 4). As peak streamflows shift earlier toward spring, there is an increased potential for soil moisture deficits late in summer and fall (Chapter 4), which is further compounded by increases in extreme precipitation events (Anandhi et al. 2013, Campbell et al. 2009, Hayhoe et al. 2007, Moore et al. 1997). Increased evapotranspiration may have greater influence than decreasing precipitation on summer soil moisture (Campbell et al. 2009). 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, such as evapotranspiration, soil moisture, and streamflows, leading to positive or negative impacts on productivity (Anandhi et al. 2013, Campbell et al. 2009, Richardson et al. 2010). Shifts in the phenology of leaf emergence in response to warmer spring temperatures have the potential to increase the vulnerability of leaves and buds to late spring frosts and freezes (Ault et al. 2013, Rollinson and Kaye 2012, Zohner et al. 2017). 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 to 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. 2012). Furthermore, in a complex landscape such as the Mid-Atlantic region, leaf phenology also depends on microclimate as characterized by proximity to urban areas, tidal streams, and elevational gradients (Elmore et al. 2012). For example, mountain valleys can be prone to overnight cooling, a phenomenon that results in the pooling of cold air and increases the potential for frost even as snowfall decreases (Anandhi et al. 2013).

Although climate change is expected to increase forest growth in many ways, it may not be possible to separate climate-driven changes from other changes that are occurring in forests. For example, past land use in the region has resulted in second-growth forests that are young compared to pre-European settlement conditions (Willard et al. 2015). Several modeling studies demonstrate that forests across the region are generally expected to accumulate carbon during the next several decades simply due to succession and forest maturation (McGarvey et al. 2015; Pan et al. 2004, 2009). 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 (Pan et al. 2009, Wang et al. 2017). Additionally, changes in land use that result in forest conversion to nonforest have the potential to decrease any carbon gained through either forest succession or growth from climate change (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 carbon dioxide on plant productivity. Elevated carbon dioxide has a direct, positive effect on photosynthesis and increases the efficiency of water use in trees (Ainsworth and Rogers 2007, Norby and Zak 2011, Ollinger et al. 2008, Pan et al. 2009). There is evidence that elevated carbon dioxide has contributed to enhanced tree growth during the past two centuries (Cole et al. 2010, Franks et al. 2013, Norby and Zak 2011) and potentially offset some of the effects of drier growing seasons (Franks et al. 2013, Wang et al. 2006).

Modeling studies examining productivity in forests across the Mid-Atlantic and Northeast consistently simulate greater increases when elevated carbon dioxide is included in modeling (Aber et al. 1995, Ollinger et al. 2008, Pan et al. 2009). For example, projections of forest growth at four sites in the Northeast generally showed increases of 9 to 25 percent in productivity under scenarios of mild and moderate climate warming without carbon dioxide fertilization; under elevated carbon dioxide, increases in productivity were much higher, ranging from 25 to 75 percent (Ollinger et al. 2008). This effect is particularly strong for deciduous forests; the benefit of carbon dioxide was projected to be less in spruce forests because of the sensitivity to temperature increases (Aber et al. 1995, Ollinger et al. 2008). Often, the models suggest that carbon dioxide fertilization has a greater effect on forest productivity than does climate (Aber et al. 1995, Hickler et al. 2015, Ollinger et al. 2008, Pan et al. 2009). As discussed earlier, warmer temperatures and longer growing seasons can lead to increased evapotranspiration, water loss, and potential for moisture stress. Elevated carbon dioxide can partially offset this effect by improving water use efficiency (Dangal et al. 2014, Ollinger et al. 2008).

Although carbon dioxide enrichment experiments and models suggest net primary productivity will increase under elevated carbon dioxide, the carbon dioxide fertilization effect is moderated by other environmental change factors, including nutrient and water availability, ozone pollution, and tree species, age, and size (Ainsworth and Long 2005, Norby and Zak 2011, Norby et al. 2005, Pan et al. 2009). Productivity increases under elevated carbon dioxide could be partially offset by reductions in productivity from warming-induced moisture stress or the effects of future disturbances (Dieleman et al. 2012, Franks et al. 2013). In fact, climate change-related disturbances such as fire, insects, disease, and management could reduce forest productivity independent of carbon dioxide fertilization.

Numerous models simulate the effects of moderately elevated carbon dioxide on tree growth, but few experiments have examined the effects of carbon dioxide on the distribution of carbon to wood production (Hickler et al. 2015). Furthermore, few studies in the Northeast have examined the effects of elevated carbon dioxide above 600 parts per million (ppm) (Ollinger et al. 2008). Thus, we know little about how regional forests may respond under even higher levels of atmospheric carbon dioxide, such as the 900 ppm levels projected under the A1FI emissions scenario for 2100 (Chapter 2).

Ozone

Forests are exposed to ozone deposition and individual plants vary in their response to ozone, independent of species or proximity to another individual (Smith et al. 2012). Some species, including black cherry, tulip tree, and white ash are injured by ozone (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 carbon dioxide-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). Recent pollution control policies have reduced emissions of ozone precursors such as nitrogen oxides and carbon monoxide, but ozone is still chronically present at moderate levels. Despite a decreasing trend in ozone-related tree

Black cherry in successional maritime forest in Gateway National Recreation Area, New Jersey. Photo by Gregory J. Edinger, New York Natural Heritage Program, used with permission.

injuries from 1994 to 2010, ozone levels in the Mid-Atlantic states have caused injury to trees in every year or two of that period (Smith et al. 2012). Ozone injury has been shown to increase with soil moisture and decrease during times of moisture deficit (Davis and Orendovici 2006, McLaughlin et al. 2007, Orendovici-Best et al. 2010, Smith et al. 2012). Ozone injury may increase with climate change as wet conditions support the reaction of volatile organic compounds and nitrogen oxides to produce ozone (Rustad et al. 2012).

Nutrient Cycling

As air temperatures warm and precipitation patterns change, the cycling of nutrients between plants, soils, and the atmosphere may also change. Many factors, including changes in temperature, precipitation, soil moisture, and acid deposition, and the interactions 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 snow melt, soil warming, and soil biological activity begin earlier in the spring while the onset of leaf-out, photosynthesis, and overstory plant nutrient uptake still happens 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). 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, McDaniel et al. 2014, Rustad et al. 2001), although the degree of soil respiration is related to the availability of soil moisture and nutrients. 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. 2012).

Decomposition of vegetation is a major component of most nutrient cycles and is carried out primarily by enzymes released from bacteria and fungi. These enzymes are sensitive to changes in temperature, and thus there is generally a positive effect of temperature on the rate of enzymatic activity as long as moisture is also sufficient (Brzostek et al. 2012, Finzi et al. 2006, Rustad et al. 2001). In studies that examined the effects of extended dry periods followed by moisture pulses on nutrient cycling, moisture pulses led to a flush of mineral nitrogen, but was not sufficient to compensate for the lack of microbial activity during dry periods (Borken and Matzner 2009, McDaniel et al. 2014). 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.

The long-term effects of past and ongoing acid deposition increase the complexity of connected nutrient cycles and their interactions. Although warmer temperatures have the potential to increase enzymatic activity and nutrient cycling, acid deposition will remain an important consideration. Anthropogenic emissions of nitrogen and sulfur increased during the last century, peaking in the 1970s. These emissions undergo chemical transformations that produce nitrates and sulfates, which are eventually deposited on the ground (Elliott et al. 2013). These sulfur and nitrogen compounds are deposited at high concentrations through rain and snow in the eastern United States, particularly in high-elevation sites (Pardo et al. 2011, Smith et al. 2016). In forest ecosystems, hydrogen ions associated with nitrogen and sulfur deposition displace 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). Nitrogen saturation has also 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 that continued acid deposition is expected to contribute to reduced ability to withstand climatic changes (Friedland et al. 1984, McNulty and Boggs 2010, Pardo et al. 2011).

Other stressors notwithstanding, some research suggests that nitrogen deposition could be beneficial and help fuel forest growth under elevated carbon dioxide (Devaraju et al. 2016, Rustad et al. 2012, Thornton et al. 2007). In a study of North American trees, earlier spring phenology has caused increased demand for nitrogen by plants (Elmore et al. 2016). Some species have been observed to respond positively to nitrogen deposition, including tulip tree, black cherry, red maple, sugar maple, and red oak, while other species responded negatively, including red pine and red spruce (Thomas et al. 2010). A study focusing on the New Jersey Pine Barrens simulated effects of fire and climate change in a nutrient-poor and nitrogen-limited landscape and predicted declining nitrogen as a result of increased leaching under higher precipitation (Lucash et al. 2014). Future rates of deposition are unknown, but have the potential to decrease in the future as an indirect effect of potential reductions in greenhouse gas emissions (Driscoll et al. 2014). The potential impacts of elevated nitrogen deposition in a changing climate remain unclear.

Sea-level Rise and Saltwater Intrusion

Forest ecosystems along coasts will be affected by climate change. Mid-Atlantic coastal ecosystems—including wetlands, salt marshes, estuaries, and forests—provide a number of benefits, such as water filtration, habitat for fish, carbon storage, and recreation for some of the most populated areas in the country (Moser et al. 2014, Scavia et al. 2002, Willard et al. 2015). Additionally, coastal ecosystems help to buffer storm surges and waves and reduce impacts from flooding. As sea levels rise, sea water is expected to inundate land, and water features that are currently inland may be subjected to increased water salinity, higher acidity, and other changes in ecosystem dynamics (Moser et al. 2014). Coastal ecosystems play an important role in buffering the extreme conditions along the coasts, and impacts on these systems can reduce their ability to protect against effects such as storm surges and flooding (Groffman et al. 2014).

Coastal habitats are threatened by a range of climatic and environmental stressors that reflect a complexity of natural and anthropogenic influences. Forested wetlands, swamps, and adjacent marshes are sensitive to changes in sea level. Several studies note that salinity increases of 2 parts per thousand can cause a freshwater swamp forest to transition to marsh (Anderson et al. 2013a, Krauss et al. 2009). Freshwater tree species can tolerate low chronic levels or acute episodes of moderately increased salinity, but may suffer during periods of higher exposure (Doyle et al. 2007a). However, low amounts of salinity can have severe effects on freshwater systems that are not usually reached by saltwater (Middleton 2016, Stanturf et al. 2007). Salinity levels can remain high for months or longer, especially in situations where soil salinity is increased, and may result in suppression of regeneration (Middleton 2016). Increased salinity can also affect nitrogen inputs, ultimately impeding forest growth (Krauss et al. 2009).

Drought can also influence saltwater intrusion; as streamflow decreases during a drought, saltwater is able to move farther upriver (Doyle et al. 2007a, Rheinhardt 1992). Drought-induced salinity stress has caused widespread mortality and long-term negative effects on tree growth in forests along the Atlantic coast (Anderson et al. 2013a; Doyle et al.

Great blue heron at Beaver Meadows Recreation Area, Allegheny National Forest, Pennsylvania. Photo by Kathleen Creek, Allegheny National Forest.

2007a, 2007b). The sea level along the Atlantic coast continues to rise, resulting in not only increased salinity and intrusion, but land subsidence and flooding (Climate Change Science Program 2009, Kearney and Stevenson 1991). Evidence suggests that coastal forests in the Mid-Atlantic region are already in decline from the effects of sea-level rise (Glick et al. 2008).

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, Itter et al. 2017, Vose et al. 2016, Weed et al. 2013), and indeed, evidence continues to mount that some disturbance events are already increasing in frequency and intensity (Dale et al. 2016). 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 Mid-Atlantic 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 consequence of more energy in the atmosphere, resulting in a greater amount of precipitation falling in large events (Chapter 4). 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, particularly when these events occur in conjunction with high tides (Frumhoff et al. 2007). This type of interaction occurred during the Great Hurricane of 1938 and Hurricane Sandy in 2012, both of which made landfall on the Mid-Atlantic coast.

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 typically found 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. The high density of roads and impervious surfaces in the Mid-Atlantic region is likely to intensify flooding and erosion potential.

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).

Wind Disturbance

Wind disturbances, including hurricanes, tornadoes, downbursts, gales, and intense windstorms, are a primary ecological driver of many regional forests; both small-scale and stand-replacing wind events influence the tree species composition, forest structure, and landscape complexity (Xi and Peet 2011). These types of disturbance events have historically been an important component of the disturbance regime for forests along the Mid-Atlantic coast, with large-tree disturbances increasing from north to south (Vanderwel et al. 2013). The effects of wind disturbances can vary greatly, occurring at different spatial scales and causing different types of damage to individual trees or landscapes, including abrasion, leaf stripping, breakage of limbs and stems, and uprooting (Stanturf et al. 2007). The physical effects of a given wind event on forests may be influenced by many factors, such as storm severity, forest composition, stand age, soils, and topography (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). Although tornadoes are relatively infrequent, intense winds generated from hurricanes (>74 miles per hour [mph]), microbursts (>170 mph), and other storms can cause trees to uproot or break (Ulbrich et al. 2008, 2009). Hurricanes affecting the Atlantic coast can cause significant wind damage and blowdowns as far inland as western Maryland and West Virginia, where wind speeds can reach 50 mph (Boucher et al. 2005).

Some evidence indicates that severe convective storms (e.g., thunderstorms, hailstorms) or extreme wind events have increased in recent decades in the region (Bryan et al. 2015, Kunkel et al. 2013b).

There is also some evidence that 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 4).

If wind disturbances do increase as a result of climate change, forest ecosystem dynamics may also change. Catastrophic wind disturbances can alter successional pathways and have long-lasting effects on species composition and diversity (Xi and Peet 2011). 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). Blowdowns appear to 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 tulip tree (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). 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.

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 especially 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 actions, such as salvage logging, may also compound the severity of these events, creating novel regeneration environments.

Ice Storms

Ice storms are particularly prevalent in the eastern United States, and these storms can cause substantial damage to ecosystems and infrastructure (Changnon 2003a, 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 (Changnon 2003a).

In forests, the accumulation of ice on trees can cause 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 appear to be particularly susceptible to branch and stem breakage, whereas conical species such as spruce and hemlock 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 (>10 inches diameter) than in pole or sapling size classes (<10 inches diameter) (Turcotte et al. 2012). Residual trees can have reduced photosynthesis due to the loss of crown or decreased productivity as resources are used to close wounds or protect against pathogens. They 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).

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 differ 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 following wildfire if climatic conditions, seed sources, or management decisions favor different forest types.

The conditions responsible for wildfire behavior are the result of weather, topography, and fuels (Moritz et al. 2012). Climate change is expected to alter temperatures, precipitation, and evapotranspiration, thereby influencing future wildfire risk. If warmer temperature and greater evapotranspiration exceed 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 early spring and late fall, when vegetation holds less moisture and the drier conditions are more favorable for wildfire (Heilman et al. 2015). 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). For example, in the Mid-Atlantic coastal plain, drought and insect damage from gypsy moth and southern pine beetle have the potential to increase standing dead fuels (La Puma et al. 2013). Fire can also promote invasive species, which may increase the flammability of an area and thus the frequency, intensity, or length of the fire season (Brooks and Lusk 2008).

Many fire-dependent communities in the northeastern United States have few quantitative data describing historical fire regime attributes such as frequency, severity, and seasonality, or how these varied through time (Marschall et al. 2016). Furthermore, relatively few studies have modeled how climate change may 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). Several recent modeling efforts suggest that wildfire risk may increase moderately (10 to 20 percent) in the Mid-Atlantic region, with the largest increases projected in August (Guyette et al. 2014, Heilman et al. 2015, Tang et al. 2015). A study of wildfire activity in the Mid-Atlantic region suggests that many models may not capture the additional atmospheric moisture from coastal humidity and tropical storm activity, resulting in overestimation of wildfire probability (Clark et al. 2013). Forest composition changes, gap disturbances, understory fuels, and fire suppression are expected to limit wildfire occurrence and severity throughout the region (Clark et al. 2013). For example, fire suppression has contributed to a shift toward northern hardwood forests and more mesic conditions in eastern forests, and fire in these systems is relatively rare (Mohan et al. 2009).

In the fire-prone Mid-Atlantic coastal plain pine barrens, urban development and land-use change have necessitated increased fire suppression, which has contributed to a shift in forest composition away from pitch pine to a mixture of oak species, especially in the wildland-urban interface (La Puma et al. 2013). Landscape modeling of climate, fire, and land-use change in the southern New Jersey pinelands suggests that pitch pine-dominated forests may continue to shift toward oak dominance or a mixture of pine and oak in the absence of fire (La Puma et al. 2013). Fire management is expected to continue to influence vegetation and succession (Nowacki and Abrams 2008).

Intensified Stressors

Moisture Stress and Drought

There is evidence for an increased risk of future moisture stress and drought in the assessment area (see Chapter 4). Temperatures are expected to rise during the next century, and evapotranspiration in ecosystems is expected to increase as a result (Kunkel et al. 2013b, Nelson Institute Center for Climatic Research 2018, U.S. Global Change Research Project 2017). Moisture stress and drought can occur when increases in evapotranspiration are not offset by a corresponding increase in precipitation and soil moisture. Within the assessment area, the potential for moisture stress and more frequent droughts during the growing season appears to be much greater under the GFDL A1FI scenario and driven by much warmer temperatures (Chapter 4). However, under the milder PCM B1 scenario, warmer temperatures may also lead to increased evapotranspiration and physiological stress if increases in precipitation do not accompany temperature increases. 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, Peters et al. 2015). These increasingly episodic events may result in higher cumulative stress on tree species and may have the potential to initiate changes in forest composition (Peters et al. 2015).

The initial soil moisture regime and drought tolerance of any system determine the positive or negative outcomes of extreme precipitation events with longer intervals between events (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 often limited by anoxia rather than soil moisture, so longer intervals between precipitation events may lower the water table, allowing oxygen to reach the roots of aquatic plants and increasing biomass productivity. However, a study that subjected Atlantic white-cedar seedlings to drought found decreases in biomass and stem diameter, suggesting that these hydric species are vulnerable to extended drought (Steven and Gaddis 2017). Mesic systems (adapted to moderately moist conditions) would be the most affected by the increasing duration and severity of soil water stress because they are not well adapted to prolonged dry periods.

Moisture availability is a critical determinant for forests worldwide and within the Mid-Atlantic region, where drought has been linked to decline of oak and ash trees (Choat et al. 2012, Clark et al. 2016, Millers et al. 1989, Mohan et al. 2009, Pederson et al. 2014). Early-season moisture is critical 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, Pederson et al. 2014). Furthermore, drought-stressed trees are typically more vulnerable to insect pests and diseases (Dale et al. 2001, Millar and Stephenson 2015, Ryan and Vose 2012, Shifley et al. 2012).

Invasive Plant Species

Nonnative invasive species are a major threat to many forest communities across the eastern United States (Chapter 1). Many invasive species are able to establish rapidly after a disturbance, and are able to outcompete native vegetation for growing space, water, nutrients, and light (Brown and Peet 2003, Dukes et al. 2009). 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). Increases in carbon dioxide 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 on kudzu seedlings have indicated increased growth, increased competition with native species, and range expansion with carbon dioxide fertilization (Sasek and Strain 1990). Models have also projected that increased carbon dioxide emissions and subsequent warmer winter temperatures are likely to expand the northern ranges of ailanthus, bush honeysuckles, privet, and kudzu (Bradley et al. 2010, Clark et al. 2014).

Kudzu. This nonnative vine kills other plants by smothering them, girdling woody stems, and toppling trees with their weight. Photo by Greg Czarnecki, Pennsylvania Department of Conservation and Natural Resources, used with permission.

Further, as discussed throughout this chapter, many potential effects of climate change are expected to increase stress and disturbance within forest ecosystems, which certainly raises the potential for invasive species to exploit altered environments (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).

Some invasive species are tolerant of drought and fire, and may be at an even greater advantage under future climate conditions. Other species, such as garlic mustard and Japanese stiltgrass, are not particularly drought tolerant, but their persistent seedbanks enable them to recover in wetter years (Fryer 2011, Munger 2001). Other invasive species may contribute to increased disturbance regimes; for example, cogongrass has contributed to altered fire regimes in the southeastern United States and is expected to advance northward with warmer temperatures (Lippincott 2000). Once established, invasive plant species can also limit regeneration of native tree species through increased competition or allelopathic defenses (Gorchov and Trisel 2003). Invasive species such as ailanthus and bush honeysuckles may exude a toxin that discourages the growth of other plants and have been shown to impair forest productivity (Hartman and McCarthy 2007, Knapp and Canham 2000).

Insect Pests and Pathogens

The response of forest insect pests and pathogens to a warmer future will vary widely by modes of infection, transmission, winter effects on pest lifecycles, and tree response (Dukes et al. 2009, Régnière et al. 2012). Pests and pathogens are generally expected to become more damaging in forest ecosystems as the climate changes, because they may 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 potential climate change impacts highlight the potential for interactions involving other stressors that increase susceptibility to these agents (Sturrock et al. 2011, Trotter 2013, Weed et al. 2013).

Although few studies have examined the effects of climate change on specific forest insects, information from a few studies suggests an intensification of insect activity. Research on the hemlock woolly adelgid suggests that its range is generally limited by cold winter temperatures with mortality occurring at temperatures below -20 °F and that warmer winters may allow it to expand (Dukes et al. 2009, Paradis et al. 2008, Skinner et al. 2003). Similarly, warmer winters have contributed to a southern pine beetle epidemic in the New Jersey Pine Barrens that is expanding northward (Ungerer et al. 1999, Weed et al. 2013). The emerald ash borer, currently devastating populations of ash species, has been observed to produce more generations under warmer conditions (DeSantis et al. 2013, Venette and Abrahamson 2010, Wei et al. 2007).

Hemlock woolly adelgid on hemlock. Photo by Greg Czarnecki, Pennsylvania Department of Conservation and Natural Resources, used with permission.

Damage from other pest outbreaks, including those of native species (e.g., forest tent caterpillar and spruce budworm), can be more severe when trees are stressed by factors such as drought (Babin-Fenske and Anand 2011, Gray 2008, Manion 1981). The interacting effects of drought and increased pests and pathogens may result in increased risk of oak decline, which is largely driven by insect pests and pathogens predisposed to invasion in drought conditions (Clatterbuck and Kauffman 2006, McConnell and Balci 2013). The fungal pathogen *Armillaria* is already widespread, but could expand or become more abundant under warmer and drier conditions, and particularly in response to drought (Kliejunas 2011). There is also evidence that climate change may be detrimental to some pest species. For example, the early survival of gypsy moth larvae depends on the availability of leaves; thus, changes in phenology could result in starvation if the eggs hatch before budburst (Ward and Masters 2007).

Effects of Vertebrate Species

Herbivory, seed predation, and disturbance by vertebrates can be important stressors in the Mid-Atlantic region. Currently, little is known about how these factors could be affected by climate change. Deer overbrowsing and seed predation may reduce the overall success of species that are otherwise projected to do well under future climate change (Ibáñez et al. 2008). For example, white oak is projected to increase in the future, but the models mentioned earlier in this chapter do not account for the herbivory of young oak regeneration by deer. Deer herbivory may also favor species which are not preferred browse species, such as eastern hophornbeam and black cherry, or invasive species such as buckthorns or Japanese barberry. Currently,

White-tailed deer fawn after a thunderstorm. Photo by Greg Czarnecki, Pennsylvania Department of Conservation and Natural Resources, used with permission.

there is little evidence to indicate how deer and other vertebrate species may respond to climate change in the assessment area. An analysis of climate change impacts on white-tailed deer in Wisconsin suggests that deer in that area are likely to be subject to a mixture of positive impacts from milder winters coupled with negative impacts from increased disease outbreaks (Wisconsin Initiative on Climate Change Impacts 2011). How these two factors may influence deer populations in the Mid-Atlantic region remains unknown.

Changes in Forest Composition

Trees and other plant species have responded to past climate change in a number of ways. The ranges of tree species in eastern North America shifted in response to climate since the last ice age (Davis 1983), and tree species are expected to shift in response to 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). High rates of migration have even been observed for American basswood, bigtooth aspen, and northern red oak (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 the range (Murphy et al. 2010, Zhu et al. 2012). However, forest composition changes slowly due to the long-lived nature of trees, and climate change may not be the only factor influencing species migration (Fei et al. 2017).

The modeling results presented earlier in this chapter describe projected changes, negative and positive, in future tree species distribution. In general, trees that are near the species range boundary 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 more 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 have a decline in seed set or declines in successful germination or establishment, whereas others may suffer reduced growth or inability to reach maturity (Ibáñez et al. 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 reproduce (Ibáñez et al. 2008).

Ecosystem models indicate that trees currently near the northern limits of the tree species range may become more abundant and more widespread under a variety of climate futures. As discussed earlier in this chapter, it is possible that some species that are not currently common or even present in the Mid-Atlantic may migrate into the region, such as black hickory and longleaf pine. However, it is expected that species may not be able to migrate northward without substantially lagging behind changes in climate (Dobrowski et al. 2013, Iverson and McKenzie 2013, Iverson et al. 2004a, Renwick and Rocca 2015). The migration of new species is constrained by a number of factors, including seed dispersal dynamics and landscape fragmentation (Ibáñez et al. 2008, Scheller and Mladenoff 2008). Catastrophic natural disturbances, such as wildfire, could help colonizing species from the south establish if environmental conditions promote germination and vigor of establishing seedlings, but also have the potential to reduce the ability to maintain forest cover (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 migration (Duveneck and Scheller 2015, Iverson and McKenzie 2013, Pedlar et al. 2012). Management of forest ecosystems, including planting and harvesting, is also expected to influence changes in forest composition but is outside the scope of this assessment (Chapter 7).

Interactions

Although this chapter focused on the potential effects of climate change on forests, substantial interactions between climate change and other changes are also occurring within the Mid-Atlantic region. Climate change has the potential to alter an array of complex ecosystem processes, and the interactions among these impacts may be critically important in determining the resulting changes to forest ecosystems across the assessment area. Although many of these potential interactions are described in this chapter, many others are not. Examples of additional community interactions that could alter forest ecosystems are 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). In the Mid-Atlantic region, factors related to land use and management heavily influence how climate change may affect natural systems but are beyond the scope of this assessment (Larsen et al. 2012, 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. 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 facing multiple interacting stressors may reach thresholds that fundamentally change ecosystem character and function (Manion 1981, Millar and Stephenson 2015). Much of the literature to date on this subject focuses on global and national analyses, resulting in greater uncertainty at the regional scale (Allen et al. 2015, Anderegg et al. 2015, Millar and Stephenson 2015).

CHAPTER SUMMARY

Although models are useful for exploring potential future changes, all models are simplified representations of reality, and no model can fully consider the entire complexity of ecosystem processes, stressors, interactions, and future changes to forest ecosystems. The DISTRIB (Tree Atlas), LINKAGES, and LANDIS PRO models suggest that conditions for some species (e.g., balsam fir, black spruce, northern white-cedar, quaking aspen, and yellow birch) will become unfavorable by the end of the century under both climate scenarios. At the same time, all three models suggest that conditions for other species (e.g., loblolly pine and shagbark hickory) will become more favorable by the end of the century, especially under GFDL A1FI. Additionally, the Tree Atlas and LINKAGES tend to agree that many species will remain stable or increase under the relatively mild PCM B1 climate scenario and decrease under GFDL A1FI. These results support the idea that a future climate like GFDL A1FI is beyond the tolerance of some species in the Mid-Atlantic region, but also that many other species could tolerate the milder warming represented by PCM B1.

Several interacting factors that are not simulated by these three models could drive forest changes, especially in the short term. 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. All of these factors must be taken into account with the model results in evaluations of the vulnerability of Mid-Atlantic forests to climate change. The vulnerability of forest ecosystems is described in Chapter 6.

CHAPTER 6: FOREST ECOSYSTEM VULNERABILITIES

Climate change is expected to drive significant changes in species composition and ecosystem processes (Ryan and Vose 2012). In addition, climate change can alter fundamental ecosystem drivers and exacerbate or ameliorate current stressors, such as insect populations or wildfire risk (Joyce et al. 2014, Rustad et al. 2012, Ryan and Vose 2012, Vose et al. 2016). This chapter is organized into two sections. In the first section, we present an overall synthesis of climate change vulnerability of the Mid-Atlantic region, organized according to drivers and stressors, ecosystem impacts, and factors that influence adaptive capacity. This synthesis is based on the current scientific consensus of published literature (Chapters 4 and 5) and regional expertise. In the second section, we present individual vulnerability determinations for 11 forest communities considered in this assessment; these determinations were developed through an expert elicitation process (Brandt et al. 2017) (described in Appendix 5).

Vulnerability is the susceptibility of a forest ecosystem to the adverse effects of climate change (Glick et al. 2011, Intergovernmental Panel on Climate Change [IPCC] 2014). It is a function of the potential climate change impacts and the adaptive capacity of the ecosystem (Fig. 36). 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 2007). It is strongly related to the concept of ecological resilience, which refers to the ability to return to prior conditions after a disturbance (Holling 1973, Stein et al. 2014). In this assessment, we consider a forest ecosystem to be vulnerable if it is at risk of a shift in composition that leads to a substantially different character for the forest, or if the forest is anticipated to suffer substantial declines in extent, health, or productivity. Although economic and social values can affect the way a forest ecosystem 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 communities 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 communities, allow them to shift toward an alternate state, direct their transition, or do nothing—will depend on the individual objectives and actions of private landowners, land management agencies, and their stakeholders.

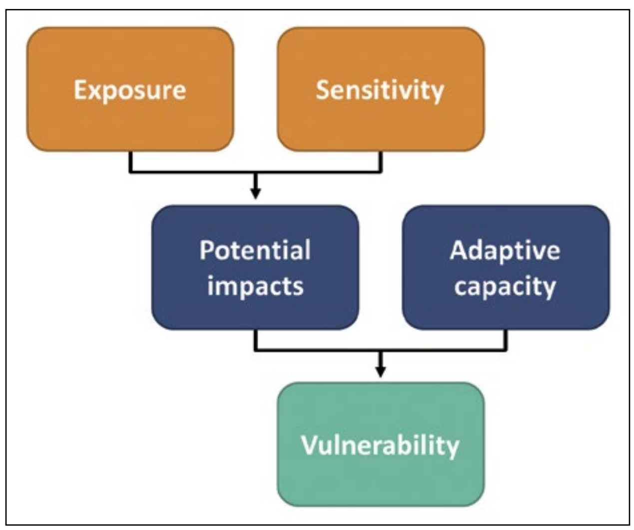


Figure 36.—Key components of vulnerability, illustrating the relationship among exposure, sensitivity, and adaptive capacity. Adapted from Glick et al. (2011).

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 level of agreement among information (Fig. 37). "Evidence" refers to the body of information available based on theory, data, models, expert judgment, and other sources. It was considered robust when multiple observations or models, as well as an established theoretical understanding to support a statement, were available. "Agreement" refers to the degree of consistent independent lines of high-quality evidence. If theories, observations, and models tended to suggest similar outcomes, then agreement was considered to be high. Agreement does not refer to the level of agreement among the authors of this assessment (more information on the process for determining confidence is found in Appendix 5).

Synthesis of Climate Change Impacts on Forest Ecosystems

Climate change is expected to cause wide-ranging direct and indirect impacts on forest 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 forest ecosystem if the changes result in improved health or productivity, a greater area occupied by the system, or a tendency to maintain the current characteristics of the forest. 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 species 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 Mid-Atlantic region through the end of this century. This synthesis is based on the current scientific knowledge in published literature and described in more detail in the preceding chapters.

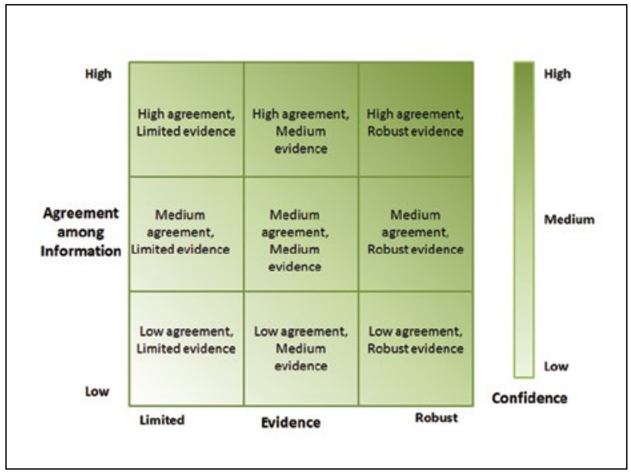


Figure 37.—Confidence determination matrix used in the assessment. Adapted from Mastrandrea et al. (2010).

Potential Impacts on Drivers and Stressors

Many physical, chemical, and biological factors contribute to the current state of forest ecosystems in the Mid-Atlantic region. These factors include drivers (the most fundamental forces that shape a particular ecosystem) and stressors (agents that can reduce forest health or productivity or impair ecosystem functions). Some factors, such as forest insects, may be drivers in one situation and stressors in another; for example, the effect of southern pine beetle on pitch pine or shortleaf pine may start out as a stressor but may eventually be a driver after it becomes a long-term agent of forest change. Other examples include the effects of chestnut blight, beech bark disease, and Dutch elm disease on unique forest communities. Similarly, some disturbances such as flooding or fire act as a driver in certain communities, but can also increase stress on communities 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

(Chapters 3 and 4). Temperatures across the Mid-Atlantic region have already exhibited substantial increases (Chapter 3). Continued temperature increases are projected for the Mid-Atlantic region even under the most conservative future climate scenarios (Chapter 4).

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

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 the 21st century (Chapters 3 and 4). Longer growing seasons have the potential to affect the timing and duration of ecosystem and physiological processes across the region (Dragoni and Rahman 2012, Elmore et al. 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, Richardson et al. 2006, Rollinson and Kaye 2012). Longer growing seasons may also result in greater growth and productivity of trees and other vegetation, but only if balanced by available water and nutrients (Chapter 5) (Keenan et al. 2014). Unfortunately, some nonnative invasive species can also be more adept at responding to temperature variation than many native plants and may become more competitive (Willis et al. 2010).

The amount and timing of precipitation will change (robust evidence, high agreement). *There is strong agreement that precipitation patterns will change across the Mid-Atlantic region.*

Among the climate projections used in this assessment (Chapter 4) and other publications, projected changes in precipitation are highly variable in magnitude and spatial distribution, more so than for temperatures (Kunkel et al. 2013a, Lynch et al. 2016, Nelson Institute Center for Climatic Research 2018). Although individual model projections for the Mid-Atlantic region differ seasonally, there is general agreement that total annual precipitation will increase during the 21st century, largely due to more intense precipitation events (Ning et al. 2015). Seasonally, total precipitation is projected to increase for the winter and spring seasons, whereas summer and fall precipitation projections range from slight increases to substantial decreases, depending on the climate scenario (Chapter 4).

Intense precipitation events will continue to become more frequent (robust evidence, high agreement). *There is strong agreement among climate models that the number of heavy precipitation events will continue to increase in the Mid-Atlantic region. If they do increase, impacts from flooding and soil erosion may become more damaging.*

Since the middle of the 20th century, heavy precipitation events have increased in number and severity in the Northeast, more so than in other regions of the United States (Horton et al. 2014, Walsh et al. 2014), and many models agree that this trend will continue during the next century (Nelson Institute Center for Climatic Research 2018, Walsh et al. 2014). Most heavy precipitation events in the Mid-Atlantic region 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 water vapor retention 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 may ultimately depend on local site conditions, current infrastructure, and land use, as well as future decisions about infrastructure and land use.

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.*

There is strong evidence that global sea levels have risen during the past century, and that they will continue to rise at an increased rate through the 21st century (Bindoff et al. 2007, Kopp et al. 2014). Evidence attributes sea-level rise to the thermal expansion of ocean waters as water warms, and the melting of land ice flowing into the ocean (Bindoff et al. 2007, Church et al. 2008). Observations from tidal gauges have shown that sea levels have risen faster along the coastline of the Mid-Atlantic region (New York to Virginia) than the global average, about 1 foot during the 20th century (Buonaiuto et al. 2010, Williams et al. 2009). Sea levels in the Mid-Atlantic region may rise another 3 feet during the 21st century, with the higher estimate expected on the coastal plain (Chapter 4) (Miller et al. 2013). Coastal forests and ecosystems will be further threatened by inundation, more frequent coastal erosion, flooding, and saltwater intrusion (Anderson et al. 2013a, Conner and Askew 1992, Kane et al. 2015). Additionally, severe storms are more destructive under higher sea levels, causing increased damage from storm surges and flooding (Buonaiuto et al. 2010, Sallenger et al. 2012).

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

Soil moisture is expected to change in response to warmer temperatures and seasonal changes in precipitation, although uncertainty remains regarding the amount and timing of precipitation (Hay et al. 2011, Lynch et al. 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 (Dai et al. 2004, Liu et al. 2013, Peters et al. 2015). Wetter conditions may become more frequent during winter and spring; 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 (Clark et al. 2016). Locations where soils and landforms cannot retain the water from intense precipitation events may be more prone to drier conditions during the growing season.

Forest vegetation may face increased risk of physiological drought during the growing season (medium evidence, medium agreement). *Warmer temperatures can lead to decreased soil moisture even without an associated decrease in precipitation, resulting in a temporary inability for a tree to meet water demand.*

Meteorological droughts (relatively prolonged moisture deficits) are not expected to change much during the 21st century, although predictions of drought are complicated by uncertainty in the timing, duration, and extent of future precipitation patterns (Allen et al. 2015, Trenberth 2011). Short-term moisture deficits are more likely and are expected to result in physiological drought and moisture stress for plants (Vose et al. 2016). Warmer temperatures can result in decreased soil moisture even without an associated decrease in precipitation, resulting in a temporary inability for a tree to meet water demand. Forests that are affected by moisture deficits and drought are more likely to have reduced tree vigor and increased mortality, both of which can affect forest composition and structure (Peters et al. 2015, Vose et al. 2016). Further, extremely hot days can drive or enhance 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).

Climate conditions will increase wildfire risk by the end of the century (medium evidence, medium agreement). *Some national and global studies suggest that conditions favorable for wildfire will increase, but few studies have specifically looked at wildfire risk in the Mid-Atlantic region. Wildfire risk will also depend on ignition, fire weather, ecosystem type, topography, fragmentation, and other regional characteristics.*

Although there is greater uncertainty around future fire behavior for the near term, model simulations tend to agree that there will be global increases in fire activity by the end of the 21st century (Guyette et al. 2014, Moritz et al. 2012). The duration of the fire season in the Mid-Atlantic region is closely linked with increases in average temperature during the summer (Liu et al. 2010). Interactions between complex patterns of land use and ownership, forest fragmentation, and both human and natural ignition sources, may ultimately determine how an increase in fire weather conditions might be manifested (Clark et al. 2013). In addition to the direct effects of temperature and precipitation, increases in fuel loads from pest-induced mortality, exotic species invasion, or blowdown events could also increase fire risk (Lovett et al. 2006). Forest fragmentation and future wildfire management decisions may limit the number, extent, or severity of individual fires even as fire risk increases.

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

A warming climate is expected to allow some pests and pathogens to become a greater threat (Chapter 5). Evidence is mounting that the warming climate can increase the susceptibility of trees to native and nonnative pests and pathogens (Paradis et al. 2008, Trân et al. 2007). Forest pests and pathogens are generally able to respond rapidly to changes in climate, and species may use different strategies to cope with change, including increasing the number of generations per year, shifting distributions, and expanding into new ecosystem types (Weed et al. 2013). The loss of a consistently cold climate and short growing season is already allowing some insect pests and pathogens, such as hemlock woolly adelgid and southern pine beetle, to expand their ranges northward (Chapter 5). Forest impacts from insect pests and pathogens are generally more severe in communities that are

Symptoms of emerald ash borer at Memorial Lake, Pennsylvania. Photo by Greg Czarnecki, Pennsylvania Department of Conservation and Natural Resources, used with permission.

stressed by drought and other stressors (Bentz et al. 2010, Sturrock et al. 2011). 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 (Weed et al. 2013). Further, due to the numerous anthropogenic and natural mechanisms of transport, we can expect the arrival of new pests and pathogens during the 21st century (Liebhold et al. 2013).

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 (Sorte et al. 2013). Native forest communities in the eastern United States compete with many species of invasive trees, shrubs, vines, herbs, and grasses, in part due to deer herbivory and human land use (Oswalt et al. 2015). Increases in carbon dioxide can enhance growth for many plant species, including some of the most invasive weeds in the United States (Ziska 2003). Milder winters may have allowed some invasive plant species, including bush honeysuckles, privet, and kudzu, to expand their ranges northward (Bradley et al. 2010). Other invasive plants have shown phenological shifts, such as earlier flowering in response to warmer temperatures and longer growing seasons (Ziska et al. 2011). Some invasive species, such as ailanthus and princess tree, are tolerant of fire; these and other drought- or fire-tolerant species may be very competitive under future climate conditions (Rebbeck 2012). Future increases in fire or flooding are likely to benefit many 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 future nonnative plant species that may enter the assessment area during the 21st century.

Potential Impacts of Climate Change on Forest Communities

Shifts in drivers and stressors just mentioned are expected to lead to shifts in suitable habitat for some dominant species and changes in species composition or function of forest communities in the Mid-Atlantic region.

Northern and remnant boreal tree species will face increasing stress from climate change (medium evidence, high agreement). *Ecosystem models agree that these species may have reduced suitable habitat and declines in biomass across the Mid-Atlantic region. These species may be less able than temperate forest species to take advantage of longer growing seasons and warmer temperatures.*

Across northern latitudes, past periods of warmer temperatures have driven species migration northward and to higher elevations (Chen et al. 2011, Parmesan and Hanley 2015), resulting in now disjunct populations of red spruce and balsam fir at high elevations (Abrams et al. 2001). Across the eastern United States, increasingly warmer temperatures are expected to become less favorable to trees near the southern (warmer) extent of the species' range (Iverson et al. 2008a, Mohan et al. 2009, Reich et al. 2015, Rustad et al. 2012). Results from climate impact models projected a decline in suitable habitat and landscape-level biomass for remnant boreal species such as black spruce, red spruce, and northern white-cedar (Iverson et al. 2016). In the absence of other mortality agents, long-lived individuals already established in cool, wet microhabitats may persist through a typical lifespan, even when habitat becomes unsuitable for regeneration (Iverson and Prasad 1998). Near the southern edge of their range, other northern species such as sugar maple and northern red oak may also be able to persist, but these trees are expected to have greater competition from southern species, suffer greater stress than individuals in cooler northern locations, and display reduced vigor (Iverson et al. 2008b).

Habitat will become more suitable for southern species (medium evidence, high agreement). *All three forest impact models project an increase in suitability and growth for southern species such as loblolly pine and shagbark hickory compared to current climate conditions.*

Model results suggest that tree species currently near their northern range limits in the Mid-Atlantic region may become more abundant and more widespread under a range of climate futures (Chapter 5). Species that are currently present in the Mid-Atlantic region and projected to gain suitable habitat include loblolly pine and shagbark hickory (Chapter 5). Some species, however, may be limited in their ability to move into new habitats by their need for specific soil or site conditions (Ibáñez et al. 2006). Habitat fragmentation or natural barriers may also hinder the northward movement of southern tree species, despite increases in habitat suitability (Clark et al. 2016, Ibáñez et al. 2008). Although tree species are expected to differ in response to climate change, most species can be expected to migrate more slowly than suitable habitats can shift on the landscape (Iverson et al. 2004a, 2004b, 2016; Woodall et al. 2009). Pests and diseases such as emerald ash borer, Asian longhorned beetle, and oak decline are also expected to limit attainment of modeled increases in habitat or biomass for some species (Iverson et al. 2016).

Forest composition will change across the landscape (medium evidence, high agreement). *Forest impact model results predict that habitat and biomass of individual tree species will change, and that tree species will respond uniquely. However, few studies have specifically examined how assemblages of species may change.*

Paleoecological studies have provided evidence of how species have responded individually to climate change over periods spanning thousands of years (Davis et al. 2005, Root et al. 2003, Webb and Bartlein 1992). Future climate change is likewise expected to affect tree species differently and drive the rearrangement of habitat for some tree species in the Mid-Atlantic region. The model results presented in Chapter 5 raise the possibility of changes in tree species distribution, particularly as climate trends generally favor southern species across the Mid-Atlantic region by the end of the century (Iverson et al. 2008a, Lenihan et al. 2008). However, some tree species may be tied to particular soils or landscape positions or be less able to expand ranges northward into new areas at a pace commensurate with changes in climate (Ibáñez et al. 2006, Woodall et al. 2009). Because mature trees are more tolerant of warming and recruitment of new species is expected to be limited, major climate-driven shifts in species composition are not expected before the mid-21st century (Wang et al. 2017). However, increases in the intensity, scope, or frequency of stand-replacing events such as windstorms, ice storms, and insect outbreaks may promote rapid shifts in species composition where these events occur (Duveneck et al. 2014, Millar and Stephenson 2015, Thompson et al. 2013). Invasive plant species may become a larger component of forest ecosystems as populations expand on the landscape, especially where native species are relatively limited in mobility following disturbances (Hellmann et al. 2008).

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; they are also expected to be more responsive to favorable conditions.*

Temperature and moisture requirements for seed dormancy and germination at the forest floor are often much more critical than habitat requirements of an adult tree (Fisichelli et al. 2013, Kitajima and

Fenner 2000). Projected changes in temperature, precipitation, growing season onset, and soil moisture may alter the duration or manifestation of germination conditions, with severity of impacts varying among individuals and species (Fisichelli et al. 2014a). For example, regeneration failure in balsam fir populations has been attributed, at least partly, to climate change (Abrams et al. 2001). Warmer winters may promote the establishment of more southerly species, although warmer temperatures alone are unlikely to drive their establishment (Abrams 2003). For species with high dispersal capabilities, climate change may result in a redistribution of species on the landscape when seeds germinate on sites where suitable conditions are met (Walck et al. 2011). Other species may fail to regenerate under altered future climate conditions, or may germinate under suboptimal conditions and then fail to survive. Climate affects species establishment following disturbance due to the sensitivity of regeneration to climate variability (Jackson et al. 2009). After establishment, saplings are still more sensitive than mature trees to disturbances such as drought, heat stress, fire, flooding, and herbivory (Fisichelli et al. 2012, Kitajima and Fenner 2000). Changes in tree regeneration and recruitment are expected to 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 Mid-Atlantic region, but they disagree on how other factors such as species composition, stand age, disturbance, or pollution may interact to influence productivity. Changes are not expected to be consistent within a species, and the diversity of forest conditions across the landscape suggests that changes will be spatially variable.*

Northern forests are currently a carbon sink (Williams et al. 2012), and growth of secondary forests, most of which are between 40 and 100 years old, is generally expected to continue or increase during the next several decades in the absence of major disturbances (Chapter 5) (Shifley et al. 2012). LANDIS PRO model results indicate increased growth for many species during the next few decades even under current climate conditions (Chapter 5). Oak-hickory forests are expected to benefit more from warmer temperatures than pines, northern hardwoods, and spruce-fir forests (Pan et al. 2009). 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, Pan et al. 2009). Many studies also point to the beneficial effects of carbon dioxide fertilization on forest productivity, 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). Changes in forest productivity are likely to be spatially variable due to the spatial heterogeneity of site conditions (Loehle et al. 2016). Increasing stressors, such as increased salinity from sea-level rise, fires, windstorms, and pest outbreaks, and changes in land use could substantially reduce forest productivity. Such disturbances have only recently been incorporated into simulation models and together constitute a significant caveat to expectations of continued productivity (Loehle et al. 2016, Scheller et al. 2012).

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 2007). The focus of adaptive capacity is on the ability to adapt to climate-related stimuli (IPCC 2007) without transitioning to a different state. We next summarize factors that could reduce or increase the adaptive capacity of Mid-Atlantic forest communities.

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

In general, forest communities that support diversity exhibit greater resilience to extreme environmental conditions and have greater potential to recover from disturbance than less diverse communities (Forrester and Bauhus 2016, Isbell et al. 2015). This suggests that communities with few species or low diversity are inherently more susceptible to future changes and stressors than those with high diversity (Forrester and Bauhus 2016). Within a community, the range of potential responses of a system to environmental change is a critical component of 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, whereas 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).

Most 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 most 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 migrate to more suitable habitat on the landscape. The degree of dispersal limitation may be influenced by the level of fragmentation (relatively high in the Mid-Atlantic region), land cover and use, and the dispersal characteristics of individual species (Ibáñez et al. 2008, 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 of seedling distributions, it has been estimated that many northern tree species could possibly migrate northward at a rate of 60 miles per century (Woodall et al. 2009), but other evidence indicates that natural migration rates could be far slower for other species (McLachlan et al. 2005, Murphy et al. 2010). Fragmentation creates additional challenges by making the landscape less permeable to migration (Jump and Peñuelas 2005, Jump et al. 2009, McGuire et al. 2016). The potential for humans to remove migration barriers or facilitate the migration of species to newly suitable areas (Pedlar et al. 2012) reflects adaptation actions that are beyond the scope of this vulnerability 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 may be impossible for tree species and forest communities with narrow habitat requirements.*

Several species and forest types in the Mid-Atlantic region are confined to certain habitats on the landscape, whether through particular requirements for temperature, hydrologic regimes, or soil types, or other reasons (Abrams et al. 2001, Manomet Center for Conservation Sciences and National Wildlife Federation 2014). Like species occurring only in fragmented landscapes, isolated species and ecosystems face additional barriers to migration (McGuire et al. 2016). For example, species restricted to riparian forests are not expected to migrate to upland areas because they depend on seasonal flood dynamics for regeneration and a competitive advantage. Similarly, Atlantic white-cedar swamps rely on a humid, maritime climate in a narrow coastal belt (Burns and Honkala 1990). These systems face greater challenges in migration than more widespread species with broad ecological tolerances. Conversely, some species that are widespread and have broad habitat requirements are expected to more easily find new habitat on the landscape.

Forest communities that have high tolerance to disturbance will be at lower risk of decline from shifting climate extremes (medium evidence, high agreement). *Basic ecological theory and other evidence suggest that communities adapted to disturbance will be at lower risk of declining on the landscape. However, some communities may tolerate only a narrow range of conditions related to a disturbance and may be susceptible to different, or more frequent and severe, disturbances.*

Disturbances such as extreme heat, drought, wildfire, flooding, and pest outbreaks are expected to increase in the Mid-Atlantic region (Chapters 4 and 5). Each disturbance affects a community in a different way, and some communities have become composed of disturbance-tolerant species (Côté and Darling 2010). Forest systems that are more tolerant of drought, flooding, or fire may be better able to withstand future changes in climate-driven disturbances (Thompson et al. 2009). For example, species in floodplain and wetland habitats have developed the capacity to exist in a wet phase or a dry phase in response to fluctuating water levels, temperature, and oxygen content; these systems repeatedly develop characteristic vegetation and return to a fully functioning system following both floods and droughts (Colloff and Baldwin 2010). Glades and barrens have become resilient to extreme weather conditions, fire, drought, and defoliation. This principle is limited, however, because it is also possible for disturbance-adapted systems to experience novel disturbances, or interacting disturbances that result in too much disruption (Dale et al. 2001). For example, pitch pine systems could cover a greater extent under drier conditions with more frequent fire, but these systems also could convert to shrubland or savanna if fire becomes too frequent or drought becomes too severe.

Vulnerability Determinations for Individual Forest Communities

Climate-induced shifts in drivers, stressors, and dominant tree species are expected to have different impacts on forest communities within the assessment area. Some forest 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 communities.

We assessed the vulnerability of 11 forest communities (described in Chapter 1) to climate change impacts. We assembled two expert panels to assess forest types in the Mid-Atlantic coastal plain and interior (Fig. 38), drawing upon scientists and managers from a variety of organizations and disciplines across the Mid-Atlantic region (Appendix 5). The 26 panelists considered the information from the previous chapters, evaluated the projected changes in climate and tree responses (Chapters 3 through 5), and used their expertise to interpret the information. For each forest community, panelists considered the potential impacts and adaptive capacity in order to assign a vulnerability determination and a level of confidence in that determination using the confidence scale described earlier in this chapter (Brandt et al. 2017). A complete description of the methods used to determine vulnerability can be found in Appendix 5.

The forest communities were assessed as having different levels of vulnerability, which ranged from low to high based on the interaction between potential impacts and adaptive capacity (Table 26). Ratings of evidence for the vulnerability determinations were medium or medium-robust partly because important interactions expected among dominant tree species and potential stressors were generally unknown. The ratings of agreement among information sources also tended to be medium or medium-high. The level of agreement was limited primarily because of uncertainty about future precipitation patterns.

In the following sections, 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 Mid-Atlantic region. In addition, we summarize the main factors contributing to the adaptive capacity of each system. Importantly, these determinations were developed for forest communities for the entire Mid-Atlantic region.

At a local scale, forest communities vary due to differences in elevation, climate, landform, soils, disturbance, past management, and numerous other factors; thus, the vulnerability in a particular location is likely to 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.

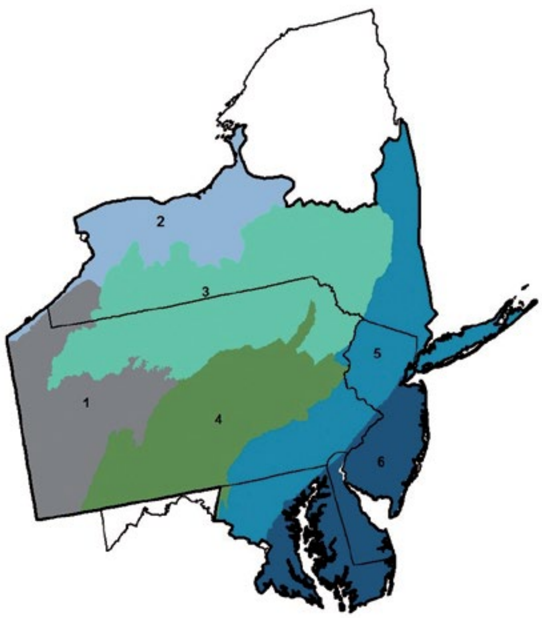


Figure 38.—Subregions of the Mid-Atlantic region. Forest types were assessed by two separate teams in order to consider differences in climate and responses to climate change in the coastal plain and interior regions. Source: McNab et al. (2007).

Table 26.—Summary of vulnerability determination for the forest communities considered in this assessment evaluated through the end of the 21st century

Forest community	Potential impacts	Adaptive capacity	Vulnerability	Evidence	Agreement
Coastal Plain					
Maritime forest	Negative	Moderate-Low	High	Medium-Robust	Medium-High
Oak-pine-hardwood	Moderate-Positive	High	Moderate-Low	Medium	Medium-High
Pine-oak barrens	Moderate	Moderate	Moderate-Low	Medium-Robust	Medium-High
Swamp	Moderate	Moderate-High	Moderate-Low	Medium	Medium
Tidal swamp	Moderate-Negative	Moderate-Low	Moderate-High	Medium	Medium-High
Interior					
Central oak-pine	Moderate-Positive	Moderate-High	Moderate-Low	Medium	Medium-High
Lowland conifer	Negative	Moderate-Low	High	Medium	Medium
Lowland and riparian hardwood	Moderate	Moderate	Moderate	Medium-Limited	Medium
Montane spruce-fir	Negative	Low	High	Medium-Robust	High
Northern hardwood	Moderate-Negative	Moderate	Moderate-High	Medium-Robust	Medium-High
Woodland, glade, and barrens	Positive	Moderate-High	Low	Medium	Medium-High

Rimrock Overlook above Kinzua Bay in the Allegheny Reservoir, Allegheny National Forest, Pennsylvania. Photo by Kathleen Creek, Allegheny National Forest.

Maritime Forest (Coastal Plain)

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

The proximity of this forest community to ocean coasts means that changes in coastal dynamics, such as sea level and storm surges, are greater drivers than changes in temperature and precipitation. Sea level and exposure to saltwater and disturbance are expected to drive changes in species composition.

Negative Potential Impacts

Drivers: This forest community represents a small percentage of forest cover in the Mid-Atlantic region, and exists only on barrier islands or in narrow bands close to the bays, estuaries, islands, and coastal zones of the Atlantic Ocean. Maritime forests are typically subjected to various impacts, depending on landscape position and exposure to salt spray, sea-level rise, and erosion. Prolonged inundation with saltwater may cause stress or mortality of trees, depending on the tolerance of individual species to salt and inundation. Shifting sands may alter soil characteristics, destabilize root systems, and cause erosion. Rising sea levels are increasing storm surge and flooding, both of which may be even more problematic if storms become more frequent or severe.

Dominant Species: Forest impact model results for the Coastal Plain subregion were used for this forest community. Forest impact models projected increases under both climate scenarios for shortleaf pine, loblolly pine, post oak, red maple, and pitch pine. Models projected decreases under both scenarios for black cherry, scarlet oak, and Virginia pine and under the high emissions scenario only for American holly, black oak, red maple, and sassafras.

Stressors: Maritime forest habitat and species are threatened by many stressors, including development, damage from off-road vehicles, nutrient and contaminant runoff and sedimentation, and continued sea-level rise and increasing coastal surge. These communities occur in dynamic coastal environments and are often converted to other community types through natural disturbances. Increases in extreme weather events, including convective and tropical storms and hurricanes, could disrupt soil structure, remove soil layers, increase exposure to contaminants, or increase salinity in the system even without added precipitation.

Moderate-Low Adaptive Capacity

This forest community is restricted to the fringes of the Atlantic coast and is already highly fragmented due to land development. Maritime forest is presumed to be the sparser, more extreme version of the oak-pine-hardwood forest existing inland, which could serve as seed sources for replenishing maritime forest after disturbance (Bellis 1995). Fire suppression is also leading to successional changes in many of these sites. Salt tolerance is expected to influence how species respond to the changing environment, but this factor was not included in modeled scenarios. Salt-tolerant species include pitch pine, red oak, white oak, black cherry, and eastern redcedar, and forests containing these species may be better able to tolerate future changes. Hickories, sweetgum, and maples are less tolerant and generally increase in relative abundance with increasing distance from the beach.

Maritime dunes at Fort Tilden in Gateway National Recreation Area, New Jersey. Photo by Gregory J. Edinger, New York Natural Heritage Program, used with permission.

Maritime redcedar forest at Sandy Hook, New Jersey, in Gateway National Recreation Area. Photo by Gregory J. Edinger, New York Natural Heritage Program, used with permission.

Successional maritime forest on Fishers Island, New York. Photo by Gregory J. Edinger, New York Natural Heritage Program, used with permission.

Oak-Pine-Hardwood (Coastal Plain)

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

This forest community is expected to benefit from changes in climate, though severe drought or fire may kill trees or change community structure. With increased frequency of drought and wildfire, pine species may become dominant.

Moderate-Positive Potential Impacts

Drivers: This community type often occupies dry sandy areas conducive to periodic fire and dominated by oak. It can also occupy moist sites on lower slopes and along rivers and streams; these sites afford natural protection from fire and favor mesic hardwood species. Moisture stress, especially during hot periods, may reduce regeneration potential and seedling establishment. Drought may also stress mature trees, leading to mortality of mesic species and shifting the species composition to oaks and pines. Increased frequency of drought and wildfire, particularly on hotter or drier sites, may favor pine species.

Dominant Species: Forest impact model results for the Coastal Plain subregion were used for this forest community. This forest community contains many species projected to increase under both climate scenarios, including shortleaf pine, southern red oak, water oak, shagbark hickory, bitternut hickory, willow oak, post oak, loblolly pine, and pitch pine. New habitat is projected under both scenarios for chinkapin oak and under the high emissions scenario for Shumard oak. Habitat decreases are projected under both scenarios for chestnut oak, Virginia pine, and bigtooth aspen. Under GFDL A1FI, bigtooth aspen is projected to lose all suitable habitat in the coastal plain by the end of the 21st century. Sugar maple is projected to gain some new suitable habitat under the low emissions scenario, and lose suitable habitat under the high emissions scenario.

Stressors: Historical logging and land development have led to habitat fragmentation in this forest community. Herbivory, particularly from deer, is currently suppressing oak regeneration and seedling establishment, and deer pressure is not expected to change substantially. Forest pests and pathogens including gypsy moth, southern pine beetle, chestnut blight, and pine looper are expected to benefit from warmer and drier conditions. Invasive shrubs may find opportunities to dominate if canopy trees become stressed; ailanthus, princess tree, autumn olive, bush honeysuckles, and multiflora rose can benefit from disturbance. Invasive vines, such as kudzu, wisteria, Japanese honeysuckle, and winter creeper, are expected to spread under a range of future climates, though increased fire frequency may help control invasive species.

High Adaptive Capacity

This forest community is relatively diverse in terms of species and ecosystem functions. It thrives across a variety of soil moisture conditions and is expected to find microhabitats and refugia in order to persist in some form on the landscape. Drought- and heat-tolerant species may become more dominant in warmer, drier conditions. The occurrence of fire is expected to strongly influence whether oak or pine species are dominant in the future, with fire likely to favor pine species, particularly in drier sites. At the same time, land development, fragmentation, and fire suppression may reduce the potential for wildfire over a large scale, which could reduce the ability of pine to increase.

Coastal oak-beech forest on Fishers Island, New York. Photo by Gregory J. Edinger, New York Natural Heritage Program, used with permission.

Coastal oak-white pine forest near Northwest Creek on Long Island, New York. Photo by David M. Hunt, New York Natural Heritage Program, used with permission.

American holly, a characteristic tree of coastal oak-holly forests and maritime holly forests in New York. Photo by Julie A. Lundgren, New York Natural Heritage Program, used with permission.

Pine-Oak Barrens (Coastal Plain)

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

This forest community is tolerant of fire, drought, and disturbance, and the future fire regime is a primary factor that will determine species composition. Moisture deficits are becoming more common and can kill young regeneration and mature trees. This system has low species diversity, and the loss of pitch pine to any stressor or combination of stressors would jeopardize the identity of this forest community.

Moderate Potential Impacts

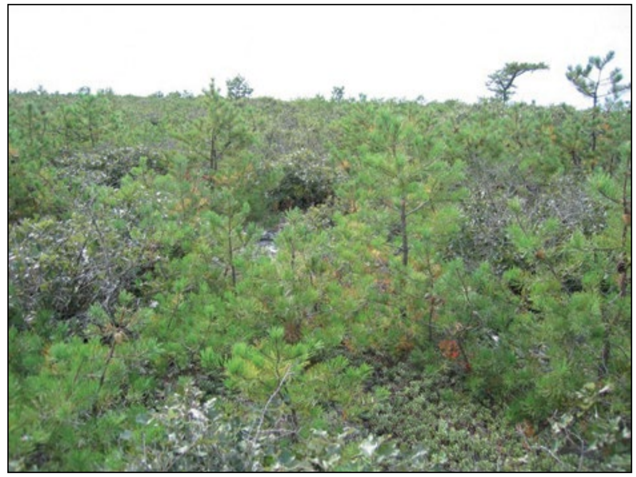
Drivers: Fire is a major driver of species composition and dominance in pine barrens; short fire return intervals tend to favor pitch pine, while longer fire return intervals favor oak species. Very frequent fire (return interval of 8 to 10 years) favors dwarf pitch pine, which reaches a maximum height of 3 to 10 feet. Windstorms resulting in blowdowns can accelerate succession to oak forests in the absence of fire. Heavy precipitation drains quickly due to sandy soils, and longer dry periods between events could increase the risk of moisture stress, which can be lethal to young regeneration of pitch pine and oaks.

Dominant Species: Forest impact model results for the Coastal Plain subregion were used for this forest community. Pitch pine, blackjack oak, and post oak are the dominant species and are projected to increase under both climate scenarios. Common associates including black oak and white oak are projected to decrease only under the high emissions scenario. Chestnut oak and scarlet oak are projected to decrease under both scenarios.

Stressors: Warmer winter temperatures contribute to the northward expansion of southern pine beetles, which can result in greater than 90 percent mortality of overstory pines in infested stands (New Jersey Department of Environmental Protection n.d., Weed et al. 2013). Invasive species in this community include barren bromegrass, cheat grass, Japanese bromegrass, spotted knapweed, Japanese honeysuckle, and garlic-mustard.

Moderate Adaptive Capacity

This forest community currently occupies one-tenth of its original extent, largely due to development (Clark et al. 2015). Fire suppression has contributed to the decline of pitch pine and the increase of oak in some areas. In fire-prone areas, trees have characteristics adapted to frequent fire, including thick bark and serotinous cones, which need fire to release the seeds. Pitch pine and scrub oak can resprout, increasing their ability to survive when fires are too frequent to permit seed regeneration. Deep roots are considered to contribute to drought tolerance and fire tolerance, although very hot droughts or very hot fires can damage roots and prevent resprouting. Adjacent oak-pine-hardwood forests serve as potential seed sources for pine-oak barrens, while the sandy, droughty soils discourage encroachment of mesic hardwood trees and associated understory communities. Although pitch pine is expected to overcome many future stressors, it is a keystone species and the loss of pitch pine to any stressor or combination of stressors would jeopardize the identity of this low-diversity forest community.



Dwarf pine plains in the Central Long Island Pine Barrens, New York. Photo by Gregory J. Edinger, New York Natural Heritage Program, used with permission.

Pitch pine cones. Photo by Stephen M. Young, New York Natural Heritage Program, used with permission.

Pitch pine-oak forest near Manorville Hills in the Central Long Island Pine Barrens, New York. Photo by Gregory J. Edinger, New York Natural Heritage Program, used with permission.

Swamp (Coastal Plain)

Moderate-Low Vulnerability (medium evidence, medium agreement)

As temperatures continue to rise, more locations may experience moisture deficits, reducing tree growth and increasing the risk of tree mortality. The hydrology of these areas may allow some changes in the position or size of swamps without complete loss of the system, though existing infrastructure and development may restrict movement.

Moderate Potential Impacts

Drivers: Although surface water within the swamps is largely derived from groundwater, precipitation can lower or raise standing water levels. Warmer temperatures may lead to greater evapotranspiration and increased risk of moisture deficits between precipitation events. Hot droughts, even of short duration, can result in mortality of swamp trees (Allen et al. 2015). Continuing sea-level rise is projected to permanently flood areas where elevation is close to sea level, compounding the effects of storm surge, flooding, and salt spray (Climate Change Science Program 2009). Saltwater intrusion can kill Atlantic white-cedar forests and may damage other species, depending on the intensity and duration of the disturbance.

Dominant Species: Forest impact model results for the Coastal Plain subregion were used for this forest community. Many species are projected to persist under a range of future climates including baldcypress, green ash, pin oak, pitch pine, sweetgum, loblolly pine, and willow oak, but ash species are highly susceptible to damage by emerald ash borer. Suitable habitat for Atlantic white-cedar, blackgum, and swamp white oak is projected to decline under both climate scenarios. Red maple is expected to become more competitive.

Stressors: Historical logging and development have reduced the extent of this forest community, and much of the alluvial soil has been converted for agricultural use. Increased flooding can increase runoff and discharge from farmland and concentrated animal feedlots, thus increasing nutrient loads. Groundwater withdrawals in the coastal plain are increasing due to inadequate recharge, lowering the water table and thus water supply for swamps (Shedlock and Bolton 2006). Disturbance may create opportunities for invasive species, such as phragmites, burning bush, multiflora rose, wineberry, and Oriental bittersweet. Deer use cedar swamps to avoid severe winter weather, and even low deer populations can be damaging.

Moderate-High Adaptive Capacity

Impacts to this forest community are expected to vary with proximity to saltwater, and reliance on groundwater. In areas disconnected from saltwater intrusion, hardwood species are likely to persist, and red maple may be more competitive on sites with reduced soil moisture. Rising sea levels, combined with storm surge and erosion, may drive the coastal zone inland, leading to rapid changes in tree species' habitat. Tree and other plant species have different tolerances to saltwater, which may allow some to persist. Atlantic white-cedar is a keystone species restricted to the coast, and rapid changes in salinity and water depth may result in the total loss of cedar swamps. For example, mortality of Atlantic white-cedar stands was highest in areas where water was impounded after Hurricane Sandy (New Jersey Department of Environmental Protection 2015).

Red maple-blackgum swamp along the Carman's River, New York. Photo by Adele M. Olivero, New York Natural Heritage Program, used with permission.

Red maple-sweetgum swamp on Staten Island, New York. Photo by Aissa L. Feldmann, New York Natural Heritage Program, used with permission.

Mature coastal plain Atlantic white-cedar swamp in the New Jersey Pine Barrens. Photo by Gregory J. Edinger, New York Natural Heritage Program, used with permission.

Tidal Swamp (Coastal Plain)

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

The combined effects of sea-level rise and saltwater intrusion due to spray and storm surge are expected to cause irreversible habitat loss and tree mortality in this forest community. As salinity increases, the salt tolerance of tree species may determine which ones persist.

Moderate-Negative Potential Impacts

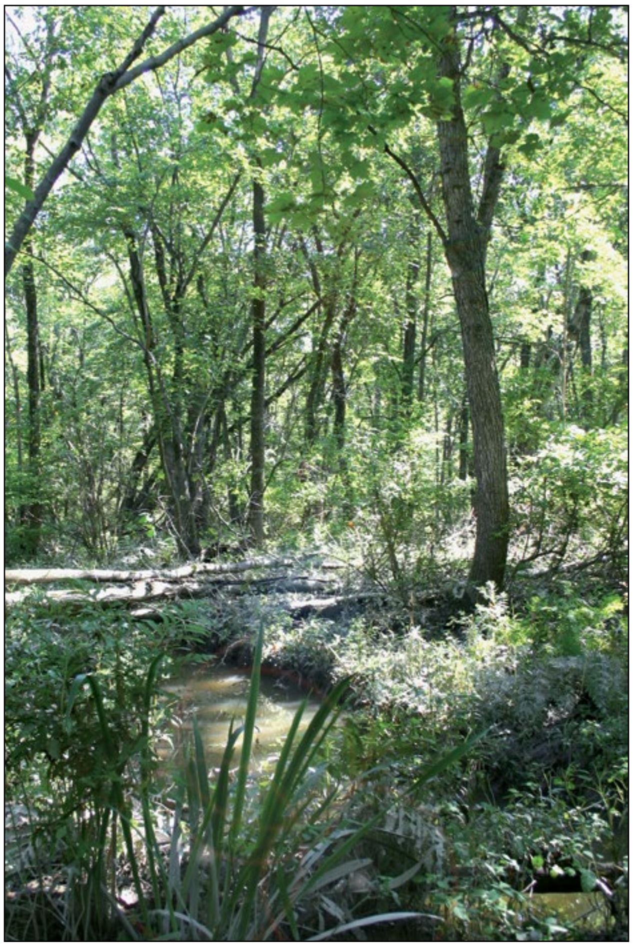
Drivers: Hydrology determines variations of this community type. Precipitation can cause changes in salinity as freshwater inputs constantly dilute saltwater inputs. Drought can reduce freshwater inputs and drive saltwater farther upstream (Moser et al. 2014). As sea level rises, increasing salinity levels may interact with other stressors, and the salt tolerance of individual trees may factor into tree response. Sea-level rise is expected to absorb current habitat for this community type. Tidal forest that undergoes salinization exceeding its tolerance may be replaced by tidal marsh (Rheinhardt 2007).

Dominant Species: Forest impact model results for the Coastal Plain subregion were used for this forest community. Many species are projected to increase or remain steady under both climate scenarios, including American elm, baldcypress, water tupelo, loblolly pine, and green ash. However, both green and pumpkin ash (not modeled) are susceptible to emerald ash borer and may face high mortality rates in the next few decades. Red maple is expected to become more competitive under both climate scenarios. Blackgum is the only species projected to decline under both scenarios.

Stressors: Historical logging and land development have reduced the extent of this forest, and much of the alluvial soil has been converted for agricultural use. Increased flooding can increase runoff and discharge from farmland and concentrated animal feedlots. Groundwater withdrawals in the coastal plain are increasing due to population pressures and inadequate recharge (Shedlock and Bolton 2006), lowering the water table and thus available water for swamps. Disturbance may create opportunities for invasive species such as phragmites, burning bush, multiflora rose, wineberry, and Oriental bittersweet.

Moderate-Low Adaptive Capacity

This forest community is expected to respond to sea-level change by changing the shape and position of wetlands and coastal habitat, depending on how changes in hydrology conform to local topography. River flow and hydrology in the coastal plain have been altered by channelization, road networks, development, and a variety of land-use changes, and these changes may inhibit the expansion of wetlands in response to climate changes. As the sea and coastal zone move inland, the habitat for current coastal species may change rapidly. Only baldcypress and green ash are resistant to salt spray. As tidal forests lose habitat, they could potentially replace nontidal riverine and lowland forests in areas where soils become saturated or seasonally inundated (Rheinhardt 2007).



Freshwater tidal swamp at Mill Creek, New York. Photo by Carly Voight, New York Natural Heritage Program, used with permission.

Freshwater tidal swamp at Mill Creek, New York. Photo by Carly Voight, New York Natural Heritage Program, used with permission.

Central Oak-Pine (Interior)

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

This diverse forest community occurs over a wide range of habitats. Many species tolerate or are adapted to dry soil conditions and fire, although young trees may be sensitive to severe drought and high-intensity fire. Many oak and hickory species are likely to benefit from projected changes in climate.

Moderate-Positive Potential Impacts

Drivers: This community is widespread and common throughout the interior portion of the Mid-Atlantic region. Warmer, drier summers may increase the occurrence and severity of drought, particularly on xeric sites, which could result in seedling mortality for some species. Higher moisture availability in spring and early summer may reduce fire risk while increasing vegetation growth. Late summer and fall moisture deficits and prolonged higher temperatures may increase fire risk, especially in places where vegetation dries or coarse woody debris accumulates from natural mortality or storm damage. Low to moderate fire intensity may benefit oak and pine species, but high-intensity fire can be fatal to trees.

Dominant Species: Most of the dominant species, including black oak, chestnut oak, mockernut hickory, northern red oak, pignut hickory, pitch pine, scarlet oak, shortleaf pine, Virginia pine, and white oak, are projected to remain stable or increase under both climate scenarios. Although no longer a dominant species, American chestnut is projected to remain stable under both climate scenarios. Several associated species are projected to lose habitat including eastern white pine, red pine, and sassafras. Red maple is generally expected to become more competitive.

Stressors: Some insect pests such as gypsy moth and southern pine beetle are already posing a serious threat to oak and pine species. Increased moisture stress combined with pests such as the two-lined chestnut borer may increase the risk of oak decline or sudden oak death (Venette and Cohen 2006). Deer herbivory is currently limiting to seedling establishment and growth, and deer populations are not expected to change due to climate change alone. Invasive species such as glossy buckthorn, honeysuckles, and garlic mustard can also impair regeneration, and may become more competitive with native species.

Moderate-High Adaptive Capacity

Many species of oak, hickory, and pine are tolerant of drought and fire and therefore expected to fare well under moderate climate changes. The relatively high species richness may increase the number of ways in which the ecosystem can adjust to changing conditions while maintaining important ecosystem functions. This community also occupies a range of site conditions over a large geographic area, which increases the potential of persistence on various sites. A history of fire suppression and increasing shade under the forest canopy have facilitated shifts to more mesic conditions in some places. Where mesic conditions have developed, northern hardwoods such as red maple, American beech, and tulip tree have established, and regeneration of oak and pine species has become a notorious forest management challenge that may affect the future composition and distribution of this community.

Appalachian oak-hickory forest in the Taconic Mountains, New York. Photo by Timothy G. Howard, New York Natural Heritage Program, used with permission.

Appalachian oak-hickory forest at Saratoga National Historical Park, New York. Photo by Gregory J. Edinger, New York Natural Heritage Program, used with permission.

Lowland Conifer (Interior)

High Vulnerability (medium evidence, medium agreement)

This forested wetland community is limited to areas that remain wetter and cooler than adjacent uplands. This community has relatively few species compared to other forest communities and many of them are threatened by insect pests. As the current dominant species decline, the functional identity of this ecosystem will be greatly challenged.

Negative Potential Impacts

Drivers: Increases in temperature and altered precipitation patterns could significantly change the hydrology of this community. Peak streamflow is expected to shift to earlier in the spring and increased precipitation is expected to intensify spring peak flows. An increase in intense precipitation is likely to result in more frequent flooding. Reduced precipitation in the summer and fall may result in drier conditions and a lower water table, which would negatively affect rain-fed ecosystems. The increasing risk of wildfire is a serious threat to drier peatlands, which contain tree species that are not fire tolerant.

Dominant Species: Fewer than a dozen species make up the lowland conifer community, and most are projected to decline under both climate scenarios, including balsam fir, black ash, black spruce, eastern hemlock, eastern white pine, red spruce, tamarack, and northern white-cedar. Yellow birch and red maple are projected to decline under the high emissions scenario only. Although no species are projected to increase under climate change, red maple may take advantage of openings and disturbance to become a dominant species in these areas.

Stressors: Warmer temperatures may dampen the effects of the eastern spruce budworm, but allow balsam woolly adelgid and hemlock woolly adelgid to increase and spread more easily (Chapter 5). Tree susceptibility to insect infestations is expected to increase as trees become moisture stressed. Historical land use has already resulted in altered hydrology in some locations; this legacy is likely to continue to stress the system as the precipitation regime changes. Deer use conifer-rich lowlands to avoid severe winter weather, and even low deer populations can be damaging. Browsing pressure on hardwood species may increase as northern white-cedar and other conifers decline.

Moderate-Low Adaptive Capacity

Impacts on lowland conifer forests are expected to vary with site conditions, and the response of these forests to climate change may be greatly influenced by surface geology, hydrology, soils, dominant tree species, and local changes in climate. Although prolonged flooding may exceed the saturation tolerance of some species, an increased risk of drought is also a serious threat that many species are not likely to withstand. Fens may not be as susceptible to water deficits due to the reliance on groundwater. The physical structure and function of conifer communities create the shady, cool microclimates where they thrive, and there are relatively few native conifers to fill this functional role. As the keystone conifers decline, the identity of this forest community may be severely compromised.

Red maple-tamarack peat swamp at Lake Superior State Park, New York. Photo by D.J. Evans, New York Natural Heritage Program, used with permission.

Spruce-fir swamp at Johnnycake Lake Swamp, New York. Photo by Gregory J. Edinger, New York Natural Heritage Program, used with permission.

Hemlock-hardwood swamp at Johnnycake Lake Swamp, New York. Photo by Gregory J. Edinger, New York Natural Heritage Program, used with permission.

Lowland and Riparian Hardwood (Interior)

Moderate Vulnerability (medium-limited evidence, medium agreement)

This community type is threatened by changes in the hydrologic cycle that increase variability in water availability. Invasive plants and insect pests are major stressors for species that are expected to decline under a range of climate scenarios. Many common species are expected to shift in distribution across the broader landscape, but persist in these moist lowlands.

Moderate Potential Impacts

Drivers: Changes to the timing and intensity of precipitation events are expected to result in increased flooding, erosion, and sedimentation during precipitation events, as well as potentially increased risk of drought between precipitation events. Hotter and drier conditions could reduce water table levels and water availability to trees. The effects of hotter and drier conditions during the growing season are likely to vary widely based on both site and weather conditions, and trees that are shallow rooted, on droughty soils, or already stressed may be most at risk. Prolonged flooding during the growing season may kill tree species that cannot withstand long periods of inundation.

Dominant Species: Many dominant species are expected to remain stable or increase under both climate scenarios, including American hornbeam, blackgum, boxelder, bur oak, eastern cottonwood, green ash, pin oak, shagbark hickory, swamp white oak, sweetgum, and sycamore. Only black ash and eastern hemlock are expected to lose a large amount of suitable habitat under both climate scenarios. Some of these species are tightly linked to moisture availability. Model projections for red maple are mixed, but the species is generally expected to become more competitive under changing conditions. Future projections for species in this community may have greater uncertainty because many of these species are less common and there are challenges to modeling wetland habitats.

Stressors: Invasive plants are very problematic in this community type, with greater impacts generally occurring downstream. Increases in flooding are likely to benefit many invasive plants that are able to establish quickly and outcompete native vegetation on disturbed sites (Dukes et al. 2009). Increases in extreme precipitation events and flooding have the potential to increase soil erosion and sedimentation, compounding existing stressors from agricultural and industrial runoff.

Moderate Adaptive Capacity

This forest community exists in many variations across the landscape, and many species are projected to remain stable or even increase under climate change. The community can cope with a high level of natural variability and disturbance and is expected to tolerate some additional change with the exception of extreme drought, extreme erosion, or prolonged flooding. However, interacting disturbances that result in too much disruption may exceed the tolerance thresholds of this disturbance-adapted system.


Floodplain forest along the Neversink River, New York. Photo by Timothy G. Howard, New York Natural Heritage Program, used with permission.


Red maple-hardwood swamp at Grand Pond Swamp, New York. Photo by Elizabeth A. Spencer, New York Natural Heritage Program, used with permission.


Mixture of riparian hardwood species in Pennsylvania. Photo by Greg Czarnecki, Pennsylvania Department of Conservation and Natural Resources, used with permission.

Montane Spruce-Fir (Interior)

High Vulnerability (medium-robust evidence, high agreement)

This forest community is restricted to cool, moist environments at the highest elevations in the Mid-Atlantic region. Northern and boreal conifer species are expected to decrease where they currently persist. Protected valleys or coves may continue to provide cool microhabitats for spruce and fir.

Negative Potential Impacts

Drivers: This community is adapted to cold temperatures and abundant moisture. Projected increases in temperature could lead to moisture stress, even without a decrease in precipitation. Red spruce seeds may not germinate if moisture is insufficient and temperatures exceed 92 °F (34 °C) for a prolonged time (Burns and Honkala 1990). Balsam fir and red spruce seedlings are at risk of mortality during periods of drought or if soil surface temperatures exceed 115 °F (47 °C). Reduced snowfall and snowpack, which lead to earlier spring melt, may also play a large role in soil moisture availability. Lack of snowpack can result in increased risk of shallow roots freezing. Fires are rare in this forest community, but extreme drought or tree mortality could increase fire risk.

Dominant Species: All dominant species in this forest community are projected to lose habitat and productivity under both climate scenarios, with more substantial impacts projected under greater warming. Balsam fir, red spruce, American mountain-ash, and paper birch are expected to decrease under both scenarios. Striped maple and yellow birch habitats are projected to remain relatively stable under the low emissions scenario and suffer large decreases under the high emissions scenario.

Stressors: This forest community is currently recovering from historical acid deposition and logging, which significantly reduced the extent of this forest. Heavy rainfall could increase runoff and soil erosion, as well as lead to increased risk from windthrow on saturated or destabilized soils. Spruce budworm outbreaks occur in periodic natural cycles in mature spruce-fir, causing individual mortality after one or more years of heavy defoliation. Warmer winter temperatures could result in higher insect mortality, and outbreaks of spruce budworm could become less prevalent in the long term.

Low Adaptive Capacity

Several factors contribute to low capacity to adapt to climate change. There is relatively low species and genetic diversity in these forests, which are isolated at the highest elevations in the region. This forest community is projected to lose physical habitat as the climate warms and the species are limited in their upward migration. At the same time, this community may benefit somewhat from isolation and its competitiveness in cold and nutrient-poor sites. For example, both balsam fir and red spruce can respond to release after many years of suppression. This community is currently expanding on the landscape as it recovers from past logging and salvage operations that had greatly reduced its extent. This current rebound of montane spruce-fir on the landscape may mask climate-induced migration or decline of the system in coming decades (Foster and D’Amato 2015). However, the typically slow rate of recovery in response to disturbance is a factor in the low adaptive capacity.

Montane fir forest on Westkill Mountain in the Catskill Mountains, New York. Photo by Timothy G. Howard, New York Natural Heritage Program, used with permission.

Montane fir forest on Blackhead Mountain in the Catskill Mountains, New York. Photo by Timothy G. Howard, New York Natural Heritage Program, used with permission.

Montane spruce-fir forest on Kaaterskill High Peak in the Catskill Mountains, New York. Photo by Kelly A. Perkins, New York Natural Heritage Program, used with permission.

Northern Hardwood (Interior)

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

Climate change may intensify several interacting stressors, such as drought, forest pests, and invasive species. Anticipated future reductions in tree species diversity in this community may decrease resilience to a variety of climate-related stressors.

Moderate-Negative Potential Impacts

Drivers: This forest community is sensitive to reduced soil moisture and possible drought that could occur on some sites under warmer and drier conditions. Changes in soil temperature and moisture and associated changes in nutrient availability or soil processes could have substantial effects on sugar maple and other dominant species (Groffman et al. 2012). A combination of severe warming and drier conditions could increase wildfire risk in the Mid-Atlantic region, but topography, fragmentation, and fire suppression are likely to limit wildfire (Guyette et al. 2014). Disturbance dynamics may also change, and increases in extreme weather events are expected to result in accelerated gap formation and regeneration.

Dominant Species: This forest community is relatively diverse in tree species. American beech, eastern hemlock (which can form homogenous pockets), and eastern white pine are generally expected to decline, especially under the warmer climate scenario. American basswood, black cherry, sugar maple, sweet birch, and tulip tree are generally projected to decline under the warmer scenario only. Northern red oak is projected to remain stable under both scenarios.

Stressors: Deer herbivory is currently limiting to seedling establishment and growth, and deer populations are not expected to change dramatically due to climate alone. Invasive species such as garlic mustard and Japanese stiltgrass are expected to expand in newly formed gaps and compete with native species. Eastern hemlock, American beech, and several ash species have already declined on the landscape due to insect pests such as hemlock woolly adelgid, beech bark disease, and emerald ash borer. Insect pests, pathogens, and interactions with drought and other disturbances may result in decline of other species in the near term, with the Asian longhorned beetle posing a serious threat to northern hardwood species.

Moderate Adaptive Capacity

Current regional strongholds for this community are fragmented on the landscape due to agriculture, development, and natural resource extraction. These factors, along with forest management, strongly influence the diversity of the forest community. Positive characteristics include a relatively high number of species with broad geographic ranges, large populations, and high genetic diversity. Even as some species decline, others are well established to fill in the new gaps on a variety of sites. Valley bottoms and other microsites in areas of complex topography may be buffered from some of the effects of climate change.

Beech-maple mesic forest at The Pinnacle in Washington County, New York. Photo by Gregory J. Edinger, New York Natural Heritage Program, used with permission.

Maple-basswood rich mesic forest at Jerden Falls, New York. Photo by Gregory J. Edinger, New York Natural Heritage Program, used with permission.

Beech-maple mesic forest at Wilcox Mountain in the Adirondack Mountains, New York. Photo by Gregory J. Edinger, New York Natural Heritage Program, used with permission.

Woodland, Glade, and Barrens (Interior)

Low Vulnerability (medium evidence, medium-high agreement)

Many of the species in this ecosystem are projected to do well under a range of future climate scenarios. Further, encroachment of novel species may be reduced because this community is geographically constrained due to extreme site conditions.

Positive Potential Impacts

Drivers: This forest community thrives in the hottest, driest, and most exposed slopes underlain by shale and limestone. Warmer, drier summers are likely to increase the risk of drought and fire in these locations, which would help maintain the open conditions that favor this community type (Tyndall 2015). Although this community is generally tolerant of short periods of severe drought, longer or more extreme drought can delay germination or kill seedlings and even long-established trees. Because the bedrock sheds water easily, increases in extreme precipitation events may increase erosion or result in the disintegration of shale downslope.

Dominant Species: This community is characterized by fewer than a dozen species, which vary based on the presence of shale or limestone bedrock. Most dominant species are projected to increase or remain stable under both climate scenarios, including eastern redcedar, eastern redbud, hackberry, northern red oak, pignut hickory, pitch pine, scrub oak, Virginia pine, and white oak. Sugar maple is projected to decline under a substantially warmer and drier climate, and would be the species most likely to disappear from this community type due to moisture deficit.

Stressors: Some invasive species, including some nonnative grasses, spotted knapweed, Japanese honeysuckle, Chinese bush clover, and ailanthus, are very competitive in this forest community. These invasive species may pose a greater threat if they can outcompete native species. Forest health is not greatly challenged by pests and pathogens, but could become degraded if the system becomes very drought stressed.

Moderate-High Adaptive Capacity

This community is adapted to extreme weather and natural disturbance, and already occupies some of the driest and hottest habitat in the region, all of which suggests that it can adapt to various climate-related stressors. The presence of fire, either natural or managed, is an important disturbance process that maintains open conditions in the barrens, glades, and woodlands. This community type can change very quickly in the absence of fire, which may allow eastern redcedar, red maple, and nonnative buckthorn to establish or increase. Both drought and fire can benefit this community by keeping an open state where it is currently present, and even potentially creating new habitat where adjacent oak-pine forest declines. Shale bedrock restricts the number of species that could compete with this community type, although invasive trees and shrubs are an increasing problem.

Wet alvar grassland (foreground) and alvar woodland (background) at Three Mile Creek Road Barrens, Jefferson County, New York. Photo by Kimberly J. Smith, New York Natural Heritage Program, used with permission.

Fissures or grikes (or grykes) in limestone in alvar pavement grassland at The Nature Conservancy's Chaumont Barrens, Jefferson County, New York. Photo by Gregory J. Edinger, New York Natural Heritage Program, used with permission.

Serpentine barrens in Soldier's Delight, Maryland. Photo by Jennifer Dean, New York Natural Heritage Program, used with permission.

Redcedar rocky summit on Mount Tom in Washington County, New York. Photo by Gregory J. Edinger, New York Natural Heritage Program, used with permission.

CHAPTER SUMMARY

Forest ecosystems across the Mid-Atlantic region will be affected by climate change, although ecosystems and individual tree species are expected to respond differently. The synthesis statements in the first half of this chapter can be applied as general principles when specific information about expected climate change impacts is lacking. Overall, we expect that forest ecosystems will be severely affected by changes in water availability. On the coastal plain, vegetation will also be vulnerable to sea-level rise and increasing salinity. Forest ecosystems that are adapted to dry conditions and frequent disturbances are expected to be less vulnerable to the range of future climates. Forest ecosystems that are adapted to tolerate a wide variety of conditions and disturbances are also expected to persist under a range of plausible climates.

The vulnerability determinations for individual forest communities are best interpreted as broad trends and expectations across the assessment area. For some species, climate-related changes over the next century may be a continuation of current trends. For other species, it may take more than 100 years before such changes become apparent. For long-lived species especially, substantial changes on the landscape within this century are likely to be influenced by succession, management, and natural disturbances. Vulnerability to anthropogenic stressors such as fragmentation and urban development are also expected to influence the adaptive capacity of an ecosystem, but are beyond the scope of this assessment. This assessment makes use of the most up-to-date information from the scientific literature, a coordinated set of ecosystem modeling results and climate projections, and the input of a large team of local experts. Even so, there are limitations and unknowns that make these determinations imperfect.

As new information continues to be generated on the potential impacts of climate change on forests in this region, this assessment should be supplemented with updated tools, scientific publications, and stand-level information such as can be obtained through stand and stock surveys. The high diversity in landforms, microclimates, hydrology, and species assemblages across the assessment area greatly complicates model projections and interpretation. In this assessment, forest communities were roughly based on NETHCS systems (Chapter 1). Forest ecosystems have the potential to manifest themselves in very different ways across the assessment area (e.g., by varying in species associations and landscape position), and it is important to have a good working knowledge of forest communities at the local level.

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

CHAPTER 7: MANAGEMENT IMPLICATIONS

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

This chapter does not make recommendations as to how management should be adjusted to cope with climate impacts. We recognize that climate change will have varying implications for different forest systems, ownerships, and management objectives. Additionally, climate change is only one of many factors considered in making land management decisions. Therefore, we provide broad summaries rather than focusing on particular management issues. A separate document, *Forest Adaptation Resources*, has been developed to assist land managers in a decisionmaking process to adapt their natural resource management to projected impacts (Swanston 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 have initiated efforts to address the issue, however. For example, the recently updated Forest Service regulations for National Forest System Land Management Planning (also known as the 2012 Planning Rule) directly address the impacts and ramifications of climate change (USDA Forest Service 2012). In fact, climate change was among the stated purposes for revising the rule (USDA Forest Service 2012: 21163-21164); the Allegheny National Forest is required to address climate change under the 2012 rule during future revisions of management plans. Similarly, recent state-level forest strategies identify climate change as a potential threat to the long-term sustainability of forests. Although most state forest management plans have not addressed climate change, climate change-related concerns are considered in some forest plans. For example, the Pennsylvania State Forest Resource Management Plan outlines climate-related impacts on forests, management strategies, and agency-wide climate change initiatives (Pennsylvania Department of Conservation and Natural Resources 2016). Another example is found in the Savage River State Forest Annual Work Plan, which describes expanding the use of native and nonnative conifers as a wildlife management component and for adaptation to climate change and invasive pests and pathogens (Maryland Forest Service 2017).

Incorporating climate change considerations into natural resource planning will always be a complicated endeavor. The uncertainties associated with planning over long time horizons are only compounded with climate change. Management plans for federal, state, and local agencies, as well as private lands, are typically written to guide management for a 10- to 25-year period, and it may not be feasible to address the potential long-term effects of climate change within a relatively short planning horizon. 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 become more challenging 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.

Corporate, industrial, and family woodland owners, who own about 73 percent of the forest land in the assessment area, are also beginning to consider the implications of climate change for their planning and management. Those who have considered climate change may be motivated by material risk posed to their forest land. For corporate or industrial owners, the interest may also be inspired by questions from outside funding, investment, and certification agencies regarding their "climate preparedness." 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 fertilization, and habitat to support novel species. In the near term, the biggest climate-driven 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 5). In the long term, managers may need to adjust for suboptimal growing conditions induced by shifts in habitat for commercially important tree species. Managers are increasingly thinking of climate change as a new lens through which to view management activities.

More Information

- More information on the Forest Service's 2012 Planning Rule can be found here: www.fs.usda.gov/planningrule
- The Climate Change Resource Center is a Web-based resource that connects land managers and decisionmakers nationwide with usable science to address climate change in planning and application. www.fs.usda.gov/ccrc
- 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 actively manage their forest and related resources, provides 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. https://doi.org/10.2737/NRS-GTR-87-2.
- 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 (a private nonprofit organization), 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 has publicly available bulletins synthesizing a wide variety of topics, as well as additional information about its services.
www.climatesmartnetwork.org/
- The National Wildlife Federation (NWF) has developed a guide to provide 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 may in turn lead to habitat changes for a variety of plant and animal species (Manomet Center for Conservation Sciences and NWF 2013, NWF and Manomet Center for Conservation Sciences 2014, 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). Climate change vulnerability assessments have been conducted for many species within the Mid-Atlantic region, especially those of conservation concern (Furedi et al. 2011, Schlesinger et al. 2011). The assessments take into account many factors including current threats, habitat and dietary specificity, genetic variation, mobility, and natural and anthropogenic barriers to movement. Although the factors for each species are unique, some generalizations can be made.

Aquatic species and those that inhabit seasonally wet habitats are nearly all rated as highly or extremely vulnerable to climate change because of warmer water temperatures, habitat specificity, natural and humanmade barriers to dispersal, and drying of high-elevation streams and isolated wetlands. Most birds, on the other hand, are rated as stable or likely to increase because of their ability to disperse over long distances, move around anthropogenic obstacles, and tolerate a wider range of temperature and hydrologic regimes. Climate change has the potential to negatively affect even common species. The brook trout, for example, is considered highly vulnerable due to warming water temperatures and habitat isolation. On the other hand, climate vulnerability analyses show that the golden-winged warbler, which is currently considered threatened in the Mid-Atlantic region, may expand due to an increase in early successional habitat (Audubon n.d.).

Golden-winged warbler in Bald Eagle State Park, Center County, Pennsylvania. Photo by Darin McNeil, Indiana University of Pennsylvania, used with permission.

Many species are expected to respond to changes in climate by moving northward, upslope, or upstream, whereas others may adapt in place or be unable to cope with changes (Staudinger et al. 2013). Climate change is expected to affect species differently, such that some species may decline while others expand under future conditions. Species that are relatively free to move around on the landscape are expected to seek favorable habitat even as the distribution of habitat changes. Because many species, such as the Appalachian cottontail, eastern spotted skunk, and eastern fence lizard, are at either the northern or southern edge of their range within the Mid-Atlantic region, range shifts are likely as habitats change. Black-capped chickadees, for example, are already retreating northward while their southern cousin, the Carolina chickadee, is moving in behind them (Taylor et al. 2014). A zone of hybridization, which is sliding northward at about 0.6 mile per year, has formed where the two species overlap in southern Pennsylvania.

Relocating in response to climate change is not an option for some species due to limited mobility, narrow habitat requirements, or codependence on other species (Trani Griep and Manley 2012). Freshwater mussels, which include some of the region's most endangered species, such as the eastern pearlshell and dwarf wedgemussel, embody all of these characteristics and are considered highly vulnerable to climate change. Another at-risk group are amphibians, such as the Jefferson salamander, that breed in vernal pools. Not only are they habitat specialists with limited mobility, but the wetlands they inhabit are at risk due to higher temperatures and extended dry periods. 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 (Climate Change Science Program 2009, NWF and Manomet Center for Conservation Sciences 2014).

Threatened and endangered species often face population declines due to a variety of nonclimatic stressors, such as habitat loss, competition from invasive species, and disease, all of which can be exacerbated by climate change. 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 of 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 nonclimatic 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 may depend on the needs and scope of a particular 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 USDA 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 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
- 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 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

Clutch of hybrid chickadees. In Pennsylvania, chickadees are hybridizing as the ranges for black-capped chickadees and Carolina chickadees shift northward. Photo by Greg Czarnecki, Pennsylvania Department of Conservation and Natural Resources, used with permission.

WILDERNESS MANAGEMENT

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. Five Wilderness areas are contained within the Mid-Atlantic region, and are managed by several federal agencies. The Hickory Creek and Allegheny Island Wilderness areas are located on the Allegheny National Forest and are managed by the Forest Service. The Great Swamp National Wildlife Refuge Wilderness and the Brigantine National Wildlife Refuge are located in New Jersey and are managed by the Fish and Wildlife Service. The Otis Pike Fire Island High Dune Wilderness is located near Long Island, NY, and is managed by the National Park Service. These areas play a special role in the regional landscape because of their remote and unmanaged character and their scenic, recreational, and ecological value. Wilderness areas are designed to "secure for the American people of present and future generations the benefits of an enduring resource of wilderness" (USDA Forest Service 2007).

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. Increased disturbances may also reduce food supply or available habitat for wildlife species within wilderness areas.

The potential for extensive ecosystem change resulting from climate change raises questions about the future management of these and other wilderness areas. In some cases, it is uncertain how climate-related impacts may 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 benefits and drawbacks. However, Special Provisions for the Otis Pike Fire Island Dune Wilderness declare that "Wilderness designation shall not preclude the repair of breaches that occur in the wilderness area, in order to prevent loss of life, flooding, and others severe economic and physical damage to the Great South Bay and surrounding areas" (Williams and Foley 2007: 8). A report from the National Park

Rock outcrop overlooking forest scenery in southeastern Pennsylvania. Photo by Greg Czarnecki, Pennsylvania Department of Conservation and Natural Resources, used with permission.

Service provides insights into the new paradigm of wilderness stewardship, which includes responses to climate change (Nelson 2015), and this topic is likely to become more important across all agencies.

More Information

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

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 a 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 et al. 2012). Climate change trends and ecosystems 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 may 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.

In the design of 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 projected stressors on the property in the future, and then to integrate those considerations into project design. Private not-for-profit organizations, government agencies, landowners, and potential funders will increasingly need research-based results on anticipated climate trends and impacts, including spatially explicit information on how these shifts may play out over the land. This science can enable effective use of funding, staff time, and other resources that are essential to advancing "climate-informed" conservation of forests in the region and shaping conservation efforts to deliver a more resilient landscape.

More Information

- The Open Space Institute developed the Resilient Landscapes Initiative to protect habitats that may 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 identified places that may 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 economies of the assessment area (Chapter 1). Tree species and forest composition are projected to change during the 21st century (Chapters 5 and 6). Changes in forest composition across the landscape may be influenced by forest management, and may in turn influence forest management and the forest products industry (Moser et al. 2016). Several commercially important species, such as beech, aspen, and eastern white pine, are projected to undergo significant declines under a range of climate scenarios during the next century. Black cherry, another important commercial species in the Mid-Atlantic region, is projected to decline only under the high emissions scenario. Black walnut is projected to gain suitable habitat under both emissions scenarios, whereas white oak is projected to gain suitable habitat only under the high emissions scenario. 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 will be able to take advantage of awareness of anticipated climate trends and shifts in forest species. 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 during the coming 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). 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 et al. 2016). There may be local differences in forest responses, as well as potential opportunities for new merchantable species to gain suitable habitat in the Mid-Atlantic region. The forest products industry has adjusted to substantial changes during the past 100 years, and continued responsiveness can help the sector remain viable.

More Information

- The 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 Northern Forests Futures Project uses the latest inventory data and scientific projections to understand how forests in the Midwest and Northeast may change as climate and other stressors change. www.nrs.fs.fed.us/futures/
- The Climate Change Tree Atlas provides information on the projected suitable habitat for tree species under climate change. www.nrs.fs.fed.us/atlas/

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 time available for conventional forest management operations. Harvest operations in lowland areas and on soils prone to compaction or erosion are often accomplished during winter months, but changes in winter climate (e.g., shorter seasons of frozen ground, more midwinter thaws, less snowpack, and more rain) may reduce the ability to harvest in those locations without damaging soil (Chapter 4). 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 may increase the need to build roads to facilitate winter harvest, which would be more expensive than conventional practices. Analysis of timber harvest records in northern Wisconsin have identified some consequences of the changes in frozen ground conditions (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 limit the spread of forest diseases can further shorten the annual harvest window.

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.

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

Marking crew staff identifying a tree to be cut during a timber sale. The objective of the silvicultural prescription was to improve the health and vigor of an oak stand on the Allegheny National Forest, Pennsylvania. Photo by Kevin Wiltsie, Allegheny National Forest.

financial return as a green timber sale. Additionally, ongoing stressors of overcapitalization, loan and insurance payments, and high fuel prices may increase 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 are often considered inadequate. The current trend of intensifying precipitation has placed additional strains on old and fragile infrastructure.

Heavy precipitation events, which are already increasing and projected to increase more in the future (Chapters 3 and 4), may overload existing infrastructure that has not been built to that capacity. For example, older road systems may be susceptible to increased rainfall events due to improper location or outdated building standards. Many of these aging structures are being replaced, with the expectation that new culverts may need to last up to 100 years and be able to sustain 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. Furthermore, forest managers may find it necessary to take additional 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 human populations (Vaughan et al. 2013). Many of these products may be affected by changes in climate; each product may 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).

Mushrooms in Fowler's Hollow State Park, Perry County, Pennsylvania. Photo by Greg Czarnecki, Pennsylvania Department of Conservation and Natural Resources, used with permission.

Maple syrup is a nontimber forest product that is important in some areas of the Mid-Atlantic region. Fur trader records show that maple sugar was an important exchange good from the early days of settlement (Emery 2002). Today, gathering and boiling sugar maple sap remains culturally and economically important in the region. Commercial production of maple syrup and related products provides millions of dollars of revenue in the Mid-Atlantic region, and this does not include maple syrup production that never enters the market, such as the product of small family operations. Sap flow necessary for maple syrup production requires a combination of warm days and freezing nights that is highly seasonal. These conditions occur earlier than in the past and this trend is projected to continue. Sugar maple habitat is also expected to decline, especially in more southerly locations where the sap flow season is also likely to be shorter (Matthews and Iverson 2017). Maple syrup producers report that their ability to adapt to changing climate conditions is largely related to the health of the forest and the ability of producers to adopt new technologies (Kuehn et al. 2016). A study concluded that additional taps would be needed to make up for projected losses of sugar maple habitat, but the required warm days and freezing nights may limit syrup production, especially in the southerly states (Matthews and Iverson 2017).

FIRE AND FUELS

Weather and climate are major drivers of fire behavior. Across the Mid-Atlantic region, the fire season is controlled by a combination of day length, weather, and fuel conditions. After snowmelt, organic material on the forest floor is exposed to sunlight and wind, which dry the material, often enough to burn. After leaf-out occurs, humidity increases on the forest floor and the litter is less flammable. 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 fire ignition and spread potential. Live trees drop leaves and go dormant in the fall, and most forests become increasingly fire prone around the same time that short days and cool temperatures return.

Projected changes in climate could affect fire and fuels management in the assessment area. Climate change is generally expected to increase total annual precipitation, but there is potential for drier conditions late in the growing season (Chapter 4). Understory and herbaceous vegetation is expected to initially become more lush during wet springs before drying out later in the growing season. This increase in forest fuels may heighten the potential for more intense fires. High-intensity wildfire can result in tree 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). Compared to the western United States, where fire frequency and severity are expected to increase significantly, wildfire frequency in the Mid-Atlantic region has generally been lower and only moderate increases in fire are expected (Clark et al. 2013). However, in fire-adapted forests such as the New Jersey Pine Barrens, prescribed fire is the primary management practice used to reduce hazardous fuels. Other wildfire-prone forests requiring fire management in the Mid-Atlantic region include pine-dominated, oak-pine, and, sometimes, oak-hickory forests (Clark et al. 2013).

A combination of warmer temperatures and greater evapotranspiration may at times (e.g., spring or fall) exceed modest precipitation increases, creating conditions that support wildfire (Guyette et al. 2014, Heilman et al. 2015). Under intense fire weather conditions, wildfires could also become a hazard and safety risk to the public, firefighters, and infrastructure near or within forest land. 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 or oak forests, for example (Brose et al. 2012, Clark et al. 2015). Projected changes in climate could also affect the ability of public, tribal, and private land managers to apply prescribed fire on the landscape. 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. www.nrs.fs.fed.us/disturbance/fire/nafse/
- The Forest Service Climate Change Resource Center provides a summary of how climate change may affect wildland fire in forest ecosystems. www.fs.fed.us/ccrc/topics/wildfire/

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 to store carbon. A longer growing season and carbon dioxide fertilization may lead to increased productivity and carbon storage in forests in the Mid-Atlantic region (Chapter 4). Several modeling studies suggest that forests are likely to continue to sequester additional carbon during the next several decades as relatively young forests continue to mature and forests benefit from slightly warmer conditions (Keenan et al. 2014, Pan et al. 2009, Scheller et al. 2012, 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. 2012, Loehle et al. 2016), 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. There is also mounting evidence that tree growth responses vary by geographic location and inherent temperature tolerance; for example, local populations of a southern species near the cold range limit have more potential for increased growth than local populations of the same species near the warm range limit (Reich et al. 2015). Carbon storage may also be affected by soil water holding capacity; reduced soil moisture in areas with typically high soil water holding capacity is expected to reduce total carbon. In areas with low water holding capacity, reduced soil moisture may not result in total carbon changes during the 21st century (Scheller et al. 2012). 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 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/forests-and-carbon-storage

Sign post at a portion of the Appalachian Trail in Pennsylvania. Photo by Greg Czarnecki, Pennsylvania Department of Conservation and Natural Resources, used with permission.

- A review article, A Synthesis of the Science on Forests and Carbon for U.S. Forests, summarizes the key issues related to forest management and carbon. www.treesearch.fs.fed.us/pubs/35006

RECREATION

Forests are the centerpieces of outdoor recreation in the Mid-Atlantic region (Chapter 1). People throughout this region enjoy a variety of recreational activities, including hunting, fishing, camping, wildlife watching, skiing, and snowboarding. People also explore trails on foot, bicycles, skis, snowshoes, and horseback, 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 may continue toward shorter, milder winters and longer, hotter summers, which could reduce opportunities for popular winter-based recreational activities in the long term. Climate change has already caused reductions in the duration of lake ice and snow in the Mid-Atlantic region (Chapter 3), and activities such as ice fishing and pond hockey have the potential to be harmed as conditions continue to change (Fairley et al. 2015). Much of the region 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, Burakowski and Magnusson 2012, Scott et al. 2008). Because impacts on winter recreation activities are closely tied to winter temperatures, southern parts of the Mid-Atlantic region are at even greater risk in coming decades than northern parts of the region and may lose recreation opportunities such as downhill skiing (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 and Scott 2013).

It is also expected that recreational activities during the spring, summer, and fall will shift in response to warmer and more variable climate 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, which could have implications for staffing (Nicholls 2012). Increasingly warm fall days may also extend the hiking season and leaf peeping season, bringing them into conflict with deer hunting season. Regional increases in average temperatures and heat waves in the summer could shift visitor behavior, depending on the magnitude of changes (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 correspond to 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 2013c). As mentioned earlier, climate change may also result in substantial changes in habitat availability and quality for wildlife and fish species (Glick et al. 2007). Big game species such as deer and elk 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 (NWF 2013b).

More Information

- The Northern Forests Futures Project uses the latest inventory data and scientific projections to understand how recreation opportunities in the Midwest and Northeast may change as climate and other stressors change. www.nrs.fs.fed.us/futures/

ARCHAEOLOGICAL AND HISTORIC RESOURCES

The remnants of past human activity, such as paintings, sculptures, historic sites and buildings, and objects from everyday life, are present within the Mid-Atlantic region. 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 (Holtz et al. 2014). 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. The Sea Level Rise Vulnerability Assessment for the State of Delaware identified 244 known historic sites that could be inundated by a sea level rise of 1.6 feet; the number of sites nearly doubles (441 sites) for a rise in sea level of 3.2 feet (Delaware Coastal Programs 2012). 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). Flooding and storm damage can also render structures unsafe or inaccessible, as was the case of Ellis Island after Hurricane Sandy; this icon of American immigration was closed to visitors for more than a year during remediation (Holtz et al. 2014). Managing cultural resources will become more challenging because of the direct and indirect impacts of climate change, and is likely to require increased protections against extreme events.

More Information

- The National Park Service has published a report on coastal assets, *Adapting to Climate Change in Coastal Parks: Estimating the Exposure of Park Assets to 1 m of Sea-level Rise*. The full report and results for individual assets describe exposure, economic values, and case studies. https://www.nature.nps.gov/geology/coastal/coastal_assets_report.cfm

Iron furnace stack at Pine Grove Furnace State Park, Pennsylvania. The Pine Grove Iron Works was a smelting facility during the Industrial Revolution and is now a historic site. Photo by Greg Czarnecki, Pennsylvania Department of Conservation and Natural Resources, used with permission.

FOREST-ASSOCIATED TOWNS AND CITIES

Many towns and cities in the Mid-Atlantic region are particularly dependent on the health and functioning of surrounding forests, whether for economic, cultural, recreational, or subsistence reasons (Morzillo et al. 2015). They include cities near or containing forest, smaller towns and remote townships surrounded by forest, and communities in between. They are responsible for balancing activities related to timber production, land sales, wildfire suppression, water supply and wastewater treatment, watershed health, and federal laws (e.g., the Endangered Species Act of 1973), and a relatively high number of jobs are tied to the forestry sector. State and municipal agencies as well as private companies are also responsible for maintaining infrastructure in the Mid-Atlantic region, including roads, power lines, sewer lines, dams, drainage ditches, and culverts. Warmer temperatures are expected to drive changes in forest tree species; some species may decline while others become more important, resulting in changes to timber supplies for specific markets, or to forest products for cultural use. 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. Climate-related changes in the frequency and severity of droughts and floods may place greater stress on water supplies and water treatment infrastructure; consequences

Kinzua Bridge in McKean County, Pennsylvania. This landmark was heavily damaged by a tornado in 2003. Photo by Greg Czarnecki, Pennsylvania Department of Conservation and Natural Resources, used with permission.

could include increased costs associated with construction of flood barriers or green infrastructure to protect existing facilities (e.g., low-lying water or wastewater treatment plants), enhanced infrastructure for groundwater recharge and storage, increased reservoir storage capacity, and relocation of existing infrastructure to higher ground (Olmstead 2014).

Every forest-associated community has particular 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. The ability of human communities to respond to environmental changes is directly related to their adaptive capacity—resources that can be leveraged by the human 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. If resource professionals, community leaders, and local organizations are to help communities adapt to changes, they must identify community vulnerabilities and sensitivities and also build 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 (Holtz et al. 2014, Woodruff and Stults 2016, Zimmerman and Faris 2010).

More Information

- The Resilience Alliance has created Assessing Resilience in Social-Ecological Systems: Workbook for Practitioners 2.0 to assess resilience of social-ecological systems. www.resalliance.org/resilience-assessment
- The U.S. Department of Energy examined current and potential future impacts of 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: https://nca2014.globalchange.gov/report/sectors/urban
  - Rural communities: https://nca2014.globalchange.gov/highlights/regions/rural-communities
  - Indigenous peoples, lands, and resources: https://nca2014.globalchange.gov/report/sectors/indigenous-peoples
- The Environmental Protection Agency's Green Streets, Green Towns, Green Jobs (G3) Initiative provides tools and resources for communities to create green infrastructure that helps manage stormwater runoff, protect water quality, address climate change, and create green jobs. https://www.epa.gov/G3/green-streets-green-jobs-green-towns-g3-initiative-and-approach

URBAN FORESTS

Climate change also affects urban forests in the assessment area, which include nature preserves, river corridors, wetlands, urban parks, street trees, gardens, buffers, and greenways. Urban environments can pose unique stresses to urban trees compared to rural trees, including vehicle exhaust, confined root environments, and road salts. Climate change is expected to exacerbate the effects of common stressors, although there is uncertainty about how stressors may interact with each other under changing conditions.

Storms, extreme temperatures, longer growing seasons, and warmer winters can pose particular challenges for infrastructure. Impervious surfaces can make urban environments more susceptible to flash floods, placing flood-intolerant species at risk. Extreme cold and freeze-thaw cycles can accelerate deterioration of concrete and other common infrastructure surrounding or containing trees. Extreme heat and longer growing seasons can result in rising costs associated with roadside and power line vegetation management.

Responses of trees to disturbances such as drought may vary by land use within an urban area, complicating predictions of how the forest may respond as a whole (Fahey et al. 2013). Native species that are projected to decline due to climate change are likely to be unable 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 that are projected to benefit from climate change. 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. For example, many community forests already address the urban heat island effect by planting species that are from hardiness zones south of the area or cultivars that tolerate a wide range of climate conditions.

Large disturbance events may also become more frequent or intense in the future, necessitating informed decisions in response. For example, wind events or pest outbreaks may be more damaging to already stressed trees. If leaf-out dates advance earlier in the spring due to climate change,

Waymart wind farm in Wayne, Pennsylvania. Photo by Greg Czarnecki, Pennsylvania Department of Conservation and Natural Resources, used with permission.

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.

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. 2016, City of Baltimore 2013, City of New York 2013, Philadelphia Water Department 2011). Shifts in temperature and changes in extreme events may have effects on species selection for planting (Yang 2009).

More Information

- The Forest Service Climate Change Resource Center provides a summary of how climate change may affect urban forests. www.fs.fed.us/ccrc/topics/urban-forests
- The Georgetown Climate Center highlights state and local adaptation plans. http://www.georgetownclimate.org/adaptation/plans.html
- Several urban areas have developed adaptation guides to help communities learn how to use urban forests to reduce climate change impacts and adapt urban forests to future conditions.
    - British Columbia: www.toolkit.bc.ca/Resource/Urban-Forests-Climate-Adaptation-Guide
    - Toronto, Ontario'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

HUMAN HEALTH

Climate change can affect in many ways the health of the people who live, work, or recreate in the forests and communities of the Mid-Atlantic region. Climate change can influence a wide array of human health issues through complex interactions in the environment and the human body (Portier et al. 2013, U.S. Global Change Research Program [USGCRP] 2016). 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 production (Ziska et al. 2011). Gastrointestinal illness could increase due to contaminated water caused by flooding or failed water infrastructure (USGCRP 2016). Extremely high temperatures can lead to heat stress, which can exacerbate cardiovascular disease or lead to heat-related illness and death.

Vector-borne diseases, such as Lyme disease and West Nile virus, pose an important risk to natural resource managers, local residents, and tourists alike, and this issue may become increasingly important during 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. Humans are typically infected incidentally when they are bitten instead of animal hosts. Changes in climate can influence vector-borne disease risk by altering the abundance and distribution of ticks or mosquitoes, the percentage of infected vectors, and the abundance, distribution, and available habitat of animal hosts. For example, blacklegged ticks (i.e., "deer ticks"), the vector for Lyme disease and several other diseases, are most abundant in wooded or brushy habitats with abundant numbers of small mammals and deer. Projected expansion of tick ranges combined with earlier seasonal activity may increase the incidence of tick-borne diseases if humans frequently visit those habitats (USGCRP 2016).

More Information

- The U.S. Global Change Research Program provides a scientific assessment of the impacts of climate change on human health in the United States, with summaries for various sectors and regions. This report was based on the 2014 National Climate Assessment. https://health2016.globalchange.gov/downloads
- The National Climate Assessment provides a summary of how climate change may affect human health. https://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/

CHAPTER SUMMARY

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

Addressing the challenge of climate change also 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 is intended as a useful foundation for land managers in that process, to be further enriched by local knowledge and site-specific information.

GLOSSARY

acid deposition
a complex chemical and atmospheric phenomenon that occurs when emissions of sulfur and nitrogen compounds are transformed in the atmosphere and deposited on land in either wet or dry form.

adaptive capacity
the ability of a species or ecosystem to accommodate or cope with potential climate change impacts with minimal disruption. It is strongly related to the concept of ecological resilience, which refers to the ability to return to prior conditions after a disturbance.

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

archaeology
the study of human history and prehistory through the excavation of sites and the analysis of artifacts and other physical remains.

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

barrens
plant communities that occur on sandy soils and are dominated by grasses, low shrubs, small trees, and scattered large trees.

baseflow
the condition of only groundwater providing the entire flow of a stream (during most of the year, streamflow is composed of both groundwater discharge and land surface runoff).

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

boreal forest
a forest that is found only between 50-55º and 65-70º N latitude and that is adapted to cool northern temperatures and low rainfall (less than 20 inches).

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

carbon sequestration
a natural or artificial process by which carbon dioxide is removed from the atmosphere and held in solid or liquid form. Forest carbon is often stored in wood, roots, leaves, and soil.

climate extreme
the occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable. For simplicity, both extreme weather events and extreme climate events are referred to collectively as “climate extremes” (IPCC 2007).

CO_2-equivalent
the concentration of CO_2 that would cause the same amount of radiative forcing as a given mixture of CO_2 and other forcing components.

coastal plain
flat, low-lying land adjacent to the Atlantic Ocean.

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.

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 processes
processes fundamental to the functioning of a healthy and sustainable ecosystem, usually involving the transfer of energy and substances from one medium or trophic level to another.

emissions scenario
a plausible representation of the future development of emissions of greenhouse gases and aerosols that are potentially radiatively active, based on certain demographic, technological, or environmental developments (IPCC 2007).

ethnobotany
the scientific study of the traditional knowledge and customs of a people concerning plants and their medical, religious, and other uses.

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

extratropical cyclone
a cyclone in the middle or high latitudes often containing a cold front that extends toward the equator for hundreds of miles.

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

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

forest type
a classification of forest land 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.

gale
an area of sustained surface winds of 39-54 miles per hour (34-47 knots).

general circulation model (GCM)
a mathematical model of the general circulation of a planetary atmosphere or ocean and based on the Navier–Stokes equations on a rotating sphere with thermodynamic terms for various energy sources.

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 weather and temperature are right for plants and crops to grow.

growing stock
a classification of timber inventory that includes live trees of commercial species meeting specified standards of quality or vigor. When associated with volume, this includes only trees 5.0 inches in diameter at breast height and larger.

habitat
those parts of the environment (aquatic, terrestrial, and atmospheric) often typified by a dominant plant form or physical characteristic, on which an organism depends, directly or indirectly, in order to carry out its life processes.

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).

impact model
simulations of impacts on trees, animals, and ecosystems; these models use GCM projections as inputs, and include additional inputs such as tree species, soil types, and life-history traits of individual species.

importance value
an index of the relative abundance of a species in a given community (0 = least abundant, 100 = most abundant).

industrial ownership
forest products companies that hold land and harvest and market timber.

intensity
amount of precipitation falling per unit of time.

interpolation
estimation of a value within two known values in a sequence of values.

Kyoto Protocol
adopted at the 1997 Third Session of the Conference of Parties to the UN Framework Convention on Climate Change in Kyoto, Japan; it contains legally binding commitments to reduce anthropogenic greenhouse gas emissions by at least 5 percent below 1990 levels in the period 2008-2012 (IPCC 2007).

lake-effect
the phenomena created in the surrounding area by weather passing over a large lake, especially any of the Great Lakes of the United States.

maritime
living near or at the ocean's edge.

mesic
pertaining to sites or habitats characterized by intermediate (moist, but neither wet nor dry) soil moisture conditions.

microclimate
the climate of a very small or restricted area, especially when this differs from the climate of the surrounding area.

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

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

nonindustrial ownership
an ownership class of private lands where the owner does not operate wood-using plants.

nonstocked
land that currently has less than 10 percent stocking but formerly met the definition of forest land. Forest conditions meeting this definition have few, if any, trees sampled. In these instances, the algorithm cannot assign a specific forest type and the resulting forest type code is 999, meaning nonstocked.

nor’easter
a storm along the East Coast of North America, so called because the winds over the coastal area are typically from the northeast. These storms may occur at any time of year but are most frequent and most violent between September and April.

northern hardwoods
forest type with wet-mesic to dry-mesic soils, medium to high soil nutrient level, and supporting trees species such as sugar maple (dominant), American basswood, hemlock, yellow birch, red maple, and white ash.

orographic lift
as an air mass is forced from a low elevation to a higher elevation, adiabatic cooling can raise the relative humidity to 100 percent, resulting in clouds and precipitation.

paleoecology
the study of fossil animals and plants in order to deduce their ecology and the environmental conditions in which they lived.

palynology
the study of pollen grains and other spores, especially as found in archaeological or geological deposits.

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 study of 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.

pioneer species
a plant capable of invading bare sites (for example, newly exposed soil), and persisting there until supplanted by successional species; or any new arrival in the early stages of succession.

plasticity
the ability of an organism to change its characteristics (gene expression or behavior) in response to changes in the environment.

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

projection
a model-derived estimate of future climate, and the pathway leading to it.

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

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

pyrophilic (pyrophobic)
a measure of fire tolerance (intolerance) related to tree attributes, such as bark thickness or leaf flammability.

radiative forcing
the change in net irradiance between different layers of the atmosphere. A positive forcing (more incoming energy) tends to warm the system; a negative forcing (more outgoing energy) tends to cool it. Causes include changes in solar radiation or concentrations of radiatively active gases and aerosols.

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.

recharge
the natural process of movement of rainwater from land areas or streams through permeable soils into water-holding rocks that provide underground storage (that is, aquifers).

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

regression analysis
a statistical process for estimating the relationships among variables. Linear regression models the past relationship among variables to predict their future behavior. It includes many techniques for modeling and analyzing several variables.

resilience
the ability to return to prior or near-prior conditions after a disturbance, albeit with sometimes fluctuating populations or shifts in condition. Resilience is effective until the degree of disturbance exceeds the ability of the system to cope, resulting in transition to another state.

respiration
the process by which plants absorb free molecules of oxygen and use them to create water, carbon dioxide, and energy, which help the plant grow. Water and carbon dioxide can be released into the air.

roundwood
logs, bolts, and other round timber generated from harvesting trees for industrial or consumer use.

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

saltwater intrusion
the movement of saline water into freshwater aquifers through several pathways, including by lateral intrusion from the ocean; by upward intrusion from deeper, more saline zones of a groundwater system; and by downward intrusion from coastal waters.

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.

sawtimber
a live tree of commercial species containing at least a 12-foot saw log or two noncontiguous 8-foot or longer saw logs, and meeting specifications for form; softwoods must be at least 9 inches, and hardwoods must be at least 11 inches, in diameter outside the bark.

scenario
a coherent, internally consistent, and plausible description of a possible future state of the world. It is not a forecast; rather, each scenario is one alternative image of how the future can unfold. A projection may serve as the raw material for a scenario, but scenarios often require additional information (IPCC 2007).

sea level
the level of the ocean's surface, which can change regularly with the tides, wind, and currents. Other factors that contribute to the sea level include water temperature and salinity, air pressure, seasonal changes, the amount of stream runoff, and the amount of water that is stored as ice or snow. The standard for terrestrial and atmospheric elevation or ocean depths is called the mean sea level and is calculated as the average of hourly tide levels.

senescence
the final stage of leaf development, which results in autumn colors in forests of deciduous trees, and is part of the process by which nutrients are recycled to other parts of the plant.

serotinous cone
resin-covered cones that require heat, such as from wildfire, to melt the resin so that the cone can open and release seeds.

significant trend
significant trends are least-squares regression p-values of observed climate trends. In this report, significant trends ($p < 0.10$) are shown by stippling on maps of observed climate trends. Where no stippling appears ($p > 0.10$), observed trends have a higher probability of being due to chance alone (Girvetz et al. 2009).

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

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

solar radiation
energy radiated from the sun in the form of electromagnetic waves, including visible and ultraviolet light and infrared radiation.

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
referring to patterns resulting from random effects.

storm surge
water that is pushed onto shore during a rising of the sea as a result of atmospheric pressure changes and wind.

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

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

threat
a source of danger or harm.

tidal flooding
the temporary inundation of low-lying areas, especially streets, during exceptionally high tide events, such as at full and new moons.

topkill
death of aboveground tree stem and branches.

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

uncertainty
a term used to describe the range of possible values around a best estimate, sometimes expressed in terms of probability or likelihood.

urban heat island effect
a term describing the condition of built-up areas that are hotter than nearby rural areas. For example, the annual mean air temperature of a city with 1 million people or more can be 1.8 to 5.4 °F (1 to 3 °C) warmer than its surroundings.

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
susceptibility to a threat.

witness trees
trees that rested at the imaginary corners and angles of the parcels to mark their boundaries; these trees were documented by early land surveyors.

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APPENDIXES

These five appendixes are an expanded version of Appendixes 1 through 5 in the print edition of Butler-Leopold and others' (2018) Mid-Atlantic Forest Ecosystem Vulnerability Assessment and Synthesis: a Report from the Mid-Atlantic Climate Change Response Framework Project. In the following pages, you'll find:

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

Table 27.—Common and scientific names of native plant species mentioned in this assessment

Common name	Scientific name
American basswood	*Tilia americana*
American beech	*Fagus grandifolia*
American chestnut	*Castanea dentata*
American elm	*Ulmus americana*
American hazelnut	*Corylus americana*
American holly	*Ilex opaca*
American hornbeam (musclewood)	*Carpinus caroliniana*
American mountain-ash	*Sorbus americana*
Atlantic white-cedar	*Chamaecyparis thyoides*
baldcypress	*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*
bluejack oak	*Quercus incana*
boxelder	*Acer negundo*
bur oak	*Quercus macrocarpa*
butternut	*Juglans cinerea*
cedar elm	*Ulmus crassifolia*
cherrybark oak	*Quercus pagoda*
chestnut oak	*Quercus prinus*
chinkapin oak	*Quercus muehlenbergii*
chokecherry	*Prunus virginiana*
common hackberry	*Celtis occidentalis*
cucumber tree	*Magnolia acuminata*
eastern cottonwood	*Populus deltoides*
eastern hemlock	*Tsuga canadensis*
eastern hophornbeam	*Ostrya virginiana*
eastern redbud	*Cercis canadensis*
eastern redcedar	*Juniperus virginiana*
eastern white pine	*Pinus strobus*
flowering dogwood	*Cornus florida*
gray birch	*Betula populifolia*
green ash	*Fraxinus pennsylvanica*
honeylocust	*Gleditsia triacanthos*
jack pine	*Pinus banksiana*
laurel oak	*Quercus laurifolia*
loblolly pine	*Pinus taeda*
longleaf pine	*Pinus palustris*
mockernut hickory	*Carya alba*
mountain maple	*Acer spicatum*
northern catalpa	*Catalpa speciosa*
northern red oak	*Quercus rubra*
northern white-cedar	*Thuja occidentalis*
Ohio buckeye	*Aesculus glabra*
Osage-orange	*Maclura pomifera*
overcup oak	*Quercus lyrata*
paper birch	*Betula papyrifera*
pawpaw	*Asimina triloba*
pecan	*Carya illinoinensis*
persimmon	*Diospyros virginiana*
pignut hickory	*Carya glabra*
pin cherry	*Prunus pensylvanica*
pin oak	*Quercus palustris*
pitch pine	*Pinus rigida*

(continued on next page)

Table 27 (continued).

Common name	Scientific name
pond pine	*Pinus serotina*
post oak	*Quercus stellata*
pumpkin ash	*Fraxinus profunda*
quaking aspen	*Populus tremuloides*
red maple	*Acer rubrum*
red mulberry	*Morus rubra*
red pine	*Pinus resinosa*
red spruce	*Picea rubens*
redbay	*Persea borbonia*
river birch	*Betula nigra*
rock elm	*Ulmus thomasii*
sassafras	*Sassafras albidum*
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*
slash pine	*Pinus elliottii*
slippery elm	*Ulmus rubra*
sourwood	*Oxydendrum arboreum*
southern red oak	*Quercus falcata*
striped maple	*Acer pensylvanicum*
sugar maple	*Acer saccharum*

Common name	Scientific name
sugarberry	*Celtis laevigata*
swamp chestnut oak	*Quercus michauxii*
swamp tupelo	*Nyssa biflora*
swamp white oak	*Quercus bicolor*
sweet birch	*Betula lenta*
sweetbay	*Magnolia virginiana*
sweetgum	*Liquidambar styraciflua*
sycamore	*Platanus occidentalis*
Table Mountain pine	*Pinus pungens*
tamarack	*Larix laricina*
tulip tree (yellow-poplar)	*Liriodendron tulipifera*
turkey oak	*Quercus cerris*
Virginia pine	*Pinus virginiana*
water elm	*Planera aquatica*
water hickory	*Carya aquatica*
water locust	*Gleditsia aquatica*
water oak	*Quercus nigra*
water tupelo	*Nyssa aquatica*
white ash	*Fraxinus americana*
white oak	*Quercus alba*
white spruce	*Picea glauca*
white trillium	*Trillium grandiflorum*
willow oak	*Quercus phellos*
winged elm	*Ulmus alata*
yellow birch	*Betula alleghaniensis*
yellow buckeye	*Aesculus flava*

Table 28.—Common and scientific names of nonnative invasive plants, and fauna, fungus, and pathogen species mentioned in this assessment

Nonnative invasive plants

Common name	Scientific name
ailanthus	*Ailanthus altissima*
garlic mustard	*Alliaria petiolata*
Japanese barberry	*Berberis thunbergii*
Japanese bromegrass	*Bromus japonicus*
barren bromegrass	*Bromus sterilis*
cheatgrass	*Bromus tectorum*
Oriental bittersweet	*Celastrus orbiculatus*
spotted knapweed	*Centaurea maculosa*
autumn olive	*Elaeagnus umbellata*
winter creeper	*Euonymus fortunei*
burning bush	*Euonymus* spp.
Japanese knotweed	*Reynoutria japonica* Houtt.
common buckthorn	*Frangula alnus*
Chinese bushclover	*Lespedeza cuneata*
privet	*Ligustrum vulgare*
Japanese honeysuckle	*Lonicera japonica*
Amur honeysuckle	*Lonicera maackii*
bush honeysuckles	*Lonicera mackii* and others
Japanese stiltgrass	*Microstegium vimineum*
princess tree	*Paulownia tomentusa*
mile-a-minute vine	*Persicaria perfoliata*
reed canarygrass	*Phalaris arundinacea*
common reed (phragmites)	*Phragmites australis*
kudzu	*Pueraria lobata*
glossy buckthorn	*Rhamnus* spp.
multiflora rose	*Rosa multiflora*
wineberry	*Rubus phoenicolasius*
crown vetch	*Securigera varia*
wisteria	*Wisteria frutescens*

Fauna, fungi, and pathogens

Common name	Scientific name
balsam woolly adelgid	*Adelges piceae*
hemlock woolly adelgid	*Adelges tsugae*
two-lined chestnut borer	*Agrilus bilineatus* (Weber)
emerald ash borer	*Agrilus planipennis*
dwarf wedgemussel	*Alasmidonta heterodon*
fall cankerworm	*Alsophila pometaria*
Jefferson salamander	*Ambystoma jeffersonianum*
Asian longhorned beetle	*Anoplophora glabripennis*
armillaria	*Armillaria mellea*
Lyme disease	*Borrelia burgdorferi*
pine looper	*Bupalus piniaria*
elm yellows	*Candidatus phytoplasma ulmi*
spruce budworm	*Choristoneura fumiferana*
chestnut blight	*Cryphonectria parasitica*
beech bark disease	a complex of the scale insect *Cryptococcus fagisuga* and the fungus *Nectria* spp.
southern pine beetle	*Dendroctonus frontalis* Zimmermann
West Nile virus	*Flavivirus* spp.
pine barrens tree frog	*Hyla andersonii*
black-legged tick	*Ixodes scapularis*
snowshoe hare	*Lepus americanus*
earthworm	*Lumbricina* spp.
gypsy moth	*Lymantria dispar dispar*
eastern tent caterpillar	*Malacosoma americanum*
forest tent caterpillar	*Malacosoma disstria*
eastern pearlshell	*Margaritifera margaritifera*
morel mushroom	*Morchella esculenta*
white-tailed deer	*Odocoileus virginianus*
Dutch elm disease	*Ophiostoma ulmi*
sudden oak death	*Phytophthora ramorum*
black-capped chickadee	*Poecile atricapillus*
Carolina chickadee	*Poecile carolinensis*
purple martin	*Progne subis*
brook trout	*Salvelinus fontinalis*
eastern fence lizard	*Sceloporus undulatus*
eastern spotted skunk	*Spilogale putorius*
Appalachian cottontail	*Sylvilagus obscurus*
golden-winged warbler	*Vermivora chrysoptera*
red fox	*Vulpes vulpes*

APPENDIX 2: TREND ANALYSIS AND HISTORICAL CLIMATE DATA

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

A 30-year climate "normal" for the assessment area was calculated from the mean for the period 1971 through 2000 (Figs. 39-40). Linear trend analysis was performed for the period of 1901 through 2011 by using restricted maximum likelihood (REML) estimation (Girvetz et al. 2009). Restricted maximum likelihood methods were used for trend analysis of past climate for the Intergovernmental Panel on Climate Change Working Group 1 Report and are considered an effective way to determine trends in climate data over time (Trenberth et al. 2007). A first-order autoregression was assumed for the residuals, meaning that values one timestep 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 by year, season, and month for each climate variable, and then mapped. An overall trend for an area is based on the trend analysis of the average value for all grid cells within the area over time (Table 29).

The developers of the Climate Wizard Tool advise users to interpret the linear trend maps in relation to the respective map of statistical confidence (Figs. 41-42). In this case, statistical confidence is described by using *p*-values from a t-test applied to the linear regression. A *p*-value can be interpreted as the probability of the slope being different from zero by chance. For this assessment, *p*-values of less than 0.1 were considered to have sufficient statistical confidence. Areas with low statistical confidence in the rate of change (gray areas on the map) should be interpreted with greater caution.

In addition, 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). Therefore,

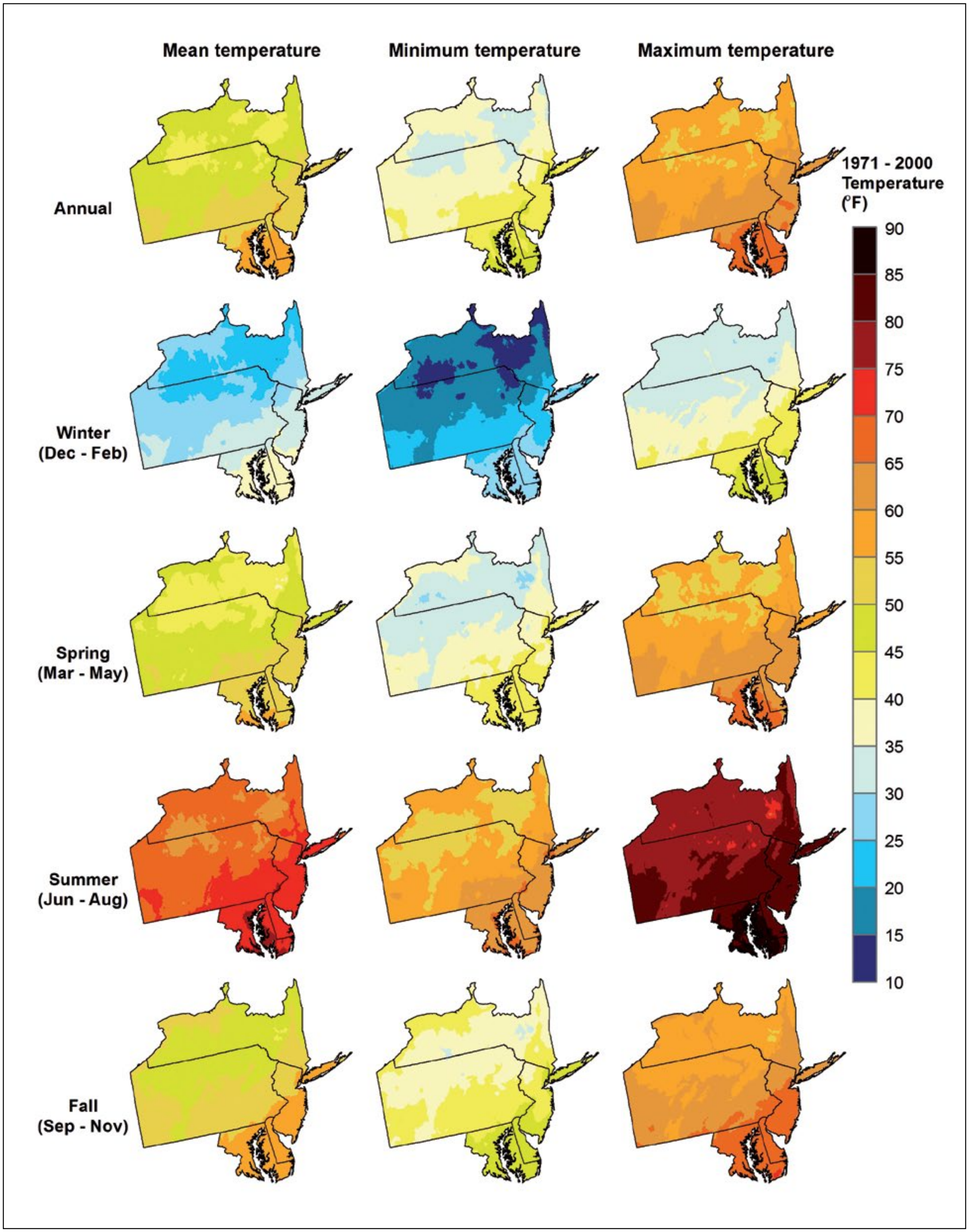

Figure 39.—Annual and seasonal mean, minimum, and maximum temperatures (°F) during the 30-year period from 1971 through 2000. Data from Climate Wizard (2014).

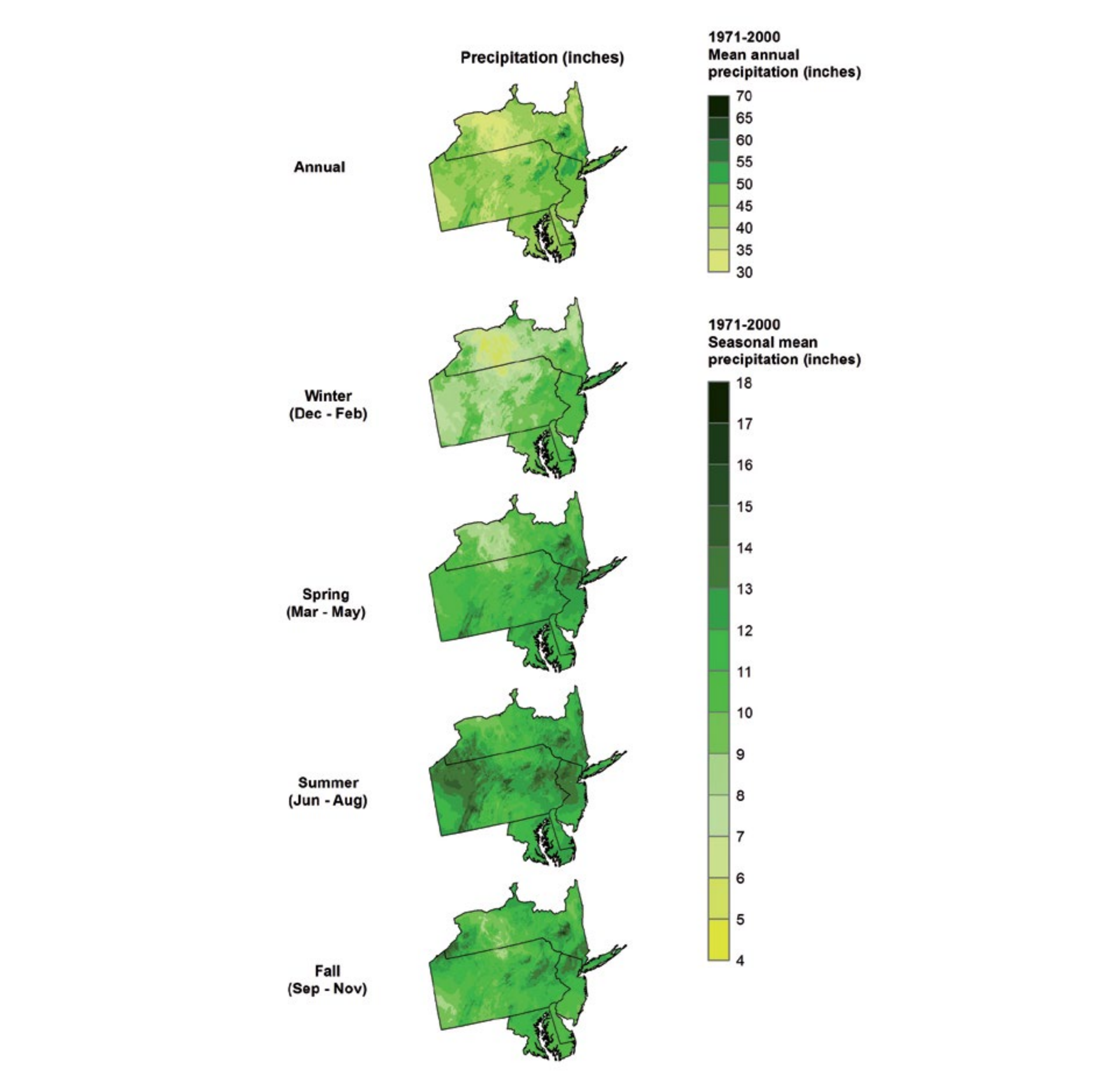

Figure 40.—Mean annual and mean seasonal precipitation during the 30-year period from 1971 through 2000. Data from Climate Wizard (2014).

Table 29.—Annual and seasonal mean, minimum, and maximum temperature and annual total precipitation in the Mid-Atlantic region for the 30-year period from 1971 through 2000 (data source: Climate Wizard [2014])

Season	Mean temperature (°F)	Minimum temperature (°F)	Maximum temperature (°F)	Mean precipitation (inches)
Annual	49.2	38.8	59.5	43.4
Winter (Dec-Feb)	28.5	19.8	37.3	9.1
Spring (Mar-May)	47.6	36.4	58.7	11.1
Summer (Jun-Aug)	69.0	57.8	80.2	12.1
Fall (Sep-Nov)	51.6	41.3	61.9	11.1

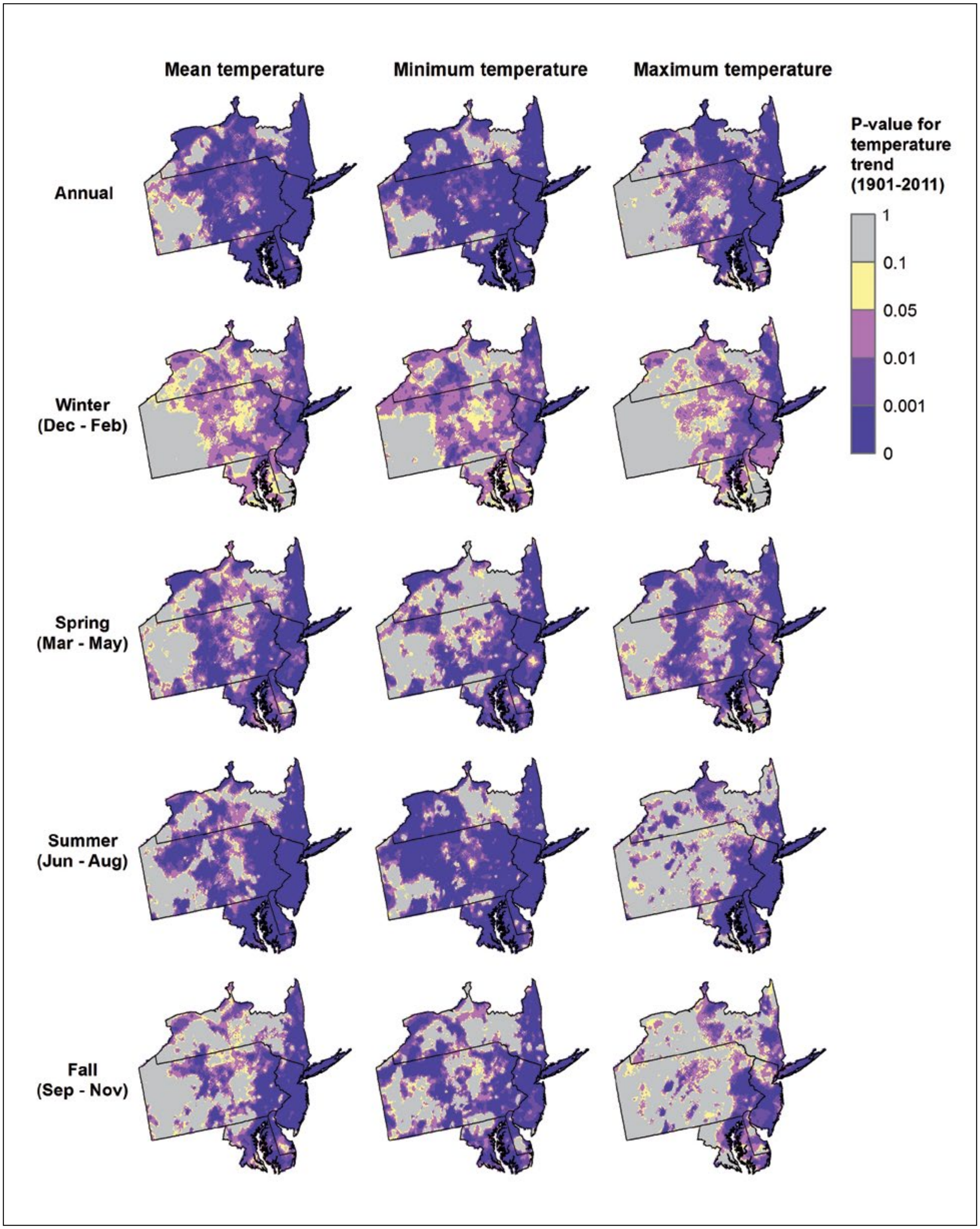

Figure 41.—Statistical confidence (*p*-values for the linear regression) for trends in temperature, 1901 through 2011. Gray values represent areas of low statistical confidence.

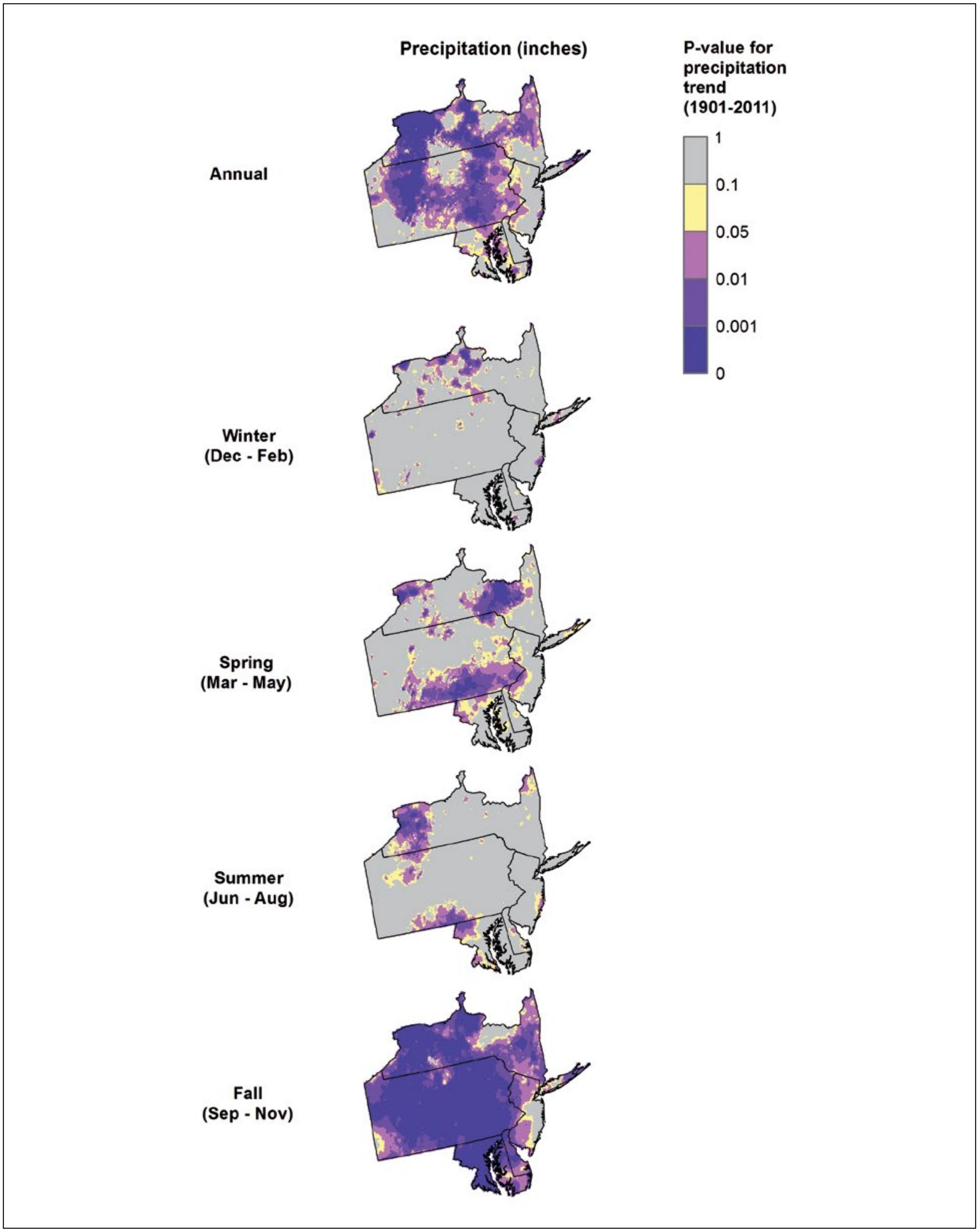

Figure 42.—Statistical confidence (*p*-values for the linear regression) for trends in precipitation, 1901 through 2011. Gray values represent areas of low statistical confidence.

interpretations should be based on many grid cells showing regional patterns of climate change with high statistical confidence. For those interested in understanding trends in climate at a particular location, it is best to refer to weather station data for the closest station in the Global Historical Climatology Network from the National Centers for Environmental Information (https://www.ncdc.noaa.gov).

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

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APPENDIX 3: ADDITIONAL FUTURE CLIMATE PROJECTIONS

This appendix provides maps of projected change in temperature and precipitation in the Mid-Atlantic region for the early and mid-21st century (Figs. 43-50) as supplementary information to Chapter 4. Also presented are graphs of historical (baseline) temperature and precipitation by season in the assessment area, and projected trends through the end of the century (Figs. 51-55).

White trillium along the Longhouse Scenic Byway, Allegheny National Forest, Pennsylvania. This byway is home to many other spring wildflowers. Photo by Kathleen Creek, Allegheny National Forest.

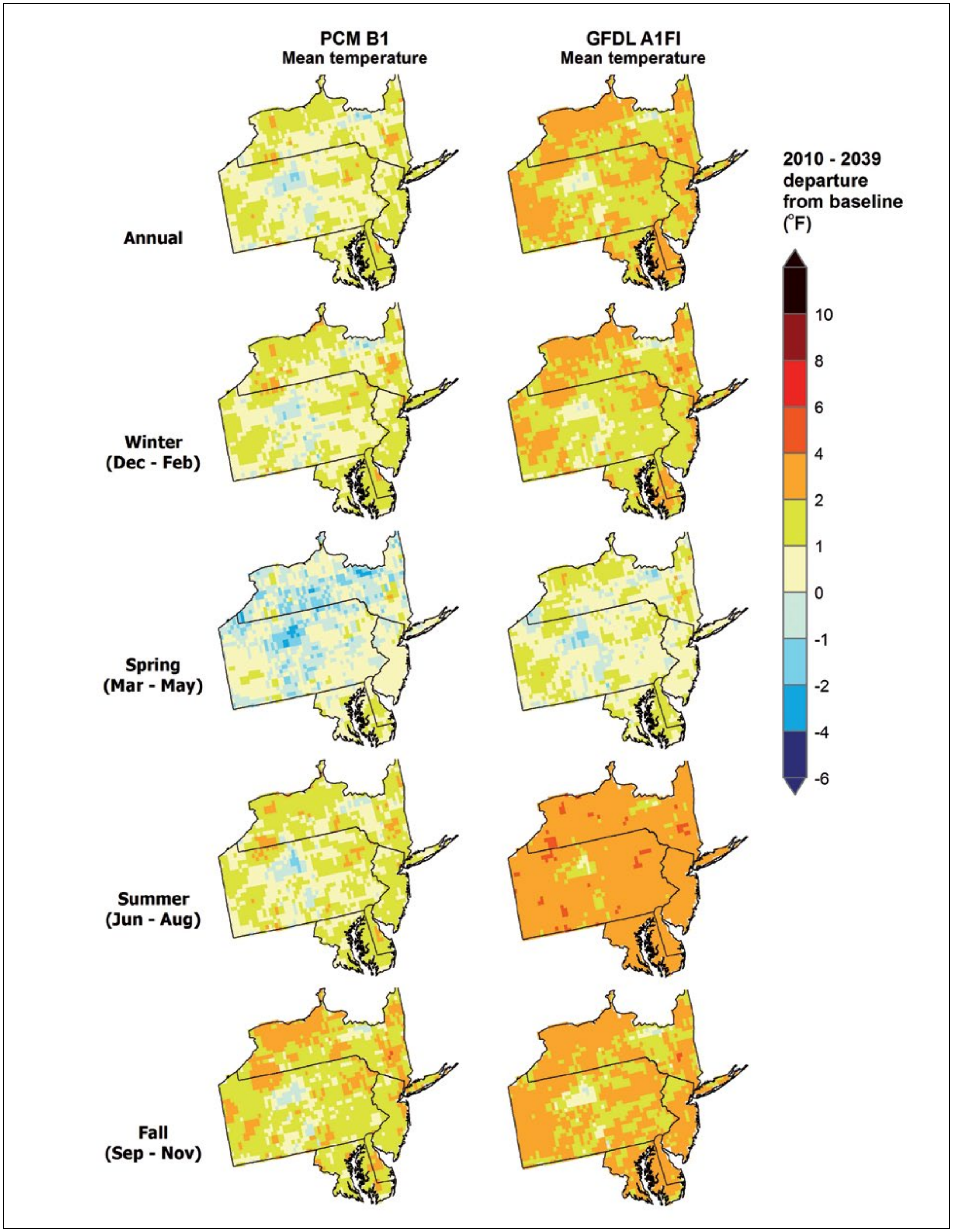

Figure 43.—Projected difference in mean daily mean temperature (°F) at the beginning of the century (2010 through 2039) compared to baseline (1971 through 2000) for two climate model-emissions scenario combinations.

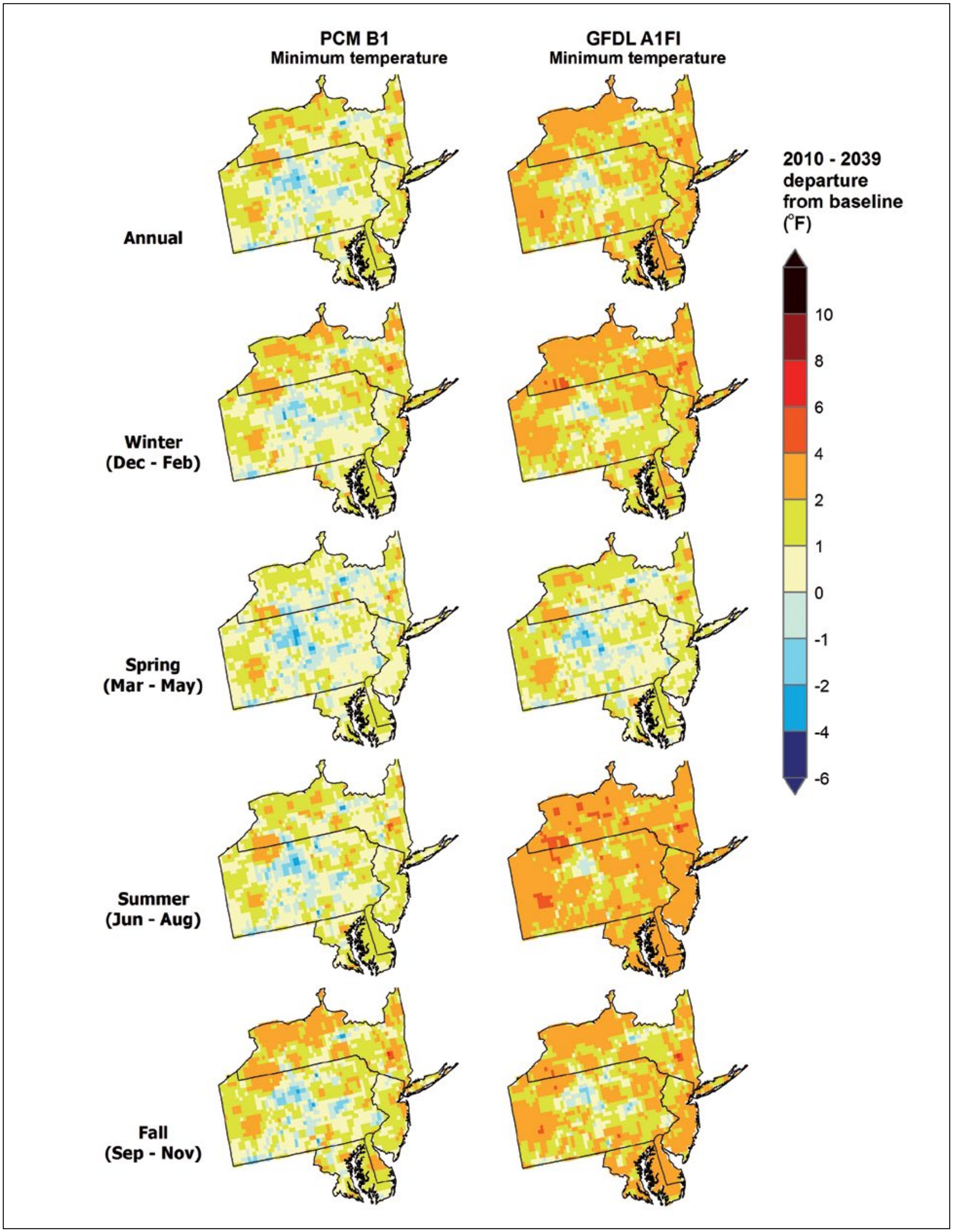

Figure 44.—Projected difference in mean daily minimum temperature (°F) at the beginning of the century (2010 through 2039) compared to baseline (1971 through 2000) for two climate model-emissions scenario combinations.

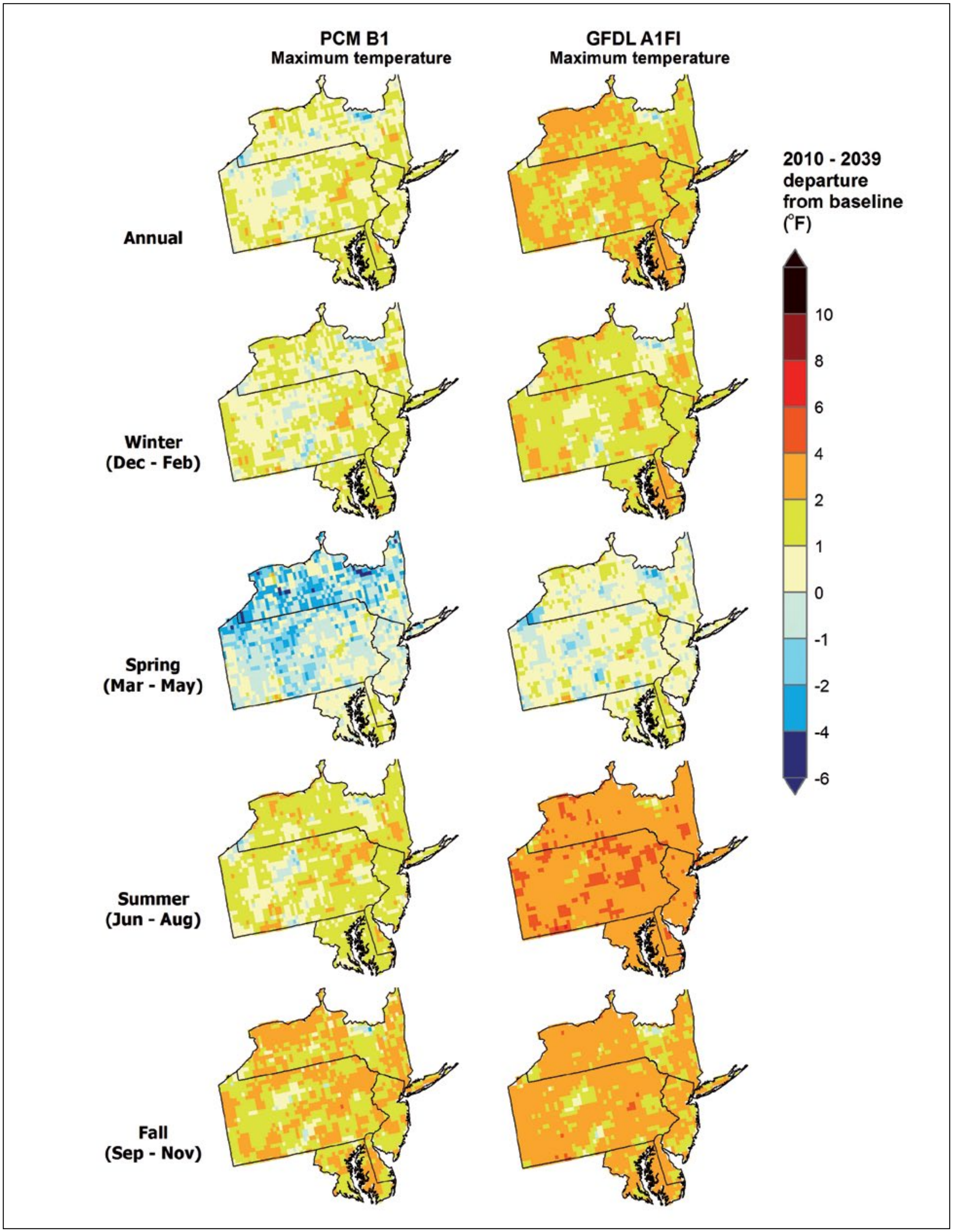

Figure 45.—Projected difference in mean daily maximum temperature (°F) at the beginning of the century (2010 through 2039) compared to baseline (1971 through 2000) for two climate model-emissions scenario combinations.

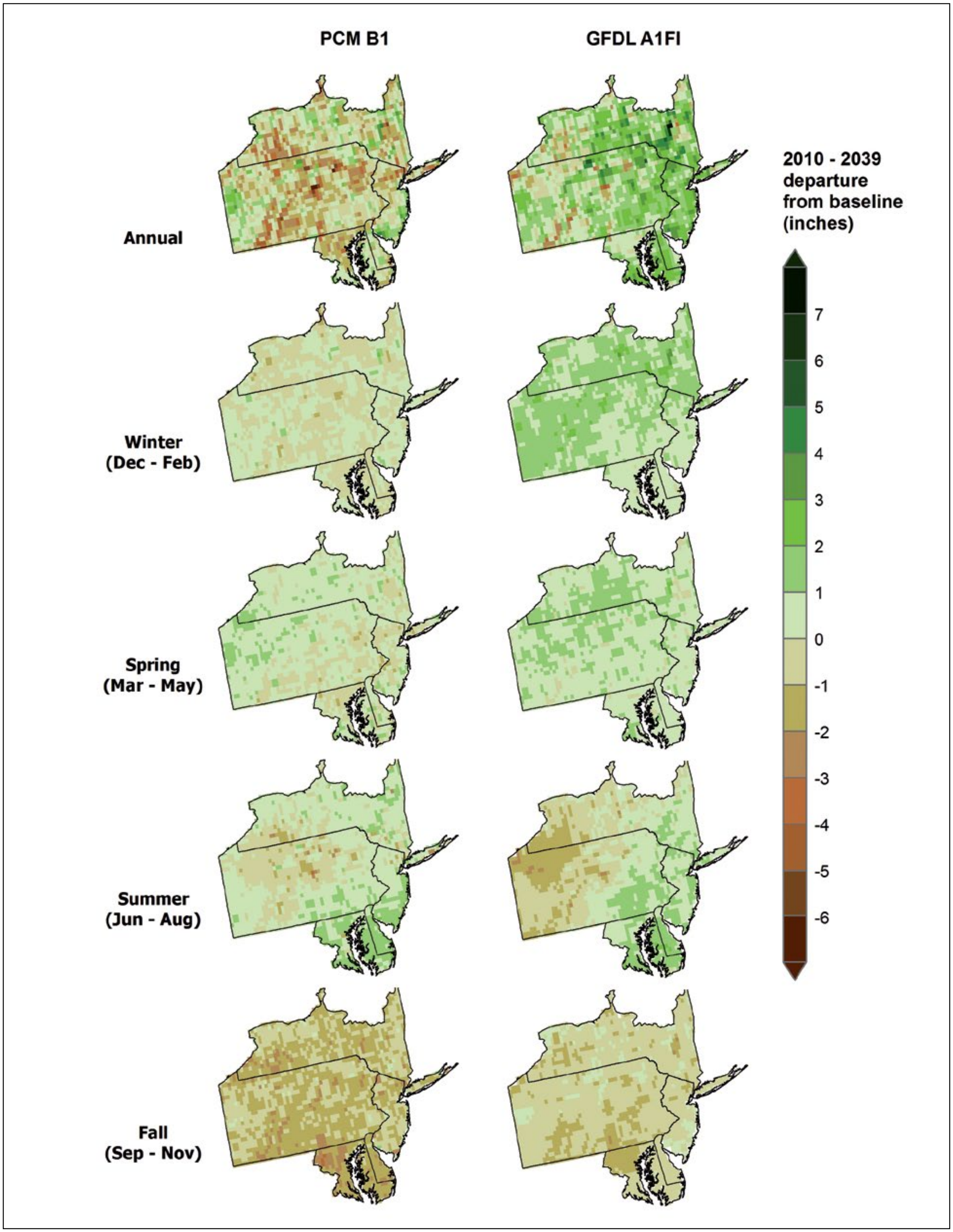

Figure 46.—Projected difference in precipitation (inches) at the beginning of the century (2010 through 2039) compared to baseline (1971 through 2000) for two climate model-emissions scenario combinations.

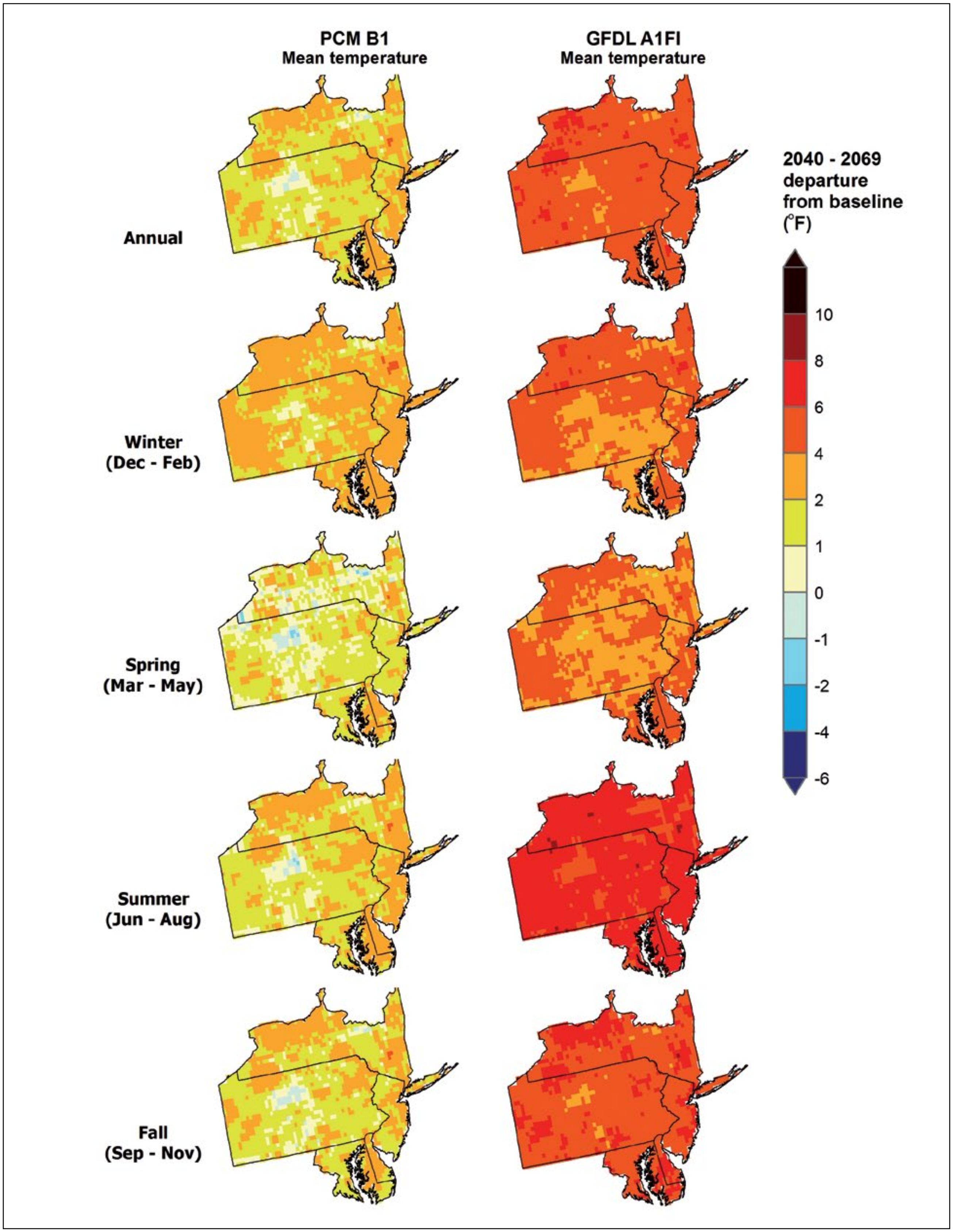

Figure 47.—Projected difference in mean daily mean temperature (°F) for the middle of the century (2040 through 2069) compared to baseline (1971 through 2000) for two climate model-emissions scenario combinations.

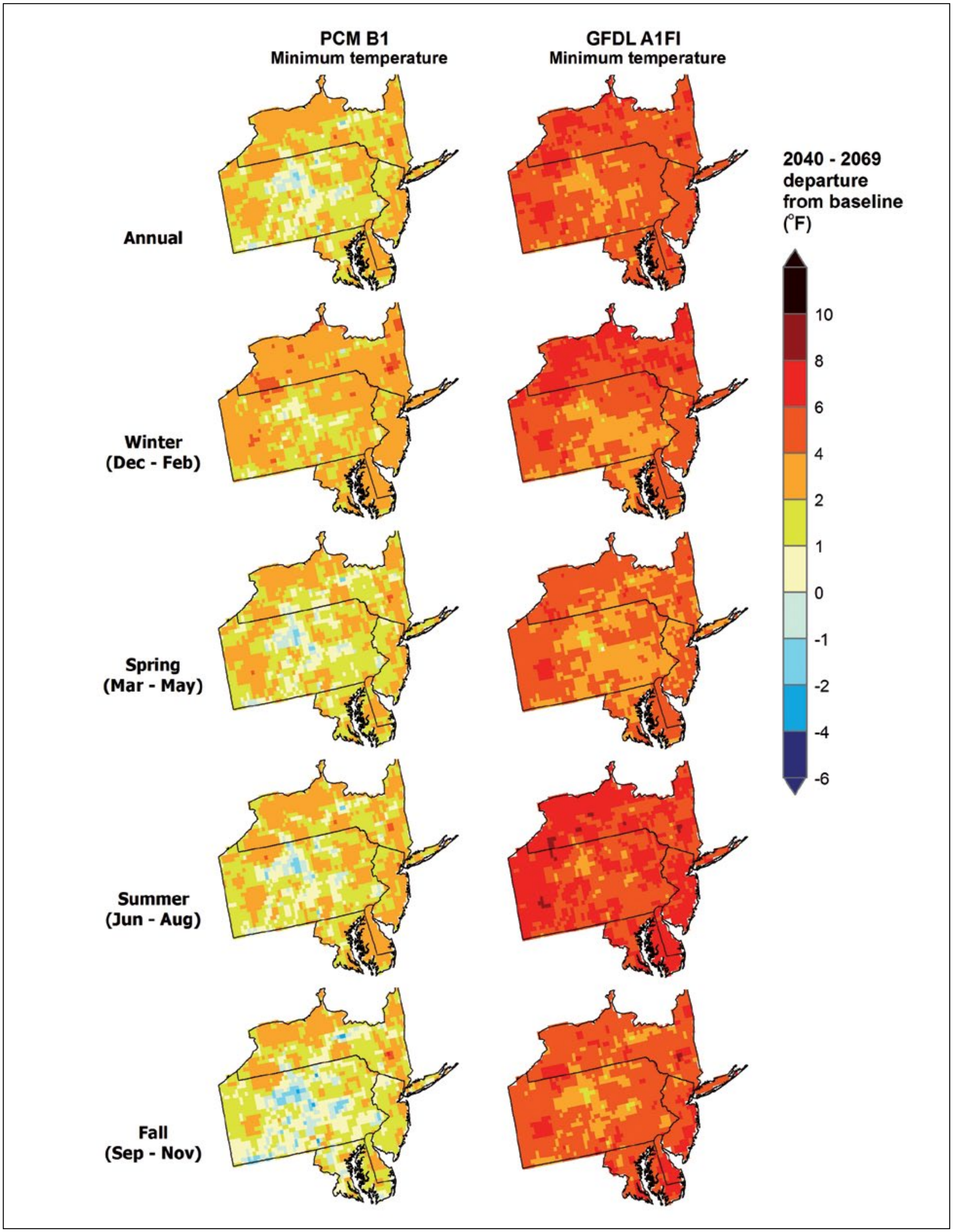

Figure 48.—Projected difference in mean daily minimum temperature (°F) for the middle of the century (2040 through 2069) compared to baseline (1971 through 2000) for two climate model-emissions scenario combinations.

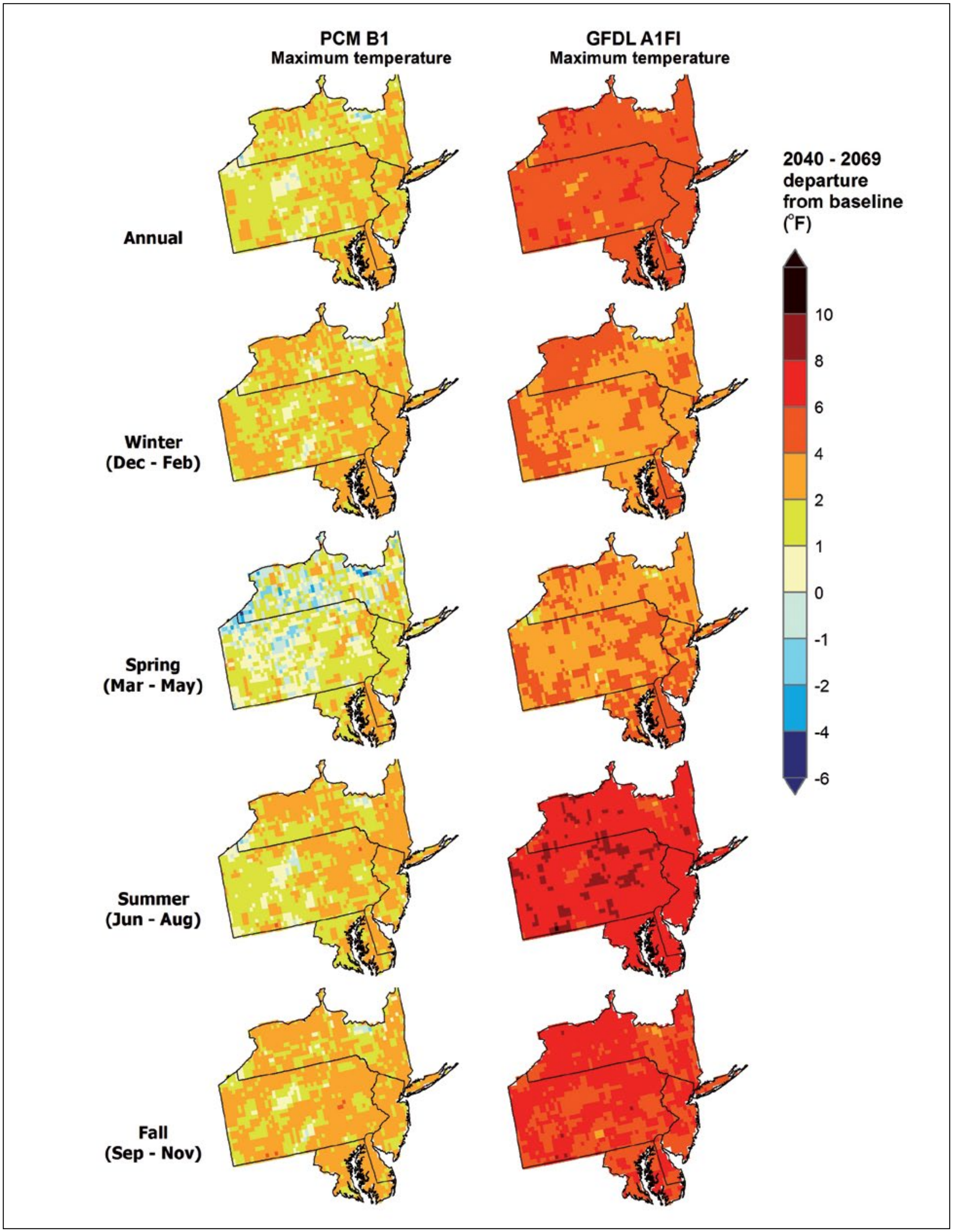

Figure 49.—Projected difference in mean daily maximum temperature (°F) for the middle of the century (2040 through 2069) compared to baseline (1971 through 2000) for two climate model-emissions scenario combinations.

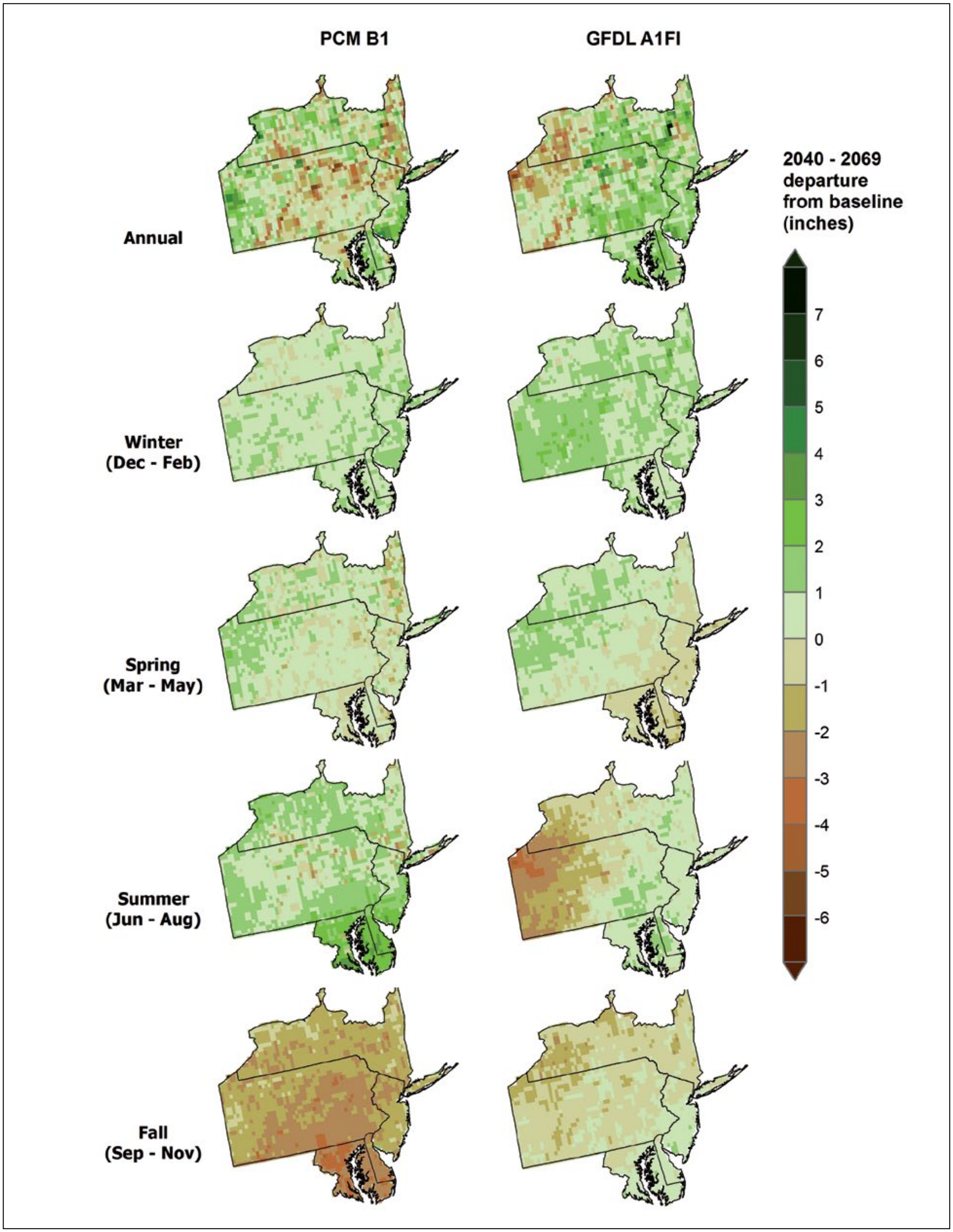

Figure 50.—Projected difference in precipitation (inches) for the middle of the century (2040 through 2069) compared to baseline (1971 through 2000) for two climate model-emissions scenario combinations.

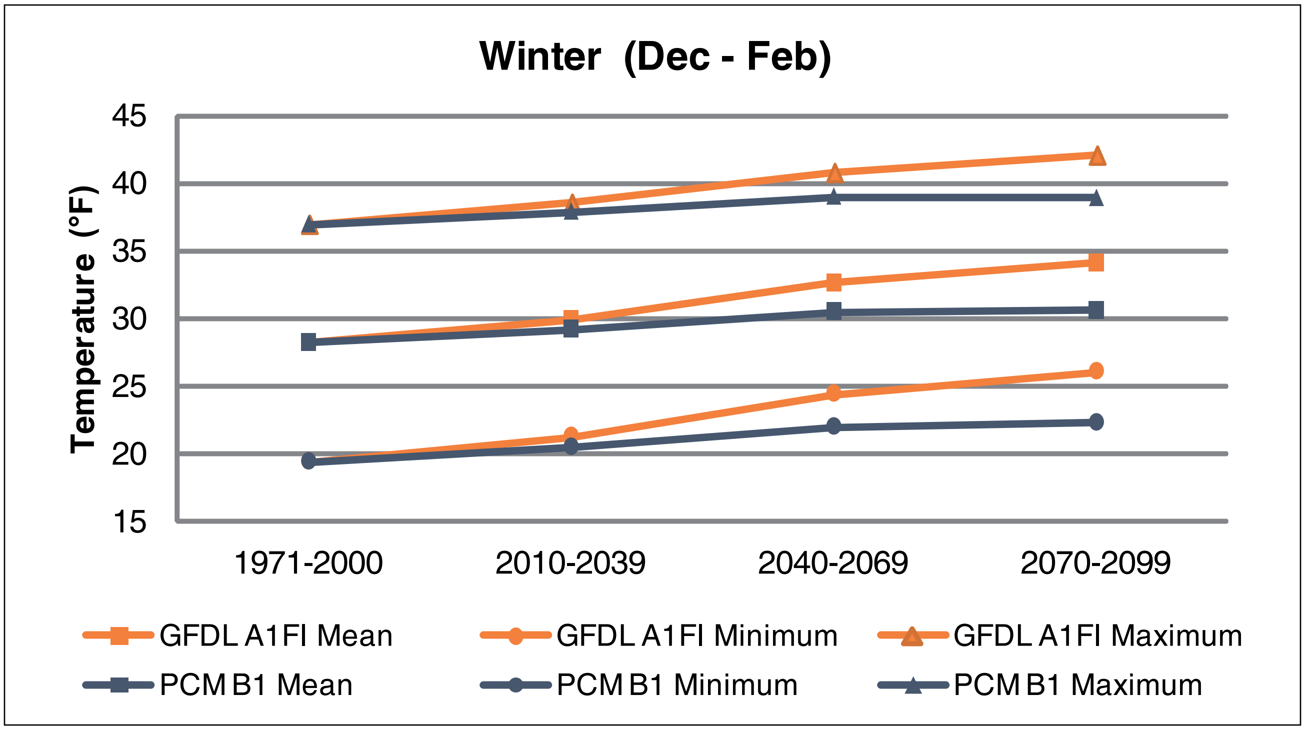

Figure 51.—Projected change in mean winter mean, minimum, and maximum temperatures in the assessment area averaged over 30-year periods for two climate model-emissions scenarios. The 1971 through 2000 value is based on observed data from weather stations.

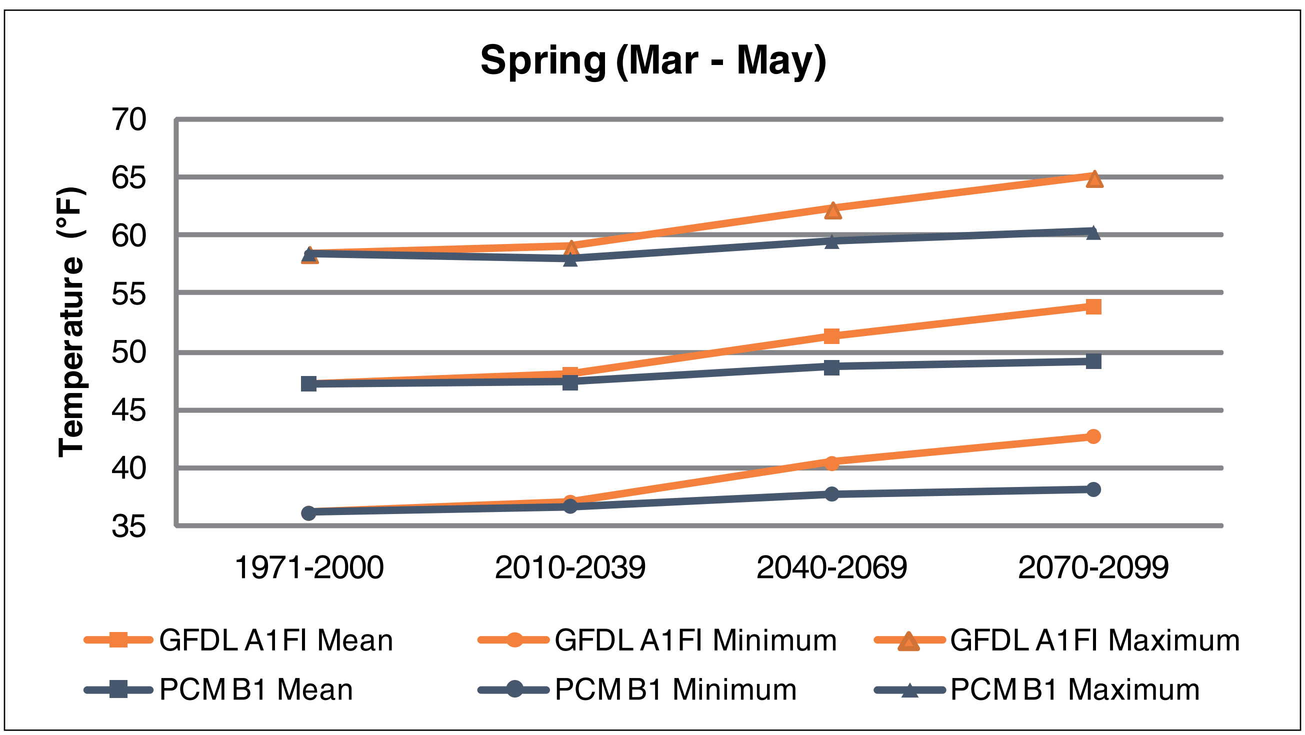

Figure 52.—Projected change in mean spring mean, minimum, and maximum temperatures in the assessment area averaged over 30-year periods for two climate model-emissions scenario combinations. The 1971 through 2000 value is based on observed data from weather stations.

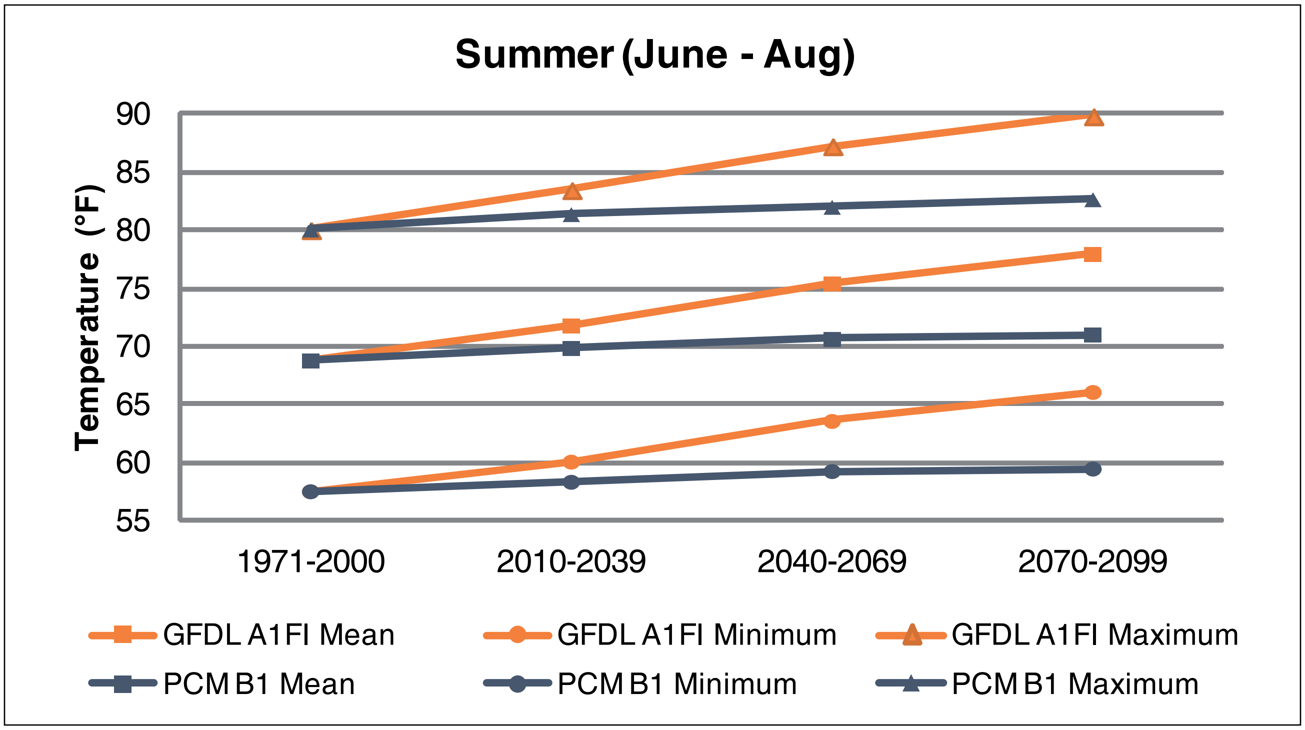

Figure 53.—Projected change in mean summer mean, minimum, and maximum temperatures in the assessment area averaged over 30-year periods for two climate model-emissions scenario combinations. The 1971 through 2000 value is based on observed data from weather stations.

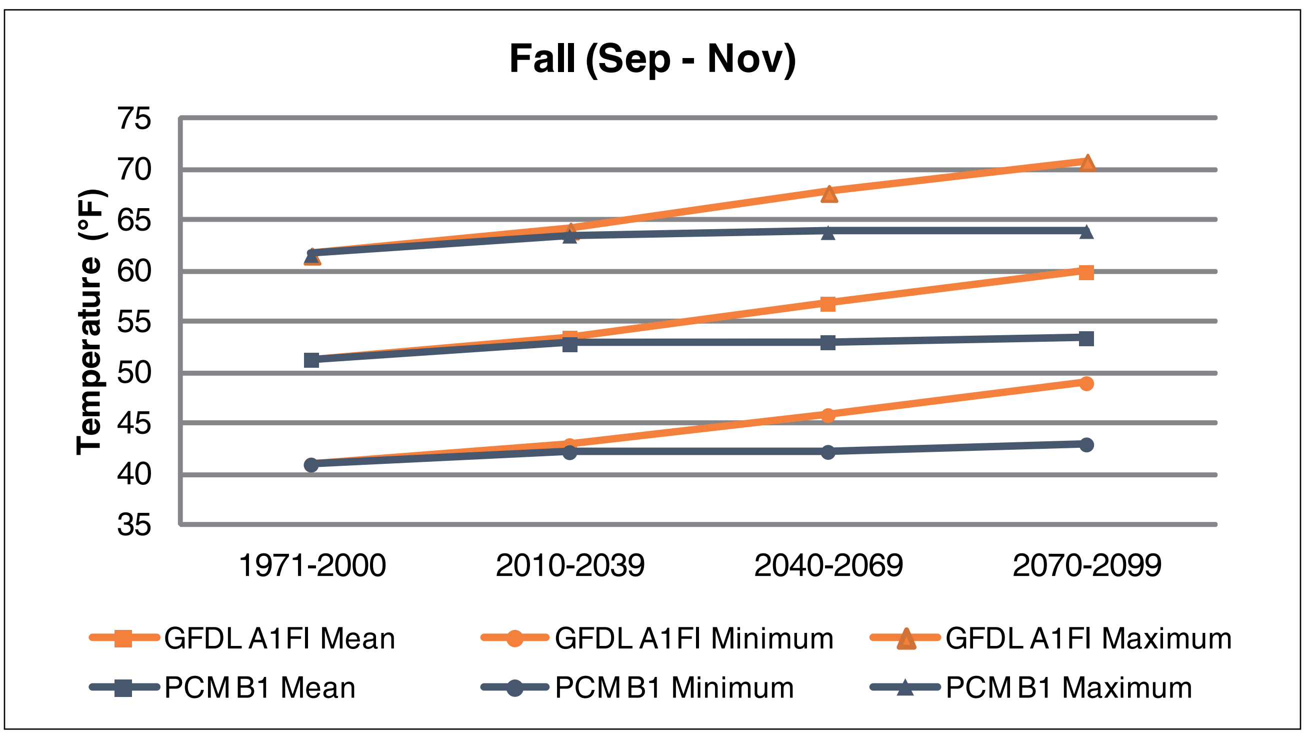

Figure 54.—Projected change in mean fall mean, minimum, and maximum temperatures in the assessment area averaged over 30-year periods for two climate model-emissions scenario combinations. The 1971 through 2000 value is based on observed data from weather stations.

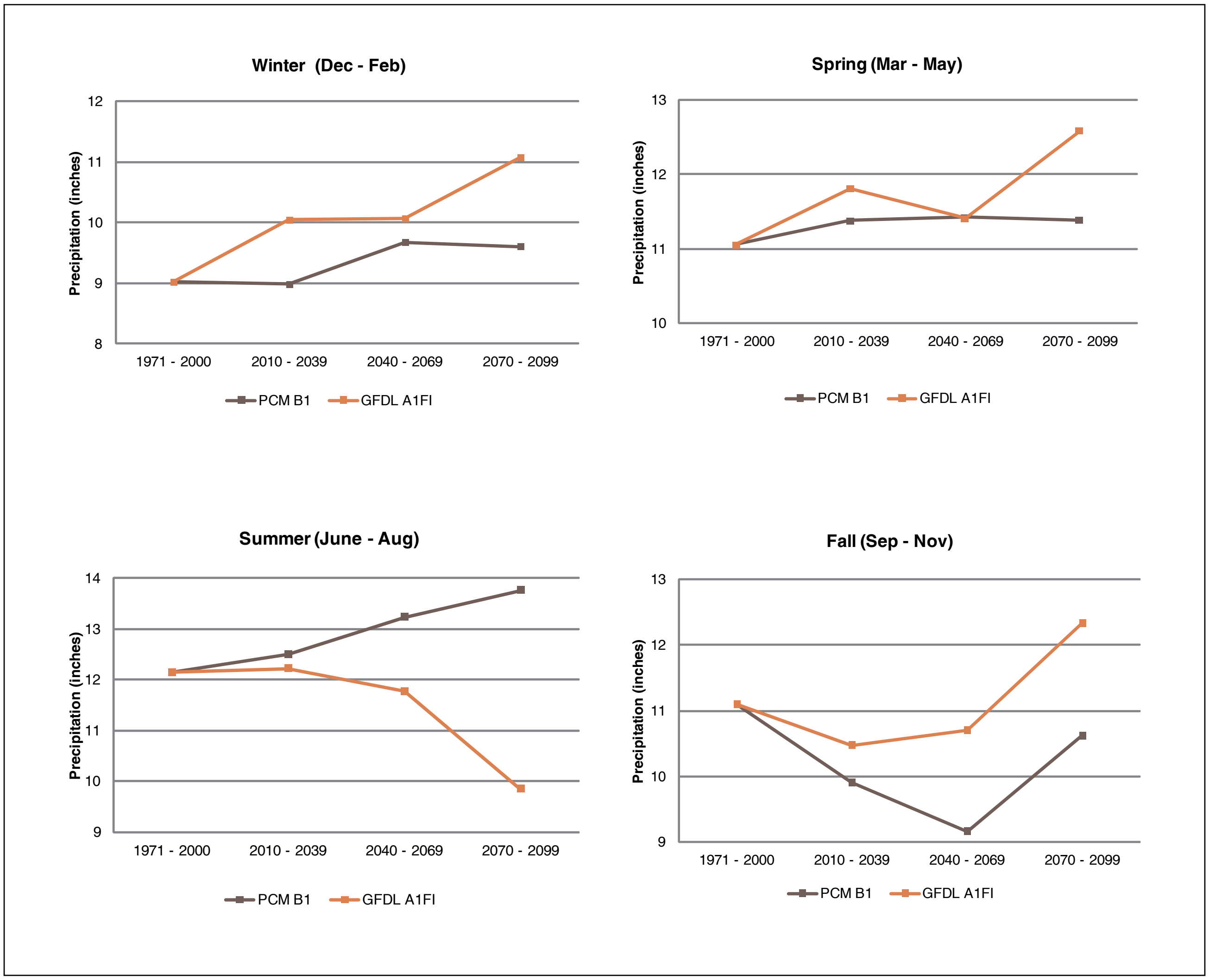

Figure 55.—Projected change in winter, spring, summer, and fall precipitation in the assessment area averaged over 30-year periods for two climate model-emissions scenario combinations. The 1971 through 2000 value is based on observed data from weather stations. Note that the precipitation axes are different depending on the season.

APPENDIX 4: ADDITIONAL IMPACT MODEL RESULTS AND DISCUSSION

This appendix provides supplementary information to Chapter 5. The following pages contain additional model results and modifying factors from the Climate Change Tree Atlas, LINKAGES, and LANDIS PRO models. We discuss each of the three forest impact models further and explain how change classes were determined for each model. Scientific names for all species are provided in Appendix 1. See Chapter 2 for a description of the models and Chapter 5 for a discussion of model results, uncertainty, and limitations.

CLIMATE CHANGE TREE ATLAS MODEL RESULTS

Tables 30 through 37, beginning on page 275, show results of the DISTRIB model used in the Tree Atlas averaged over the whole assessment area, and for each subregion within the assessment area. Measured area-weighted importance values (IVs) from Forest Service Forest Inventory and Analysis (FIA) as well as modeled current (1971 through 2000) and future IVs (2010 through 2039, 2040 through 2069, 2070 through 2099) from the DISTRIB models were calculated for each time period. 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) in the Mid-Atlantic region, it was deleted from the list because the species either does not have or is not projected to have sufficient habitat in the region, or there were not enough data. Therefore, only a subset of 112 of the 134 possible species is shown in Table 30, and a subset of 116 species is shown in Table 31. Black maple was rare within individual subregions and was modeled only at the regional level. Bluejack oak, pecan, water elm, and water locust were modeled only at the subregional level. Species establishment, growth, and habitat suitability are assumed to be a function of current (FIA) values. Therefore, it is possible for model results to show species occupying areas where they do not naturally occur (e.g., pine plantations). Conversely, rare species are especially difficult to model at a large regional scale, and may not appear in the FIA data, despite botanical evidence that documents their existence.

A set of rules was established to determine change classes for the years 2070 through 2099, which was used to create Tables 21, 23, and 24 in Chapter 5. For most species, the following rules applied, based on the ratio of future IVs to current modeled IVs:

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

A few exceptions applied to these general rules. When there was a zero in the numerator or denominator, a ratio could not be calculated. Instead, a species was classified as gaining new habitat if its FIA value was 0 and the future IV was greater than 3. A species' habitat was considered to be extirpated if the future IV was 0 and its FIA value was 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 pixels in the assessment area (each pixel is a 12.5-mile × 12.5-mile cell). The change classes are calculated differently for these species because their current infrequency tends to inflate the projected percent change. The cutoffs for each portion of the assessment area were as follows:

	Pixels	Cutoff IV for rare species
Mid-Atlantic region	789	78.9
Subregion 1: Western Allegheny Plateau	121	12.1
Subregion 2: Erie and Ontario Lake Plain	76	7.6
Subregion 3: Northern Allegheny Plateau	217	21.7
Subregion 4: Ridge and Valley	138	13.8
Subregion 5: Piedmont	158	15.8
Subregion 6: Coastal Plain	79	7.9

When a species was below the cutoff, it was considered rare, and the following rules applied:

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

“Extirpated” was not used in this case because of low confidence.

Special rules also applied to species that were known to be present (current FIA IV >0) but not modeled as present (current modeled IV = 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.

Tables 38 and 39, beginning on page 309, describe the modifying factors and adaptability scores used in the Tree Atlas. These factors were developed by using a literature-based scoring system to capture the potential adaptability of species to changes in climate that cannot be adequately captured by the DISTRIB model (Matthews et al. 2011). This approach was used to assess the capacity for each species to adapt and considered nine biological traits reflecting innate characteristics such as competition for light and edaphic specificity. Twelve disturbance characteristics addressed the general response of a species to events such as drought, insect pests, and fire. This information is used to determine whether a species is likely to be more tolerant of (or sensitive to) environmental changes than the habitat models alone suggest.

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

To arrive at an overall adaptability score for the species that could be compared across all modeled tree species, the mean, rescaled (0 through 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 through 8.5.

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 prone to flooding. Or a species may be subjected to local impacts of insects and disease that reduce its adaptability in that area. Only the traits that elicited a combination of a strong positive or negative response, high certainty, and high future relevance for a combined score of 4.5 or greater are listed in Table 39 for each species.

Model results are arranged alphabetically, but it may also be practical to arrange results by relative abundance, forest community, genus, or other category; thus, editable model results are available online at https://www.fs.fed.us/nrs/atlas/products, or can be provided by the authors of this assessment.

American chestnut seed hulls, found near Rimrock Overlook, Allegheny National Forest, Pennsylvania. These hulls came from a native population of American chestnuts. Photo by Kathleen Creek, Allegheny National Forest.

Table 30.—Complete DISTRIB model results for 112 tree species in the Mid-Atlantic region

				Modeled IV						Future:Current suitable habitat[d]						Change class[e]	
				2010 - 2039		2040 - 2069		2070 - 2099		2010 - 2039		2040 - 2069		2070 - 2099		2070-2099	
Common name	FIA IV[a]	Current IV[b]	Model reliability[c]	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	502	569	M	484	531	494	440	491	362	0.85	0.93	0.87	0.77	0.86	0.64	No	dec
American beech	3308	3309	H	3085	2117	2741	1346	2612	1041	0.93	0.64	0.83	0.41	0.79	0.32	dec	DEC
American chestnut	108	40	M	79	66	78	51	80	40	1.98	1.65	1.95	1.28	2.00	1.00	No	No
American elm	943	1221	M	1007	1839	1007	2265	1095	2325	0.83	1.51	0.83	1.86	0.90	1.90	No	inc
American holly	235	238	H	262	248	292	187	277	161	1.10	1.04	1.23	0.79	1.16	0.68	No	dec
American hornbeam	791	839	M	754	807	757	831	781	806	0.90	0.96	0.90	0.99	0.93	0.96	No	No
American mountain-ash	9	0	M	3	1	2	1	1	1	0.33	0.11	0.22	0.11	0.11	0.11	DEC	DEC
Atlantic white-cedar	82	71	L	60	48	52	44	49	41	0.85	0.68	0.73	0.62	0.69	0.58	No	dec
Baldcypress	1	22	M	29	78	53	105	82	168	1.32	3.55	2.41	4.77	3.73	7.64	No	inc
Balsam fir	21	91	H	28	12	12	4	12	6	0.31	0.13	0.13	0.04	0.13	0.07	DEC	DEC
Balsam poplar	13	6	H	2	2	2	1	2	2	0.33	0.33	0.33	0.17	0.33	0.33	dec	dec
Bigtooth aspen	553	610	H	532	446	510	190	490	54	0.87	0.73	0.84	0.31	0.80	0.09	No	DEC
Bitternut hickory	91	66	L	66	260	81	502	116	654	1.00	3.94	1.23	7.61	1.76	9.91	No	INC
Black ash	131	133	H	76	41	57	12	44	9	0.57	0.31	0.43	0.09	0.33	0.07	DEC	DEC
Black cherry	5163	4927	H	4702	3762	4369	2124	4299	1483	0.95	0.76	0.89	0.43	0.87	0.30	No	DEC
Black hickory	0	15	H	40	333	62	1159	106	1926	2.67	22.20	4.13	77.27	7.07	128.40	New	New
Black locust	637	732	L	774	845	862	989	853	989	1.06	1.15	1.18	1.35	1.17	1.35	No	No
Black maple	5	12	L	4	2	5	0	4	0	0.33	0.17	0.42	0.00	0.33	0.00	dec	DEC
Black oak	1099	1379	H	1389	1972	1531	2974	1599	3501	1.01	1.43	1.11	2.16	1.16	2.54	No	INC
Black spruce	13	8	H	6	2	4	0	2	0	0.75	0.25	0.50	0.00	0.25	0.00	dec	DEC
Black walnut	363	440	M	438	740	534	914	623	868	1.00	1.68	1.21	2.08	1.42	1.97	inc	inc
Black willow	352	345	L	261	531	251	616	288	737	0.76	1.54	0.73	1.79	0.84	2.14	No	INC
Blackgum	1053	1060	H	1135	1195	1222	1329	1273	1465	1.07	1.13	1.15	1.25	1.20	1.38	inc	inc
Blackjack oak	10	30	M	49	240	76	876	112	1653	1.63	8.00	2.53	29.20	3.73	55.10	No	INC
Boxelder	371	338	M	321	393	334	414	355	483	0.95	1.16	0.99	1.23	1.05	1.43	No	inc
Bur oak	29	17	M	13	41	11	76	13	159	0.77	2.41	0.65	4.47	0.77	9.35	No	INC
Butternut	113	64	L	70	44	57	15	42	10	1.09	0.69	0.89	0.23	0.66	0.16	No	DEC

(continued on next page)

Table 30 (continued).—Complete DISTRIB model results for 112 tree species in the Mid-Atlantic region

				Modeled IV						Future:Current suitable habitat[d]						Change class[e]	
				2010 - 2039		2040 - 2069		2070 - 2099		2010 - 2039		2040 - 2069		2070 - 2099		2070-2099	
Common name	FIA IV[a]	Current IV[b]	Model reliability[c]	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
Cedar elm	0	0	L	0	23	0	117	1	352	NA	New	NA	New	NA	New	NA	New
Cherrybark oak	6	9	M	19	39	25	94	33	142	2.11	4.33	2.78	10.44	3.67	15.78	No	INC
Chestnut oak	2048	1985	H	2189	2068	2379	1978	2344	1654	1.10	1.04	1.20	1.00	1.18	0.83	No	No
Chinkapin oak	8	14	M	23	152	37	422	58	556	1.64	10.86	2.64	30.14	4.14	39.71	inc	INC
Chokecherry	342	275	L	240	123	225	13	207	3	0.87	0.45	0.82	0.05	0.75	0.01	dec	DEC
Cucumber tree	129	87	H	115	78	117	54	121	52	1.32	0.90	1.35	0.62	1.39	0.60	inc	dec
Eastern cottonwood	166	169	L	141	363	131	729	153	1196	0.83	2.15	0.78	4.31	0.91	7.08	No	INC
Eastern hemlock	1770	1794	H	1589	1396	1444	889	1424	704	0.89	0.78	0.81	0.50	0.79	0.39	dec	DEC
Eastern hophornbeam	964	1031	M	926	990	897	1062	919	1201	0.90	0.96	0.87	1.03	0.89	1.17	No	No
Eastern redbud	38	63	M	80	318	140	804	193	947	1.27	5.05	2.22	12.76	3.06	15.03	No	INC
Eastern redcedar	362	449	M	485	1267	604	2341	751	2800	1.08	2.82	1.35	5.21	1.67	6.24	inc	INC
Eastern white pine	1274	1500	H	1305	1320	1234	964	1200	701	0.87	0.88	0.82	0.64	0.80	0.47	dec	DEC
Flowering dogwood	791	992	H	1096	1633	1369	2233	1476	2202	1.11	1.65	1.38	2.25	1.49	2.22	inc	INC
Gray birch	185	167	M	132	144	120	103	129	91	0.79	0.86	0.72	0.62	0.77	0.55	dec	dec
Green ash	331	346	M	293	427	288	601	310	815	0.85	1.23	0.83	1.74	0.90	2.36	No	INC
Hackberry	65	112	M	89	484	125	973	169	1199	0.80	4.32	1.12	8.69	1.51	10.71	inc	INC
Honeylocust	7	24	L	17	188	26	556	45	1030	0.71	7.83	1.08	23.17	1.88	42.92	No	INC
Jack pine	7	16	H	4	4	1	0	1	0	0.25	0.25	0.06	0.00	0.06	0.00	DEC	DEC
Laurel oak**	0	0	H	0	1	5	12	10	30	NA	NA	New	New	New	New	New	New
Loblolly pine	343	395	H	498	619	653	843	661	1388	1.26	1.57	1.65	2.13	1.67	3.51	inc	INC
Longleaf pine**	0	3	H	0	4	10	11	66	16	0.00	1.33	3.33	3.67	22.00	5.33	New	New
Mockernut hickory	495	702	H	643	842	770	1197	782	1424	0.92	1.20	1.10	1.71	1.11	2.03	No	INC
Mountain maple	27	4	H	7	4	3	0	2	0	1.75	1.00	0.75	0.00	0.50	0.00	dec	DEC
Northern catalpa	16	5	L	6	6	6	5	6	26	1.20	1.20	1.20	1.00	1.20	5.20	No	inc
Northern red oak	2643	2708	H	2675	2656	2625	2479	2587	2277	0.99	0.98	0.97	0.92	0.96	0.84	No	No
Northern white-cedar	28	71	H	18	8	11	9	10	12	0.25	0.11	0.16	0.13	0.14	0.17	DEC	DEC
Ohio buckeye**	0	0	L	4	43	6	47	18	22	New	New	New	New	New	New	New	New

(continued on next page)

Table 30 (continued).—Complete DISTRIB model results for 112 tree species in the Mid-Atlantic region

				Modeled IV						Future:Current suitable habitat[d]						Change class[e]	
				2010 - 2039		2040 - 2069		2070 - 2099		2010 - 2039		2040 - 2069		2070 - 2099		2070-2099	
Common name	FIA IV[a]	Current IV[b]	Model reliability[c]	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
Osage-orange	19	48	M	33	117	42	209	53	303	0.69	2.44	0.88	4.35	1.10	6.31	No	inc
Overcup oak**	0	9	M	0	10	1	57	3	93	0.00	1.11	0.11	6.33	0.33	10.33	NA	New
Paper birch	138	175	H	124	73	75	3	63	1	0.71	0.42	0.43	0.02	0.36	0.01	DEC	DEC
Pawpaw	65	47	L	46	84	54	115	80	116	0.98	1.79	1.15	2.45	1.70	2.47	No	No
Persimmon	47	79	M	116	403	150	1126	185	1821	1.47	5.10	1.90	14.25	2.34	23.05	INC	INC
Pignut hickory	581	835	H	765	1024	914	1294	983	1276	0.92	1.23	1.10	1.55	1.18	1.53	No	inc
Pin cherry	194	141	M	126	39	94	11	82	9	0.89	0.28	0.67	0.08	0.58	0.06	dec	DEC
Pin oak	144	157	M	152	286	171	343	243	329	0.97	1.82	1.09	2.19	1.55	2.10	inc	INC
Pitch pine	691	567	H	564	521	493	545	478	584	1.00	0.92	0.87	0.96	0.84	1.03	No	No
Pond pine	6	1	H	5	33	5	59	23	61	5.00	33.00	5.00	59.00	23.00	61.00	inc	inc
Post oak	23	100	H	203	984	300	3378	379	5705	2.03	9.84	3.00	33.78	3.79	57.05	INC	INC
Quaking aspen	771	851	H	678	380	519	34	445	8	0.80	0.45	0.61	0.04	0.52	0.01	dec	DEC
Red maple	8807	8789	H	8664	7374	8477	5012	8400	3755	0.99	0.84	0.97	0.57	0.96	0.43	No	DEC
Red mulberry	21	21	L	19	253	26	713	50	1188	0.91	12.05	1.24	33.95	2.38	56.57	No	INC
Red pine	209	252	M	172	169	151	31	145	15	0.68	0.67	0.60	0.12	0.58	0.06	dec	DEC
Red spruce	59	75	H	36	39	30	20	32	16	0.48	0.52	0.40	0.27	0.43	0.21	dec	dec
Redbay**	0	0	H	0	0	0	0	11	0	NA	NA	NA	NA	New	NA	New	NA
River birch	37	21	L	20	27	21	28	29	53	0.95	1.29	1.00	1.33	1.38	2.52	No	No
Rock elm	8	7	L	8	33	7	36	24	63	1.14	4.71	1.00	5.14	3.43	9.00	No	INC
Sassafras	1128	1191	H	1258	1403	1387	1480	1512	1484	1.06	1.18	1.17	1.24	1.27	1.25	inc	inc
Scarlet oak	621	655	H	705	762	824	936	818	987	1.08	1.16	1.26	1.43	1.25	1.51	inc	inc
Scrub oak (bear oak)	192	110	L	140	178	146	195	162	183	1.27	1.62	1.33	1.77	1.47	1.66	inc	inc
Serviceberry	665	608	M	618	578	610	491	608	444	1.02	0.95	1.00	0.81	1.00	0.73	No	dec
Shagbark hickory	187	254	M	227	505	272	774	330	840	0.89	1.99	1.07	3.05	1.30	3.31	inc	INC
Shellbark hickory	4	1	L	0	47	0	106	2	131	0.00	47.00	0.00	106.00	2.00	131.00	No	INC
Shingle oak	26	14	M	18	127	23	309	44	367	1.29	9.07	1.64	22.07	3.14	26.21	No	INC
Shortleaf pine	35	74	H	99	268	109	954	131	1911	1.34	3.62	1.47	12.89	1.77	25.82	No	INC

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Table 30 (continued).—Complete DISTRIB model results for 112 tree species in the Mid-Atlantic region

				Modeled IV						Future:Current suitable habitat[d]						Change class[e]	
				2010 - 2039		2040 - 2069		2070 - 2099		2010 - 2039		2040 - 2069		2070 - 2099		2070-2099	
Common name	FIA IV[a]	Current IV[b]	Model reliability[c]	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
Shumard oak**	0	0	L	0	6	0	80	0	234	NA	New	NA	New	NA	New	NA	New
Silver maple	227	321	M	183	674	187	976	244	1152	0.57	2.10	0.58	3.04	0.76	3.59	dec	INC
Slash pine	0	0	H	0	0	0	17	21	98	NA	NA	NA	New	New	New	New	New
Slippery elm	373	452	M	419	654	480	770	528	792	0.93	1.45	1.06	1.70	1.17	1.75	No	inc
Sourwood	2	28	H	77	22	169	14	146	42	2.75	0.79	6.04	0.50	5.21	1.50	inc	No
Southern red oak	138	148	H	181	256	203	506	217	973	1.22	1.73	1.37	3.42	1.47	6.57	inc	INC
Striped maple	677	651	H	626	509	591	348	549	292	0.96	0.78	0.91	0.54	0.84	0.45	No	DEC
Sugar maple	4411	4707	H	4323	3983	4073	3224	4148	2373	0.92	0.85	0.87	0.69	0.88	0.50	No	dec
Sugarberry**	0	8	M	9	79	16	315	27	767	1.13	9.88	2.00	39.38	3.38	95.88	New	New
Swamp chestnut oak	15	8	M	11	18	15	19	16	17	1.38	2.25	1.88	2.38	2.00	2.13	No	No
Swamp tupelo	3	18	H	20	57	54	72	146	77	1.11	3.17	3.00	4.00	8.11	4.28	INC	inc
Swamp white oak	87	69	L	53	80	59	85	67	69	0.77	1.16	0.86	1.23	0.97	1.00	No	No
Sweet birch	1817	1667	H	1787	1460	1785	1056	1736	810	1.07	0.88	1.07	0.63	1.04	0.49	No	DEC
Sweetbay	58	68	H	53	60	61	56	92	62	0.78	0.88	0.90	0.82	1.35	0.91	No	No
Sweetgum	723	740	H	810	1033	931	1269	1054	1749	1.10	1.40	1.26	1.72	1.42	2.36	inc	INC
Sycamore	155	187	M	210	371	247	614	288	664	1.12	1.98	1.32	3.28	1.54	3.55	inc	INC
Table Mountain pine	7	2	M	1	2	1	4	1	6	0.50	1.00	0.50	2.00	0.50	3.00	dec	No
Tamarack	43	21	H	15	13	10	6	8	7	0.71	0.62	0.48	0.29	0.38	0.33	dec	dec
Tulip tree	1308	1348	H	1536	1230	1744	1139	1737	984	1.14	0.91	1.29	0.85	1.29	0.73	inc	dec
Turkey oak	0	0	H	0	1	2	0	29	8	NA	NA	NA	NA	New	New	New	New
Virginia pine	458	514	H	503	353	571	501	474	603	0.98	0.69	1.11	0.98	0.92	1.17	No	No
Water hickory	0	0	M	0	0	0	19	0	24	NA	NA	NA	New	NA	New	NA	New
Water oak	44	48	H	75	115	95	282	96	532	1.56	2.40	1.98	5.88	2.00	11.08	No	INC
Water tupelo	20	25	M	18	43	43	59	61	82	0.72	1.72	1.72	2.36	2.44	3.28	No	No
White ash	5067	4834	H	4530	4272	4285	3295	4326	2556	0.94	0.88	0.89	0.68	0.90	0.53	No	dec
White oak	1809	2197	H	2239	2829	2394	3667	2437	3909	1.02	1.29	1.09	1.67	1.11	1.78	No	inc
White spruce	87	56	M	35	23	26	14	20	12	0.63	0.41	0.46	0.25	0.36	0.21	dec	dec

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Table 30 (continued).—Complete DISTRIB model results for 112 tree species in the Mid-Atlantic region

				Modeled IV						Future:Current suitable habitat[d]						Change class[e]	
				2010 - 2039		2040 - 2069		2070 - 2099		2010 - 2039		2040 - 2069		2070 - 2099		2070-2099	
Common name	FIA IV[a]	Current IV[b]	Model reliability[c]	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
Willow oak	54	62	M	65	113	77	204	84	280	1.05	1.82	1.24	3.29	1.36	4.52	No	inc
Winged elm	1	15	H	79	335	129	1157	190	2365	5.27	22.33	8.60	77.13	12.67	157.67	INC	INC
Yellow birch	601	635	H	572	395	527	190	526	163	0.90	0.62	0.83	0.30	0.83	0.26	No	DEC
Yellow buckeye	12	10	M	8	6	8	8	11	8	0.80	0.60	0.80	0.80	1.10	0.80	No	No

[a] FIA IV is the measured area-weighted importance values (IVs) as reported from Forest Inventory and Analysis.
[b] Current Modeled IV (1971 through 2000) and Modeled IV for future time periods (2010 through 2039, 2040 through 2069, and 2070 through 2099) are simulated from the DISTRIB model; importance values are the sum of the average IV for each pixel in the assessment area.
[c] Model reliability for DISTRIB scores, which is based on statistically quantified measures of fitness (Matthews et al. 2011), is abbreviated L (low), M (medium), and H (high).
[d] Future:Current suitable habitat is a ratio of projected importance value to current importance value. This is a measure of habitat change (not where a species will be), where a ratio of ~1 = no change; ratio<1 = decrease; ratio>1 = increase.
[e] Change classes are based on rules in Appendix 4 and abbreviated No (no change), inc (small increase), INC (large increase), dec (small decrease), DEC (large decrease), New (new habitat), and NA (not detected).
**Not observed in the Forest Inventory and Analysis data, but other data suggest species is present, but rare.

Table 31.—Change classes[a] for the end of century (2070 through 2099) period projected by the DISTRIB model for 116 tree species in the Mid-Atlantic region and six subregions[b]

Common name	Mid-Atlantic region		Subregion 1		Subregion 2		Subregion 3		Subregion 4		Subregion 5		Subregion 6	
	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	No	dec	No	No	dec	DEC	No	dec	dec	dec	No	No	-	-
American beech	dec	DEC	dec	DEC	dec	DEC	dec	DEC	No	DEC	No	DEC	No	DEC
American chestnut	No	No	No	dec	-	-	No	No	inc	No	No	No	dec	dec
American elm	No	inc	dec	DEC	No	No	No	dec	No	INC	No	inc	inc	INC
American holly	No	dec	-	-	-	-	-	-	-	-	NA	NA	No	dec
American hornbeam	No	No	No	dec	No	No	No	No	dec	inc	No	No	No	No
American mountain-ash	DEC	DEC	-	-	-	-	DEC	DEC	-	-	-	-	-	-
Atlantic white-cedar	No	dec	-	-	dec	dec	-	-	-	-	NA	NA	dec	dec
Baldcypress	No	inc	-	-	-	-	-	-	-	-	NA	New	INC	INC
Balsam fir	DEC	DEC	-	-	DEC	DEC	DEC	X	-	-	DEC	DEC	-	-
Balsam poplar	dec	dec	-	-	-	-	No	DEC	-	-	-	-	-	-
Bigtooth aspen	No	DEC	dec	DEC	No	No	No	No	dec	DEC	dec	DEC	DEC	X
Bitternut hickory	No	INC	No	INC	No	INC	No	INC	inc	INC	inc	INC	No	INC
Black ash	DEC	DEC	dec	dec	DEC	DEC	dec	DEC	-	-	dec	DEC	-	-
Black cherry	No	DEC	No	DEC	No	INC	No	No	No	DEC	dec	DEC	dec	DEC
Black hickory	New	New	NA	New	NA	New	NA	New	New	New	New	New	New	New
Black locust	No	No	No	inc	inc	INC	INC	INC	No	No	No	No	No	DEC
Black maple	dec	DEC	-	-	-	-	-	-	-	-	-	-	-	-
Black oak	No	INC	inc	INC	No	INC	inc	INC	No	INC	No	inc	No	dec
Black spruce	dec	DEC	-	-	-	-	dec	DEC	DEC	DEC	-	-	-	-
Black walnut	inc	inc	inc	INC	inc	INC	INC	INC	inc	inc	inc	No	No	DEC
Black willow	No	INC	dec	DEC	No	dec	dec	DEC	DEC	INC	No	INC	dec	INC
Blackgum	inc	inc	inc	INC	INC	INC	inc	INC	inc	inc	No	No	dec	dec
Blackjack oak	No	INC	New	New	NA	New	NA	New	New	New	New	New	INC	INC
Bluejack oak	-	-	-	-	-	-	-	-	-	-	-	-	NA	New
Boxelder	No	inc	No	dec	No	INC	inc	INC	No	inc	No	No	inc	No
Bur oak	No	INC	dec	No	dec	DEC	DEC	inc	DEC	inc	No	inc	-	-
Butternut	No	DEC	No	DEC	dec	DEC	No	DEC	dec	DEC	dec	DEC	-	-
Cedar elm	NA	New	NA	New	NA	New	NA	New	NA	New	NA	New	NA	New
Cherrybark oak	No	INC	-	-	-	-	-	-	NA	New	NA	New	inc	INC
Chestnut oak	No	No	No	inc	inc	INC	inc	INC	No	dec	No	dec	dec	DEC
Chinkapin oak	inc	INC	inc	inc	No	inc	DEC	inc	No	INC	No	inc	New	New
Chokecherry	dec	DEC	dec	DEC	dec	DEC	No	dec	dec	X	DEC	DEC	-	-
Cucumber tree	inc	dec	inc	inc	No	DEC	inc	DEC	No	dec	-	-	-	-
Eastern cottonwood	No	INC	No	INC	No	inc	No	INC	DEC	INC	No	INC	dec	INC
Eastern hemlock	dec	DEC	dec	DEC	dec	DEC	No	dec	dec	DEC	dec	DEC	inc	inc
Eastern hophornbeam	No	No	No	DEC	No	dec	No	DEC	No	inc	No	inc	inc	INC

(continued on next page)

Table 31 (continued).—Change classes[a] for the end of century (2070 through 2099) period projected by the DISTRIB model for 116 tree species in the Mid-Atlantic region and six subregions[b]

Common name	Mid-Atlantic region		Subregion 1		Subregion 2		Subregion 3		Subregion 4		Subregion 5		Subregion 6	
	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
Eastern redbud	No	INC	inc	INC	New	New	inc	inc	INC	INC	INC	INC	No	inc
Eastern redcedar	inc	INC	New	New	INC	INC	INC	INC	inc	INC	inc	INC	No	inc
Eastern white pine	dec	DEC	dec	DEC	dec	DEC	No	DEC	No	DEC	dec	DEC	DEC	DEC
Flowering dogwood	inc	INC	inc	INC	INC	INC	INC	INC	inc	inc	No	inc	No	No
Gray birch	dec	dec	dec	DEC	DEC	DEC	No	No	dec	dec	dec	DEC	No	No
Green ash	No	INC	inc	INC	No	No	No	INC	No	INC	dec	inc	No	INC
Hackberry	inc	INC	inc	INC	NA	New	No	INC	No	INC	inc	INC	No	INC
Honeylocust	No	INC	No	INC	NA	New	No	inc	No	INC	No	INC	NA	New
Jack pine	DEC	DEC	-	-	NA	NA	DEC	DEC	-	-	NA	NA	-	-
Laurel oak**	New	New	-	-	-	-	-	-	-	-	New	NA	New	New
Loblolly pine	inc	INC	NA	New	NA	New	New	New	NA	New	INC	INC	inc	INC
Longleaf pine**	New	New	-	-	-	-	-	-	-	-	New	NA	New	New
Mockernut hickory	No	INC	inc	INC	No	inc	No	INC	No	INC	No	inc	dec	inc
Mountain maple	dec	DEC	-	-	-	-	dec	DEC	-	-	No	DEC	-	-
Northern catalpa	No	inc	-	-	NA	NA	DEC	No	NA	New	inc	INC	inc	inc
Northern red oak	No	No	No	DEC	No	inc	No	inc	No	dec	No	dec	dec	DEC
Northern white-cedar	DEC	DEC	-	-	DEC	DEC	DEC	X	-	-	dec	dec	-	-
Ohio buckeye**	New	New	New	New	New	New	NA	New	-	-	NA	New	-	-
Osage-orange	No	inc	No	No	inc	INC	No	inc	No	inc	No	inc	NA	New
Overcup oak**	NA	New	-	-	-	-	-	-	-	-	NA	New	NA	New
Paper birch	DEC	DEC	dec	DEC	DEC	DEC	DEC	DEC	DEC	X	DEC	DEC	-	-
Pawpaw	No	No	inc	inc	New	New	NA	New	No	No	inc	INC	DEC	DEC
Pecan	-	-	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Persimmon	INC	INC	inc	inc	NA	New	NA	New	inc	INC	INC	INC	inc	INC
Pignut hickory	No	inc	inc	INC	No	INC	inc	INC	No	inc	No	No	dec	No
Pin cherry	dec	DEC	DEC	X	dec	DEC	dec	DEC	DEC	X	dec	DEC	No	dec
Pin oak	inc	INC	No	inc	NA	New	No	inc	No	inc	inc	inc	INC	INC
Pitch pine	No	No	No	inc	No	No	inc	INC	No	No	dec	dec	No	No
Pond pine	inc	inc	-	-	-	-	-	-	-	-	inc	inc	inc	inc
Post oak	INC	INC	New	New	NA	New	NA	New	New	New	inc	INC	INC	INC
Quaking aspen	dec	DEC	DEC	X	DEC	DEC	dec	DEC	DEC	X	DEC	DEC	DEC	DEC
Red maple	No	DEC	No	dec	No	inc	No	inc	No	DEC	No	DEC	No	DEC
Red mulberry**	No	INC	NA	New	New	New	NA	New	No	INC	No	INC	No	INC
Red pine	dec	DEC	dec	DEC	dec	DEC	dec	DEC	dec	X	dec	DEC	-	-
Red spruce	dec	dec	DEC	DEC	DEC	DEC	DEC	DEC	dec	DEC	DEC	DEC	-	-
Redbay**	New	NA	-	-	-	-	-	-	-	-	New	NA	New	NA
River birch	No	No	-	-	-	-	No	No	No	inc	No	inc	inc	inc

(continued on next page)

Table 31 (continued).—Change classes[a] for the end of century (2070 through 2099) period projected by the DISTRIB model for 116 tree species in the Mid-Atlantic region and six subregions[b]

Common name	Mid-Atlantic region		Subregion 1		Subregion 2		Subregion 3		Subregion 4		Subregion 5		Subregion 6	
	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
Rock elm	No	INC	dec	No	dec	No	No	inc	NA	New	inc	inc	New	NA
Sassafras	inc	inc	inc	INC	INC	INC	inc	INC	inc	No	No	No	No	DEC
Scarlet oak	inc	inc	inc	INC	INC	INC	INC	INC	No	inc	inc	No	dec	DEC
Scrub oak (bear oak)	inc	inc	No	No	-	-	INC	INC	inc	inc	INC	INC	dec	No
Serviceberry	No	dec	No	No	inc	INC	No	No	No	dec	No	dec	dec	DEC
Shagbark hickory	inc	INC	inc	INC	No	inc	inc	INC	No	INC	inc	inc	INC	INC
Shellbark hickory**	No	INC	-	-	NA	New	DEC	inc	DEC	inc	NA	inc	NA	New
Shingle oak	No	INC	inc	inc	NA	New	No	inc	No	INC	No	INC	No	inc
Shortleaf pine	No	INC	New	New	NA	New	NA	New	inc	INC	No	INC	inc	INC
Shumard oak**	NA	New	NA	New	NA	New	NA	New	NA	New	NA	New	NA	New
Silver maple	dec	INC	dec	DEC	No	dec	dec	DEC	dec	INC	No	INC	dec	INC
Slash pine	New	New	-	-	-	-	-	-	-	-	New	New	New	New
Slippery elm	No	inc	No	inc	inc	INC	inc	INC	No	inc	No	inc	No	INC
Sourwood	inc	No	INC	DEC	-	-	inc	inc	New	NA	New	New	INC	dec
Southern red oak	inc	INC	NA	New	NA	New	NA	New	No	inc	No	INC	inc	inc
Striped maple	No	DEC	dec	DEC	dec	dec	No	DEC	No	dec	dec	DEC	-	-
Sugar maple	No	dec	No	dec	No	dec	dec	DEC	No	dec	No	DEC	inc	DEC
Sugarberry**	New	New	NA	New	NA	New	NA	New	New	New	New	New	New	New
Swamp chestnut oak	No	No	-	-	-	-	-	-	No	DEC	NA	inc	inc	No
Swamp tupelo	INC	inc	-	-	-	-	-	-	-	-	New	NA	INC	INC
Swamp white oak	No	No	No	No	dec	DEC	inc	inc	-	-	inc	inc	DEC	dec
Sweet birch	No	DEC	No	No	No	inc	inc	INC	No	DEC	No	DEC	DEC	DEC
Sweetbay	No	No	-	-	-	-	-	-	-	-	No	dec	inc	No
Sweetgum**	inc	INC	NA	New	NA	New	inc	inc	INC	INC	inc	INC	inc	inc
Sycamore	inc	INC	inc	INC	INC	INC	No	INC	inc	INC	inc	inc	No	INC
Table Mountain pine	dec	No	-	-	-	-	-	-	No	No	-	-	-	-
Tamarack (native)	dec	dec	-	-	DEC	dec	dec	DEC	No	dec	No	No	-	-
Tulip tree	inc	dec	inc	INC	INC	INC	INC	INC	inc	dec	No	DEC	dec	DEC
Turkey oak	New	New	-	-	-	-	-	-	-	-	New	NA	New	New
Virginia pine	No	No	INC	INC	New	New	No	dec	No	inc	No	dec	dec	DEC
Water elm	-	-	-	-	-	-	-	-	-	-	NA	NA	-	-
Water hickory	NA	New	-	-	-	-	-	-	-	-	NA	NA	NA	NA
Water locust	-	-	-	-	-	-	-	-	-	-	-	-	NA	New
Water oak	No	INC	NA	New	-	-	-	-	NA	New	NA	New	inc	INC
Water tupelo	No	No	-	-	-	-	-	-	-	-	No	No	INC	INC
White ash	No	dec	No	DEC	No	No	No	dec	No	dec	No	DEC	No	dec
White oak	No	inc	No	inc	No	inc	inc	INC	No	inc	No	inc	No	dec

(continued on next page)

Table 31 (continued).—Change classes[a] for the end of century (2070 through 2099) period projected by the DISTRIB model for 116 tree species in the Mid-Atlantic region and six subregions[b]

Common name	Mid-Atlantic region		Subregion 1		Subregion 2		Subregion 3		Subregion 4		Subregion 5		Subregion 6	
	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
White spruce	dec	dec	No	DEC	DEC	DEC	DEC	X	dec	dec	dec	dec	-	-
Willow oak	No	inc	-	-	NA	New	-	-	NA	New	NA	New	inc	INC
Winged elm	INC	INC	NA	New	NA	New	DEC	inc	New	New	New	New	New	New
Yellow birch	No	DEC	dec	DEC	dec	DEC	No	dec	dec	DEC	dec	DEC	-	-
Yellow buckeye	No	No	No	No	-	-	-	-	-	-	-	-	-	-

[a] Change classes are based on rules in Appendix 4 and abbreviated No (no change), inc (small increase), INC (large increase), dec (small decrease), DEC (large decrease), New (new habitat), X (extirpated), and NA (not detected). Dash (-) indicates not present in modeled or future habitat.

[b] See Figure 38 (Chapter 6, p. 144) for location of subregions.

** Not observed in the Forest Inventory and Analysis data, but other data suggest species is present, but rare.

Table 32.—Complete DISTRIB model results for 83 tree species in subregion 1 (West Allegheny Plateau)

				Modeled IV						Future:Current suitable habitat[d]						Change class[e]	
				2010 - 2039		2040 - 2069		2070 - 2099		2010 - 2039		2040 - 2069		2070 - 2099		2070-2099	
Common name	FIA IV[a]	Current IV[b]	Model reliability[c]	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	100	109	M	99	100	106	69	105	47	0.91	0.92	0.97	0.63	0.96	0.43	No	No
American beech	558	592	H	518	326	455	222	426	150	0.88	0.55	0.77	0.38	0.72	0.25	dec	DEC
American chestnut	8	3	M	5	4	5	2	5	1	1.67	1.33	1.67	0.67	1.67	0.33	No	dec
American elm	229	292	M	240	370	232	449	234	409	0.82	1.27	0.80	1.54	0.80	1.40	dec	DEC
American hornbeam	162	167	M	148	152	152	133	159	130	0.89	0.91	0.91	0.80	0.95	0.78	No	dec
Bigtooth aspen	201	177	H	175	117	151	24	138	0	0.99	0.66	0.85	0.14	0.78	0.00	dec	DEC
Bitternut hickory	23	8	L	11	47	18	107	21	122	1.38	5.88	2.25	13.38	2.63	15.25	No	INC
Black ash	7	7	H	2	2	0	1	2	2	0.29	0.29	0.00	0.14	0.29	0.29	dec	dec
Black cherry	2117	1767	H	1761	1157	1525	382	1501	250	1.00	0.66	0.86	0.22	0.85	0.14	No	DEC
Black hickory	0	0	H	0	29	1	230	3	441	NA	New	NA	New	NA	New	NA	New
Black locust	168	198	L	210	206	226	203	213	195	1.06	1.04	1.14	1.03	1.08	0.99	No	inc
Black oak	160	215	H	222	397	266	764	289	911	1.03	1.85	1.24	3.55	1.34	4.24	inc	INC
Black walnut	72	99	M	102	175	131	201	153	179	1.03	1.77	1.32	2.03	1.55	1.81	inc	INC
Black willow	61	48	L	30	71	29	100	37	108	0.63	1.48	0.60	2.08	0.77	2.25	dec	DEC
Blackgum	123	162	H	186	235	232	267	252	288	1.15	1.45	1.43	1.65	1.56	1.78	inc	INC
Blackjack oak	0	0	M	1	35	3	241	6	486	NA	New	NA	New	New	New	New	New
Boxelder	39	46	M	38	46	41	57	43	62	0.83	1.00	0.89	1.24	0.94	1.35	No	dec
Bur oak	7	0	M	2	3	2	6	2	19	0.29	0.43	0.29	0.86	0.29	2.71	dec	No
Butternut	11	2	L	3	2	3	0	2	0	1.50	1.00	1.50	0.00	1.00	0.00	No	DEC
Cedar elm	0	0	L	0	0	0	3	0	87	NA	NA	NA	New	NA	New	NA	New
Chestnut oak	167	321	H	310	353	384	337	377	238	0.97	1.10	1.20	1.05	1.17	0.74	No	inc
Chinkapin oak	2	1	M	6	50	12	121	21	127	6.00	50.00	12.00	121.00	21.00	127.00	inc	inc
Chokecherry	131	76	L	77	16	75	0	59	0	1.01	0.21	0.99	0.00	0.78	0.00	dec	DEC
Cucumber tree	74	53	H	70	46	70	27	71	24	1.32	0.87	1.32	0.51	1.34	0.45	inc	inc
Eastern cottonwood	23	8	L	10	27	10	58	10	166	1.25	3.38	1.25	7.25	1.25	20.75	No	INC
Eastern hemlock	333	341	H	280	172	233	91	213	73	0.82	0.50	0.68	0.27	0.63	0.21	dec	DEC
Eastern hophornbeam	130	175	M	142	151	146	173	149	215	0.81	0.86	0.83	0.99	0.85	1.23	No	DEC

(continued on next page)

Table 32 (continued).—Complete DISTRIB model results for 83 tree species in subregion 1 (West Allegheny Plateau)

				Modeled IV						Future:Current suitable habitat[d]						Change class[e]	
				2010 - 2039		2040 - 2069		2070 - 2099		2010 - 2039		2040 - 2069		2070 - 2099		2070-2099	
Common name	FIA IV[a]	Current IV[b]	Model reliability[c]	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
Eastern redbud	2	10	M	24	82	47	195	57	179	2.40	8.20	4.70	19.50	5.70	17.90	inc	INC
Eastern redcedar	0	8	M	26	271	46	536	98	599	3.25	33.88	5.75	67.00	12.25	74.88	New	New
Eastern white pine	116	194	H	151	222	153	121	156	69	0.78	1.14	0.79	0.62	0.80	0.36	dec	DEC
Flowering dogwood	185	241	H	291	436	387	536	419	487	1.21	1.81	1.61	2.22	1.74	2.02	inc	INC
Gray birch	2	7	M	0	2	2	0	2	1	0.00	0.29	0.29	0.00	0.29	0.14	dec	DEC
Green ash	50	32	M	43	50	49	97	49	136	1.34	1.56	1.53	3.03	1.53	4.25	inc	INC
Hackberry	9	16	M	11	75	16	177	22	215	0.69	4.69	1.00	11.06	1.38	13.44	inc	INC
Honeylocust	1	4	L	4	27	6	64	11	155	1.00	6.75	1.50	16.00	2.75	38.75	No	INC
Loblolly pine	0	0	H	0	0	0	1	0	52	NA	NA	NA	New	NA	New	NA	New
Mockernut hickory	70	136	H	137	196	180	300	183	352	1.01	1.44	1.32	2.21	1.35	2.59	inc	INC
Northern red oak	553	550	H	527	509	513	464	500	447	0.96	0.93	0.93	0.84	0.91	0.81	No	DEC
Ohio buckeye**	0	0	L	1	17	1	14	5	4	NA	New	NA	New	New	New	New	New
Osage-orange	9	24	M	14	44	18	54	22	83	0.58	1.83	0.75	2.25	0.92	3.46	No	No
Paper birch	5	5	H	2	1	2	0	2	0	0.40	0.20	0.40	0.00	0.40	0.00	dec	DEC
Pawpaw	2	1	L	6	12	5	10	8	5	6.00	12.00	5.00	10.00	8.00	5.00	inc	inc
Pecan	0	45	L	0	0	0	3	0	22	0.00	0.00	0.00	0.07	0.00	0.49	NA	NA
Persimmon	2	0	M	6	49	13	228	9	373	3.00	24.50	6.50	114.00	4.50	186.50	inc	inc
Pignut hickory	82	154	H	150	215	198	278	210	274	0.97	1.40	1.29	1.81	1.36	1.78	inc	INC
Pin cherry	59	29	M	35	1	22	1	12	1	1.21	0.03	0.76	0.03	0.41	0.03	DEC	X
Pin oak	9	24	M	22	35	27	50	28	41	0.92	1.46	1.13	2.08	1.17	1.71	No	inc
Pitch pine	15	14	H	12	24	12	30	16	33	0.86	1.71	0.86	2.14	1.14	2.36	No	inc
Post oak	0	3	H	5	201	15	911	25	1486	1.67	67.00	5.00	303.67	8.33	495.33	New	New
Quaking aspen	197	147	H	140	33	97	0	72	0	0.95	0.22	0.66	0.00	0.49	0.00	DEC	X
Red maple	1840	1738	H	1725	1368	1655	758	1643	527	0.99	0.79	0.95	0.44	0.95	0.30	No	dec
Red mulberry**	0	0	L	1	28	2	116	3	221	NA	New	NA	New	NA	New	NA	New
Red pine	27	29	M	24	30	23	2	21	2	0.83	1.03	0.79	0.07	0.72	0.07	dec	DEC
Red spruce	5	1	H	0	0	0	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00	DEC	DEC

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Table 32 (continued).—Complete DISTRIB model results for 83 tree species in subregion 1 (West Allegheny Plateau)

				Modeled IV						Future:Current suitable habitat[d]						Change class[e]	
				2010 - 2039		2040 - 2069		2070 - 2099		2010 - 2039		2040 - 2069		2070 - 2099		2070-2099	
Common name	FIA IV[a]	Current IV[b]	Model reliability[c]	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
Rock elm	5	0	L	3	3	2	7	2	9	0.60	0.60	0.40	1.40	0.40	1.80	dec	No
Sassafras	357	307	H	357	386	403	388	418	350	1.16	1.26	1.31	1.26	1.36	1.14	inc	INC
Scarlet oak	73	109	H	122	156	157	218	160	221	1.12	1.43	1.44	2.00	1.47	2.03	inc	INC
Scrub oak (bear oak)	2	8	L	3	9	3	12	5	14	0.38	1.13	0.38	1.50	0.63	1.75	No	No
Serviceberry	138	120	M	120	104	117	83	118	79	1.00	0.87	0.98	0.69	0.98	0.66	No	No
Shagbark hickory	34	41	M	40	97	48	154	67	152	0.98	2.37	1.17	3.76	1.63	3.71	inc	INC
Shingle oak	25	1	M	10	26	9	65	10	59	10.00	26.00	9.00	65.00	10.00	59.00	inc	inc
Shortleaf pine	0	2	H	1	34	4	241	17	551	0.50	17.00	2.00	120.50	8.50	275.50	New	New
Shumard oak**	0	0	L	0	0	0	8	0	54	NA	NA	NA	New	NA	New	NA	New
Silver maple	25	46	M	24	58	19	107	25	121	0.52	1.26	0.41	2.33	0.54	2.63	dec	DEC
Slippery elm	186	177	M	179	213	188	201	188	166	1.01	1.20	1.06	1.14	1.06	0.94	No	inc
Sourwood	1	6	H	26	1	80	0	58	0	4.33	0.17	13.33	0.00	9.67	0.00	INC	DEC
Southern red oak	0	0	H	0	1	0	48	0	196	NA	NA	NA	New	NA	New	NA	New
Striped maple	64	103	H	71	52	70	31	66	29	0.69	0.51	0.68	0.30	0.64	0.28	dec	DEC
Sugar maple	907	941	H	915	807	885	575	882	373	0.97	0.86	0.94	0.61	0.94	0.40	No	dec
Sugarberry	0	0	M	0	0	0	13	0	139	NA	NA	NA	New	NA	New	NA	New
Swamp white oak	18	16	L	16	17	17	16	17	6	1.00	1.06	1.06	1.00	1.06	0.38	No	No
Sweet birch	329	319	H	328	260	326	144	329	98	1.03	0.82	1.02	0.45	1.03	0.31	No	No
Sweetgum**	0	0	H	0	8	1	47	3	125	NA	New	NA	New	NA	New	NA	New
Sycamore	23	40	M	45	84	57	119	61	126	1.13	2.10	1.43	2.98	1.53	3.15	inc	INC
Tulip tree	268	267	H	367	327	463	279	483	187	1.38	1.23	1.73	1.05	1.81	0.70	inc	INC
Virginia pine	10	25	H	53	51	98	88	88	102	2.12	2.04	3.92	3.52	3.52	4.08	INC	INC
Water oak	0	0	H	0	0	0	0	0	24	0.00	NA	NA	NA	NA	New	NA	New
White ash	687	723	H	655	635	627	429	655	330	0.91	0.88	0.87	0.59	0.91	0.46	No	DEC
White oak	306	385	H	383	619	430	921	451	882	1.00	1.61	1.12	2.39	1.17	2.29	No	inc
White spruce	13	1	M	5	1	5	0	3	0	5.00	1.00	5.00	0.00	3.00	0.00	No	DEC
Winged elm	0	0	H	0	10	0	184	1	579	0.00	New	0.00	New	NA	New	NA	New

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Table 32 (continued).—Complete DISTRIB model results for 83 tree species in subregion 1 (West Allegheny Plateau)

				Modeled IV						Future:Current suitable habitat[d]						Change class[e]	
				2010 - 2039		2040 - 2069		2070 - 2099		2010 - 2039		2040 - 2069		2070 - 2099		2070-2099	
Common name	FIA IV[a]	Current IV[b]	Model reliability[c]	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
Yellow birch	130	131	H	107	33	87	3	79	2	0.82	0.25	0.66	0.02	0.60	0.02	dec	DEC
Yellow buckeye	11	6	M	8	6	8	5	11	5	1.33	1.00	1.33	0.83	1.83	0.83	No	No

[a] FIA IV is the measured area-weighted importance values (IVs) as reported from Forest Inventory and Analysis.

[b] Current Modeled IV (1971 through 2000) and Modeled IV for future time periods (2010 through 2039, 2040 through 2069, and 2070 through 2099) are simulated from the DISTRIB model; importance values are the sum of the average IV for each pixel in the subregion.

[c] Model reliability for DISTRIB scores, which is based on statistically quantified measures of fitness (Matthews et al. 2011), is abbreviated L (low), M (medium), and H (high).

[d] Future:Current suitable habitat is a ratio of projected importance value to current importance value. This is a measure of habitat change (not where a species will be), where a ratio of ~1 = no change; ratio<1 = decrease; ratio>1 = increase.

[e] Change classes are based on rules in Appendix 4 and abbreviated No (no change), inc (small increase), INC (large increase), dec (small decrease), DEC (large decrease), New (new habitat), X (extirpated), and NA (not detected).

** Not observed in the Forest Inventory and Analysis data, but other data suggest species is present, but rare.

Table 33.—Complete DISTRIB model results for 86 tree species in subregion 2 (Erie and Ontario Lake Plain)

				Modeled IV						Future:Current suitable habitat[d]						Change class[e]	
				2010 - 2039		2040 - 2069		2070 - 2099		2010 - 2039		2040 - 2069		2070 - 2099		2070-2099	
Common name	FIA IV[a]	Current IV[b]	Model reliability[c]	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	156	157	M	134	138	124	93	118	64	0.85	0.88	0.79	0.59	0.75	0.41	dec	DEC
American beech	257	334	H	284	239	269	179	261	125	0.85	0.72	0.81	0.54	0.78	0.37	dec	DEC
American elm	286	327	M	298	379	300	427	311	420	0.91	1.16	0.92	1.31	0.95	1.28	No	No
American hornbeam	153	135	M	130	138	127	135	126	136	0.96	1.02	0.94	1.00	0.93	1.01	No	No
Atlantic white-cedar	8	0	L	4	4	4	4	4	4	0.50	0.50	0.50	0.50	0.50	0.50	dec	dec
Balsam fir	4	20	H	6	3	5	3	5	3	0.30	0.15	0.25	0.15	0.25	0.15	DEC	DEC
Bigtooth aspen	47	85	H	76	77	82	27	79	5	0.89	0.91	0.97	0.32	0.93	0.06	No	No
Bitternut hickory	19	17	L	19	51	20	78	19	86	1.12	3.00	1.18	4.59	1.12	5.06	No	INC
Black ash	110	82	H	56	22	43	7	32	5	0.68	0.27	0.52	0.09	0.39	0.06	DEC	DEC
Black cherry	553	525	H	545	564	576	315	583	187	1.04	1.07	1.10	0.60	1.11	0.36	No	INC
Black hickory	0	0	H	0	0	0	74	0	181	NA	NA	NA	New	NA	New	NA	New
Black locust	48	62	L	83	110	107	152	107	173	1.34	1.77	1.73	2.45	1.73	2.79	inc	INC
Black oak	14	98	H	77	118	105	227	114	333	0.79	1.20	1.07	2.32	1.16	3.40	No	INC
Black walnut	39	54	M	60	132	88	180	100	191	1.11	2.44	1.63	3.33	1.85	3.54	inc	INC
Black willow	185	152	L	136	156	127	155	137	176	0.90	1.03	0.84	1.02	0.90	1.16	No	dec
Blackgum	18	15	H	27	33	42	65	47	71	1.80	2.20	2.80	4.33	3.13	4.73	INC	INC
Blackjack oak	0	0	M	0	0	0	72	0	201	NA	NA	NA	New	NA	New	NA	New
Boxelder	99	97	M	95	123	99	130	107	146	0.98	1.27	1.02	1.34	1.10	1.51	No	INC
Bur oak	16	9	M	7	21	6	34	5	58	0.78	2.33	0.67	3.78	0.56	6.44	dec	DEC
Butternut	20	20	L	18	14	16	4	15	1	0.90	0.70	0.80	0.20	0.75	0.05	dec	DEC
Cedar elm	0	0	L	0	0	0	0	0	17	NA	NA	NA	NA	NA	New	NA	New
Chestnut oak	9	76	H	82	121	132	168	135	130	1.08	1.59	1.74	2.21	1.78	1.71	inc	INC
Chinkapin oak	1	0	M	1	21	1	84	1	96	1.00	21.00	1.00	84.00	1.00	96.00	No	inc
Chokecherry	83	87	L	80	38	65	4	64	2	0.92	0.44	0.75	0.05	0.74	0.02	dec	DEC
Cucumber tree	16	0	H	12	3	11	2	12	2	0.75	0.19	0.69	0.13	0.75	0.13	No	DEC
Eastern cottonwood	98	72	L	81	128	74	216	76	249	1.13	1.78	1.03	3.00	1.06	3.46	No	inc
Eastern hemlock	209	241	H	206	159	188	97	183	80	0.86	0.66	0.78	0.40	0.76	0.33	dec	DEC

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Table 33 (continued).—Complete DISTRIB model results for 86 tree species in subregion 2 (Erie and Ontario Lake Plain)

				Modeled IV						Future:Current suitable habitat[d]						Change class[e]	
				2010 - 2039		2040 - 2069		2070 - 2099		2010 - 2039		2040 - 2069		2070 - 2099		2070-2099	
Common name	FIA IV[a]	Current IV[b]	Model reliability[c]	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
Eastern hophornbeam	133	173	M	158	170	152	159	154	162	0.91	0.98	0.88	0.92	0.89	0.94	No	dec
Eastern redbud	0	1	M	1	86	11	195	27	226	1.00	86.00	11.00	195.00	27.00	226.00	New	New
Eastern redcedar	14	23	M	34	183	67	374	82	436	1.48	7.96	2.91	16.26	3.57	18.96	INC	INC
Eastern white pine	101	221	H	163	201	171	143	173	84	0.74	0.91	0.77	0.65	0.78	0.38	dec	DEC
Flowering dogwood	31	48	H	84	145	122	216	129	229	1.75	3.02	2.54	4.50	2.69	4.77	INC	INC
Gray birch	8	31	M	12	13	9	5	12	7	0.39	0.42	0.29	0.16	0.39	0.23	DEC	DEC
Green ash	190	133	M	136	170	125	213	123	258	1.02	1.28	0.94	1.60	0.93	1.94	No	No
Hackberry	0	13	M	11	99	28	196	38	233	0.85	7.62	2.15	15.08	2.92	17.92	NA	New
Honeylocust	0	8	L	6	77	10	154	17	211	0.75	9.63	1.25	19.25	2.13	26.38	NA	New
Jack pine	1	5	H	1	2	0	0	0	0	0.20	0.40	0.00	0.00	0.00	0.00	NA	NA
Loblolly pine	0	0	H	0	1	0	4	0	10	NA	NA	NA	New	NA	New	NA	New
Mockernut hickory	68	94	H	76	112	90	150	92	164	0.81	1.19	0.96	1.60	0.98	1.75	No	inc
Northern catalpa	0	2	L	0	0	0	0	0	5	0.00	0.00	0.00	0.00	0.00	2.50	NA	NA
Northern red oak	110	254	H	225	345	245	384	255	315	0.89	1.36	0.97	1.51	1.00	1.24	No	inc
Northern white-cedar	18	36	H	9	1	5	3	4	6	0.25	0.03	0.14	0.08	0.11	0.17	DEC	DEC
Ohio buckeye	0	0	L	3	25	5	29	13	14	NA	New	New	New	New	New	New	New
Osage-orange	3	12	M	8	38	13	56	16	61	0.67	3.17	1.08	4.67	1.33	5.08	inc	INC
Paper birch	2	30	H	16	8	8	0	6	0	0.53	0.27	0.27	0.00	0.20	0.00	DEC	DEC
Pawpaw**	0	0	L	0	6	3	23	7	30	NA	New	NA	New	New	New	New	New
Pecan	0	52	L	0	0	0	14	0	32	0.00	0.00	0.00	0.27	0.00	0.62	NA	NA
Persimmon	0	0	M	0	0	0	85	0	160	NA	NA	NA	New	NA	New	NA	New
Pignut hickory	68	102	H	89	129	108	175	113	175	0.87	1.27	1.06	1.72	1.11	1.72	No	INC
Pin cherry	26	22	M	23	8	15	4	14	3	1.05	0.36	0.68	0.18	0.64	0.14	dec	DEC
Pin oak	0	20	M	36	58	47	85	47	93	1.80	2.90	2.35	4.25	2.35	4.65	NA	New
Pitch pine	2	5	H	2	4	4	4	4	4	0.40	0.80	0.80	0.80	0.80	0.80	No	No
Post oak	0	0	H	0	2	1	300	1	668	NA	NA	NA	New	NA	New	NA	New
Quaking aspen	178	216	H	173	69	129	5	102	4	0.80	0.32	0.60	0.02	0.47	0.02	DEC	DEC

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Table 33 (continued).—Complete DISTRIB model results for 86 tree species in subregion 2 (Erie and Ontario Lake Plain)

				Modeled IV						Future:Current suitable habitat[d]						Change class[e]	
				2010 - 2039		2040 - 2069		2070 - 2099		2010 - 2039		2040 - 2069		2070 - 2099		2070-2099	
Common name	FIA IV[a]	Current IV[b]	Model reliability[c]	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
Red maple	711	805	H	795	723	796	549	792	439	0.99	0.90	0.99	0.68	0.98	0.55	No	inc
Red mulberry	0	0	L	0	67	2	127	6	163	NA	New	NA	New	New	New	New	New
Red pine	41	72	M	45	34	42	5	41	4	0.63	0.47	0.58	0.07	0.57	0.06	dec	DEC
Red spruce	7	11	H	7	4	5	3	4	3	0.64	0.36	0.46	0.27	0.36	0.27	DEC	DEC
Rock elm	1	6	L	1	4	1	6	2	22	0.17	0.67	0.17	1.00	0.33	3.67	dec	No
Sassafras	10	41	H	54	84	82	125	93	144	1.32	2.05	2.00	3.05	2.27	3.51	INC	INC
Scarlet oak	5	16	H	22	37	43	76	45	87	1.38	2.31	2.69	4.75	2.81	5.44	INC	INC
Serviceberry	66	55	M	68	65	67	54	66	48	1.24	1.18	1.22	0.98	1.20	0.87	inc	INC
Shagbark hickory	20	46	M	33	79	42	157	46	148	0.72	1.72	0.91	3.41	1.00	3.22	No	inc
Shellbark hickory	0	0	L	0	2	0	33	0	37	NA	NA	NA	New	NA	New	NA	New
Shingle oak	0	3	M	1	14	2	90	2	92	0.33	4.67	0.67	30.00	0.67	30.67	NA	New
Shortleaf pine	0	1	H	0	1	0	15	1	91	0.00	1.00	0.00	15.00	1.00	91.00	NA	New
Shumard oak**	0	0	L	0	0	0	0	0	6	NA	NA	NA	NA	NA	New	NA	New
Silver maple	96	94	M	67	200	73	257	76	268	0.71	2.13	0.78	2.73	0.81	2.85	No	dec
Slippery elm	35	66	M	61	122	86	134	97	142	0.92	1.85	1.30	2.03	1.47	2.15	inc	INC
Southern red oak	0	0	H	0	0	0	0	0	29	NA	NA	NA	NA	NA	New	NA	New
Striped maple	27	50	H	40	42	40	36	40	34	0.80	0.84	0.80	0.72	0.80	0.68	dec	dec
Sugar maple	869	790	H	777	704	729	599	728	424	0.98	0.89	0.92	0.76	0.92	0.54	No	dec
Sugarberry	0	0	M	0	0	0	17	0	76	NA	NA	NA	New	NA	New	NA	New
Swamp white oak	5	22	L	11	15	14	30	13	24	0.50	0.68	0.64	1.36	0.59	1.09	dec	DEC
Sweet birch	15	84	H	65	66	84	64	84	48	0.77	0.79	1.00	0.76	1.00	0.57	No	inc
Sweetgum	0	3	H	1	4	2	26	7	59	0.33	1.33	0.67	8.67	2.33	19.67	NA	New
Sycamore	7	17	M	26	62	40	83	49	90	1.53	3.65	2.35	4.88	2.88	5.29	INC	INC
Tamarack	6	6	H	2	2	0	1	0	2	0.33	0.33	0.00	0.17	0.00	0.33	DEC	dec
Tulip tree	26	22	H	48	63	74	82	82	81	2.18	2.86	3.36	3.73	3.73	3.68	INC	INC
Virginia pine	0	1	H	6	1	12	35	6	40	6.00	1.00	12.00	35.00	6.00	40.00	New	New
White ash	1379	1152	H	1169	1148	1098	781	1080	526	1.02	1.00	0.95	0.68	0.94	0.46	No	No

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Table 33 (continued).—Complete DISTRIB model results for 86 tree species in subregion 2 (Erie and Ontario Lake Plain)

				Modeled IV						Future:Current suitable habitat[d]						Change class[e]	
				2010 - 2039		2040 - 2069		2070 - 2099		2010 - 2039		2040 - 2069		2070 - 2099		2070-2099	
Common name	FIA IV[a]	Current IV[b]	Model reliability[c]	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
White oak	39	155	H	118	184	148	375	154	404	0.76	1.19	0.96	2.42	0.99	2.61	No	inc
White spruce	14	11	M	5	7	4	4	5	3	0.46	0.64	0.36	0.36	0.46	0.27	DEC	DEC
Willow oak	0	0	M	0	0	0	0	0	5	NA	NA	NA	NA	NA	New	NA	New
Winged elm	0	0	H	0	0	0	21	0	152	NA	NA	NA	New	NA	New	NA	New
Yellow birch	90	92	H	83	44	79	24	72	16	0.90	0.48	0.86	0.26	0.78	0.17	dec	DEC

[a] FIA IV is the measured area-weighted importance values (IVs) as reported from Forest Inventory and Analysis.

[b] Current Modeled IV (1971 through 2000) and Modeled IV for future time periods (2010 through 2039, 2040 through 2069, and 2070 through 2099) are simulated from the DISTRIB model; importance values are the sum of the average IV for each pixel in the subregion.

[c] Model reliability for DISTRIB scores, which is based on statistically quantified measures of fitness (Matthews et al. 2011), is abbreviated L (low), M (medium), and H (high).

[d] Future:Current suitable habitat is a ratio of projected importance value to current importance value. This is a measure of habitat change (not where a species will be), where a ratio of ~1 = no change; ratio<1 = decrease; ratio>1 = increase.

[e] Change classes are based on rules in Appendix 4 and abbreviated No (no change), inc (small increase), INC (large increase), dec (small decrease), DEC (large decrease), New (new habitat), and NA (not detected).

** Not observed in the Forest Inventory and Analysis data, but other data suggest species is present, but rare.

Table 34.—Complete DISTRIB model results for 92 tree species in subregion 3 (North Allegheny Plateau)

				Modeled IV						Future:Current suitable habitat[d]						Change class[e]	
				2010 - 2039		2040 - 2069		2070 - 2099		2010 - 2039		2040 - 2069		2070 - 2099		2070-2099	
Common name	FIA IV[a]	Current IV[b]	Model reliability[c]	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	235	256	M	235	250	245	247	240	213	0.92	0.98	0.96	0.97	0.94	0.83	No	dec
American beech	2196	2115	H	1990	1214	1684	700	1539	570	0.94	0.57	0.80	0.33	0.73	0.27	dec	DEC
American chestnut	45	9	M	29	29	33	27	33	18	3.22	3.22	3.67	3.00	3.67	2.00	No	No
American elm	213	284	M	227	593	239	824	257	889	0.80	2.09	0.84	2.90	0.91	3.13	No	dec
American hornbeam	340	357	M	327	349	321	339	315	298	0.92	0.98	0.90	0.95	0.88	0.84	No	No
American mountain-ash	6	0	M	2	1	1	1	1	1	0.33	0.17	0.17	0.17	0.17	0.17	DEC	DEC
Balsam fir	9	56	H	8	4	1	0	1	0	0.14	0.07	0.02	0.00	0.02	0.00	DEC	X
Balsam poplar	8	1	H	1	1	1	0	1	0	1.00	1.00	1.00	0.00	1.00	0.00	No	DEC
Bigtooth aspen	244	250	H	242	262	254	156	253	47	0.97	1.05	1.02	0.62	1.01	0.19	No	No
Bitternut hickory	20	7	L	8	32	9	98	10	204	1.14	4.57	1.29	14.00	1.43	29.14	No	INC
Black ash	16	21	H	9	8	6	0	6	0	0.43	0.38	0.29	0.00	0.29	0.00	dec	DEC
Black cherry	1501	1666	H	1612	1635	1691	1114	1730	596	0.97	0.98	1.02	0.67	1.04	0.36	No	No
Black hickory	0	0	H	0	1	0	112	0	558	NA	NA	NA	New	NA	New	NA	New
Black locust	67	110	L	154	230	232	416	221	441	1.40	2.09	2.11	3.78	2.01	4.01	INC	INC
Black oak	156	192	H	222	395	306	777	336	1245	1.16	2.06	1.59	4.05	1.75	6.48	inc	INC
Black spruce	7	7	H	6	2	4	0	2	0	0.86	0.29	0.57	0.00	0.29	0.00	dec	DEC
Black walnut	41	35	M	46	169	72	338	96	391	1.31	4.83	2.06	9.66	2.74	11.17	INC	INC
Black willow	109	146	L	98	217	95	241	112	290	0.67	1.49	0.65	1.65	0.77	1.99	dec	DEC
Blackgum	82	115	H	141	234	189	368	211	435	1.23	2.04	1.64	3.20	1.84	3.78	inc	INC
Blackjack oak	0	0	M	0	0	0	66	0	428	NA	NA	NA	New	NA	New	NA	New
Boxelder	54	37	M	38	68	42	89	48	126	1.03	1.84	1.14	2.41	1.30	3.41	inc	INC
Bur oak	4	2	M	1	4	2	11	0	50	0.50	2.00	1.00	5.50	0.00	25.00	DEC	inc
Butternut	38	18	L	24	17	21	4	14	2	1.33	0.94	1.17	0.22	0.78	0.11	No	DEC
Cedar elm	0	0	L	0	0	0	0	0	8	NA	NA	NA	NA	NA	New	NA	New
Chestnut oak	479	513	H	608	707	754	950	761	800	1.19	1.38	1.47	1.85	1.48	1.56	inc	INC
Chinkapin oak	3	0	M	0	8	0	99	0	225	0.00	2.67	0.00	33.00	0.00	75.00	DEC	inc
Chokecherry	97	102	L	91	72	99	10	100	1	0.89	0.71	0.97	0.10	0.98	0.01	No	dec

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Table 34 (continued).—Complete DISTRIB model results for 92 tree species in subregion 3 (North Allegheny Plateau)

				Modeled IV						Future:Current suitable habitat[d]						Change class[e]	
				2010 - 2039		2040 - 2069		2070 - 2099		2010 - 2039		2040 - 2069		2070 - 2099		2070-2099	
Common name	FIA IV[a]	Current IV[b]	Model reliability[c]	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
Cucumber tree	42	38	H	43	29	47	22	52	23	1.13	0.76	1.24	0.58	1.37	0.61	inc	DEC
Eastern cottonwood	17	20	L	12	85	14	253	19	525	0.60	4.25	0.70	12.65	0.95	26.25	No	INC
Eastern hemlock	1002	977	H	922	917	871	593	883	440	0.94	0.94	0.89	0.61	0.90	0.45	No	dec
Eastern hophornbeam	518	515	M	482	462	448	475	426	478	0.94	0.90	0.87	0.92	0.83	0.93	No	DEC
Eastern redbud	1	0	M	2	25	6	291	11	414	2.00	25.00	6.00	291.00	11.00	414.00	inc	inc
Eastern redcedar	55	39	M	56	157	66	705	83	1018	1.44	4.03	1.69	18.08	2.13	26.10	INC	INC
Eastern white pine	688	645	H	613	668	575	625	568	452	0.95	1.04	0.89	0.97	0.88	0.70	No	DEC
Flowering dogwood	94	111	H	152	452	269	927	311	1016	1.37	4.07	2.42	8.35	2.80	9.15	INC	INC
Gray birch	96	76	M	71	88	67	58	77	45	0.93	1.16	0.88	0.76	1.01	0.59	No	No
Green ash	53	40	M	39	47	42	73	46	149	0.98	1.18	1.05	1.83	1.15	3.73	No	INC
Hackberry	2	6	M	3	95	7	356	11	503	0.50	15.83	1.17	59.33	1.83	83.83	No	INC
Honeylocust	3	3	L	2	40	4	252	5	542	0.67	13.33	1.33	84.00	1.67	180.67	No	inc
Jack pine	2	8	H	1	1	0	0	0	0	0.13	0.13	0.00	0.00	0.00	0.00	DEC	DEC
Loblolly pine	0	1	H	1	1	1	4	4	56	1.00	1.00	1.00	4.00	4.00	56.00	New	New
Mockernut hickory	92	143	H	114	190	164	348	165	464	0.80	1.33	1.15	2.43	1.15	3.25	No	INC
Mountain maple	17	4	H	3	2	2	0	1	0	0.75	0.50	0.50	0.00	0.25	0.00	dec	DEC
Northern catalpa	2	3	L	0	0	0	0	0	5	0.00	0.00	0.00	0.00	0.00	1.67	DEC	No
Northern red oak	900	917	H	975	1004	965	1083	970	1055	1.06	1.10	1.05	1.18	1.06	1.15	No	inc
Northern white-cedar	7	25	H	5	0	3	0	2	0	0.20	0.00	0.12	0.00	0.08	0.00	DEC	X
Ohio buckeye**	0	0	L	0	4	0	12	1	8	NA	New	NA	New	New	New	NA	New
Osage-orange	1	2	M	3	24	4	93	5	118	1.50	12.00	2.00	46.50	2.50	59.00	No	inc
Paper birch	84	89	H	68	38	37	1	32	0	0.76	0.43	0.42	0.01	0.36	0.00	DEC	DEC
Pawpaw**	0	0	L	1	6	2	25	3	29	NA	New	NA	New	NA	New	NA	New
Pecan	0	151	L	0	0	1	14	1	75	0.00	0.00	0.01	0.09	0.01	0.50	NA	NA
Persimmon	0	0	M	0	6	0	153	0	545	NA	New	NA	New	NA	New	NA	New
Pignut hickory	100	156	H	138	245	203	418	229	478	0.89	1.57	1.30	2.68	1.47	3.06	inc	INC
Pin cherry	75	74	M	64	17	55	1	48	1	0.87	0.23	0.74	0.01	0.65	0.01	dec	DEC

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Table 34 (continued).—Complete DISTRIB model results for 92 tree species in subregion 3 (North Allegheny Plateau)

				Modeled IV						Future:Current suitable habitat[d]						Change class[e]	
				2010 - 2039		2040 - 2069		2070 - 2099		2010 - 2039		2040 - 2069		2070 - 2099		2070-2099	
Common name	FIA IV[a]	Current IV[b]	Model reliability[c]	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 oak	25	10	M	17	28	21	47	22	51	1.70	2.80	2.10	4.70	2.20	5.10	No	inc
Pitch pine	59	29	H	44	57	46	72	47	81	1.52	1.97	1.59	2.48	1.62	2.79	inc	INC
Post oak**	0	0	H	0	7	1	384	2	1644	NA	New	NA	New	NA	New	NA	New
Quaking aspen	462	528	H	435	310	363	22	331	0	0.82	0.59	0.69	0.04	0.63	0.00	dec	DEC
Red maple	3340	3247	H	3395	3184	3401	2390	3405	1581	1.05	0.98	1.05	0.74	1.05	0.49	No	inc
Red mulberry	0	1	L	0	39	1	261	3	493	0.00	39.00	1.00	261.00	3.00	493.00	NA	New
Red pine	122	130	M	95	95	80	15	74	1	0.73	0.73	0.62	0.12	0.57	0.01	dec	DEC
Red spruce	33	46	H	16	26	18	11	20	8	0.35	0.57	0.39	0.24	0.44	0.17	DEC	DEC
River birch	4	2	L	1	2	1	2	2	3	0.50	1.00	0.50	1.00	1.00	1.50	No	No
Rock elm	1	0	L	1	1	0	1	1	11	1.00	1.00	0.00	1.00	1.00	11.00	No	inc
Sassafras	148	166	H	204	285	287	465	322	526	1.23	1.72	1.73	2.80	1.94	3.17	inc	INC
Scarlet oak	101	89	H	134	195	198	332	198	452	1.51	2.19	2.23	3.73	2.23	5.08	INC	INC
Scrub oak (bear oak)	67	33	L	52	74	62	86	71	72	1.58	2.24	1.88	2.61	2.15	2.18	INC	INC
Serviceberry	380	356	M	364	351	364	301	362	257	1.02	0.99	1.02	0.85	1.02	0.72	No	No
Shagbark hickory	44	30	M	41	87	48	215	52	296	1.37	2.90	1.60	7.17	1.73	9.87	inc	INC
Shellbark hickory	1	0	H	0	1	0	7	0	15	0.00	1.00	0.00	7.00	0.00	15.00	DEC	inc
Shingle oak	3	0	M	0	6	2	54	2	121	0.00	2.00	0.67	18.00	0.67	40.33	No	inc
Shortleaf pine	0	4	H	3	8	3	94	5	436	0.75	2.00	0.75	23.50	1.25	109.00	NA	New
Shumard oak**	0	0	L	0	0	0	0	0	8	NA	NA	NA	NA	NA	New	NA	New
Silver maple	34	47	M	23	97	26	191	30	237	0.49	2.06	0.55	4.06	0.64	5.04	dec	DEC
Slippery elm	57	66	M	63	164	89	261	115	314	0.96	2.49	1.35	3.96	1.74	4.76	inc	INC
Sourwood	1	1	H	8	3	24	3	8	13	8.00	3.00	24.00	3.00	8.00	13.00	inc	inc
Southern red oak	0	0	H	0	0	0	13	0	100	NA	NA	NA	New	NA	New	NA	New
Striped maple	403	420	H	400	330	386	230	365	184	0.95	0.79	0.92	0.55	0.87	0.44	No	DEC
Sugar maple	2409	2513	H	2252	1796	2010	1628	1950	1362	0.90	0.72	0.80	0.65	0.78	0.54	dec	DEC
Sugarberry	0	1	M	0	0	0	12	0	105	0.00	0.00	0.00	12.00	0.00	105.00	NA	New
Swamp white oak	22	4	L	11	14	16	18	17	17	2.75	3.50	4.00	4.50	4.25	4.25	inc	inc

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Table 34 (continued).—Complete DISTRIB model results for 92 tree species in subregion 3 (North Allegheny Plateau)

				Modeled IV						Future:Current suitable habitat[d]						Change class[e]	
				2010 - 2039		2040 - 2069		2070 - 2099		2010 - 2039		2040 - 2069		2070 - 2099		2070-2099	
Common name	FIA IV[a]	Current IV[b]	Model reliability[c]	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
Sweet birch	689	675	H	771	724	824	597	811	426	1.14	1.07	1.22	0.88	1.20	0.63	inc	INC
Sweetgum	2	1	H	4	13	5	59	14	209	4.00	13.00	5.00	59.00	14.00	209.00	inc	inc
Sycamore	28	9	M	17	72	21	206	31	220	1.89	8.00	2.33	22.89	3.44	24.44	No	INC
Tamarack	26	12	H	6	8	4	0	3	0	0.50	0.67	0.33	0.00	0.25	0.00	dec	DEC
Tulip tree	60	104	H	152	193	260	407	279	399	1.46	1.86	2.50	3.91	2.68	3.84	INC	INC
Virginia pine	12	26	H	24	19	37	154	25	228	0.92	0.73	1.42	5.92	0.96	8.77	No	dec
White ash	2113	2078	H	1942	1943	1859	1747	1847	1348	0.94	0.94	0.90	0.84	0.89	0.65	No	dec
White oak	545	473	H	617	769	690	1179	711	1648	1.30	1.63	1.46	2.49	1.50	3.48	inc	INC
White spruce	34	33	M	17	7	10	2	8	1	0.52	0.21	0.30	0.06	0.24	0.03	DEC	X
Winged elm	1	0	H	0	1	0	40	0	349	0.00	1.00	0.00	40.00	0.00	349.00	DEC	inc
Yellow birch	338	377	H	358	279	358	128	370	111	0.95	0.74	0.95	0.34	0.98	0.29	No	dec

[a] FIA IV is the measured area-weighted importance values (IVs) as reported from Forest Inventory and Analysis.

[b] Current Modeled IV (1971 through 2000) and Modeled IV for future time periods (2010 through 2039, 2040 through 2069, and 2070 through 2099) are simulated from the DISTRIB model; importance values are the sum of the average IV for each pixel in the subregion.

[c] Model reliability for DISTRIB scores, which is based on statistically quantified measures of fitness (Matthews et al. 2011), is abbreviated L (low), M (medium), and H (high).

[d] Future:Current suitable habitat is a ratio of projected importance value to current importance value. This is a measure of habitat change (not where a species will be), where a ratio of ~1 = no change; ratio<1 = decrease; ratio>1 = increase.

[e] Change classes are based on rules in Appendix 4 and abbreviated No (no change), inc (small increase), INC (large increase), dec (small decrease), DEC (large decrease), New (new habitat), X (extirpated), and NA (not detected).

**Not observed in the Forest Inventory and Analysis data, but other data suggest species is present, but rare.

Table 35.—Complete DISTRIB model results for 88 tree species in subregion 4 (Ridge and Valley)

				Modeled IV						Future:Current suitable habitat[d]						Change class[e]	
				2010 - 2039		2040 - 2069		2070 - 2099		2010 - 2039		2040 - 2069		2070 - 2099		2070-2099	
Common name	FIA IV[a]	Current IV[b]	Model reliability[c]	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	98	115	M	89	112	90	84	91	68	0.77	0.97	0.78	0.73	0.79	0.59	dec	dec
American beech	308	356	H	295	264	275	239	296	169	0.83	0.74	0.77	0.67	0.83	0.48	No	DEC
American chestnut	55	26	M	45	36	42	28	44	27	1.73	1.39	1.62	1.08	1.69	1.04	inc	No
American elm	90	158	M	107	331	115	430	130	415	0.68	2.10	0.73	2.72	0.82	2.63	No	INC
American hornbeam	56	104	M	60	88	61	127	69	135	0.58	0.85	0.59	1.22	0.66	1.30	dec	inc
Bigtooth aspen	125	162	H	126	72	103	11	96	2	0.78	0.44	0.64	0.07	0.59	0.01	dec	DEC
Bitternut hickory	30	14	L	17	67	18	134	25	142	1.21	4.79	1.29	9.57	1.79	10.14	inc	INC
Black cherry	1183	1120	H	1099	816	981	357	957	329	0.98	0.73	0.88	0.32	0.85	0.29	No	DEC
Black hickory	0	1	H	1	64	5	366	5	511	1.00	64.00	5.00	366.00	5.00	511.00	New	New
Black locust	229	255	L	266	245	258	249	238	244	1.04	0.96	1.01	0.98	0.93	0.96	No	No
Black oak	372	392	H	409	562	432	891	441	993	1.04	1.43	1.10	2.27	1.13	2.53	No	INC
Black spruce	4	0	H	0	0	0	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00	DEC	DEC
Black walnut	94	122	M	109	168	124	177	152	165	0.89	1.38	1.02	1.45	1.25	1.35	inc	inc
Black willow	4	21	L	6	54	7	88	8	112	0.29	2.57	0.33	4.19	0.38	5.33	DEC	INC
Blackgum	366	356	H	394	423	428	414	450	441	1.11	1.19	1.20	1.16	1.26	1.24	inc	inc
Blackjack oak	0	0	M	1	47	5	317	6	502	NA	New	New	New	New	New	New	New
Boxelder	79	51	M	56	62	55	62	60	81	1.10	1.22	1.08	1.22	1.18	1.59	No	inc
Bur oak	2	0	M	0	0	0	15	0	39	0.00	0.00	0.00	7.50	0.00	19.50	DEC	inc
Butternut	16	9	L	8	2	4	0	3	0	0.89	0.22	0.44	0.00	0.33	0.00	dec	DEC
Cedar elm	0	0	L	0	0	0	16	0	101	NA	NA	NA	New	NA	New	NA	New
Cherrybark oak	0	0	M	0	2	0	3	2	9	NA	NA	NA	NA	NA	New	NA	New
Chestnut oak	1232	1047	H	1152	1061	1142	757	1118	620	1.10	1.01	1.09	0.72	1.07	0.59	No	dec
Chinkapin oak	2	10	M	6	44	8	130	15	138	0.60	4.40	0.80	13.00	1.50	13.80	No	INC
Chokecherry	57	39	L	31	13	28	1	20	0	0.80	0.33	0.72	0.03	0.51	0.00	dec	X
Cucumber tree	42	31	H	33	26	33	22	32	19	1.07	0.84	1.07	0.71	1.03	0.61	No	dec
Eastern cottonwood	13	15	L	4	33	6	131	6	227	0.27	2.20	0.40	8.73	0.40	15.13	DEC	INC

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Table 35 (continued).—Complete DISTRIB model results for 88 tree species in subregion 4 (Ridge and Valley)

				Modeled IV						Future:Current suitable habitat[d]						Change class[e]	
				2010 - 2039		2040 - 2069		2070 - 2099		2010 - 2039		2040 - 2069		2070 - 2099		2070-2099	
Common name	FIA IV[a]	Current IV[b]	Model reliability[c]	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
Eastern hemlock	367	357	H	312	259	274	154	269	132	0.87	0.73	0.77	0.43	0.75	0.37	dec	DEC
Eastern hophornbeam	137	159	M	135	160	134	190	148	254	0.85	1.01	0.84	1.20	0.93	1.60	No	inc
Eastern redbud	27	32	M	36	107	58	165	70	168	1.13	3.34	1.81	5.16	2.19	5.25	INC	INC
Eastern redcedar	63	96	M	95	322	117	566	155	660	0.99	3.35	1.22	5.90	1.62	6.88	inc	INC
Eastern white pine	283	302	H	288	283	268	174	256	117	0.95	0.94	0.89	0.58	0.85	0.39	No	DEC
Flowering dogwood	215	319	H	315	446	387	537	412	471	0.99	1.40	1.21	1.68	1.29	1.48	inc	inc
Gray birch	60	26	M	28	22	21	19	20	20	1.08	0.85	0.81	0.73	0.77	0.77	dec	dec
Green ash	51	55	M	43	66	45	96	48	144	0.78	1.20	0.82	1.75	0.87	2.62	No	INC
Hackberry	31	35	M	33	128	33	235	38	271	0.94	3.66	0.94	6.71	1.09	7.74	No	INC
Honeylocust	2	6	L	3	12	4	113	7	189	0.50	2.00	0.67	18.83	1.17	31.50	No	INC
Loblolly pine	0	12	H	7	11	13	34	12	190	0.58	0.92	1.08	2.83	1.00	15.83	NA	New
Mockernut hickory	125	190	H	171	227	217	338	218	390	0.90	1.20	1.14	1.78	1.15	2.05	No	INC
Northern catalpa	0	1	L	0	0	0	0	0	13	0.00	0.00	0.00	0.00	0.00	13.00	NA	New
Northern red oak	912	823	H	847	750	809	592	775	529	1.03	0.91	0.98	0.72	0.94	0.64	No	dec
Osage-orange	5	6	M	5	11	6	24	7	48	0.83	1.83	1.00	4.00	1.17	8.00	No	inc
Paper birch	11	15	H	5	1	4	0	3	0	0.33	0.07	0.27	0.00	0.20	0.00	DEC	X
Pawpaw	5	10	L	4	16	8	27	11	23	0.40	1.60	0.80	2.70	1.10	2.30	No	No
Pecan	0	71	L	0	4	0	29	0	41	0.00	0.06	0.00	0.41	0.00	0.58	NA	NA
Persimmon	2	6	M	7	103	15	371	24	502	1.17	17.17	2.50	61.83	4.00	83.67	inc	INC
Pignut hickory	136	218	H	199	255	237	319	252	288	0.91	1.17	1.09	1.46	1.16	1.32	No	inc
Pin cherry	43	21	M	21	3	11	0	10	0	1.00	0.14	0.52	0.00	0.48	0.00	DEC	X
Pin oak	18	24	M	13	28	12	47	22	38	0.54	1.17	0.50	1.96	0.92	1.58	No	inc
Pitch pine	96	101	H	96	119	94	113	93	119	0.95	1.18	0.93	1.12	0.92	1.18	No	No
Post oak	0	8	H	8	245	39	1157	53	1651	1.00	30.63	4.88	144.63	6.63	206.38	New	New
Quaking aspen	54	72	H	36	12	18	1	15	0	0.50	0.17	0.25	0.01	0.21	0.00	DEC	X
Red maple	2063	2021	H	1983	1611	1879	905	1905	688	0.98	0.80	0.93	0.45	0.94	0.34	No	DEC
Red mulberry	6	7	L	5	40	5	192	8	293	0.71	5.71	0.71	27.43	1.14	41.86	No	INC

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Table 35 (continued).—Complete DISTRIB model results for 88 tree species in subregion 4 (Ridge and Valley)

				Modeled IV						Future:Current suitable habitat[d]						Change class[e]	
				2010 - 2039		2040 - 2069		2070 - 2099		2010 - 2039		2040 - 2069		2070 - 2099		2070-2099	
Common name	FIA IV[a]	Current IV[b]	Model reliability[c]	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
Red pine	40	31	M	29	24	18	0	18	0	0.94	0.77	0.58	0.00	0.58	0.00	dec	X
Red spruce	9	4	H	0	0	1	0	1	0	0.00	0.00	0.25	0.00	0.25	0.00	dec	DEC
River birch	7	3	L	4	6	4	6	5	14	1.33	2.00	1.33	2.00	1.67	4.67	No	inc
Rock elm**	0	0	L	0	3	0	7	2	18	NA	NA	NA	New	NA	New	NA	New
Sassafras	463	436	H	466	510	486	478	533	439	1.07	1.17	1.12	1.10	1.22	1.01	inc	No
Scarlet oak	191	205	H	209	235	243	296	241	266	1.02	1.15	1.19	1.44	1.18	1.30	No	inc
Scrub oak (bear oak)	111	63	L	77	100	76	95	89	92	1.22	1.59	1.21	1.51	1.41	1.46	inc	inc
Serviceberry	167	161	M	155	145	149	119	152	115	0.96	0.90	0.93	0.74	0.94	0.71	No	dec
Shagbark hickory	51	66	M	54	134	60	180	67	182	0.82	2.03	0.91	2.73	1.02	2.76	No	INC
Shellbark hickory	1	0	L	0	5	0	11	0	11	0.00	5.00	0.00	11.00	0.00	11.00	DEC	inc
Shingle oak	4	5	M	1	31	2	61	5	55	0.20	6.20	0.40	12.20	1.00	11.00	No	INC
Shortleaf pine	2	4	H	8	70	14	373	17	677	2.00	17.50	3.50	93.25	4.25	169.25	inc	INC
Shumard oak**	0	0	L	0	1	0	10	0	71	NA	NA	NA	New	NA	New	NA	New
Silver maple	41	50	M	27	140	24	172	32	191	0.54	2.80	0.48	3.44	0.64	3.82	dec	INC
Slippery elm	98	127	M	105	146	112	176	117	175	0.83	1.15	0.88	1.39	0.92	1.38	No	inc
Sourwood	0	12	H	22	8	40	7	41	18	1.83	0.67	3.33	0.58	3.42	1.50	New	NA
Southern red oak	1	2	H	2	19	5	105	6	281	1.00	9.50	2.50	52.50	3.00	140.50	No	inc
Striped maple	220	173	H	186	148	172	102	155	90	1.08	0.86	0.99	0.59	0.90	0.52	No	dec
Sugar maple	526	680	H	559	622	536	586	575	419	0.82	0.92	0.79	0.86	0.85	0.62	No	dec
Sugarberry**	0	1	M	0	13	2	79	4	223	0.00	13.00	2.00	79.00	4.00	223.00	New	New
Swamp chestnut oak	13	5	M	4	9	3	5	5	0	0.80	1.80	0.60	1.00	1.00	0.00	No	DEC
Sweet birch	849	672	H	736	554	691	332	658	278	1.10	0.82	1.03	0.49	0.98	0.41	No	DEC
Sweetgum	1	15	H	10	61	25	133	45	269	0.67	4.07	1.67	8.87	3.00	17.93	INC	INC
Sycamore	39	39	M	38	75	44	120	56	141	0.97	1.92	1.13	3.08	1.44	3.62	inc	INC
Table Mountain pine	7	1	M	1	1	1	2	1	3	1.00	1.00	1.00	2.00	1.00	3.00	No	No
Tamarack	16	2	H	3	1	2	1	2	1	1.50	0.50	1.00	0.50	1.00	0.50	No	dec
Tulip tree	253	318	H	366	323	447	250	480	177	1.15	1.02	1.41	0.79	1.51	0.56	inc	dec
Virginia pine	119	136	H	133	121	174	149	150	185	0.98	0.89	1.28	1.10	1.10	1.36	No	inc

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Table 35 (continued).—Complete DISTRIB model results for 88 tree species in subregion 4 (Ridge and Valley)

				Modeled IV						Future:Current suitable habitat[d]						Change class[e]	
				2010 - 2039		2040 - 2069		2070 - 2099		2010 - 2039		2040 - 2069		2070 - 2099		2070-2099	
Common name	FIA IV[a]	Current IV[b]	Model reliability[c]	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
Water oak	0	0	H	0	0	0	6	0	44	NA	NA	NA	New	NA	New	NA	New
White ash	873	730	H	757	658	701	477	709	396	1.04	0.90	0.96	0.65	0.97	0.54	No	dec
White oak	516	603	H	585	774	613	1000	622	934	0.97	1.28	1.02	1.66	1.03	1.55	No	inc
White spruce	17	5	M	2	2	3	3	2	3	0.40	0.40	0.60	0.60	0.40	0.60	dec	dec
Willow oak	0	1	M	1	1	1	5	1	10	1.00	1.00	1.00	5.00	1.00	10.00	NA	New
Winged elm	0	0	H	3	43	6	338	8	727	New	New	New	New	New	New	New	New
Yellow birch	81	90	H	64	40	56	11	58	7	0.71	0.44	0.62	0.12	0.64	0.08	dec	DEC

[a] FIA IV is the measured area-weighted importance values (IVs) as reported from Forest Inventory and Analysis.

[b] Current Modeled IV (1971 through 2000) and Modeled IV for future time periods (2010 through 2039, 2040 through 2069, and 2070 through 2099) are simulated from the DISTRIB model; importance values are the sum of the average IV for each pixel in the subregion.

[c] Model reliability for DISTRIB scores, which is based on statistically quantified measures of fitness (Matthews et al. 2011), is abbreviated L (low), M (medium), and H (high).

[d] Future:Current suitable habitat is a ratio of projected importance value to current importance value. This is a measure of habitat change (not where a species will be), where a ratio of ~1 = no change; ratio<1 = decrease; ratio>1 = increase.

[e] Change classes are based on rules in Appendix 4 and abbreviated No (no change), inc (small increase), INC (large increase), dec (small decrease), DEC (large decrease), New (new habitat), X (extirpated), and NA (not detected).

** Not observed in the Forest Inventory and Analysis data, but other data suggest species is present, but rare.

Table 36.—Complete DISTRIB model results for 107 tree species in subregion 5 (Piedmont)

				Modeled IV						Future:Current suitable habitat[d]						Change class[e]	
				2010 - 2039		2040 - 2069		2070 - 2099		2010 - 2039		2040 - 2069		2070 - 2099		2070-2099	
Common name	FIA IV[a]	Current IV[b]	Model reliability[c]	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	45	86	M	57	81	63	75	74	74	0.66	0.94	0.73	0.87	0.86	0.86	No	No
American beech	566	548	H	546	439	526	289	539	224	1.00	0.80	0.96	0.53	0.98	0.41	No	DEC
American chestnut	30	8	M	23	16	20	12	21	10	2.88	2.00	2.50	1.50	2.63	1.25	No	No
American elm	276	371	M	291	533	298	549	345	536	0.78	1.44	0.80	1.48	0.93	1.45	No	inc
American holly	0	19	H	20	37	31	46	34	45	1.05	1.95	1.63	2.42	1.79	2.37	NA	NA
American hornbeam (musclewood)	197	204	M	195	201	197	200	211	206	0.96	0.99	0.97	0.98	1.03	1.01	No	No
Atlantic white-cedar	0	19	L	7	7	7	5	7	5	0.37	0.37	0.37	0.26	0.37	0.26	NA	NA
Baldcypress	0	16	M	13	33	19	41	33	68	0.81	2.06	1.19	2.56	2.06	4.25	NA	New
Balsam fir	12	33	H	15	5	6	1	6	3	0.46	0.15	0.18	0.03	0.18	0.09	DEC	DEC
Bigtooth aspen	78	103	H	67	60	72	20	66	7	0.65	0.58	0.70	0.19	0.64	0.07	dec	DEC
Bitternut hickory	25	35	L	25	116	33	162	60	188	0.71	3.31	0.94	4.63	1.71	5.37	inc	INC
Black ash	13	42	H	18	16	14	4	11	2	0.43	0.38	0.33	0.10	0.26	0.05	dec	DEC
Black cherry	954	920	H	792	567	687	406	627	379	0.86	0.62	0.75	0.44	0.68	0.41	dec	DEC
Black hickory	0	7	H	21	179	38	421	52	544	3.00	25.57	5.43	60.14	7.43	77.71	New	New
Black locust	182	192	L	197	200	207	220	219	189	1.03	1.04	1.08	1.15	1.14	0.98	No	No
Black oak	413	520	H	524	679	543	820	556	806	1.01	1.31	1.04	1.58	1.07	1.55	No	inc
Black walnut	165	182	M	184	241	211	224	240	170	1.01	1.32	1.16	1.23	1.32	0.93	inc	No
Black willow	48	70	L	43	145	48	158	61	188	0.61	2.07	0.69	2.26	0.87	2.69	No	INC
Blackgum	306	322	H	356	327	360	339	382	380	1.11	1.02	1.12	1.05	1.19	1.18	No	No
Blackjack oak	0	17	M	28	140	47	282	70	383	1.65	8.24	2.77	16.59	4.12	22.53	New	New
Boxelder	185	159	M	154	178	162	162	171	169	0.97	1.12	1.02	1.02	1.08	1.06	No	No
Bur oak	1	8	M	3	18	3	25	6	35	0.38	2.25	0.38	3.13	0.75	4.38	No	inc
Butternut	51	34	L	36	23	31	10	22	8	1.06	0.68	0.91	0.29	0.65	0.24	dec	DEC
Cedar elm	0	0	L	0	3	0	49	1	114	NA	NA	NA	New	NA	New	NA	New
Cherrybark oak	0	7	M	6	17	7	39	14	78	0.86	2.43	1.00	5.57	2.00	11.14	NA	New
Chestnut oak	730	532	H	649	466	636	383	624	344	1.22	0.88	1.20	0.72	1.17	0.65	No	dec

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Table 36 (continued).—Complete DISTRIB model results for 107 tree species in subregion 5 (Piedmont)

				Modeled IV						Future:Current suitable habitat[d]						Change class[e]	
				2010 - 2039		2040 - 2069		2070 - 2099		2010 - 2039		2040 - 2069		2070 - 2099		2070-2099	
Common name	FIA IV[a]	Current IV[b]	Model reliability[c]	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
Chinkapin oak	3	10	M	14	53	21	106	30	123	1.40	5.30	2.10	10.60	3.00	12.30	No	inc
Chokecherry	43	48	L	33	21	30	1	23	0	0.69	0.44	0.63	0.02	0.48	0.00	DEC	DEC
Eastern cottonwood	40	70	L	49	143	45	194	63	274	0.70	2.04	0.64	2.77	0.90	3.91	No	INC
Eastern hemlock	320	398	H	319	272	283	179	280	159	0.80	0.68	0.71	0.45	0.70	0.40	dec	DEC
Eastern hophornbeam	217	241	M	201	258	205	272	237	326	0.83	1.07	0.85	1.13	0.98	1.35	No	inc
Eastern redbud	17	31	M	34	78	50	149	69	181	1.10	2.52	1.61	4.81	2.23	5.84	INC	INC
Eastern redcedar	275	316	M	334	497	382	654	428	717	1.06	1.57	1.21	2.07	1.35	2.27	inc	INC
Eastern white pine	406	474	H	386	301	354	171	348	156	0.81	0.64	0.75	0.36	0.73	0.33	dec	DEC
Flowering dogwood	316	392	H	405	478	443	494	468	473	1.03	1.22	1.13	1.26	1.19	1.21	No	inc
Gray birch	60	71	M	50	47	45	39	40	34	0.70	0.66	0.63	0.55	0.56	0.48	dec	DEC
Green ash	39	131	M	75	145	77	179	97	225	0.57	1.11	0.59	1.37	0.74	1.72	dec	inc
Hackberry	42	68	M	51	203	67	256	91	277	0.75	2.99	0.99	3.77	1.34	4.07	inc	INC
Honeylocust	5	13	L	9	71	13	125	17	206	0.69	5.46	1.00	9.62	1.31	15.85	No	INC
Jack pine	0	4	H	1	2	0	0	0	0	0.25	0.50	0.00	0.00	0.00	0.00	NA	NA
Laurel oak**	0	0	H	0	0	0	0	5	0	NA	NA	NA	NA	New	NA	New	NA
Loblolly pine	17	51	H	50	120	91	255	131	565	0.98	2.35	1.78	5.00	2.57	11.08	INC	INC
Longleaf pine**	0	3	H	0	2	7	1	39	1	0.00	0.67	2.33	0.33	13.00	0.33	New	NA
Mockernut hickory	205	250	H	255	277	269	329	277	355	1.02	1.11	1.08	1.32	1.11	1.42	No	inc
Mountain maple	12	2	H	6	2	2	0	2	0	3.00	1.00	1.00	0.00	1.00	0.00	No	DEC
Northern catalpa	13	1	L	5	5	5	4	5	9	5.00	5.00	5.00	4.00	5.00	9.00	inc	INC
Northern red oak	820	757	H	741	673	712	546	701	501	0.98	0.89	0.94	0.72	0.93	0.66	No	dec
Northern white-cedar	8	24	H	8	7	6	5	6	5	0.33	0.29	0.25	0.21	0.25	0.21	dec	dec
Ohio buckeye**	0	0	L	0	3	0	4	2	4	NA	NA	NA	New	NA	New	NA	New
Osage-orange	6	12	M	12	31	12	36	16	68	1.00	2.58	1.00	3.00	1.33	5.67	No	inc
Overcup oak**	0	7	M	0	3	1	20	2	38	0.00	0.43	0.14	2.86	0.29	5.43	NA	New
Paper birch	52	73	H	54	33	36	2	30	1	0.74	0.45	0.49	0.03	0.41	0.01	DEC	DEC

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Table 36 (continued).—Complete DISTRIB model results for 107 tree species in subregion 5 (Piedmont)

				Modeled IV						Future:Current suitable habitat[d]						Change class[e]	
				2010 - 2039		2040 - 2069		2070 - 2099		2010 - 2039		2040 - 2069		2070 - 2099		2070-2099	
Common name	FIA IV[a]	Current IV[b]	Model reliability[c]	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
Pawpaw	49	29	L	32	53	39	60	57	63	1.10	1.83	1.35	2.07	1.97	2.17	inc	INC
Pecan	0	137	L	1	18	3	36	6	69	0.01	0.13	0.02	0.26	0.04	0.50	NA	NA
Persimmon	19	33	M	54	206	82	377	108	491	1.64	6.24	2.49	11.42	3.27	14.88	INC	INC
Pignut hickory	256	317	H	306	341	326	342	347	299	0.97	1.08	1.03	1.08	1.10	0.94	No	No
Pin cherry	32	27	M	18	13	13	5	15	4	0.67	0.48	0.48	0.19	0.56	0.15	dec	DEC
Pin oak	113	96	M	85	157	94	150	147	133	0.89	1.64	0.98	1.56	1.53	1.39	inc	inc
Pitch pine	66	106	H	84	72	74	70	71	74	0.79	0.68	0.70	0.66	0.67	0.70	dec	dec
Pond pine	2	0	H	1	5	1	10	12	11	0.50	2.50	0.50	5.00	6.00	5.50	inc	inc
Post oak	3	55	H	117	538	200	1121	248	1483	2.13	9.78	3.64	20.38	4.51	26.96	inc	INC
Quaking aspen	107	116	H	88	51	62	8	53	4	0.76	0.44	0.53	0.07	0.46	0.03	DEC	DEC
Red maple	2039	2112	H	2001	1591	1905	1097	1856	920	0.95	0.75	0.90	0.52	0.88	0.44	No	DEC
Red mulberry	8	16	L	9	116	14	189	31	324	0.56	7.25	0.88	11.81	1.94	20.25	No	INC
Red pine	29	55	M	28	35	31	11	31	9	0.51	0.64	0.56	0.20	0.56	0.16	dec	DEC
Red spruce	29	28	H	19	14	12	10	13	9	0.68	0.50	0.43	0.36	0.46	0.32	DEC	DEC
Redbay	0	0	H	0	0	0	0	6	0	NA	NA	NA	NA	New	NA	New	NA
River birch	9	7	L	4	10	5	10	9	29	0.57	1.43	0.71	1.43	1.29	4.14	No	inc
Rock elm	1	1	L	3	25	3	22	19	25	3.00	25.00	3.00	22.00	19.00	25.00	inc	inc
Sassafras	300	354	H	351	382	380	365	412	347	0.99	1.08	1.07	1.03	1.16	0.98	No	No
Scarlet oak	236	214	H	244	245	260	233	261	203	1.14	1.15	1.22	1.09	1.22	0.95	inc	No
Scrub oak (bear oak)	68	20	L	44	46	46	51	47	47	2.20	2.30	2.30	2.55	2.35	2.35	INC	INC
Serviceberry	125	102	M	105	96	105	83	103	79	1.03	0.94	1.03	0.81	1.01	0.78	No	dec
Shagbark hickory	72	122	M	102	216	127	221	155	219	0.84	1.77	1.04	1.81	1.27	1.80	inc	inc
Shellbark hickory	1	0	L	0	44	0	67	2	77	0.00	44.00	0.00	67.00	2.00	77.00	NA	inc
Shingle oak	1	9	M	6	70	11	104	31	121	0.67	7.78	1.22	11.56	3.44	13.44	No	INC
Shortleaf pine	1	21	H	37	134	45	329	55	533	1.76	6.38	2.14	15.67	2.62	25.38	No	INC
Shumard oak**	0	0	L	0	2	0	17	0	74	NA	NA	NA	New	NA	New	NA	New

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Table 36 (continued).—Complete DISTRIB model results for 107 tree species in subregion 5 (Piedmont)

				Modeled IV						Future:Current suitable habitat[d]						Change class[e]	
				2010 - 2039		2040 - 2069		2070 - 2099		2010 - 2039		2040 - 2069		2070 - 2099		2070-2099	
Common name	FIA IV[a]	Current IV[b]	Model reliability[c]	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
Silver maple	65	131	M	68	279	78	342	122	373	0.52	2.13	0.60	2.61	0.93	2.85	No	INC
Slash pine	0	0	H	0	0	0	0	16	4	NA	NA	NA	NA	New	New	New	New
Slippery elm	54	112	M	87	148	102	171	119	179	0.78	1.32	0.91	1.53	1.06	1.60	No	inc
Sourwood	0	8	H	14	12	28	8	27	26	1.75	1.50	3.50	1.00	3.38	3.25	New	New
Southern red oak	12	24	H	43	112	68	246	81	379	1.79	4.67	2.83	10.25	3.38	15.79	No	INC
Striped maple	101	92	H	88	71	78	46	72	38	0.96	0.77	0.85	0.50	0.78	0.41	dec	DEC
Sugar maple	846	940	H	877	971	871	686	953	454	0.93	1.03	0.93	0.73	1.01	0.48	No	DEC
Sugarberry**	0	7	M	7	42	14	173	24	287	1.00	6.00	2.00	24.71	3.43	41.00	New	New
Swamp chestnut oak	1	0	M	0	3	0	7	0	10	0.00	3.00	0.00	7.00	0.00	10.00	NA	inc
Swamp tupelo	0	8	H	1	8	9	12	46	15	0.13	1.00	1.13	1.50	5.75	1.88	New	NA
Swamp white oak	46	25	L	23	48	28	36	38	33	0.92	1.92	1.12	1.44	1.52	1.32	inc	inc
Sweet birch	479	425	H	441	322	412	227	391	184	1.04	0.76	0.97	0.53	0.92	0.43	No	DEC
Sweetbay	8	13	H	5	8	9	7	29	7	0.39	0.62	0.69	0.54	2.23	0.54	No	dec
Sweetgum	127	196	H	221	372	291	493	392	705	1.13	1.90	1.49	2.52	2.00	3.60	inc	INC
Sycamore	78	90	M	103	135	110	171	123	179	1.14	1.50	1.22	1.90	1.37	1.99	inc	inc
Tamarack	15	5	H	8	5	6	3	5	3	1.60	1.00	1.20	0.60	1.00	0.60	No	No
Tulip tree	652	593	H	639	416	641	284	605	254	1.08	0.70	1.08	0.48	1.02	0.43	No	DEC
Turkey oak	0	0	H	0	0	1	0	9	0	NA	NA	NA	NA	New	NA	New	NA
Virginia pine	106	159	H	168	109	201	107	157	122	1.06	0.69	1.26	0.67	0.99	0.77	No	dec
Water elm	0	5	L	2	2	2	2	2	6	0.40	0.40	0.40	0.40	0.40	1.20	NA	NA
Water hickory	0	5	M	1	2	0	3	1	7	0.20	0.40	0.00	0.60	0.20	1.40	NA	NA
Water oak	0	3	H	3	13	7	77	9	218	1.00	4.33	2.33	25.67	3.00	72.67	NA	New
Water tupelo	11	9	M	5	8	8	14	14	21	0.56	0.89	0.89	1.56	1.56	2.33	No	No
White ash	1372	1252	H	1150	923	1047	634	1072	519	0.92	0.74	0.84	0.51	0.86	0.42	No	DEC
White oak	463	612	H	642	792	700	869	716	886	1.05	1.29	1.14	1.42	1.17	1.45	No	inc
White spruce	34	18	M	12	14	12	9	8	8	0.67	0.78	0.67	0.50	0.44	0.44	dec	dec

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Table 36 (continued).—Complete DISTRIB model results for 107 tree species in subregion 5 (Piedmont)

				Modeled IV						Future:Current suitable habitat[d]						Change class[e]	
				2010 - 2039		2040 - 2069		2070 - 2099		2010 - 2039		2040 - 2069		2070 - 2099		2070-2099	
Common name	FIA IV[a]	Current IV[b]	Model reliability[c]	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
Willow oak	0	11	M	11	22	14	77	20	128	1.00	2.00	1.27	7.00	1.82	11.64	NA	New
Winged elm	0	6	H	36	186	67	517	105	828	6.00	31.00	11.17	86.17	17.50	138.00	New	New
Yellow birch	134	137	H	122	86	98	58	99	51	0.89	0.63	0.72	0.42	0.72	0.37	dec	DEC

[a] FIA IV is the measured area-weighted importance values (IVs) as reported from Forest Inventory and Analysis.

[b] Current Modeled IV (1971 through 2000) and Modeled IV for future time periods (2010 through 2039, 2040 through 2069, and 2070 through 2099) are simulated from the DISTRIB model; importance values are the sum of the average IV for each pixel in the subregion.

[c] Model reliability for DISTRIB scores, which is based on statistically quantified measures of fitness (Matthews et al. 2011), is abbreviated L (low), M (medium), and H (high).

[d] Future:Current suitable habitat is a ratio of projected importance value to current importance value. This is a measure of habitat change (not where a species will be), where a ratio of ~1 = no change; ratio<1 = decrease; ratio>1 = increase.

[e] Change classes are based on rules in Appendix 4 and abbreviated No (no change), inc (small increase), INC (large increase), dec (small decrease), DEC (large decrease), New (new habitat), and NA (not detected).

** Not observed in the Forest Inventory and Analysis data, but other data suggest species is present, but rare.

Table 37.—Complete DISTRIB model results for 91 tree species in subregion 6 (Coastal Plain)

				Modeled IV						Future:Current suitable habitat[d]						Change class[e]	
				2010 - 2039		2040 - 2069		2070 - 2099		2010 - 2039		2040 - 2069		2070 - 2099		2070-2099	
Common name	FIA IV[a]	Current IV[b]	Model reliability[c]	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 beech	247	228	H	228	146	218	88	205	76	1.00	0.64	0.96	0.39	0.90	0.33	No	DEC
American chestnut	4	3	M	1	1	1	1	1	1	0.33	0.33	0.33	0.33	0.33	0.33	dec	dec
American elm	33	60	M	47	122	47	205	73	285	0.78	2.03	0.78	3.42	1.22	4.75	inc	INC
American holly	235	235	H	258	235	283	162	266	134	1.10	1.00	1.20	0.69	1.13	0.57	No	dec
American hornbeam	61	94	M	74	80	79	91	84	94	0.79	0.85	0.84	0.97	0.89	1.00	No	No
Atlantic white-cedar	73	58	L	50	38	42	35	39	32	0.86	0.66	0.72	0.60	0.67	0.55	dec	dec
Baldcypress	1	11	M	20	58	41	82	61	129	1.82	5.27	3.73	7.46	5.55	11.73	INC	INC
Bigtooth aspen	20	9	H	3	0	2	0	1	0	0.33	0.00	0.22	0.00	0.11	0.00	DEC	X
Bitternut hickory	1	5	L	1	15	5	64	17	88	0.20	3.00	1.00	12.80	3.40	17.60	No	INC
Black cherry	311	302	H	212	146	176	134	152	138	0.70	0.48	0.58	0.44	0.50	0.46	dec	DEC
Black hickory	0	12	H	30	136	37	249	72	244	2.50	11.33	3.08	20.75	6.00	20.33	New	New
Black locust	103	88	L	75	74	71	23	87	5	0.85	0.84	0.81	0.26	0.99	0.06	No	DEC
Black oak	272	313	H	296	339	281	276	289	187	0.95	1.08	0.90	0.88	0.92	0.60	No	dec
Black walnut	26	52	M	33	51	36	27	49	6	0.64	0.98	0.69	0.52	0.94	0.12	No	DEC
Black willow	9	14	L	9	33	8	41	10	72	0.64	2.36	0.57	2.93	0.71	5.14	dec	INC
Blackgum	368	363	H	324	276	290	269	281	285	0.89	0.76	0.80	0.74	0.77	0.79	dec	dec
Blackjack oak	10	21	M	30	77	41	104	60	112	1.43	3.67	1.95	4.95	2.86	5.33	INC	INC
Bluejack oak	0	0	M	0	1	0	1	0	8	NA	NA	NA	NA	NA	New	NA	New
Boxelder	72	40	M	51	52	52	42	52	39	1.28	1.30	1.30	1.05	1.30	0.98	inc	No
Cedar elm	0	0	L	0	23	0	73	1	84	NA	New	NA	New	NA	New	NA	New
Cherrybark oak	6	4	M	15	27	22	70	24	84	3.75	6.75	5.50	17.50	6.00	21.00	inc	INC
Chestnut oak	122	129	H	111	57	108	37	94	34	0.86	0.44	0.84	0.29	0.73	0.26	dec	DEC
Chinkapin oak**	0	1	M	1	6	4	9	4	7	1.00	6.00	4.00	9.00	4.00	7.00	New	New
Eastern cottonwood	6	20	L	8	31	7	60	11	97	0.40	1.55	0.35	3.00	0.55	4.85	dec	INC
Eastern hemlock	30	9	H	15	14	15	13	16	13	1.67	1.56	1.67	1.44	1.78	1.44	inc	inc
Eastern hophornbeam	16	24	M	25	37	27	51	38	81	1.04	1.54	1.13	2.13	1.58	3.38	inc	INC
Eastern redbud	1	3	M	1	5	1	15	2	28	0.33	1.67	0.33	5.00	0.67	9.33	No	inc
Eastern redcedar	50	91	M	70	114	80	145	98	135	0.77	1.25	0.88	1.59	1.08	1.48	No	inc

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Table 37 (continued).—Complete DISTRIB model results for 91 tree species in subregion 6 (Coastal Plain)

				Modeled IV						Future:Current suitable habitat[d]						Change class[e]	
				2010 - 2039		2040 - 2069		2070 - 2099		2010 - 2039		2040 - 2069		2070 - 2099		2070-2099	
Common name	FIA IV[a]	Current IV[b]	Model reliability[c]	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
Eastern white pine	15	30	H	19	4	13	0	11	1	0.63	0.13	0.43	0.00	0.37	0.03	DEC	DEC
Flowering dogwood	132	136	H	129	133	129	140	132	148	0.95	0.98	0.95	1.03	0.97	1.09	No	No
Gray birch	10	4	M	4	4	4	4	4	6	1.00	1.00	1.00	1.00	1.00	1.50	No	No
Green ash	16	35	M	26	46	22	81	29	96	0.74	1.31	0.63	2.31	0.83	2.74	No	INC
Hackberry	2	13	M	4	17	5	29	13	45	0.31	1.31	0.39	2.23	1.00	3.46	No	INC
Honeylocust**	0	1	L	0	2	0	2	0	17	0.00	2.00	0.00	2.00	0.00	17.00	NA	New
Laurel oak	0	0	H	0	1	5	12	10	30	NA	NA	New	New	New	New	New	New
Loblolly pine	329	355	H	464	545	591	669	574	810	1.31	1.54	1.67	1.89	1.62	2.28	inc	INC
Longleaf pine	0	2	H	0	2	4	11	42	16	0.00	1.00	2.00	5.50	21.00	8.00	New	New
Mockernut hickory	48	78	H	53	55	50	65	52	94	0.68	0.71	0.64	0.83	0.67	1.21	dec	inc
Northern catalpa	12	1	L	5	5	5	4	5	5	5.00	5.00	5.00	4.00	5.00	5.00	inc	inc
Northern red oak	132	180	H	140	115	134	114	130	69	0.78	0.64	0.74	0.63	0.72	0.38	dec	DEC
Osage-orange**	0	1	M	1	2	1	1	1	6	1.00	2.00	1.00	1.00	1.00	6.00	NA	New
Overcup oak**	0	1	M	0	9	1	48	3	66	0.00	9.00	1.00	48.00	3.00	66.00	NA	New
Pawpaw	9	23	L	9	7	6	1	11	1	0.39	0.30	0.26	0.04	0.48	0.04	DEC	DEC
Pecan**	0	49	L	0	5	2	6	6	13	0.00	0.10	0.04	0.12	0.12	0.27	NA	NA
Persimmon	38	59	M	75	127	75	219	89	263	1.27	2.15	1.27	3.71	1.51	4.46	inc	INC
Pignut hickory	70	100	H	72	90	75	98	79	101	0.72	0.90	0.75	0.98	0.79	1.01	dec	No
Pin cherry	13	5	M	4	2	4	1	6	1	0.80	0.40	0.80	0.20	1.20	0.20	No	dec
Pin oak	19	20	M	15	44	14	40	41	50	0.75	2.20	0.70	2.00	2.05	2.50	INC	INC
Pitch pine	533	402	H	408	331	337	341	324	362	1.02	0.82	0.84	0.85	0.81	0.90	No	No
Pond pine	6	1	H	5	32	5	55	21	57	5.00	32.00	5.00	55.00	21.00	57.00	inc	inc
Post oak	21	64	H	125	211	127	351	148	358	1.95	3.30	1.98	5.48	2.31	5.59	INC	INC
Quaking aspen	9	8	H	2	2	2	2	2	2	0.25	0.25	0.25	0.25	0.25	0.25	DEC	DEC
Red maple	1317	1253	H	1156	943	1154	641	1096	567	0.92	0.75	0.92	0.51	0.88	0.45	No	DEC
Red mulberry*	9	6	L	8	11	7	12	10	56	1.33	1.83	1.17	2.00	1.67	9.33	No	INC

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Table 37 (continued).—Complete DISTRIB model results for 91 tree species in subregion 6 (Coastal Plain)

Common name	FIA IV[a]	Current IV[b]	Model reliability[c]	Modeled IV 2010 - 2039 PCM B1	Modeled IV 2010 - 2039 GFDL A1FI	Modeled IV 2040 - 2069 PCM B1	Modeled IV 2040 - 2069 GFDL A1FI	Modeled IV 2070 - 2099 PCM B1	Modeled IV 2070 - 2099 GFDL A1FI	Future:Current suitable habitat[d] 2010 - 2039 PCM B1	Future:Current suitable habitat[d] 2010 - 2039 GFDL A1FI	Future:Current suitable habitat[d] 2040 - 2069 PCM B1	Future:Current suitable habitat[d] 2040 - 2069 GFDL A1FI	Future:Current suitable habitat[d] 2070 - 2099 PCM B1	Future:Current suitable habitat[d] 2070 - 2099 GFDL A1FI	Change class[e] 2070-2099 PCM B1	Change class[e] 2070-2099 GFDL A1FI
Redbay**	0	0	H	0	0	0	0	10	0	NA	NA	NA	NA	New	NA	New	NA
River birch	28	13	L	16	17	16	18	22	21	1.23	1.31	1.23	1.39	1.69	1.62	inc	inc
Rock elm**	0	0	L	1	9	2	1	7	0	NA	New	NA	NA	New	NA	New	NA
Sassafras	218	239	H	200	176	173	103	194	95	0.84	0.74	0.72	0.43	0.81	0.40	No	DEC
Scarlet oak	198	191	H	172	106	151	48	139	51	0.90	0.56	0.79	0.25	0.73	0.27	dec	DEC
Scrub oak (bear oak)	23	17	L	15	13	13	14	13	16	0.88	0.77	0.77	0.82	0.77	0.94	dec	No
Serviceberry	4	0	M	3	1	1	1	2	0	0.75	0.25	0.25	0.25	0.50	0.00	dec	DEC
Shagbark hickory	3	13	M	10	29	18	44	30	68	0.77	2.23	1.39	3.39	2.31	5.23	INC	INC
Shellbark hickory**	0	1	L	0	5	0	9	0	18	0.00	5.00	0.00	9.00	0.00	18.00	NA	New
Shingle oak*	1	3	M	3	5	2	9	5	12	1.00	1.67	0.67	3.00	1.67	4.00	No	inc
Shortleaf pine	33	60	H	75	96	71	175	72	212	1.25	1.60	1.18	2.92	1.20	3.53	inc	INC
Shumard oak	0	0	L	0	5	0	54	0	70	NA	New	NA	New	NA	New	NA	New
Silver maple	23	34	M	22	62	21	142	26	231	0.65	1.82	0.62	4.18	0.77	6.79	dec	INC
Slash pine	0	0	H	0	0	0	17	13	95	NA	NA	NA	New	New	New	New	New
Slippery elm	7	15	M	8	20	11	20	17	44	0.53	1.33	0.73	1.33	1.13	2.93	No	INC
Sourwood	1	5	H	23	5	38	0	44	2	4.60	1.00	7.60	0.00	8.80	0.40	INC	dec
Southern red oak	135	139	H	165	184	165	220	171	250	1.19	1.32	1.19	1.58	1.23	1.80	inc	inc
Sugar maple	3	119	H	91	127	102	45	153	8	0.77	1.07	0.86	0.38	1.29	0.07	inc	DEC
Sugarberry**	0	2	M	5	46	7	100	13	115	2.50	23.00	3.50	50.00	6.50	57.50	New	New
Swamp chestnut oak	14	8	M	11	17	15	15	16	7	1.38	2.13	1.88	1.88	2.00	0.88	inc	No
Swamp tupelo	3	16	H	20	57	53	70	132	72	1.25	3.56	3.31	4.38	8.25	4.50	INC	INC
Swamp white oak	14	10	L	4	5	2	4	4	6	0.40	0.50	0.20	0.40	0.40	0.60	DEC	dec
Sweet birch	9	23	H	5	5	5	6	6	2	0.22	0.22	0.22	0.26	0.26	0.09	DEC	DEC
Sweetbay	58	62	H	53	59	60	56	82	62	0.86	0.95	0.97	0.90	1.32	1.00	inc	No
Sweetgum	701	658	H	714	779	773	786	798	809	1.09	1.18	1.18	1.20	1.21	1.23	inc	inc
Sycamore	19	37	M	31	40	31	73	34	82	0.84	1.08	0.84	1.97	0.92	2.22	No	INC
Tulip tree	495	441	H	427	259	392	167	340	145	0.97	0.59	0.89	0.38	0.77	0.33	dec	DEC

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Table 37 (continued).—Complete DISTRIB model results for 91 tree species in subregion 6 (Coastal Plain)

				Modeled IV						Future:Current suitable habitat[d]						Change class[e]	
				2010 - 2039		2040 - 2069		2070 - 2099		2010 - 2039		2040 - 2069		2070 - 2099		2070-2099	
Common name	FIA IV[a]	Current IV[b]	Model reliability[c]	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
Turkey oak	0	0	H	0	1	1	0	26	8	NA	NA	NA	NA	New	New	New	New
Virginia pine	286	271	H	225	132	181	105	155	97	0.83	0.49	0.67	0.39	0.57	0.36	dec	DEC
Water hickory**	0	5	M	1	3	0	5	1	7	0.20	0.60	0.00	1.00	0.20	1.40	NA	NA
Water locust	0	0	L	0	0	0	18	0	19	NA	NA	NA	New	NA	New	NA	New
Water oak	44	46	H	74	111	93	248	92	357	1.61	2.41	2.02	5.39	2.00	7.76	inc	INC
Water tupelo	9	21	M	14	37	38	53	54	72	0.67	1.76	1.81	2.52	2.57	3.43	INC	INC
White ash	164	159	H	116	140	145	114	156	122	0.73	0.88	0.91	0.72	0.98	0.77	No	dec
White oak	496	542	H	509	421	463	333	437	299	0.94	0.78	0.85	0.61	0.81	0.55	No	dec
Willow oak	54	57	M	60	105	70	160	75	189	1.05	1.84	1.23	2.81	1.32	3.32	inc	INC
Winged elm	0	14	H	60	183	90	330	124	352	4.29	13.07	6.43	23.57	8.86	25.14	New	New

[a] FIA IV is the measured area-weighted importance values (IVs) as reported from Forest Inventory and Analysis.

[b] Current Modeled IV (1971 through 2000) and Modeled IV for future time periods (2010 through 2039, 2040 through 2069, and 2070 through 2099) are simulated from the DISTRIB model; importance values are the sum of the average IV for each pixel in the subregion.

[c] Model reliability for DISTRIB scores, which is based on statistically quantified measures of fitness (Matthews et al. 2011), is abbreviated L (low), M (medium), and H (high).

[d] Future:Current suitable habitat is a ratio of projected importance value to current importance value. This is a measure of habitat change (not where a species will be), where a ratio of ~1 = no change; ratio<1 = decrease; ratio>1 = increase.

[e] Change classes are based on rules in Appendix 4 and abbreviated No (no change), inc (small increase), INC (large increase), dec (small decrease), DEC (large decrease), New (new habitat), X (extirpated), and NA (not detected).

* Species is present but rare.

** Not observed in the Forest Inventory and Analysis data, but other data suggest species is present, but rare.

Table 38.—Key to modifying factor codes[a]

Code	Title	Type	Description (if positive)	Description (if negative)
COL	Competition-light	Biological	Tolerant of shade or limited light conditions	Intolerant of shade or limited light conditions
DISE	Disease	Disturbance	N/A	Has a high number and/or severity of known pathogens that attack the species
DISP	Dispersal	Biological	High ability to effectively produce and distribute seeds	N/A
DRO	Drought	Biological	Drought tolerant	Susceptible to drought
EHS	Environmental habitat specificity	Biological	Wide range of suitable habitat conditions	Narrow range of suitable habitat conditions
ESP	Edaphic specificity	Biological	Wide range of soil tolerance	Narrow range of soil requirements
FRG	Fire regeneration	Disturbance	Regenerates well after fire	N/A
FTK	Fire topkill	Disturbance	Resistant to fire topkill	Susceptible to fire topkill
INP	Invasive plants	Disturbance	N/A	Strong negative effects of invasive plants on the species, either through competition for nutrients or as a pathogen
INS	Insect pests	Disturbance	N/A	Has a high number and/or severity of known insects that attack the species
POL	Pollution	Disturbance	N/A	Strong negative effects of pollution on the species
SES	Seedling establishment	Biological	High ability to regenerate with seeds to maintain future populations	Low ability to regenerate with seeds to maintain future populations
TGR	Temperature gradient	Disturbance	Has a high tolerance for a large variation in temperature	Has a low tolerance for a large variation in temperature
VRE	Vegetative reproduction	Biological	Capable of vegetative reproduction through stump sprouts or cloning	N/A

[a] These codes are used to describe positive or negative modifying factors. 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.

Table 39.—Modifying factor[a] and adaptability[b] information for the 116 tree species in the assessment area that were modeled using DISTRIB

		Modifying factors		Adaptability scores			
Common name	DISTRIB model reliability	Positive traits	Negative traits	DistFact	BioFact	Adapt	Adapt Class
American basswood	Medium	COL	FTK	0.3	0.2	4.6	o
American beech	High	COL	INS FTK	-1.1	0.0	3.6	o
American chestnut	Medium	COL	DISE FTK	0.1	0.3	4.5	o
American elm	Medium	EHS	DISE INS	-0.8	0.3	4.0	o
American holly	High	COL EHS	FTK	-0.1	0.5	4.5	o
American hornbeam (musclewood)	Medium	COL SES	FTK DRO	0.6	0.6	5.1	o
American mountain-ash	Medium		FTK COL EHS	-0.2	-1.6	3.1	-
Atlantic white-cedar	Low	DISP	FTK DRO EHS	-0.6	-1.2	3.0	-
Baldcypress	Medium	DISP	FTK	0.4	-1.0	3.9	o
Balsam fir	High	COL	INS FTK DRO	-3.0	-0.4	2.7	-
Balsam poplar	High	FRG VRE	COL DRO	0.1	-0.6	4.0	o
Bigtooth aspen	High	FRG DISP	COL DRO FTK	1.0	0.2	5.1	o
Bitternut hickory	Low	DRO	COL	2.2	-0.8	5.6	+
Black ash	High		INS COL DISP DRO SES FTK ESP	-1.3	-3.0	1.7	-
Black cherry	High	DRO EHS	INS FTK COL	-1.6	-0.3	3.0	-
Black hickory	High		EHS COL	1.0	-2.3	4.1	o
Black locust	Low		COL INS	0.0	-0.6	3.8	o
Black maple	Low	COL EHS	FTK	0.5	0.9	5.2	o
Black oak	High	DRO EHS	INS DISE	0.5	0.4	4.9	o
Black spruce	High	COL EHS DISP	FTK INS DRO	-2.1	1.2	4.3	o
Black walnut	Medium	SES	COL DRO	0.4	-0.8	4.0	o
Black willow	Low		COL FTK DRO	-0.3	-2.1	2.8	-
Blackgum	High	COL FTK		1.5	0.8	5.9	+
Blackjack oak	Medium	DRO SES FRG VRE	COL FTK	1.6	0.2	5.6	+
Bluejack oak	Medium			0.7	0.0	4.8	o
Boxelder	Medium	SES DISP DRO COL TGR	FTK	2.4	2.1	7.4	+
Bur oak	Medium	DRO FTK		2.8	-0.2	6.4	+
Butternut	Low		FTK COL DRO DISE	-1.4	-1.3	2.3	-
Cedar elm	Low		DISE	-0.3	-1.2	3.3	o
Cherrybark oak	Medium		INS FTK	-0.5	0.1	3.9	o
Chestnut oak	High	SES VRE EHS FTK	INS DISE	1.4	1.3	6.1	+
Chinkapin oak	Medium	TGR		1.2	-0.7	4.8	o
Chokecherry	Low		COL	0.2	-0.9	3.8	o

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Table 39 (continued).—Modifying factor[a] and adaptability[b] information for the 116 tree species in the assessment area that were modeled using DISTRIB

		Modifying factors		Adaptability scores			
Common name	DISTRIB model reliability	Positive traits	Negative traits	DistFact	BioFact	Adapt	Adapt Class
Cucumber tree	High		FTK	0.0	-1.1	3.6	o
Eastern cottonwood	Low	TGR	INS COL DISE FTK	0.2	-0.8	3.9	o
Eastern hemlock	High	COL	INS DRO	-1.3	-0.9	2.7	-
Eastern hophornbeam	Medium	COL EHS TGR		1.7	1.3	6.4	+
Eastern redbud	Medium	--	--	0.9	0.0	4.9	o
Eastern redcedar	Medium	DRO	FTK COL INS	0.6	-1.5	3.9	o
Eastern white pine	High	DISP	DRO FTK INS	-2.0	0.1	3.3	o
Flowering dogwood	High	COL		0.1	1.0	5.0	o
Gray birch	Medium	DISP EHS	FTK COL INS DISE	-1.1	0.0	3.6	o
Green ash	Medium		INS FTK COL	-0.1	-0.3	4.0	o
Hackberry	Medium	DRO	FTK	1.7	0.3	5.7	+
Honeylocust	Low		COL	1.9	-0.5	5.5	+
Jack pine	High	DRO	COL INS	1.9	-1.2	5.2	o
Laurel oak	High	COL TGR	FTK	0.2	0.1	4.5	o
Loblolly pine	High	EHS	INS INP DRO COL	-0.5	-0.7	3.4	o
Longleaf pine	High	FTK	COL	1.0	-1.7	4.2	o
Mockernut hickory	High		FTK	1.7	-0.3	5.4	+
Mountain maple	High	COL VRE EHS	DRO FTK	0.8	1.5	5.9	+
Northern catalpa	Low		COL EHS	0.9	-1.6	4.2	o
Northern red oak	High		INS	1.4	0.1	5.4	+
Northern white-cedar	High	COL	FTK	-0.7	0.5	4.2	o
Ohio buckeye	Low	COL	SES FTK	0.4	-1.9	3.5	o
Osage-orange	Medium	EHS ESP		2.3	0.3	6.3	+
Overcup oak	Medium		FTK INS DRO	-0.5	-1.0	3.2	-
Paper birch	High	FRG DISP EHS	FTK COL INS DRO	-1.7	0.2	3.4	o
Pawpaw	Low	COL	DRO	-0.5	-0.3	3.7	o
Pecan	Low		FTK INS COL	-1.2	-1.7	2.2	-
Persimmon	Medium	COL EHS		1.2	1.0	5.8	+
Pignut hickory	High	EHS	INS DRO	0.2	0.4	4.7	o
Pin cherry	Medium	SES FRG FTK	COL	0.5	-0.7	4.2	o
Pin oak	Medium		FTK COL INS DISE	-0.7	-1.4	2.8	-
Pitch pine	High		COL INS	0.6	-1.8	3.8	o
Pond pine	High		DRO COL INS DISP	-1.1	-1.5	2.4	-
Post oak	High	DRO TGR FTK	COL INS DISE	2.2	-0.6	5.7	+
Quaking aspen	High	TGR FRG EHS	COL DRO FTK	0.6	0.0	4.7	o
Red maple	High	SES EHS ESP COL DISP		3.0	3.0	8.5	+

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Table 39 (continued).—Modifying factor[a] and adaptability[b] information for the 116 tree species in the assessment area that were modeled using DISTRIB

		Modifying factors		Adaptability scores			
Common name	DISTRIB model reliability	Positive traits	Negative traits	DistFact	BioFact	Adapt	Adapt Class
Red mulberry	Low	COL DISP	FTK	0.1	0.6	4.7	o
Red pine	Medium		INS COL DISP	0.9	-2.4	3.9	o
Red spruce	High	EHS COL	FTK SES	-1.3	-0.6	2.9	-
Redbay	High	INS DISP COL		2.6	-0.1	6.3	+
River birch	Low	DISP	FTK COL DRO	-0.5	-0.3	3.7	o
Rock elm	Low		EHS ESP SES	-0.2	-2.6	2.8	-
Sassafras	High		COL FTK	0.5	-0.6	4.2	o
Scarlet oak	High	VRE EHS ESP	INS DISE FTK	-0.4	0.7	4.6	o
Scrub oak (bear oak)	Low	FRG VRE	COL FTK	1.0	-0.8	4.6	o
Serviceberry	Medium	COL SES	DRO	-0.4	1.0	4.8	o
Shagbark hickory	Medium		INS FTK	-0.2	0.4	4.4	o
Shellbark hickory	Low	COL	FTK EHS	-0.5	-0.3	3.7	o
Shingle oak	Medium	EHS	COL	1.3	-0.7	4.9	o
Shortleaf pine	High	EHS	COL INS DRO	0.0	-1.0	3.6	o
Shumard oak	Low	DRO TGR	COL	2.5	-1.0	5.8	+
Silver maple	Medium	DISP SES COL	DRO FTK	0.1	1.6	5.6	+
Slash pine	High	DISP FTK	COL INS	1.1	-1.7	4.3	o
Slippery elm	Medium	COL	FTK DISE	0.0	0.7	4.8	o
Sourwood	High	COL EHS		2.6	1.0	6.9	+
Southern red oak	High	TGR		1.2	0.2	5.3	+
Striped maple	High	COL SES	DRO	1.0	0.3	5.1	o
Sugar maple	High	COL EHS		0.9	1.3	5.8	+
Sugarberry	Medium	COL SES	FTK	-0.2	0.6	4.6	o
Swamp chestnut oak	Medium	TGR	COL INS	1.1	-0.8	4.6	o
Swamp tupelo	High		DRO FTK COL EHS	-0.7	-1.7	2.7	-
Swamp white oak	Low	--	--	1.0	-0.3	4.9	o
Sweet birch	High	DISP	FTK COL INS DISE	-1.3	-0.3	3.2	-
Sweetbay	High	FTK	INS	1.4	-0.5	5.1	o
Sweetgum	High	VRE EHS	FTK COL DRO	-0.4	0.2	4.1	o
Sycamore	Medium	--	--	1.3	-0.9	4.8	o
Table Mountain pine	Medium	DRO	COL	2.6	-1.1	5.9	+
Tamarack	High		FTK COL INS	-0.5	-1.2	3.1	-
Tulip tree	High	SES DISP EHS	INP	0.1	1.3	5.3	+
Turkey oak	High	SES DRO TGR	COL	2.6	-0.9	6.0	+
Virginia pine	High		COL POL	0.1	-0.8	3.8	o
Water elm	Low	COL	FTK EHS	0.1	-0.8	3.8	o
Water hickory	Medium		FTK EHS	0.9	-2.0	4.0	o
Water locust	Low	--	--	0.0	-0.6	3.8	o

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Table 39 (continued).—Modifying factor[a] and adaptability[b] information for the 116 tree species in the assessment area that were modeled using DISTRIB

		Modifying factors		Adaptability scores			
Common name	DISTRIB model reliability	Positive traits	Negative traits	DistFact	BioFact	Adapt	Adapt Class
Water oak	High	TGR	FTK COL	-0.2	-0.6	3.7	o
Water tupelo	Medium		DRO FTK COL EHS	-0.9	-2.1	2.3	-
White ash	High		INS FTK COL	-2.0	-0.5	2.7	-
White oak	High	EHS ESP TGR FTK	INS DISE	1.7	1.0	6.1	+
White spruce	Medium		INS	0.1	-0.6	3.9	o
Willow oak	Medium	SES TGR	COL	0.6	0.0	4.7	o
Winged elm	High		INS DISE	-0.6	-0.3	3.6	o
Yellow birch	High	DISP	FTK INS DISE	-1.4	0.0	3.4	o
Yellow buckeye	Medium	COL	DRO SES FTK EHS DISP	0.0	-2.1	3.1	-

[a] Modifying factor codes are described in Table 38.
[b] Adaptability scores are described in the Appendix 4 text.

LINKAGES MODEL RESULTS

LINKAGES 3.0 was used to evaluate tree species growth potential and total biomass production under alternative climate scenarios. This information is utilized here to understand species potential under future climate. This information was also used to parameterize the forest landscape model LANDIS PRO, which is also used in this assessment to evaluate forest succession under climate change.

Change in early growth is based on biomass predicted by the LINKAGES model after 30 years of establishment and growth from bare ground and calculated as predicted biomass for the future climate scenario divided by predicted biomass under current climate. Change values were put into categories. Break points for the change classes were calculated by first dividing the modeled future biomass by the current climate biomass. Change was classified according to the following divisions:

Modeled:Current biomass	Class
<0.4	large decrease
0.4 through <0.8	small decrease
0.8 through <1.2	no change
1.2 through <2.0	small increase
>2.0	large increase
current climate = 0 and future climate model = 0	not present
current climate > 0 and future climate model = 0	extirpated

Future biomass projections for 24 tree species are presented for the assessment area as a whole and by subregion for the end-of-century period (2070 through 2099) (Table 40). Early growth potential (first 30 years) was also mapped for each species modeled by LINKAGES (Fig. 56).

Table 40.—Change in tree species growth potential measured in maximum biomass reached in 30 years starting from bare ground as projected by the LINKAGES model in the Mid-Atlantic region (MAR) and six subregions under a current climate scenario (1980-2009) and two climate model-emissions scenarios at the end of the century (2070-2099)

		Current climate	PCM B1					GFDL A1FI				
Tree species	Region or subregion[a]	Biomass in 2100 (metric tons/ acre)	Biomass in 2100 (metric tons/ acre)	Change from current climate biomass in 2100 (metric tons/ acre)	Change from current climate biomass in 2100 (%)	F:C[b]	Change class[c]	Biomass in 2100 (metric tons/ acre)	Change from current climate biomass in 2100 (metric tons/ acre)	Change from current climate biomass in 2100 (%)[b]	F:C[b]	Change class[c]
American beech	MAR	96.30	87.36	-8.93	-9	**0.91**	No	14.99	-81.30	-84	**0.16**	DEC
	1	100.96	42.01	-58.95	-58	**0.42**	DEC	0.00	-100.96	-100	**0.00**	X
	2	113.85	128.57	14.72	13	**1.13**	No	43.16	-70.69	-62	**0.38**	DEC
	3	113.76	111.89	-1.87	-2	**0.98**	No	26.47	-87.29	-77	**0.23**	DEC
	4	121.70	80.09	-41.61	-34	**0.66**	dec	8.23	-113.47	-93	**0.07**	DEC
	5	91.34	100.68	9.33	10	**1.10**	No	10.50	-80.85	-89	**0.11**	DEC
	6	14.08	41.14	27.06	192	**2.92**	INC	0.01	-14.07	-100	**0.00**	X
Balsam fir	MAR	2.74	0.89	-1.85	-67	**0.33**	DEC	0.00	-2.74	-100	**0.00**	X
	1	1.33	1.51	0.18	13	**1.13**	No	0.00	-1.33	-100	**0.00**	X
	2	5.59	0.08	-5.51	-99	**0.01**	DEC	0.00	-5.59	-100	**0.00**	X
	3	4.06	1.58	-2.48	-61	**0.39**	DEC	0.00	-4.06	-100	**0.00**	X
	4	4.71	1.35	-3.36	-71	**0.29**	DEC	0.00	-4.71	-100	**0.00**	X
	5	0.49	0.10	-0.39	-80	**0.20**	DEC	0.00	-0.49	-100	**0.00**	X
	6	-	-	-	-	**-**	-	-	-	-	**-**	-
Black cherry	MAR	106.58	114.52	7.94	7	**1.07**	No	71.47	-35.12	-33	**0.67**	dec
	1	135.09	82.78	-52.31	-39	**0.61**	dec	133.74	-1.35	-1	**0.99**	No
	2	142.16	172.40	30.24	21	**1.21**	inc	74.40	-67.76	-48	**0.52**	dec
	3	94.62	120.29	25.67	27	**1.27**	inc	51.48	-43.14	-46	**0.54**	dec
	4	130.43	91.40	-39.03	-30	**0.70**	dec	130.51	0.07	0	**1.00**	No
	5	109.41	125.04	15.63	14	**1.14**	No	45.35	-64.05	-59	**0.41**	dec
	6	37.09	105.16	68.07	184	**2.84**	INC	5.68	-31.41	-85	**0.15**	DEC
Black oak	MAR	88.74	101.42	12.68	14	**1.14**	No	60.13	-28.61	-32	**0.68**	dec
	1	127.07	77.00	-50.08	-39	**0.61**	dec	41.10	-85.98	-68	**0.32**	DEC
	2	97.05	132.90	35.85	37	**1.37**	inc	78.67	-18.37	-19	**0.81**	dec
	3	41.92	88.48	46.56	111	**2.11**	INC	64.87	22.95	55	**1.55**	inc
	4	135.25	91.06	-44.19	-33	**0.67**	dec	130.35	-4.90	-4	**0.96**	No
	5	106.90	117.33	10.42	10	**1.10**	No	35.92	-70.99	-66	**0.34**	DEC
	6	51.83	120.19	68.36	132	**2.32**	INC	0.19	-51.64	-100	**0.00**	X

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Table 40 (continued).—Change in tree species growth potential measured in maximum biomass reached in 30 years starting from bare ground as projected by the LINKAGES model in the Mid-Atlantic region (MAR) and six subregions under a current climate scenario (1980-2009) and two climate model-emissions scenarios at the end of the century (2070-2099)

		Current climate	PCM B1					GFDL A1FI				
Tree species	Region or subregion[a]	Biomass in 2100 (metric tons/ acre)	Biomass in 2100 (metric tons/ acre)	Change from current climate biomass in 2100 (metric tons/ acre)	Change from current climate biomass in 2100 (%)	F:C[b]	Change class[c]	Biomass in 2100 (metric tons/ acre)	Change from current climate biomass in 2100 (metric tons/ acre)	Change from current climate biomass in 2100 (%)[b]	F:C[b]	Change class[c]
Black spruce	MAR	0.27	0.04	-0.24	-86	**0.14**	DEC	0.00	-0.27	-100	**0.00**	X
	1	-	-	-	-	**-**	-	-	-	-	**-**	-
	2	0.38	0.00	-0.38	-100	**0.00**	X	0.00	-0.38	-100	**0.00**	X
	3	0.66	0.11	-0.55	-83	**0.17**	DEC	0.00	-0.66	-100	**0.00**	X
	4	-	-	-	-	**-**	-	-	-	-	**-**	-
	5	0.09	0.01	-0.08	-91	**0.09**	DEC	0.00	-0.09	-100	**0.00**	X
	6	-	-	-	-	**-**	-	-	-	-	**-**	-
Chestnut oak	MAR	84.95	101.08	16.13	19	**1.19**	No	71.39	-13.56	-16	**0.84**	No
	1	124.85	78.94	-45.91	-37	**0.63**	dec	40.57	-84.28	-68	**0.32**	DEC
	2	87.88	145.02	57.14	65	**1.65**	inc	110.30	22.42	26	**1.26**	inc
	3	19.71	64.43	44.73	227	**3.27**	INC	98.04	78.33	397	**4.97**	INC
	4	121.39	85.43	-35.96	-30	**0.70**	dec	131.06	9.66	8	**1.08**	No
	5	117.27	133.08	15.81	13	**1.13**	No	30.65	-86.62	-74	**0.26**	DEC
	6	81.80	140.71	58.90	72	**1.72**	inc	0.04	-81.76	-100	**0.00**	X
Eastern hemlock	MAR	19.05	17.34	-1.71	-9	**0.91**	No	0.93	-18.12	-95	**0.05**	DEC
	1	39.94	19.47	-20.47	-51	**0.49**	DEC	0.00	-39.94	-100	**0.00**	X
	2	18.86	23.78	4.92	26	**1.26**	inc	0.05	-18.81	-100	**0.00**	X
	3	6.86	13.05	6.19	90	**1.90**	inc	0.12	-6.74	-98	**0.02**	DEC
	4	52.81	48.16	-4.64	-9	**0.91**	No	5.27	-47.53	-90	**0.10**	DEC
	5	4.39	3.07	-1.32	-30	**0.70**	dec	0.04	-4.35	-99	**0.01**	DEC
	6	0.20	0.03	-0.17	-86	**0.14**	DEC	0.00	-0.20	-100	**0.00**	X
Eastern white pine	MAR	50.47	53.26	2.79	6	**1.06**	No	3.69	-46.78	-93	**0.07**	DEC
	1	63.90	56.04	-7.86	-12	**0.88**	No	0	-63.90	-100	**0.00**	X
	2	54.02	81.45	27.42	51	**1.51**	inc	1.93	-52.09	-96	**0.04**	DEC
	3	43.20	74.66	31.46	73	**1.73**	inc	2.34	-40.87	-95	**0.05**	DEC
	4	85.17	76.80	-8.36	-10	**0.90**	No	16.01	-69.16	-81	**0.19**	DEC
	5	47.39	20.65	-26.73	-56	**0.44**	dec	0.89	-46.49	-98	**0.02**	DEC
	6	7.59	0.27	-7.31	-96	**0.04**	DEC	0	-7.59	-100	**0.00**	X

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Table 40 (continued).—Change in tree species growth potential measured in maximum biomass reached in 30 years starting from bare ground as projected by the LINKAGES model in the Mid-Atlantic region (MAR) and six subregions under a current climate scenario (1980-2009) and two climate model-emissions scenarios at the end of the century (2070-2099)

		Current climate	PCM B1					GFDL A1FI				
Tree species	Region or subregion[a]	Biomass in 2100 (metric tons/ acre)	Biomass in 2100 (metric tons/ acre)	Change from current climate biomass in 2100 (metric tons/ acre)	Change from current climate biomass in 2100 (%)	F:C[b]	Change class[c]	Biomass in 2100 (metric tons/ acre)	Change from current climate biomass in 2100 (metric tons/ acre)	Change from current climate biomass in 2100 (%)[b]	F:C[b]	Change class[c]
Loblolly pine	MAR	42.84	55.62	12.78	30	**1.30**	inc	87.13	44.29	103	**2.03**	INC
	1	93.72	92.15	-1.56	-2	**0.98**	No	231.70	137.98	147	**2.47**	INC
	2	0	0.01	0.01	0	**-**	-	25.68	25.68	New	**-**	New
	3	0	0	0	0	**-**	-	4.69	4.69	New	**-**	New
	4	74.30	87.01	12.71	17	**1.17**	No	242.73	168.43	227	**3.27**	INC
	5	14.92	76.05	61.14	410	**5.10**	INC	51.58	36.67	246	**3.46**	INC
	6	113.64	106.86	-6.78	-6	**0.94**	No	3.65	-109.98	-97	**0.03**	DEC
Northern red oak	MAR	147.06	136.18	-10.87	-7	**0.93**	No	83.25	-63.81	-43	**0.57**	dec
	1	141.79	89.83	-51.95	-37	**0.63**	dec	41.95	-99.84	-70	**0.30**	DEC
	2	157.00	160.05	3.05	2	**1.02**	No	139.49	-17.51	-11	**0.89**	No
	3	153.29	156.07	2.78	2	**1.02**	No	125.66	-27.63	-18	**0.82**	No
	4	144.13	99.49	-44.64	-31	**0.69**	dec	131.49	-12.64	-9	**0.91**	No
	5	151.86	150.51	-1.36	-1	**0.99**	No	36.43	-115.43	-76	**0.24**	DEC
	6	128.18	151.85	23.67	18	**1.18**	No	0.02	-128.16	-100	**0.00**	X
Northern white-cedar	MAR	2.38	0.49	-1.89	-79	**0.21**	DEC	0	-2.38	-100	**0.00**	X
	1	-	-	-	-	**-**	-	-	-	-	**-**	-
	2	4.35	0.33	-4.01	-92	**0.08**	DEC	0	-4.35	-100	**0.00**	X
	3	4.47	1.36	-3.11	-69	**0.31**	DEC	0	-4.47	-100	**0.00**	X
	4	1.60	0	-1.60	-100	**0.00**	X	0	-1.60	-100	**0.00**	X
	5	0.61	0.08	-0.53	-87	**0.13**	DEC	0	-0.61	-100	**0.00**	X
	6	-	-	-	-	**-**	-	-	-	-	**-**	-
Pignut hickory	MAR	85.62	98.38	12.76	15	**1.15**	No	60.09	-25.53	-30	**0.70**	dec
	1	116.29	76.13	-40.16	-35	**0.65**	dec	128.05	11.77	10	**1.10**	No
	2	102.65	132.38	29.73	29	**1.29**	inc	57.89	-44.77	-44	**0.56**	dec
	3	63.22	99.06	35.84	57	**1.57**	inc	40.58	-22.64	-36	**0.64**	dec
	4	117.59	85.25	-32.34	-28	**0.72**	dec	116.85	-0.74	-1	**0.99**	No
	5	99.09	110.56	11.47	12	**1.12**	No	29.42	-69.67	-70	**0.30**	DEC
	6	24.14	92.96	68.82	285	**3.85**	INC	1.02	-23.11	-96	**0.04**	DEC

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Table 40 (continued).—Change in tree species growth potential measured in maximum biomass reached in 30 years starting from bare ground as projected by the LINKAGES model in the Mid-Atlantic region (MAR) and six subregions under a current climate scenario (1980-2009) and two climate model-emissions scenarios at the end of the century (2070-2099)

		Current climate	PCM B1					GFDL A1FI				
Tree species	Region or subregion[a]	Biomass in 2100 (metric tons/ acre)	Biomass in 2100 (metric tons/ acre)	Change from current climate biomass in 2100 (metric tons/ acre)	Change from current climate biomass in 2100 (%)	F:C[b]	Change class[c]	Biomass in 2100 (metric tons/ acre)	Change from current climate biomass in 2100 (metric tons/ acre)	Change from current climate biomass in 2100 (%)[b]	F:C[b]	Change class[c]
Pitch pine	MAR	35.88	27.42	-8.46	-24	**0.76**	dec	7.86	-28.01	-78	**0.22**	DEC
	1	-	-	-	-	**-**	-	-	-	-	**-**	-
	2	46.71	53.94	7.24	15	**1.15**	No	7.75	-38.96	-83	**0.17**	DEC
	3	29.49	43.97	14.48	49	**1.49**	inc	20.33	-9.16	-31	**0.69**	dec
	4	48.89	2.01	-46.89	-96	**0.04**	DEC	0.00	-48.89	-100	**0.00**	X
	5	39.86	29.31	-10.55	-26	**0.74**	dec	2.34	-37.52	-94	**0.06**	DEC
	6	17.78	1.48	-16.29	-92	**0.08**	DEC	0	-17.78	-100	**0.00**	X
Quaking aspen	MAR	86.96	55.20	-31.77	-37	**0.63**	DEC	0	-86.96	-100	**0.00**	X
	1	-	-	-	-	**-**	-	-	-	-	**-**	-
	2	129.86	101.24	-28.62	-22	**0.78**	dec	0	-129.86	-100	**0.00**	X
	3	118.84	122.63	3.79	3	**1.03**	No	0	-118.84	-100	**0.00**	X
	4	131.16	0	-131.16	-100	**0.00**	X	0	-131.16	-100	**0.00**	X
	5	38.27	20.07	-18.20	-48	**0.52**	dec	0	-38.27	-100	**0.00**	X
	6	-	-	-	-	**-**	-	-	-	-	**-**	-
Red maple	MAR	131.36	135.82	4.46	3	**1.03**	No	89.96	-41.40	-32	**0.68**	dec
	1	144.40	117.09	-27.32	-19	**0.81**	No	155.40	11.00	8	**1.08**	No
	2	148.23	158.32	10.10	7	**1.07**	No	92.72	-55.51	-37	**0.63**	dec
	3	137.74	146.17	8.43	6	**1.06**	No	71.34	-66.40	-48	**0.52**	dec
	4	145.37	119.93	-25.44	-18	**0.82**	No	149.64	4.27	3	**1.03**	No
	5	138.36	140.04	1.68	1	**1.01**	No	68.86	-69.50	-50	**0.50**	dec
	6	61.20	130.71	69.51	114	**2.14**	INC	9.59	-51.61	-84	**0.16**	DEC
Red spruce	MAR	1.89	0.78	-1.11	-59	**0.41**	dec	0	-1.89	-100	**0.00**	X
	1	0	1.65	1.65	New	**-**	New	-	-	-	**-**	-
	2	3.86	0.24	-3.62	-94	**0.06**	DEC	0	-3.86	-100	**0.00**	X
	3	2.79	1.15	-1.64	-59	**0.41**	dec	0	-2.79	-100	**0.00**	X
	4	3.86	1.19	-2.67	-69	**0.31**	DEC	0	-3.86	-100	**0.00**	X
	5	0.48	0.07	-0.40	-84	**0.16**	DEC	0	-0.48	-100	**0.00**	X
	6	-	-	-	-	**-**	-	-	-	-	**-**	-

(continued on next page)

Table 40 (continued).—Change in tree species growth potential measured in maximum biomass reached in 30 years starting from bare ground as projected by the LINKAGES model in the Mid-Atlantic region (MAR) and six subregions under a current climate scenario (1980-2009) and two climate model-emissions scenarios at the end of the century (2070-2099)

		Current climate	PCM B1					GFDL A1FI				
Tree species	Region or subregion[a]	Biomass in 2100 (metric tons/ acre)	Biomass in 2100 (metric tons/ acre)	Change from current climate biomass in 2100 (metric tons/ acre)	Change from current climate biomass in 2100 (%)	F:C[b]	Change class[c]	Biomass in 2100 (metric tons/ acre)	Change from current climate biomass in 2100 (metric tons/ acre)	Change from current climate biomass in 2100 (%)[b]	F:C[b]	Change class[c]
Scarlet oak	MAR	91.38	99.62	8.24	9	**1.09**	No	58.49	-32.89	-36	**0.64**	dec
	1	129.67	79.14	-50.54	-39	**0.61**	dec	45.58	-84.09	-65	**0.35**	DEC
	2	99.39	125.76	26.37	27	**1.27**	inc	74.63	-24.76	-25	**0.75**	dec
	3	54.38	94.31	39.93	73	**1.73**	inc	63.72	9.34	17	**1.17**	No
	4	136.99	90.99	-46.00	-34	**0.66**	dec	135.33	-1.66	-1	**0.99**	No
	5	100.31	109.93	9.63	10	**1.10**	No	23.62	-76.69	-76	**0.24**	DEC
	6	48.89	108.24	59.35	121	**2.21**	INC	0.09	-48.80	-100	**0.00**	X
Shagbark hickory	MAR	60.82	83.28	22.46	37	**1.37**	inc	18.96	-41.86	-69	**0.31**	DEC
	1	-	-	-	-	**-**	-	-	-	-	**-**	-
	2	75.38	111.75	36.37	48	**1.48**	inc	45.25	-30.13	-40	**0.60**	dec
	3	33.29	67.81	34.51	104	**2.04**	INC	33.82	0.52	2	**1.02**	No
	4	104.74	97.60	-7.14	-7	**0.93**	No	0.00	-104.74	-100	**0.00**	X
	5	78.85	90.47	11.62	15	**1.15**	No	13.1	-65.78	-83	**0.17**	DEC
	6	23.10	63.91	40.81	177	**2.77**	INC	0.0	-23.08	-100	**0.00**	X
Sugar maple	MAR	123.80	107.84	-15.97	-13	**0.87**	No	28.89	-94.91	-77	**0.23**	DEC
	1	128.77	91.26	-37.51	-29	**0.71**	dec	0.00	-128.77	-100	**0.00**	X
	2	134.29	137.50	3.21	2	**1.02**	No	54.36	-79.94	-60	**0.40**	dec
	3	132.99	134.41	1.42	1	**1.01**	No	69.41	-63.58	-48	**0.52**	dec
	4	132.53	114.62	-17.91	-14	**0.86**	No	13.13	-119.41	-90	**0.10**	DEC
	5	127.40	113.21	-14.19	-11	**0.89**	No	11.85	-115.55	-91	**0.09**	DEC
	6	73.58	28.58	-44.99	-61	**0.39**	DEC	0	-73.58	-100	**0.00**	X
Tulip tree	MAR	182.12	220.43	38.31	21	**1.21**	inc	207.85	25.73	14	**1.14**	No
	1	229.25	178.62	-50.63	-22	**0.78**	dec	298.35	69.10	30	**1.30**	inc
	2	201.99	272.97	70.98	35	**1.35**	inc	243.66	41.66	21	**1.21**	inc
	3	78.41	183.74	105.33	134	**2.34**	INC	205.59	127.18	162	**2.62**	INC
	4	225.95	190.65	-35.29	-16	**0.84**	No	285.86	59.92	27	**1.27**	inc
	5	238.38	264.97	26.59	11	**1.11**	No	186.33	-52.05	-22	**0.78**	dec
	6	193.89	274.41	80.52	42	**1.42**	inc	15.47	-178.42	-92	**0.08**	DEC

(continued on next page)

Table 40 (continued).—Change in tree species growth potential measured in maximum biomass reached in 30 years starting from bare ground as projected by the LINKAGES model in the Mid-Atlantic region (MAR) and six subregions under a current climate scenario (1980-2009) and two climate model-emissions scenarios at the end of the century (2070-2099)

		Current climate	PCM B1					GFDL A1FI				
Tree species	Region or subregion[a]	Biomass in 2100 (metric tons/ acre)	Biomass in 2100 (metric tons/ acre)	Change from current climate biomass in 2100 (metric tons/ acre)	Change from current climate biomass in 2100 (%)	F:C[b]	Change class[c]	Biomass in 2100 (metric tons/ acre)	Change from current climate biomass in 2100 (metric tons/ acre)	Change from current climate biomass in 2100 (%)[b]	F:C[b]	Change class[c]
Virginia pine	MAR	12.34	29.42	17.08	138	**2.38**	INC	6.01	-6.33	-51	**0.49**	dec
	1	-	-	-	-	**-**	-	-	-	-	**-**	-
	2	1.58	32.55	30.97	1965	**20.65**	INC	19.20	17.63	1118	**12.18**	INC
	3	0.07	2.22	2.15	2903	**30.03**	New	8.74	8.66	11707	**118.07**	New
	4	9.23	68.75	59.53	645	**7.45**	INC	0	-9.23	-100	**0.00**	X
	5	32.46	45.68	13.22	41	**1.41**	inc	4.39	-28.07	-86	**0.14**	DEC
	6	20.89	8.83	-12.06	-58	**0.42**	dec	0	-20.88	-100	**0.00**	X
White ash	MAR	159.45	166.85	7.40	5	**1.05**	No	93.01	-66.44	-42	**0.58**	dec
	1	162.33	129.41	-32.92	-20	**0.80**	dec	55.27	-107.06	-66	**0.34**	DEC
	2	193.09	199.36	6.27	3	**1.03**	No	147.96	-45.13	-23	**0.77**	dec
	3	174.88	182.88	8.01	5	**1.05**	No	109.53	-65.35	-37	**0.63**	dec
	4	153.81	131.62	-22.19	-14	**0.86**	No	159.97	6.16	4	**1.04**	No
	5	171.36	175.50	4.15	2	**1.02**	No	70.74	-100.61	-59	**0.41**	DEC
	6	86.10	180.76	94.66	110	**2.10**	INC	0.68	-85.42	-99	**0.01**	DEC
White oak	MAR	130.63	124.12	-6.51	-5	**0.95**	No	116.08	-14.56	-11	**0.89**	No
	1	126.84	77.13	-49.71	-39	**0.61**	dec	135.14	8.30	7	**1.07**	No
	2	141.69	148.95	7.26	5	**1.05**	No	134.83	-6.85	-5	**0.95**	No
	3	122.37	139.96	17.59	14	**1.14**	No	125.22	2.85	2	**1.02**	No
	4	132.59	86.90	-45.69	-34	**0.66**	dec	131.29	-1.31	-1	**0.99**	No
	5	141.25	142.20	0.95	1	**1.01**	No	116.15	-25.10	-18	**0.82**	No
	6	125.03	143.44	18.40	15	**1.15**	No	40.81	-84.22	-67	**0.33**	DEC
Yellow birch	MAR	96.74	61.54	-35.19	-36	**0.64**	dec	0.03	-96.71	-100	**0.00**	X
	1	-	-	-	-	**-**	-	-	-	-	**-**	-
	2	131.00	128.23	-2.77	-2	**0.98**	No	0	-131.00	-100	**0.00**	X
	3	128.94	124.67	-4.26	-3	**0.97**	No	0	-128.94	-100	**0.00**	X
	4	133.59	0	-133.59	-100	**0.00**	X	0	-133.59	-100	**0.00**	X
	5	65.06	31.33	-33.72	-52	**0.48**	dec	0.14	-64.92	-100	**0.00**	X
	6	-	-	-	-	-	-	-	-	-	-	-

[a] Subregions: 1—Western Allegheny Plateau, 2—Erie and Ontario Lake Plain, 3—Northern Allegheny Plateau, 4—Ridge and Valley, 5—Piedmont, 6—Coastal Plain. See Figure 38 (Chapter 6, p. 144) for locations.

[b] F:C is the ratio of biomass projected under the climate model-emissions scenario to biomass projected under a current climate scenario for the period 2070 through 2100.

[c] Change classes are abbreviated No (no change), inc (small increase), INC (large increase), dec (small decrease), DEC (large decrease), New (new habitat), and X (extirpated). Dash (-) indicates not present.

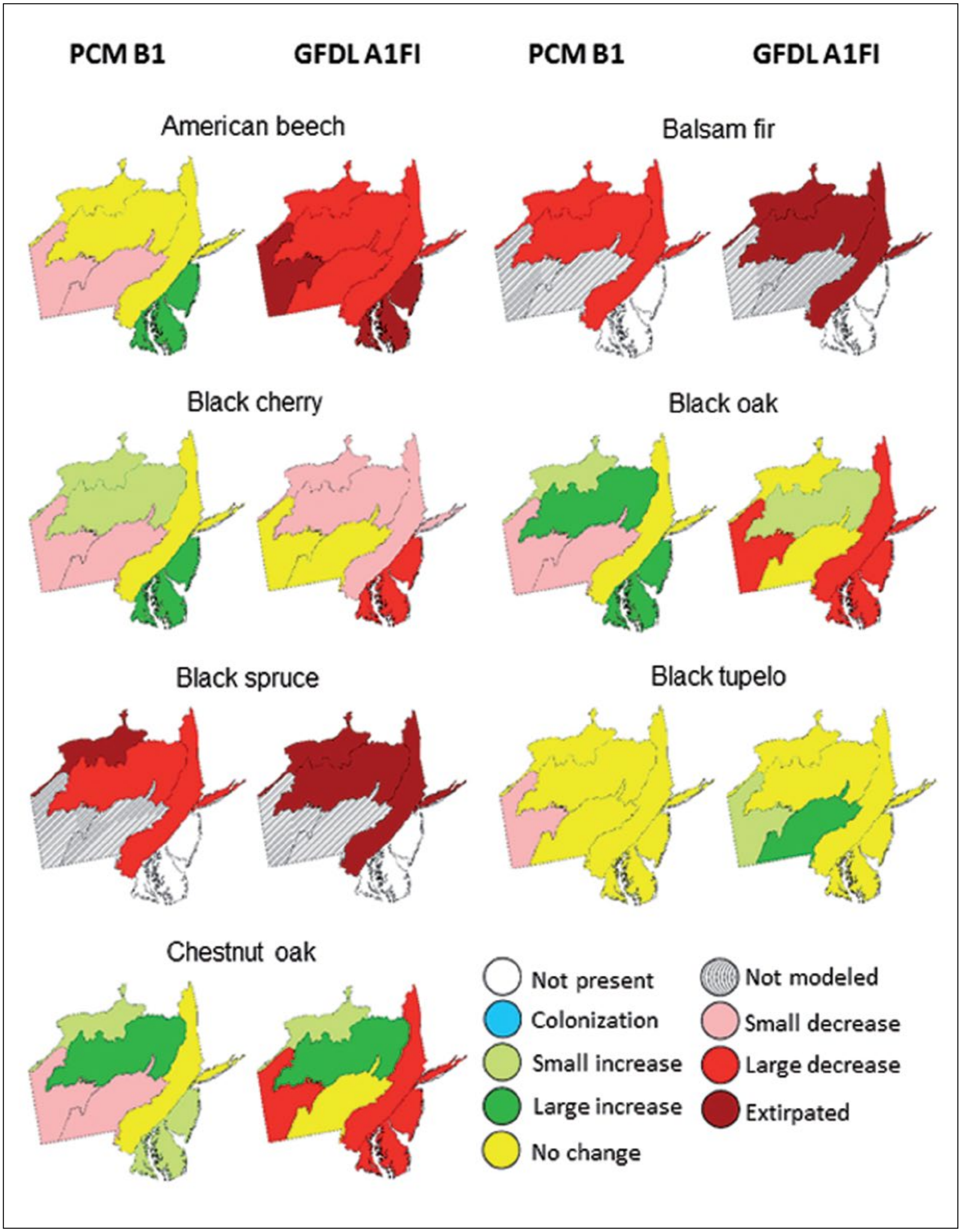

Figure 56.—Change in growth potential projected by the LINKAGES model for 30 tree species under two climate model-emissions scenario combinations at year 2100 relative to a current climate scenario (1980 through 2009).

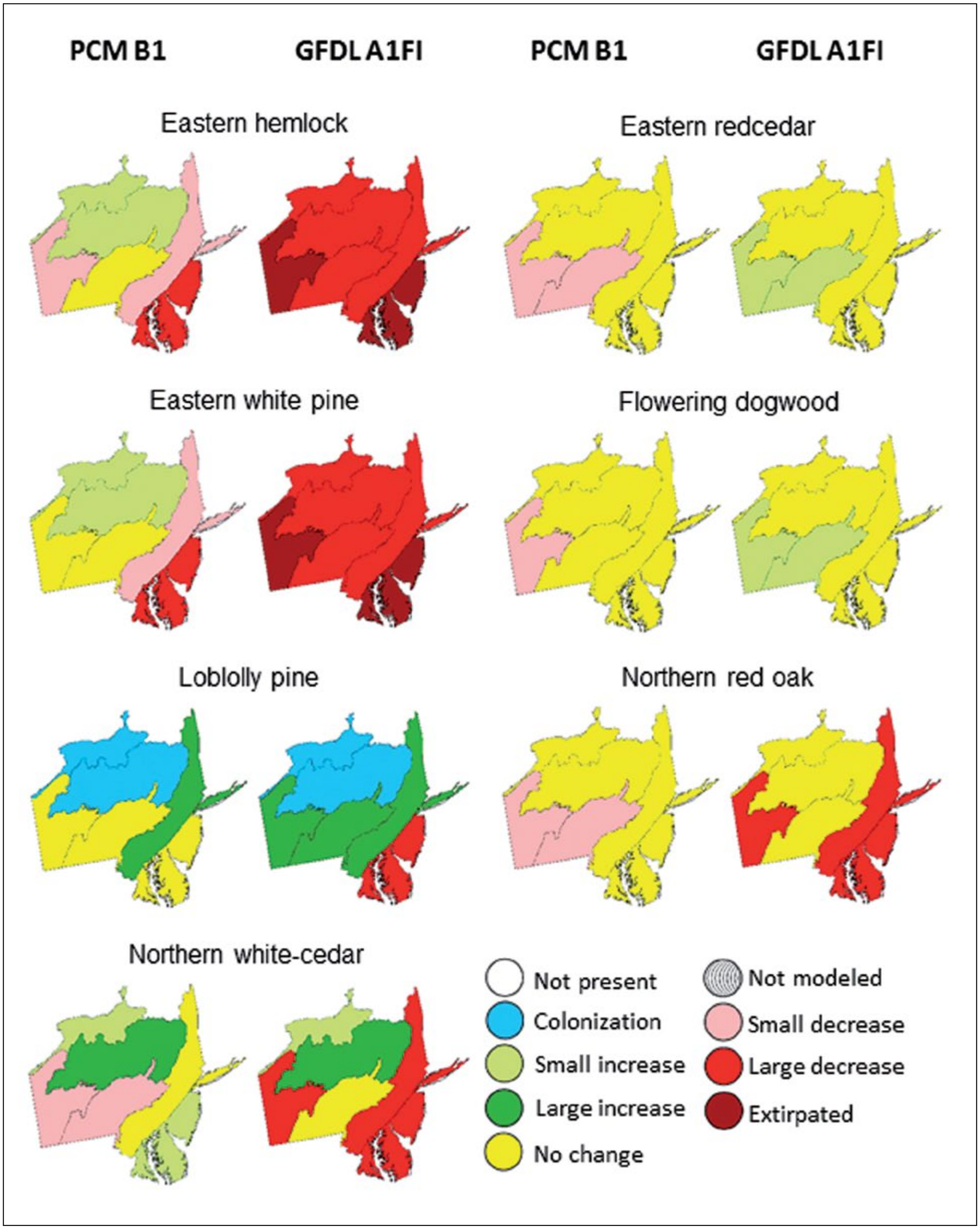

Figure 56 (continued).—Change in growth potential projected by the LINKAGES model for 30 tree species under two climate model-emissions scenario combinations at year 2100 relative to a current climate scenario (1980 through 2009).

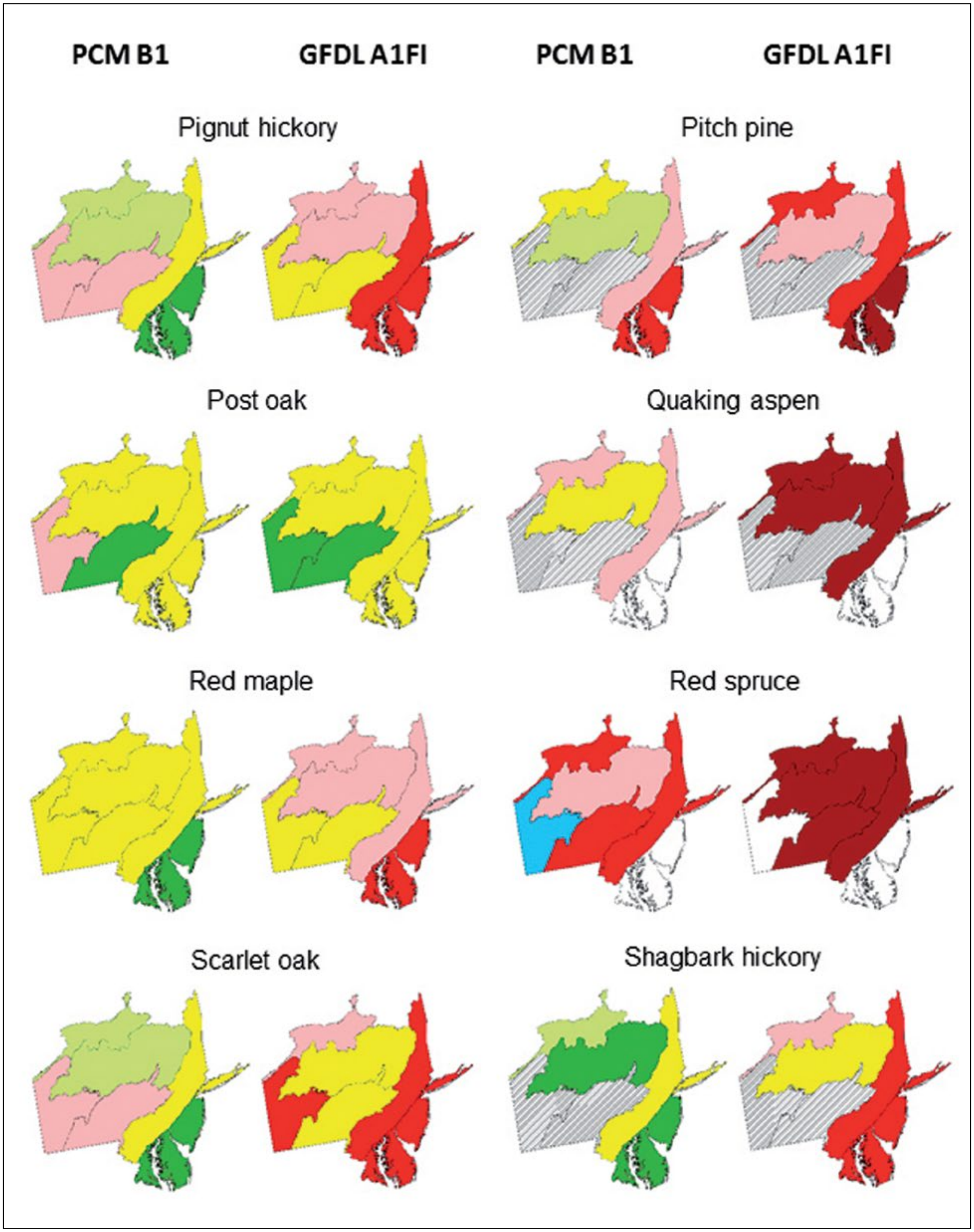

Figure 56 (continued).—Change in growth potential projected by the LINKAGES model for 30 tree species under two climate model-emissions scenario combinations at year 2100 relative to a current climate scenario (1980 through 2009).

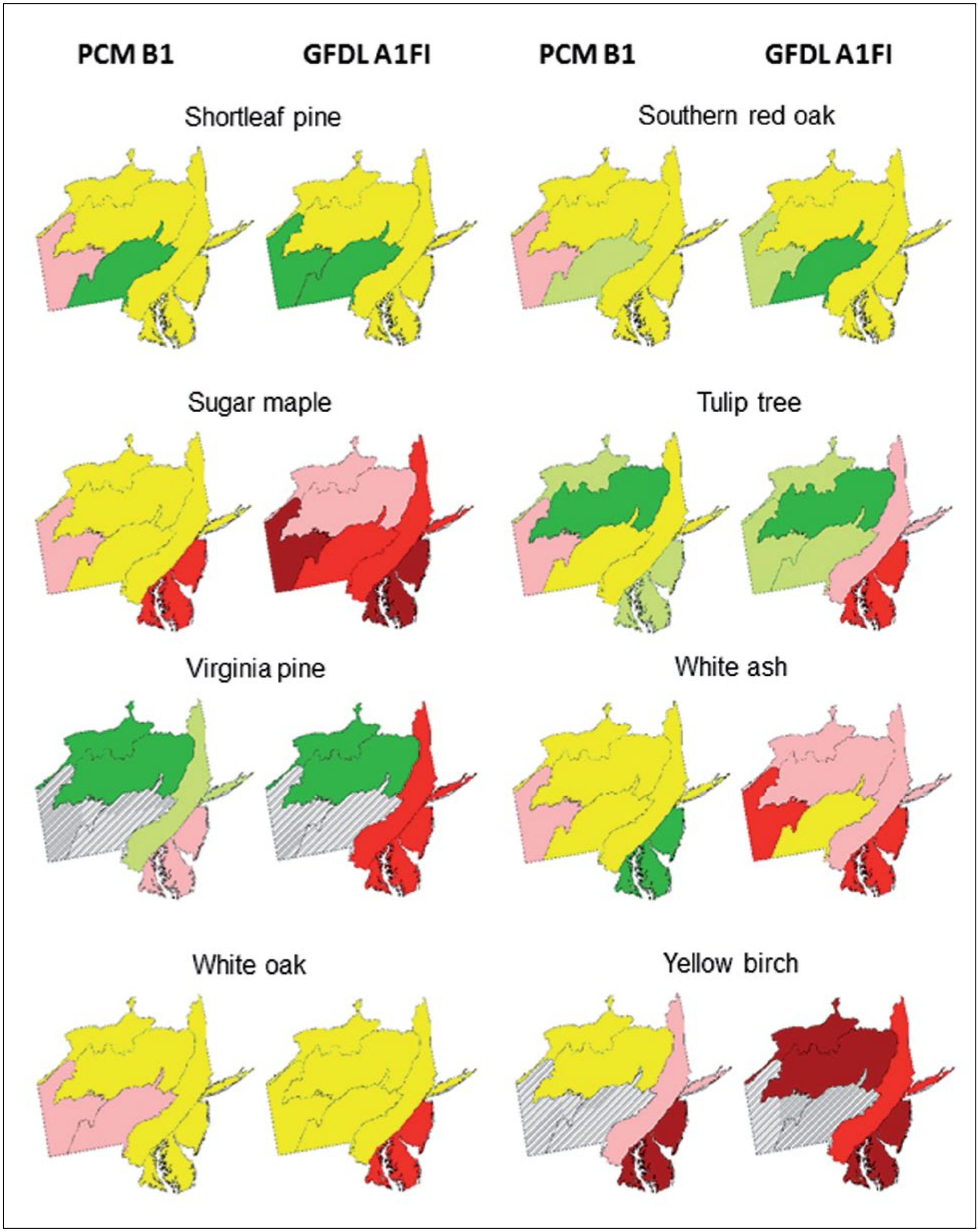

Figure 56 (continued).—Change in growth potential projected by the LINKAGES model for 30 tree species under two climate model-emissions scenario combinations at year 2100 relative to a current climate scenario (1980 through 2009).

LANDIS PRO MODEL RESULTS

In contrast to predictions by LINKAGES, LANDIS PRO simulates stand- and landscape-level processes such as competition, management, seed dispersal, and disturbance. In the following scenarios, however, these factors were held constant among model simulations, so that differences among current climate and future climate scenarios are the result of the effects of precipitation and temperature on species basal area (square feet per acre) and trees per acre.

"Change from 2000 under current climate" represents the difference in basal area and trees per acre between a future climate period and at the year 2000 due to succession and management, but not climate. "Change from current climate" under PCM B1 and GFDL A1FI represents the difference in basal area and trees per acre at a particular future time period and represents the potential change due to climate change alone. In both cases, it is important for the reader to consider both the absolute and the percent changes, especially if considering multiple species. Percent changes are relative only to a particular species and may exaggerate a projected change, especially if the species is currently low in abundance or density. Furthermore, the effects of climate change are calculated from the effects of succession and management during a 30-year period. Therefore, it may be useful for the reader to examine the change in succession and management while interpreting the change under the two future climate change scenarios.

Change classes are also presented to assist the reader in interpreting the percent change from current climate under each scenario for each time period and are based on percent change, as follows:

Percent change in basal area or trees per acre	Class	Abbreviation for change class
-100%	extirpated	X
-41% to -99%	large decrease	DEC
-21% to -40%	small decrease	Dec
-20% to +20%	no change	No
+21% to +100%	small increase	Inc
+101% or greater	large increase	INC

Future tree abundance (basal area) and density (trees per acre) were projected for 24 common tree species within the assessment area by subregion for 4 years: 2040 (Table 41), 2070 (Table 42), 2100 (Table 43), and 2200 (Table 44). Estimated and projected abundance are graphed in Figure 57 on pages 350 and 351. Relative amount and direction of change in projected tree abundance at year 2100 was also mapped for each species modeled by LANDIS PRO, except for loblolly pine and Virginia pine (Fig. 58, beginning on page 352).

LITERATURE CITED

Matthews, S.N.; Iverson, L.R.; Prasad, A.M.; Peters, M.P.; Rodewald, P.G. 2011. **Modifying climate change habitat models using tree species-specific assessments of model uncertainty and life history-factors.** Forest Ecology and Management. 262(8): 1460-1472. https://doi.org/10.1016/j.foreco.2011.06.047.

Table 41.—Absolute and percentage change in basal area (BA) and trees per acre (TPA) in the six subregions of the Mid-Atlantic region, as projected by the LANDIS PRO model for 24 species under a current climate scenario (1980 through 2009) and two climate model-emissions scenario combinations in the year 2040

		Current climate			PCM B1			GFDL A1FI			Current climate			PCM B1			GFDL A1FI		
Tree species	Sub-region[a]	BA in 2000 (ft^2/acre)	BA in 2040 (ft^2/acre)	Change from 2000[b]	BA in 2040 (ft^2/acre)	Change from current climate[c]	Change class[d]	BA in 2040 (ft^2/acre)	Change from current climate[c]	Change class[d]	TPA in 2000	TPA in 2040	Change from 2000[b]	TPA in 2040	Change from current climate[c]	Change class[d]	TPA in 2040	Change from current climate[c]	Change class[d]
American beech	1	2.5	2.1	-16%	2.1	0%	No	2.1	-2%	No	10.9	3.6	-67%	3.6	0%	No	3.3	-9%	No
	2	3.3	4.5	35%	4.5	0%	No	4.5	0%	No	21.4	13.9	-35%	13.9	0%	No	14.1	1%	No
	3	7.0	10.2	47%	10.2	0%	No	10.2	0%	No	58.6	34.3	-41%	32.0	-7%	No	37.5	9%	No
	4	1.7	1.2	-29%	1.2	0%	No	1.1	-4%	No	8.4	2.0	-76%	2.0	1%	No	1.8	-10%	No
	5	2.0	3.0	47%	3.0	0%	No	3.0	0%	No	18.4	8.1	-56%	7.8	-3%	No	9.4	16%	No
	6	1.9	2.0	7%	2.0	0%	No	2.0	0%	No	10.2	3.8	-63%	3.8	1%	No	4.0	4%	No
Balsam fir	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	2	0.3	0.4	8%	0.4	0%	No	0.4	0%	No	3.6	0.9	-74%	0.9	-4%	No	1.0	3%	No
	3	0.0	0.0	16%	0.0	0%	No	0.0	0%	No	0.1	0.0	-74%	0.0	0%	No	0.0	1%	No
	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	5	0.1	0.1	-4%	0.1	0%	No	0.1	0%	No	0.8	0.2	-79%	0.2	-2%	No	0.2	2%	No
	6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Black cherry	1	18.8	34.3	82%	34.3	0%	No	34.2	0%	No	58.0	42.3	-27%	42.2	0%	No	41.7	-1%	No
	2	7.2	6.0	-17%	6.0	0%	No	6.0	0%	No	17.5	39.4	125%	38.8	-2%	No	40.7	3%	No
	3	8.2	5.5	-33%	5.5	0%	No	5.5	0%	No	21.7	23.7	9%	22.6	-4%	No	25.4	7%	No
	4	10.2	18.0	77%	18.0	0%	No	17.9	0%	No	34.5	17.4	-50%	17.6	1%	No	17.5	0%	No
	5	2.5	5.4	115%	5.4	0%	No	5.4	0%	No	8.7	22.6	159%	22.4	-1%	No	24.2	7%	No
	6	1.0	2.6	173%	2.6	0%	No	2.6	0%	No	6.4	9.7	52%	10.2	5%	No	10.6	9%	No
Black oak	1	2.3	3.6	58%	3.6	0%	No	3.6	0%	No	4.5	3.5	-22%	3.5	0%	No	3.4	-3%	No
	2	0.2	0.1	-23%	0.1	0%	No	0.1	0%	No	0.2	0.6	284%	0.6	0%	No	0.6	3%	No
	3	1.2	0.7	-38%	0.7	0%	No	0.7	0%	No	1.6	1.7	5%	1.7	2%	No	1.8	9%	No
	4	4.0	6.1	50%	6.1	0%	No	6.1	0%	No	5.9	3.4	-42%	3.5	1%	No	3.4	1%	No
	5	3.2	2.8	-14%	2.8	0%	No	2.8	0%	No	2.7	9.7	254%	9.7	-1%	No	9.9	1%	No
	6	1.6	2.2	38%	2.2	0%	No	2.2	0%	No	3.0	6.4	113%	6.6	3%	No	6.6	4%	No

(continued on next page)

Table 41 (continued).—Absolute and percentage change in basal area (BA) and trees per acre (TPA) in the six subregions of the Mid-Atlantic region, as projected by the LANDIS PRO model for 24 species under a current climate scenario (1980 through 2009) and two climate model-emissions scenario combinations in the year 2040

		Current climate			PCM B1			GFDL A1FI			Current climate			PCM B1			GFDL A1FI		
Tree species	Sub-region[a]	BA in 2000 (ft²/acre)	BA in 2040 (ft²/acre)	Change from 2000[b]	BA in 2040 (ft²/acre)	Change from current climate[c]	Change class[d]	BA in 2040 (ft²/acre)	Change from current climate[c]	Change class[d]	TPA in 2000	TPA in 2040	Change from 2000[b]	TPA in 2040	Change from current climate[c]	Change class[d]	TPA in 2040	Change from current climate[c]	Change class[d]
Black spruce	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	2	0.0	0.0	-13%	0.0	0%	No	0.0	0%	No	0.2	0.1	-13%	0.1	-15%	No	0.1	-1%	No
	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	5	0.0	0.0	-22%	0.0	0%	No	0.0	0%	No	0.0	0.0	-61%	0.0	-29%	dec	0.0	-29%	dec
	6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Chestnut oak	1	2.8	2.6	-10%	2.6	0%	No	2.5	-3%	No	5.7	10.7	89%	10.7	0%	No	9.6	-11%	No
	2	0.3	0.4	55%	0.4	0%	No	0.4	0%	No	0.3	2.5	722%	2.7	6%	No	3.1	22%	inc
	3	3.4	4.4	29%	4.4	0%	No	4.4	0%	No	5.1	14.2	178%	16.8	19%	No	21.3	50%	inc
	4	13.4	11.0	-18%	11.0	0%	No	10.5	-5%	No	31.9	24.6	-23%	26.1	6%	No	25.5	4%	No
	5	4.6	8.5	84%	8.5	0%	No	8.5	0%	No	6.4	51.9	705%	50.8	-2%	No	57.4	11%	No
	6	1.5	2.7	76%	2.7	0%	No	2.7	0%	No	3.6	17.0	369%	17.9	6%	No	18.6	10%	No
Eastern hemlock	1	6.4	4.3	-32%	4.3	0%	No	4.2	-2%	No	18.8	5.9	-68%	5.9	-1%	No	5.4	-9%	No
	2	4.8	5.7	19%	5.7	0%	No	5.7	0%	No	22.9	10.9	-53%	11.3	4%	No	10.5	-4%	No
	3	9.1	9.4	3%	9.4	0%	No	9.4	0%	No	24.6	9.8	-60%	9.5	-3%	No	10.3	5%	No
	4	5.2	3.4	-33%	3.4	-1%	No	3.3	-4%	No	18.0	4.2	-77%	4.3	3%	No	3.8	-9%	No
	5	2.9	2.9	-1%	2.9	0%	No	2.9	0%	No	12.9	3.3	-75%	3.1	-5%	No	3.3	2%	No
	6	0.1	0.1	-20%	0.1	0%	No	0.1	0%	No	0.2	0.0	-80%	0.0	7%	No	0.0	35%	inc
Eastern white pine	1	1.6	1.8	15%	1.8	0%	No	1.7	-5%	No	5.9	11.5	93%	11.5	1%	No	9.3	-19%	No
	2	2.2	3.1	40%	3.1	0%	No	3.1	0%	No	3.1	18.8	499%	19.3	3%	No	18.0	-4%	No
	3	6.5	7.2	11%	7.2	0%	No	7.2	0%	No	14.1	27.9	98%	27.0	-3%	No	28.1	1%	No
	4	2.6	2.6	1%	2.6	0%	No	2.4	-6%	No	13.1	12.6	-4%	12.7	1%	No	10.2	-19%	No
	5	3.6	4.6	27%	4.6	0%	No	4.6	0%	No	9.0	16.4	82%	15.4	-6%	No	16.0	-2%	No
	6	0.3	0.3	10%	0.3	0%	No	0.3	0%	No	0.5	0.5	4%	0.5	-4%	No	0.6	4%	No

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Table 41 (continued).—Absolute and percentage change in basal area (BA) and trees per acre (TPA) in the six subregions of the Mid-Atlantic region, as projected by the LANDIS PRO model for 24 species under a current climate scenario (1980 through 2009) and two climate model-emissions scenario combinations in the year 2040

		Current climate			PCM B1			GFDL A1FI			Current climate			PCM B1			GFDL A1FI		
Tree species	Sub-region[a]	BA in 2000 (ft^2/acre)	BA in 2040 (ft^2/acre)	Change from 2000[b]	BA in 2040 (ft^2/acre)	Change from current climate[c]	Change class[d]	BA in 2040 (ft^2/acre)	Change from current climate[c]	Change class[d]	TPA in 2000	TPA in 2040	Change from 2000[b]	TPA in 2040	Change from current climate[c]	Change class[d]	TPA in 2040	Change from current climate[c]	Change class[d]
Loblolly pine	1	0.0	0.0	398%	0.0	2%	No	0.0	3%	No	0.1	0.0	-97%	0.0	10%	No	0.0	15%	No
	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	4	0.0	0.0	117%	0.0	2%	No	0.0	9%	No	0.1	0.0	-94%	0.0	9%	No	0.0	42%	inc
	5	0.1	0.1	110%	0.1	0%	No	0.1	0%	No	0.2	0.3	71%	0.3	-3%	No	0.4	15%	No
	6	10.2	12.1	18%	12.1	0%	No	12.1	0%	No	29.0	45.5	57%	45.4	0%	No	50.1	10%	No
Northern red oak	1	7.3	6.6	-10%	6.6	0%	No	6.5	-1%	No	14.9	6.1	-59%	6.6	8%	No	6.9	13%	No
	2	1.9	1.9	-3%	1.9	0%	No	1.9	0%	No	3.1	5.7	84%	5.4	-4%	No	6.1	8%	No
	3	7.6	6.5	-15%	6.5	0%	No	6.5	0%	No	9.7	15.1	56%	14.3	-6%	No	16.2	7%	No
	4	11.7	12.4	6%	12.4	0%	No	12.2	-2%	No	22.3	9.2	-59%	9.5	3%	No	9.9	8%	No
	5	6.0	4.9	-17%	4.9	0%	No	4.9	0%	No	6.8	7.9	15%	7.6	-3%	No	8.3	5%	No
	6	1.1	0.8	-23%	0.8	0%	No	0.8	0%	No	2.1	1.9	-9%	1.9	1%	No	2.1	9%	No
Northern white-cedar	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	2	0.4	0.3	-22%	0.3	0%	No	0.3	0%	No	7.2	2.3	-67%	2.4	2%	No	2.6	13%	No
	3	0.0	0.0	-18%	0.0	0%	No	0.0	0%	No	0.1	0.1	-53%	0.0	-45%	DEC	0.1	3%	No
	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	5	0.0	0.0	18%	0.0	0%	No	0.0	0%	No	0.0	0.0	52%	0.0	-7%	No	0.0	3%	No
	6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pignut hickory	1	0.7	0.7	5%	0.7	0%	No	0.7	-1%	No	1.8	1.5	-16%	1.5	0%	No	1.5	-1%	No
	2	0.4	0.5	37%	0.5	0%	No	0.5	0%	No	1.2	1.7	45%	1.7	-2%	No	1.9	9%	No
	3	0.6	0.9	49%	0.9	0%	No	0.9	0%	No	1.8	2.2	23%	2.2	0%	No	2.3	4%	No
	4	1.1	1.3	12%	1.3	0%	No	1.2	-1%	No	4.6	2.0	-57%	2.1	5%	No	2.1	4%	No
	5	1.4	2.2	55%	2.2	0%	No	2.2	0%	No	5.2	6.6	28%	6.4	-3%	No	7.2	10%	No
	6	0.4	0.4	21%	0.4	0%	No	0.4	0%	No	1.3	1.0	-21%	1.1	5%	No	1.1	5%	No

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Table 41 (continued).—Absolute and percentage change in basal area (BA) and trees per acre (TPA) in the six subregions of the Mid-Atlantic region, as projected by the LANDIS PRO model for 24 species under a current climate scenario (1980 through 2009) and two climate model-emissions scenario combinations in the year 2040

		Current climate			PCM B1			GFDL A1FI			Current climate			PCM B1			GFDL A1FI		
Tree species	Sub-region[a]	BA in 2000 (ft²/acre)	BA in 2040 (ft²/acre)	Change from 2000[b]	BA in 2040 (ft²/acre)	Change from current climate[c]	Change class[d]	BA in 2040 (ft²/acre)	Change from current climate[c]	Change class[d]	TPA in 2000	TPA in 2040	Change from 2000[b]	TPA in 2040	Change from current climate[c]	Change class[d]	TPA in 2040	Change from current climate[c]	Change class[d]
Pitch pine	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	2	0.0	0.0	23%	0.0	0%	No	0.0	0%	No	0.0	0.1	455%	0.0	-21%	dec	0.1	-11%	No
	3	0.4	0.6	51%	0.6	0%	No	0.6	0%	No	1.0	1.9	85%	1.7	-9%	No	2.1	9%	No
	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	5	2.7	7.6	179%	7.6	0%	No	7.6	0%	No	11.8	62.8	432%	62.8	0%	No	66.8	6%	No
	6	9.5	16.0	68%	16.0	0%	No	16.0	0%	No	36.9	82.2	123%	84.4	3%	No	93.9	14%	No
Quaking aspen	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	2	2.4	7.6	209%	7.6	0%	No	7.6	0%	No	5.9	79.6	1243%	76.1	-4%	No	78.0	-2%	No
	3	1.7	4.2	150%	4.2	0%	No	4.2	0%	No	5.5	36.3	557%	33.5	-8%	No	35.2	-3%	No
	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	5	0.9	1.4	56%	1.4	0%	No	1.4	0%	No	1.7	9.8	490%	9.5	-3%	No	9.6	-2%	No
	6	0.0	0.0	417%	0.0	0%	No	0.0	0%	No	0.0	0.0	-38%	0.0	0%	No	0.0	2%	No
Red maple	1	20.6	38.4	86%	38.4	0%	No	38.4	0%	No	95.2	71.4	-25%	71.6	0%	No	71.5	0%	No
	2	12.3	14.5	18%	14.5	0%	No	14.5	0%	No	59.9	142.6	138%	141.4	-1%	No	146.9	3%	No
	3	22.5	22.1	-2%	22.1	0%	No	22.1	0%	No	81.3	72.0	-11%	69.2	-4%	No	75.2	4%	No
	4	18.1	31.6	75%	31.6	0%	No	31.4	-1%	No	105.7	56.9	-46%	58.0	2%	No	57.5	1%	No
	5	8.7	13.4	55%	13.4	0%	No	13.4	0%	No	39.3	88.2	124%	88.2	0%	No	90.6	3%	No
	6	11.9	15.0	26%	15.0	0%	No	15.0	0%	No	61.4	102.7	67%	108.8	6%	No	106.0	3%	No
Red spruce	1	0.3	0.1	-66%	0.1	0%	No	0.1	0%	No	1.0	0.1	-89%	0.1	0%	No	0.1	0%	No
	2	0.4	0.8	93%	0.8	0%	No	0.8	0%	No	4.6	5.4	18%	4.6	-14%	No	5.0	-7%	No
	3	0.2	0.2	13%	0.2	0%	No	0.2	0%	No	2.2	0.8	-63%	0.7	-14%	No	0.8	2%	No
	4	0.2	0.1	-56%	0.1	-1%	No	0.1	-2%	No	0.6	0.2	-62%	0.2	-14%	No	0.2	-17%	No
	5	0.4	0.5	22%	0.5	0%	No	0.5	0%	No	1.9	1.1	-45%	1.0	-10%	No	1.1	-2%	No
	6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

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Table 41 (continued).—Absolute and percentage change in basal area (BA) and trees per acre (TPA) in the six subregions of the Mid-Atlantic region, as projected by the LANDIS PRO model for 24 species under a current climate scenario (1980 through 2009) and two climate model-emissions scenario combinations in the year 2040

		Current climate			PCM B1			GFDL A1FI			Current climate			PCM B1			GFDL A1FI		
Tree species	Sub-region[a]	BA in 2000 (ft^2/acre)	BA in 2040 (ft^2/acre)	Change from 2000[b]	BA in 2040 (ft^2/acre)	Change from current climate[c]	Change class[d]	BA in 2040 (ft^2/acre)	Change from current climate[c]	Change class[d]	TPA in 2000	TPA in 2040	Change from 2000[b]	TPA in 2040	Change from current climate[c]	Change class[d]	TPA in 2040	Change from current climate[c]	Change class[d]
Scarlet oak	1	1.2	1.9	58%	1.9	0%	No	1.9	0%	No	2.0	1.3	-33%	1.3	0%	No	1.3	-4%	No
	2	0.0	0.0	74%	0.0	0%	No	0.0	0%	No	0.0	0.0	267%	0.0	-5%	No	0.0	-4%	No
	3	0.6	0.8	36%	0.8	0%	No	0.8	0%	No	1.3	1.8	41%	1.8	-1%	No	1.8	4%	No
	4	3.0	4.8	63%	4.8	0%	No	4.8	0%	No	6.4	3.4	-47%	3.4	1%	No	3.3	-1%	No
	5	1.6	3.5	120%	3.5	0%	No	3.5	0%	No	3.9	11.5	193%	11.5	0%	No	11.7	2%	No
	6	2.1	3.3	55%	3.3	0%	No	3.3	0%	No	4.7	8.8	87%	9.0	2%	No	9.1	3%	No
Shagbark hickory	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	2	0.8	1.7	115%	1.7	0%	No	1.7	0%	No	5.6	8.2	46%	8.2	0%	No	8.6	6%	No
	3	0.6	0.7	26%	0.7	0%	No	0.7	0%	No	1.5	1.7	12%	1.7	-3%	No	1.9	11%	No
	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	5	0.5	0.9	71%	0.9	0%	No	0.9	0%	No	1.8	2.7	52%	2.6	-3%	No	2.9	7%	No
	6	0.0	0.0	-24%	0.0	0%	No	0.0	0%	No	0.0	0.0	7%	0.0	23%	inc	0.0	53%	inc
Sugar maple	1	5.9	5.3	-10%	5.3	0%	No	5.2	-2%	No	28.7	12.9	-55%	12.8	-1%	No	11.3	-13%	No
	2	10.6	11.8	11%	11.8	0%	No	11.8	0%	No	53.7	25.9	-52%	25.3	-2%	No	26.6	3%	No
	3	14.0	16.1	15%	16.1	0%	No	16.1	0%	No	49.0	28.5	-42%	27.0	-5%	No	30.7	8%	No
	4	3.5	3.3	-6%	3.3	0%	No	3.1	-4%	No	21.5	9.9	-54%	10.0	1%	No	8.4	-15%	No
	5	4.1	5.1	25%	5.1	0%	No	5.1	0%	No	16.0	8.2	-48%	7.9	-4%	No	8.2	0%	No
	6	0.1	0.1	-32%	0.1	0%	No	0.1	0%	No	0.8	0.2	-80%	0.2	12%	No	0.2	11%	No
Tulip tree	1	2.6	3.1	19%	3.1	0%	No	3.0	-1%	No	5.5	13.3	140%	13.5	2%	No	13.4	1%	No
	2	0.1	0.2	215%	0.2	0%	No	0.2	0%	No	0.2	4.2	2084%	4.2	0%	No	4.8	14%	No
	3	0.7	0.3	-53%	0.3	0%	No	0.3	0%	No	0.4	1.4	248%	1.6	14%	No	1.9	37%	inc
	4	2.4	2.8	17%	2.8	0%	No	2.7	-2%	No	6.6	6.4	-3%	6.7	4%	No	6.7	5%	No
	5	5.6	6.0	7%	6.0	0%	No	6.0	0%	No	6.4	74.8	1075%	72.9	-2%	No	93.0	24%	inc
	6	5.6	4.5	-20%	4.5	0%	No	4.5	0%	No	7.4	59.7	704%	60.6	1%	No	67.1	12%	No

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Table 41 (continued).—Absolute and percentage change in basal area (BA) and trees per acre (TPA) in the six subregions of the Mid-Atlantic region, as projected by the LANDIS PRO model for 24 species under a current climate scenario (1980 through 2009) and two climate model-emissions scenario combinations in the year 2040

		Current climate			PCM B1			GFDL A1FI			Current climate			PCM B1			GFDL A1FI		
Tree species	Sub-region[a]	BA in 2000 (ft²/acre)	BA in 2040 (ft²/acre)	Change from 2000[b]	BA in 2040 (ft²/acre)	Change from current climate[c]	Change class[d]	BA in 2040 (ft²/acre)	Change from current climate[c]	Change class[d]	TPA in 2000	TPA in 2040	Change from 2000[b]	TPA in 2040	Change from current climate[c]	Change class[d]	TPA in 2040	Change from current climate[c]	Change class[d]
Virginia pine	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	2	0.0	0.0	-7%	0.0	0%	No	0.0	0%	No	0.0	0.0	-62%	0.0	2%	No	0.0	6%	No
	3	0.0	0.1	3%	0.1	0%	No	0.1	0%	No	0.1	0.0	-56%	0.0	4%	No	0.0	9%	No
	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	5	0.7	1.3	79%	1.3	0%	No	1.3	0%	No	1.4	6.9	402%	7.0	1%	No	7.3	6%	No
	6	2.6	3.0	15%	3.0	0%	No	3.0	0%	No	6.2	16.1	161%	16.3	1%	No	16.4	2%	No
White ash	1	3.9	5.0	29%	5.0	0%	No	5.0	-1%	No	19.2	20.2	5%	20.9	3%	No	20.5	1%	No
	2	5.5	13.5	147%	13.5	0%	No	13.5	0%	No	23.9	93.0	290%	92.3	-1%	No	99.6	7%	No
	3	7.3	11.2	53%	11.2	0%	No	11.2	0%	No	23.7	53.9	127%	50.9	-6%	No	58.2	8%	No
	4	2.7	3.3	18%	3.2	0%	No	3.2	-2%	No	14.5	5.7	-61%	5.8	2%	No	5.7	1%	No
	5	3.9	10.5	170%	10.5	0%	No	10.5	0%	No	11.2	48.8	337%	48.1	-1%	No	51.9	6%	No
	6	0.9	1.3	44%	1.3	0%	No	1.3	0%	No	2.0	7.0	254%	7.9	12%	No	7.8	11%	No
White oak	1	3.1	3.0	-5%	3.0	0%	No	2.9	-2%	No	5.7	11.6	102%	11.7	1%	No	11.5	0%	No
	2	0.5	0.6	30%	0.6	0%	No	0.6	0%	No	0.3	3.4	933%	3.3	-3%	No	3.6	7%	No
	3	3.4	5.3	53%	5.3	0%	No	5.3	0%	No	4.9	24.5	402%	23.0	-6%	No	27.4	12%	No
	4	5.7	5.2	-10%	5.1	0%	No	5.0	-4%	No	11.9	16.0	35%	16.3	1%	No	15.9	-1%	No
	5	3.2	5.1	61%	5.1	0%	No	5.1	0%	No	7.2	15.9	121%	15.4	-3%	No	18.8	18%	No
	6	5.7	8.9	56%	8.9	0%	No	8.9	0%	No	13.0	42.4	227%	43.1	2%	No	48.0	13%	No
Yellow birch	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	2	1.7	3.4	102%	3.4	0%	No	3.4	0%	No	9.3	20.3	118%	19.8	-3%	No	20.2	-1%	No
	3	1.9	3.1	63%	3.1	0%	No	3.1	0%	No	6.8	12.4	82%	11.7	-6%	No	12.3	-1%	No
	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	5	0.8	1.3	69%	1.3	0%	No	1.3	0%	No	4.6	5.0	10%	4.8	-4%	No	4.9	-2%	No
	6	0.1	0.0	-28%	0.0	0%	No	0.0	0%	No	0.2	0.0	-84%	0.0	5%	No	0.0	8%	No

[a] Subregions: 1 – Western Allegheny Plateau, 2 – Erie and Ontario Lake Plain, 3 – Northern Allegheny Plateau, 4 – Ridge and Valley, 5 – Piedmont, 6 – Coastal Plain. See Figure 38 (Chapter 6, p. 144).
[b] Change under current climate represents the difference from year 2009 through year 2040 due to succession and management, but not climate.
[c] Change is the difference between this scenario and current climate in 2040 and represents the potential change due to climate change.
[d] Change classes are abbreviated No (no change), inc (small increase), and dec (small decrease). Dash (-) indicates not present.

Table 42.—Absolute and percentage change in basal area (BA) and trees per acre (TPA) in the six subregions of the Mid-Atlantic region, as projected by the LANDIS PRO model for 24 species under a current climate scenario (1980 through 2009) and two climate-model emissions scenario combinations in the year 2070

		Current climate			PCM B1			GFDL A1FI			Current climate			PCM B1			GFDL A1FI		
Tree species	Sub-region[a]	BA in 2000 (ft²/acre)	BA in 2070 (ft²/acre)	Change from 2000[b]	BA in 2070 (ft²/acre)	Change from current climate[c]	Change class[d]	BA in 2070 (ft²/acre)	Change from current climate[c]	Change class[d]	TPA in 2000	TPA in 2070	Change from 2000[b]	TPA in 2070	Change from current climate[c]	Change class[d]	TPA in 2070	Change from current climate[c]	Change class[d]
American beech	1	2.5	2.2	-14%	2.2	0%	No	2.1	-4%	No	10.9	3.5	-68%	3.6	2%	No	2.3	-36%	dec
	2	3.3	5.8	73%	5.6	-3%	No	6.3	9%	No	21.4	16.0	-25%	15.1	-5%	No	14.5	-9%	No
	3	7.0	12.8	84%	11.8	-8%	No	14.8	15%	No	58.6	31.0	-47%	26.5	-14%	No	32.6	5%	No
	4	1.7	1.2	-25%	1.2	-1%	No	1.2	-7%	No	8.4	1.8	-79%	1.8	2%	No	1.3	-26%	dec
	5	2.0	3.7	82%	3.5	-5%	No	4.2	13%	No	18.4	6.6	-64%	6.0	-8%	No	7.3	11%	No
	6	1.9	2.3	25%	2.4	2%	No	2.6	10%	No	10.2	4.8	-53%	5.4	14%	No	4.1	-13%	No
Balsam fir	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	2	0.4	0.3	-6%	0.3	-3%	No	0.4	13%	No	3.6	0.6	-84%	0.4	-27%	dec	0.5	-7%	No
	3	0.0	0.0	18%	0.0	0%	No	0.0	6%	No	0.1	0.0	-83%	0.0	0%	No	0.0	-2%	No
	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	5	0.1	0.1	-18%	0.1	-2%	No	0.1	7%	No	0.8	0.1	-90%	0.1	-2%	No	0.1	6%	No
	6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Black cherry	1	18.9	28.7	52%	28.7	0%	No	28.5	-1%	No	58.0	36.3	-37%	35.9	-1%	No	35.3	-3%	No
	2	7.2	5.9	-18%	5.9	-1%	No	6.1	4%	No	17.5	23.8	36%	23.7	-1%	No	25.6	7%	No
	3	8.2	5.5	-33%	5.3	-5%	No	5.9	8%	No	21.7	19.1	-12%	17.3	-9%	No	21.6	13%	No
	4	10.2	16.0	57%	16.0	0%	No	15.9	-1%	No	34.5	13.0	-62%	13.7	6%	No	13.8	6%	No
	5	2.5	6.4	150%	6.2	-2%	No	7.1	12%	No	8.7	12.3	41%	11.9	-3%	No	14.4	17%	No
	6	1.0	4.4	350%	4.5	4%	No	5.0	15%	No	6.4	7.9	24%	9.2	17%	No	8.8	11%	No
Black oak	1	2.3	2.6	16%	2.6	0%	No	2.6	-1%	No	4.5	3.0	-34%	3.0	0%	No	2.6	-11%	No
	2	0.2	0.2	21%	0.2	-1%	No	0.2	2%	No	0.2	0.5	230%	0.6	5%	No	0.6	17%	No
	3	1.2	0.7	-43%	0.7	0%	No	0.7	6%	No	1.6	1.6	-1%	1.7	7%	No	1.9	22%	inc
	4	4.1	2.9	-27%	3.0	0%	No	2.9	0%	No	5.9	1.9	-67%	2.1	9%	No	2.2	12%	No
	5	3.2	4.3	36%	4.3	-1%	No	4.6	5%	No	2.7	7.5	175%	7.5	0%	No	7.7	2%	No
	6	1.6	3.1	90%	3.2	3%	No	3.4	8%	No	3.0	4.9	63%	5.5	13%	No	5.1	5%	No

(continued on next page)

Table 42 (continued).—Absolute and percentage change in basal area (BA) and trees per acre (TPA) in the six subregions of the Mid-Atlantic region, as projected by the LANDIS PRO model for 24 species under a current climate scenario (1980 through 2009) and two climate-model emissions scenario combinations in the year 2070

		Current climate			PCM B1			GFDL A1FI			Current climate			PCM B1			GFDL A1FI		
Tree species	Sub-region[a]	BA in 2000 (ft^2/acre)	BA in 2070 (ft^2/acre)	Change from 2000[b]	BA in 2070 (ft^2/acre)	Change from current climate[c]	Change class[d]	BA in 2070 (ft^2/acre)	Change from current climate[c]	Change class[d]	TPA in 2000	TPA in 2070	Change from 2000[b]	TPA in 2070	Change from current climate[c]	Change class[d]	TPA in 2070	Change from current climate[c]	Change class[d]
Black spruce	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	2	0.0	0.0	-23%	0.0	-25%	dec	0.0	-5%	No	0.2	0.1	-45%	0.1	-33%	dec	0.1	-21%	dec
	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	5	0.0	0.0	-67%	0.0	30%	inc	0.0	54%	inc	0.0	0.0	-92%	0.0	33%	inc	0.0	67%	inc
	6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Chestnut oak	1	2.9	2.5	-13%	2.5	-1%	No	2.2	-10%	No	5.7	11.6	104%	11.4	-1%	No	8.2	-29%	dec
	2	0.3	0.5	78%	0.5	0%	No	0.6	27%	inc	0.3	2.6	756%	3.3	24%	inc	4.4	68%	inc
	3	3.4	4.8	41%	4.9	2%	No	6.4	33%	inc	5.1	16.5	223%	24.7	50%	inc	41.6	153%	INC
	4	13.4	9.9	-26%	10.0	1%	No	9.3	-6%	No	31.9	20.8	-35%	25.1	21%	inc	23.9	15%	No
	5	4.6	8.5	85%	8.2	-4%	No	10.0	17%	No	6.4	37.8	487%	36.6	-3%	No	41.9	11%	No
	6	1.5	2.8	80%	3.0	8%	No	3.5	27%	inc	3.6	12.0	231%	14.0	17%	No	11.1	-7%	No
Eastern hemlock	1	6.4	3.9	-39%	3.9	0%	No	3.8	-4%	No	18.8	5.8	-69%	5.7	-1%	No	3.6	-37%	dec
	2	4.8	6.0	23%	5.8	-2%	No	6.4	7%	No	22.9	7.6	-67%	8.1	6%	No	6.6	-14%	No
	3	9.1	9.7	6%	9.1	-6%	No	10.9	12%	No	24.6	6.6	-73%	6.2	-7%	No	6.5	-1%	No
	4	5.2	3.1	-40%	3.1	-1%	No	2.9	-7%	No	18.0	2.9	-84%	3.1	9%	No	2.2	-24%	dec
	5	2.9	3.1	6%	2.9	-5%	No	3.3	8%	No	12.9	1.9	-85%	1.7	-9%	No	1.9	-1%	No
	6	0.1	0.1	-11%	0.1	14%	No	0.1	39%	inc	0.2	0.0	-74%	0.0	5%	No	0.1	38%	inc
Eastern white pine	1	1.6	1.8	12%	1.8	0%	No	1.5	-15%	No	5.9	9.1	54%	9.2	1%	No	4.4	-52%	DEC
	2	2.2	2.5	14%	2.4	-3%	No	2.6	4%	No	3.1	9.1	189%	8.7	-4%	No	6.9	-23%	dec
	3	6.5	6.2	-4%	5.8	-8%	No	6.8	9%	No	14.1	17.5	24%	15.6	-11%	No	14.2	-19%	No
	4	2.6	2.5	-4%	2.4	-2%	No	2.1	-16%	No	13.1	8.3	-36%	8.4	1%	No	4.3	-48%	DEC
	5	3.6	3.9	6%	3.7	-4%	No	4.1	6%	No	9.0	5.9	-35%	5.0	-14%	No	5.1	-13%	No
	6	0.3	0.3	-1%	0.3	0%	No	0.3	3%	No	0.5	0.2	-61%	0.2	-2%	No	0.2	-3%	No

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Table 42 (continued).—Absolute and percentage change in basal area (BA) and trees per acre (TPA) in the six subregions of the Mid-Atlantic region, as projected by the LANDIS PRO model for 24 species under a current climate scenario (1980 through 2009) and two climate-model emissions scenario combinations in the year 2070

		Current climate			PCM B1			GFDL A1FI			Current climate			PCM B1			GFDL A1FI		
Tree species	Sub-region[a]	BA in 2000 (ft^2/acre)	BA in 2070 (ft^2/acre)	Change from 2000[b]	BA in 2070 (ft^2/acre)	Change from current climate[c]	Change class[d]	BA in 2070 (ft^2/acre)	Change from current climate[c]	Change class[d]	TPA in 2000	TPA in 2070	Change from 2000[b]	TPA in 2070	Change from current climate[c]	Change class[d]	TPA in 2070	Change from current climate[c]	Change class[d]
Loblolly pine	1	0.0	0.0	774%	0.0	3%	No	0.0	2%	No	0.1	0.0	-98%	0.0	46%	inc	0.0	78%	inc
	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	4	0.0	0.0	237%	0.0	4%	No	0.0	15%	No	0.1	0.0	-95%	0.0	18%	No	0.0	61%	inc
	5	0.1	0.1	99%	0.1	-6%	No	0.1	19%	No	0.2	0.1	-36%	0.1	6%	No	0.2	35%	inc
	6	10.2	10.5	3%	10.6	1%	No	12.0	15%	No	29.0	28.7	-1%	29.0	1%	No	30.8	7%	No
Northern red oak	1	7.4	6.5	-12%	6.6	1%	No	6.5	1%	No	14.9	5.1	-66%	7.1	39%	inc	8.5	67%	inc
	2	1.9	2.2	13%	2.1	-3%	No	2.3	7%	No	3.1	5.1	67%	4.9	-4%	No	6.1	19%	No
	3	7.6	6.1	-20%	5.7	-6%	No	6.5	7%	No	9.7	16.8	73%	14.4	-15%	No	18.2	8%	No
	4	11.7	12.4	6%	12.4	0%	No	12.1	-2%	No	22.3	7.1	-68%	8.2	15%	No	10.8	51%	inc
	5	6.0	4.4	-27%	4.3	-2%	No	4.6	5%	No	6.8	5.0	-26%	4.8	-4%	No	5.3	5%	No
	6	1.1	0.8	-26%	0.9	5%	No	1.0	18%	No	2.1	1.4	-31%	1.6	9%	No	1.4	-3%	No
Northern white-cedar	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	2	0.4	0.2	-35%	0.2	-13%	No	0.3	7%	No	7.2	1.7	-76%	1.0	-41%	DEC	1.3	-27%	dec
	3	0.0	0.0	-20%	0.0	-41%	DEC	0.0	-9%	No	0.1	0.0	-61%	0.0	-71%	DEC	0.0	-52%	DEC
	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	5	0.0	0.0	-9%	0.0	0%	No	0.0	25%	inc	0.0	0.0	-27%	0.0	-42%	DEC	0.0	9%	No
	6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pignut hickory	1	0.7	0.7	9%	0.7	0%	No	0.7	-1%	No	1.8	1.5	-17%	1.5	0%	No	1.5	-1%	No
	2	0.4	0.6	65%	0.6	-1%	No	0.6	7%	No	1.2	1.8	54%	1.9	2%	No	2.0	9%	No
	3	0.6	1.1	79%	1.1	-4%	No	1.2	7%	No	1.8	2.4	36%	2.4	-1%	No	2.4	1%	No
	4	1.1	1.3	20%	1.3	0%	No	1.3	-3%	No	4.6	1.4	-70%	1.6	14%	No	1.6	16%	No
	5	1.4	2.7	92%	2.6	-4%	No	3.1	11%	No	5.2	5.1	-1%	5.0	-2%	No	5.5	6%	No
	6	0.4	0.5	31%	0.5	5%	No	0.5	11%	No	1.3	0.8	-36%	1.0	17%	No	0.8	-4%	No

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Table 42 (continued).—Absolute and percentage change in basal area (BA) and trees per acre (TPA) in the six subregions of the Mid-Atlantic region, as projected by the LANDIS PRO model for 24 species under a current climate scenario (1980 through 2009) and two climate-model emissions scenario combinations in the year 2070

		Current climate			PCM B1			GFDL A1FI			Current climate			PCM B1			GFDL A1FI		
Tree species	Sub-region[a]	BA in 2000 (ft²/acre)	BA in 2070 (ft²/acre)	Change from 2000[b]	BA in 2070 (ft²/acre)	Change from current climate[c]	Change class[d]	BA in 2070 (ft²/acre)	Change from current climate[c]	Change class[d]	TPA in 2000	TPA in 2070	Change from 2000[b]	TPA in 2070	Change from current climate[c]	Change class[d]	TPA in 2070	Change from current climate[c]	Change class[d]
Pitch pine	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	2	0.0	0.0	-23%	0.0	-14%	No	0.0	-12%	No	0.0	0.0	43%	0.0	-1%	No	0.0	0%	No
	3	0.4	0.5	27%	0.4	-8%	No	0.5	6%	No	1.0	0.8	-27%	0.7	-9%	No	0.8	12%	No
	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	5	2.7	7.5	175%	7.4	-1%	No	8.5	14%	No	11.8	25.6	116%	24.8	-3%	No	26.2	2%	No
	6	9.5	14.8	55%	15.5	4%	No	17.5	18%	No	36.9	27.9	-24%	28.0	0%	No	32.0	15%	No
Quaking aspen	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	2	2.4	9.0	270%	8.7	-4%	No	9.0	-1%	No	5.9	69.3	1069%	61.2	-12%	No	51.0	-26%	dec
	3	1.7	5.9	251%	5.3	-9%	No	5.7	-2%	No	5.5	49.9	805%	41.8	-16%	No	33.7	-32%	dec
	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	5	0.9	1.3	43%	1.3	-3%	No	1.3	0%	No	1.7	6.8	310%	6.1	-10%	No	5.2	-23%	dec
	6	0.0	0.0	720%	0.0	9%	No	0.0	19%	No	0.0	0.0	-64%	0.0	15%	No	0.0	24%	inc
Red maple	1	20.7	44.1	113%	44.1	0%	No	44.0	0%	No	95.2	57.1	-40%	57.9	1%	No	59.0	3%	No
	2	12.3	16.5	34%	16.3	-1%	No	17.3	5%	No	59.9	73.7	23%	72.5	-2%	No	81.2	10%	No
	3	22.6	20.7	-8%	20.2	-2%	No	21.4	3%	No	81.3	39.9	-51%	36.9	-8%	No	42.9	7%	No
	4	18.1	39.1	116%	39.2	0%	No	38.7	-1%	No	105.7	46.5	-56%	49.1	6%	No	49.1	6%	No
	5	8.7	16.3	88%	16.2	-1%	No	17.4	7%	No	39.3	50.1	28%	50.5	1%	No	55.7	11%	No
	6	11.9	17.8	49%	18.4	4%	No	19.6	10%	No	61.4	63.5	3%	70.0	10%	No	72.8	15%	No
Red spruce	1	0.3	0.0	-83%	0.0	0%	No	0.0	0%	No	1.0	0.0	-96%	0.0	0%	No	0.0	-1%	No
	2	0.4	0.8	82%	0.7	-6%	No	0.8	7%	No	4.6	3.1	-32%	2.3	-25%	dec	2.4	-21%	dec
	3	0.2	0.2	-3%	0.2	-13%	No	0.2	13%	No	2.2	0.4	-82%	0.2	-38%	dec	0.3	-12%	No
	4	0.2	0.0	-71%	0.0	-4%	No	0.0	-9%	No	0.6	0.1	-85%	0.1	-34%	dec	0.1	-39%	dec
	5	0.4	0.5	20%	0.4	-4%	No	0.5	8%	No	1.9	0.5	-76%	0.4	-14%	No	0.4	-4%	No
	6	0.0	0.0	0%	0.0	0%	No	0.0	0%	No	0.0	0.0	0%	0.0	0%	No	0.0	0%	No

(continued on next page)

Table 42 (continued).—Absolute and percentage change in basal area (BA) and trees per acre (TPA) in the six subregions of the Mid-Atlantic region, as projected by the LANDIS PRO model for 24 species under a current climate scenario (1980 through 2009) and two climate-model emissions scenario combinations in the year 2070

		Current climate			PCM B1			GFDL A1FI			Current climate			PCM B1			GFDL A1FI		
Tree species	Sub-region[a]	BA in 2000 (ft²/ acre)	BA in 2070 (ft²/ acre)	Change from 2000[b]	BA in 2070 (ft²/ acre)	Change from current climate[c]	Change class[d]	BA in 2070 (ft²/ acre)	Change from current climate[c]	Change class[d]	TPA in 2000	TPA in 2070	Change from 2000[b]	TPA in 2070	Change from current climate[c]	Change class[d]	TPA in 2070	Change from current climate[c]	Change class[d]
Scarlet oak	1	1.2	1.2	0%	1.2	0%	No	1.2	-2%	No	2.0	0.9	-52%	0.9	0%	No	0.8	-19%	No
	2	0.0	0.0	88%	0.0	1%	No	0.0	-7%	No	0.0	0.0	391%	0.0	-38%	dec	0.0	10%	No
	3	0.6	0.9	45%	0.9	-3%	No	0.9	3%	No	1.3	1.7	35%	1.7	1%	No	1.8	6%	No
	4	3.0	3.8	28%	3.8	0%	No	3.8	-1%	No	6.4	2.3	-64%	2.4	6%	No	2.2	-5%	No
	5	1.6	4.6	187%	4.5	-1%	No	4.8	5%	No	3.9	7.5	92%	7.5	-1%	No	7.5	0%	No
	6	2.1	4.0	85%	4.1	3%	No	4.3	9%	No	4.7	6.2	33%	6.9	11%	No	6.2	-1%	No
Shagbark hickory	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	2	0.8	2.6	216%	2.5	-1%	No	2.8	10%	No	5.6	9.4	68%	10.2	9%	No	10.9	16%	No
	3	0.6	0.9	57%	0.9	-7%	No	1.0	12%	No	1.5	2.3	47%	2.2	-2%	No	2.7	20%	No
	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	5	0.5	1.2	115%	1.2	-2%	No	1.3	9%	No	1.8	2.3	29%	2.4	3%	No	2.4	3%	No
	6	0.0	0.0	-30%	0.0	11%	No	0.0	29%	inc	0.0	0.0	-61%	0.0	122%	INC	0.0	49%	inc
Sugar maple	1	5.9	5.3	-11%	5.3	0%	No	5.0	-5%	No	28.7	14.7	-49%	14.9	1%	No	8.6	-41%	DEC
	2	10.6	12.5	18%	12.1	-3%	No	13.6	9%	No	53.7	22.1	-59%	20.4	-8%	No	22.5	2%	No
	3	14.0	17.2	23%	16.0	-7%	No	19.0	10%	No	49.0	23.6	-52%	20.6	-13%	No	26.1	10%	No
	4	3.5	3.3	-5%	3.3	-1%	No	3.0	-9%	No	21.5	11.3	-47%	11.5	2%	No	6.7	-41%	DEC
	5	4.1	5.6	38%	5.4	-4%	No	6.0	6%	No	16.0	7.2	-55%	6.4	-11%	No	6.9	-4%	No
	6	0.1	0.1	-20%	0.1	11%	No	0.1	25%	inc	0.8	0.4	-43%	0.6	29%	inc	0.4	-1%	No
Tulip tree	1	3.2	3.1	0%	3.2	0%	No	3.0	-3%	No	5.5	16.0	191%	16.5	3%	No	16.2	1%	No
	2	0.1	0.2	185%	0.2	-1%	No	0.3	28%	inc	0.2	2.2	1019%	2.2	1%	No	3.3	52%	inc
	3	0.7	0.2	-68%	0.2	6%	No	0.3	32%	inc	0.4	1.0	157%	1.5	40%	inc	2.4	132%	INC
	4	5.7	5.4	-5%	5.4	0%	No	5.1	-6%	No	6.6	18.6	182%	19.6	5%	No	18.8	1%	No
	5	5.6	5.4	-4%	5.3	-2%	No	7.1	31%	inc	6.4	33.1	420%	31.8	-4%	No	51.4	55%	inc
	6	5.6	3.7	-34%	3.9	3%	No	4.6	22%	inc	7.4	29.8	302%	32.1	8%	No	33.6	13%	No

(continued on next page)

Table 42 (continued).—Absolute and percentage change in basal area (BA) and trees per acre (TPA) in the six subregions of the Mid-Atlantic region, as projected by the LANDIS PRO model for 24 species under a current climate scenario (1980 through 2009) and two climate-model emissions scenario combinations in the year 2070

		Current climate			PCM B1			GFDL A1FI			Current climate			PCM B1			GFDL A1FI		
Tree species	Sub-region[a]	BA in 2000 (ft^2/acre)	BA in 2070 (ft^2/acre)	Change from 2000[b]	BA in 2070 (ft^2/acre)	Change from current climate[c]	Change class[d]	BA in 2070 (ft^2/acre)	Change from current climate[c]	Change class[d]	TPA in 2000	TPA in 2070	Change from 2000[b]	TPA in 2070	Change from current climate[c]	Change class[d]	TPA in 2070	Change from current climate[c]	Change class[d]
Virginia pine	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	2	0.0	0.0	-67%	0.0	28%	inc	0.0	-2%	No	0.0	0.0	-91%	0.0	106%	INC	0.0	36%	inc
	3	0.0	0.0	-39%	0.0	-2%	No	0.0	3%	No	0.1	0.0	-83%	0.0	4%	No	0.0	66%	inc
	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	5	0.7	1.3	83%	1.3	0%	No	1.5	10%	No	1.4	3.4	149%	3.6	4%	No	3.2	-5%	No
	6	2.6	2.9	12%	3.0	1%	No	3.2	9%	No	6.2	7.9	28%	8.2	3%	No	7.9	-1%	No
White ash	1	2.6	3.4	31%	3.4	0%	No	3.3	-1%	No	19.2	16.3	-15%	17.2	6%	No	17.2	6%	No
	2	5.5	11.3	106%	10.9	-3%	No	12.5	11%	No	23.9	37.3	56%	35.1	-6%	No	44.4	19%	No
	3	7.3	11.1	51%	10.2	-7%	No	12.4	12%	No	23.7	30.4	28%	26.5	-13%	No	35.2	16%	No
	4	2.4	3.1	29%	3.1	1%	No	3.0	-2%	No	14.5	8.7	-40%	9.5	9%	No	9.8	13%	No
	5	3.9	8.7	123%	8.4	-3%	No	9.7	12%	No	11.2	18.1	62%	17.4	-4%	No	20.7	14%	No
	6	0.9	1.1	23%	1.2	9%	No	1.3	23%	inc	2.0	3.2	61%	4.0	25%	inc	3.2	1%	No
White oak	1	3.9	5.6	43%	5.6	0%	No	5.5	-2%	No	5.7	19.2	235%	21.0	10%	No	20.1	5%	No
	2	0.5	0.7	40%	0.7	-3%	No	0.8	16%	No	0.3	4.9	1395%	4.5	-7%	No	6.7	38%	inc
	3	3.4	6.0	73%	5.3	-11%	No	6.9	15%	No	4.9	37.0	659%	30.9	-17%	No	44.1	19%	No
	4	2.8	3.6	32%	3.6	0%	No	3.5	-4%	No	11.9	4.0	-67%	4.3	8%	No	4.3	9%	No
	5	3.2	4.7	47%	4.5	-4%	No	5.4	15%	No	7.2	13.8	91%	12.6	-9%	No	18.2	32%	inc
	6	5.7	9.4	65%	9.7	3%	No	11.7	24%	inc	13.0	58.6	352%	62.4	6%	No	73.0	24%	inc
Yellow birch	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	2	1.7	3.7	117%	3.6	-3%	No	3.9	7%	No	9.3	15.4	65%	14.8	-4%	No	12.1	-21%	dec
	3	1.9	4.3	129%	4.0	-7%	No	4.6	6%	No	6.8	14.8	117%	13.1	-12%	No	11.1	-25%	dec
	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	5	0.8	1.6	114%	1.6	-4%	No	1.7	5%	No	4.6	3.6	-21%	3.3	-8%	No	3.0	-18%	No
	6	0.1	0.0	-24%	0.0	5%	No	0.0	8%	No	0.2	0.0	-89%	0.0	7%	No	0.0	11%	No

[a] Subregions: 1 – Western Allegheny Plateau, 2 – Erie and Ontario Lake Plain, 3 – Northern Allegheny Plateau, 4 – Ridge and Valley, 5 – Piedmont, 6 – Coastal Plain. See Figure 38 (Chapter 6, p. 144).
[b] Change under current climate represents the difference from year 2009 through year 2070 due to succession and management, but not climate.
[c] Change is the difference between this scenario and current climate in 2070 and represents the potential change due to climate change.
[d] Change classes are abbreviated No (no change), inc (small increase), INC (large increase), dec (small decrease), and DEC (large decrease). Dash (-) indicates not present.

Table 43.—Absolute and percentage change in basal area (BA) and trees per acre (TPA) in the six subregions of the Mid-Atlantic region, as projected by the LANDIS PRO model for 24 species under a current climate scenario (1980 through 2009) and two climate-model emissions scenario combinations in the year 2100

		Current climate			PCM B1			GFDL A1FI			Current climate			PCM B1			GFDL A1FI		
Tree species	Sub-region[a]	BA in 2000 (ft^2/acre)	BA in 2100 (ft^2/acre)	Change from 2000[b]	BA in 2100 (ft^2/acre)	Change from current climate[c]	Change class[d]	BA in 2100 (ft^2/acre)	Change from current climate[c]	Change class[d]	TPA in 2000	TPA in 2100	Change from 2000[b]	TPA in 2100	Change from current climate[c]	Change class[d]	TPA in 2100	Change from current climate[c]	Change class[d]
American beech	1	2.5	2.3	-7%	2.3	0%	No	2.1	-11%	No	10.9	5.7	-48%	5.9	4%	No	1.8	-68%	DEC
	2	3.3	7.0	109%	6.7	-4%	No	7.7	11%	No	21.4	21.4	0%	20.4	-5%	No	18.0	-16%	No
	3	7.0	14.8	113%	13.3	-10%	No	17.7	19%	No	58.6	41.0	-30%	32.9	-20%	No	34.5	-16%	No
	4	1.7	1.3	-20%	1.3	-1%	No	1.2	-11%	No	8.4	2.4	-72%	2.5	6%	No	1.5	-37%	dec
	5	2.0	4.4	117%	4.1	-7%	No	5.1	16%	No	18.4	13.9	-24%	13.0	-7%	No	9.8	-29%	dec
	6	1.9	2.8	51%	3.0	6%	No	3.0	8%	No	10.2	8.7	-15%	10.6	22%	inc	3.7	-58%	DEC
Balsam fir	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	2	0.4	0.3	-22%	0.3	-7%	No	0.3	11%	No	3.6	0.5	-86%	0.2	-61%	inc	0.2	-52%	DEC
	3	0.0	0.0	-3%	0.0	-4%	No	0.0	4%	No	0.1	0.0	-88%	0.0	-18%	No	0.0	-29%	dec
	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	5	0.1	0.1	-36%	0.1	-7%	No	0.1	6%	No	0.8	0.1	-90%	0.0	-39%	dec	0.0	-35%	dec
	6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Black cherry	1	18.9	20.9	11%	20.7	-1%	No	20.4	-2%	No	58.0	42.4	-27%	41.3	-3%	No	46.2	9%	No
	2	7.2	7.1	0%	7.0	-1%	No	7.6	6%	No	17.5	23.4	34%	23.5	0%	No	25.4	8%	No
	3	8.2	6.1	-25%	5.7	-7%	No	6.9	12%	No	21.7	19.2	-12%	16.4	-15%	No	22.6	18%	No
	4	10.2	10.7	5%	10.8	1%	No	10.6	-1%	No	34.5	12.1	-65%	13.9	15%	No	14.8	22%	inc
	5	2.5	7.2	184%	7.0	-3%	No	8.3	15%	No	8.7	11.5	32%	11.2	-3%	No	14.2	23%	inc
	6	1.0	5.3	443%	5.7	8%	No	6.1	17%	No	6.4	8.7	37%	12.0	38%	inc	8.5	-2%	No
Black oak	1	2.3	2.1	-9%	2.1	0%	No	1.9	-6%	No	4.5	3.5	-21%	3.5	-1%	No	2.7	-24%	dec
	2	0.2	0.3	60%	0.3	0%	No	0.3	7%	No	0.2	0.6	277%	0.7	14%	No	0.7	20%	No
	3	1.2	0.7	-37%	0.8	1%	No	0.9	15%	No	1.6	1.8	13%	2.1	15%	No	2.5	38%	inc
	4	4.1	1.4	-65%	1.5	3%	No	1.4	2%	No	5.9	1.6	-73%	2.0	24%	inc	2.1	35%	inc
	5	3.2	5.8	83%	5.7	-2%	No	6.3	7%	No	2.7	7.8	186%	7.7	-2%	No	7.1	-9%	No
	6	1.6	3.8	134%	4.0	6%	No	4.2	11%	No	3.0	5.4	79%	7.0	31%	inc	4.6	-14%	No

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Table 43 (continued).—Absolute and percentage change in basal area (BA) and trees per acre (TPA) in the six subregions of the Mid-Atlantic region, as projected by the LANDIS PRO model for 24 species under a current climate scenario (1980 through 2009) and two climate-model emissions scenario combinations in the year 2100

		Current climate			PCM B1			GFDL A1FI			Current climate			PCM B1			GFDL A1FI		
Tree species	Sub-region[a]	BA in 2000 (ft²/acre)	BA in 2100 (ft²/acre)	Change from 2000[b]	BA in 2100 (ft²/acre)	Change from current climate[c]	Change class[d]	BA in 2100 (ft²/acre)	Change from current climate[c]	Change class[d]	TPA in 2000	TPA in 2100	Change from 2000[b]	TPA in 2100	Change from current climate[c]	Change class[d]	TPA in 2100	Change from current climate[c]	Change class[d]
Black spruce	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	2	0.0	0.0	-46%	0.0	-30%	dec	0.0	5%	No	0.2	0.1	-67%	0.0	-62%	DEC	0.0	-41%	DEC
	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Chestnut oak	1	2.9	2.8	-3%	2.7	-2%	No	2.2	-21%	dec	5.7	14.5	156%	14.1	-3%	No	7.3	-49%	DEC
	2	0.3	0.6	129%	0.6	2%	No	0.9	56%	inc	0.3	3.7	1110%	5.6	50%	inc	8.7	132%	INC
	3	3.4	5.2	53%	5.9	14%	No	9.3	80%	inc	5.1	21.6	325%	42.3	96%	inc	92.1	326%	INC
	4	13.4	9.8	-26%	10.2	4%	No	9.2	-7%	No	31.9	21.8	-32%	29.9	37%	inc	28.9	32%	inc
	5	4.6	9.2	100%	8.7	-6%	No	11.4	24%	inc	6.4	51.0	691%	49.7	-2%	No	42.7	-16%	No
	6	1.5	3.6	135%	4.0	13%	No	4.5	26%	inc	3.6	21.5	495%	28.1	31%	inc	9.6	-55%	DEC
Eastern hemlock	1	6.4	3.9	-38%	3.9	-1%	No	3.6	-9%	No	18.8	9.7	-49%	9.4	-3%	No	2.8	-71%	DEC
	2	4.8	5.8	20%	5.6	-3%	No	6.3	9%	No	22.9	7.5	-67%	8.7	16%	No	4.1	-46%	DEC
	3	9.1	9.1	-1%	8.4	-8%	No	10.4	15%	No	24.6	6.4	-74%	6.3	-1%	No	4.9	-23%	dec
	4	5.2	3.0	-42%	3.0	0%	No	2.7	-11%	No	18.0	4.0	-78%	5.5	37%	inc	2.0	-51%	DEC
	5	2.9	3.1	8%	2.9	-6%	No	3.4	8%	No	12.9	3.2	-75%	2.1	-35%	dec	1.5	-53%	DEC
	6	0.1	0.1	5%	0.1	7%	No	0.1	33%	inc	0.2	0.1	-18%	0.1	-50%	DEC	0.1	-54%	DEC
Eastern white pine	1	1.6	1.8	15%	1.8	-1%	No	1.3	-28%	dec	5.9	9.2	55%	9.2	1%	No	1.5	-84%	DEC
	2	2.2	2.0	-7%	2.0	-4%	No	2.1	2%	No	3.1	7.8	148%	8.4	9%	No	3.6	-54%	DEC
	3	6.5	5.1	-22%	4.5	-12%	No	5.5	8%	No	14.1	16.4	16%	13.2	-19%	No	8.2	-50%	DEC
	4	2.6	2.4	-6%	2.3	-4%	No	1.8	-26%	dec	13.1	8.0	-39%	7.9	-2%	No	2.0	-75%	DEC
	5	3.6	3.1	-16%	2.9	-7%	No	3.3	7%	No	9.0	4.6	-49%	3.1	-31%	dec	2.4	-46%	DEC
	6	0.3	0.2	-25%	0.2	-1%	No	0.2	4%	No	0.5	0.2	-70%	0.1	-29%	dec	0.1	-40%	dec

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Table 43 (continued).—Absolute and percentage change in basal area (BA) and trees per acre (TPA) in the six subregions of the Mid-Atlantic region, as projected by the LANDIS PRO model for 24 species under a current climate scenario (1980 through 2009) and two climate-model emissions scenario combinations in the year 2100

		Current climate			PCM B1			GFDL A1FI			Current climate			PCM B1			GFDL A1FI		
Tree species	Sub-region[a]	BA in 2000 (ft²/acre)	BA in 2100 (ft²/acre)	Change from 2000[b]	BA in 2100 (ft²/acre)	Change from current climate[c]	Change class[d]	BA in 2100 (ft²/acre)	Change from current climate[c]	Change class[d]	TPA in 2000	TPA in 2100	Change from 2000[b]	TPA in 2100	Change from current climate[c]	Change class[d]	TPA in 2100	Change from current climate[c]	Change class[d]
Loblolly pine	1	0.0	0.0	1107%	0.0	13%	No	0.0	23%	inc	0.1	0.0	-98%	0.0	100%	inc	0.0	228%	INC
	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	4	0.0	0.0	249%	0.0	6%	No	0.0	24%	inc	0.1	0.0	-96%	0.0	17%	No	0.0	172%	INC
	5	0.1	0.1	91%	0.1	-13%	No	0.1	17%	No	0.2	0.2	-18%	0.2	13%	No	0.3	106%	INC
	6	10.2	9.0	-12%	9.1	1%	No	11.1	24%	inc	29.0	25.3	-13%	27.5	9%	No	24.7	-2%	No
Northern red oak	1	7.4	6.1	-17%	6.6	7%	No	6.8	11%	No	14.9	5.1	-65%	9.8	92%	inc	15.6	204%	INC
	2	1.9	2.4	23%	2.2	-6%	No	2.7	15%	No	3.1	5.7	87%	5.5	-4%	No	7.6	33%	inc
	3	7.6	5.8	-23%	5.0	-14%	No	6.5	11%	No	9.7	20.3	109%	14.6	-28%	dec	20.5	1%	No
	4	11.7	11.5	-2%	11.7	2%	No	12.0	4%	No	22.3	6.4	-71%	9.0	40%	inc	17.1	166%	INC
	5	6.0	3.2	-46%	3.1	-5%	No	3.6	10%	No	6.8	4.3	-37%	3.8	-12%	No	4.1	-4%	No
	6	1.1	0.8	-25%	0.9	7%	No	1.0	25%	inc	2.1	1.6	-22%	1.8	10%	No	0.9	-42%	DEC
Northern white-cedar	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	2	0.4	0.2	-41%	0.2	-22%	dec	0.2	4%	No	7.2	1.6	-78%	0.5	-66%	DEC	0.5	-66%	DEC
	3	0.0	0.0	-16%	0.0	-55%	DEC	0.0	-28%	dec	0.1	0.1	-54%	0.0	-91%	DEC	0.0	-86%	DEC
	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	5	0.0	0.0	-17%	0.0	-17%	No	0.0	12%	No	0.0	0.0	-65%	0.0	-59%	DEC	0.0	-21%	dec
	6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pignut hickory	1	0.7	0.6	-12%	0.6	-1%	No	0.6	-2%	No	1.8	2.2	22%	2.2	-1%	No	2.5	13%	No
	2	0.4	0.7	97%	0.7	-3%	No	0.8	14%	No	1.2	2.4	101%	2.5	3%	No	2.5	2%	No
	3	0.6	1.2	97%	1.2	-6%	No	1.3	9%	No	1.8	3.2	79%	3.2	1%	No	3.0	-7%	No
	4	1.1	1.1	1%	1.1	0%	No	1.1	-4%	No	4.6	1.2	-75%	1.5	25%	inc	1.6	40%	inc
	5	1.4	2.9	102%	2.7	-6%	No	3.3	15%	No	5.2	4.9	-4%	4.7	-4%	No	4.5	-10%	No
	6	0.4	0.5	28%	0.5	9%	No	0.5	15%	No	1.3	0.8	-37%	1.2	46%	inc	0.6	-22%	dec

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Table 43 (continued).—Absolute and percentage change in basal area (BA) and trees per acre (TPA) in the six subregions of the Mid-Atlantic region, as projected by the LANDIS PRO model for 24 species under a current climate scenario (1980 through 2009) and two climate-model emissions scenario combinations in the year 2100

		Current climate			PCM B1			GFDL A1FI			Current climate			PCM B1			GFDL A1FI		
Tree species	Sub-region[a]	BA in 2000 (ft^2/ acre)	BA in 2100 (ft^2/ acre)	Change from 2000[b]	BA in 2100 (ft^2/ acre)	Change from current climate[c]	Change class[d]	BA in 2100 (ft^2/ acre)	Change from current climate[c]	Change class[d]	TPA in 2000	TPA in 2100	Change from 2000[b]	TPA in 2100	Change from current climate[c]	Change class[d]	TPA in 2100	Change from current climate[c]	Change class[d]
Pitch pine	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	2	0.0	0.0	-62%	0.0	-25%	dec	0.0	-13%	No	0.0	0.0	-32%	0.0	-24%	dec	0.0	-8%	No
	3	0.4	0.4	4%	0.3	-14%	No	0.4	8%	No	1.0	0.5	-49%	0.5	-12%	No	0.6	20%	No
	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	5	2.7	6.4	137%	6.4	-1%	No	7.8	21%	inc	11.8	11.5	-3%	10.9	-5%	No	11.3	-2%	No
	6	9.5	11.7	22%	12.4	6%	No	14.6	25%	inc	36.9	15.9	-57%	14.2	-11%	No	13.4	-15%	No
Quaking aspen	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	2	2.4	13.5	453%	12.5	-7%	No	11.5	-15%	No	5.9	101.1	1605%	84.5	-16%	No	30.8	-70%	DEC
	3	1.7	9.7	480%	8.1	-16%	No	7.6	-21%	dec	5.5	86.1	1460%	63.3	-26%	dec	23.0	-73%	DEC
	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	5	0.9	1.6	73%	1.5	-6%	No	1.5	-8%	No	1.7	8.1	387%	6.2	-23%	dec	2.9	-64%	DEC
	6	0.0	0.0	915%	0.0	11%	No	0.0	6%	No	0.0	0.0	-78%	0.0	8%	No	0.0	14%	No
Red maple	1	20.7	38.6	87%	38.7	0%	No	39.1	1%	No	95.2	75.4	-21%	78.0	3%	No	102.2	36%	inc
	2	12.3	16.8	36%	16.5	-2%	No	18.2	9%	No	59.9	47.4	-21%	46.0	-3%	No	54.0	14%	No
	3	22.6	15.9	-29%	15.2	-5%	No	16.9	6%	No	81.3	25.8	-68%	22.6	-12%	No	27.5	7%	No
	4	18.1	37.5	107%	38.0	1%	No	37.3	-1%	No	105.7	53.4	-50%	61.6	15%	No	68.0	28%	inc
	5	8.7	17.8	104%	17.7	-1%	No	19.9	12%	No	39.3	33.4	-15%	33.7	1%	No	39.5	18%	No
	6	11.9	19.7	65%	20.8	6%	No	23.4	19%	No	61.4	38.6	-37%	44.0	14%	No	52.7	36%	inc
Red spruce	1	0.3	0.0	-88%	0.0	0%	No	0.0	-1%	No	1.0	0.0	-98%	0.0	0%	No	0.0	-1%	No
	2	0.4	0.8	80%	0.7	-9%	No	0.8	7%	No	4.6	2.9	-36%	1.4	-50%	DEC	1.2	-58%	DEC
	3	0.2	0.2	-7%	0.2	-18%	No	0.2	13%	No	2.2	0.2	-89%	0.1	-53%	DEC	0.2	-33%	dec
	4	0.2	0.0	-77%	0.0	-10%	No	0.0	-18%	No	0.6	0.1	-85%	0.0	-70%	DEC	0.0	-74%	DEC
	5	0.4	0.5	20%	0.4	-5%	No	0.5	9%	No	1.9	0.3	-84%	0.2	-30%	dec	0.2	-23%	dec
	6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

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Table 43 (continued).—Absolute and percentage change in basal area (BA) and trees per acre (TPA) in the six subregions of the Mid-Atlantic region, as projected by the LANDIS PRO model for 24 species under a current climate scenario (1980 through 2009) and two climate-model emissions scenario combinations in the year 2100

		Current climate			PCM B1			GFDL A1FI			Current climate			PCM B1			GFDL A1FI		
Tree species	Sub-region[a]	BA in 2000 (ft^2/acre)	BA in 2100 (ft^2/acre)	Change from 2000[b]	BA in 2100 (ft^2/acre)	Change from current climate[c]	Change class[d]	BA in 2100 (ft^2/acre)	Change from current climate[c]	Change class[d]	TPA in 2000	TPA in 2100	Change from 2000[b]	TPA in 2100	Change from current climate[c]	Change class[d]	TPA in 2100	Change from current climate[c]	Change class[d]
Scarlet oak	1	1.2	0.7	-45%	0.7	-1%	No	0.6	-12%	No	2.0	1.1	-46%	1.0	-1%	No	0.5	-54%	DEC
	2	0.0	0.0	188%	0.0	-5%	No	0.0	3%	No	0.0	0.0	394%	0.0	-14%	No	0.0	48%	inc
	3	0.6	1.0	61%	0.9	-4%	No	1.0	5%	No	1.3	2.0	62%	2.2	7%	No	2.2	7%	No
	4	3.0	2.0	-34%	2.0	2%	No	1.9	-4%	No	6.4	1.7	-73%	2.1	22%	inc	1.5	-16%	No
	5	1.6	5.8	265%	5.7	-2%	No	6.2	6%	No	3.9	8.2	110%	8.4	2%	No	6.8	-18%	No
	6	2.1	4.6	116%	4.9	6%	No	5.0	8%	No	4.7	8.8	87%	10.9	24%	inc	5.8	-33%	dec
Shagbark hickory	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	2	0.8	3.5	329%	3.5	0%	No	4.1	17%	No	5.6	14.1	152%	15.2	8%	No	17.1	21%	inc
	3	0.6	1.2	100%	1.1	-8%	No	1.4	21%	inc	1.5	3.3	117%	3.5	5%	No	4.4	33%	inc
	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	5	0.5	1.3	132%	1.2	-3%	No	1.4	10%	No	1.8	2.6	46%	2.7	4%	No	2.5	-6%	No
	6	0.0	0.0	-37%	0.0	20%	No	0.0	40%	inc	0.0	0.0	-48%	0.0	191%	INC	0.0	-5%	No
Sugar maple	1	5.9	6.4	8%	6.4	0%	No	5.3	-18%	No	28.7	39.6	38%	38.9	-2%	No	7.6	-81%	DEC
	2	10.6	12.6	18%	12.0	-4%	No	14.0	12%	No	53.7	30.6	-43%	28.9	-5%	No	29.0	-5%	No
	3	14.0	16.9	20%	15.2	-10%	No	19.3	14%	No	49.0	34.0	-31%	27.8	-18%	No	37.5	10%	No
	4	3.5	4.1	17%	4.0	-1%	No	3.3	-18%	No	21.5	26.4	23%	26.8	1%	No	11.4	-57%	DEC
	5	4.1	6.2	52%	5.8	-7%	No	6.5	3%	No	16.0	21.7	36%	18.0	-17%	No	9.8	-55%	DEC
	6	0.1	0.2	57%	0.2	13%	No	0.2	13%	No	0.8	1.5	102%	1.7	12%	No	0.6	-61%	DEC
Tulip tree	1	3.2	4.0	26%	4.0	0%	No	3.8	-4%	No	5.5	21.5	290%	22.6	5%	No	23.9	11%	No
	2	0.1	0.2	194%	0.2	0%	No	0.4	71%	inc	0.2	2.7	1283%	2.8	7%	No	6.4	141%	INC
	3	0.7	0.2	-76%	0.2	30%	inc	0.4	124%	INC	0.4	1.0	145%	2.2	118%	INC	5.3	432%	INC
	4	5.7	6.4	12%	6.5	1%	No	5.9	-8%	No	6.6	24.0	264%	26.4	10%	No	25.4	6%	No
	5	5.6	4.4	-22%	4.2	-4%	No	6.7	54%	inc	6.4	18.4	189%	16.7	-9%	No	43.0	134%	INC
	6	5.6	3.0	-46%	3.2	5%	No	4.1	35%	inc	7.4	21.0	183%	24.5	17%	No	19.3	-8%	No

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Table 43 (continued).—Absolute and percentage change in basal area (BA) and trees per acre (TPA) in the six subregions of the Mid-Atlantic region, as projected by the LANDIS PRO model for 24 species under a current climate scenario (1980 through 2009) and two climate-model emissions scenario combinations in the year 2100

		Current climate			PCM B1			GFDL A1FI			Current climate			PCM B1			GFDL A1FI		
Tree species	Sub-region[a]	BA in 2000 (ft^2/acre)	BA in 2100 (ft^2/acre)	Change from 2000[b]	BA in 2100 (ft^2/acre)	Change from current climate[c]	Change class[d]	BA in 2100 (ft^2/acre)	Change from current climate[c]	Change class[d]	TPA in 2000	TPA in 2100	Change from 2000[b]	TPA in 2100	Change from current climate[c]	Change class[d]	TPA in 2100	Change from current climate[c]	Change class[d]
Virginia pine	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	2	0.0	0.0	-100%	-	-	-	-	-	-	0.0	0.0	-100%	-	-	-	-	-	-
	3	0.0	0.0	-96%	0.0	10%	No	0.0	121%	INC	0.1	0.0	-98%	0.0	56%	inc	0.0	1060%	INC
	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	5	0.7	1.6	122%	1.6	1%	No	1.8	15%	No	1.4	2.4	75%	2.5	5%	No	2.0	-19%	No
	6	2.6	3.1	19%	3.2	2%	No	3.5	13%	No	6.2	4.9	-21%	4.7	-3%	No	3.7	-23%	dec
White ash	1	2.6	3.3	29%	3.4	1%	No	3.5	4%	No	19.2	26.9	40%	29.1	8%	No	38.2	42%	inc
	2	5.5	12.8	133%	12.2	-5%	No	15.2	19%	No	23.9	43.4	82%	40.4	-7%	No	57.8	33%	inc
	3	7.3	11.9	63%	10.4	-13%	No	14.3	20%	No	23.7	38.9	64%	31.0	-20%	No	47.3	22%	inc
	4	2.4	3.0	28%	3.1	3%	No	3.0	-1%	No	14.5	15.6	8%	17.7	13%	No	18.7	20%	No
	5	3.9	10.1	159%	9.7	-4%	No	12.1	20%	No	11.2	20.6	85%	19.6	-5%	No	24.1	17%	No
	6	0.9	1.2	35%	1.4	18%	No	1.6	31%	inc	2.0	4.3	114%	5.9	37%	inc	2.6	-38%	dec
White oak	1	3.9	5.6	44%	5.7	1%	No	5.6	0%	No	5.7	21.7	279%	25.3	16%	No	30.4	40%	inc
	2	0.5	0.9	85%	0.9	-7%	No	1.2	31%	inc	0.3	7.7	2269%	7.1	-8%	No	11.6	50%	inc
	3	3.4	7.2	109%	5.9	-18%	No	8.6	19%	No	4.9	48.7	899%	34.7	-29%	dec	57.6	18%	No
	4	2.8	3.6	31%	3.6	0%	No	3.4	-5%	No	11.9	3.3	-72%	3.8	16%	No	4.0	23%	inc
	5	3.2	5.0	57%	4.7	-6%	No	6.2	24%	inc	7.2	19.9	177%	18.2	-8%	No	32.2	62%	inc
	6	5.7	11.7	105%	12.1	3%	No	16.5	41%	inc	13.0	86.9	569%	93.5	8%	No	115.4	33%	inc
Yellow birch	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	2	1.7	3.2	88%	3.0	-4%	No	3.4	6%	No	9.3	12.1	30%	11.1	-8%	No	5.1	-58%	DEC
	3	1.9	4.8	151%	4.1	-13%	No	4.8	0%	No	6.8	17.2	151%	13.4	-22%	dec	6.6	-61%	DEC
	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	5	0.8	1.4	89%	1.3	-9%	No	1.5	3%	No	4.6	2.9	-36%	2.3	-21%	dec	1.4	-53%	DEC
	6	0.1	0.0	-42%	0.0	8%	No	0.0	11%	No	0.2	0.0	-94%	0.0	9%	No	0.0	13%	No

[a] Subregions: 1 – Western Allegheny Plateau, 2 – Erie and Ontario Lake Plain, 3 – Northern Allegheny Plateau, 4 – Ridge and Valley, 5 – Piedmont, 6 – Coastal Plain. See Figure 38 (Chapter 6, p. 144).
[b] Change under current climate represents the difference from year 2009 through year 2100 due to succession and management, but not climate.
[c] Change is the difference between this scenario and current climate in 2100 and represents the potential change due to climate change.
[d] Change classes are abbreviated No (no change), inc (small increase), INC (large increase), dec (small decrease), and DEC (large decrease). Dash (-) indicates not present.

Table 44.—Absolute and percentage change in basal area (BA) and trees per acre (TPA) in the six subregions of the Mid-Atlantic region, as projected by the LANDIS PRO model for 24 species under a current climate scenario (1980 through 2009) and two climate-model emissions scenario combinations in the year 2200

		Current climate			PCM B1			GFDL A1FI			Current climate			PCM B1			GFDL A1FI		
Tree species	Sub-region[a]	BA in 2000 (ft²/ acre)	BA in 2200 (ft²/ acre)	Change from 2000[b]	BA in 2200 (ft²/ acre)	Change from current climate[c]	Change class[d]	BA in 2200 (ft²/ acre)	Change from current climate[c]	Change class[d]	TPA in 2000	TPA in 2200	Change from 2000[b]	TPA in 2200	Change from current climate[c]	Change class[d]	TPA in 2200	Change from current climate[c]	Change class[d]
American beech	1	2.5	4.0	58%	4.0	2%	No	1.6	-60%	DEC	10.9	5.5	-50%	5.6	3%	No	0.5	-90%	DEC
	2	3.3	15.6	368%	14.8	-5%	No	14.3	-8%	No	21.4	53.1	148%	51.0	-4%	No	36.5	-31%	dec
	3	7.0	20.2	189%	18.1	-10%	No	18.4	-9%	No	58.6	62.7	7%	51.7	-18%	No	35.6	-43%	DEC
	4	1.7	2.4	45%	2.4	0%	No	1.4	-41%	DEC	8.4	3.3	-60%	3.5	5%	No	1.2	-63%	DEC
	5	2.0	6.1	198%	5.9	-4%	No	7.2	18%	No	18.4	19.9	8%	18.7	-6%	No	17.3	-13%	No
	6	1.9	7.1	285%	8.1	13%	No	2.5	-64%	DEC	10.2	12.2	20%	14.8	22%	inc	0.9	-93%	DEC
Balsam fir	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	2	0.4	0.1	-74%	0.0	-95%	DEC	0.0	-92%	DEC	3.6	0.3	-92%	0.0	-99%	DEC	0.0	-99%	DEC
	3	0.0	0.0	-97%	0.0	148%	INC	0.0	-84%	DEC	0.1	0.0	-99%	0.0	173%	INC	0.0	-96%	DEC
	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	5	0.1	0.0	-94%	0.0	-63%	DEC	0.0	-82%	DEC	0.8	0.0	-98%	0.0	-78%	DEC	0.0	-94%	DEC
	6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Black cherry	1	18.9	27.8	47%	26.0	-6%	No	27.6	-1%	No	58.0	44.8	-23%	41.8	-7%	No	44.3	-1%	No
	2	7.2	6.8	-6%	7.1	5%	No	6.7	-1%	No	17.5	37.2	112%	40.6	9%	No	36.4	-2%	No
	3	8.2	5.6	-31%	5.2	-8%	No	6.2	11%	No	21.7	18.2	-16%	15.4	-15%	No	18.7	3%	No
	4	10.2	7.4	-27%	9.1	23%	inc	9.4	26%	inc	34.5	8.6	-75%	11.5	33%	inc	12.1	41%	inc
	5	2.5	4.1	62%	4.1	1%	No	4.5	10%	No	8.7	12.8	47%	13.1	2%	No	15.2	19%	No
	6	1.0	5.3	444%	6.8	30%	inc	4.0	-24%	dec	6.4	12.7	99%	20.9	64%	inc	8.6	-33%	dec
Black oak	1	2.3	4.2	86%	4.1	-2%	No	3.1	-27%	dec	4.5	6.7	49%	6.6	-1%	No	4.6	-32%	dec
	2	0.2	0.6	211%	0.7	16%	No	0.7	19%	No	0.2	2.0	1098%	2.2	14%	No	2.3	18%	No
	3	1.2	1.0	-19%	1.3	33%	inc	1.4	49%	inc	1.6	2.6	64%	3.4	32%	inc	4.3	64%	inc
	4	4.1	1.7	-58%	2.4	39%	inc	2.9	69%	inc	5.9	1.8	-70%	2.7	54%	inc	3.4	96%	inc
	5	3.2	7.0	117%	6.8	-2%	No	4.9	-30%	dec	2.7	20.4	644%	19.8	-3%	No	13.2	-35%	dec
	6	1.6	5.2	218%	6.5	24%	inc	2.9	-45%	DEC	3.0	12.2	309%	16.4	34%	inc	5.4	-56%	DEC

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Table 44 (continued).—Absolute and percentage change in basal area (BA) and trees per acre (TPA) in the six subregions of the Mid-Atlantic region, as projected by the LANDIS PRO model for 24 species under a current climate scenario (1980 through 2009) and two climate-model emissions scenario combinations in the year 2200

		Current climate			PCM B1			GFDL A1FI			Current climate			PCM B1			GFDL A1FI		
Tree species	Sub-region[a]	BA in 2000 (ft²/acre)	BA in 2200 (ft²/acre)	Change from 2000[b]	BA in 2200 (ft²/acre)	Change from current climate[c]	Change class[d]	BA in 2200 (ft²/acre)	Change from current climate[c]	Change class[d]	TPA in 2000	TPA in 2200	Change from 2000[b]	TPA in 2200	Change from current climate[c]	Change class[d]	TPA in 2200	Change from current climate[c]	Change class[d]
Black spruce	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	2	0.0	0.0	-86%	0.0	-86%	DEC	0.0	-55%	DEC	0.2	0.0	-94%	0.0	-98%	DEC	0.0	-91%	DEC
	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Chestnut oak	1	2.9	3.9	38%	3.6	-8%	No	1.6	-59%	DEC	5.7	17.6	210%	15.7	-11%	No	2.9	-83%	DEC
	2	0.3	1.6	536%	2.1	29%	inc	3.8	132%	INC	0.3	8.1	2525%	13.6	68%	inc	23.8	194%	INC
	3	3.4	6.3	86%	13.5	115%	INC	27.6	340%	INC	5.1	27.8	445%	76.4	175%	INC	198.8	616%	INC
	4	13.4	10.0	-26%	11.4	14%	No	9.9	-1%	No	31.9	17.0	-47%	28.0	65%	inc	25.1	48%	inc
	5	4.6	16.0	246%	15.1	-5%	No	19.3	21%	inc	6.4	78.0	1110%	74.8	-4%	No	66.0	-15%	No
	6	1.5	10.5	585%	11.2	7%	No	6.2	-40%	dec	3.6	42.5	1077%	50.2	18%	No	5.4	-87%	DEC
Eastern hemlock	1	6.4	3.0	-54%	2.9	-3%	No	1.7	-42%	DEC	18.8	4.4	-77%	4.2	-5%	No	0.5	-89%	DEC
	2	4.8	2.4	-50%	2.6	7%	No	1.9	-20%	No	22.9	6.3	-72%	8.2	29%	inc	0.8	-87%	DEC
	3	9.1	2.4	-74%	2.2	-8%	No	2.6	11%	No	24.6	2.3	-91%	2.3	2%	No	1.1	-52%	DEC
	4	5.2	2.2	-58%	2.5	13%	No	1.4	-36%	dec	18.0	2.3	-87%	3.3	43%	inc	0.4	-82%	DEC
	5	2.9	1.3	-55%	1.0	-25%	dec	0.9	-28%	dec	12.9	2.1	-84%	1.0	-52%	DEC	0.4	-82%	DEC
	6	0.1	0.0	-47%	0.0	-31%	dec	0.0	3%	No	0.2	0.0	-79%	0.0	-73%	DEC	0.0	-75%	DEC
Eastern white pine	1	1.6	1.5	-7%	1.4	-6%	No	0.4	-70%	DEC	5.9	7.1	19%	6.6	-6%	No	0.1	-98%	DEC
	2	2.2	0.8	-61%	0.9	12%	No	0.5	-45%	DEC	3.1	4.9	56%	5.8	17%	No	0.5	-89%	DEC
	3	6.5	1.7	-74%	1.3	-22%	dec	1.1	-35%	dec	14.1	8.6	-39%	5.7	-34%	dec	1.2	-86%	DEC
	4	2.6	1.5	-40%	1.2	-23%	dec	0.5	-65%	DEC	13.1	5.3	-59%	4.0	-24%	dec	0.3	-94%	DEC
	5	3.6	0.6	-83%	0.5	-19%	No	0.5	-15%	No	9.0	1.5	-83%	0.9	-42%	DEC	0.2	-83%	DEC
	6	0.3	0.0	-96%	0.0	7%	No	0.0	24%	inc	0.5	0.0	-95%	0.0	-35%	dec	0.0	-87%	DEC

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Table 44 (continued).—Absolute and percentage change in basal area (BA) and trees per acre (TPA) in the six subregions of the Mid-Atlantic region, as projected by the LANDIS PRO model for 24 species under a current climate scenario (1980 through 2009) and two climate-model emissions scenario combinations in the year 2200

		Current climate			PCM B1			GFDL A1FI			Current climate			PCM B1			GFDL A1FI		
Tree species	Sub-region[a]	BA in 2000 (ft^2/acre)	BA in 2200 (ft^2/acre)	Change from 2000[b]	BA in 2200 (ft^2/acre)	Change from current climate[c]	Change class[d]	BA in 2200 (ft^2/acre)	Change from current climate[c]	Change class[d]	TPA in 2000	TPA in 2200	Change from 2000[b]	TPA in 2200	Change from current climate[c]	Change class[d]	TPA in 2200	Change from current climate[c]	Change class[d]
Loblolly pine	1	0.0	0.0	1337%	0.0	236%	INC	0.0	465%	INC	0.1	0.0	-97%	0.0	467%	INC	0.0	1348%	INC
	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	4	0.0	0.0	-35%	0.0	149%	INC	0.0	1772%	INC	0.1	0.0	-99%	0.0	145%	INC	0.0	3215%	INC
	5	0.1	0.0	-20%	0.1	27%	inc	0.1	75%	inc	0.2	0.1	-59%	0.2	115%	INC	0.2	189%	INC
	6	10.2	4.8	-53%	4.4	-9%	No	4.7	-4%	No	29.0	15.8	-46%	14.3	-9%	No	11.2	-29%	dec
Northern red oak	1	7.4	2.5	-66%	5.8	131%	INC	10.9	335%	INC	14.9	2.9	-80%	12.3	320%	INC	34.8	1090%	INC
	2	1.9	2.7	40%	2.5	-9%	No	4.0	48%	inc	3.1	6.3	105%	5.4	-14%	No	10.6	69%	inc
	3	7.6	7.4	-3%	4.8	-35%	dec	6.9	-7%	No	9.7	20.8	114%	9.1	-56%	DEC	15.2	-27%	dec
	4	11.7	4.2	-64%	6.9	64%	inc	15.5	270%	INC	22.3	4.5	-80%	10.6	132%	INC	39.2	764%	INC
	5	6.0	1.3	-78%	1.2	-13%	No	1.5	10%	No	6.8	2.2	-67%	1.7	-22%	dec	2.0	-10%	No
	6	1.1	0.8	-27%	0.7	-8%	No	0.3	-57%	DEC	2.1	2.4	17%	2.3	-5%	No	0.2	-93%	DEC
Northern white-cedar	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	2	0.4	0.1	-64%	0.1	-54%	DEC	0.1	-38%	dec	7.2	0.9	-87%	0.1	-88%	DEC	0.0	-96%	DEC
	3	0.0	0.0	-62%	0.0	-59%	DEC	0.0	-56%	DEC	0.1	0.0	-83%	0.0	-96%	DEC	0.0	-98%	DEC
	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	5	0.0	0.0	-82%	0.0	-36%	dec	0.0	-37%	dec	0.0	0.0	-96%	0.0	-81%	DEC	0.0	-81%	DEC
	6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pignut hickory	1	0.7	0.1	-81%	0.1	-6%	No	0.1	-26%	dec	1.8	0.5	-71%	0.5	-4%	No	0.4	-21%	dec
	2	0.4	1.3	276%	1.4	7%	No	1.4	6%	No	1.2	4.7	291%	5.0	7%	No	4.3	-9%	No
	3	0.6	2.5	301%	2.6	2%	No	2.0	-21%	dec	1.8	6.5	268%	6.5	-1%	No	4.2	-36%	dec
	4	1.1	0.1	-92%	0.1	19%	No	0.1	2%	No	4.6	0.3	-95%	0.4	52%	inc	0.4	47%	inc
	5	1.4	2.8	96%	2.7	-4%	No	2.2	-20%	No	5.2	5.0	-3%	4.9	-2%	No	2.9	-42%	DEC
	6	0.4	0.4	5%	0.6	51%	inc	0.2	-35%	dec	1.3	0.9	-33%	1.8	110%	INC	0.3	-70%	DEC

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Table 44 (continued).—Absolute and percentage change in basal area (BA) and trees per acre (TPA) in the six subregions of the Mid-Atlantic region, as projected by the LANDIS PRO model for 24 species under a current climate scenario (1980 through 2009) and two climate-model emissions scenario combinations in the year 2200

		Current climate			PCM B1			GFDL A1FI			Current climate			PCM B1			GFDL A1FI		
Tree species	Sub-region[a]	BA in 2000 (ft^2/acre)	BA in 2200 (ft^2/acre)	Change from 2000[b]	BA in 2200 (ft^2/acre)	Change from current climate[c]	Change class[d]	BA in 2200 (ft^2/acre)	Change from current climate[c]	Change class[d]	TPA in 2000	TPA in 2200	Change from 2000[b]	TPA in 2200	Change from current climate[c]	Change class[d]	TPA in 2200	Change from current climate[c]	Change class[d]
Pitch pine	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	2	0.0	0.0	-96%	0.0	-14%	No	0.0	-8%	No	0.0	0.0	-84%	0.0	23%	inc	0.0	-13%	No
	3	0.4	0.0	-89%	0.0	-34%	dec	0.0	19%	No	1.0	0.2	-83%	0.1	-54%	DEC	0.2	1%	No
	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	5	2.7	2.9	8%	2.8	-3%	No	3.2	10%	No	11.8	9.5	-20%	8.7	-9%	No	1.3	-86%	DEC
	6	9.5	1.9	-80%	1.9	1%	No	2.3	24%	inc	36.9	7.0	-81%	4.1	-42%	DEC	0.8	-88%	DEC
Quaking aspen	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	2	2.4	40.9	1575%	32.7	-20%	No	2.5	-94%	DEC	5.9	332.2	5503%	247.5	-25%	dec	1.8	-99%	DEC
	3	1.7	34.6	1976%	25.5	-26%	dec	2.5	-93%	DEC	5.5	234.9	4157%	149.4	-36%	dec	1.7	-99%	DEC
	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	5	0.9	3.6	292%	2.4	-34%	dec	0.2	-95%	DEC	1.7	25.0	1405%	14.2	-43%	DEC	0.1	-100%	X
	6	0.0	0.0	-97%	0.0	-60%	DEC	0.0	224%	INC	0.0	0.0	-99%	0.0	-95%	DEC	0.0	-57%	DEC
Red maple	1	20.7	41.8	102%	42.9	2%	No	57.6	38%	inc	95.2	63.5	-33%	66.1	4%	No	103.6	63%	inc
	2	12.3	5.9	-52%	5.8	-3%	No	7.0	17%	No	59.9	56.5	-6%	57.5	2%	No	73.5	30%	inc
	3	22.6	3.8	-83%	3.3	-13%	No	3.7	-3%	No	81.3	14.9	-82%	12.7	-14%	No	17.2	16%	No
	4	18.1	39.8	120%	47.6	20%	No	52.7	32%	inc	105.7	55.5	-48%	74.1	33%	inc	88.1	59%	inc
	5	8.7	6.0	-31%	6.1	2%	No	7.3	22%	inc	39.3	39.5	1%	41.6	5%	No	44.8	13%	No
	6	11.9	9.2	-23%	10.4	13%	No	11.5	26%	inc	61.4	56.1	-9%	67.9	21%	inc	52.7	-6%	No
Red spruce	1	0.3	0.0	-92%	0.0	0%	No	0.0	-2%	No	1.0	0.0	-99%	0.0	-6%	No	0.0	-8%	No
	2	0.4	0.5	11%	0.3	-40%	dec	0.3	-37%	dec	4.6	1.6	-65%	0.3	-83%	DEC	0.1	-94%	DEC
	3	0.2	0.1	-69%	0.1	-22%	dec	0.1	4%	No	2.2	0.1	-98%	0.0	-72%	DEC	0.0	-69%	DEC
	4	0.2	0.0	-84%	0.0	-21%	dec	0.0	-29%	dec	0.6	0.1	-91%	0.0	-89%	DEC	0.0	-90%	DEC
	5	0.4	0.1	-68%	0.1	-2%	No	0.1	9%	No	1.9	0.1	-97%	0.0	-52%	DEC	0.0	-50%	DEC
	6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

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Table 44 (continued).—Absolute and percentage change in basal area (BA) and trees per acre (TPA) in the six subregions of the Mid-Atlantic region, as projected by the LANDIS PRO model for 24 species under a current climate scenario (1980 through 2009) and two climate-model emissions scenario combinations in the year 2200

		Current climate			PCM B1			GFDL A1FI			Current climate			PCM B1			GFDL A1FI		
Tree species	Sub-region[a]	BA in 2000 (ft^2/acre)	BA in 2200 (ft^2/acre)	Change from 2000[b]	BA in 2200 (ft^2/acre)	Change from current climate[c]	Change class[d]	BA in 2200 (ft^2/acre)	Change from current climate[c]	Change class[d]	TPA in 2000	TPA in 2200	Change from 2000[b]	TPA in 2200	Change from current climate[c]	Change class[d]	TPA in 2200	Change from current climate[c]	Change class[d]
Scarlet oak	1	1.2	1.4	20%	1.4	-2%	No	0.3	-76%	DEC	2.0	2.0	0%	1.9	-1%	No	0.2	-89%	DEC
	2	0.0	0.0	486%	0.0	-9%	No	0.0	6%	No	0.0	0.0	1413%	0.0	7%	No	0.0	12%	No
	3	0.6	1.4	131%	1.6	12%	No	1.3	-10%	No	1.3	3.3	163%	3.6	9%	No	2.8	-15%	No
	4	3.0	1.6	-47%	2.2	38%	inc	1.1	-27%	dec	6.4	1.5	-76%	2.3	49%	inc	1.0	-34%	dec
	5	1.6	6.0	277%	6.2	4%	No	3.9	-35%	dec	3.9	16.7	325%	17.4	4%	No	8.7	-48%	DEC
	6	2.1	5.7	165%	7.1	26%	inc	2.1	-63%	DEC	4.7	13.9	194%	20.5	48%	inc	3.3	-76%	DEC
Shagbark hickory	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	2	0.8	8.4	932%	8.9	7%	No	10.3	23%	inc	5.6	29.1	419%	32.9	13%	No	36.7	26%	inc
	3	0.6	2.6	339%	2.7	5%	No	3.5	36%	inc	1.5	7.2	367%	7.5	5%	No	10.3	44%	inc
	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	5	0.5	1.4	152%	1.5	5%	No	1.3	-5%	No	1.8	2.4	36%	2.8	13%	No	1.9	-21%	dec
	6	0.0	0.0	-80%	0.0	98%	inc	0.0	-14%	No	0.0	0.0	-70%	0.0	72%	inc	0.0	-87%	DEC
Sugar maple	1	5.9	10.5	78%	10.2	-2%	No	4.0	-62%	DEC	28.7	26.2	-9%	24.9	-5%	No	1.5	-94%	DEC
	2	10.6	11.5	9%	10.6	-8%	No	14.1	22%	inc	53.7	44.5	-17%	39.2	-12%	No	48.2	8%	No
	3	14.0	18.1	29%	16.7	-8%	No	24.8	37%	inc	49.0	40.1	-18%	35.4	-12%	No	54.8	37%	inc
	4	3.5	9.3	166%	8.4	-9%	No	4.1	-56%	DEC	21.5	29.8	39%	26.4	-11%	No	5.5	-82%	DEC
	5	4.1	17.5	326%	15.8	-10%	No	10.7	-39%	dec	16.0	53.4	234%	46.9	-12%	No	23.3	-56%	DEC
	6	0.1	1.3	1148%	1.3	-3%	No	0.3	-76%	DEC	0.8	3.9	415%	3.9	-1%	No	0.1	-97%	DEC
Tulip tree	1	3.2	7.1	126%	7.2	1%	No	6.3	-11%	No	5.5	29.9	442%	31.8	6%	No	32.7	9%	No
	2	0.1	0.6	656%	0.7	26%	inc	1.6	177%	INC	0.2	6.9	3496%	9.8	41%	inc	23.4	238%	INC
	3	0.7	0.1	-80%	0.4	174%	INC	1.4	970%	INC	0.4	1.2	203%	3.2	163%	INC	17.6	1337%	INC
	4	5.7	10.8	89%	11.2	3%	No	9.5	-12%	No	6.6	32.9	400%	37.5	14%	No	34.4	5%	No
	5	5.6	3.1	-44%	3.0	-4%	No	5.4	73%	inc	6.4	15.4	142%	14.8	-4%	No	36.8	138%	INC
	6	5.6	2.6	-54%	2.7	7%	No	3.2	27%	inc	7.4	19.6	164%	22.1	13%	No	14.3	-27%	dec

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Table 44 (continued).—Absolute and percentage change in basal area (BA) and trees per acre (TPA) in the six subregions of the Mid-Atlantic region, as projected by the LANDIS PRO model for 24 species under a current climate scenario (1980 through 2009) and two climate-model emissions scenario combinations in the year 2200

		Current climate			PCM B1			GFDL A1FI			Current climate			PCM B1			GFDL A1FI		
Tree species	Sub-region[a]	BA in 2000 (ft²/acre)	BA in 2200 (ft²/acre)	Change from 2000[b]	BA in 2200 (ft²/acre)	Change from current climate[c]	Change class[d]	BA in 2200 (ft²/acre)	Change from current climate[c]	Change class[d]	TPA in 2000	TPA in 2200	Change from 2000[b]	TPA in 2200	Change from current climate[c]	Change class[d]	TPA in 2200	Change from current climate[c]	Change class[d]
Virginia pine	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	5	0.7	0.6	-17%	0.8	24%	inc	0.2	-63%	DEC	1.4	3.3	144%	4.3	28%	inc	0.4	-89%	DEC
	6	2.6	1.1	-57%	1.0	-12%	No	0.1	-87%	DEC	6.2	9.5	53%	9.4	-1%	No	0.0	-100%	X
White ash	1	2.6	7.6	196%	7.5	-2%	No	8.9	17%	No	19.2	51.6	169%	55.4	7%	No	77.0	49%	inc
	2	5.5	14.9	172%	14.3	-4%	No	22.4	50%	inc	23.9	50.8	113%	48.1	-5%	No	91.6	80%	inc
	3	7.3	14.8	102%	12.2	-18%	No	20.0	35%	inc	23.7	43.0	81%	30.0	-30%	dec	60.4	40%	inc
	4	2.4	6.8	186%	7.5	10%	No	5.6	-18%	No	14.5	34.3	137%	38.9	13%	No	32.9	-4%	No
	5	3.9	12.3	217%	11.8	-4%	No	14.4	17%	No	11.2	30.4	172%	28.8	-5%	No	35.1	15%	No
	6	0.9	1.5	71%	1.8	22%	inc	0.8	-50%	DEC	2.0	6.7	235%	8.8	32%	inc	0.7	-89%	DEC
White oak	1	3.9	1.7	-58%	1.8	10%	No	1.1	-34%	dec	5.7	11.7	105%	13.7	17%	No	8.0	-32%	dec
	2	0.5	2.0	298%	1.7	-11%	No	3.7	87%	inc	0.3	10.4	3103%	9.6	-8%	No	23.3	124%	INC
	3	3.4	11.9	244%	6.8	-43%	DEC	11.2	-6%	No	4.9	58.4	1097%	22.5	-62%	DEC	39.7	-32%	dec
	4	2.8	0.2	-93%	0.2	19%	No	0.2	10%	No	11.9	0.6	-95%	0.8	39%	inc	0.8	37%	inc
	5	3.2	4.2	33%	4.0	-4%	No	9.4	123%	INC	7.2	12.1	68%	11.0	-10%	No	44.8	270%	INC
	6	5.7	19.1	235%	18.1	-5%	No	36.8	93%	inc	13.0	104.9	708%	104.1	-1%	No	182.8	74%	inc
Yellow birch	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	2	1.7	1.6	-4%	1.5	-5%	-	0.7	-58%	DEC	9.3	7.5	-19%	7.1	-6%	No	0.2	-97%	DEC
	3	1.9	6.3	232%	4.8	-24%	dec	1.9	-70%	DEC	6.8	18.9	176%	12.3	-35%	dec	0.7	-96%	DEC
	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	5	0.8	0.7	-11%	0.5	-22%	dec	0.4	-43%	DEC	4.6	1.7	-62%	1.2	-32%	dec	0.1	-92%	DEC
	6	0.1	0.0	-100%	0.0	51%	inc	0.0	94%	inc	0.2	0.0	-100%	-	-	-	-	-	-

[a] Subregions: 1 – Western Allegheny Plateau, 2 – Erie and Ontario Lake Plain, 3 – Northern Allegheny Plateau, 4 – Ridge and Valley, 5 – Piedmont, 6 – Coastal Plain. See Figure 38 (Chapter 6, p. 144).

[b] Change under current climate represents the difference from year 2009 through year 2200 due to succession and management, but not climate.

[c] Change is the difference between this scenario and current climate in 2200 and represents the potential change due to climate change.

[d] Change classes are abbreviated No (no change), inc (small increase), INC (large increase), dec (small decrease), DEC (large decrease), New (new habitat), and X (extirpated). Dash (-) indicates not present. These projections illustrate how changes that we begin to see in 2100 may continue through 2200, but are not used in this vulnerability assessment for forest ecosystems.

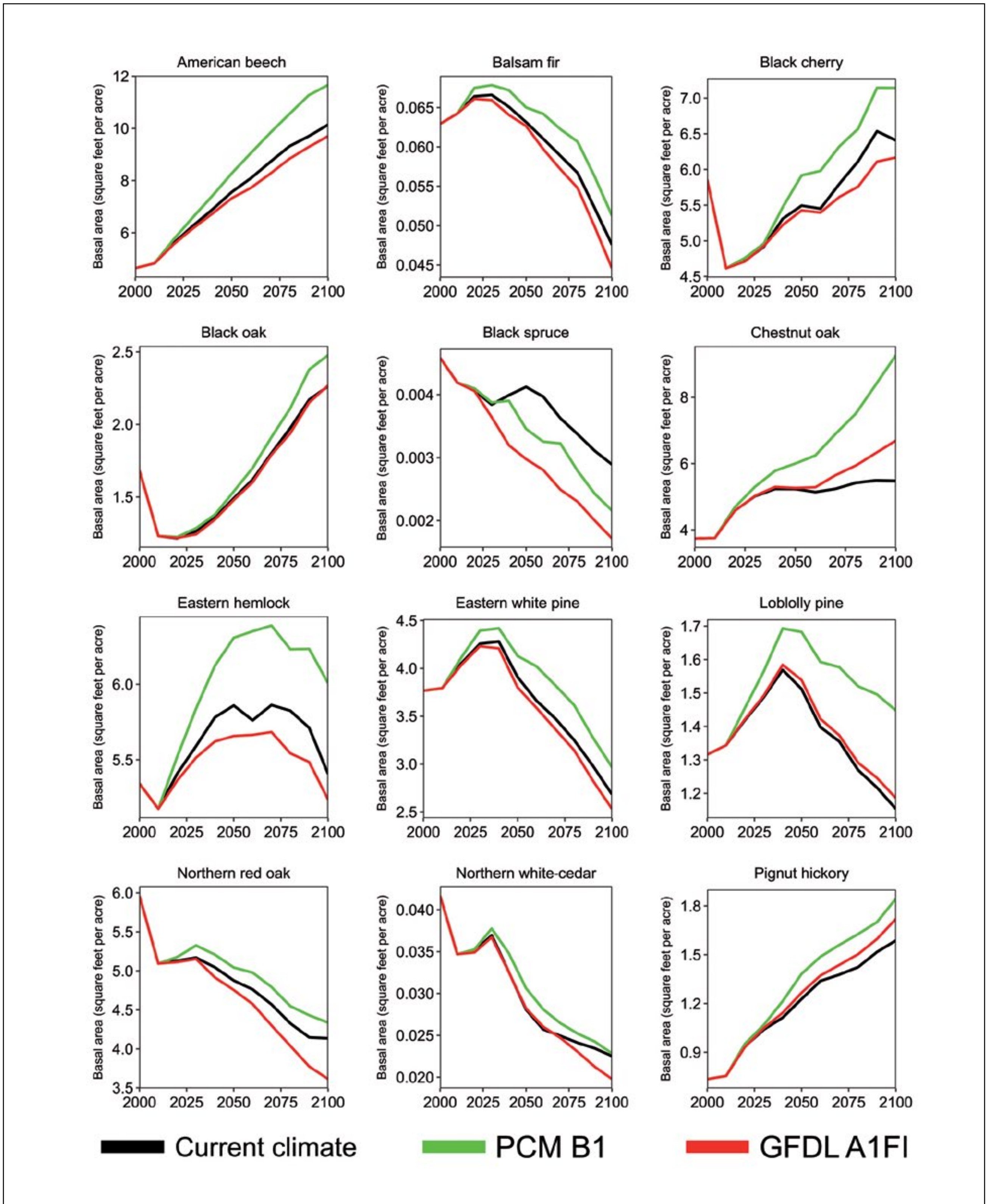


Figure 57.—Change in basal area projected by the LANDIS PRO model for 24 species within the assessment area. Assessment area values were derived from the weighted average of sections. The black line indicates projected change due to succession and management. The green and red lines indicate projected change due to a low (green) and high (red) climate model-emissions scenario.

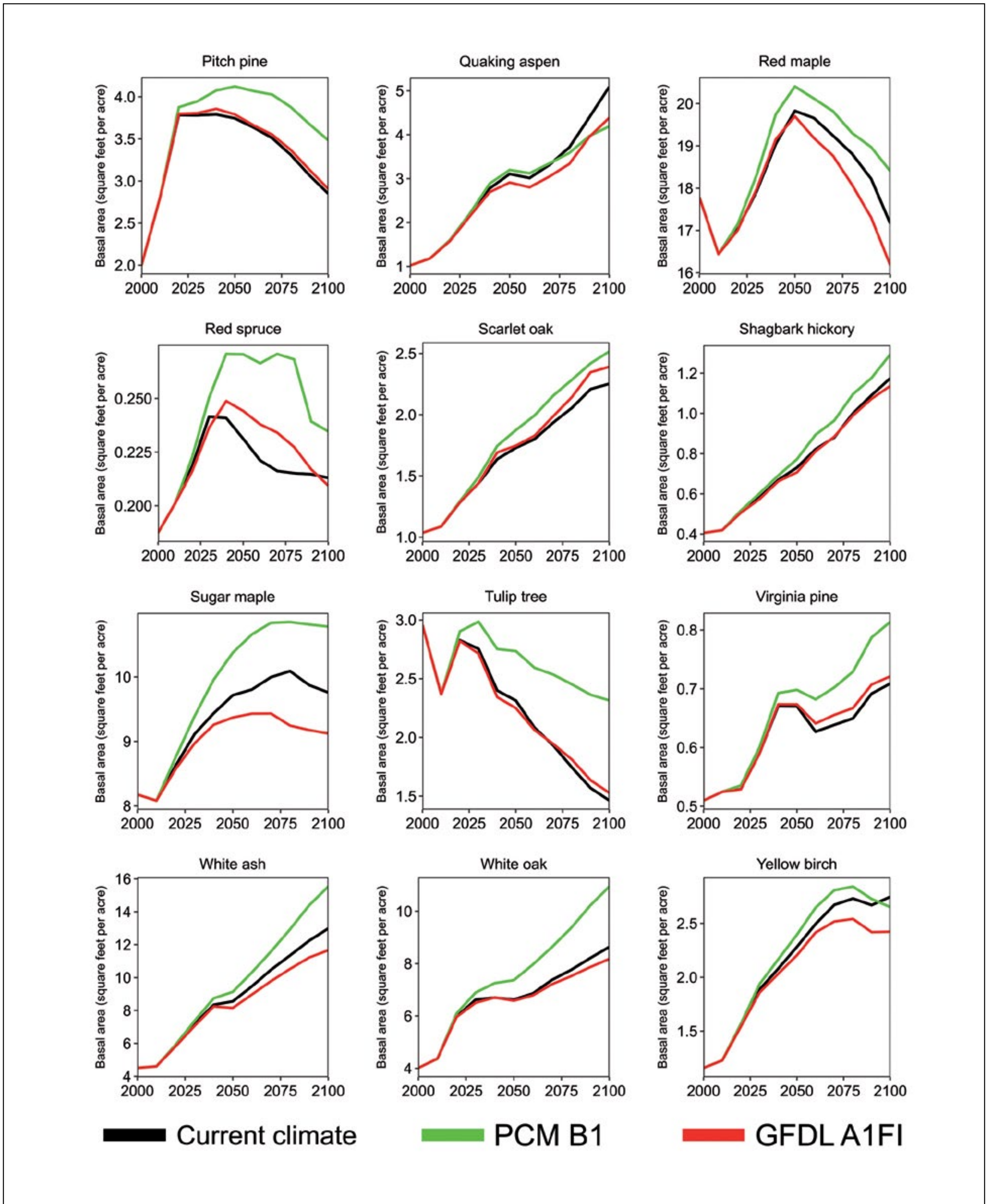


Figure 57 (continued).—Change in basal area projected by the LANDIS PRO model for 24 species within the assessment area. Assessment area values were derived from the weighted average of sections. The black line indicates projected change due to succession and management. The green and red lines indicate projected change due to a low (green) and high (red) climate model-emissions scenario.

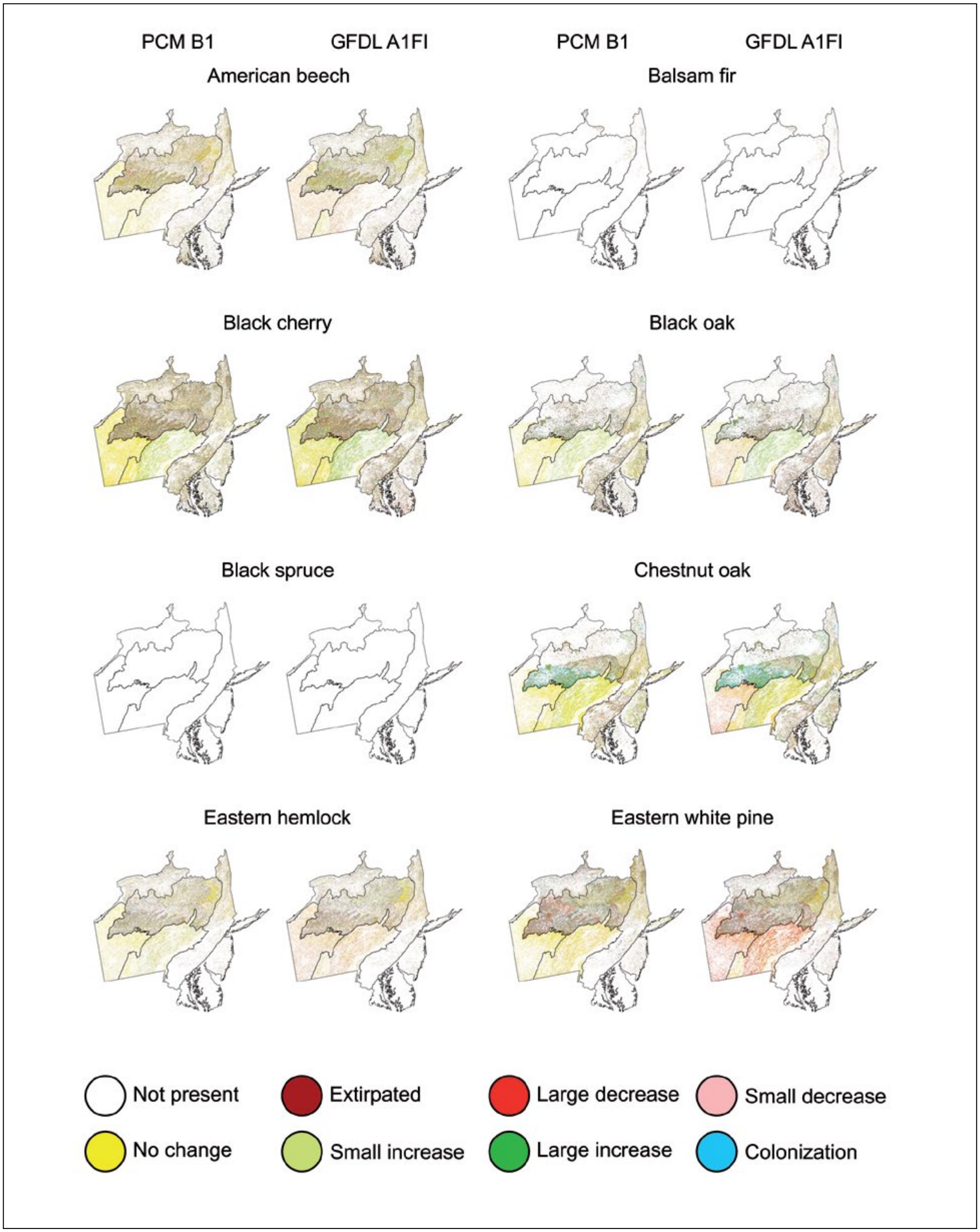


Figure 58.—Change in basal area projected by the LANDIS PRO model for 22 species under two climate model-emissions scenario combinations at year 2100 relative to a current climate scenario (1980 through 2009). Assessment area values were derived from the weighted average of sections.

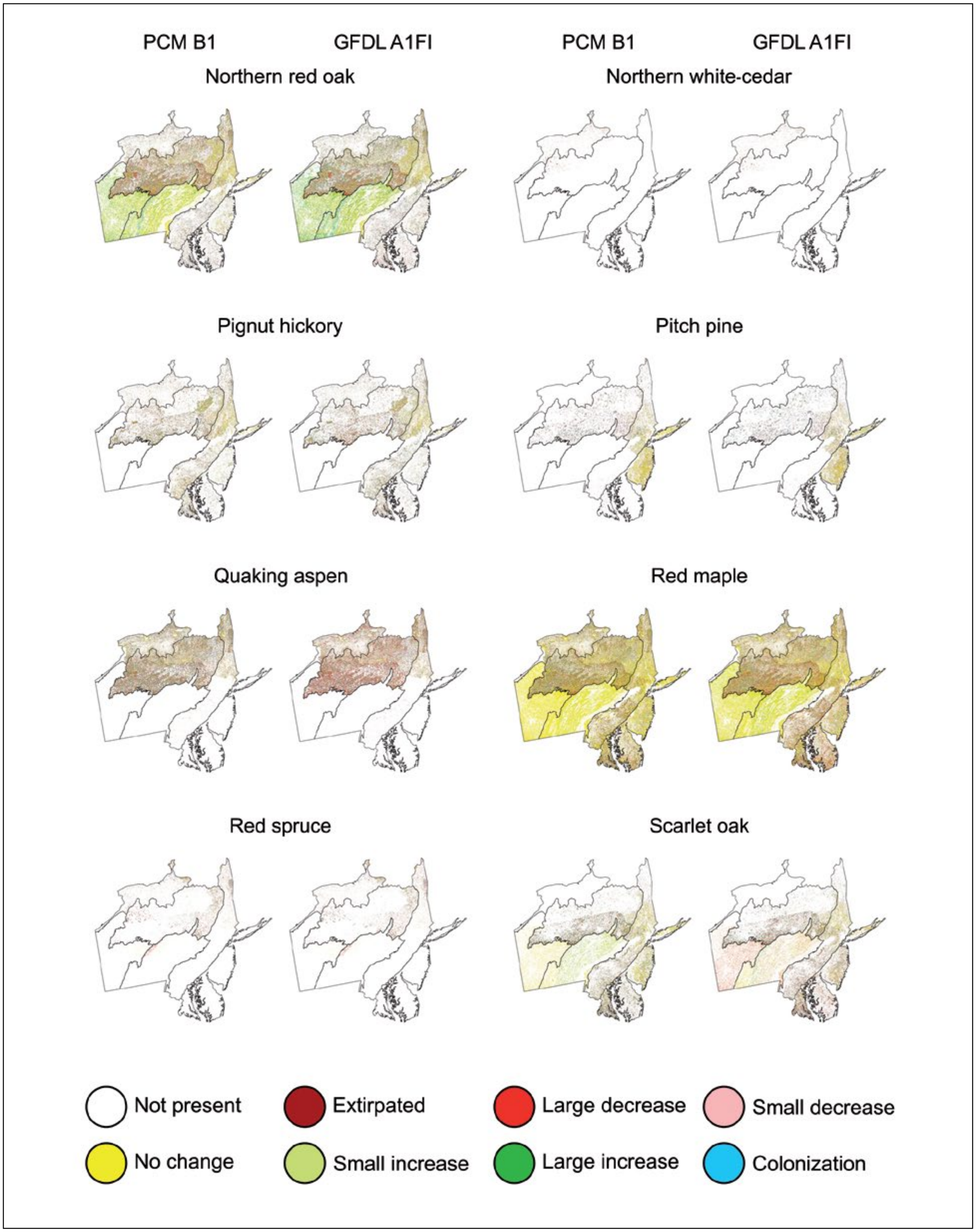


Figure 58 (continued).—Change in basal area projected by the LANDIS PRO model for 22 species under two climate model-emissions scenario combinations at year 2100 relative to a current climate scenario (1980 through 2009). Assessment area values were derived from the weighted average of sections.

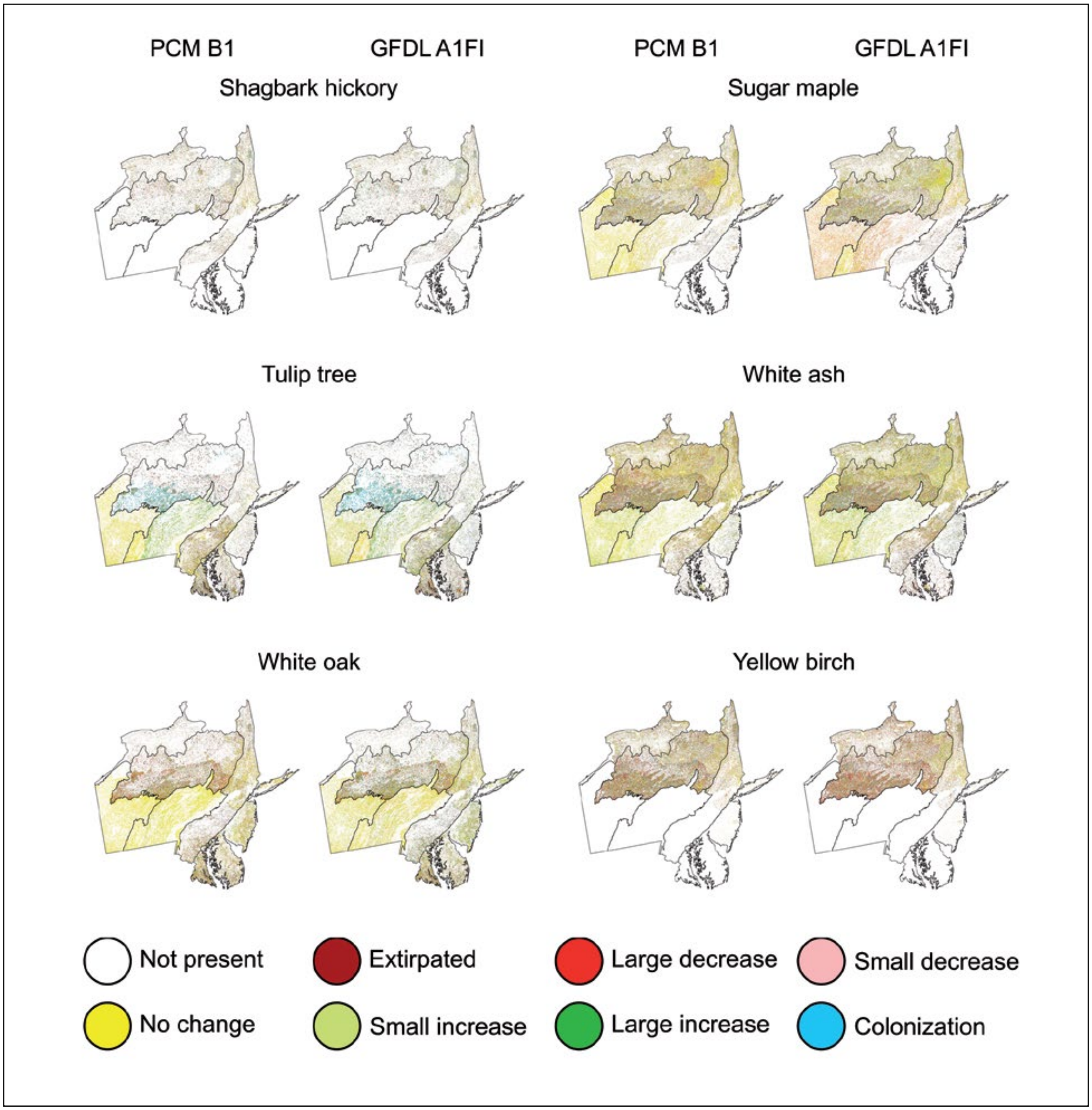


Figure 58 (continued).—Change in basal area projected by the LANDIS PRO model for 22 species under two climate model-emissions scenario combinations at year 2100 relative to a current climate scenario (1980 through 2009). Assessment area values were derived from the weighted average of sections.

APPENDIX 5: VULNERABILITY AND CONFIDENCE DETERMINATION

To assess vulnerabilities to climate change for each forest community, we elicited input from 26 experts from a variety of land management and research organizations across the Mid-Atlantic region (Table 45). We sought two teams of panelists who would be able to contribute a diversity of subject area expertise, knowledge of management history, and organizational perspectives on the interior and coastal forest communities of the Mid-Atlantic region. Most panelists had extensive knowledge

Table 45.—Participants in the November 2015 expert panel workshop

Name	Affiliation at time of workshop
Scott Bearer	The Nature Conservancy
Alex Bryan	Department of the Interior Northeast Climate Science Center
Ken Clark	USDA Forest Service, Northern Research Station
Greg Czarnecki	Pennsylvania Department of Conservation and Natural Resources
Phil DeSenze	USDA Forest Service, Northeastern Area State & Private Forestry
Paul Gugger	University of Maryland Center for Environmental Science Appalachian Laboratory
Andrea Hille	Allegheny National Forest
Justin Hynicka	Maryland Forest Service
Louis Iverson	USDA Forest Service, Northern Research Station
Katrina Krause	USDA Northeast Climate Hub
Deborah Landau	The Nature Conservancy: Maryland/DC Chapter
Laura Leites	Pennsylvania State University
Patricia Leopold[1]	Northern Institute of Applied Climate Science and Michigan Technological University
Evan Madlinger	Natural Resources Conservation Service
Gulnihal (Rose) Ozbay	Delaware State University
David Schmit	Pennsylvania Department of Conservation and Natural Resources, Bureau of Forestry
Danielle Shannon[1]	Northern Institute of Applied Climate Science and Michigan Technological University
Collin Shephard	Allegheny National Forest
Rebecca Shirer	The Nature Conservancy: New York
Nick Skrowronski	USDA Forest Service, Northern Research Station
Al Steele	USDA Forest Service, Northeastern Area State & Private Forestry
Susan Stout	USDA Forest Service, Northern Research Station
Frank Thompson	USDA Forest Service, Northern Research Station
John Thompson	Mohonk Preserve
David Weinstein	Cornell University
Alfonso Yáñez	Delaware Basin Project

[1]Workshop facilitator

about the ecology, management, and climate change impacts on forests in the assessment area. These panels were assembled in Germantown, PA, in November 2015. Here we describe the structured discussion process that the panels used.

FOREST ECOSYSTEMS ASSESSED

The authors of this assessment decided to use forest communities based on the Northeast Habitat Classification System (NETHCS) for classifying and describing forest ecosystems within the assessment area (see Chapter 1 and Table 10). For each forest ecosystem, we characterized the dominant species, major ecosystem drivers, and stressors from the relevant ecological literature. The panelists were asked to suggest modifications to the forest ecosystem descriptions, based on their experience and expertise in the assessment area, and those suggestions were incorporated into the descriptions.

POTENTIAL IMPACTS

To examine potential impacts, the panels were given several sources of background information on past and future climate change in the region (summarized in Chapters 3 and 4) and projected impacts on dominant tree species (summarized in Chapter 5). The panels were 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 panels assessed impacts by considering a range of climate futures bracketed by two scenarios: GFDL A1FI and PCM B1. Panelists were then led through a structured discussion process to consider this information for each forest ecosystem in the assessment area.

Potential impacts on ecosystem 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 ecosystem drivers in a way that would be more or less favorable for that forest ecosystem. Impacts on stressors were considered negative if they increased the influence of that stressor on the forest ecosystem or positive if they decreased the influence of that stressor on the forest ecosystem. Panelists were also asked to consider the potential for climate change to facilitate new stressors in the assessment area during the 21st 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 panels evaluated how much agreement existed among 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 ecosystem based on their ecological knowledge and management experience with the forest composition in the assessment area. Panelists were told to focus on ecosystem characteristics that would increase or decrease the adaptive capacity of that system. Factors that the panels considered included characteristics of dominant species within each ecosystem (for example, dispersal ability, genetic diversity, range limits) as well as comprehensive ecosystem characteristics (for example, 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 ecosystem 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 ecosystem to arrive at a vulnerability rating. Each participant was provided with a worksheet (Fig. 59) and asked to list which impacts they felt were most important to a forest ecosystem in addition to the major factors that would contribute to the adaptive capacity of that ecosystem.

Panelists were directed to mark their rating in two-dimensional space on the individual worksheet and on a large group poster (Fig. 60A). 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 forest ecosystem 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. 60B). 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 11 forest ecosystems considered in this assessment are displayed in Figures 61 through 71. 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 ecosystems were identified and developed into the vulnerability statements (boldface text) and supporting text in Chapter 6. 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 panels for review. Panelists were asked to review each statement for accuracy, whether the confidence determination should be raised or lowered, whether there was additional literature that was overlooked, and whether any additional statements 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.

Example Vulnerability Determination Worksheet

Name:____________________________ **Forest ecosystem:** ________________________

How familiar are you with this ecosystem? (circle one)

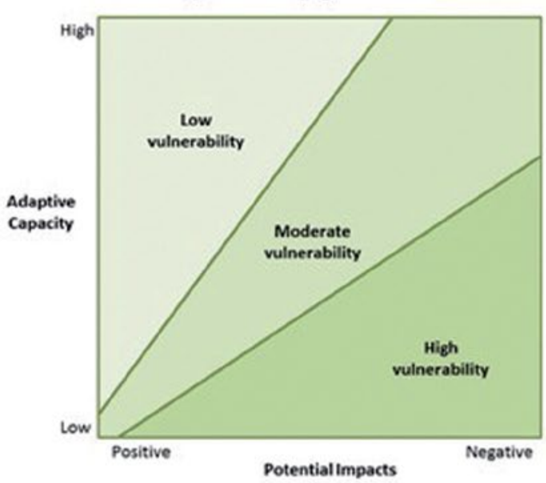
Low	Medium	High
I have some basic knowledge about this system and how it operates	I do some management or research in this system, or have read a lot about it.	I regularly do management or research in this system

What do you think are the greatest potential impacts to the ecosystem?

What factors do you think contribute most to the adaptive capacity of the ecosystem?

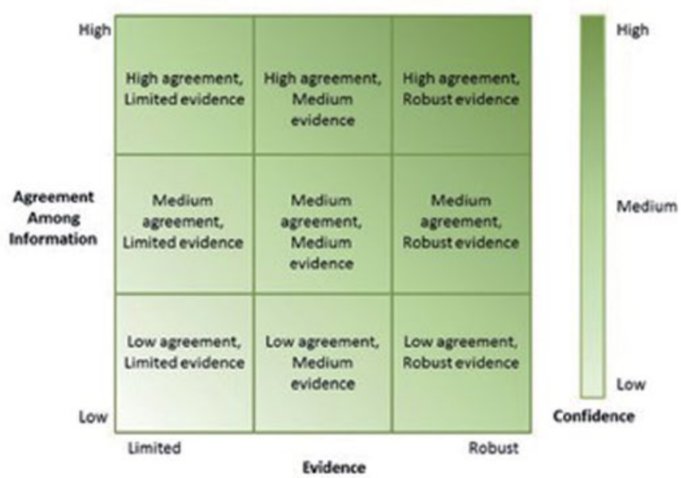
Vulnerability Determination

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



Confidence Rating

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



The ratings above are for the entire analysis area. Please note where you think potential impacts or adaptive capacity may vary substantially within the analysis area (e.g., forests in the eastern portion may be more prone to impact X).

Figure 59.—Worksheet used for vulnerability and confidence determination by expert panelists, based on Swanston and Janowiak (2016).

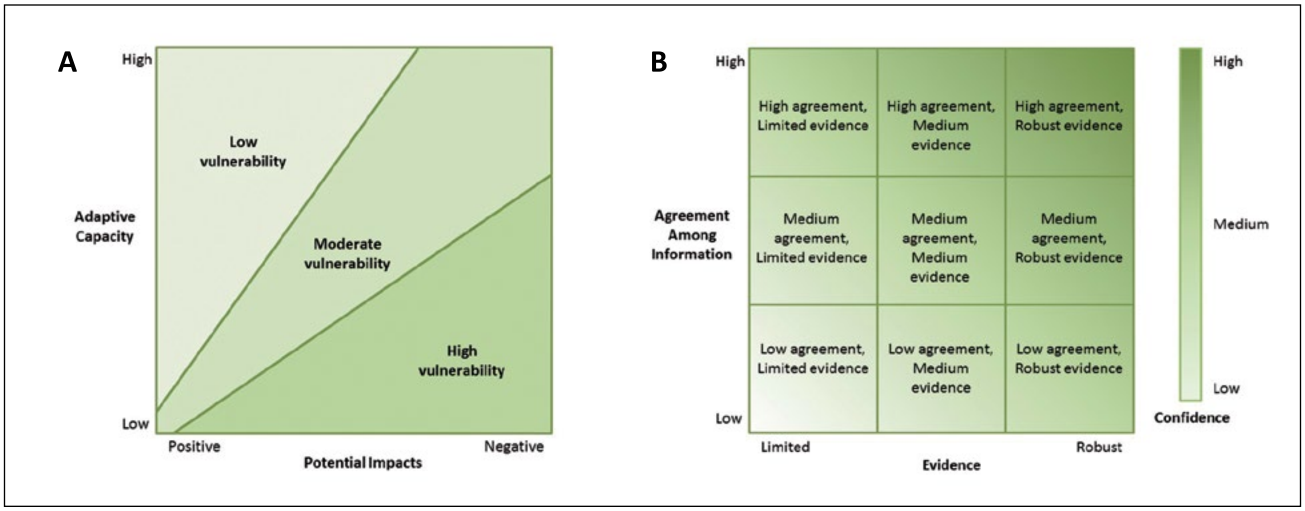


Figure 60.—Figure used for (A) vulnerability determination by expert panelists, based on Swanston and Janowiak (2016) and described by Brandt et al. (2017); and (B) confidence rating among expert panelists, adapted from Mastrandrea et al. (2010).

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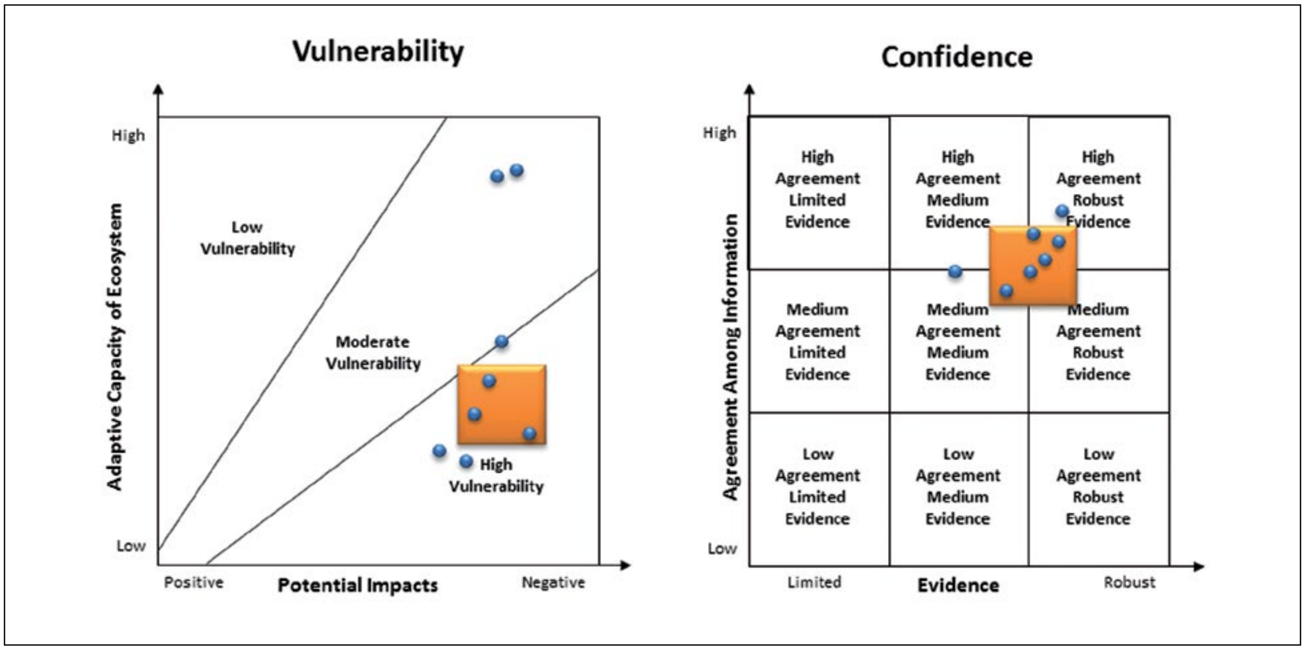

Figure 61.—Vulnerability and confidence determinations for the maritime forest (coastal plain) community. Circles indicate individual determinations by each panelist and squares indicate the group determination after consensus was reached.

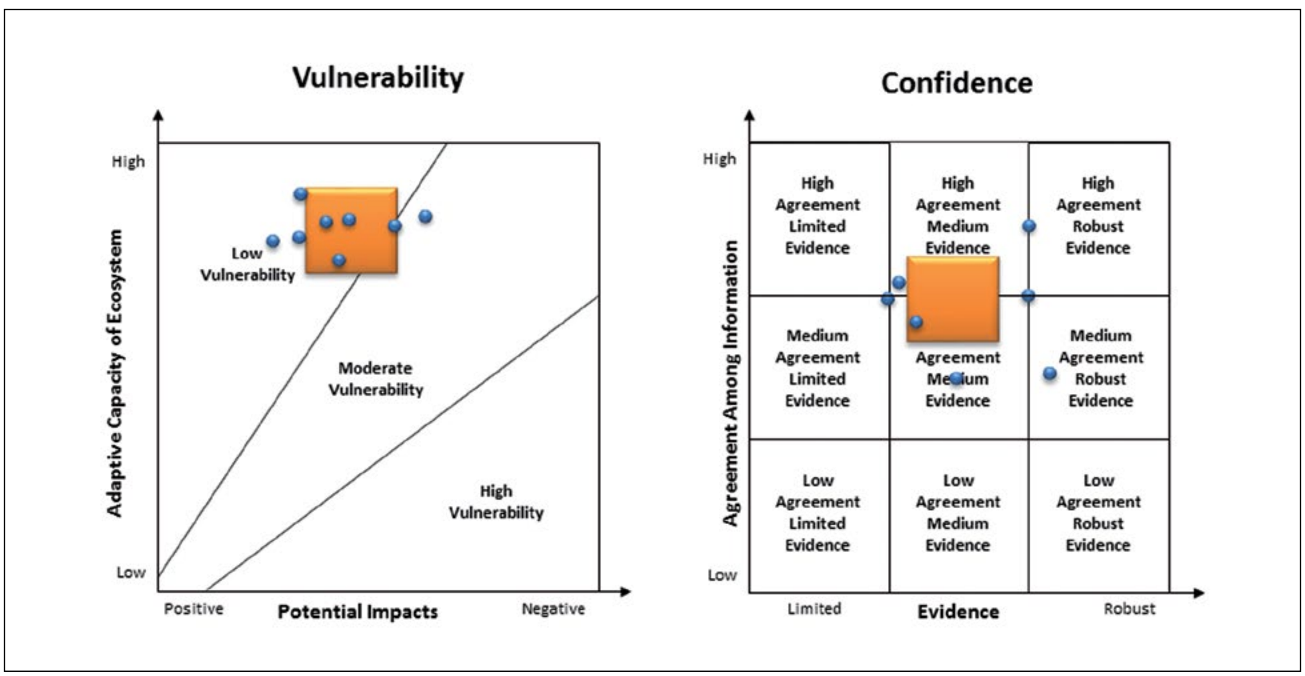

Figure 62.—Vulnerability and confidence determinations for the oak-pine-hardwood (coastal plain) forest community. Circles indicate individual determinations by each panelist and squares indicate the group determination after consensus was reached.

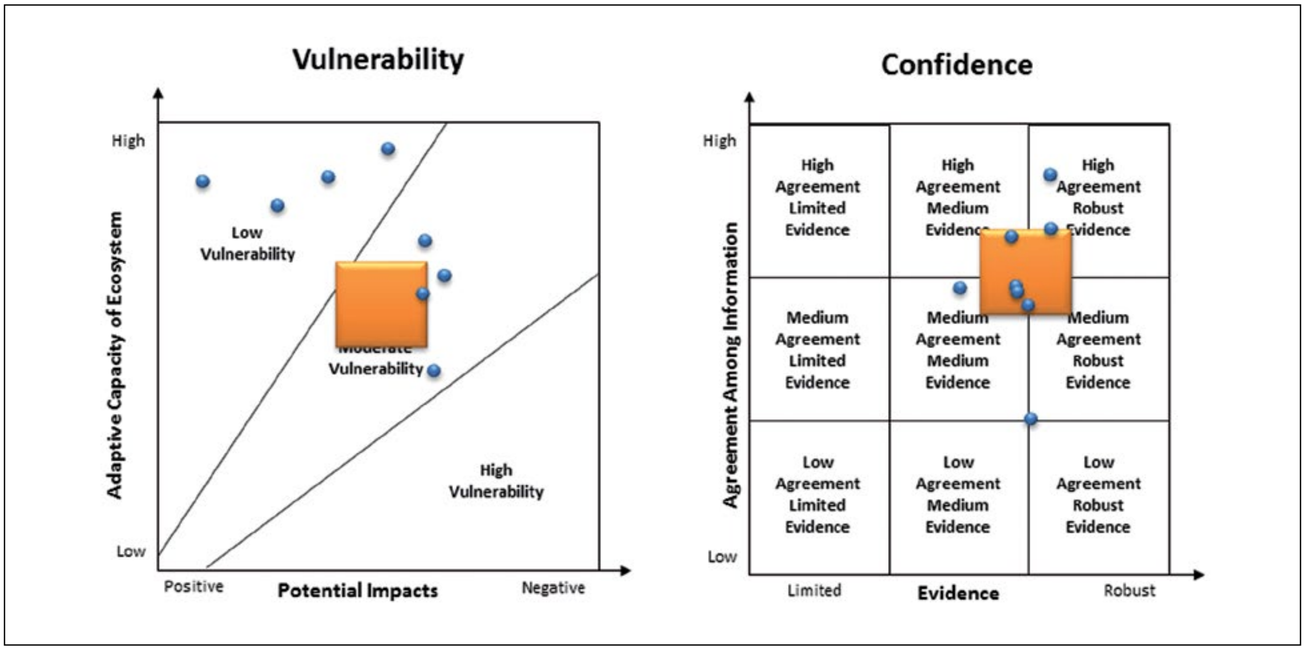

Figure 63.—Vulnerability and confidence determinations for the pine-oak barrens (coastal plain) forest community. Circles indicate individual determinations by each panelist and squares indicate the group determination after consensus was reached.

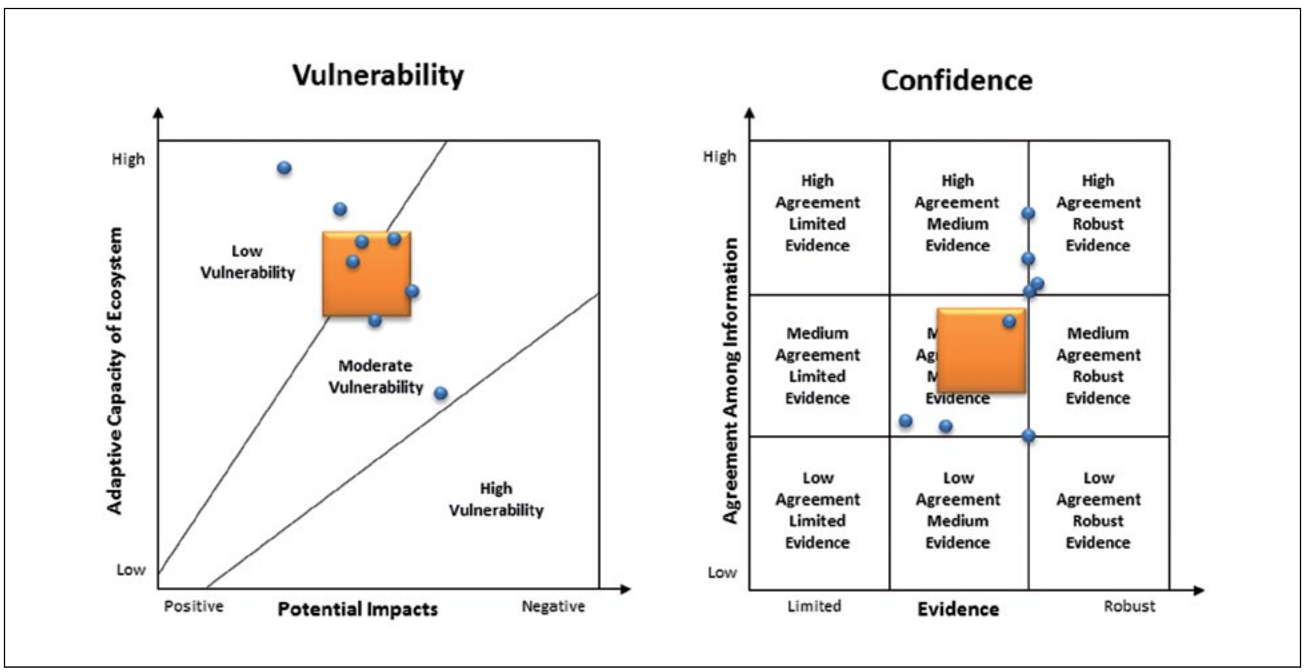

Figure 64.—Vulnerability and confidence determinations for the swamp (coastal plain) forest community. Circles indicate individual determinations by each panelist and squares indicate the group determination after consensus was reached.

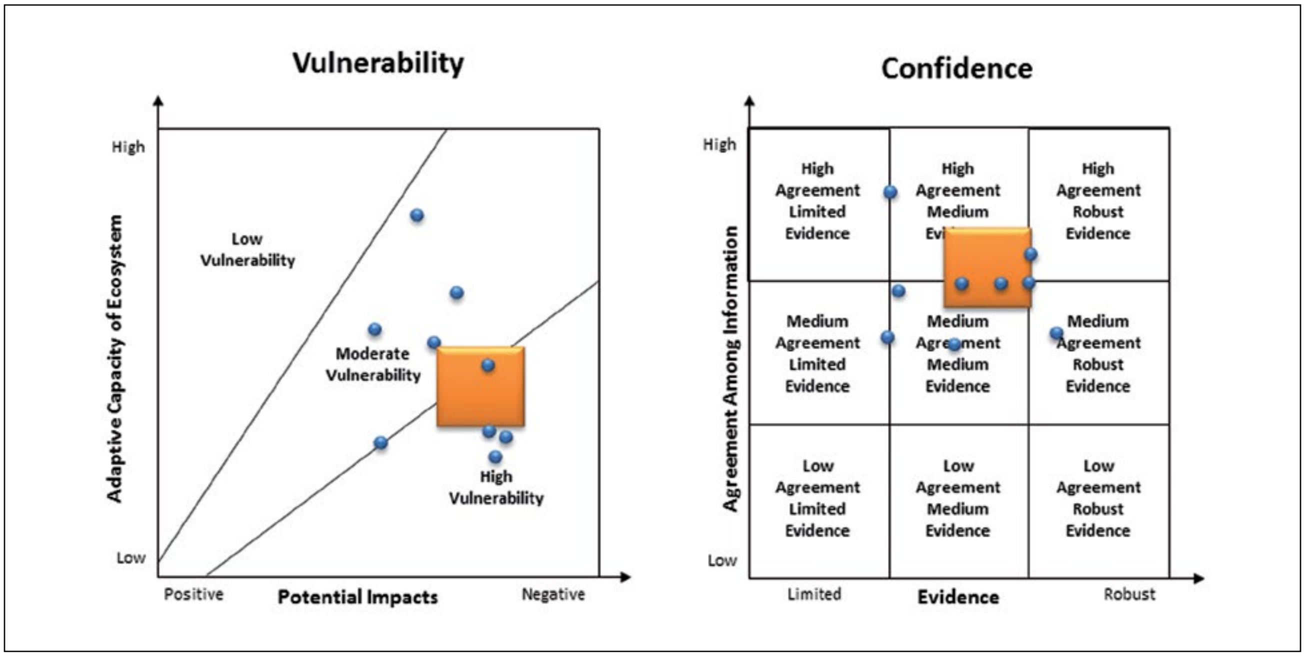

Figure 65.—Vulnerability and confidence determinations for the tidal swamp (coastal plain) forest community. Circles indicate individual determinations by each panelist and squares indicate the group determination after consensus was reached.

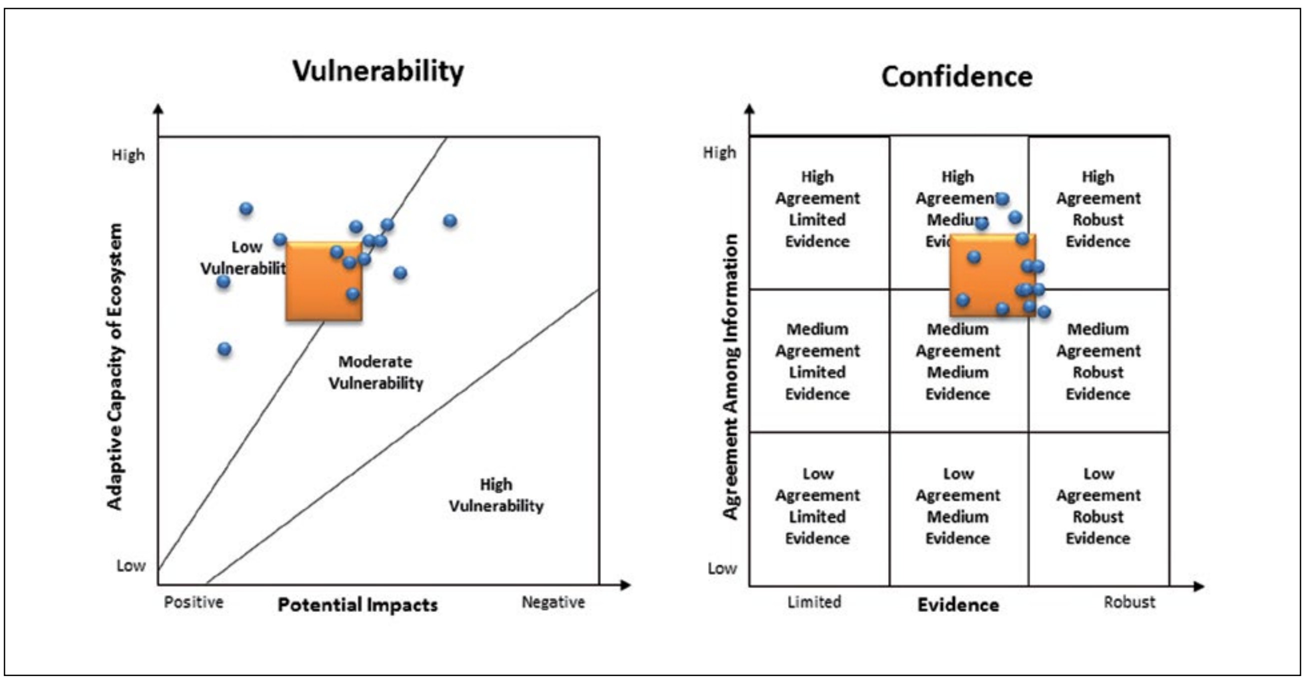

Figure 66.—Vulnerability and confidence determinations for the central oak-pine (interior) forest community. Circles indicate individual determinations by each panelist and squares indicate the group determination after consensus was reached.

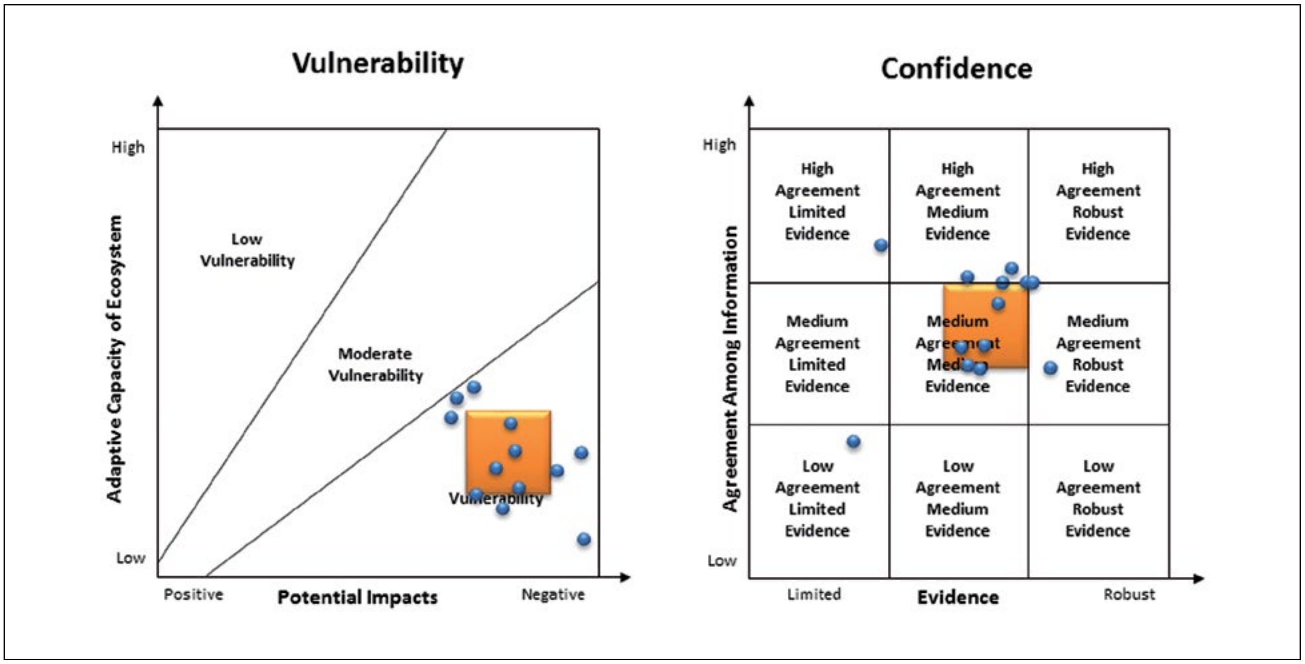

Figure 67.—Vulnerability and confidence determinations for the lowland conifer (interior) forest community. Circles indicate individual determinations by each panelist and squares indicate the group determination after consensus was reached.

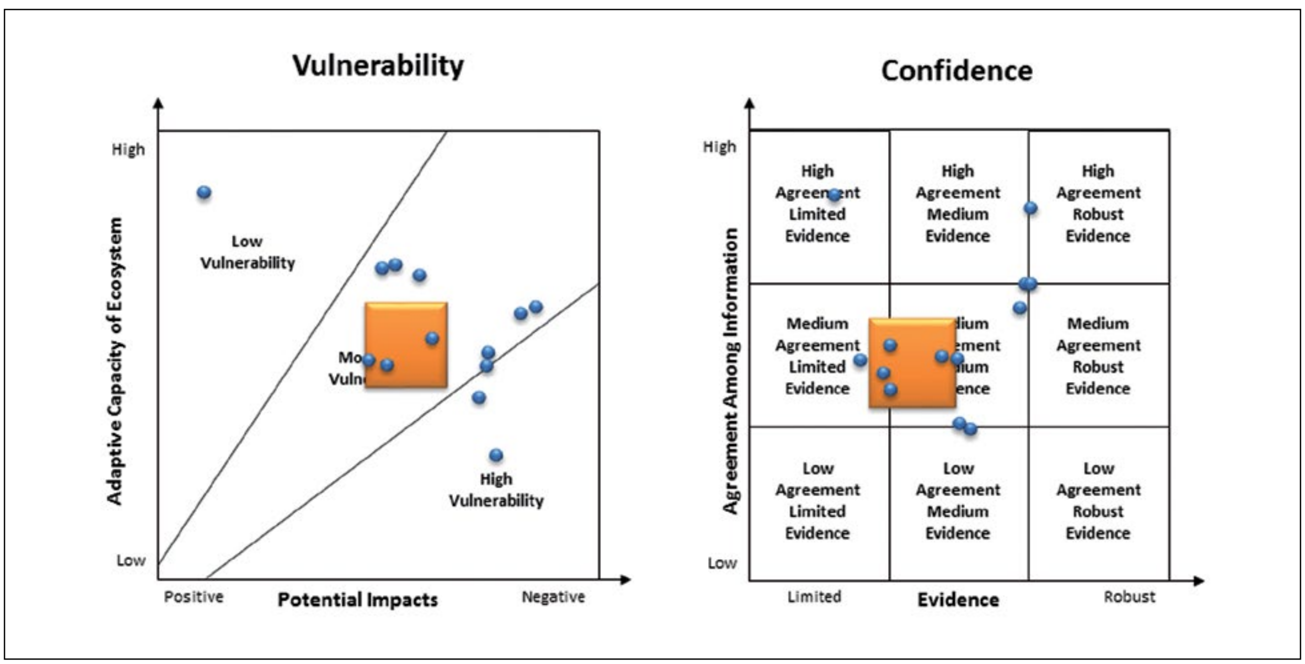

Figure 68.—Vulnerability and confidence determinations for the lowland and riparian hardwood (interior) forest community. Circles indicate individual determinations by each panelist and squares indicate the group determination after consensus was reached.

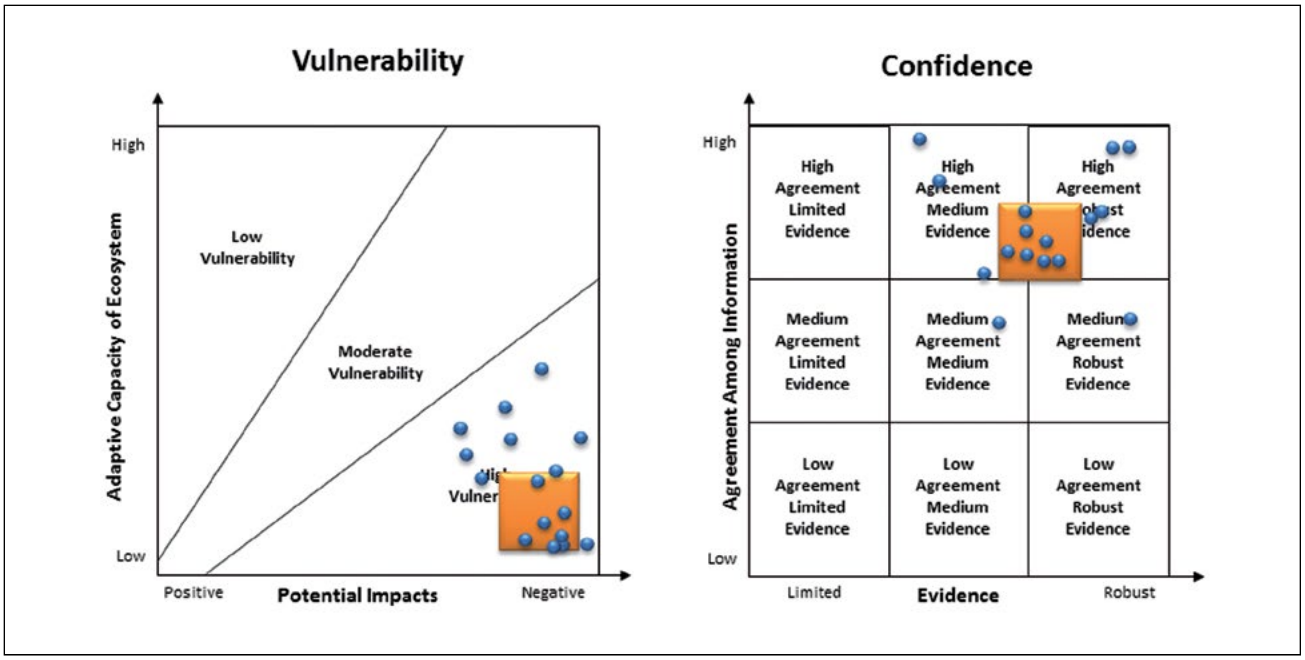

Figure 69.—Vulnerability and confidence determinations for the montane spruce-fir (interior) forest community. Circles indicate individual determinations by each panelist and squares indicate the group determination after consensus was reached.

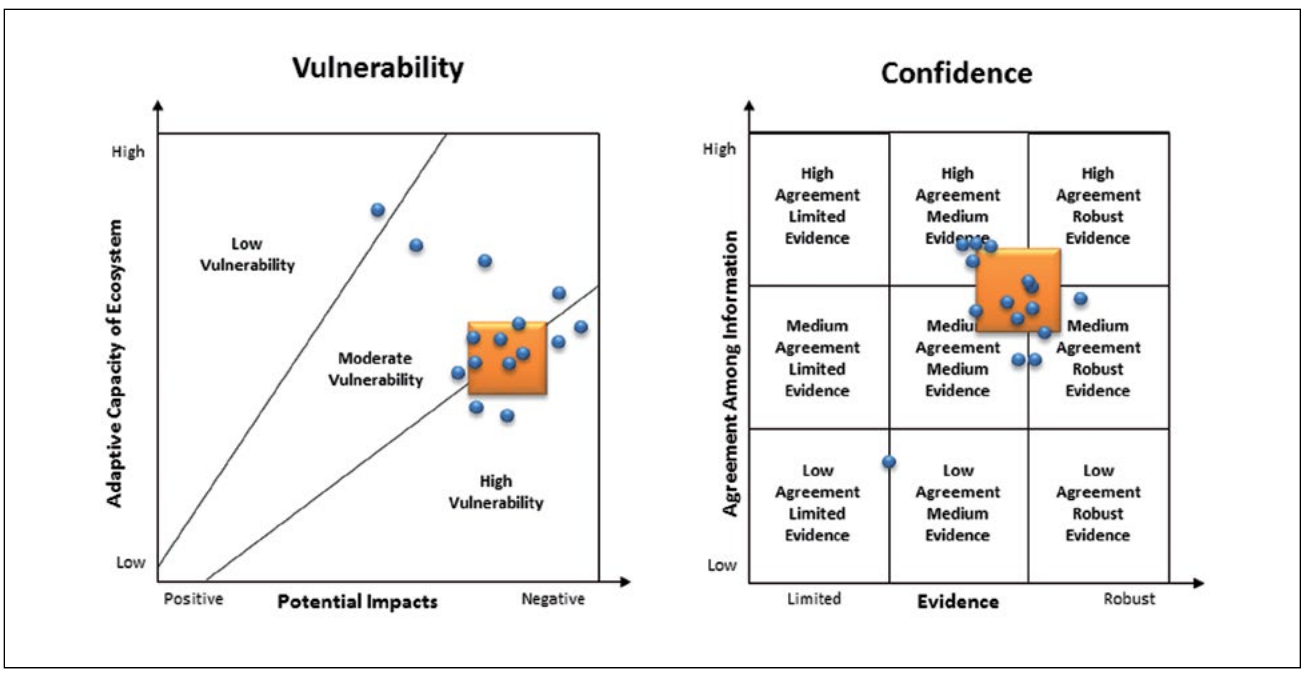

Figure 70.—Vulnerability and confidence determinations for the northern hardwood (interior) forest community. Circles indicate individual determinations by each panelist and squares indicate the group determination after consensus was reached.

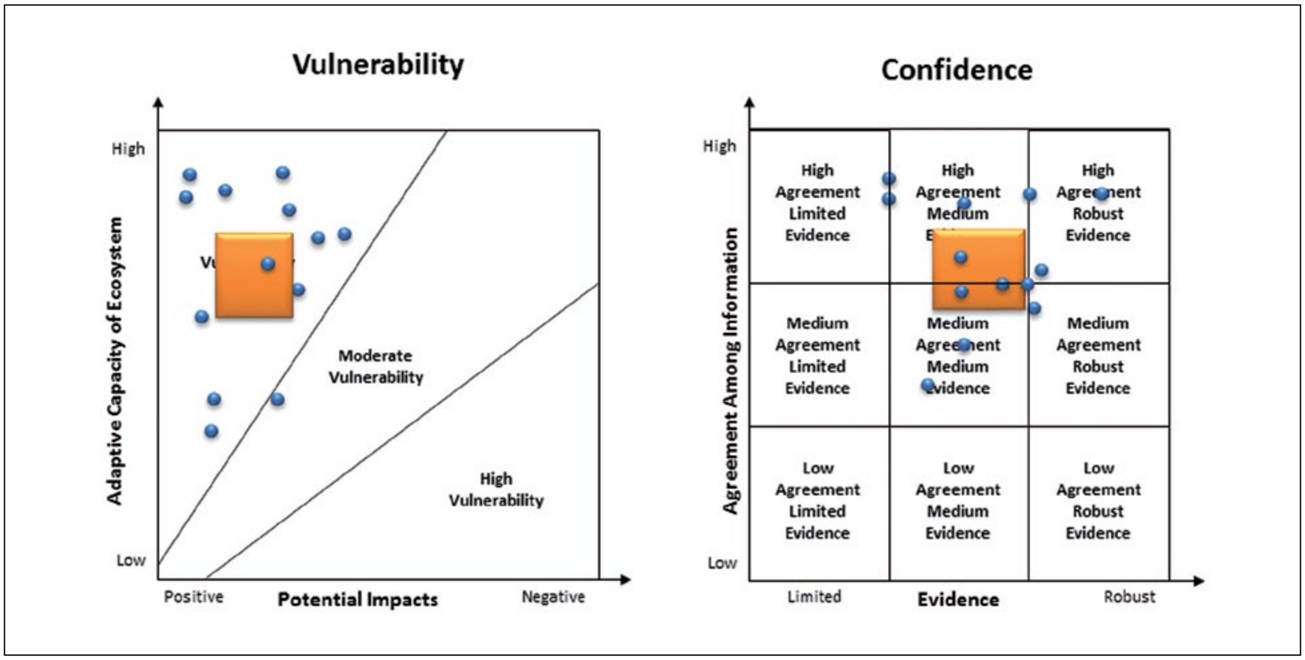

Figure 71.—Vulnerability and confidence determinations for the woodland, glade, and barrens (interior) forest community. Circles indicate individual determinations by each panelist and squares indicate the group determination after consensus was reached.

Butler-Leopold, Patricia R.; Iverson, Louis R.; Thompson, Frank R., III; Brandt, Leslie A.; Handler, Stephen D.; Janowiak, Maria K.; Shannon, P. Danielle; Swanston, Christopher W.; Bearer, Scott; Bryan, Alexander M.; Clark, Kenneth L.; Czarnecki, Greg; DeSenze, Philip; Dijak, William D.; Fraser, Jacob S.; Gugger, Paul F.; Hille, Andrea; Hynicka, Justin; Jantz, Claire A.; Kelly, Matthew C.; Krause, Katrina M.; La Puma, Inga Parker; Landau, Deborah; Lathrop, Richard G.; Leites, Laura P.; Madlinger, Evan; Matthews, Stephen N.; Ozbay, Gulnihal; Peters, Matthew P.; Prasad, Anantha; Schmit, David A.; Shephard, Collin; Shirer, Rebecca; Skowronski, Nicholas S.; Steele, Al; Stout, Susan; Thomas-Van Gundy, Melissa; Thompson, John; Turcotte, Richard M.; Weinstein, David A.; Yáñez, Alfonso. 2018. **Mid-Atlantic forest ecosystem vulnerability assessment and synthesis: a report from the Mid-Atlantic Climate Change Response Framework project.** Gen. Tech. Rep. NRS-181. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 294 p. https://doi.org/10.2737/NRS-GTR-181.

Forest ecosystems will be affected directly and indirectly by a changing climate over the 21st century. This assessment evaluates the vulnerability of 11 forest ecosystems in the Mid-Atlantic region (Pennsylvania, New Jersey, Delaware, eastern Maryland, and southern New York) 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 forest impact models, which provided a range of potential tree responses to climate. Finally, we brought these results before two multidisciplinary panels of scientists and land managers familiar with the forests of this region to assess ecosystem vulnerability through a formal consensus-based expert elicitation process.

Analysis of climate records indicates that average temperatures and total precipitation in the region have increased. Downscaled climate models project potential increases in temperature in every season, but vary in projections for precipitation. The forest impact models project declines in growth and suitable habitat for many mesic species, including American beech, eastern hemlock, eastern white pine, red spruce, and sugar maple. Species that tolerate hotter, drier conditions are projected to persist or increase, including black oak, northern red oak, pignut hickory, sweetgum, and white oak. The montane spruce-fir and lowland conifer forest communities were determined to be the most vulnerable ecosystems in the interior portion of the Mid-Atlantic region. Maritime and tidal swamp forest communities were determined to be the most vulnerable ecosystems in the coastal plain portion of the region. The woodland, glade, and barrens forest community was perceived as less vulnerable to projected changes in climate. These projected changes in climate and the associated impacts and vulnerabilities will have important implications for economically valuable timber species, forest-dependent 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, Delaware, Maryland, New Jersey, New York, Pennsylvania

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