10 Climate-Induced Migration of Native Tree Populations and Consequences for Forest Composition

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CONTENTS

The climate of the 13 Southern United States is generally thought to be changing in response to global and continental scale influences; and by 2060, average annual temperature is predicted to be higher and precipitation lower than for the year 2000, the date defined as current for the purposes of this analysis (Figure 10.1). Some southern forest species and communities may be highly vulnerable to the effects of changing climate, possibly resulting in conversion of woodland to savanna or grassland (Bosworth et al. 2008). In addition to the effects of temperature and precipitation on regeneration and growth, future forests will be affected by other factors contributing to climate change—such as carbon dioxide (CO_2) emissions resulting from economic and population growth—and to length of growing season, insect pollinators, plant demography, and other environmental influences not addressed here.

In this chapter "climate" is viewed as average annual temperature and precipitation, and "change" is the increase or decrease of those two variables from 2000 to 2060. In response to a changing climate in the Southern Region, the three objectives of this chapter are to: (1) assess vulnerability of major tree species; (2) evaluate risk to forest communities consisting of groups of species; and (3) briefly review silvicultural adaptation options available to managers and landowners. Our method used graphical displays of temperature and precipitation limits for individual tree species in the Southern Regions (Coastal Plain, Piedmont, Appalachian-Cumberland Highland, Mississippi

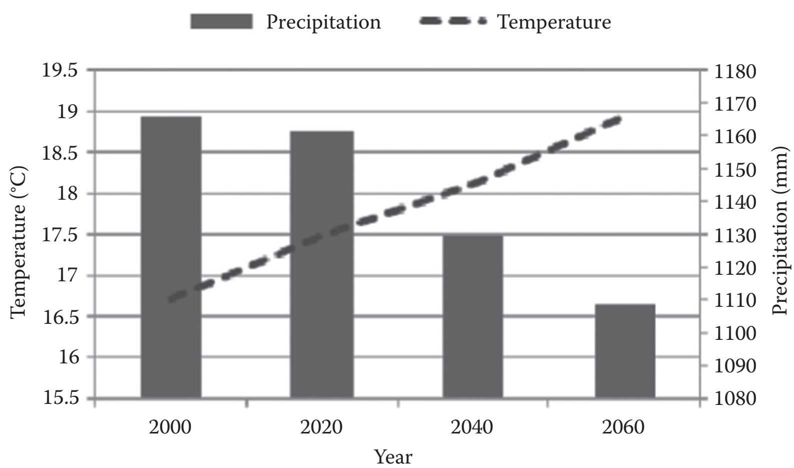

FIGURE 10.1 Average annual temperature and precipitation for the Southern Region from 2000 (current) and through 2060 (predicted).

Alluvial Valley, and Mid-South) (Burns and Honkala 1990), but we rely on spatial analysis of climatic data (Wear and Greis 2012).

This chapter, like others in this book, uses much of the framework described in Chapter 1 and outcomes of the Southern Forest Futures Project (SFFP, Wear and Greis 2012; Chapter 2). For example, climate models and production of CO_2 emissions based on economic projections are taken from the SFFP (Chapter 2). This chapter is organized around three major components:

- *Species vulnerability assessment*: Defined as the threat presented by future climate scenarios to the current distribution of selected upland tree species. Results are based almost entirely on future temperature and precipitation predictions generated by the SFFP (Chapter 2). Extensive graphic displays of current and possible future climates are presented for subdivisions of the major physiological provinces of the Southern Region.
- *Ecosystem risk analysis*: Defined as determining the probability that the climate scenarios will affect tree diversity (either negatively or positively) of ecosystems over time. Biodiversity will be quantified as species richness and defined as the number of tree species in an area of interest. This definition reduces the influence of individual species in ecosystems and considers only the total number reacting to climate change, which could include nonnative species. Biodiversity, or species richness, is largely a function of climate, soil, and disturbance, and has been used as an expression of ecosystem health (Kimmins 1997). Analysis of the effects of climate change on selected high-risk communities are presented in detailed case studies at the end of this chapter, which draw on either new research or available knowledge in the published literature combined with data from one or more climate scenarios.
- *Adaptation options*: Management techniques available to reduce vulnerability and risk for selected species and ecosystems. Mitigation is defined as the actions that address causes of climate change (namely, increasing CO_2 and other hydrocarbon gases such as methane), which is viewed primarily as the function of governments, achieved through policy and regulation, and therefore are beyond the scope of this chapter. This part of the vegetation chapter will reference and draw heavily on material presented in other chapters of the book.

Response of vegetation to climate change cannot be associated only with the stresses of changing temperature and precipitation. Other influences on vegetation include disturbances from insects, disease, and fire (Dale et al. 2001). Also, vegetation changes will affect wildlife habitat, water yields, recreational experiences, and demand for certain forest products; and will in turn be influenced by other environmental stresses and disturbances. The contents of this chapter, therefore, provide only a portion of the likely effects of climate change and should be considered with other chapters for a clearer evaluation of the overall future environment likely to be present in the ecologically diverse Southern Region.

Our approach to evaluating risk and vulnerability of vegetation to climate change will be based primarily on spatial analysis of climatic data across a range of scales. The broadest scale will be subregions of the Southern Region, which are large, ecologically similar areas that extend across several states. The smallest scale will be the individual counties within a state, which will be treated as sample units. A middle scale is sections, which are ecologically uniform areas of a dozen or more counties that nest within subregions.

This chapter can be used both as a stand-alone document and a source of information referenced by other chapters. As a stand-alone document, it presents the information that supports the assessment and analysis of climate change on vegetation and thereby facilitates presentation of information in a compact format without requiring the reader to consult other chapters. Vegetation information should be combined with that from other chapters, however, to provide a complete view of the effects of climate change on forests of the Southern Region that may occur over the next half century. The scope of information in this chapter is limited to trees because of their economic significance, their importance as a major component of wildlife habitat, and because more is known about the effects of climate on tree distribution than for shrubs and grasses. Also, this chapter should not be viewed as providing an exhaustive and detailed review of the literature on what is known about climate change on vegetation in the South; much of that type of information is provided in the SFFP (Wear and Greis 2012) and elsewhere in this book. Rather, this chapter uses a simple approach to assess vulnerability and risks to southern forests based on data from several climate scenarios that encompass a range of potential future environments for the Southern Region.

SOUTHERN FORESTS TODAY

Forests are the dominant vegetation on about 128 million ha in the 13 southern states, and comprise nearly 59% of a region where climate is particularly well suited for the occurrence of a large number of conifer and hardwood tree species (Conner and Hartsell 2002). The climate of much of the Southern Region is classified as humid subtropical, where a zone of hot, humid summers and mild-to-cool winters is controlled largely by maritime influences from the Atlantic Ocean and Gulf of Mexico (Bailey 1995). The average annual temperature throughout the Southern Region decreases from south to north and has a relatively narrow range, from 23.9°C in the Florida keys to 12.8°C in western Oklahoma. Annual precipitation averages about 127 cm throughout most of the region from Arkansas and Louisiana eastward, the exceptions being areas of mountainous topography, such as the escarpment of the Southern Appalachian Mountains where precipitation is higher. Annual precipitation decreases sharply from eastern Texas and Oklahoma westward, resulting in a near arid climate farthest west. In contrast, the Everglades of southern Florida represent a subtropical, hydric environment.

The Southern Region has diverse climates and vegetation. Except for drier parts of central and western Texas, most of the Southern Region consists of humid temperate climate dominated by forests of tall broadleaf deciduous hardwood and evergreen conifers (Bailey 1995), which are the focus of this chapter. Barbour and Billings (2000) list a number of hardwood and conifer forest types that have boundaries largely defined by climate.

Common Tree Species

From eastern Texas and Oklahoma to the Atlantic Ocean, forests are the potential natural vegetation cover of about 80% of the Southern Region. Currently, however, only 40% of this region is classified as forest land, which ranges from 10% in Texas to 70% in Alabama (Smith et al. 2004). Deciduous forests of the Southern Region are dominated mainly by upland hardwoods, particularly the oak–hickory (*Quercus* spp–*Carya* spp) type (Table 10.1). Except for small areas of pinyon–juniper (*Pinus edulis*–*Juniperus* spp) woodlands in central and western Texas and high-elevation spruce–fir (*Picea rubens*–*Abies fraseri*) in the Southern Appalachians, the conifer forest types consist almost entirely of southern pines: shortleaf (*Pinus echinata*), longleaf (*Pinus palustris*), loblolly (*Pinus taeda*), and slash (*Pinus elliottii*). Hardwood forests, both upland and lowland, are dominated by one or more species of oak and hickory, with minor amounts of other species including some conifers, such as cypress (*Taxodium* spp) and tupelo (*Nyssa* spp). Uncommon tree communities are associated with small areas of topography and soils that combine to produce unusual environmental conditions; for example, the sand pine (*Pinus clausa*) forests on the deep, excessively drained soils of central Florida. The sand pine forest is one example of an ecosystem [others include cedar glades of central Tennessee (Barbour and Billings 2000) and granite outcrops of Georgia] within the generalized southern pine forest cover type that may be vulnerable to a changing climate but were not included in our assessment. Possible effects of climate change on spruce–fir and other selected tree-dominated ecosystems and some key understory components—such as wiregrass (*Aristida stricta*)—will be described in more detail in case studies. Overall, however, southern forests are largely characterized by high species diversity and high productivity as a result of favorable current

TABLE 10.1
Extent of Major Forest Types in the Southern United States

Forest Type[a]	Area (million ha)	Percent
Oak–hickory	32.9	37.8
Loblolly–shortleaf pine	21.0	24.2
Oak–gum–cypress	12.4	14.3
Oak–pine	12.2	14.0
Longleaf–slash pine	5.6	6.5
Elm–ash–cottonwood	1.1	1.3
Other[b]	0.7	0.8
Maple–beech–birch	0.4	0.5
White–red–jack pine	0.3	0.4
Nonstocked	0.2	0.2
Spruce–fir	<0.1	<0.1
Total	86.9	100.0

Source: Adapted from Smith, W.B. et al. 2004. Forest resources of the United States: 2002. Gen. Tech. Rep. NC-241. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station. 137pp.

[a] Excludes 40,000 ha of nonforested lands, mostly in central and western Texas and Oklahoma.

[b] Includes pinyon–juniper woodlands in Texas and Oklahoma.

climatic conditions, but also due to fertility resulting from underlying geologic formations and various types of disturbance regimes. Ownership of forest land in the Southern Region is primarily by individuals (71%), followed by forest industry (17%), and government (12%) (reclassified from Smith et al. 2004).

Threats to Forest Health

As elsewhere in the United States, southern forests are facing threats from many sources, mainly from population growth, economic development, invasive species, diseases, and climate change (Wear and Greis 2012). Excluding environmental factors, the area covered by southern forests is projected to decline by 1.2 million ha between the years 1997 and 2050, largely in the vicinity of metropolitan areas in response to population growth and associated economic activities (Alig and Butler 2004). Climate change and environmental stresses can trigger interrelated health problems, such as nonnative plant invasions, increased wildfire risk, reduced prescribed burning, and insect and disease outbreaks—all of which directly result in rapid and large-scale changes in ecosystem function, structure, and productivity (Boisvenue and Running 2006).

The distribution of vegetation across a range of scales is strongly influenced by environmental factors. Climate clearly determines forest types at the upper scales, from continental to regional. At the lower scales of stand and site, moisture availability during the growing season affects species composition as well as productivity. Disturbance by fire is equally important for maintaining some vegetation types, such as the southern pines in general and longleaf pine in particular.

Temperature versus Precipitation Effects

The distribution of tree species across a range of geographic scales is limited primarily by temperature and precipitation and the integrated influences of relative humidity, potential evapotranspiration, and moisture deficits (Leininger 1998; Stephenson 1998; Whittaker 1975; Woodward 1987). Minimum annual average temperature typically limits the northern range of distribution of many species by affecting the growing degree days necessary for physiological processes, such as spring budburst, flowering, pollen production, and seed production (Karlsson 2002; Linkosalo et al. 2000). Recent evidence suggests species are rapidly expanding their northern ranges in response to warming climates (Chen et al. 2011; Woodall et al. 2009). In the Southern Region, the ranges of tree species are limited to the south by the Gulf of Mexico and to the west by availability of water during the growing season (Schmidtling 2001; Stephenson 1998). Favorable temperatures and availability of water during the growing season are critical to optimum tree growth (Leininger 1998). Detrimental physiological impacts can occur when the limits of temperature and precipitation are reached for a given tree species (Kozlowski et al. 1991). For instance, drought can result in disruption and blockage of water movement through xylem vessels (Sperry and Sullivan 1992). Water availability and temperature are probably the most important environmental factor affecting the geographic distribution and structure of vegetation (Chen et al. 2011; Woodall et al. 2009; Woodward 1987). Trees have lower limits of annual precipitation that determine their regional distribution, and these limits have been reported for many important U.S. species (Burnes and Honkala 1990).

Stress to trees under a changing climate can produce changes in survival and distribution. For instance, in work reviewed by Hansen et al. (2001) climate change resulted in a 32% reduction in loblolly-shortleaf pine habitat in the United States. In that same study it was predicted that shortleaf pine distribution would shift north and west while being replaced in its current zone by oak–pine habitat. Also, it was predicted that the area of oak–hickory forests would increase by 34% in the Eastern United States.

Drought during the frost-free season, whether induced by climate change or other mechanisms, is considered a major contributor to forest decline (Leininger 1998; Manion 1981). For example, a drought- induced oak decline event in Arkansas and Missouri from 2000 to 2005 affected up to 120,000 ha in the Ozark National Forest of Arkansas alone (Starkey et al. 2004). VanMantgem et al. (2009) attributed widespread increase of tree mortality in the Western United States to water deficit and regional warming. Many other recent drought-related tree mortality occurrences have taken place across the globe (Allen et al. 2010).

Other Associated Studies

Some studies have used a habitat approach to assessing the effects of climate change on vegetation, where altitude, aspect, soil characteristics, and other factors are considered in addition to climate. Schwartz et al. (2001) used habitat variables to predict the future distribution of tree species in Ohio under differing future climate scenarios. In an extensive study using multiple environmental variables that affect the range of many eastern tree species, Iverson et al. (2008) found that annual or seasonal precipitation and temperature are important factors, in combination with habitat variables (e.g., elevation, soil) associated with the current range of 134 tree species in the Eastern United States. Similar approaches to assess climate change effects on trees based on habitat modeling have been done in southern Africa (O'Brien 1988, 1993). Prediction equations with both habitat and climate can be used to approximate the future ranges of species, but the importance of climatic variables cannot be separated from the effects of soil and topography, or their interaction.

METHODS, MODELS, AND DATA SOURCES

As described in other chapters of this book and in the SFFP (Wear and Greis 2012), changes in the species composition of forests in the Southern Region are influenced primarily by components of climate, such as temperature, precipitation, and potential evapotranspiration. Other important factors include insects and disease, and subtle influences such as presence of insect pollinators and soil microfauna. Climate, however, is the principal factor addressed in this chapter.

Climate Predictions

We used three downscaled general circulation models described by the SFFP and summarized in detail in Chapter 2 (Wear and Greis 2012):

- *MIROC3.2*: Model for Interdisciplinary Research on Climate developed by the Center for Climate System Research at the University of Tokyo; includes essential components of ocean temperature models and dynamic thermodynamic sea-ice sheet models.
- *CSIROMK2 and MK3.5*: Models developed by the Commonwealth Scientific and Industrial Research Organization, the Australian national science agency.
- *HadCM3*: Model developed by the Hadley Centre for Climate Change, an organization established in England in 1990 to coordinate all climate change research.

Although more than 20 general circulation models are currently being evaluated as appropriate for predicting future global meteorological conditions (Jun et al. 2008), the rationale for selecting these three is presented by Wear and Greis (2012).

Two future socioeconomic scenarios affecting CO_2 emissions were used (Intergovernmental Panel on Climate Change 2007):

- *A1B*: representing low population/high economic growth and high-energy use.
- *B2*: representing moderate growth and low-energy use.

Land-use change is an important driver of future climates, particularly use resulting from food production, and is implicitly considered in the two storylines (Wear and Greis 2012).

The three general circulation models and two emissions scenarios were grouped into four outcomes (Table 10.2) used in this chapter to assess effects of climate change on vegetation in the Southern Region. The combinations of the three general circulation models and two economic possibilities for the year 2060 were selected to encompass the range of likely outcomes of climate change. For the 13 southern states, the four scenarios are variable in their predictions for future temperature and precipitation, but in general suggest a somewhat warmer (Figure 10.2) and slightly dryer climate (Figure 10.3). The four scenarios suggest greater variability in temperature than precipitation for the entire Southern Region. Evaluation of climate change based on the Southern Region as a whole is too broad a scale as evidenced by the existing variation of temperature and precipitation. Smaller ecological units are required to more fully evaluate the effects of climate change.

TABLE 10.2
The Principal Cornerstone Future Forecasts of General Climate Models Utilized by Southern Forest Futures Project[a]

	Population and Income Growth Rate[b]	
Timber Prices	**High**	**Low**
High	Cornerstone A (MIROC + A1B)	Cornerstone C (CSIROMK2 + B2)
Low	Cornestone B (CSIROMK3.5 + A1B)	Cornerstone D (HadCM3 + B2)

[a] Not shown are two cornerstones that are based on rates of replanting harvested lands.

[b] The three general circulation models (MIROC, CSIRO, Hadley) used in this subchapter are representative of many developed to predict possible changes in temperature and precipitation over time (Jun et al. 2008). Iverson et al. (2008), for example, based their species range projections for the Hadley and two other GCMs (Jun et al. 2008).

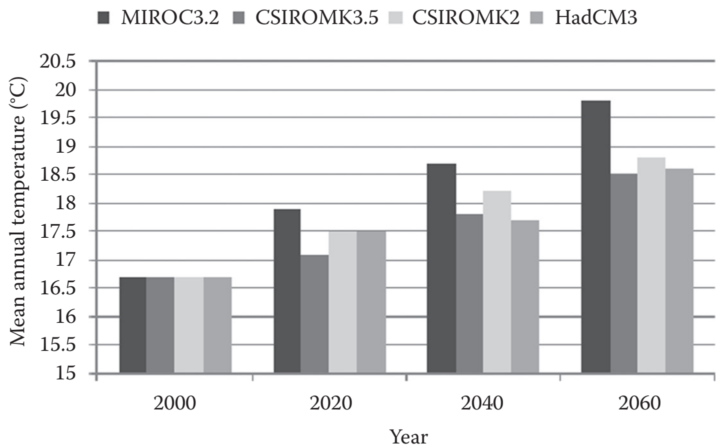

FIGURE 10.2 Average annual temperature 2000 (current) through 2060 (predicted) for four climate scenarios in the Southern United States (Wear et al. in press); scenarios were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high-energy use and B2 represents moderate population growth/low-energy use).

Climate change in the Southern Region was assessed in greater detail by downscaling to five ecological subregions (Figure 10.4). The largest subregion is the Mid-South, which includes much of Texas, Oklahoma, and Arkansas and accounts for about a third of the region, followed by the Coastal Plain and Piedmont, each of which occupies about a quarter of the region. The subregions, each of which represents a multi-state area of relatively uniform climate and vegetation, are based on ecoregionalization work by Cleland et al. (2007). For example, the Appalachian-Cumberland Highland is generally dominated by hardwoods, whereas the forests of the Coastal Plain are largely pines. The strongest connection of subregions with vegetation and climate change is in the Mid-South, where diminishing annual precipitation results in transition from closed canopy pine forests currently found in Arkansas and eastern Texas, to sparse oak woodlands and shrublands of central Texas and Oklahoma, and to grasslands farther west (Allred and Mitchell 1955).

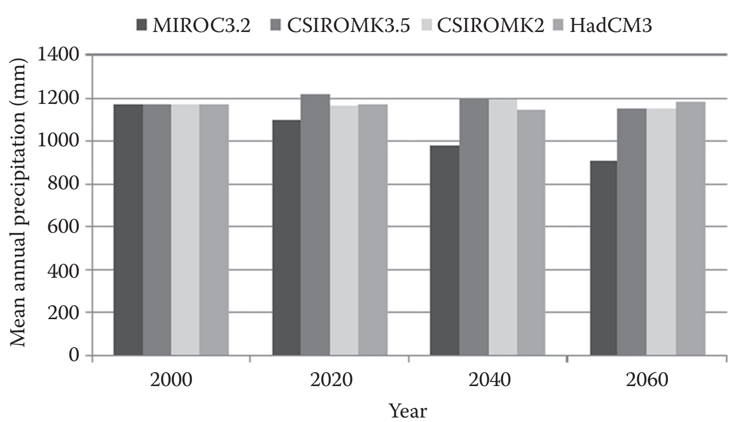

FIGURE 10.3 Average annual precipitation 2000 (current) through 2060 (predicted) for four climate scenarios for the Southern United States (Wear et al. in press); scenarios were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high-energy use and B2 represents moderate population growth/low-energy use).

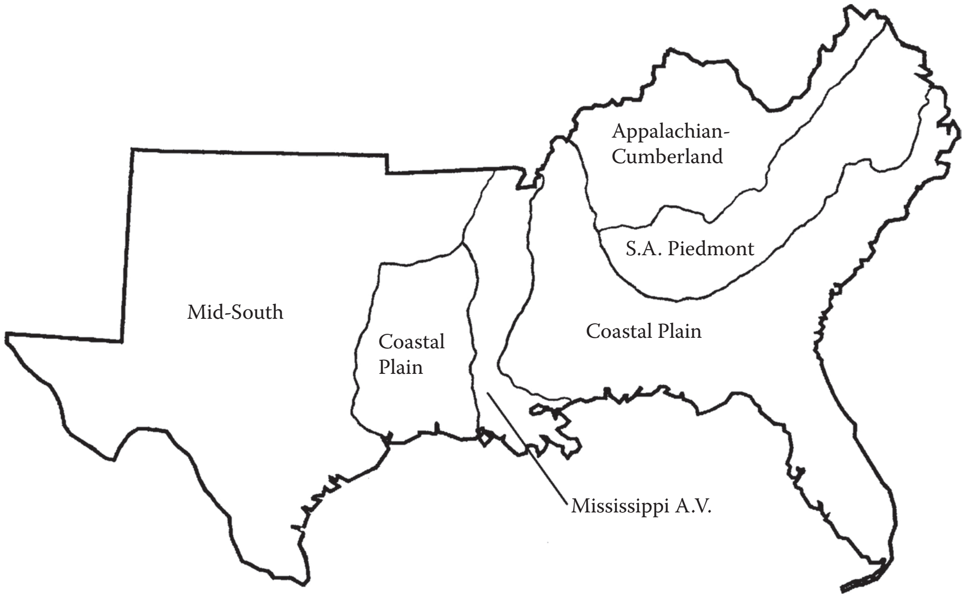

FIGURE 10.4 Subregions of the Southern United States delineated by the Southern Forest Futures Project. (Wear and Greis 2012) that represent areas of ecological similarity.

Temperature and precipitation predictions: Trends of climate change, manifested by variation of annual temperature and precipitation, are expected to be relatively uniform within subregions of the Southern Region when predictions of the four climate scenarios are averaged (Figures 10.5 and 10.6). From 2000 to 2060, temperature is predicted to increase by about 3°C and precipitation will decrease by an annual average of 100 mm. The most change in average annual precipitation is predicted to occur in the Mississippi Alluvial Valley and parts of the Mid-South; least change is expected in the Piedmont and Appalachian-Cumberland Highland.

Variations among models: Predictions by the individual scenarios suggest the potential for greater variability of temperature (Figure 10.7) and precipitation (Figure 10.8) across the Southern Region. The MIROC3.2 A1B scenario, for example, predicts the largest increase of temperature in the Mississippi Alluvial Valley by 2060 and smaller increases in the Coastal Plain and Mid-South.

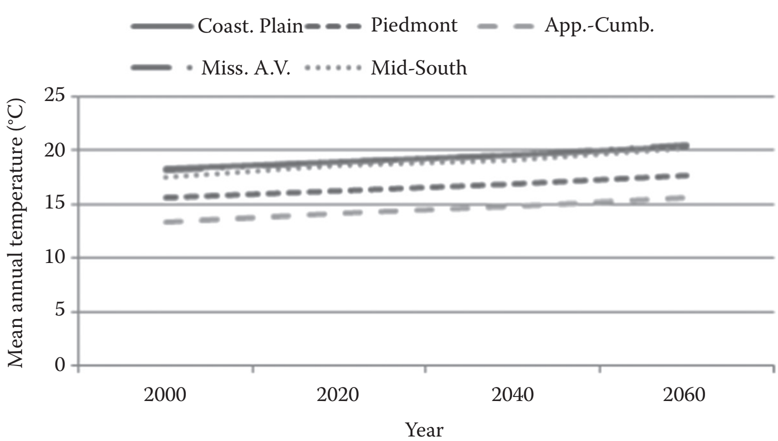

FIGURE 10.5 Average annual temperature from 2000 (current) to 2060 (predicted) for the five subregions of the Southern United States.

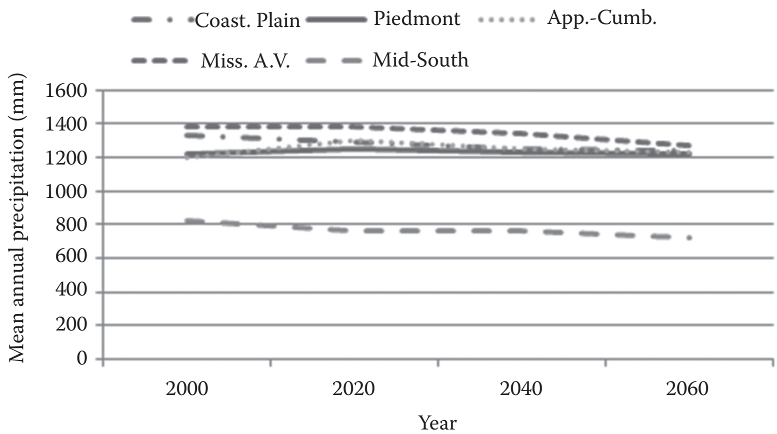

FIGURE 10.6 Average annual precipitation from 2000 (current) to 2060 (predicted) for the five subregions in the Southern United States.

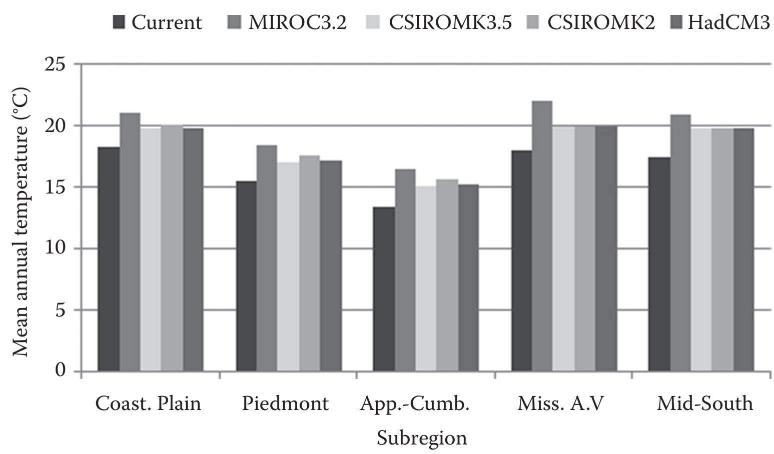

FIGURE 10.7 Average annual temperature currently (2000) and predicted through 2060 by the four climate scenarios for the five subregions of the Southern United States (Wear et al. in press); scenarios were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high energy use and B2 represents moderate population growth/low energy use).

Future precipitation predicted by the MIROC3.2 A1B scenario for these same three subregions, however, indicates similar decreases for the Mississippi Alluvial Valley and the Coastal Plain, with a smaller decrease for the Mid-South. Climate change forecasts by the other scenarios show similar patterns of variability among subregions, but with smaller differences in magnitude. Consistency of predictions among the four scenarios is problematic when used to assess the effects of climate changes with some degree of confidence because both the moisture and temperature budgets are important (and sometimes counteracting) influences on the composition and productivity of forests (Whittaker 1975; Woodward 1987).

Tree Species Distribution Effects

Predicting the effects of future temperature and precipitation on forest vegetation is only an approximation; models are lacking that directly associate the magnitude of environmental variables with

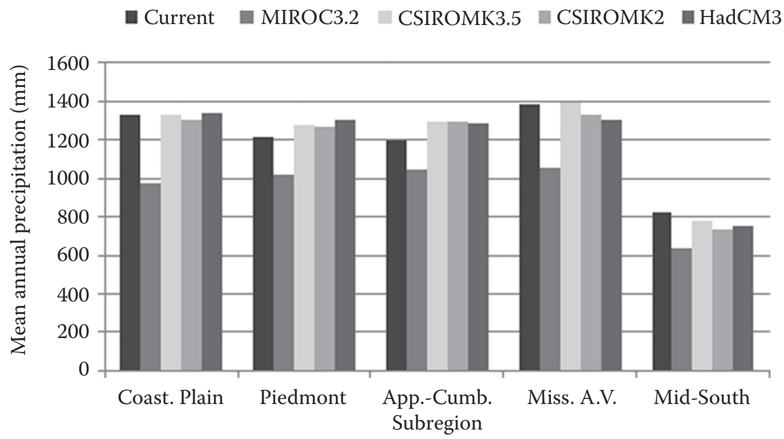

FIGURE 10.8 Average annual precipitation currently (2000) and predicted through 2060 by the four climate scenarios for the five subregions of the Southern United States (Wear et al. in press); scenarios were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high energy use and B2 represents moderate population growth/low energy use).

the reproduction and growth of plants. Although considerable knowledge is available on the species and community relationships with associated gradients of temperature and moisture at the stand level (Whittaker 1975) and for selected commercial species such loblolly pine (Nedlo et al. 2009), relatively few prediction models provide information that is relevant to most of the common forest tree species and that can be applied uniformly throughout the Southern Region. Simple correlation models that are available to evaluate the effects of climate change on vegetation are likely the most appropriate given the lack of agreement of future conditions forecasted by the scenarios (Agren et al. 1991; Hijmans and Graham 2006).

We evaluated vulnerability based on the range of distribution of tree species commonly occurring in each subregion of the Southern Region. Projecting the effects of future climate on plant distribution was based on the premise proposed by Woodward (1987) that the annual water budget (precipitation minus evapotranspiration) is a critical environmental climatic variable. We reduced complexity of the water budget approach by limiting our analysis to temperature and precipitation only; evapotranspiration was excluded because estimates of soil moisture storage and losses would be required, which was beyond the scope of our study. The northern limit of shortleaf pine, for example, is associated with a minimum annual temperature of about 10°C; its western range coincides with minimum annual precipitation of about 1020 mm (Burns and Honkala 1990). In a similar manner, they reported the minimum temperature and precipitation requirements for many common forest species in the Southern Region. We used temperature and precipitation recorded for 2000 and predicted for 2060 by each climate scenario to compare the current and potential future range of common tree species using the 1342 counties of the 13 southern states as unbiased sample units.

Our method of analysis is illustrated by examining the current occurrence of shortleaf pine in the Southern Region and its predicted occurrence for the four climate scenarios (Table 10.3). Shortleaf pine currently (2000) occurs in 1084, or 81%, of the 1342 counties in the 13 southern states. Under the four climate scenarios, the potential suitable environment for shortleaf pine ranges from 451 to 1070 counties. The most severe change could occur with the MIROC3.2 A1B scenario in the western part of the region where precipitation is predicted to be reduced, thereby increasing stress and likely resulting in a reduction in the range of shortleaf pine. Temperature, however, is forecasted to increase, which would allow a potential expansion of the northern limits of the species. Considering both climate factors simultaneously, however, suggests unlikely northern expansion of

TABLE 10.3
Current (2000) and Predicted (2060) Range of Shortleaf Pine in the Southern United States in Response to Four Climate Scenarios[a]

Climate Scenario	Shortleaf Pine Occurrence	Relative Occurrence
	Counties[b]	%
Current (2000)	1084	81
MIROC3.2 (2060)	451	34
CSIROMK3.5 (2060)	1070	80
CSIROMK2 (2060)	1042	78
HadCM3 (2060)	1045	78

Source: Adapted from Wear, D.N., R. Huggett, and J.G. Greis. In press. Constructing alternative futures. *Southern Forest Futures Project Technical Report.*

[a] Scenarios were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high-energy use and B2 represents moderate population growth/low-energy use).

[b] The 13 southern states are subdivided into 1342 counties.

its range with favorable temperature if precipitation is limited. The predicted effect on the range of shortleaf pine for the other three scenarios would be similar but much less severe, particularly for the CSIROMK3.5 A1B scenario.

Scope of assessment: A more complete assessment of potential climate change on forests of the Southern Region would need to include other tree species in the temperature and precipitation analysis, in addition to shortleaf pine. Burns and Honkala (1990) present information on the range of 63 native southern tree species that are associated with annual temperature and precipitation (Table 10.4), as well as several introduced species, such as tree of heaven (*Ailanthus altissima*). Some species—such as sourwood (*Oxydendrum arboreum*), downy serviceberry (*Amelanchier arborea*), and Chinese tallow tree (*Sapium sebiferum*)—are excluded from our analysis because generally recognized climatic limits associated with their ranges are not available.

Our method also excluded subtropical red mangrove (*Rhizophora mangle*) and other coastal species associated with normally hydric to subhydric habitats as well as species and communities of freshwater estuaries and floodplains of major river systems, such as bottomland hardwoods, bald cypress (*Taxodium distichum*), and tupelo swamps. These species and communities are expected to adjust their local distribution primarily in relation to changing sea levels and tidal influences and not resulting from changes in temperature and precipitation (see Chapter 13, Wear and Greis 2012).

Our vulnerability assessment, which uses a simplified measure of species' presence, was based on the assumption that a species will be present if the minimum precipitation threshold is met. As recognized earlier, this simplistic approach to assessing vulnerability of species to climate change has shortcomings, but appears appropriate considering the scope and information available for this assessment.

We recognize that other environmental components also influence the range of tree species, such as geologic parent material, disturbance, and soils (Fletcher and McDermott 1957), but temperature and moisture have the most important effect on distribution in the northern and western limits of tree ranges (Schmidtling 2001). Although we included both temperature and precipitation in our evaluations, we placed greater emphasis on the latter variable because its effects would likely be most apparent on survival, growth, and regeneration during the relatively short period of 60 years of our assessment. An unaccounted for source of variation in our simplified model of tree distribution is the effect of increased temperature on transpiration and evaporation (i.e., evapotranspiration) on availability of soil moisture, which could be more important than precipitation (McNulty et al.

TABLE 10.4
Average Annual Temperature (ºC) and Precipitation (mm) Associated with the Northern and Western Range Limits of Tree Species Occurring Throughout Each Subregion[a]

Species[b]	Annual Temperature (ºC)[c]	Annual Precipitation (mm)[d]	CP	P	AC	MAV	MS			
			All Sections	All Sections	All Sections	All Sections	Ozark-Ouachita	Cross Timbers	High Plains	West Texas
Gray oak	13	250								*
Lacey oak	15	250							*	
Mexican pinyon	4	250								*
Oneseed juniper	11	250							*	*
Plains cottonwood	0	250							*	
Tree of heaven[e]	0	360	*	*	*	*				
Eastern redcedar	4	380	*	*	*		*	*		
American elm	0	380	*	*	*	*				
Eastern cottonwood	0	380	*	*		*				
Bur oak	0	380					*	*		
Boxelder	0	380		*	*	*				
Green ash	0	380				*				
Blackjack oak	10	420	*	*	*		*	*		
Black willow	4	460	*	*	*	*				
Cedar elm	14	460						*		
Chinkapin oak	4	500		*	*		*	*		
Sugarberry	12	510	*	*		*				
Sugar maple	0	510			*		*			
Eastern redbud	7	510						*		
Silver maple	4	510		*	*	*				
Honeylocust	7	510		*	*	*				
Slippery elm	4	540		*	*	*				
American basswood	0	540			*		*			
Post oak	10	560	*	*	*		*	*		
Red maple	0	640	*	*	*	*	*			
Bitternut hickory	4	640	*		*		*	*		
Black walnut	7	640		*	*		*			
Black oak	7	760	*	*	*		*	*		
Flowering dogwood	7	760	*	*	*		*			
Sassafras	7	760	*	*	*	*	*			
White oak	4	760	*	*	*		*			
Pignut hickory	7	760	*	*	*		*			
American sycamore	7	760	*	*	*	*				
Yellow poplar	7	760	*	*	*					
Persimmon	10	760	*	*	*	*				
White ash	4	760		*	*		*			
American beech	4	760					*			
Northern red oak	4	760			*		*			
Shagbark hickory	4	760			*		*			
Scarlet oak	10	760		*	*					
Chestnut oak	10	810			*					
Mockernut hickory	10	880	*	*	*		*			
Cucumber tree	7	880			*		*			

continued

TABLE 10.4 (continued)
Average Annual Temperature (ºC) and Precipitation (mm) Associated with the Northern and Western Range Limits of Tree Species Occurring Throughout Each Subregion[a]

			CP	P	AC	MAV	MS			
Species[b]	Annual Temperature (ºC)[c]	Annual Precipitation (mm)[d]	All Sections	All Sections	All Sections	All Sections	Ozark-Ouachita	Cross Timbers	High Plains	West Texas
Virginia pine	10	880		*	*					
Black cherry	4	960	*	*	*		*			
Red mulberry	7	1010	*	*	*	*				
Winged elm	13	1010		*	*		*	*		
Sweetgum	10	1020	*	*	*	*	*			
Southern red oak	12	1020	*	*	*	*	*			
Loblolly pine	13	1020	*	*			*			
American holly	13	1020	*	*	*	*	*			
Water hickory	15	1020	*			*				
Black gum	7	1020	*	*	*	*		*		
Paulownia[e]	7	1020	*		*	*				
Red bay	16	1020	*							
Umbrella magnolia	12	1020					*			
Shortleaf pine	10	1020		*	*		*			
Black locust	10	1020			*					
Longleaf pine	16	1090	*							
Shumard's oak	10	1140	*	*	*			*		
Overcup oak	13	1140	*	*		*				
Sweet birch	7	1140			*					
Sweetbay	16	1220	*							
Laurel oak	16	1250	*							
Slash pine	17	1270	*							
Southern magnolia	18	1270	*							
Water oak	16	1270	*	*		*				

[a] Coastal plain (CP), Piedmont (P), Appalachian-Cumberland Highland (AC), Mississippi Alluvial Valley (MAV)—and sections within the Mid-South subregion (MS) of the Southern United States.
[b] Asterisk indicates that species within subregions and sections were evaluated for effects of climate change.
[c] Approximated for some species by comparing maps of their distribution with average annual temperature isolines.
[d] Species regional precipitation limit values are mostly from Burns and Honkala (1990) except for some species, such as blackjack oak and black gum, for which the precipitation limits were taken from the Natural Resource Conservation Service plants database at plants.usda.gov/characteristics.html.
[e] Nonnative species.

1998). Other limitations include competition by other species, soil fertility, mycorrhizal relationships, and interactions with the wildlife necessary for seed dispersal (Schwartz 1993). Confers and many hardwood species are wind pollinated but for some species, such as American basswood (*Tilia americana* var. *heterophylla*) and yellow poplar (*Liriodendron tulipifera*), climate change could affect occurrence of the necessary insect pollinators.

Despite our simple approach, we believe our methods are appropriate for several reasons: (1) lack of consensus on the accuracy of the GCMs for predicting future environmental conditions (especially for precipitation at finer spatial scales), (2) lack of available information on physiological response of forest species to variation of temperature and precipitation, and (3) our goal of making a broad scale assessment across a large region of how various tree species might be affected only by a changing climate. Although the four scenarios generally agree in forecasting warmer temperatures, which would allow for potential expansions of species ranges, there were considerable differences for predicted precipitation in some subregions, which would result in altered ranges for many species. An example of using regression to model the effects of temperature, precipitation, and potential evapotranspiration on the current and future ranges of a tree species is presented in a case study in this chapter.

Smaller, more detailed southern ecological units (subregions and sections) will be used to identify specific areas of potentially highest vulnerability and risk to trees that could result from a changing climate (Figure 10.9). With the exception of one subregion (Mid-South), a single group of endemic tree species occurring throughout was used for assessment of vulnerability to climate change within all of the included sections. In the large and climatically variable Mid-South subregion, where temperature and precipitation decrease markedly with increasing northerly latitude and westerly longitude, we used a separate group of species for each section to better account for the effects of climate change.

Other data sources: Our assessment also included additional plant communities or species for which we used different analyses. We included several uncommon or rare plant communities because these species are more vulnerable and inhabit the southernmost edge of their ranges or are isolated; an example is the island-like spruce–fir communities that are limited to a few peaks of the highest altitudes of the Southern Appalachians. Another example is *Eucalyptus grandis*, an introduced species from temperate to subtropical areas of Australia, which is being grown commercially for a range of products.

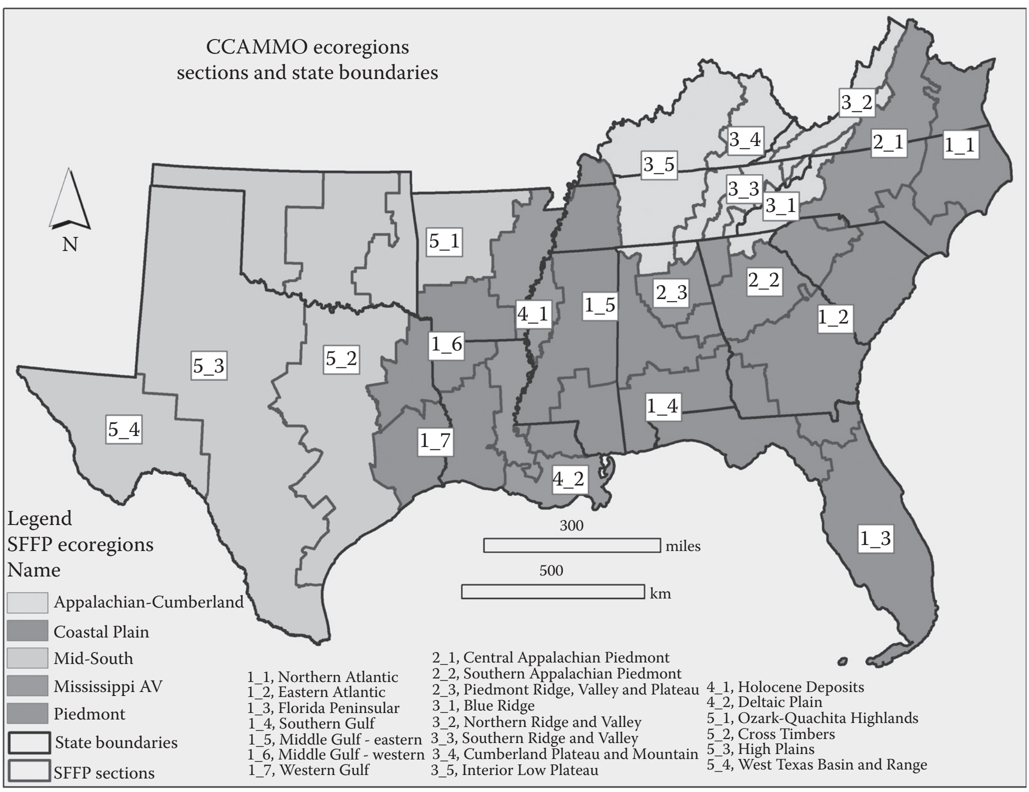

FIGURE 10.9 U.S. subregions (Cleland et al. 2007) and sections (Wear and Greis 2012) developed for the Southern Forest Futures Project (SFFP).

Our assessment of vulnerability of vegetation to climate change is based entirely on prediction of future temperature and precipitation by the four climate scenarios. Except for the study of climate on the regional productivity and distribution of an occasional commercial species (McNulty et al. 1998) and the habitat approach of Iverson et al. (2008), we found no references pertaining to both major and minor tree species throughout the Southern Region that included variables (temperature, precipitation) for use in assessment of the effects of climate. Using the four scenario predictions of future climate with simple spreadsheet-type models based on temperature and precipitation limits allowed us to analyze the Southern Region as a whole rather than drawing inferences from a patchwork of unrelated small studies with unknown ranges of applicability. Finally, our systematic, quantitative process of vulnerability assessment on individual species provided data for statistical analysis of risk to forest composition.

Forest Diversity Effects

Assessment of climate change on individual tree species may be beneficial for some forestry activities such as future conditions that might affect stand establishment and growth, environmental stress, insect problems, and other pine plantation management concerns. However, a more complete assessment of climate change on forests can be obtained by examining the group of species predicted to be present on a particular landscape. To accomplish this, we determined species richness for each climate scenario. Richness, defined as the number of species occurring per sample unit (county), is a measure of biological diversity represented by overlapping ranges of species. The value ranges from zero to the number of tree species that was used in the precipitation analysis. Richness included both native and nonnative species.

Species richness was analyzed to provide a basis for comparison of the four climate scenarios. The hypothesis tested was that predictions of future climate by each climate scenario result in no real difference in tree diversity between 2000 and 2060. We used the nonparametric paired Wilcoxon signed-rank test to account for likely violation of normality (Zar 1996). We selected a systematic sample of 50% of the total counties from the population within a subregion or section and applied a finite population correction (Zar 1996). Tests of significant differences were made at the $p < 0.05$ level.

Our assessment of vulnerability proceeds in geographic sequence of decreasing current temperature and precipitation, beginning with the humid eastern Coastal Plain, westward through the Piedmont, Appalachian-Cumberland Highland, Mississippi Alluvial Valley, and finally the xeric environment of the Mid-South of Texas and Oklahoma. Vulnerability analysis for two sections of the Mid-South, the High Plains and West Texas Basin and Range, was more limited than for subregions in other sections because only a few tree species are present throughout.

COASTAL PLAIN

The Coastal Plain occupies about 37% (801,081 km^2) of the southern region. Conifers are the characteristic forest type of the subregion with upland forests dominated by one or more species of southern yellow pines, particularly loblolly and formerly longleaf. Extensive areas of hardwoods are present along the floodplains of the major rivers. This subregion has been subdivided into seven sections: Northern Atlantic (9.1%), Eastern Atlantic (20.4%), Florida Peninsular (13.0%), Southern Gulf (18.8%), Middle Gulf-East (18.3%), Middle Gulf-West (10.6%), and Western Gulf (9.7%).

Climate Scenario Predictions

Temperatures in the Coastal Plain are predicted to increase from 2000 to 2060 based on an average of forecasts across the four climate scenarios (Figure 10.10). The rate of increase is approximately 0.5°C per decade for each of the seven sections. Annual temperature is highest in the Florida Peninsular section and lowest for the North Atlantic section. With the exception of the Middle

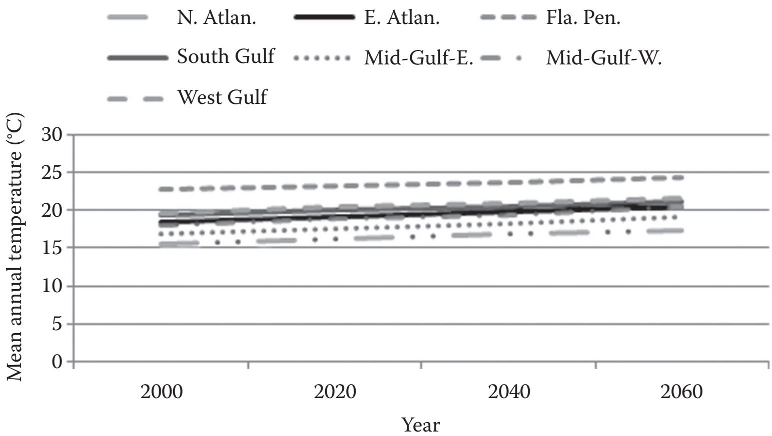

FIGURE 10.10 Average annual temperature from 2000 (current) to 2060 (predicted) for sections of the southern Coastal Plain; bidecadal temperatures for each section are the average of predictions from four climate scenarios (Wear et al. in press); that were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high-energy use and B2 represents moderate population growth/low-energy use).

Gulf-East, the sections are quite similar. For precipitation, the average of predictions from the climate scenarios indicates a long-term trend of decreasing amounts (Figure 10.11); again, the trend for the Middle Gulf-East section differs from the other sections—in this instance, an increase from 2000 to 2020, then a decrease to the 2000 level. An average of the four climate scenarios suggests a total temperature increase of about 3°C and a precipitation decrease of about 100 mm across all sections, although amounts vary for each climate scenario.

Three of the four scenarios forecast only slight changes in average annual precipitation from 2000 to 2060 for most sections of the Coastal Plain; only the MIROC3.2 A1B scenario predicts a large decrease across all sections. Future precipitation predictions by the other scenarios are

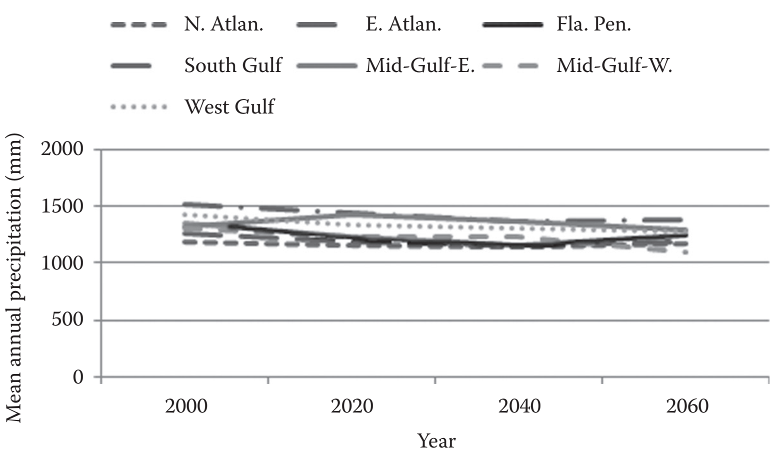

FIGURE 10.11 Average annual precipitation from 2000 (current) to 2060 (predicted) for sections of the southern Coastal Plain; bidecadal precipitation for each section represents the average of four climate scenarios (Wear et al. in press); that were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high-energy use and B2 represents moderate population growth/low-energy use).

variable among sections, ranging from similar amounts for the Middle Gulf-East section to somewhat variable amounts for the Western Gulf section. Comparison of predictions indicates the largest increase in precipitation for the CSIROMK3.5 A1B scenario and largest decrease in precipitation for the MIROC3.2 A1B scenario. The CSIROMK3.5 A1B scenario predicts a slight precipitation increase, by about 50 mm, in the Florida Peninsular and Middle Gulf-East and a decrease in the Southern Gulf and Middle Gulf-West sections. Overall, the climate of the Coastal Plain is predicted to become warmer and dryer by the year 2060.

Effects on Tree Species Distribution in Coastal Plain Sections

Thirty-seven tree species were used for assessment of the effects of precipitation on forests in the Coastal Plain (Table 10.4). Minimum limits for temperature and precipitationrequirements for native species ranged from 0°C and 380 mm for American elm (*Ulmus americana*) to 18°C and 1270 mm for southern magnolia (*Magnolia grandiflora*). Temperature and precipitation predicted by three of the climate scenarios is expected to be greater than the minimum requirements for all species. For the fourth, MIROC3.2 A1B, precipitation is expected to be slightly less than adequate for 10 species and much less for eight. Tree species with annual precipitation requirements greater than 950 mm, such as slash pine and water oak (*Q. nigra*), are predicted to decrease in areas of occurrence.

Effects of climate change on the occurrence of selected tree species in the Coastal Plain are likely to be highest in the Florida Peninsular section. In Lee and Lakeland Counties, for example, precipitation is predicted to be 400 mm less than the current level of 1700 mm. Temperature for those counties is predicted to decrease by an average of 1°C, which, when considered with reduced precipitation, will possibly affect several of the tree species that have the largest annual water requirements, such as sweetbay and water oak.

Northern Atlantic: Vulnerability of tree species to climate change in the Northern Atlantic section of the Coastal Plain is predicted to be highest under the MIROC3.2 A1B scenario, which would result in an average 23% decrease in the range of the 37 tree species (Table 10.5). An average 47% decline is predicted for 18 species, with the greatest decline (80%) for longleaf pine under the MIROC3.2 A1B scenario. An increase in range of eight species is predicted for two scenarios (CSIROMK2 B2 and HadCM3 B2). Little or no change of area of occurrence is predicted for 19 species. Overall, effects of climate change in the Northern Atlantic section of the Coastal Plain are predicted to be minimal because of minimal changes in annual temperature and precipitation.

Eastern Atlantic: Vulnerability of selected tree species to climate change in the Eastern Atlantic section of the Coastal Plain is predicted to be highest under the MIROC3.2 A1B scenario, which would result in an average 42% decrease in the range of the 37 tree species (Table 10.6). An average 81% reduction in area of occurrence is predicted for 19 species, including red mulberry (*Morus rubra*), southern red oak (*Q. falcata*), and loblolly pine, under the MIROC3.2 A1B scenario. An increase in range of seven species is predicted by the HadCM3 B2 scenario. Little or no change of area of occurrence is predicted for 18 species, including post oak (*Q. stellata*), red maple (*Acer rubrum*), and white oak (*Q. alba*). Overall, effects of climate change on species in the Eastern Atlantic section of the Coastal Plain are predicted to be moderate because of small-to-moderate changes in annual temperature and precipitation.

Florida Peninsular: Vulnerability of tree species to climate change in the Florida Peninsular section of the Coastal Plain is predicted to be highest under the MIROC3.2 A1B scenario, which would result in an average 66% decrease in the range of the 37 tree species (Table 10.7). An average 90% reduction in area of occurrence is predicted for 17 species, including sweetgum (*Liquidambar styraciflua*), loblolly pine, and water hickory (*Carya aquatica*), under the MIROC3.2 A1B scenario. A small increase in range of four species (laurel oak, slash pine, southern magnolia, and water oak) is predicted by the CSIROMK3.5 A1B scenario based on changes of annual temperature and precipitation. Little or no change of area of occurrence is predicted for 10 species including American elm, blackjack oak (*Q. marilandica*), and red maple. Overall, effects of climate change

TABLE 10.5
Predicted Change (%) in Area of Distribution of Selected Tree Species in the North Atlantic Section of the Coastal Plains from 2000 to 2060 in Response to Four Climate Scenarios[a]

	Species Area Change (%)			
Species[b]	**MIROC3.2**	**CSIROMK3.5**	**CSIROMK2**	**HadCM3**
Black cherry	−7.1	0.0	0.0	0.0
Red mulberry	−55.7	0.0	0.0	0.0
Sweetgum	−61.4	−1.4	0.0	0.0
Southern red oak	−61.4	−1.4	0.0	0.0
Loblolly pine	−61.4	−1.4	0.0	0.0
American holly	−61.4	−1.4	0.0	0.0
Water hickory	−61.4	−1.4	0.0	0.0
Black tupelo	−61.4	−1.4	0.0	0.0
Paulownia	−61.4	−1.4	0.0	0.0
Red bay	−61.4	−1.4	0.0	0.0
Longleaf pine	−80.0	4.3	7.1	8.6
Shumard's oak	−65.7	−14.3	22.9	25.7
Overcup oak	−65.7	−14.3	22.9	25.7
Sweetbay	−31.4	−11.4	14.3	21.4
Laurel oak	−15.7	0.0	24.3	25.7
Slash pine	−11.4	0.0	18.6	28.6
Southern magnolia	−11.4	0.0	18.6	28.6
Water oak	−11.4	0.0	18.6	28.6
Average[c]	−22.9	−1.3	4.0	5.2

Source: Adapted from Wear, D.N., R. Huggett, and J.G. Greis. In press. Constructing alternative futures. *Southern Forest Futures Project Technical Report.*

[a] Scenarios were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high-energy use and B2 represents moderate population growth/low-energy use).

[b] Species with no change in each of the four scenarios are not listed.

[c] Species with no change are included.

in the Florida Peninsular section are predicted to be severe because of increased temperature and reduction of annual precipitation.

Southern Gulf: Vulnerability of tree species to climate change in the Southern Gulf section of the Coastal Plain is predicted to be highest under the MIROC3.2 A1B scenario, which would result in an average 31% decrease in the range of the 37 tree species (Table 10.8). An average 58% reduction in area of occurrence is predicted for 19 species, with five species, including sweetbay, slash pine, and southern magnolia (*Magnolia grandiflora*) being extirpated under the MIROC3.2 A1B scenario. None of the scenarios predicts an increase in range of any species. Little or no change of area of occurrence is predicted for 18 species including eastern redcedar (*Juniperus virginiana*), sugarberry (*Celtis laevigata*), and black oak (*Q. velutina*). Overall, effects of climate change on tree species in the Southern Gulf section are predicted to be moderate because of small-to-medium reductions in annual temperature and precipitation.

Middle Gulf-East: Vulnerability of tree species to climate change in the Middle Gulf-East section of the Coastal Plain is predicted to be highest under the MIROC3.2 A1B scenario, which would result in an average 19% decrease in the range of the 37 tree species (Table 10.9). An average 41% reduction in area of occurrence is predicted for 17 species including overcup oak (*Q. lyrata*), Shumard's oak,

TABLE 10.6
Predicted Change (%) in Area of Distribution of Selected Tree Species in the Eastern Atlantic Section of the Coastal Plains from 2000 to 2060 in Response to Four Climate Scenarios[a]

	Species Area Change (%)			
Species[b]	**MIROC3.2**	**CSIROMK3.5**	**CSIROMK2**	**HadCM3**
Mockernut hickory	−55.4	0.0	0.0	0.0
Black cherry	−86.0	0.0	0.0	0.0
Red mulberry	−96.7	0.0	0.0	0.0
Sweetgum	−96.7	0.0	0.0	0.0
Southern red oak	−96.7	0.0	0.0	0.0
Loblolly pine	−96.7	0.0	0.0	0.0
American holly	−96.7	0.0	0.0	0.0
Water hickory	−96.7	0.0	0.0	0.0
Black tupelo	−96.7	0.0	0.0	0.0
Paulownia	−96.7	0.0	0.0	0.0
Red bay	−96.7	0.0	0.0	0.0
Longleaf pine	−97.5	0.0	0.0	0.0
Shumard's oak	−96.7	1.7	0.8	3.3
Overcup oak	−96.7	1.7	0.8	3.3
Sweetbay	−66.1	−2.5	−4.1	31.4
Laurel oak	−46.3	−2.5	1.7	34.7
Slash pine	−41.3	−4.1	−5.0	29.8
Southern magnolia	−41.3	−4.1	−5.0	29.8
Water oak	−41.3	−4.1	−5.0	29.8
Average[c]	−41.6	−0.4	−0.4	4.4

Source: Adapted from Wear, D.N., R. Huggett, and J.G. Greis. In press. Constructing alternative futures. *Southern Forest Futures Project Technical Report.*

[a] Scenarios were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high-energy use and B2 represents moderate population growth/low-energy use).

[b] Species with no change in each of the four scenarios are omitted.

[c] Species with no change are included.

and laurel oak (*Q. laurifolia*) under the MIROC3.2 A1B scenario. An increase in range of six species is predicted by the CSIROMK3.5 A1B and CSIROMK2 B2 scenarios. Little or no change of area of occurrence is predicted for 20 species including red maple, sweetbay (*Persea borbonia*), yellow poplar, and black oak. Overall, effects of climate change in the Middle Gulf-East section are predicted to be moderate primarily because of moderate reductions in annual precipitation.

Middle Gulf-West: Vulnerability of tree species to climate change in the Middle Gulf-West section of the Coastal Plain is predicted to be largest under the MIROC3.2 A1B scenario, which would result in an average 42% decrease in the range of the 37 tree species (Table 10.10). An average 82% reduction in area of occurrence is predicted for 19 species, including overcup oak, longleaf pine, Shumard's oak, sweetbay, and laurel oak under the MIROC3.2 A1B scenario. None of the climate scenarios predicts an increase in the range of tree species. Little or no change in area of occurrence is predicted for 18 species under any scenario, including sassafras (*Sassafras* spp), white oak, and persimmon (*Diospyros* spp). Overall, effects of climate change in the Middle Gulf-West section are predicted to be moderate-to-severe because of moderate reductions in annual precipitation.

TABLE 10.7
Predicted Change (%) in Area of Distribution of Selected Tree Species in the Florida Peninsular Section of the Coastal Plains from 2000 to 2060 in Response to Four Climate Scenarios[a]

	Species Area Change (%)			
Species[b]	MIROC3.2	A1B CSIRO	CSIROMK2	HadCM3
Black oak	−69.4	0.0	0.0	0.0
Flowering dogwood	−69.4	0.0	0.0	0.0
Sassafras	−69.4	0.0	0.0	0.0
White oak	−69.4	0.0	0.0	0.0
Pignut hickory	−69.4	0.0	0.0	0.0
American sycamore	−69.4	0.0	0.0	0.0
Yellow poplar	−69.4	0.0	0.0	0.0
Persimmon	−69.4	0.0	0.0	0.0
Mockernut hickory	−97.2	0.0	0.0	0.0
Black cherry	−100.0	0.0	0.0	0.0
Red mulberry	−100.0	0.0	0.0	0.0
Sweetgum	−100.0	0.0	0.0	0.0
Southern red oak	−100.0	0.0	0.0	0.0
Loblolly pine	−100.0	0.0	0.0	0.0
American holly	−100.0	0.0	0.0	0.0
Water hickory	−100.0	0.0	0.0	0.0
Black tupelo	−100.0	0.0	0.0	0.0
Paulownia	−100.0	0.0	0.0	0.0
Red bay	−100.0	0.0	0.0	0.0
Longleaf pine	−100.0	0.0	0.0	0.0
Shumard's oak	−100.0	0.0	0.0	0.0
Overcup oak	−100.0	0.0	0.0	0.0
Sweetbay	−100.0	0.0	0.0	0.0
Laurel oak	−97.2	2.8	−8.3	2.8
Slash pine	−94.4	5.6	−5.6	0.0
Southern magnolia	−94.4	5.6	−5.6	0.0
Water oak	−94.4	5.6	−5.6	0.0
Average[c]	−65.8	0.5	−0.7	0.1

Source: Adapted from Wear, D.N., R. Huggett, and J.G. Greis. In press. Constructing alternative futures. *Southern Forest Futures Project Technical Report.*

[a] Scenarios were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high-energy use and B2 represents moderate population growth/low-energy use).

[b] Species with no change in each of the four scenarios are not listed.

[c] Species with no change are included.

Western Gulf: Vulnerability of tree species to climate change in the Western Gulf section of the Coastal Plain is predicted to be highest under the MIROC3.2 A1B scenario, which would result in an average 32% decrease in the range of the 37 tree species (Table 10.11). An average 52% reduction in area of occurrence is predicted for 19 species including laurel oak, southern magnolia, and longleaf pine under the MIROC3.2 A1B scenario. None of the scenarios predicts an increase in range of the selected tree species. Little or no change in area of occurrence is predicted for 18 species including black willow (*Salix nigra*), white oak, Shumard's oak, overcup oak, and flowering dogwood

TABLE 10.8
Predicted Change (%) in Area of Distribution of Selected Tree Species in the Southern Gulf Section of the Coastal Plains from 2000 to 2060 in Response to Four Climate Scenarios[a]

	Species Area Change (%)			
Species[b]	**MIROC3.2**	**CSIROMK3.5**	**CSIROMK2**	**HadCM3**
Mockernut hickory	−5.9	0.0	0.0	0.0
Black cherry	−30.6	0.0	0.0	0.0
Red mulberry	−41.2	0.0	0.0	0.0
Sweetgum	−44.7	0.0	0.0	0.0
Southern red oak	−44.7	0.0	0.0	0.0
Loblolly pine	−44.7	0.0	0.0	0.0
American holly	−44.7	0.0	0.0	0.0
Water hickory	−44.7	0.0	0.0	0.0
Black tupelo	−44.7	0.0	0.0	0.0
Paulownia	−44.7	0.0	0.0	0.0
Red bay	−44.7	0.0	0.0	0.0
Longleaf pine	−58.8	0.0	0.0	0.0
Shumard’s oak	−77.6	0.0	0.0	0.0
Overcup oak	−77.6	0.0	0.0	0.0
Sweetbay	−100.0	−1.2	0.0	0.0
Laurel oak	−100.0	−3.5	−1.2	0.0
Slash pine	−100.0	−5.9	−4.7	0.0
Southern magnolia	−100.0	−5.9	−4.7	0.0
Water oak	−100.0	−5.9	−4.7	0.0
Average[c]	−31.1	−0.6	−0.4	0.0

Source: Adapted from Wear, D.N., R. Huggett, and J.G. Greis. In press. Constructing alternative futures. *Southern Forest Futures Project Technical Report.*

[a] Scenarios were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high-energy use and B2 represents moderate population growth/low-energy use).

[b] Species with no change in each of the four scenarios are not listed.

[c] Species with no change are included.

(*Cornus florida*) under any scenario. Overall, effects of climate change in the Western Gulf section are predicted to be moderate because of moderate reductions in annual precipitation.

Summary: Overall effects of future climate change will likely be variable among the seven sections of the Coastal Plain. The highest threats to forest tree species are predicted to occur in the Florida Peninsular, Southern Gulf, and Middle Gulf-West sections. The lowest threats are likely to occur in the Northern Atlantic and Middle Gulf-East sections. Tree species most vulnerable to climate change in the Coastal Plain could include slash pine, southern red oak, Shumard’s oak, and water oak. Among climate scenarios, the MIROC3.2 A1B scenario forecasts the highest threats to plants resulting from possible climate change by 2060; the lowest threats are associated with the CSIROMK2 B2 and HadCM3 B2 scenarios.

Forest Diversity Effects

Future diversity of forest tree species in the Coastal Plain is predicted to significantly decrease according to the MIROC3.2 A1B climate scenario (down from an average of 35.5 species currently

TABLE 10.9
Predicted Change (%) in Area of Distribution of Selected Tree Species in the Middle Gulf-East Section of the Coastal Plains Subregion from 2000 to 2060 in Response to Four Climate Scenarios[a]

	Species Area Change (%)			
Species[b]	**MIROC3.2**	**CSIROMK3.5**	**CSIROMK2**	**HadCM3**
Red mulberry	−2.0	0.0	0.0	0.0
Sweetgum	−5.9	0.0	0.0	0.0
Southern red oak	−5.9	0.0	0.0	0.0
Loblolly pine	−5.9	0.0	0.0	0.0
American holly	−5.9	0.0	0.0	0.0
Water hickory	−5.9	0.0	0.0	0.0
Black tupelo	−5.9	0.0	0.0	0.0
Paulownia	−5.9	0.0	0.0	0.0
Red bay	−5.9	0.0	0.0	0.0
Longleaf pine	−71.6	0.0	0.0	0.0
Shumard's oak	−71.6	0.0	0.0	0.0
Overcup oak	−96.1	1.0	1.0	1.0
Sweetbay	−88.2	9.8	11.8	3.9
Laurel oak	−85.3	11.8	14.7	−2.0
Slash pine	−76.5	16.7	16.7	0.0
Southern magnolia	−76.5	16.7	16.7	0.0
Water oak	−76.5	16.7	16.7	0.0
Average[c]	−18.7	2.0	2.1	0.1

Source: Adapted from Wear, D.N., R. Huggett, and J.G. Greis. In press. Constructing alternative futures. *Southern Forest Futures Project Technical Report.*

[a] Scenarios were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high-energy use and B2 represents moderate population growth/low-energy use).

[b] Species with no change in each of the four scenarios are not listed.

[c] Species with no change are included.

to 22.7 in the year 2060), and to fluctuate by section according to the other three scenarios (Table 10.12). The CSIROMK3.5 A1B and CSIROMK2 B2 scenarios predicted a significant decrease in tree species richness, but the B2HadCM3 B2 scenario predicted no change.

Coastal Plain section scale: Among the seven sections of the Coastal Plain, predicted richness is most variable for the MIROC3.2 A1B scenario, ranging from 11.3 to 28.7 species in 2060 (Table 10.12). Predictions of diversity by the other three scenarios were generally consistent and may increase slightly in some areas of the Coastal Plain, particularly in the Northern Atlantic and Middle Gulf-East sections. The highest risks to diversity were in the Middle Gulf-West section where all scenarios predicted significant declines from the current level of 35.7 species to between 20.5 and 30.1 species in the year 2060. In contrast, the other three scenarios predicted little or no overall changes in diversity.

County scale: Changes in tree species diversity at the county level in the Coastal Plain indicate that the largest declines would occur in the Middle Gulf-West section. In that section, average diversity across all climate scenarios could decrease by 10 species for Morris and Smith Counties in Texas. Large decreases could also occur for Osceola County and Glades County in Florida, the Florida Peninsular section, and San Jacinto County and Montgomery County in the Texas portion of the Western Gulf section. Diversity was predicted to increase in small areas of the Middle

TABLE 10.10
Predicted Change (%) in Area of Distribution of Selected Tree Species in the Middle Gulf-West Section of the Coastal Plains from 2000 to 2060 in Response to Four Climate Scenarios[a]

	Species Area Change (%)			
Species[b]	**MIROC3.2**	**CSIROMK3.5**	**CSIROMK2**	**HadCM3**
Mockernut hickory	−24.4	0.0	0.0	0.0
Black cherry	−55.6	0.0	0.0	0.0
Red mulberry	−80.0	0.0	−8.9	−6.7
Sweetgum	−88.9	0.0	−11.1	−6.7
Southern red oak	−88.9	0.0	−11.1	−6.7
Loblolly pine	−88.9	0.0	−11.1	−6.7
American holly	−88.9	0.0	−11.1	−6.7
Water hickory	−88.9	0.0	−11.1	−6.7
Black tupelo	−88.9	0.0	−11.1	−6.7
Paulownia	−88.9	0.0	−11.1	−6.7
Red bay	−88.9	0.0	−11.1	−6.7
Longleaf pine	−100.0	−11.1	−37.8	−20.0
Shumard's oak	−97.8	−31.1	−46.7	−37.8
Overcup oak	−97.8	−31.1	−46.7	−37.8
Sweetbay	−93.3	−60.0	−80.0	−68.9
Laurel oak	−86.7	−66.7	−84.4	−73.3
Slash pine	−71.1	−62.2	−71.1	−64.4
Southern magnolia	−71.1	−62.2	−71.1	−64.4
Water oak	−71.1	−62.2	−71.1	−64.4
Average[c]	−42.2	−10.5	−16.4	−13.3

Source: Adapted from Wear, D.N., R. Huggett, and J.G. Greis. In press. Constructing alternative futures. *Southern Forest Futures Project Technical Report.*

[a] Scenarios were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high-energy use and B2 represents moderate population growth/low-energy use).

[b] Species with no change in each of the four scenarios are not listed.

[c] Species with no change are included.

Gulf-East section, where species richness would be greater by 2-to-4 species for Marshall County and Calloway County in Kentucky. Diversity will also likely increase slightly, by several species, for Green County in North Carolina and Lexington County in South Carolina.

Overall, the MIROC3.2 A1B scenario consistently predicts decreased tree species diversity in 2060, but predictions by the other climate scenarios are variable, ranging from little or no change to small increases. Future diversity averaged across the four climate scenarios indicated a decrease throughout most of the Coastal Plain (Figure 10.12).

PIEDMONT

The Piedmont is a transition zone between the Coastal Plain and Appalachian-Cumberland Highland that occupies about 9% (197,155 km^2) of the Southern Region. This subregion was heavily disturbed by settlement during the 1800s, when much of the forest land was cleared for cotton production and subsistence agriculture. Forests are a mixture of loblolly pine and hardwoods on uplands, and hardwoods on floodplains of major rivers. The Piedmont is subdivided into three sections: Central

TABLE 10.11
Predicted Change (%) in Area of Distribution of Selected Tree Species in the Western Gulf Section of the Coastal Plains from 2000 to 2060 in Response to Four Climate Scenarios[a]

	Species Area Change (%)			
Species[b]	**MIROC3.2**	**CSIROMK3.5**	**CSIROMK2**	**HadCM3**
Mockernut hickory	−11.4	0.0	0.0	0.0
Black cherry	−31.4	0.0	0.0	0.0
Red mulberry	−42.9	0.0	0.0	0.0
Sweetgum	−45.7	0.0	0.0	0.0
Southern red oak	−45.7	0.0	0.0	0.0
Loblolly pine	−45.7	0.0	0.0	0.0
American holly	−45.7	0.0	0.0	0.0
Water hickory	−45.7	0.0	0.0	0.0
Black tupelo	−45.7	0.0	0.0	0.0
Paulownia	−45.7	0.0	0.0	0.0
Red bay	−45.7	0.0	0.0	0.0
Longleaf pine	−71.4	0.0	−2.9	−5.7
Shumard’s oak	−97.1	0.0	−8.6	−20.0
Overcup oak	−97.1	−2.9	−22.9	−31.4
Sweetbay	−94.3	0.0	−22.9	−34.3
Laurel oak	−94.3	0.0	−22.9	−34.3
Slash pine	−94.3	−5.7	−25.7	−34.3
Southern magnolia	−94.3	−5.7	−25.7	−34.3
Water oak	−94.3	−5.7	−25.7	−34.3
Average[c]	−32.1	−0.5	−4.2	−6.2

Source: Adapted from Wear, D.N., R. Huggett, and J.G. Greis. In press. Constructing alternative futures. *Southern Forest Futures Project Technical Report.*

[a] Scenarios were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high-energy use and B2 represents moderate population growth/low-energy use).

[b] Species with no change in each of the four scenarios are not listed.

[c] Species with no change are included.

Appalachian Piedmont (45.4%), Southern Appalachian Piedmont (38.5%), and Piedmont Ridge, Valley, and Plateau (16.2%).

Climate Scenario Predictions

The long-term trend of temperature in the Piedmont is predicted to increase from 2000 to 2060 based on averaged forecasts across the four climate scenarios (Figure 10.13). The rate of increase is approximately 0.2°C per decade for each of the three sections. Annual predicted change in temperature is highest in the Central Appalachian Piedmont section and lowest in the Central Appalachian Piedmont section. With the exception of the Central Appalachian Piedmont, changes in temperature among the sections are quite similar. For precipitation, the average prediction from the climate scenarios indicates a long-term trend of almost uniform amounts over time (Figure 10.14). The trend for the Piedmont Ridge, Valley, and Plateau section differs from the others in that precipitation there increases from the year 2000 to 2020 then returns to the 2000 level. An average of the four climate scenarios suggests a total temperature increase of about 3°C and precipitation remaining

TABLE 10.12
Forest Diversity, Expressed as Average Tree Species Richness (Standard Deviation) for Coastal Plain Sections from 2000 to 2060 Estimated by a Model Based on Predictions of Annual Precipitation from Four Climate Scenarios[a]

Section	Current Diversity	Future (2060) Diversity Predicted by Each Scenario			
		MIROC3.2	CSIROMK3.5	CSIROMK2	HadCM3
		N Tree Species (SD)			
Northern Atlantic	32.1 (2.2)	23.5 (4.7)[b]	31.8 (2.3)	33.5 (2.5)[b]	34.1 (2.5)[b]
Eastern Atlantic	34.2 (2.3)	19.1 (2.5)[b]	33.9 (2.2)	33.8 (2.2)	35.9 (1.8)[b]
Florida Peninsula	37.0 (0)	11.3 (3.1)[b]	37.0 (0)	36.6 (1.3)	36.8 (0.7)
Southern Gulf	37.0 (0)	25.2 (5.8)[b]	36.7 (1.1)	36.8 (0.9)	37.0 (0)
Mid Gulf—East	36.0 (1.9)	28.7 (2.5)[b]	36.8 (0.7)[b]	36.8 (0.7)[b]	36.0 (1.7)
Mid Gulf—West	35.7 (2.1)	20.5 (3.6)[b]	32.1 (2.3)[b]	29.6 (4.2)[b]	30.8 (4.0)[b]
Western Gulf	37.0 (0)	24.1 (5.7)[b]	36.6 (1.0)	35.0 (2.6)[b]	34.2 (3.2)[b]
Coastal Plains subregion	35.2 (2.4)	22.7 (6.1)[b]	34.9 (2.6)[b]	34.8 (3.0)[b]	35.3 (2.7)

Source: Adapted from Wear, D.N., R. Huggett, and J.G. Greis. In press. Constructing alternative futures. *Southern Forest Futures Project Technical Report.*

[a] Scenarios were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high-energy use and B2 represents moderate population growth/low-energy use).

[b] Indicates significant difference between current (2000) and future (2060) species richness at the $p = 0.05$ level of probability.

almost constant across all sections, although amounts vary among the climate scenarios. Based on warmer temperatures alone, the ranges of several species could expand, but a warmer temperature will increase moisture stress from potential evapotranspiration.

Three of the climate scenarios forecast only small changes in average annual precipitation from 2000 to 2060 for most sections of the Piedmont; only the MIROC3.2 A1B scenario predicts a large decrease across all sections. The trend of future precipitation by the other three scenarios is similar among the sections, with a small increase of about 50 mm above current amounts. The scenarios predict the smallest increase of future precipitation will occur in the Central Appalachian Piedmont section and the largest increase will be in the Piedmont Ridge and Valley section. Comparison of precipitation predictions among climate change models indicates the largest increase for the HadCM3 B2 scenario and largest decrease in precipitation for the MIROC3.2 A1B scenario. Overall, climate of the Appalachian Piedmont subregion in 2060 is predicted to be warmer and drier as a result of little change in precipitation and increased evapotranspiration.

Effects on Tree Species Distribution in the Piedmont Sections

Thirty-nine selected tree species were used for assessment of the effects of temperature and precipitation in 2060 on forests in the Piedmont (Table 10.4). The forecasted future temperatures exceeded the minimum limits for all species evaluated. Minimum precipitation requirements for native species ranged from 380 mm for boxelder (*Acer negundo*) to 1270 mm for water oak. Precipitation predicted for three of the scenarios is expected to be greater than the minimum requirements for all species except for water oak. For the fourth, MIROC3.2 A1B, precipitation is expected to be slightly less than adequate for eight species and much less for three. Tree species with annual precipitation requirements greater than 1020 mm, such as Shumard's oak and water oak, are regarded as vulnerable and their area of occurrence could decrease.

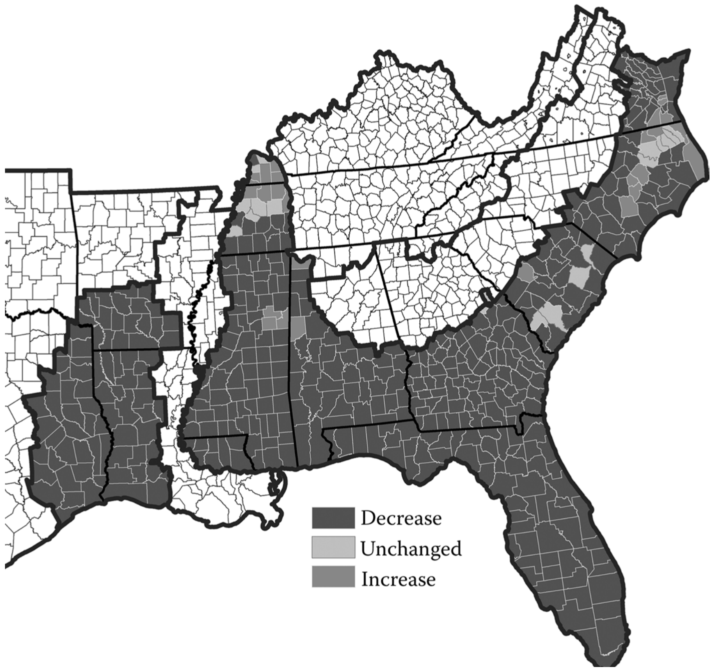

FIGURE 10.12 Future (2060) diversity (species richness) expressed as a percent of current (2000) diversity averaged across four climate scenarios for the southern Coastal Plain (Wear et al. in press) that were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high-energy use and B2 represents moderate population growth/low-energy use). Diversity is predicted to decrease in counties shaded dark gray (<97.5% of current), remain generally unchanged in counties shaded light gray (97.5 to 102.5% of current) and increase in counties shaded medium gray (>102.5% of current).

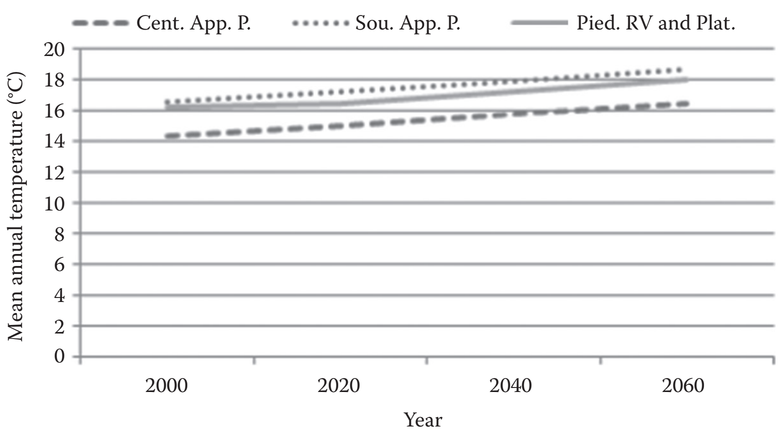

FIGURE 10.13 Average annual temperature from 2000 (current) to 2060 (predicted for sections of the southern Piedmont; temperature for each section represents the average of four climate scenarios (Wear et al. in press); that were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high-energy use and B2 represents moderate population growth/low-energy use).

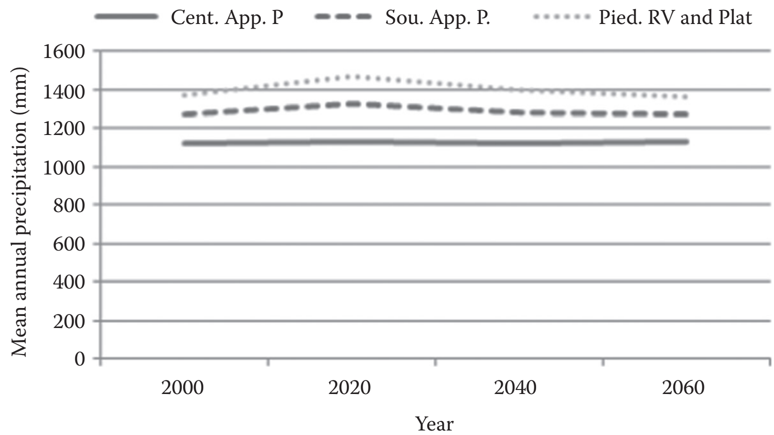

FIGURE 10.14 Average annual precipitation from 2000 (current) to 2060 (predicted) for sections of the southern Piedmont; precipitation for each section represents the average of four climate scenarios (Wear et al. in press); that were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high-energy use and B2 represents moderate population growth/low-energy use).

TABLE 10.13
Predicted Change (%) in Area of Distribution of Selected Tree Species in the Central Appalachian Piedmont Section of the Piedmont from 2000 to 2060 in Response to Four Climate Scenarios[a]

	Species Area Change (%)			
Species[b]	**MIROC3.2**	**CSIROMK3.5**	**CSIROMK2**	**HadCM3**
Black cherry	−37.5	0.0	0.0	0.0
Red mulberry	−83.0	2.3	0.0	0.0
Sweetgum	−83.0	3.4	3.4	3.4
Southern red oak	−83.0	3.4	3.4	3.4
Loblolly pine	−83.0	3.4	3.4	3.4
American holly	−83.0	3.4	3.4	3.4
Blackgum	−83.0	3.4	3.4	3.4
Shortleaf pine	−83.0	3.4	3.4	3.4
Winged elm	−83.0	3.4	3.4	3.4
Shumard's oak	−33.0	27.3	28.4	46.6
Overcup oak	−33.0	27.3	28.4	46.6
Water oak	−3.4	9.1	6.8	14.8
Average[c]	−19.8	2.3	2.2	3.4

Source: Adapted from Wear, D.N., R. Huggett, and J.G. Greis. In press. Constructing alternative futures. *Southern Forest Futures Project Technical Report.*

[a] Scenarios were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high-energy use and B2 represents moderate population growth/low-energy use).

[b] Species with no change in each of the four scenarios are not listed.

[c] Species with no change are included.

Central Appalachian Piedmont: Vulnerability of tree species to climate change in the Central Appalachian Piedmont section is predicted to be highest under the MIROC3.2 A1B scenario, which would result in an average 20% decrease in the range of the 39 tree species (Table 10.13). An average 64% reduction in area of occurrence is predicted for 12 species including sweetgum, southern red oak, and laurel oak under the MIROC3.2 A1B scenario. Three of the scenarios predict an increase in the occurrence of 10–11 species including southern red oak, black gum, and Shumard's oak. Overall, effects of climate change in the Central Appalachian Piedmont section of the Piedmont are predicted to be minor to moderate because of small increases in annual temperature and minimal reductions in annual precipitation.

Southern Appalachian Piedmont: Vulnerability of tree species to climate change in the Southern Appalachian Piedmont section is predicted to be highest under the MIROC3.2 A1B scenario, which would result in an average 17% decrease in the range of the 39 tree species (Table 10.14). An average 55% reduction in area of occurrence is predicted for 12 species including red mulberry, Shumard's oak, loblolly pine, and overcup oak under the MIROC3.2 A1B scenario. The other three climate scenarios predict an increase in the range of Shumard's oak, overcup oak, and water oak. Little or no change is predicted for the ranges of 27 species, including chinkapin oak (*A. Muehlenbergii*), red maple, and sassafras. Overall, the effects of climate change in the Southern Appalachian Piedmont section are predicted to be minor because of little or no changes in annual precipitation.

Piedmont Ridge, Valley, and Plateau: Vulnerability of tree species to climate change in the Piedmont Ridge, Valley, and Plateau section is predicted to be highest under the MIROC3.2 A1B scenario, which would result in an average 6% decrease in the range of the 39 tree species (Table 10.15).

TABLE 10.14
Predicted Change (%) in Area of Distribution of Selected Tree Species in the Southern Appalachian Piedmont Section of the Piedmont from 2000 to 2060 in Response to Four Climate Scenarios[a]

	Species Area Change (%)			
Species[b]	**MIROC3.2**	**CSIROMK3.5**	**CSIROMK2**	**HadCM3**
Black cherry	−27.3	0.0	0.0	0.0
Red mulberry	−50.6	0.0	0.0	0.0
Sweetgum	−54.5	0.0	0.0	0.0
Southern red oak	−54.5	0.0	0.0	0.0
Loblolly pine	−54.5	0.0	0.0	0.0
American holly	−54.5	0.0	0.0	0.0
Black tupelo	−54.5	0.0	0.0	0.0
Shortleaf pine	−54.5	0.0	0.0	0.0
Winged elm	−54.5	0.0	0.0	0.0
Shumard's oak	−79.2	6.5	6.5	6.5
Overcup oak	−79.2	6.5	6.5	6.5
Water oak	−41.6	15.6	11.7	44.2
Average[c]	−16.9	0.7	0.6	1.5

Source: Adapted from Wear, D.N., R. Huggett, and J.G. Greis. In press. Constructing alternative futures. *Southern Forest Futures Project Technical Report.*

[a] Scenarios were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high-energy use and B2 represents moderate population growth/low-energy use).

[b] Species with no change in each of the four scenarios are not listed.

[c] Species with no change are included.

TABLE 10.15
Predicted Change (%) in Area of Distribution of Selected Tree Species in the Northern Ridge and Valley Section of the Piedmont from 2000 to 2060 in Response to Four Climate Scenarios[a]

	Species Area Change (%)			
Species[b]	MIROC3.2	CSIROMK3.5	CSIROMK2	HadCM3
Shumard's oak	−70.8	0.0	0.0	0.0
Overcup oak	−70.8	0.0	0.0	0.0
Water oak	−100.0	0.0	0.0	0.0
Average[c]	−6.2	0.0	0.0	0.0

Source: Adapted from Wear, D.N., R. Huggett, and J.G. Greis. In press. Constructing alternative futures. *Southern Forest Futures Project Technical Report.*

[a] Scenarios were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high-energy use and B2 represents moderate population growth/low-energy use).

[b] Species with no change in each of the four scenarios are not listed.

[c] Species with no change are included.

An average 81% reduction in area of occurrence is predicted for three species, Shumard's oak, water oak, and overcup oak under the MIROC3.2 A1B scenario. None of the climate scenarios predicts an increase in range of the selected tree species. Little or no change is predicted for the ranges of 36 species, including silver maple (*Acer saccharinum*), flowering dogwood, and white ash (*Fraxinus americana*). Overall, the effects of climate change in the Piedmont Ridge, Valley, and Plateau section are predicted to be minor because of minimal reductions in annual precipitation.

Summary: Overall effects of future climate change will likely be relatively consistent among the three sections of the Piedmont. The most serious threat to forest tree species is predicted to occur along the southern edge of the Southern Appalachian section bordering the Eastern Atlantic section of the Coastal Plain subregion. The lowest threat may occur in the Piedmont Ridge, Valley, and Plateau section and in the northern part of the Central Appalachian Piedmont section, where species richness could increase in several counties. Tree species most vulnerable to climate change in the Coastal Plain will probably include Shumard's oak and water oak. Among climate scenarios, the MIROC3.2 A1B scenario forecasts the highest threats to plants resulting from possible climate change by 2060; the lowest threats are associated with the CSIROMK2 B2 and HadCM3 B2 scenarios.

Forest Diversity Effects in the Piedmont Region

Future diversity of forest tree species throughout the Piedmont could significantly change according to predictions by all climate scenarios, although the direction (increase or decrease) is unclear (Table 10.16). The MIROC3.2 A1B climate scenario predicted a large decrease in diversity (averaging about six species), compared to predictions of small increases by the other three scenarios.

Piedmont section scale: Predicted future tree diversity is most variable among the three sections of the Piedmont for the MIROC3.2 A1B scenario, where species richness could decrease from an average of 7.4 to 2.5 species in the year 2060 (Table 10.16). Predictions among the other three climate scenarios were less variable and some areas of the Piedmont, particularly in the Central and Southern Appalachian Piedmont sections, could actually experience increases in species richness. The highest risks to changes of future diversity are associated with the Northern Ridge and Valley

TABLE 10.16
Forest Diversity, Expressed as Average Tree Species Richness (Standard Deviation) for Piedmont Sections from 2000 to 2060 Estimated by a Model Based on Predictions of Annual Precipitation from Four Climate Scenarios[a]

Section	Current Diversity	Future (2060) Diversity Predicted by Each Scenario			
		MIROC3.2	CSIROMK3.5	CSIROMK2	HadCM3
		N Tree Species (SD)			
Central Piedmont	36.5 (2.1)	29.1 (3.4)[b]	37.4 (1.7)[b]	37.2 (1.8)[b]	37.6 (1.8)[b]
Southern Piedmont	38.4 (0.6)	32.1 (4.6)[b]	38.6 (0.5)[b]	38.6 (0.5)[b]	38.9 (0.2)[b]
Pied. Ridg. and Valley	39.0 (0.9)	36.5 (0.9)[b]	39.0 (0.0)	39.0 (0.0)	39.0 (0.0)
Piedmont Subregion	37.2 (1.8)	31.3 (4.5)[b]	38.1 (1.4)[b]	38.0 (1.5)[b]	38.3 (1.4)[b]

Source: Adapted from Wear, D.N., R. Huggett, and J.G. Greis. In press. Constructing alternative futures. *Southern Forest Futures Project Technical Report.*

[a] Scenarios were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high-energy use and B2 represents moderate population growth/low-energy use).

[b] Indicates significant difference between current (2000) and future (2060) species richness at the $p = 0.05$ level of probability.

section, where the four scenarios predicted either a significant decline or continuation at the current level of 39.0 species. If the large decreases predicted by the MIROC3.2 A1B scenario were excluded, the other sections of the Piedmont could be expected to experience a small but significant decrease in diversity.

County scale: Changes in tree species diversity at the county level in the Piedmont indicate that the largest declines would occur in the Central Appalachian Piedmont section, where diversity averaged across all climate scenarios could decrease by up to four species for South Boston County in Virginia. Areas that could experience decreases in diversity of two to three species are McCormick County in South Carolina and Meriwether County in Georgia. Increased diversity was predicted in small areas of the Piedmont section, where richness will be greater by four to five species for Fredericksburg County and Stafford County in Virginia. Three models predict that diversity of trees will increase slightly, by several species, for Gwinnett County and Madison County in Georgia. The most consistent effects of climate change on diversity will occur in the lower Piedmont of Georgia and South Carolina and in most of Virginia, where numbers of tree species are predicted to decrease slightly in all counties.

Overall, the MIROC3.2 A1B scenario consistently predicted the likely loss of two to three species in most counties, but predictions by the other climate scenarios were variable, ranging from little or no change to small increases for some counties. Future diversity averaged across the four climate scenarios indicated little or no change in about half of the counties of the Piedmont and a decrease of more than three species in the others (Figure 10.15).

APPALACHIAN-CUMBERLAND HIGHLAND

Forests of this hilly to mountainous subregion cover about 11% (242,596 km^2) of the South; upland forests consist mainly of deciduous hardwoods dominated by one or more species of oak and hickory. This subregion was subdivided into five sections: Blue Ridge (13.7%), Northern Ridge and Valley (14.0%), Southern Ridge and Valley (7.2%), Cumberland Plateau and Mountain (18.9%), and Interior Low Plateau (46.1%).

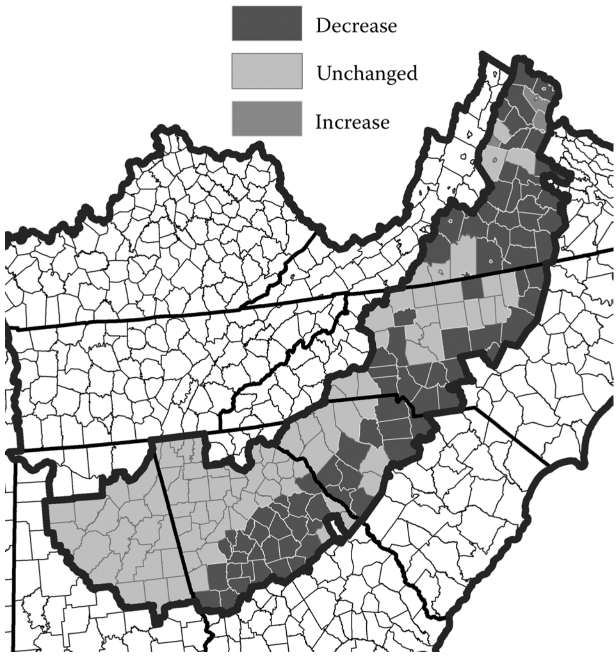

FIGURE 10.15 Future (2060) diversity (species richness) expressed as a percent of current (2000) diversity averaged across four climate scenarios for the Piedmont (Wear et al. in press); that were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high-energy use and B2 represents moderate population growth/low-energy use). Diversity is predicted to decrease in counties shaded dark gray (<97.5% of current), remain generally unchanged in counties shaded light gray (97.5 to 102.5% of current) and increase in counties shaded medium gray (>102.5% of current).

Climate Scenario Predictions

The long-term trend of temperature in the Appalachian-Cumberland Highland is predicted to increase from the year 2000 to 2060 based on averaged forecasts across the four climate scenarios (Figure 10.16). The rate of increase is approximately 0.3°C per decade for each of the five sections. Predicted changes in annual temperature are greatest in the Interior Low Plateau section and least in the Northern Ridge and Valley section. With the exception of the Blue Ridge and Northern Ridge and Valley, predicted changes in temperature among the sections are quite similar. For precipitation, the average of predictions from the climate scenarios indicates a long-term trend of nearly constant amounts (Figure 10.17); again. The trend for the Northern Ridge and Valley section differs from the other sections—in this instance, a smaller increase from 2000 to 2020 and then little change through 2060. An average of the four climate scenarios suggests a total temperature increase of about 3°C and a precipitation decrease of about 100 mm across all sections, although amounts vary for each climate scenario.

Three of the four climate scenarios forecast moderate changes in average annual precipitation from the year 2000 to 2060 for most sections of the Appalachian-Cumberland Highland; only the MIROC3.2 A1B scenario predicts a large decrease across all sections. Future precipitation predictions by the other scenarios vary among sections, ranging from similar amounts for the Cumberland Plateau and Mountain section to somewhat variable amounts for the Interior Low Plateau section. Comparison of predictions indicates the largest increase of precipitation for the CSIROMK3.5 A1B and HadCM3 B2 scenarios and largest decrease in precipitation for the MIROC3.2 A1B scenario. For all climate scenarios except the MIROC3.2 A1, precipitation is predicted to increase slightly, by

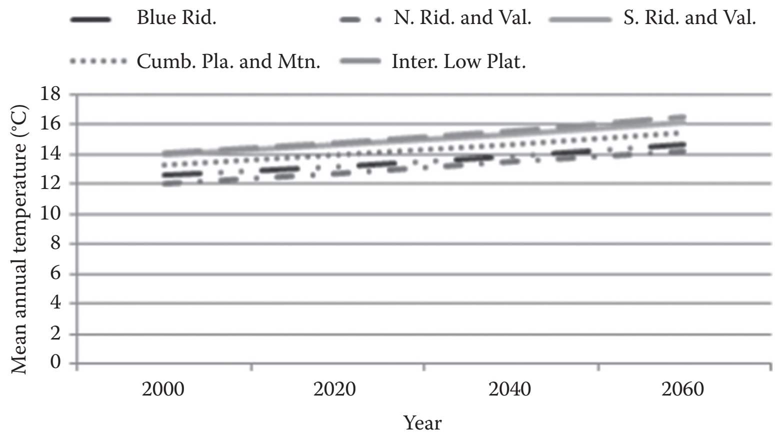

FIGURE 10.16 Average annual temperature from 2000 (current) to 2060 (predicted) for sections of the Appalachian-Cumberland Highland; temperature for each section represents the average of four climate scenarios (Wear et al. in press); that were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high-energy use and B2 represents moderate population growth/low-energy use).

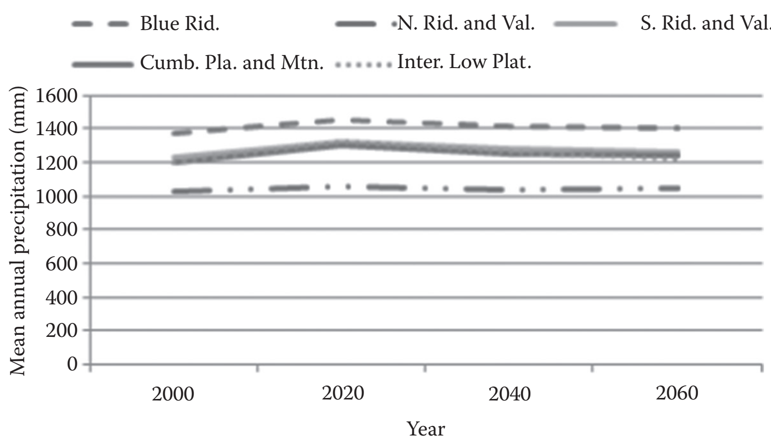

FIGURE 10.17 Average annual precipitation from 2000 (current) to 2060 (predicted) for sections of the Appalachian-Cumberland Highland; precipitation for each section represents the average of four climate scenarios (Wear et al. in press); that were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high-energy use and B2 represents moderate population growth/low-energy use).

about 60 mm, in the Blue Ridge and Southern Ridge and Valley sections and remain above-current levels in all sections. Overall, climate of the Appalachian-Cumberland Highland is predicted to be warmer and wetter in 2060.

Effects on Tree Species Distribution in Appalachian-Cumberland Highland Sections

Forty-four selected tree species were used for assessment of the effects of temperature and precipitation on forests in the Appalachian-Cumberland Highland (Table 10.4). Minimum annual temperature limits on the distribution of evaluated species ranged from below 0°C for boxelder to 13°C for winged elm (*Ulmus alata*). Precipitation requirements for native species ranged from 380 mm for American elm to 1260 mm for Shumard's oak. Temperature and precipitation predicted by three of the scenarios is expected to be greater than the minimum requirements for all species. For the fourth, MIROC3.2 A1B, precipitation is expected to be slightly greater than adequate for nine species and slightly less for two. Tree species with annual precipitation requirements greater than 1050 mm, such as sweet birch (*Betula lenta*) and Shumard's oak, are predicted to decrease in area of occurrence.

Blue Ridge: Vulnerability of tree species to climate change in the Blue Ridge section of the Appalachian-Cumberland Highland is predicted to be highest under the MIROC3.2 A1B scenario, which would result in an average 6% decrease in the range of the 44 tree species (Table 10.17). A 21% average reduction in area of occurrence is predicted for 12 species including sweetgum, shortleaf pine, and sweet birch under the MIROC3.2 A1B scenario, whereas an increase in the range of 10 species is predicted for the other three climate scenarios. Little or no change is predicted for the ranges of 32 species, including boxelder, honeylocust (*Gleditsia triacanthos*), and red maple. Overall, the effects of climate change in the Blue Ridge section are predicted to be minor because of minimal reductions in annual precipitation.

Northern Ridge and Valley: Vulnerability of tree species to climate change in the Northern Ridge and Valley section of the Appalachian-Cumberland Highland is predicted to be greatest under the MIROC3.2 A1B scenario, which would result in an average 15% decrease in the range of the 44 tree species (Table 10.18). An average 41% reduction in area of occurrence is predicted for 16 species, including sweetgum, southern red oak, and shortleaf pine under the MIROC3.2 A1B scenario, whereas an increase in range is predicted for 15 species under the other three scenarios.

TABLE 10.17
Predicted Change (%) in Area of Distribution of Selected Tree Species in the Blue Ridge Section of the Appalachian-Cumberland Highland from 2000 to 2060 in Response to Four Climate Scenarios[a]

	Species Area Change (%)			
Species[b]	**MIROC3.2**	**CSIROMK3.5**	**CSIROMK2**	**HadCM3**
Black cherry	−5	0	0	0
Red mulberry	−20	0	0	0
Sweetgum	−20	2.5	2.5	2.5
Southern red oak	−20	2.5	2.5	2.5
American holly	−20	2.5	2.5	2.5
Black tupelo	−20	2.5	2.5	2.5
Paulownia	−20	2.5	2.5	2.5
Shortleaf pine	−20	2.5	2.5	2.5
Black locust	−20	2.5	2.5	2.5
Winged elm	−20	2.5	2.5	2.5
Shumard's oak	−35	10	10	10
Sweet birch	−35	10	10	10
Average[c]	−5.8	0.9	0.9	0.9

Source: Adapted from Wear, D.N., R. Huggett, and J.G. Greis. In press. Constructing alternative futures. *Southern Forest Futures Project Technical Report.*

[a] Scenarios were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high-energy use and B2 represents moderate population growth/low-energy use).

[b] Species with no change in each of the four scenarios are not listed.

[c] Species with no change are included.

TABLE 10.18
Predicted Change (%) in Area of Distribution of Selected Tree Species in the Northern Ridge and Valley Section of the Appalachian-Cumberland Highland from 2000 to 2060 in Response to Four Climate Scenarios[a]

	Species Area Change (%)			
Species[b]	**MIROC3.2**	**CSIROMK3.5**	**CSIROMK2**	**HadCM3**
Chestnut oak	–5.4	0.0	0.0	0.0
Mockernut hickory	–29.7	5.4	5.4	5.4
Cucumber tree	–29.7	5.4	5.4	5.4
Virginia pine	–29.7	5.4	5.4	5.4
Black cherry	–70.3	10.8	8.1	10.8
Red mulberry	–54.1	37.8	21.6	24.3
Sweetgum	–54.1	32.4	18.9	24.3
Southern red oak	–54.1	32.4	18.9	24.3
American holly	–54.1	32.4	18.9	24.3
Black tupelo	–54.1	32.4	18.9	24.3
Paulownia	–54.1	32.4	18.9	24.3
Shortleaf pine	–54.1	32.4	18.9	24.3
Black locust	–54.1	32.4	18.9	24.3
Winged elm	–54.1	32.4	18.9	24.3
Shumard's oak	–2.7	35.1	18.9	35.1
Sweet birch	–2.7	35.1	18.9	35.1
Average[c]	–14.9	9.0	5.3	7.2

Source: Adapted from Wear, D.N., R. Huggett, and J.G. Greis. In press. Constructing alternative futures. *Southern Forest Futures Project Technical Report.*

[a] Scenarios were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high-energy use and B2 represents moderate population growth/low-energy use).

[b] Species with no change in each of the four scenarios are not listed.

[c] Species with no change are included.

Little or no change is predicted for 28 of the species, including blackjack oak, slippery elm (*Ulmus rubra*), and black oak. Overall, the effects of climate change in the Northern Ridge and Valley section are predicted to be minor because of minimal reductions in annual precipitation.

Southern Ridge and Valley: Vulnerability of tree species to climate change in the Southern Ridge and Valley section of the Appalachian-Cumberland Highland is predicted to be greatest under the MIROC3.2 A1B scenario, which would result in an average 10% decrease in the range of the 44 tree species (Table 10.19). An average 36% reduction in area of occurrence is predicted for 12 species, including sweetgum, shortleaf pine, and black locust (*Robinia pseudoacacia*) under the MIROC3.2 A1B scenario, whereas an increase in range of two species is predicted for the other three scenarios. Little or no change is predicted for the ranges of 32 species, including black willow, post oak, and northern red oak (*Q. rubra*). Overall, the effects of climate change in the Southern Ridge and Valley section are predicted to be minor because of minimal reductions in annual precipitation.

Cumberland Plateau and Mountain: Vulnerability of tree species to climate change in the Cumberland Plateau and Mountain section of the Appalachian-Cumberland Highland is predicted to be greatest under the MIROC3.2 A1B scenario, which would result in an average 11% decrease in the range of the 44 tree species of trees (Table 10.20). An average 42% reduction in area of occurrence is predicted for 12 species including sweetgum, southern red oak, and American holly (*Ilex*

TABLE 10.19
Predicted Change (%) in Area of Distribution of Selected Tree Species in the Southern Ridge and Valley Section of the Appalachian-Cumberland Highland from 2000 to 2060 in Response to Four Climate Scenarios[a]

	Species Area Change (%)			
Species[b]	**MIROC3.2**	**CSIROMK3.5**	**CSIROMK2**	**HadCM3**
Black cherry	−5.9	0.0	0.0	0.0
Red mulberry	−29.4	0.0	0.0	0.0
Sweetgum	−35.3	0.0	0.0	0.0
Southern red oak	−35.3	0.0	0.0	0.0
American holly	−35.3	0.0	0.0	0.0
Black tupelo	−35.3	0.0	0.0	0.0
Paulownia	−35.3	0.0	0.0	0.0
Shortleaf pine	−35.3	0.0	0.0	0.0
Black locust	−35.3	0.0	0.0	0.0
Winged elm	−35.3	0.0	0.0	0.0
Shumard's oak	−58.8	23.5	23.5	23.5
Sweet birch	−58.8	23.5	6.3	6.3
Average[c]	−9.9	1.1	0.7	0.7

Source: Adapted from Wear, D.N., R. Huggett, and J.G. Greis. In press. Constructing alternative futures. *Southern Forest Futures Project Technical Report.*

[a] Scenarios were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high-energy use and B2 represents moderate population growth/low-energy use).

[b] Species with no change in each of the four scenarios are not listed.

[c] Species with no change are included.

opaca) under the MIROC3.2 A1B scenario, whereas a small increase in the range of two species is predicted for the other three scenarios. Little or no change is predicted for the ranges of 32 species, including American basswood, red maple, and American sycamore (*Platanus occidentalis*). Overall, the effects of climate change in the Cumberland Plateau and Mountain section are predicted to be minor because of minimal reductions in annual precipitation.

Interior Low Plateau: Vulnerability of tree species to climate change in the Interior Low Plateau section of the Appalachian-Cumberland Highland is predicted to be highest under the MIROC3.2 A1B scenario, which would result in an average 11% decrease in the range of the 44 tree species (Table 10.21). An average 41% reduction in area of occurrence is predicted for 12 species including black cherry (*Prunus serotina*), shortleaf pine, Shumards's oak, and winged elm under the MIROC3.2 A1B scenario. An increase in the ranges of two species is predicted by the other three. Little or no change is predicted for the ranges of 32 species, including boxelder, post oak, and flowering dogwood. Overall, the effects of climate change in the Interior Low Plateau section are predicted to be minor because of minimal reductions in annual precipitation.

Summary: Overall effects of future climate change will likely be relatively consistent among the five sections of the Appalachian-Cumberland Highland. The highest threat to forest tree species could occur in the Northern Ridge and Valley section and the lowest threat may occur in the Blue Ridge section. Tree species most vulnerable to climate change in this subregion will probably include sweet birch and black locust. Among climate scenarios, the MIROC3.2 A1B scenario forecasts the highest threats to trees by 2060; the lowest threats are associated with the CSIROMK3.5 A1B and HadCM3 B2 scenarios.

TABLE 10.20
Predicted Change (%) in Area of Distribution of Selected Tree Species in the Cumberland Plateau and Mountain Section of the Appalachian-Cumberland Highland from 2000 to 2060 in Response to Four Climate Scenarios[a]

	Species Area Change (%)			
Species[b]	MIROC3.2	CSIROMK3.5	CSIROMK2	HadCM3
Black cherry	−23.1	0.0	0.0	0.0
Red mulberry	−36.5	0.0	0.0	0.0
Sweetgum	−44.2	0.0	0.0	0.0
Southern red oak	−44.2	0.0	0.0	0.0
American holly	−44.2	0.0	0.0	0.0
Black tupelo	−44.2	0.0	0.0	0.0
Paulownia	−44.2	0.0	0.0	0.0
Shortleaf pine	−44.2	0.0	0.0	0.0
Black locust	−44.2	0.0	0.0	0.0
Winged elm	−44.2	0.0	0.0	0.0
Shumard's oak	−44.2	17.3	21.2	21.2
Sweet birch	−44.2	17.3	21.2	21.2
Average[c]	−11.4	0.8	1.0	1.0

Source: Adapted from Wear, D.N., R. Huggett, and J.G. Greis. In press. Constructing alternative futures. *Southern Forest Futures Project Technical Report.*

[a] Scenarios were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high-energy use and B2 represents moderate population growth/low-energy use).

[b] Species with no change in each of the four scenarios are not listed.

[c] Species with no change are included.

Forest Diversity Effects

Future diversity in the Appalachian-Cumberland Highland could significantly decrease according to predictions by the MIROC3.2 A1B climate scenario, where average species richness could drop from 42.8 currently to 37.9 by 2060 (Table 10.22). Predictions from the other three scenarios suggest possible benefits from climate change resulting from small but significant increases in diversity of major tree species.

Appalachian-Cumberland Highland section scale: Among the five sections of the Appalachian-Cumberland Highland, predicted diversity is most variable for the MIROC3.2 A1B scenario, where future species richness could range from 31.2 to 40.8 species in 2060 (Table 10.22). Predictions of diversity by the other three climate scenarios differed, but generally indicated no decline in species richness and increases in richness for some areas, particularly in the Northern Ridge and Valley and Cumberland Plateau and Mountain section, where the changes are significant at the $p < 0.05$ level of probability. The highest risks to diversity are associated with climate change in the Blue Ridge and Southern Ridge and Valley sections, where, on average, the climate scenarios predicted either a significant decline or no significant difference between the current and future species richness.

County scale: Changes in tree species diversity at the county level indicate that the largest declines would occur in the Interior Low Plateau section—specifically northern Alabama, central Tennessee, and western Kentucky—and that average diversity across all climate scenarios could decrease by an average of almost four species for Carroll County in Kentucky. Decreases in diversity of about three species could occur also in the Blue Ridge section (Carroll County and Floyd County in Virginia),

TABLE 10.21
Predicted Change (%) in Area of Distribution of Selected Tree Species in the Interior Low Plateau Section of the Appalachian-Cumberland Highland from 2000 to 2060 in Response to Four Climate Scenarios[a]

	Species Area Change (%)			
Species[b]	**MIROC3.2**	**CSIROMK3.5**	**CSIROMK2**	**HadCM3**
Black cherry	−12.6	0.0	0.0	0.0
Red mulberry	−33.6	0.0	0.0	0.0
Sweetgum	−40.3	0.0	0.0	0.0
Southern red oak	−40.3	0.0	0.0	0.0
American holly	−40.3	0.0	0.0	0.0
Black tupelo	−40.3	0.0	0.0	0.0
Paulownia	−40.3	0.0	0.0	0.0
Shortleaf pine	−40.3	0.0	0.0	0.0
Black locust	−40.3	0.0	0.0	0.0
Winged elm	−40.3	0.0	0.0	0.0
Shumard's oak	−63.0	16.0	26.1	16.8
Sweet birch	−63.0	16.0	26.1	16.8
Average[c]	−11.2	0.7	1.2	0.8

Source: Adapted from Wear, D.N., R. Huggett, and J.G. Greis. In press. Constructing alternative futures. *Southern Forest Futures Project Technical Report.*

[a] Scenarios were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high-energy use and B2 represents moderate population growth/low-energy use).

[b] Species with no change in each of the four scenarios are not listed.

[c] Species with no change are included.

the Southern Ridge and Valley section (Grainger County in Tennessee), and the Cumberland Plateau and Mountain section (Perry County and Knott County in Kentucky). Diversity of trees is predicted to increase by six to seven species in Waynesboro County and Augusta County in Virginia, and gain five species in Buena Vista County, Virginia. The most consistent effects of climate change on diversity will likely occur in Scott County, Tennessee, and other counties in the Cumberland Plateau and Mountain section, where the four models predicted little or no change of diversity.

Overall, the effects of climate change on diversity at the county scale are expected to be variable, probably resulting from the Appalachian-Cumberland Highland's diverse topography effects on precipitation, with diversity generally declining by several species throughout, but increasing by two to five species in several counties of most sections. The MIROC3.2 A1B scenario consistently predicted the likely loss of two to three species in most counties, but predictions by the other climate scenarios were variable, ranging from little or no change to small increases in some counties. Future diversity averaged across the four climate scenarios indicated little or no change will likely occur in most counties in the Appalachian-Cumberland Highland, but a decline in diversity could occur in many of the northern counties of Kentucky and an increase is possible in the northern Virginia counties of the Northern Ridge and Valley section (Figure 10.18).

MISSISSIPPI ALLUVIAL VALLEY

The extensive floodplain of the Mississippi River is the smallest of the five subregions of the Southern Region, occupying about 5% (114,702 km^2) of the total area. Except for the wetlands near

TABLE 10.22
Forest Diversity, Expressed as Mean Tree Species Richness (Standard Deviation) for Appalachian-Cumberland Sections from 2000 to 2060 Estimated by a Model Based on Predictions of Annual Precipitation from Four Change Scenarios[a]

Section	Current Diversity	Future (2060) Diversity Predicted by Each Scenario			
		MIROC3.2	CSIROMK3.5	CSIROMK2	HadCM3
		N Tree Species (SD)			
Blue Ridge	43.8 (0.6)	40.8 (4.7)[b]	44.0 (0.0)	44.0 (0.0)	44.0 (0.0)
Northern Ridge and Valley	37.3 (5.2)	31.2 (1.7)[b]	41.5 (3.4)[b]	39.7 (4.6)[b]	41.1 (4.8)[b]
S. Ridge and Valley	43.5 (0.9)	37.9 (5.0)[b]	44.0 (0.0)	44.0 (0.0)	44.0 (0.0)
Cumb. Plat. and Mtn.	43.8 (0.8)	38.3 (5.1)[b]	43.9 (0.4)[b]	43.9 (0.4)[b]	43.9 (0.4)[b]
Interior Low Plat.	43.6 (0.8)	38.5 (4.7)[b]	43.6 (0.6)	44.0 (0.3)[b]	43.8 (0.6)
App.-Cumb. Subregion	42.8 (3.0)	37.9 (5.2)[b]	43.5 (1.5)[b]	43.4 (2.2)[b]	43.4 (2.2)[b]

Source: Adapted from Wear, D.N., R. Huggett, and J.G. Greis. In press. Constructing alternative futures. *Southern Forest Futures Project Technical Report.*

[a] Scenarios were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high-energy use and B2 represents moderate population growth/low-energy use).

[b] Indicates significant difference between current (2000) and future (2060) species richness at the $p = 0.05$ level of probability.

the confluence of the Mississippi River with the Gulf of Mexico, much of this subregion of largely alluvial soils has been cleared for agriculture. Historically, the region was dominated by bottomland hardwood forests, consisting mainly of oaks, blackgum, sweetgum, and bald cypress. The Mississippi Alluvial Valley is subdivided into two sections: Holocene Deposits (74.8%) and Deltaic Plain (25.2%).

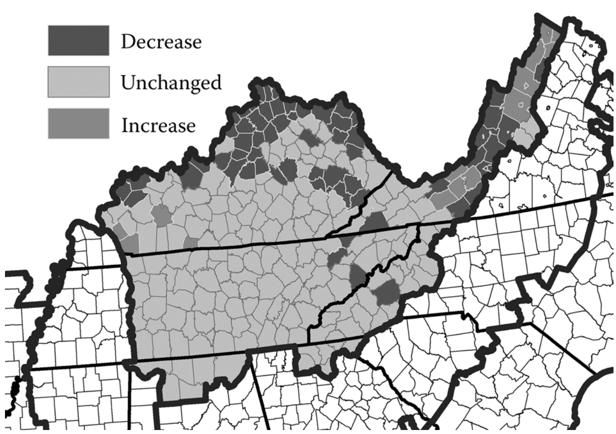

FIGURE 10.18 Future (2060) diversity (species richness) expressed as a percent of current (2000) diversity averaged across four climate scenarios for the Appalachian-Cumberland Highland (Wear et al. in press); that were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high-energy use and B2 represents moderate population growth/low-energy use). Diversity is predicted to decrease in counties shaded dark gray (<97.5% of current), remain generally unchanged in counties shaded light gray (97.5 to 102.5% of current) and increase in counties shaded medium gray (>102.5% of current).

Climate Scenario Predictions

The long-term temperature trend in the Mississippi Alluvial Valley is predicted to increase from 2000 to 2060 when averaged across the four climate scenarios (Figure 10.19). The rate of increase is approximately 0.3°C per decade for each of the two sections. The difference in average temperature (~3°C) between the two sections remains relatively constant during the 60-year forecast period. For precipitation, the average of predictions from the climate scenarios indicates a long-term trend of decreasing amounts (Figure 10.20). The trend for the Deltaic Plain section

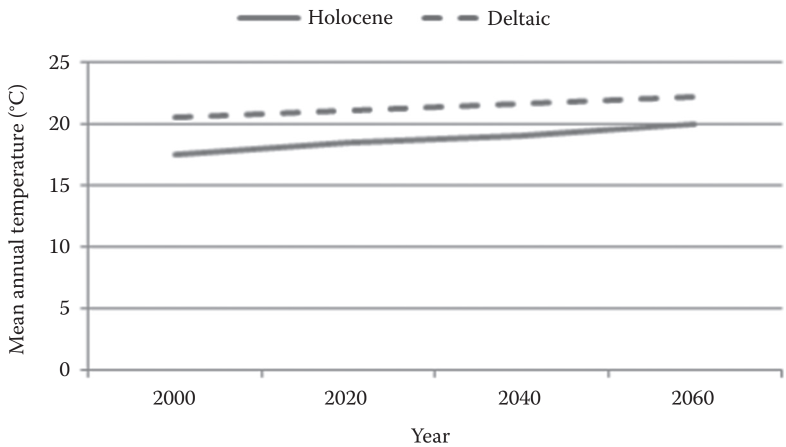

FIGURE 10.19 Average annual temperature from 2000 (current) through 2060 (predicted) for sections of the Mississippi Alluvial Valley; temperature for each section represents the average of four climate scenarios (Wear et al. in press); that were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high-energy use and B2 represents moderate population growth/low-energy use).

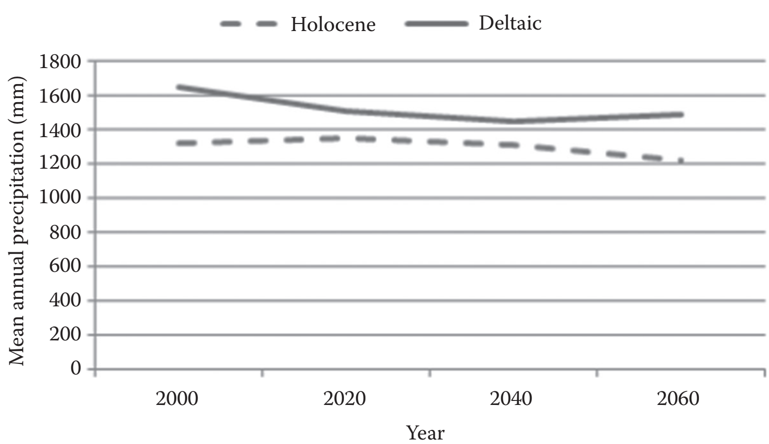

FIGURE 10.20 Average annual precipitation from 2000 (current) through 2060 (predicted) for sections of the Mississippi Alluvial Valley; precipitation for each section represents the average of four climate scenarios (Wear et al. in press); that were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high-energy use and B2 represents moderate population growth/low-energy use).

decreases from 2040 to 2060, compared to a slight increase for the Holocene Deposits section. An average of the four climate scenarios suggests a total temperature increase of about 5°C and a precipitation decrease of about 150 mm across the two sections, although amounts vary for each climate scenario.

Three of the four climate scenarios forecast only slight changes in average annual precipitation from 2000 to 2060 for the two sections of the Mississippi Alluvial Valley. Only the MIROC3.2 A1B scenario predicts a large decrease across both sections. Future precipitation predictions by the other climate scenarios vary between the sections, forecasting similar amounts for the Holocene Deposits section but relatively different amounts for the Deltaic Plain section. Comparison of predictions indicates equal or increased precipitation for the CSIROMK3.5 A1B scenario and the largest decrease in precipitation for the MIROC3.2 A1B scenario. The HadCM3 B2 scenario predicts that precipitation will decrease slightly, by about 50 mm, in the Holocene Deposits section and will decrease by almost 100 mm in the Deltaic Plain section. Overall, climate of the Mississippi Alluvial Valley is predicted to be warmer and dryer in 2060.

Effects on Tree Species Distribution in Mississippi Alluvial Valley Sections

Twenty-three selected tree species were used for assessment of the effects of precipitation on forests in the Mississippi Alluvial Valley (Table 10.4). Minimum temperature limits on the occurrence of species ranged from 0°C for American elm to 16°C for water oak. Minimum precipitation requirements for native species ranged from 380 mm for eastern cottonwood (*Populus deltoides*) and American elm to 1270 mm for water oak. Mean annual temperatures predicted by the four climate scenarios are likely to be higher than the minimums associated with the northern limits of the distributions for all species. Precipitation predicted by three of the climate scenarios is expected to be greater than the minimum requirements for all species. For the MIROC3.2 A1B scenario, precipitation is expected to be slightly more than adequate for seven species but less than adequate for water oak and overcup oak. Tree species with annual precipitation requirements greater than 1050 mm, such as water oak and overcup oak, could decrease in area of occurrence.

Holocene Deposits: Vulnerability of tree species to climate change in the Holocene Deposits section of the Mississippi Alluvial Valley is predicted to be highest under the MIROC3.2 A1B scenario, which would result in an average 21% decrease in the range of the 23 tree species (Table 10.23). An averaged 54% reduction in area of occurrence is predicted for nine species including southern red oak, water oak, and overcup oak under the MIROC3.2 A1B scenario. None of the climate scenarios predicts an increase in the distribution of species. Little or no change is predicted for the ranges of 14 species, including green ash (*Fraxinus pennsylvanica*), red maple, water oak, and black willow. Overall, the effects of climate change on trees in the Holocene Deposits section are predicted to be small because of minor influence of slightly higher temperature and minimal reductions in annual precipitation.

Deltaic Plain: Vulnerability of tree species to climate change in the Deltaic Plain section of the Mississippi Alluvial Valley is predicted to be highest under the MIROC3.2 A1B scenario, which would result in an average 5% decrease in the range of the 23 tree species (Table 10.24). An average 63% reduction in area of occurrence is predicted for only two species: overcup oak and water oak. None of the climate scenarios predicts an increase in the distribution of species. Little or no change is predicted for the ranges of 21 of the 23 species studied, including sugarberry, slippery elm, and red maple. Overall, the effects of climate change on trees in the Deltaic Plain section could be minor because of minimal reductions in annual precipitation and probably little immediate influence of slightly higher temperatures.

Summary: Overall effects of future climate change will likely vary between the two sections of the Mississippi Alluvial Valley as a result of precipitation rather than temperature. The ranges of tree species will probably not be affected by slightly higher temperatures. A higher threat to forest

TABLE 10.23
Predicted Change (%) in Area of Distribution of Selected Tree Species in the Holocene Deposits Section of the Mississippi River Alluvial Valley from 2000 to 2060 in Response to Four Climate Scenarios[a]

	Species Area Change (%)			
Species[b]	**MIROC3.2**	**CSIROMK3.5**	**CSIROMK2**	**HadCM3**
Red mulberry	−42.3	0.0	0.0	0.0
Sweetgum	−50.0	0.0	0.0	0.0
Southern red oak	−50.0	0.0	0.0	0.0
American holly	−50.0	0.0	0.0	0.0
Water hickory	−50.0	0.0	0.0	0.0
Black tupelo	−50.0	0.0	0.0	0.0
Paulownia	−50.0	0.0	0.0	0.0
Overcup oak	−94.2	0.0	−1.9	−15.4
Water oak	−53.8	0.0	−13.5	−9.6
Average[c]	−21.3	0.0	−0.7	−1.1

Source: Adapted from Wear, D.N., R. Huggett, and J.G. Greis. In press. Constructing alternative futures. *Southern Forest Futures Project Technical Report.*

[a] Scenarios were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high-energy use and B2 represents moderate population growth/low-energy use).

[b] Species with no change in each of the four scenarios are not listed.

[c] Species with no change are included.

tree species could occur in the Holocene Deposits section, where future annual precipitation could decrease. The tree species most vulnerable to climate change in this subregion will probably include overcup oak and water oak. Among climate scenarios, the MIROC3.2 A1B scenario forecasts the highest threat to plants resulting from possible climate change by 2060; the lowest threats are associated with the CSIROMK3.5 A1B and HadCM3 B2 scenarios.

TABLE 10.24
Predicted Change (%) in Area of Distribution of Selected Tree Species in the Deltaic Plain Section of the Mississippi River Alluvial Valley from 2000 to 2060 in Response to Four Climate Scenarios[a]

	Species Area Change (%)			
Species[b]	**MIROC3.2**	**CSIROMK3.5**	**CSIROMK2**	**HadCM3**
Overcup oak	−25.0	0.0	0.0	0.0
Water oak	−100.0	0.0	0.0	0.0
Average[b]	−5.4	0.0	0.0	0.0

Source: Adapted from Wear, D.N., R. Huggett, and J.G. Greis. In press. Constructing alternative futures. *Southern Forest Futures Project Technical Report.*

[a] Scenarios were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high-energy use and B2 represents moderate population growth/low-energy use).

[b] Species with no change in each of the four scenarios are not listed.

[c] Species with no change are included.

Forest Diversity Effects

Tree diversity in the Mississippi Alluvial Valley is likely to significantly decrease according to predictions of future climate change by the MIROC3.2 A1B scenario, or to remain near current levels according to forecasts by the other three scenarios (Table 10.25). The largest change in diversity resulted from predictions by the MIROC3.2 A1B scenario, where the mean tree species richness could decrease from 22.6 currently to 18.8 in 2060. For the subregion as a whole, the data analysis suggests little change to tree diversity from the year 2000 to 2060 if the MIROC3.2 A1B scenario is considered unlikely to occur and is disregarded.

Mississippi Alluvial Valley section scale: For both sections of the Mississippi Alluvial Valley, the predicted future diversity was most variable for the MIROC3.2 A1B scenario, where species richness could decrease from the current average of 22.6 species in both regions to 18.1 species for the Holocene Deposits section and 21.8 species for the Deltaic Plain section in 2060 (Table 10.25). Predictions of diversity by the other scenarios were generally consistent and indicated no significant differences between current and future diversity. Overall risk to future diversity resulting from climate change is predicted to be low.

County scale: Changes in tree species diversity at the county level in the Mississippi Alluvial Valley indicate that the greatest declines would occur in the Holocene Deposits section, which extends in a broad band along the Mississippi River from central Louisiana to northern Arkansas. In that section, diversity averaged across all climate scenarios could decrease by an average of about three species for Bolivar County in Mississippi and Chicot County in Arkansas. Diversity would remain at current levels for Coahoma County and Tunica County in Mississippi, but would decrease slightly, by an average of one to two species, in other counties. Decreases in diversity of about one species could occur uniformly throughout much of the Deltaic Plain section in southern Louisiana, with no particular hotspot of obvious decline of tree species.

Overall, the effects of climate change on diversity at the county scale in the Mississippi Alluvial Valley could be a more or less uniform decline of several species throughout. The MIROC3.2 A1B scenario consistently predicted the likely loss of two to three species in most counties, but predictions by the other scenarios were variable, ranging from little or no change to small decreases

TABLE 10.25
Forest Diversity, Expressed as Mean Tree Species Richness (Standard Deviation) for Mississippi Alluvial Valley Sections from 2000 to 2060 Estimated by a Model Based on Predictions of Annual Precipitation from Four Climate Scenarios[a]

Section	Current Diversity	Future (2060) Diversity Predicted by Each Scenario			
		MIROC3.2	CSIROMK3.5	CSIROMK2	HadCM3
		N Tree Species (SD)			
Holocene Deposits	22.5 (0.6)	18.1 (3.6)[b]	22.5 (0.6)	22.3 (0.6)	22.3 (0.7)
Deltaic Plain	23.0 (0.4)	21.8 (0.4)[b]	23.0 (0.0)	23.0 (0.0)	23.0 (0.0)
Miss. Valley Subregion	22.6 (0.5)	18.8 (3.5)[b]	22.6 (0.5)	22.5 (0.6)	22.4 (0.7)[b]

Source: Adapted from Wear, D.N., R. Huggett, and J.G. Greis. In press. Constructing alternative futures. *Southern Forest Futures Project Technical Report.*

[a] Scenarios were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high-energy use and B2 represents moderate population growth/low-energy use).

[b] Indicates significant difference between current (2000) and future (2060) species richness at the $p = 0.05$ level of probability.

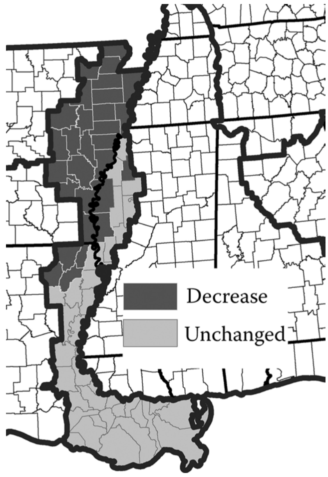

FIGURE 10.21 Future (2060) diversity expressed as a percent of current (2000) diversity averaged across four climate scenarios for the Mississippi Alluvial Valley (Wear et al. in press); that were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high-energy use and B2 represents moderate population growth/low-energy use). Diversity is predicted to decrease in counties shaded dark gray (<97.5% of current), remain generally unchanged in counties shaded light gray (97.5 to 102.5% of current) and increase in counties shaded medium gray (>102.5% of current).

for some counties. Future diversity averaged across the four scenarios indicated a decrease in the northern part of the subregion and little or no change likely in southern part (Figure 10.21).

MID-SOUTH

Vegetation of the Mid-South, which occupies about 37% (806,944 km^2) of the Southern Region, is variable, ranging from oak and pine forests in the east, through a transition woodlands zone of Cross Timbers, to the grassland plains of central Texas, and finally to the scrublands of near desert conditions in western Texas. The four sections of this subregion are the Ozark-Ouachita Highlands (11.1%), Cross Timbers (27.2%), High Plains (48.7%), and the West Texas Basin and Range (13.0%). From east to west, they define zones of progressively decreasing precipitation.

Ecotones are likely to be particularly sensitive to changes in precipitation and temperature since tree species that exist there are at their climatic range limits (Risser 1995; Stahle and Hehr 1984). Post oak in the Cross Timbers section ecotone is one example. A study conducted in Arkansas, Oklahoma, and Texas by Stahle and Hehr (1984) showed increased climate sensitivity of post oak with declining rainfall. Most of the sites in their study were in the Ozark-Ouachita Highlands and Cross Timbers sections that we examine below.

Climate Scenario Predictions

The long-term trend of temperature in the Mid-South is predicted to increase from the year 2000 to 2060 based on forecasts for all sections averaged over the four climate scenarios (Figure 10.22). The rate of increase is approximately 0.5°C per decade for each of the four sections. An almost constant difference of about 2°C separates the Ozark-Ouachita Highlands section from the other three for the 60-year forecast period. For precipitation, the averaged prediction from the climate scenarios indicates a long-term trend of decreasing amounts (Figure 10.23). The precipitation trend for the West Texas Basin and Range section remains about constant from the year 2000 to 2060, compared

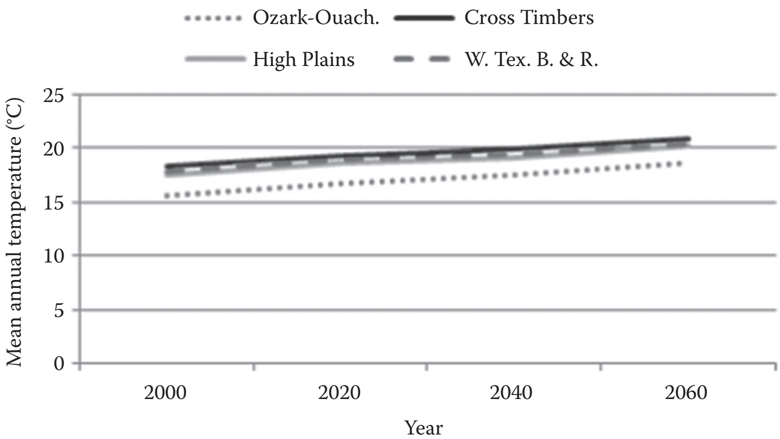

FIGURE 10.22 Average annual temperature from 2000 (current) to 2060 (predicted) for sections of the Mid-South; temperature for each section represents the average of four climate scenarios (Wear et al. in press); that were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high-energy use and B2 represents moderate population growth/low-energy use).

to a decrease for the other sections (especially the Ozark-Ouachita Highlands and Cross Timbers sections). An average of the four climate scenarios suggests a total temperature increase of about 5°C and a precipitation decrease of about 100 mm across the four sections, although amounts vary for each climate scenario.

Three of the four climate scenarios forecast only slight changes in average annual precipitation from the year 2000 to 2060 for the four sections of the Mid-South; only the MIROC3.2 A1B scenario predicts a large decrease across all sections. Future precipitation predictions by the other climate scenarios differ among sections, ranging from similar amounts for the High Plains and West Texas Ranges and Basins sections to differing amounts for the Ozark-Ouachita Highlands section. The CSIROMK3.5 A1B scenario predicts precipitation to decrease by about 150 mm in

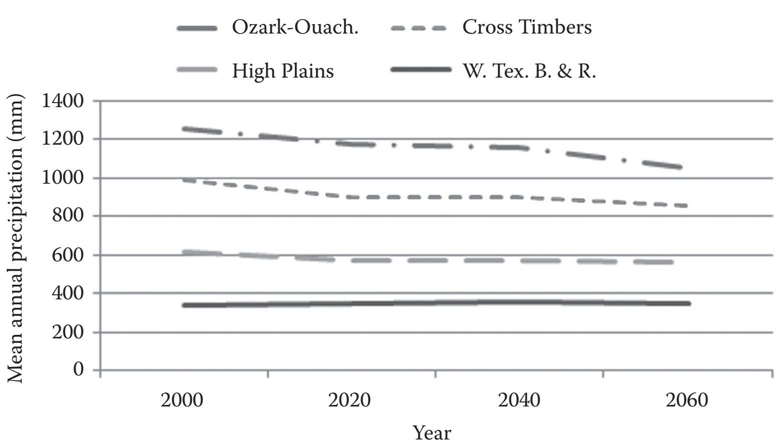

FIGURE 10.23 Average annual precipitation from 2000 (current) to 2060 (predicted) for sections of the Mid-South; precipitation for each section represents the average of four climate scenarios (Wear et al. in press); that were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high-energy use and B2 represents moderate population growth/low-energy use).

the Ozark-Ouachita Highlands section and almost 100 mm in the Cross Timbers section. With the exception of the MIROC3.2 A1B scenario, all climate scenarios forecast future precipitation to remain constant or increase slightly in the High Plains and West Texas sections. Overall, climate of the Mid-South is predicted to be warmer and dryer in 2060.

Under all four climate scenarios, temperature is predicted to increase while precipitation is predicted to decrease over the 60-year period from 2000 to 2060 in the Ozark-Ouachita Highlands and Cross Timbers regions. Of the four climate scenarios, MIROC3.2 A1B predicts the largest reduction in average annual precipitation and largest increase in temperature: a 301-mm precipitation decrease and 4.2°C temperature increase in the Ozark-Ouachita Highlands; a 231-mm precipitation decrease and 4.0°C temperature increase in the Cross Timbers section of Oklahoma; and a 50-mm precipitation decrease and 3.1°C temperature increase in the Texas portion of the Cross Timbers section. Although both sections are predicted to follow a generally decreasing trend in annual precipitation, the Cross Timbers section is predicted to receive at least 200 mm less than the Ozark-Ouachita Highlands over the 60-year period.

The Mid-South was subdivided in two zones (eastern and western) to facilitate evaluation of vulnerability. Tree cover in eastern zone, consisting of the Ozark Plateau and Cross Timbers sections, includes over a dozen species. In the drier western zone (High Plains and West Texas Ranges and Basins sections), shrubs predominate and trees are limited to two or three species that are associated with increased moisture in ravines or higher mountains.

Eastern zone: The Ozark-Ouachita Highlands, also known as the Interior Highlands, encompasses both the Ozark Mountains and the Ouachita Mountains in Arkansas and Oklahoma. The Ozark area is mainly forested, consisting primarily of upland hardwoods with pine as a secondary but economically important component, whereas the Ouachita Mountains are dominated by shortleaf pine with a hardwood component. The Cross Timbers section runs from central Texas through central Oklahoma and into the southeastern corner of Kansas. This section forms an ecotone between the treeless Great Plains to the west and the forests to the east. Dominant tree species are blackjack and post oak with eastern redcedar being a major invader where fire has been suppressed.

Leininger (1998) reported on a study that examined the impact of elevated temperature and drought on tree seedlings. He predicted that trees over a broad area could be susceptible to decline that is induced by a prolonged reduction in annual precipitation. Additionally, the combination of increased temperature and declining precipitation could significantly change both the frequency and severity of southern pine beetle (*Dendroctonus frontalis*) outbreaks in shortleaf pine stands between now and 2060 (McNulty et al. 1998). Gan (2004) predicted that under future climate change the southern pine beetle could kill from 4 to 7.5 times the 2004 value of trees killed by the beetle. Changes in winter climatic conditions could also affect populations of pine engraver beetles (*Ips* spp), which are also serious pests of southern pines (Lombardero et al. 2000).

Western zone: The High Plains section is an area of mostly hilly landscapes that extends in a broad zone from the panhandle of western Oklahoma southward through central Texas to Mexico, with vegetation that ranges from grasslands to shrub lands. The northern part of this zone borders on the grasslands of the Great Plains where predominant vegetation consists of short prairie grasses with some juniper woodlands. The middle part of the zone, in central Texas, occupies an area known as the Edwards Plateau, where the dissected, hilly topography is underlain by limestone and granite formations and vegetation ranges from oak woodlands to juniper in eroded areas of rock outcrops and steep bluffs. In the southern part of the High Plains section, bordering the Rio Grande River, topography becomes more plains-like with vegetation ranging from low trees on woodlands to thorny brush on shrublands.

The West Texas Basin and Range section, which occupies the Big Bend part of Texas, is northern part of the Mexican Chihuahua Desert and includes the most mountainous area of the Mid-South subregion. Desert grass and scrub lands separate the six to eight relatively short mountain ranges where tree vegetation is a scattered mixture of low scrub oaks and junipers. Elevations range from about 900 to 1200 m on valley floors, to 1500 to 2650 m on mountain peaks. Precipitation ranges from less than 20 cm in the low desert valleys to about 50 cm on the highest mountains.

Effects on Tree Species Distribution in Eastern Zone Sections of the Mid-South

Cross Timbers: Eleven tree species were selected to assess the effects of temperature and precipitation on forests in the Cross Timbers section of the Mid-South (Table 10.4). All four climate scenarios predicted higher temperature and lower precipitation. Vulnerability of tree species to climate change is predicted to be highest under the MIROC3.2 A1B scenario, which would result in an average 12% decrease in the range of the 11 species (Table 10.26). An averaged 5% reduction in area of occurrence is predicted under the CSIROMK3.5 A1B, CSIROMK2 B2, and HadCM3 B2 scenarios for black oak, winged elm, and Shumard's oak by 2060. Much of the possible change in area of predicted occurrence could result from reduced precipitation; the predicted, slightly higher temperatures could have little immediate effects on the distribution of tree species.

The average annual precipitation predicted by the MIROC3.2 A1B scenario in the year 2060 (736 mm) would drop below the average minimum precipitation requirement for Shumard's oak, winged elm, and black oak. However, in the westernmost counties of Oklahoma, the scenario predicts average annual precipitation to be 675 mm. This decreased level of precipitation would likely impact black oak more severely but not add species to the precipitation deficit list. In the rest of the area, average annual precipitation is 789 mm—above minimum annual precipitation for black oak but still below that of winged elm and Shumard's oak. Temperature would increase by 4°C in Oklahoma and 3.1°C in Texas. The other three climate scenarios predicted temperature increases of 3°C in Oklahoma and from 2.0 (CSIROMK3.5 A1B and CSIROMK2 B2) to 2.3°C (HadCM3 B2) in Texas.

Ozark-Ouachita Highlands: Thirty-one tree species were selected to assess the effects of temperature and precipitation on forests in the Ozark-Ouachita Highlands of Arkansas and Oklahoma (Table 10.4). All of the scenarios predicted temperatures above the minimum associated with the current range of the evaluated species. Only one of the four climate scenarios (MIROC3.2 A1B) predicts average precipitation to drop below the average minimum needed by any of the 31 species. Eleven species are predicted to be in a precipitation deficit situation, including nine hardwoods and two conifers. The two most important pines in the area, shortleaf and loblolly, are predicted to be affected. Vulnerability of tree species is predicted to be highest under the MIROC3.2 A1B scenario, which would result in an average 26% decrease of the 31 species (Table 10.27). By 2060, precipitation in the Ozark-Ouachita Highlands section (1050 mm) is forecasted to begin approaching the

TABLE 10.26
Predicted Change (%) in Area of Distribution of Selected Tree Species in the Cross-Timbers Section of the Mid-South from 2000 to 2060 in Response to Four Climate Scenarios[a]

	Species Area Change (%)			
Species[b]	**MIROC3.2**	**CSIROMK3.5**	**CSIROMK2**	**HadCM3**
Black oak	−51.4	−1.8	−18.9	−5.4
Winged elm	−44.1	−22.5	−29.7	−34.2
Shumard's oak	−17.1	−14.4	−14.4	−17.1
Average[c]	−11.9	−3.5	−5.9	−5.2

Source: Adapted from Wear, D.N., R. Huggett, and J.G. Greis. In press. Constructing alternative futures. *Southern Forest Futures Project Technical Report.*

[a] Scenarios were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high-energy use and B2 represents moderate population growth/low-energy use).

[b] Species with no change in each of the four scenarios are not listed.

[c] Species with no change are included.

TABLE 10.27
Predicted Change (%) in Area of Distribution of Selected Tree Species in the Ozark-Ouachita Highlands Section of the Mid-South from 2000 to 2060 in Response to Four Climate Scenarios[a]

	Species Area Change (%)			
Species[b]	**MIROC3.2**	**CSIROMK3.5**	**CSIROMK2**	**HadCM3**
Mockernut hickory	−6.1	0.0	0.0	0.0
Cucumber tree	−6.1	0.0	0.0	0.0
Black cherry	−57.1	0.0	−20.4	0.0
Winged elm	−87.8	−4.1	−32.7	−12.2
Sweetgum	−91.8	−6.1	−32.7	−22.4
Southern red oak	−91.8	−6.1	−32.7	−22.4
Loblolly pine	−91.8	−6.1	−32.7	−22.4
American holly	−91.8	−6.1	−32.7	−22.4
Black gum	−91.8	−6.1	−32.7	−22.4
Umbrella magnolia	−91.8	−6.1	−32.7	−22.4
Shortleaf pine	−91.8	−6.1	−32.7	−22.4
Average[c]	−25.8	−1.5	−9.1	−5.5

Source: Adapted from Wear, D.N., R. Huggett, and J.G. Greis. In press. Constructing alternative futures. *Southern Forest Futures Project Technical Report.*

[a] Scenarios were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high-energy use and B2 represents moderate population growth/low-energy use).

[b] Species with no change in each of the four scenarios are not listed.

[c] Species with no change are included.

2000 level in the Cross Timbers section (991 mm), a difference of only 59 mm. If the trend continues, the Ozark-Ouachita Highlands section could begin to emulate the vegetation and habitat characteristics of the Cross Timbers section.

Several nonnative invasive species that already threaten forests in the region could gain a competitive advantage as some competing species die and others become stressed at 2060 precipitation levels. The following species, listed with their lower precipitation requirements, could be particularly competitive: Russian olive (*Elaegnus angustifolia*)—305 mm; tree of heaven—356 mm; and Siberian elm (*Ulmus pumila*)—406 mm. Although Russian olive is not currently listed as a nonnative of concern in Arkansas, it has been reported in nearby Oklahoma, Texas, Missouri, and Tennessee (Invasive.org).

Summary: The trends of all four climate scenarios indicate declining precipitation and increasing temperature in the Cross Timbers and Ozark-Ouachita Highlands sections. Although predictions do not indicate some species to be in a deficit situation, trees may become stressed if the predicted decreases in annual precipitation continue to drop close to their limits.

Given these possibilities, in management over the next 15 years it would be wise to focus on species diversity to maintain all species components. Beyond the next 15 years, greater emphasis could be given to the maintenance of those species most likely to survive through 2060. However, periodic reassessment will be needed as part of an adaptive management strategy.

Effects on Tree Species Distribution in Western Zone Sections of the Mid-South

High Plains: Three selected tree species—plains cottonwood (*Populus deltoides* spp), Lacey oak (*Q. laceyi*), and oneseed juniper (*Juniperus monosperma*)—were used for assessment of the effects of temperature and precipitation in 2060 on forests in the High Plains section of the Mid-South (Table 10.4). The minimum temperatures associated with their current northern and western distributions ranged from 0°C for plains cottonwood to 15°C for Lacey oak. Minimum precipitation requirement was 250 mm for all species. Temperature and precipitation predicted for 2060 by the four climate scenarios is expected to be greater than the minimum requirements for all species.

Vulnerability of tree species to climate change in the High Plains section is predicted to be similar under all climate scenarios and should have little effect on the current range of the three tree species (Table 10.28). Overall, effects of climate change on tree species in the High Plains section of the Mid-South are predicted to be minor because of minimal changes in annual temperature and precipitation.

West Texas Basin and Range: Three selected tree species—gray oak (*Q. grisea*), oneseed juniper, and Mexican pinyon (*Pinus cembroides*)—were used for assessment of the effects of temperature and precipitation in the year 2060 on forests in the West Texas Basin and Range section of the Mid-South (Table 10.4). The minimum temperature associated with their current northern and western distributions ranged from 4°C for Mexican pinyon to 13°C for Gray oak. The minimum precipitation requirement is 250 mm for all species. Precipitation predicted for 2060 by the four climate scenarios is expected to be greater than the minimum requirements for all species.

Vulnerability of tree species to climate change in the West Texas Basin and Range section is predicted to be similar under all climate scenarios and should have little effect on the current range of the three selected tree species (Table 10.29). Overall, effects of climate change on tree species in this section of the Mid-South are predicted to be minor because of little likely immediate effects of somewhat higher temperature and minimal changes in annual precipitation.

Summary: Overall effects of future climate change on vegetation will likely be relatively small for both the High Plains and West Texas Basin and Range sections of the Mid-South. Warmer temperatures will likely affect potential evapotranspiration, but will be above the minimums that limit the northern and western distribution of tree species. A slightly greater threat to forest tree species could occur in the High Plains section, where future annual precipitation could decrease; precipitation in the West Texas Range and Basins section is predicted to either remain similar to current amounts or increase slightly. Tree species are about equal in vulnerability to reduced precipitation and their future distributions should show little changes. Among climate scenarios, the MIROC3.2 A1B scenario forecasts the highest threat to trees, followed by the CSIROMK2 B2 scenario.

TABLE 10.28

Predicted Change (%) in Area of Distribution of Selected Tree Species in the High Plains Section of the Mid-South from 2000 to 2060 in Response to Four Climate Scenarios[a]

	Species Area Change (%)			
Species	**MIROC3.2**	**CSIROMK3.5**	**CSIROMK2**	**HadCM3**
Oneseed juniper	0.0	0.0	0.0	0.0
Plains cottonwood	0.0	0.0	0.0	0.0
Lacey oak	0.0	0.0	0.0	0.0
Average	0.0	0.0	0.0	0.0

Source: Adapted from Wear, D.N., R. Huggett, and J.G. Greis. In press. Constructing alternative futures. *Southern Forest Futures Project Technical Report.*

[a] Scenarios were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high-energy use and B2 represents moderate population growth/low-energy use).

TABLE 10.29
Predicted Change (%) in Area of Distribution of Selected Tree Species in the West Texas Basin and Range Section of the Mid-South from 2000 to 2060 in Response to Four Climate Scenarios[a]

	Species Area Change (%)			
Species	**MIROC3.2**	**CSIROMK3.5**	**CSIROMK2**	**HadCM3**
Oneseed juniper	−6.7	0.0	0.0	6.7
Mexican pinyon	−6.7	0.0	0.0	6.7
Gray oak	−6.7	0.0	0.0	6.7
Average	−6.7	0.0	0.0	6.7

Source: Adapted from Wear, D.N., R. Huggett, and J.G. Greis. In press. Constructing alternative futures. *Southern Forest Futures Project Technical Report.*

[a] Scenarios were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high-energy use and B2 represents moderate population growth/low-energy use).

Forest Diversity Effects

Future tree diversity will likely decrease in the eastern zone of the Mid-South and remain unchanged in the dry western zone (Table 10.30). In the eastern zone, differences between the current and future species richness are largest for the MIROC3.2 A1B climate scenario (3.6 species) compared to an average decrease of about 1.1 species for the other climate scenarios. All scenarios predict no change in diversity for the western zone.

TABLE 10.30
Forest Diversity, Expressed as Mean Tree Species Richness (Standard Deviation) for Mid-South Sections from 2000 to 2060 Estimated by a Model Based on Predictions of Annual Precipitation from Four Climate Scenarios[a]

Section and Zone	Current Diversity	Future (2060) Diversity Predicted by Each Scenario			
		MIROC3.2	**CSIROMK3.5**	**CSIROMK2**	**HadCM3**
		***N* Tree Species (SD)**			
Ozark-Ouachita	31.0 (0.0)	22.6 (2.0)[b]	30.3 (2.2)[b]	27.8 (4.3)[b]	29.1 (3.4)[b]
Cross Timbers	09.7 (0.9)	08.3 (0.7)[b]	09.2 (0.5)[b]	08.9 (0.7)[b]	09.0 (0.4)[b]
Eastern zone	16.2 (9.9)	12.6 (6.7)[b]	15.6 (9.9)[b]	14.6 (9.1)[b]	15.1 (9.5)[b]
High Plains	03.0 (0.0)	03.0 (0.0)	03.0 (0.0)	03.0 (0.0)	03.0 (0.0)
West Texas R&B	03.0 (0.0)	03.0 (0.0)	03.0 (0.0)	03.0 (0.0)	03.0 (0.0)
Western zone	03.0 (0.0)	03.0 (0.0)	03.0 (0.0)	03.0 (0.0)	03.0 (0.0)

Source: Adapted from Wear, D.N., R. Huggett, and J.G. Greis. In press. Constructing alternative futures. *Southern Forest Futures Project Technical Report.*

[a] Scenarios were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high-energy use and B2 represents moderate population growth/low-energy use).

[b] Indicates significant difference between current (2000) and future (2060) species richness at the $p = 0.05$ level of probability.

Mid-South section scale: Predicted changes in future diversity were greatest for the Ozark-Ouachita Highlands section, where diversity in the year 2060 could decrease by an average of 0.7–8.4 species (Table 10.30). Prediction of diversity by the year 2060 in the Cross Timbers section varied less, with estimates of change ranging from 0.5 to 1.4 species. Risk of tree diversity being affected by climate change is likely to be moderate to high in the eastern sections. In the western two sections, risk of climate change affecting diversity is likely to be low.

County scale: Changes in tree species diversity at the county level in the Mid-South indicate that the largest declines would occur in the eastern zone, which includes the Ozark-Ouachita Highlands section (northwestern Arkansas and eastern Oklahoma) and the Cross Timbers section (central Oklahoma and eastern central Texas). For many counties in the eastern zone, including Polk and Saline in Arkansas, diversity of tree species would remain at current levels. Climate change would be most apparent in two Oklahoma hotspots, with richness declining by nine species in McIntosh County and seven species in Mayes County. Diversity changes in the adjacent Cross Timbers section to the west would be similar but not as severe. Average diversity was predicted to increase for Nueces County and Calhoun County near the Gulf of Mexico. An average of two tree species would be lost by Rogers County and Okfuskee County in Oklahoma, but little or no measurable change in diversity will occur in counties throughout much of this section.

The least change in tree-species richness at the county level in the Southern Region would occur in the western zone of the Mid-South subregion, where the current dry and hot environment is suitable for few species of trees. Throughout the 170 counties in this zone, diversity is predicted to decline only for Loving County in Texas (near New Mexico) and only by one tree species. The MIROC3.2 A1B scenario consistently predicted the likely loss of two to three species in most counties in the Cross Timbers section, but predictions by the other climate scenarios were slight, ranging from little or no change to small decreases for some counties. Future diversity averaged across the four climate scenarios indicated decreased diversity in the Cross Timbers section and little or no change likely in the High Plains and West Texas Basin and Range sections, where most species present are tolerant of drought (Figure 10.24).

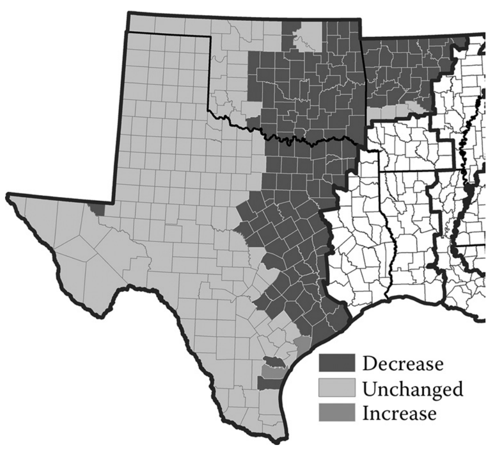

FIGURE 10.24 Future (2060) diversity expressed as a percent of current (2000) diversity averaged across four climate scenarios for the Mid-South (Wear et al. in press); that were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high energy use and B2 represents moderate population growth/low energy use). Diversity is predicted to decrease in counties shaded dark gray (<97.5% of current), remain generally unchanged in counties shaded light gray (97.5 to 102.5% of current) and increase in counties shaded medium gray (>102.5% of current).

CASE STUDIES

Case Study 1: Understory Vegetation in Longleaf Pine Stands of the Coastal Plain's Western Gulf

If climate change results in more intensive droughts in the Coastal Plain's Western Gulf, understory vegetation would be affected as well as overstory trees (U.S. Global Change Research Program 2009). To examine drought patterns, Palmer Drought Severity Index values from the National Climatic Data Center (2011) were applied for the four climate scenarios over the historical range of longleaf pine (*Pinus palustris*)—central Louisiana, western central Louisiana, northern central Louisiana, and eastern Texas. From 1895 through 2009, droughts occurred 36% of the time in the longleaf pine range based on drought severity classifications from Hayes (2010), which were severe to extreme 6% of the time. In the last 50 years, droughts occurred 33% of the time with severe-to-extreme droughts occurring 5% of the time. This suggests that drought conditions are moderating, with the exception of 2000–2009, when they again occurred 36% of the time and were severe-to-extreme 6% of the time. Year-to-year climate is highly variable, but clearly, forests in the Western Gulf have been subjected to recurring droughts that become severe to extreme only occasionally.

However, should the pattern of drought intensify, as predicted by some climate scenarios (Global Change Research Program 2009), then forests that have adapted to mild-to-moderate droughts 36% of the time would become more stressed and at risk for wildfires (Outcalt and Wade 2004). This would favor the dominant bluestem grasses (*Andropogon* spp and *Schizachyrium* spp) and other common herbaceous plants (Haywood and Harris 2000; Wade et al. 2000) that are indicative of longleaf pine understories that Turner et al. (1999) described. Although favored by recurring fires, herbaceous plant yields are negatively affected by drought as expressed in the following relationship for longleaf pine stands (Wolters 1982):

$$\text{HP} = 2094.75 + 10.10\ [\text{April through October precipitation (cm)}] - 106.96 \times \text{BA},$$

where HP is herbaceous plant production in kg/ha and BA is basal area in m^2/ha.

Production of herbaceous plant material varied widely among the four climate scenarios between 2000 and 2060 (Figure 10.25). The MIROC3.2 model predicted a small increase of herbaceous production for 2020, followed by a sharp decline in 2040 and 2060. In contrast, the CSIROMK2 scenario predicts a decline for 2020, followed by recovery to current levels by 2040, and a large increase in 2060. The CSIROMK3.5 model predicts little or no change in production by 2060. The uncertainty of future herbaceous plant production likely arises from variation in estimates of growing season precipitation by the four scenarios because all other variables in the model were held constant, which demonstrates the challenges facing future resource management in consideration of a changing climate.

Changing climate has been found to be partly a response to rising CO_2 levels in the atmosphere (Intergovernmental Panel on Climate Change 2007). Three herbaceous plant species—wiregrass (*Aristida stricta*), rattlebox (*Crotalaria rotundifolia*), and butterfly milkweed (*Asclepias tuberosa*)—growing with longleaf pine in open-top chambers, had lower growth rates when exposed to elevated CO_2 concentrations compared to ambient CO_2 concentrations (Runion et al. 2006). However, longleaf pine had higher growth rates under the elevated CO_2 concentrations. Nevertheless, in field environments, higher temperatures increased respiration rates and droughts have been shown to reduce the amount of water available to plants and disrupt plant physiology (Sword Sayer and Haywood 2006), possibly leading to lower growth rates of trees as predicted in the Canadian climate scenario (U.S. Global Change Research Program 2009).

If the climate of the Southern United States becomes warmer with droughts occurring more frequently, wildfires will become more extensive and intense (U.S. Global Change Research Program

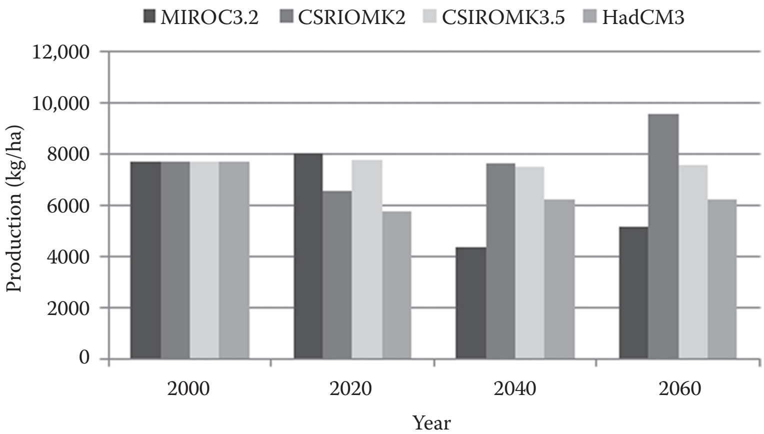

FIGURE 10.25 Herbaceous plant production in longleaf pine stands (25 m^2/ha) in the Western Gulf section of the southern Coastal Plain predicted by four climate scenarios (Wear et al. in press); scenarios were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high-energy use and B2 represents moderate population growth/low-energy use).

2009; Chapter 5). Under normal climatic conditions, forest floor duff is moist and consumption of duff is minor, which protects tree roots during fires (Varner et al. 2007). However, as drought conditions lead to the drying out of the duff layer, virtually all of the forest floor can be consumed, and pine mortality can be severe (Outcalt and Wade 2004). Overstory and midstory pine and hardwood mortality can transform dense mixed pine and hardwood stands into open woodlands (Brockway et al. 2006; Haywood 2009; Haywood 2011; Wade et al. 2000), as occurs in national forests and other holdings where prescribed fire is continually reapplied, which is desirable to promote forest wildlife habitat.

Case Study 2: Effects of Climate Change on the Potential Range of *Eucalyptus grandis* in Florida

The genus Eucalyptus (*Eucalyptus*) consists of more than 700 species that are endemic primarily to Australia and Tasmania in regions of temperate conditions where winters are mild and the onset of freezing temperatures is gradual (Boland et al. 2006). The favorable tree form, wood properties, and growth rate of some species has resulted in extensive plantings of eucalypts in many countries beyond their native range, particularly Brazil, South Africa, Spain, and India (Booth and Pryor 1991). In the United States, commercial and trial plantings of eucalypts have been made in southern California and throughout much of Florida (Geary et al. 1983).

The potential for growing eucalypts in Florida has long been recognized (Meskimen and Francis 1990; Zon and Briscoe 1911). Eucalypts have been systematically evaluated for industrial wood products since the 1970s, initially as a source of hardwood pulp for fine papers and more recently for a range of other products, including fuelwood and mulch (Geary and others 1983; Meskimen and Franklin 1978; Rockwood 2012). Because the eucalypts vary in their sensitivity to frost, field trials have resulted in delineation of climatic zones based on severity of freeze damage to various species (Geary and others 1983). Most field research with eucalyptus has been done in southern Florida, where severe winter freezes (–5°C for 12 h) are uncommon (Meskimen et al. 1987). Within the southern climatic zone, planting sites vary primarily by their soil moisture regime, which ranges from excessively drained sandy ridges to poorly drained swampy prairies.

Considerable observations and data are available for *E. grandis*, a highly productive species that is suitable for a broad range of planting sites, except for the extreme driest or wettest soils (Geary

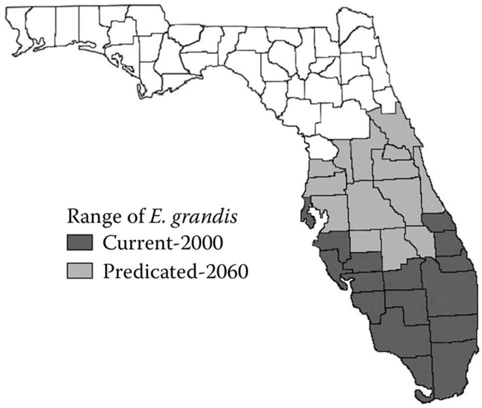

FIGURE 10.26 Current (2000) and predicted (2060) range of *Eucalyptus grandis* in Florida in response to the HadCM3 general circulation model and the B2 storyline (moderate population growth and low-energy use) scenario for a prediction model based on mean annual air temperature and mean annual potential evapotranspiration.

et al. 1983). *E. grandis* is sensitive to freezing temperatures and has long been recommended as suitable for planting in southern Florida, where the risk of frost damage is lowest (Figure 10.26). However, this species has been the subject of field trials and selection of clones for tolerance of freezing temperatures, which would allow it to be planted north of its currently recommended range (Keller et al. 2009; Meskimen et al. 1987; Rockwood 2012). The potential effects of a warmer climate on the potential area suitable for growing *E. grandis* has been reported for Australia (Hughes et al. 1996), but such information is not available for Florida.

The purpose of this case study was to investigate the probable effects of climate change on the area that might be suitable for management of *E. grandis* in Florida in 2060. A classification model was developed based on current values of commonly reported meteorological variables associated with the current range of *E. grandis* and the model was applied to estimate the potential future range of the species based on a future climate change scenario forecasted for Florida in 2060.

Methods: The source of current (2000) and predicted (2060) climate data for Florida was presented for four scenarios by Wear and others (in press). The four scenarios predict higher temperature and potential evapotranspiration for 2060 compared to 2000 (Table 10.31). Precipitation predictions will be variable, however, with the CSIROMK2 forecasting slightly less than current values and the MIROC3.2 scenario projecting much less. The HadCM3 scenario was selected because it forecasted moderate conditions that were generally between the extreme predictions of the other models.

E. grandis has been planted at a number of locations throughout Florida to evaluate survival, growth, and productivity (Geary et al. 1983). Evaluation of the field plantings revealed that the survival and growth of *E. grandis* in Florida appeared to be related to the magnitude and duration of subfreezing winter temperature (Meskimen and others 1987). The subpopulation of sites with satisfactory performance of *E. grandis* was used to identify counties currently suitable for its commercial production, thereby defining the current range of the species in Florida (Figure 10.1 in Geary et al. 1983). The current range of *E. grandis* passed through the interior of nine counties that represent a transition zone; transition counties were classified as either inside or outside the range based the greatest area of each category. Correlation analysis was used to evaluate the relationship of the climatic variables for all Florida counties with their geographic location (quantified by latitude and longitude). Analysis of variance was used to test for significant differences of individual climate variables for counties inside and outside of the current range for *E. grandis*. Results of both the correlation and variance analyses were used to interpret climate gradients for development of a predictive model that describes the current climate conditions associated with the range of *E. grandis* in Florida in 2000.

TABLE 10.31
Current (2000) and Predicted (2060) Levels of Climate Variables in Response to Four Climate Change Scenarios for Florida[a]

Climate Variable[b]	Current (2000)	Predicted Change (%) by Scenario for 2060			
		MIROC3.2	CSIROMK3.5	CSIROMK2	HadCM3
Temperature (°C)	21.5	110.4	107.2	107.2	106.1
Precipitation (mm)	1416.9	58.6	105.0	97.7	104.9
PET[c] (mm)	2588.8	118.1	111.0	111.1	108.5

Source: Adapted from Wear, D.N., R. Huggett, and J.G. Greis. In press. Constructing alternative futures. *Southern Forest Futures Project Technical Report.*

[a] Scenarios were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high-energy use and B2 represents moderate population growth/low-energy use).

[b] Sample units are Florida counties ($n = 67$); climate variables were weighted by area and are expressed as average annual values.

[c] PET: potential evapotranspiration.

An incidence analysis of climate in the counties in which *E. grandis* currently occurs was performed to develop a function for predicting its potentially suitable range. Each county was assigned a binary code of 0 or 1, depending on whether it was outside or inside the current range. An incidence function was developed from three meteorological variables associated with current climate: average annual temperature, average annual precipitation, and average annual potential evapotranspiration. Maximum likelihood logistic regression was used to determine the interrelationships of climatic variables with the current occurrence of *E. grandis* (Crawley 2005). The model was

$$P\ (\text{presence} = 1) = \exp(\ b_i X_i)/1 + \exp(b_i X_i),$$

where P is the estimated probability of *E. grandis* occurrence, b_i is the vector of regression coefficients, X_i is the vector of explanatory variables, and exp is the base of the natural logarithms. Each of the three climatic variables was tested for its level of statistical significance in the regression analysis individually and in combination with the other variables. Effects of multicollinearity were reduced by excluding highly correlated variables from the final model. Predicted future occurrence of *E. grandis* in each county was classified as absent if the estimated probability (P) was ≤ 0.5 or as present if $P > 0.5$. The best model for prediction was determined based on the lowest Akaike Information Criterion (Menard 1995).

Results and discussion: The current annual averages of the three climatic variables were significantly correlated with latitude and longitude (Table 10.32). Current annual temperature decreased from southern to northern latitudes ($r = -0.97$) and from eastern to western longitudes ($r = -0.80$). Trends of precipitation were generally opposite those of temperature; it increased from south to north ($r = 0.63$) and from east to west ($r = 0.82$), particularly in the panhandle region of northern Florida. Potential evapotranspiration followed the trends of temperature, but with weaker geographical relationships.

The difference between average annual temperature and precipitation varied significantly inside compared to outside of the current range of *E. grandis* (Table 10.33). Current temperature was higher (23.2°C) inside compared to outside (20.9°C). Average annual precipitation, however, was 106.1 mm lower inside the range compared to outside. Potential evapotranspiration did not differ inside or outside the range.

TABLE 10.32
Pearson Correlation Coefficients among Climate Variables and Geographic Location of County Sample Units ($n = 67$) for Florida in 2000

Climate Variable[a]	Temperature	Precipitation	PET[b]	Latitude	Longitude
Temperature (°C)	1.00				
Precipitation (mm)	–0.75[c]	1.00			
PET[b] (mm)	0.44[c]	–0.70[c]	1.00		
Latitude (deg)	–0.97[c]	0.63[c]	–0.34[c]	1.00	
Longitude (deg)	–0.80[c]	0.82[c]	–0.54[c]	0.69[c]	1.00

[a] Sample units are Florida counties ($n = 67$); climate variables were weighted by area and are expressed as average annual values.
[b] PET: potential evapotranspiration.
[c] Correlation coefficient is significant at the $P < 0.05$ level of probability.

Seven formulations of logistic regression models were evaluated for predicting the current range of *E. grandis* (Table 10.34). Models formulated with a single climate variable, average annual precipitation, produced the highest level of significance ($p = 0.002$) followed by temperature ($p = 0.047$); potential evapotranspiration did not account for significant variation ($p = 0.480$) of *E. grandis* occurrence. AIC was lowest for the single-variable model based on temperature (13.192) than for either precipitation (64.137) or potential evapotranspiration (79.382). The prediction model based on both mean annual temperature and mean annual potential evapotranspiration produced the lowest AIC (12.503) among all formulations evaluated. I selected it to use for predicting the potential future range of *E. grandis* based on the climate forecasted by the HadCM3 scenario for 2060.

Model performance using the current climate data set resulted in correct classification of 97% of the counties. The two misclassified counties were in the transition zone and represented one case each of a false-positive and false-negative prediction. Application of the prediction model to the climate predicted by the HadCM3 scenario for 2060 resulted in correct classification of all 17 counties in the current range in southern Florida and expansion of the range of *E. grandis* into 14 additional counties in the central part of the state (Figure 10.26). The classification probability for the 31 counties predicted as inside the future range was high (>0.99) for all but one ($p = 0.77$); probabilities were near zero for the 36 counties predicted as outside the range of *E. grandis* in 2060. Findings

TABLE 10.33
Average Annual Climate Conditions (SD) of Florida Counties in Relation to the Current (2000) Range of *Eucalyptus grandis*

	County Location		
Climate Variable[a]	Inside Range ($n = 17$)	Outside Range ($n = 50$)	Difference
Temperature (°C)	23.23 (0.42)	20.92 (1.02)	2.31[b]
Precipitation (mm)	1337.68 (69.41)	1443.82 (111.13)	–106.14[c]
PET[d] (mm)	2596.88 (51.78)	2586.05 (56.00)	10.83

[a] Sample units are Florida counties ($n = 67$); climate variables were weighted by area and are expressed as average annual values.
[b] Difference is significant ($p < 0.00001$).
[c] Difference is significant ($p = 0.00046$).
[d] PET: potential evapotranspiration.

TABLE 10.34
Statistical Significance and Associated AIC for Full and Reduced Formulations of Logistic Regression Models Based on Combinations of Climate Variables to Predict the Occurrence of *Eucalyptus grandis* in Florida Counties in 2000

Climate Variables in Model Formulation	Climate Variable			
	Temperature	Precipitation	PET[b]	AIC[a]
Temperature (°C)	0.047	na[c]	na	13.192
Precipitation (mm)	na	0.002	na	64.137
PET (mm)	na	na	0.480	79.382
Temperature + precipitation	0.048	0.867	na	15.165
Temperature + PET	0.170	na	0.317	12.503
Precipitation + PET	na	0.001	0.034	61.033
Temperature + precipitation + PET	0.179	0.951	0.313	14.500

[a] Akaike Information Criterion.
[b] PET: potential evapotranspiration.
[c] na: not applicable.

from my study agree with those of others (Zon and Briscoe 1911; Geary et al. 1983; Rockwood 2012) that temperature is more important than precipitation for defining the area potentially suitable for planting *E. grandis* in Florida.

The area in central Florida potentially suitable for *E. grandis* with a moderate climate change is similar to the potential planting regions identified by Rockwood (2012) as suitable for current plantings of cold-tolerant cultivars. Rockwood (2012), however, includes 11 counties farther north than those classified as suitable for *E. grandis* based on 2060 climate forecasts by the HadCM3 scenario in my analysis. Because the HadCM3 scenario forecasted the smallest increase of temperature for 2060 (Table 10.32), a model based any of the other three scenarios (particularly the MIROC3.2) would have likely resulted in a proposed area suitable for *E. grandis* similar to that presented by Rockwood (2012).

In summary, predicting the results of a changing climate on the potential future range suitable for *E. grandis* will be more complex than illustrated by this study. For example, *E. grandis* is particularly sensitive to the abrupt onset of freezing temperatures in the normally temperate climate of south Florida, such as associated with strong fast-moving winter cold fronts from Arctic latitudes. Also, future survival of *E. grandis* on some sites could be influenced by moisture stresses associated with variation of precipitation resulting from climate change, which was not evaluated in my model. My model was based on *E. grandis* with average sensitivity to the winter climate of south Florida. Use of *E. grandis* planting stock from clones selected for increased tolerance of frost could provide an adaptive management strategy to increase the resilience of new plantings of the species to the effects of possible climate change.

Case Study 3: Effects of Climate Change on High-Elevation Southern Appalachian Forests

During the Pleistocene, boreal-type forests extended as far south as South Carolina 12,800 to 19,100 years ago; warming during the Holocene caused these forests to retreat north to their present locations (Delcourt and Delcourt 1998). Because of persistent cold climates found at high elevation sites in the Southern Appalachian Mountains, forests of red spruce (*Picea rubens*) and Fraser fir (*Abies fraseri*) remain on the highest peaks. These "sky islands" are some of the most uncommon forests of the South (White et al. 1993). They are widely dispersed and separated by a sea of lower elevation hardwood forest (Payne et al. 1989).

In Virginia, red spruce follows a 20°C July isotherm (Pielke 1981), and is associated with sites having >140 frost days, average annual temperatures ≤8°C and average precipitation ≥140 cm (Nowacki and Wendt 2010). Cogbill and White (1991) found that across the Appalachians the transition zone (ecotone) between spruce–fir and adjacent hardwood forest corresponds with a 17°C average annual July temperature and suggested that an elevation of 1610 m is the average lower boundary of continuous spruce–fir forest in the Southern Appalachians. However, pockets of this forest type may occur as much as 400 m lower in ravines, depressions, or other cold air pockets (Delcourt and Delcourt 1998). During the mid-Holocene period, temperatures may have been about 2°C higher than today (Delcourt and Delcourt 1998), and this short period of warming would have displaced the spruce–fir upward limits by 70–130 m, causing extinction on sites less than 1740 m high (Whittaker 1956) and explaining the rarity of these forests at lower elevations today.

To forecast persistence of these forests over the next 50 years, we modeled potential effects of climate change on high-elevation spruce–fir forests using best-case and worst-case scenarios, selected from four possible climate scenarios (Wear et al. in press).

Methods: The reduction in temperature with increasing elevation is termed the "lapse rate," which varies by season, climate, and topography. Cogbill and White (1991) suggested that spruce–fir forests ecotones correspond with a 17°C temperature in July. Thus, we used the average July lapse rate (−6.3°C/km) for the entire Appalachian Mountain range (Leffler 1981). Although steeper than the average annual lapse rate (−5.8°C/km), this lapse rate was similar to regional July rates modeled by Bolstad et al. (1998) for the Southern Appalachians (~6.5°C/km). Our selection of 1610 m as the current elevation for persistence of continuous spruce–fir forests in the Southern Appalachians was based on calculations by Cogbill and White (1991), and is congruent with modeling by Hayes et al. (2007) on combined average minimum elevation (1605 m) required for continuous spruce–fir forests on both previously logged (1698 m) and unlogged (1513 m) sites. Although spruce–fir forests generally do not occur on peaks lower than 1740 m in elevation, we included these peaks because our goal was to determine areas that could retain spruce–fir forests or may be suitable habitat for restoration of this forest type in the future.

In selecting the best-case scenario, we opted for the one that predicted wetter cooler summers (average temperature increase of 1.5°C in July; CSIROMK2 B2) over the one that predicted lower annual temperatures (1.5°C) but higher average temperatures in July (2.4°C; CSIROMK3.5 A1B). The best-case scenario (Figure 10.27) predicted an increase in July temperatures of 1.0–2.0°C and precipitation increases of 3–21 cm (9.2 cm average). Our worst-case scenario (MIROC3.2 A1B) predicted increased July temperatures of 2.5–3.3°C (2.9°C average) and decreases in precipitation of 11–24 cm (18.2 cm average) (Figure 10.28).

Results: Based on a July lapse rate of −6.3°C/km with an average annual increase in July temperatures of 1.5°C, the best-case scenario for climate change would produce a 238 m increase in the minimum elevation of continuous spruce–fir forests by the year 2060. An average annual increase of 2.9°C would increase the elevation of the spruce–fir ecotone by 460 m under the worst-case scenario. Based on these estimates, the elevation of the northern hardwood/spruce–fir ecotone (or elevations thermally suitable for restoration) would move upward from a minimum of 1610 m to 1848 m (an increase of 238 m) under the best-case scenario (Figure 10.29). Alternatively, the worst-case scenario predicts a raise in the lower limit of the spruce–fir ecotone to 2070 m (an increase of 460 m). Based on these estimates, approximately 25,785 ha are currently suitable for spruce–fir forests, but only around 1685 ha of suitable spruce–fir habitat would remain by 2060 under the best-case scenario, a reduction of 94%. Under the worst-case scenario, our estimated lower limit of spruce–fir forests (2,070 m) is higher than the highest elevation (2037 m, Mount Mitchell in North Carolina), which would mean extirpation of these forests from the Southern Appalachians. These results are in agreement with Delcourt and Delcourt (1998), who suggested that expiration would occur with a 3°C increase in average July temperature.

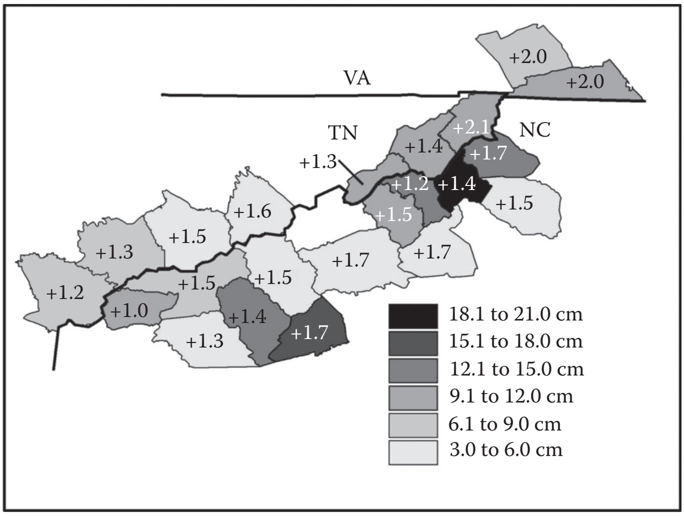

FIGURE 10.27 Projected changes from 2000 to 2060 in annual precipitation and projected rise in average July temperatures for high-elevation counties of the Southern Appalachian Mountains under a best-case scenario (CSIROMK2 B2), based on climate scenarios (Wear et al. in press); that were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high-energy use and B2 represents moderate population growth/low-energy use); numbers within counties indicate expected rise in average temperature (°C). Overall average July temperature change is +1.5°C and average annual precipitation change is +9.2 cm for all counties combined.

Discussion: Four parameters complicate predictions of spruce–fir persistence. First, Cogbill and White (1991) suggested that the current lowest elevation where spruce–fir ecotones currently exist is 1610 m, which is the current basal elevation we used. However, Hayes et al. (2007) suggested the minimum elevation for spruce–fir in the Great Smoky Mountain National Park is 200 m higher than what was found before widespread logging in the past 100 years. Hayes et al. (2007) developed

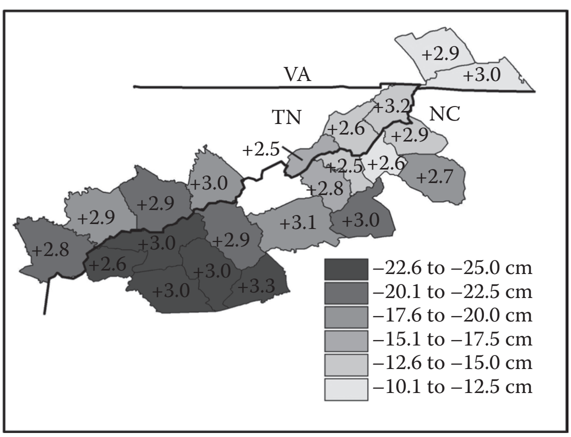

FIGURE 10.28 Projected changes from 2000 to 2060 in annual precipitation and projected rise in average July temperatures for high-elevation counties of the Southern Appalachian Mountains under a worst-case scenario (MIROC3.2 A1B), based on climate scenarios (Wear et al. in press); that were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high-energy use and B2 represents moderate population growth/low-energy use); numbers within counties indicate expected rise in average temperatures (°C). Overall average July temperature change is +2.9°C and average annual precipitation change is –18.2 cm for all counties combined.

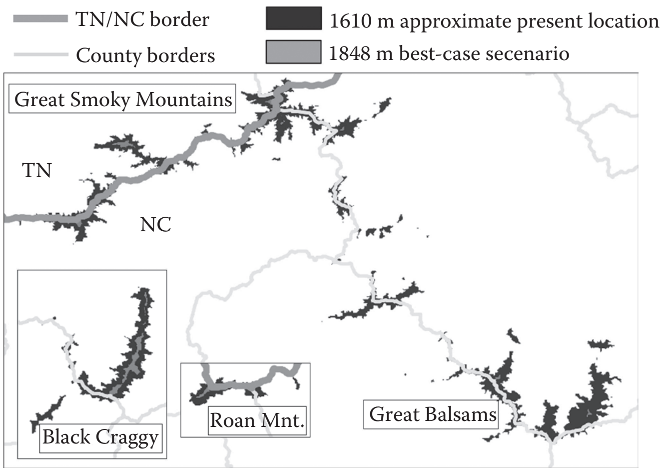

FIGURE 10.29 Estimated current location of continuous spruce–fir forests in the Southern Appalachian Mountains based on a minimum elevation of 1610 m above sea level, and potential location resulting from climate change by the year 2060 under a best-case scenario (MIROC3.2 A1B), based on climate scenarios (Wear et al. in press); that were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and two emissions storylines (A1B represents low population growth/high-energy use and B2 represents moderate population growth/low-energy use) (1848 m).

models that indicated spruce–fir forests typically occur >1513 m in areas not previously logged, compared to >1698 m at sites that were previously logged. Furthermore, minimum elevation on north and south slopes was similar in areas that were not previously logged, whereas minimum elevation was approximately 100 m higher on south slopes in areas that were previously logged. Thus, there is not a concrete consensus as to what minimum elevation spruce–fir forests can potentially inhabit given the effects of aspect and previous logging.

Second, estimating exact lapse rates at any one time or location is difficult because the lapse rates may vary by season, time of day, aspect, wind direction, humidity, topography, changes in elevation, presence of snow, atmospheric instability, cloud cover, and ground cover (Barry 1992). Lapse rates may also differ over mountain slopes compared to those in a free atmosphere, but average environmental lapse rates approximate −6°C/km (Barry 1992). Various average annual lapse rates, ranging from −4.9 to −5.8°C/km, have been used in studies to estimate temperature changes with elevation change in the Southern Appalachians (Cogbill et al. 1997; Delcourt and Delcourt 1998; Flebbe et al. 2006; Meisner 1990). Slight differences in the estimated lapse rate could lead to significantly different results, and variations in lapse rates resulting from topography could lead to greater or lesser than average changes in the minimum elevation associated with spruce–fir forests. Thus, constant or long-term average lapse rates should be used with caution (Bolstad et al. 1998).

Third, a retreat of spruce–fir forest could be exacerbated by reductions in precipitation predicted by the worst-case scenario. Spruce–fir forests are dependent on high atmospheric moisture, precipitation, and snowfall (Nowacki et al. 2010) and require moist conditions for germination and seedling survival (Hayes et al. 2007). Cloud cover also plays an important role (Hayes et al. 2007). The worst-case scenario predicted reduced atmospheric moisture, which could exacerbate the retreat and potentially reduce the possibility of remnant patches. Alternatively, the result of best-case scenario could lead to greater cloud cover, which might mitigate the effects of increased temperature. Thus, increases in the minimum elevation of spruce–fir forests from increased temperature could be lessened by increases in cloud cover.

Fourth, although large areas of continuous spruce–fir may be eliminated, some cold-pool areas and north slopes could potentially retain small patches of spruce–fir forests. These areas could retain spruce–fir forests, thus reducing the likelihood of complete elimination of spruce–fir under either scenario.

Although parameters for this modeling effort may be overly simplified, it illustrates the possible outcomes that could occur with increases in temperature. Given the uncertainty in precipitation changes among the various models and variable lapse rates, exact predictions would require substantially more effort but may still be tentative. An additional unknown is the interaction of climate change and the balsam woolly adelgid (*Adelges piceae*), which has killed large areas of mature forests of Fraser fir.

Case Study 4: Predicting Growth of Oak and Maple in an Old-Growth Forest in the Cumberland Plateau Tablelands

Old-growth forests are relatively rare in the Eastern United States, but some have been located in hardwood forests of the Cumberland Plateau, nearly all within plateau gorges (Clark et al. 2007; Martin 1975; Quarterman et al. 1972; Schmalzer et al. 1978). Only one large expanse of forest with old-growth potential (~600 ha) has been discovered on the tableland surface of the Cumberland Plateau (Haney and Lydic 1999). This forest is located in Tennessee's Grundy County on Savage Gulf Natural Area, which is listed as a National Natural Landmark by the U.S. Department of the Interior because of its biodiversity and unique geologic features (DeSelm and Clark 1975). The forest represents a unique opportunity to quantify long-term patterns of stand development, forest succession, and climate–tree growth relationships.

Using tree-ring and climate data to study old-growth forests can improve our understanding of the processes that influence forest communities (Henry and Swan 1974; Lorimer 1985; Oliver and Stephens 1977), eventually helping forest managers incorporate information about historical ranges of variability into silvicultural treatments that mimic past disturbance characteristics (Coates and Burton 1997; Swetnam et al. 1999; Webster and Lorimer 2005) and mitigating for the effects of climate change.

We examined climate–tree growth relationships of two dominant hardwoodgenera, oak (*Quercus* spp) and maple (*Acer* spp). Oaks have been continuously recruited at Savage Gulf for 300 years or more. Recently (~80 years) abundant, maple recruitment represents a species composition shift from the historically dominant oaks. This same species shift has been has been widely reported throughout the Central Hardwood Forest (Abrams 1998; McEwan et al. 2011; Nowacki and Abrams 2008). What is unknown is how these changing forests will respond to changes in climate.

Methods: We established 87, 0.04 ha fixed-radius plots throughout a 600-ha old-growth remnant, and we collected increment core samples from all oaks (*Q. alba*, *Q. prinus*, *Q. velutina*, *Q. coccinea*, and *Q. stellata*) and red maples (*A. rubrum*) ≥20 cm DBH. Once all rings were visually dated, we measured raw-ring width to the nearest 0.001 mm using a Velmex measuring stage interfaced with Measure J2X software; data were quality checked using the computer program COFECHA (Grissino-Mayer 2001; Holmes 1983). We created tree-ring chronologies using 98 oak series and 42 red maple series that had ≥0.5 species-specific interseries correlations to the composite chronology created by COFECHA. We used program ARSTAN (Cook, 1985) to produce the standard chronologies using negative exponential and negative linear detrending. We calculated predicted standardized tree-ring widths using instrumental climate variables from 1930 to 2009 with multiple regression. Our independent variables were 32 monthly climate variables (total precipitation and average daily temperature) from the year's previous July to current October. Instrumental climate data were downloaded for NOAA Climate Division 2 for Tennessee from the National Climate Data Center (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Climatic Data Center 2011). We used a stepwise selection to limit results to the most important monthly variables ($p < 0.05$) that predicted tree-ring widths. We used the final regression models to predict tree-ring widths for 2001 to 2060 using monthly climate variables derived for an ensemble of three emission scenarios (Mote and Shepherd 2011; Chapter 2): A1B representing low population with high economic growth and energy use, A2 representing a divided world with local environmental sustainability, and B1 representing rapid change toward an service and information economy with a strong emphasis on clean and resource-efficient technologies (Intergovernmental Panel on Climate Change 2007).

Results: Patterns of annual tree growth in oak and red maple (Figure 10.30) could be significantly predicted by monthly variability in climate. Oak had the strongest relationship with temperature of the current year's June and this relationship was negative (Table 10.35). Oak tree-ring variability was also weakly and positively related to current year's June precipitation and the previous year's August precipitation. Unlike oak, red maple had the strongest relationships with previous year's October precipitation and weaker but significant relationships with current year's February precipitation and January temperature; and all three of these variables were positively related to red maple tree-ring growth. Red maple was weakly and positively related to current year's August precipitation and negatively related to current year's May temperature.

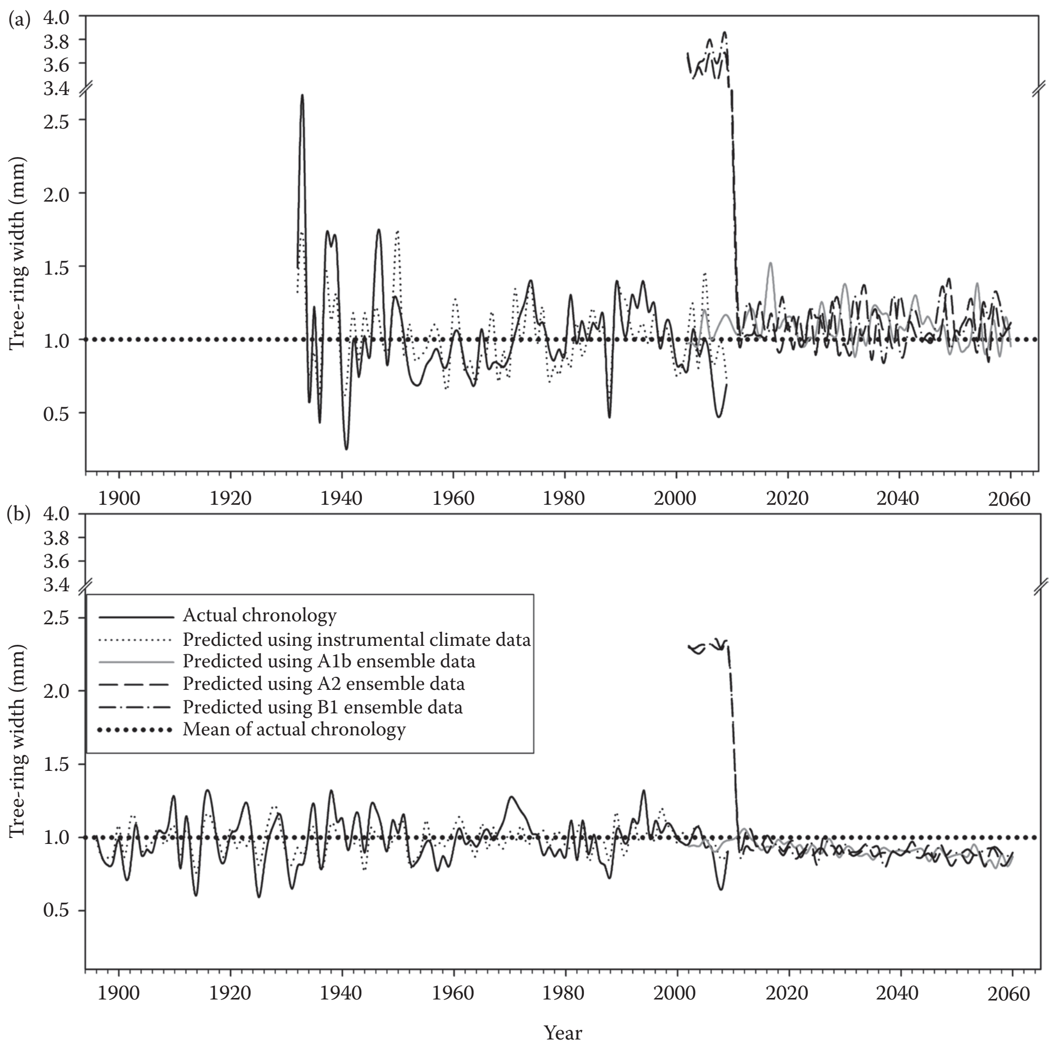

FIGURE 10.30 Actual and predicted tree-ring chronologies for (a) red maple and (b) oak species based on three emissions storylines (Wear et al. in press); scenarios were developed from three general circulation models (MIROC3.2, CSIROMK2 and 3.5, and HadCM3) and three emissions storylines (A1B represents low population growth/high-energy use, A2 represents a divided world with local environmental sustainability, and B2 represents moderate population growth/low-energy use).

TABLE 10.35
Regression Equations for Oak Species and Red Maple Derived from Instrumental Climate Data That Were Used to Predict Standardized Tree-Ring Widths from Ensemble Climate Model Data

Regression Equation	Independent Variable	Partial R-Square Value
Oak		
$Y = 1.770 + (0.001 * \text{JunePrecip}) + (0.002 * \text{previousAugustPrecip}) + (-0.046 * \text{JuneTemp})$ ($R^2 = 0.37$, $p < 0.0001$)		
	Current June precipitation	0.18
	Current June temperature	0.10
	Previous August precipitation	0.09
Red Maple		
$Y = 1.20530 + (0.00371 * \text{Octoberppt}) + (0.052025 * \text{JanuaryTemp}) + (0.00204 * \text{FebruaryPrecip}) +$ (⊠0.05741 * MayTemp) + (0.00173 * AugustPrecip) ($R^2 = 0.47$, $p < 0.0001$)		
	Previous October precipitation	0.14
	Current January temperature	0.15
	Current February precipitation	0.11
	Current May temperature	0.05
	Current August precipitation	0.03

Source: Adapted from Wear, D.N., R. Huggett, and J.G. Greis. In press. Constructing alternative futures. *Southern Forest Futures Project Technical Report.*

The three predicted tree-ring chronologies are similar in terms of long-term trends within the two species. The only noticeable difference among the predicted chronologies is from 2000 to 2009: the A2 and B1 chronologies have unusually high rates of predicted growth, and they exceed the A1 chronologies by approximately 1.3 for oak and 2.6 mm for red maple. Compared to the average of the species actual chronologies (1.0 mm), the tree-ring chronologies predicted from the ensemble emissions storylines indicated that red maple would slightly increase in tree-ring growth from 2010 to 2060, but oak would show a decrease.

Discussion: Our data suggest that the effect of climate change on oak and red maple will depend largely on the season of drought. We predict that oak trees on the tablelands of the Savage Gulf Natural Area will be most productive during years with cool and wet springs preceded by a wet summer. The documented spring temperature signal likely corresponded to water stress of oak by the influence of temperature on evapotranspiration rates. Climate–growth investigations of various oak species in the Appalachian-Cumberland Highland have revealed similar relationships (Copenheaver et al. 2010; Speer et al. 2009; White et al. 2011). In contrast, a cold and dry winter preceded by a dry autumn would most negatively affect red maple. Moisture availability during the previous year supports the production and storage of carbohydrates and, when coupled with abundant moisture during the subsequent growing season, results in increased productivity for both species. Red maple was not negatively affected by summer temperature, and in fact, favored higher winter temperatures.

The ensemble emissions scenario for the Cumberland Plateau and for Grundy County predicts approximately no change in precipitation from 2010 to 2060 (<50 mm change), but show an approximate 1.0°C (B1 ensemble) to 1.5°C (A1 and A2 ensembles) increase in temperature for the same time period. The effect on red maple and the oak is speculative, but based on our data, we suggest that oak will be more negatively impacted by predicted temperature increases compared to red maple if precipitation stays the same or shows a marked decrease. We also predict that rising spring temperatures without a corresponding increase in spring and/or summer precipitation would negatively affect both species. Climate change could result in oak mortality at the Savage Gulf and elsewhere in the region if temperature increases are particularly high in the spring without a corresponding precipitation increase. While oaks are considered to be drought tolerant generally, drought has been documented to cause oak mortality in the Southern Appalachian Mountains (Clinton et al. 1993, 1994).

In contrast to oak, red maple's growth was favored by higher winter temperatures, suggesting temperature increases related to climate change could actually favor dominance of this species. However, red maple could be negatively affected if precipitation was lacking in winter and previous autumn months. Effect of drought on red maple is not well understood in long-term field studies, but short-term physiological tests show the species is less tolerant to drought than associated oak species (Abrams and Mostoller 1995).

The Savage Gulf offers the rare opportunity to study climate-tree growth relationships of a sub-xeric forest that contains some of the oldest hardwood and pine (*Pinus* spp) individuals recorded in the Eastern United States (Hart et al. in press). To maintain the historic oak component in this ecosystem in the face of predicted climate change, resource managers would likely need to reduce basal area and stem density of shade-tolerant competitors, particularly invading red maple, in all canopy strata. Klos et al. (2009) noted that drought-induced mortality was smallest on sites with low stem density and basal area, flat terrain, and high species richness. The tablelands of the Savage Gulf exhibit all four of these characteristics and may therefore, have low susceptibility to drought-induced oak mortality. This management protocol would help mitigate effects of predicted future temperature increases on oak, and would aid in the long-term sustainability (Abrams 1998; Nowacki and Abrams 2008). Because mechanical tree harvesting is not a management option in the Savage Gulf, the use of prescribed fire in conjunction with natural disturbances that create canopy gaps may be a viable option for maintaining and restoring conditions to the pre-invasion levels of the mid-1900s (Abrams 2005).

SUMMARY OF FINDINGS

Effects on Tree Species Distribution

Vulnerability of tree species to climate change in the Southern Region is potentially highest (measured by number of tree species predicted to decrease their range) in the Mid-Gulf-West of the Coastal Plain, the Central Appalachian Piedmont, and the Ozark-Ouachita Highlands section of the Mid-South. In contrast, the ranges of many tree species are predicted to expand in the Southern Appalachian Piedmont and in the Blue Ridge and Northern Ridge and Valley sections of the Appalachian-Cumberland Highland. For most areas of the Southern Region, however, the predicted range of tree species is projected to remain little changed.

Vulnerability assessments varied considerably among the four climate predictions, particularly when comparing the MIROC3.2 A1B scenario to the other three model and scenario combinations. This is not an unexpected result, as the MIROC3.2 A1B projected the most extreme changes in temperature and precipitation over the region (Chapter 2) and our simple models were driven by changes in those two climate variables. For the Coastal Plain, the MIROC3.2 A1B scenario predicted a decrease in range for half or more of the species across all sections. Vulnerability of species was particularly high in the Florida Peninsular section where 27 of the 37 species evaluated were predicted to reduce their ranges. Future climate and vulnerability in the Florida Peninsular section are uncertain because the other three scenarios predict an increase in the ranges of 1–4 species.

We also found conflicting vulnerability predictions for the Northern Ridge and Valley section of the Appalachian-Cumberland Highland, where the MIROC3.2 A1B scenario predicted that 16 of 44 species would potentially decrease their ranges. The other three climate scenarios, however, predicted that 15 of the 44 species would possibly increase their ranges. Vulnerability of species will likely be marginal in the Mississippi Alluvial Valley, where all scenarios except the MIROC3.2 A1B predicted few changes.

Decrease or increase in the ranges of single species offers a simplistic approach to assess vulnerability to climate change. With few exceptions (such as the slash pine and longleaf pine forests of central and northern Florida), most southern upland communities consist of multiple species. Mixtures of the species selected in each section for the vulnerability assessment generally may not occur naturally, but are used here as an index of diversity for comparison of predictions from the climate scenarios.

Risk to Future Forest Diversity

Tree species: The overall effect of climate change on diversity of southern trees was predicted to result in small reductions of species richness in most of the 21 ecological sections studied, although the number of species may remain constant or increase slightly in several sections by the year 2060. Future diversity (quantified by species richness) was predicted to range between 95% and 100% of current levels for over half of the region. The largest changes in diversity, where species richness could be less than 85% of current levels, occurred in three sections, all in the Coastal Plain. Adverse effects were predicted to be least in the Northern Ridge and Valley section of the Appalachian-Cumberland Highland, where species richness could increase to 105% of current levels. Although the magnitude of results varied somewhat among climate scenarios, the overall trends were generally consistent that tree diversity could decrease throughout the Southern Region by the year 2060, with the highest risks occurring in certain sections of the Coastal Plain, Piedmont, and eastern zone of the Mid-South.

The effects of climate change on diversity at the county scale are likely to occur in about half of the Southern Region. Potential loss of tree species will likely be largest throughout the Coastal Plain, the Piedmont, and the eastern zone of the Mid-South. Few or no changes in diversity are expected to occur in most of the Appalachian-Cumberland Highland, the western zone of the Mid-South, or the Mississippi Alluvial Valley. In the Deltaic Plain section of the Mississippi Alluvial Valley, however, some bottomland species excluded from our analysis rely on periodic flooding (e.g., baldcypress, *Taxodium distichum*) and could be affected by reduction in precipitation in other regions, such as the upper Midwest. However, because predictions of future climatic conditions—particularly annual precipitation—were variable among the four climate scenarios, determining which scenario is most relevant is currently largely conjecture; averaging predictions from an ensemble (Mote and Shepherd 2011) of the four models would be one way to account for climate changes in planning and reduce risk from making an incorrect choice.

Rare plant communities: Small areas of infrequently occurring plant communities have been identified in the Southern Region that may be particularly vulnerable to climate change (Grossman et al. 1994) (Table 10.36). Many of these communities are associated with unusual combinations of geology and topography that form unusually wet or dry environments occupied by characteristic species. For most of these communities, assessing vulnerability and risk from climate change was beyond the scope of this chapter, but consideration of special conservation measures is important as well as recognition that many species may be important where they occur.

MANAGEMENT OPTIONS TO REDUCE VULNERABILITY AND RISK

Because of the long-term nature of forestry, all landowners actively engaged in resource management will face challenges resulting from climate change. Landowners with holdings in areas of the Southern Region that face the highest threat to vulnerability for certain species (such as shortleaf pine in western Arkansas) and high risk to species diversity (such as in the Ozark-Ouachita Highlands section of the Mid-South) will be among those who need relevant information on resource management the earliest. Required information related to climate change is available for many species, especially loblolly pine (Huang et al. 2011; McNulty et al. 1998; Schmidtling 1994) and others (Ge et al. 2011) with high commercial value. However, information is lacking for other "nontimber" (or lower

TABLE 10.36
Examples of Currently Rare Plant Communities of the Southern United States (Grossman et al. 1994) That Have Increased Vulnerability to Climate Change Resulting from Increased Annual Temperature and Decreased Annual Precipitation

Species or Community	State
Florida Torreya	FL
Crowley's Ridge Forest	AR
Red Spruce–Fraser Fir Forest	NC, TN, VA
White Oak/*Vaccinium* spp Dwarf Forest	AR, OK
Sabal mexicana Wetland Forest	TX
Barrier Island Depression Forest	GA, NC, SC, VA
Coastal Plain Calcarious Mesic Forest	All
Gulf Coast Maritime Forest	AL, FL, MS
South Atlantic Island Maritime Forest	FL, GA, SC

commercial valued) species, particularly hardwoods that increase species richness by providing foraging and cover habitat for wildlife; examples are water oak, southern magnolia, and sweetgum. Detailed assessment of specific issues of resource management is beyond the scope of this chapter; however, the following paragraphs provide an overview of regeneration and other critical forest management issues that will be required to address the impacts of climate change on tree species in the Southern Region. In addition, other chapters address forest management issues that are associated with climate change, such as productivity and increased threat from wildfire and insects.

Changes to vegetation resulting from climate change will likely occur slowly in some subregions and may be inconspicuous in many areas of the Southern Region, particularly where temperature and precipitation remain similar to current levels. Because trees are relatively long lived, the earliest observed climate-related effects in forests may not be in species diversity, but changes of disturbances associated with drought, fire, insects, and storms (Dale et al. 2001). Previous widespread occurrences of both southern pine and engraver beetles have been associated with stress caused by lower than average rainfall during the growing season and warmer winters (Lombardero et al. 2000). The combination of increased temperature and declining precipitation could significantly change both the frequency and severity of bark beetle outbreaks in shortleaf pine stands (McNulty et al. 1998). Gan (2004) predicted that under future climate change, the southern pine beetle could kill from 4 to 7.5 times the 2004 value of trees killed annually by the beetle. As another example, the fungus that causes fusiform rust (*Cronartium quercuum* f. sp. *fusiforme*) is highly sensitive to temperature and humidity and further illustrates the effects of climate change on the threat of disease in southern pine (Chapter 6). This disease also affects hardwood species in upland oak hardwoods, particularly the northern red oaks, but also including water, willow, and laurel oaks. Additional information on effects of climate change on future insect and disease threats associated with the four specific climate scenarios may be found in Chapter 6.

Species composition changes are likely to occur in most subregions and many sections of the Southern Region. But those changes, driven by a failure to regenerate successfully (particularly for some species of oaks) will likely occur slowly and, therefore, could be less apparent than those associated with insects and diseases. Lack of oak regeneration success may result from reduced seed production by some species, such as many conifers and several hardwoods, such as yellow poplar and red maple. To maintain an historic oak component in some ecosystems in the likely event of climate change, land managers may need to consider reducing basal area and stem density of shade-tolerant competitors, such as red maple, in all canopy strata; or implementing management activities that favor more drought-tolerant oak species. In addition, even if seed production is adequate, regeneration failure may result from changing environmental conditions that do not support establishment and survival of newly established seedlings. Regeneration of stands using natural methods, such as shelterwood and single-tree selection (Chapter 7) are well suited for many upland hardwood types, but may not produce reliable results in some areas of the Southern Region, particularly where annual precipitation may be reduced and temperature may increase, thereby creating additional moisture stress. Planting has a number of advantages over natural methods as a means of controlling species composition in areas where climate change may adversely affect environmental conditions needed for successful regeneration. Schmidtling (1994) suggests that provenance tests offer an available source of information on performance of planted species under a changing climate. Although artificial methods may be more expensive to implement than natural regeneration, site preparation followed by planting will usually provide reliable results for certain species. In addition, planting allows the resource manager to select seedling sources that might be better suited for predicted future climatic conditions compared to that which currently exist on the site (Schmidtling 2001). Artificial regeneration of preferred tree species by planting could be a viable alternative to natural methods for resource managers concerned about short-term effects of climate change on species composition. Aitken et al. (2008) suggest that genetic selection from natural variability within a species offers a realistic method for resource managers to respond to climate change when trends of future temperature and precipitation become more apparent for an area. Additional information on using artificial regeneration for controlling species composition in response to climate change is presented in Chapter 7.

In conclusion, our simple analyses provide just a glimpse of how climate change may impact the distribution and diversity of some tree species in the Southern Region. Indeed, the rapid pace of climate change may preclude migration of species to new suitable habitats and the only viable approach to maintain species and communities will be through active and aggressive (e.g., facilitated migration) forest management. However, as noted in Chapter 7, it is unlikely that coordinated large-scale activities will be implemented across the vast array of ownerships in the South, at least in the short term. If some of the more extreme projections of climate change (such as MIROC3.2 A1B) are observed and disturbance regimes increase in frequency and severity as projected (Vose et al. 2012), then it is likely that forest composition and diversity will change in many areas in the South. These changes could have important ramifications for other resources such as wildlife habitat (Chapter 11) and water resources (Chapter 9).

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