CHAPTER 9

Managing Effects of Drought in the Southeast United States

Steven McNulty, Aurelia Baca, Michael Bowker, Steven Brantley, Tyler Dreaden, Steven W. Golladay, Tom Holmes, Natasha James, Shan Liu, Rima Lucardi, Albert Mayfield, Ge Sun, Emrys Treasure, L. Mike Conner, Lora L. Smith, and James M. Vose

S. McNulty is the Director of the Southeast Climate Hub, U.S. Department of Agriculture, Forest Service, Southern Research Station, Research Triangle Park, NC 27709.

A. Baca is a Climate Specialist, North Carolina State Climate Office, Raleigh, NC 27506.

M. Bowker is a Research Social Scientist, U.S. Department of Agriculture, Forest Service, Southern Research Station, Athens, GA 30602.

S. Brantley is an Ecohydrologist, Joseph W. Jones Ecological Research Center at Ichauway, Newton, GA 39870.

T. Dreaden is a Plant Pathologist, U.S. Department of Agriculture, Forest Service, Southern Research Station, Forest Health Research and Education Center, Lexington, KY 40546.

S.W. Golladay is an Aquatic Biologist, Joseph W. Jones Ecological Research Center at Ichauway, Newton, GA 39870.

T. Holmes is a Research Forest Economist, U.S. Department of Agriculture, Forest Service, Southern Research Station, Research Triangle Park, NC 27709.

N. James is a Research Economist, U.S. Department of Agriculture, Forest Service, Southern Research Station, Research Triangle Park, NC 27709.

S. Liu is a Data Scientist, Cisco, Date and Insights, Morrisville, NC 27560.

R. Lucardi is a Research Ecologist, U.S. Department of Agriculture, Forest Service, Southern Research Station, Athens, GA 30602.

A. Mayfield is a Research Entomologist, U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC 28804.

G. Sun is a Research Hydrologist, U.S. Department of Agriculture, Forest Service, Southern Research Station, Research Triangle Park, NC 27709.

E. Treasure is the Regional Inventory, Monitoring, Assessment, and Climate Change Coordinator, U.S. Department of Agriculture, Forest Service, National Forest System, Southern Region, Atlanta, GA 30309.

L.M. Conner is a Wildlife Ecologist, Joseph W. Jones Ecological Research Center at Ichauway, Newton, GA 39870.

L.L. Smith is a Wildlife Ecologist, Joseph W. Jones Ecological Research Center at Ichauway, Newton, GA 39870.

J.M. Vose is a Senior Research Ecologist, U.S. Department of Agriculture, Forest Service, Southern Research Station, Center for Integrated Forest Science, Research Triangle Park, NC 27709.

INTRODUCTION

The Southeast United States (i.e., Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, Tennessee, Texas, South Carolina, Virginia) is considered to be a water-rich region. In an average year, precipitation is about 20 times more than is needed for human use within the region (Sun et al. 2008). However, the precipitation is not evenly distributed over time and space, and periodic droughts can occur almost anywhere in the region and at any time throughout the year. If drought is not considered in forest management, the risks of forest mortality, insect and disease outbreaks, wildfires, and other disturbances all increase. (McNulty et al. 2013). This chapter explores why droughts occur in the Southeast; how these droughts can affect ecosystem structure, function, goods, and services; and how forest managers can reduce drought impacts through forest management. This information will become even more valuable in the future as climate variability increases (IPCC 2014).

Climate of the Southeast

The climate of the Southeast is variable and is influenced by many factors, especially the region's topography, proximity to the ocean, and latitude. Generally, the average temperature decreases with latitude and elevation, and precipitation tends to decrease further inland from the Gulf and Atlantic coasts. The Southeast often receives systems capable of producing floods, but the region also has frequent droughts. Compared to droughts in the Southwest and Great Plains, droughts in the Southeast are relatively short (i.e., usually 1–3 years) (Seager et al. 2009). Drought conditions can rapidly develop across the region, caused by a lack of tropical cyclone activity, warm-season rainfall variability, higher rates of plant evapotranspiration (ET), and increased water usage (Kunkel et al. 2013). The position of the Bermuda High in the northwest quadrant of the Southeast strongly influences summer precipitation. The Bermuda High is a semi-permanent high-pressure area in the Atlantic Ocean. Shifts in the location of this high can cause drought across the Southeastern United States (fig. 9.1).

Another influence on the precipitation patterns across the Southeast is the El Niño-Southern Oscillation (ENSO). Unlike the Bermuda High, the strongest ENSO effects typically occur during the winter months. El Niño-Southern Oscillation consists of two phases determined by sea surface temperatures (SST) across the equatorial Pacific. If the SSTs are above normal, then ENSO is considered an El Niño, or warm phase. If the SSTs are below normal, then ENSO is a La Niña, or cool phase. An El Niño causes above-average precipitation across the region and reduces the probability of winter temperature extremes across the Southeast (Higgins et al. 2002). Unlike El Niño, La Niña is associated with drier weather, a higher risk of drought (Mo et al. 2009), and warmer than normal temperatures (Higgins et al. 2002).

The Southeast is one of the few regions of the world that did not show a statistically significant warming

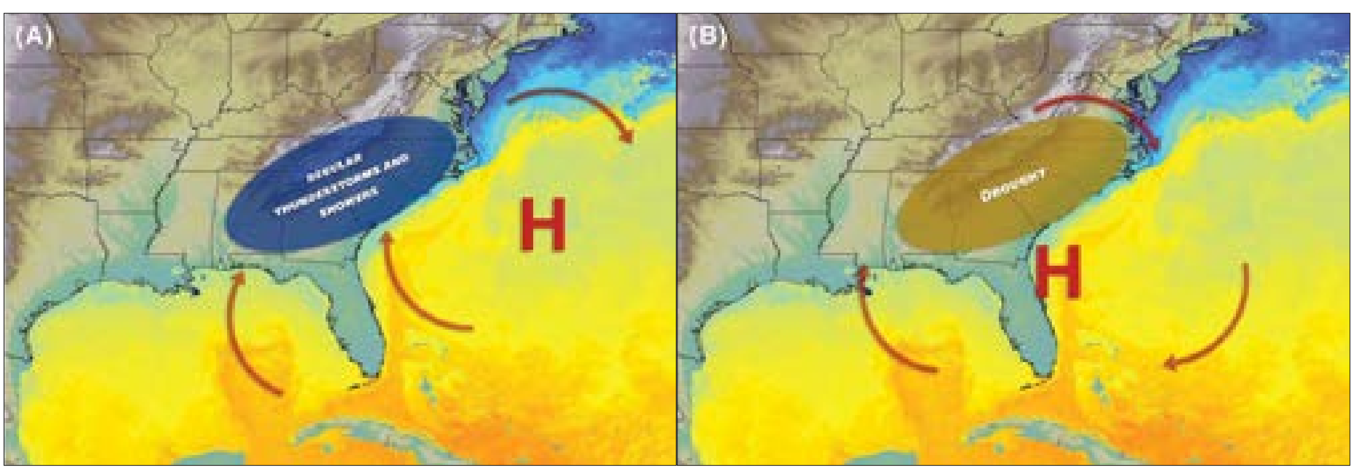

Figure 9.1—The Bermuda High position during the summer months. The left figure (A) indicates when the high pressure is just offshore, consequently causing thunderstorms across the region. The right figure (B) depicts when the high pressure is closer inland, causing drought conditions to materialize across the Southeast United States. The arrows indicate the surface air circulating around the high-pressure system. (Source: State Climate Office of North Carolina: http://climate.ncsu.edu/images/drought_images/BermudaHigh_Droughtwide.png, http://climate.ncsu.edu/images/drought_images/BermudaHigh_Typicalwide.png)

trend during the 20th century (IPCC 2014). Instead, the region varied in both annual and seasonal air temperature. A warm peak occurred during the 1930s and 1940s, followed by a brief midcentury period of cooler temperatures. From 1901 to 2016, the average temperature of the Southeast increased 0.46 °F (Vose et al. 2017). Since the 1970s, mean temperatures have increased by about 2 °F. For most regions, mean temperature has increased over the 20th century, mostly because minimum air temperatures have increased (Powell and Keim 2015), especially in the summer (Kunkel et al. 2013). Since the late 20th century, the number of days exceeding maximum temperatures of 95 °F has been increasing, and the number of days below 10 °F has decreased (Kunkel et al. 2013).

Southeast annual precipitation has also varied during the 20th century. However, two overall trends emerged. First, the summer months had significantly less precipitation, by about -2.54 mm per decade (Kunkel et al. 2013). Second, extreme precipitation events increased over the 20th century (Powell and Keim 2015, Wuebbles et al. 2014), particularly since the 1970s (Easterling et al. 2000). Many parts of the region showed an overall decrease in the number of consecutive wet days but an increase in very wet days (Powell and Keim 2015). Thus, precipitation events are becoming more intense, especially over Louisiana, Mississippi, Georgia, Florida, and Tennessee.

Historical drought in the Southeast—Based on paleoclimate data, historical drought conditions were frequent across the Southeast (Cook et al. 2007, Seager et al. 2009) and were most severe during the 14th and 16th centuries (Cook et al. 2007). Although drought conditions are common across the Southeast, and severe and extreme drought occurred intermittently during the 20th century, no long-term trend emerged for this period (Easterling et al. 2000).

However, changes in temperatures and precipitation occurred during the 20th century. Summers (but not the whole year) had a pronounced warming trend, a significant decrease in annual precipitation (Kunkel et al. 2013), and more time between precipitation events (Powell and Keim 2015), which in turn increased soil evaporation and reduced soil moisture. Between 1948 and 2012, the number of consecutive wet days decreased, and the number of days of extreme precipitation increased (Powell and Keim 2015).

Widespread drought conditions occurred across much of the Southeast during 1998–2002 and again in 2007–2008. Although not as geographically large as the Dust Bowl of the 1930s, the 1999–2002 drought set meteorological and hydrological records across the region (NOAA NCEI 2003). The precipitation totals from December 1999 to September 2000 were the lowest on record for the Deep South (i.e., Alabama, Georgia, Mississippi, and South Carolina), and the 2000 hydrological year was the fourth driest on record (NOAA NCEI 2001). The record dry conditions from 2001 continued into 2002, with extreme dryness affecting almost the entire East Coast. Overall, precipitation deficits were well below the annual average for the entire drought period of 1998–2002. Between August 2001 and July 2002, precipitation totals for Virginia, North Carolina, South Carolina, and Georgia were the lowest on record (NOAA NCEI 2003).

Another abnormally dry period began in December 2006 and continued throughout 2007. During the spring and summer months, the position of the Bermuda High deflected tropical storms away from the Southeast. By the summer of 2007, La Niña conditions were present across the equatorial Pacific, contributing to the drought. The culminating effect caused every month in 2007 (except October and December) to be drier than average (NOAA NCEI 2008). By November 2007, parts of the Southeastern United States experienced the worst drought on record while others ranked among the top 10 worst recorded droughts (Maxwell and Soulé 2009).

Types of drought—There are five types of drought: meteorological, agricultural, ecological, hydrological, and socioeconomic (Wilhite and Glantz 1985). Meteorological drought is defined as lack of precipitation and is region-specific. Agricultural drought occurs when precipitation shortages affect crop production. Ecological drought relates to the negative impacts of drought on ecosystem services. Hydrological drought refers to the effects of precipitation shortages on surface or subsurface water supply (e.g., groundwater, streamflow, lake levels). Socioeconomic drought refers to the effect of drought on the supply and demand of economic goods or on people's behavior, and it is the most difficult to quantify.

Several indices are used to describe types of meteorological and hydrological drought. The Standardized Precipitation Index (SPI) measures meteorological drought by comparing observed precipitation values to the climatic normal (Keyantash

2016). Anomalies determine abnormal wetness or dryness for short- and long-term droughts compared to a reference period (Keyantash 2016). An extension of the SPI is the Standardized Precipitation Evapotranspiration Index (SPEI), which incorporates potential ET along with precipitation (Vicente-Serrano 2015). The Palmer Drought Severity Index (PDSI) measures hydrological drought, using temperature and precipitation data to determine relative dryness. The PDSI is a measure for long-term droughts (over 12 months) and can capture effects of changing climate through potential ET (Dai 2017). The PDSI increased at a rate of about 0.04 per century (Cook et al. 2014), indicating a slight shift towards wetter conditions across the Southeast. Over the latter part of the 20th century, the frequency of both very wet and very dry summers increased (Groisman and Knight 2008, Wang et al. 2010), and drought conditions were more likely to result from rainfall deficits from the previous spring than from rainfall deficits during the summer (Wang et al. 2010).

Forecast for future drought in the Southeast—A lack of precipitation causes drought conditions, and warming temperatures can exacerbate these conditions (Strzepek et al. 2010, Zhao and Dai 2015). Climate projections agree that average temperature will rise during the 21st century, but there is less agreement on the direction, magnitude, and timing of changes in precipitation (Easterling et al. 2017, Kunkel et al. 2013, Sobolowski and Pavelsky 2012, Wuebbles et al. 2014).

Future climate in the Southeast was modeled using the Coupled Model Intercomparison Project Phase 3 (CMIP3), using high and low greenhouse gas emissions scenarios (Kunkel et al. 2013). Relative to the reference period of 1971–1999, the high emissions scenario model projected increases in mean annual temperatures of 3.5–5.5 °F by 2055 and 4.5–8.5 °F by 2085 (Kunkel et al. 2013) (fig. 9.2).

The North American Regional Climate Change Assessment Program (NARCCAP) uses multi-model regional climate model simulations (fig. 9.3) to project mean annual temperatures; it gives similar results to the CMIP3 model and includes seasonal projections (Kunkel et al. 2013). Relative to the 1971–1999 reference period, 2041–2070 mean temperatures will increase in all seasons in the Southeast. Summers will be 3.5–6.0 °F warmer (with the greatest warming in the northwestern part of the region), autumn will be 3.0–5.0 °F warmer (with most warming in the northern and western part of the region), winters will be 2.5–5.0 °F warmer (with the greatest warming in the northern part of the region), and springs will be 2.5–3.0 °F warmer throughout the region. Similarly, by the middle of the 21st century, summer surface temperatures are predicted to increase by 5.4 °F across most of the region, with intense warming continuing into the fall (Sobolowski and Pavelsky 2012). Winter and spring surface temperatures are also predicted to increase by 2.7 °F and 3.6 °F, respectively.

Future precipitation in the Southeast was also modeled using the CMIP3 and NARCCAP multi-model simulations. The CMIP3 evaluated high and low emissions scenarios for 2021–2050, 2041–2070, and 2070–2099, relative to the 1971–1999 reference period (Kunkel et al. 2013) (fig. 9.4). Overall, both emissions scenarios showed little change (<3 percent) in the amount of precipitation on average across the region throughout the 21st century. Less precipitation is predicted in the western part of the Southeast and more in the central and eastern parts. The largest predicted changes occur under the high emissions scenario for 2070–2099. However, some States could observe changes in precipitation that are larger than the regional average. By late in the 21st century, annual precipitation may increase up to 3–6 percent in North Carolina and Virginia and up to 12 percent in parts of Louisiana (Kunkel et al. 2013). Overall, annual precipitation rates in the Southeast are not expected to change much from current levels, but the seasonality and precipitation rates for a specific location could be more variable than the regional average.

The NARCCAP multi-model regional climate simulations (fig. 9.5) show differing results from the CMIP3. According to the NARCCAP high emissions scenario, annual precipitation is expected to increase across much of the Southeast, with the largest projected increase along the Gulf Coast (about 9–12 percent) and the largest projected decrease in southern Florida (up to 6 percent) (Kunkel et al. 2013).

NARCCAP simulations also predict increases in precipitation for every season (except summer) (Kunkel et al. 2013). Greatest precipitation increases are expected in the winter in the northern tier of the region and southern Florida (>15 percent), and in the fall along the Gulf Coast (>15 percent). In the spring, precipitation increases generally are predicted throughout the Southeast (15–20 percent), but with decreases (>10 percent) predicted in southern Florida and western Louisiana. Using NARCCAP, Sobolowski and Pavelsky (2012) determined similar results for precipitation. By the middle of the 21st century, precipitation is predicted

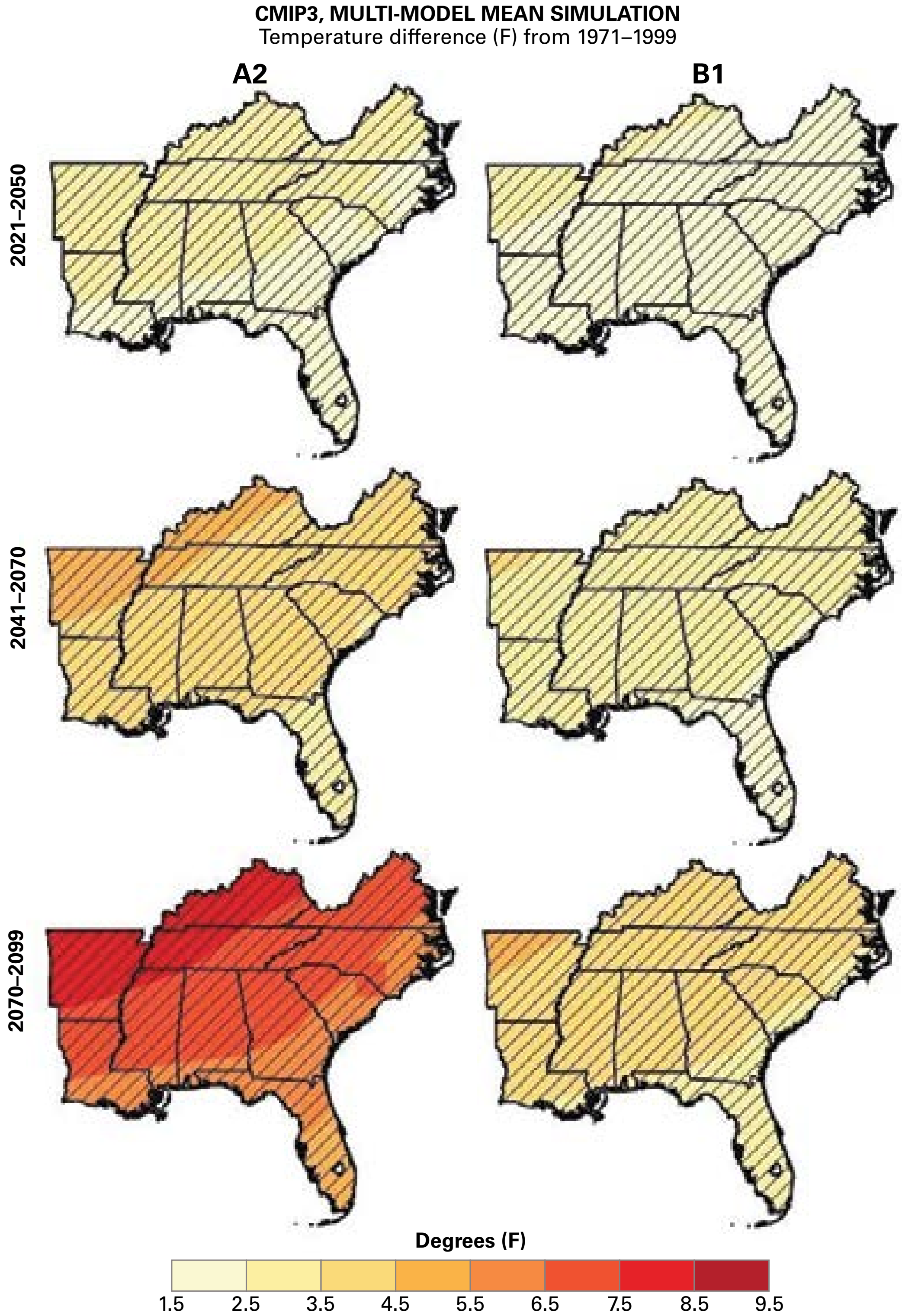

Figure 9.2—Projected annual mean temperatures (°F) across the Southeast. Both high (A2) and low (B1) emissions scenarios are shown over three time periods: 2021–2050, 2041–2070, and 2070–2099, relative to the reference period of 1971–1999. Annual mean temperature is positive for each emissions scenario and each model period. Hatching indicates that >50 percent of the models agreed that the change in temperature is statistically significant and 67 percent agree on the sign change. CMIP3 = Coupled Model Intercomparison Project Phase 3. (Source: Kunkel et al. 2013)

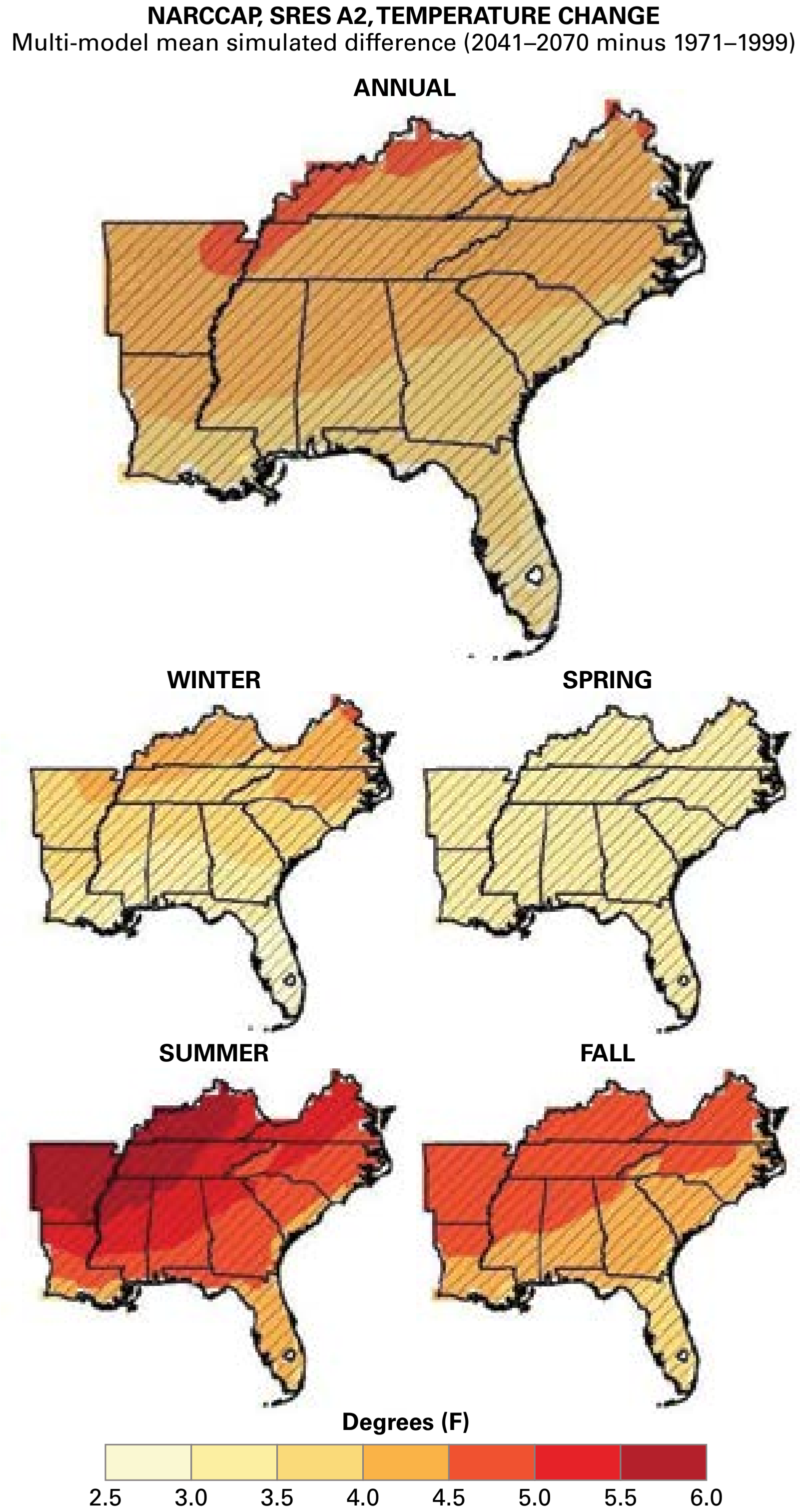

Figure 9.3—Projected annual and seasonal mean temperatures (°F) across the Southeast. The projections are for the high emissions scenario (A2) during 2041–2070 with a reference period of 1971–1999. The annual and seasonal mean temperature is positive across the entire region. The hatching indicates that >50 percent of the models agree there is a statistical significance and 67 percent agree on the sign change. NARCCAP = North American Regional Climate Change Assessment Program. (Source: Kunkel et al. 2013)

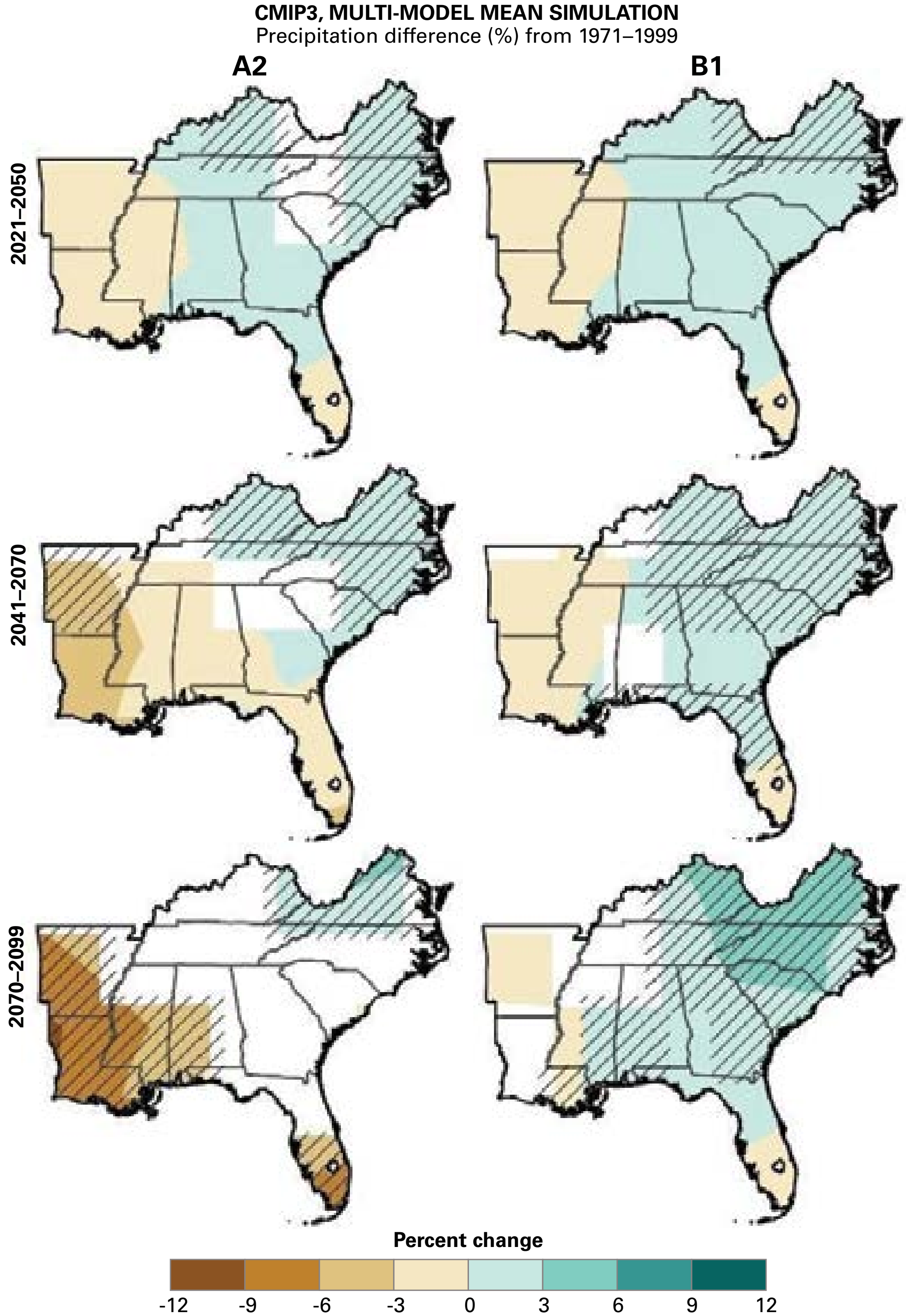

Figure 9.4—Projected difference in annual precipitation (percent) across the Southeast. Both high (A2) and low (B1) emissions scenarios are shown over each time period (2021–2050, 2041–2070, and 2070–2099). The reference period is 1971–1999. Color only indicates that <50 percent of models determined the change is statistically significant. Color with hatching indicates that >50 percent of the models agree there is a statistical significance and 67 percent agree on the sign change. CMIP3 = Coupled Model Intercomparison Project Phase 3. (Source: Kunkel et al. 2013)

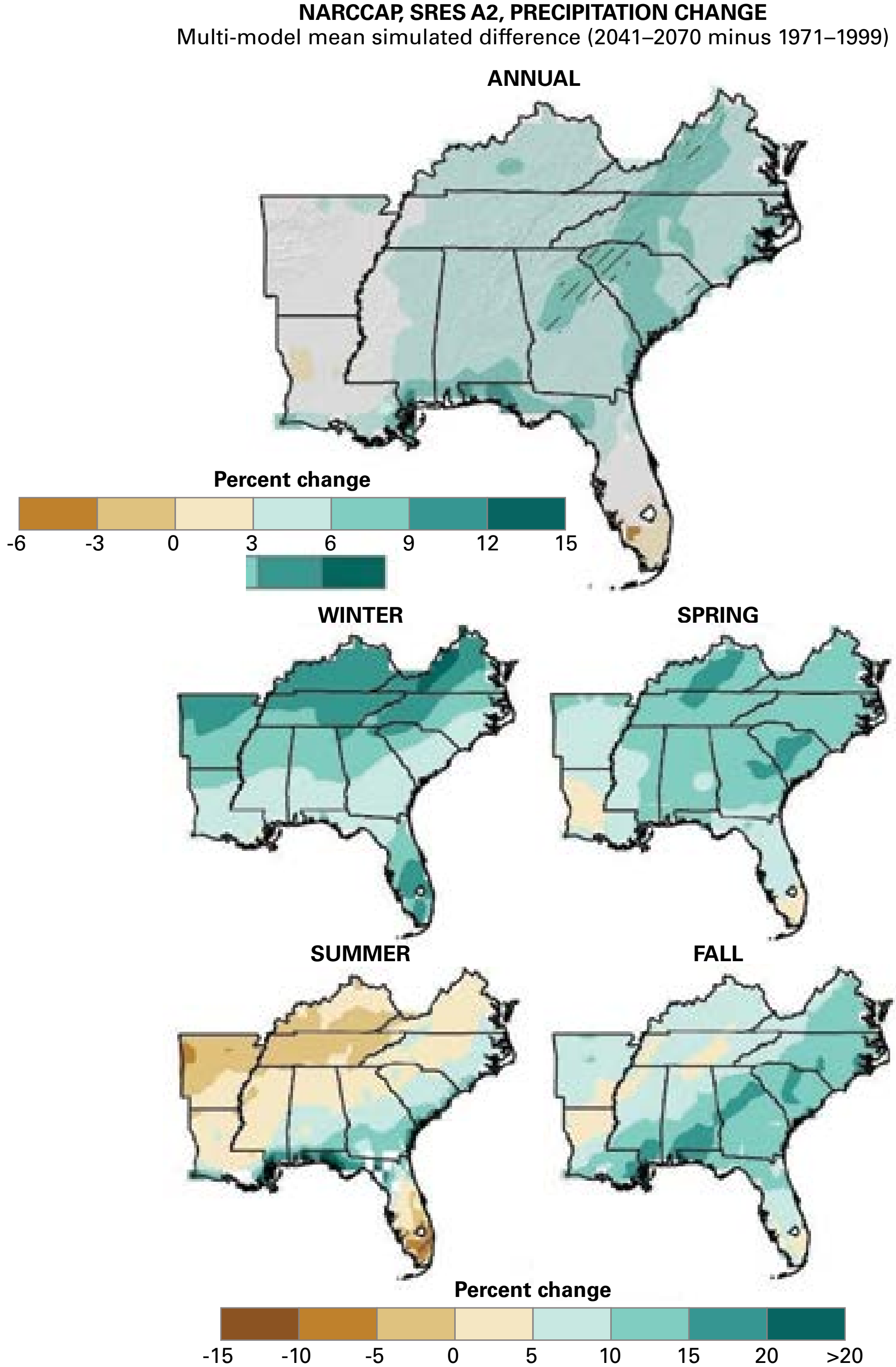

Figure 9.5—Projected annual and seasonal precipitation change (percent) across the Southeast. The projections are for the high emissions scenario (A2) during 2041–2070 with a reference period of 1971–1999. Color only indicates that <50 percent of models determined the change is statistically significant. Color with hatching indicates that >50 percent of the models agree there is a statistical significance and 67 percent agree on the sign change. NARCCAP = North American Regional Climate Change Assessment Program. (Source: Kunkel et al. 2013)

to decrease most (about 15 percent) during summer, and increase most (10 percent) across most of the region during the winter and spring, as well as along the southeast coast in the fall.

Variability in summer precipitation is strongly correlated with the location of the Bermuda High (Li et al. 2012). The position of the Bermuda High can cause drought conditions across the Southeast (Li et al. 2012) (fig. 9.1). Simulations suggest that rainfall will become more variable in the 21st century (Li et al. 2011, 2013; Wuebbles et al. 2014) due to a western shift in the Bermuda High that may lead to both exceptionally wet and exceptionally dry summers (Li et al. 2013, Wuebbles et al. 2014).

In addition to these likely future increases in summer precipitation variability, the overall net surface water gain in the Southeast is projected to significantly decrease in all seasons except summer under a high emissions scenario (Sobolowski and Pavelsky 2012). Furthermore, drought is more likely to occur when rainfall deficits start in the previous season (Wang et al. 2010). The findings taken together—the likelihood of future warming temperatures, a possible westward shift of the Bermuda High, and more summertime precipitation variability—suggest that summertime droughts may occur more frequently in the Southeast by the middle or end of this century.

In another simulation study of future precipitation in the Southeast, Swain and Hayhoe (2015) projected a standardized precipitation index (SPI) for the spring and summer seasons using two emissions scenarios (high [8.5] and low [4.5]) and three future periods (2020–2039, 2050–2069, and 2080–2099). Regardless of emissions scenario and time period, the Southeast is projected to experience future drier conditions in the spring (fig. 9.6), as well as in the summer for Florida and the Gulf Coast. However, the rest of the region is projected to become wetter during the summer (fig. 9.7).

Despite projections that precipitation will increase throughout most of the Southeast, drought frequency and intensity are projected to increase throughout the 21st century (Strzepek et al. 2010, Zhao and Dai 2015). As air temperature increases, so do ET rates, which lead to reductions in soil moisture and the development of drought conditions. As a result, moderate hydrological drought may increase by 5 percent, and severe hydrological drought may increase by 30 percent (Zhao and Dai 2015).

By the late 21st century, even the low emissions scenario predicts that moderate agricultural drought conditions may increase by as much as 50–100 percent, and severe agricultural drought may increase by 100–200 percent (Zhao and Dai 2015). Both short-term (4–6 months) and long-term (12 months) soil moisture deficits are projected to increase throughout the 21st century, and the spatial extent of soil moisture deficit conditions may also increase (Sheffield and Wood 2008). Based on the 3-month SPEI, the spatial extent of drought will increase the most during the summer (Ahmadalipour et al. 2017). Regardless of emissions scenario, drought intensity and frequency are projected to increase throughout this century (Ahmadalipour et al. 2017) (fig. 9.8).

Factors Interacting With Drought

Fire—Available fuel is often the determining factor for wildfire risk. For a wildfire to ignite, fuel must be of a certain size and moisture content. Large-diameter wood is more difficult to ignite and slow to dry, whereas small-diameter wood (i.e., twigs, sticks, small branches) has a high surface-to-mass ratio, and thus more exposure to oxygen and less moisture.

Fire can be either prescribed (i.e., intentional) or wild (i.e., unintentional). Prescribed fires are important to forest management, especially in pine forests to reduce hardwood competition. Prescribed fires can also be a cost-effective management practice to reduce competition, restore nutrients to the soil, and change competition for soil water (Renninger et al. 2013, Waldrop and Goodrick 2012). Roughly 9 million acres are burned in prescribed forest fires each year. Approximately 7 million acres of these fires occur in southeast forests (Melvin 2015). Most prescribed burning in the Southeast is conducted during winter and spring to help contain the fire and more effectively manage smoke.

Wildland fires, or wildfires, are often contained through fire suppression. Unlike prescribed fires, wildfires are destructive, causing over $5 billion in property damage in the United States between 2007 and 2017 (III 2017). Although most of the fire-burned acreage occurs in the Western United States, about 45,000 wildfires and 1 million acres burn annually across the Southeast. By the middle of the 21st century, climate change and other factors could triple the incidence of wildfire across the Southeast (Barbero et al. 2015).

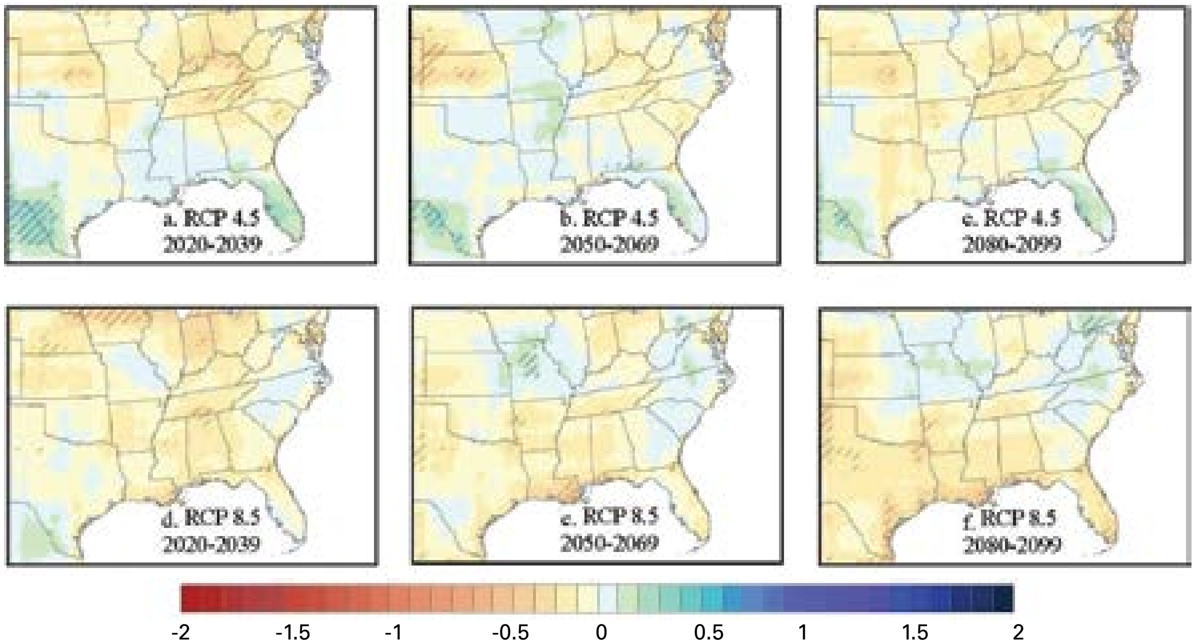

Figure 9.6—Ensemble mean Standard Precipitation Index (SPI) anomalies in spring (March, April, May) across the Southeast at three future time periods (2020–2039, 2050–2069, and 2080–2099) and under two emissions scenarios (RCP 4.5 and RCP 8.5). Anomalies were calculated as the future SPI minus the SPI for the historical base period of 1971–2000. Blue hatched areas: significantly higher SPI (wetter). Red hatched areas: significantly lower SPI (drier). RCP = representative concentration pathways. (Source: Swain and Hayhoe 2015)

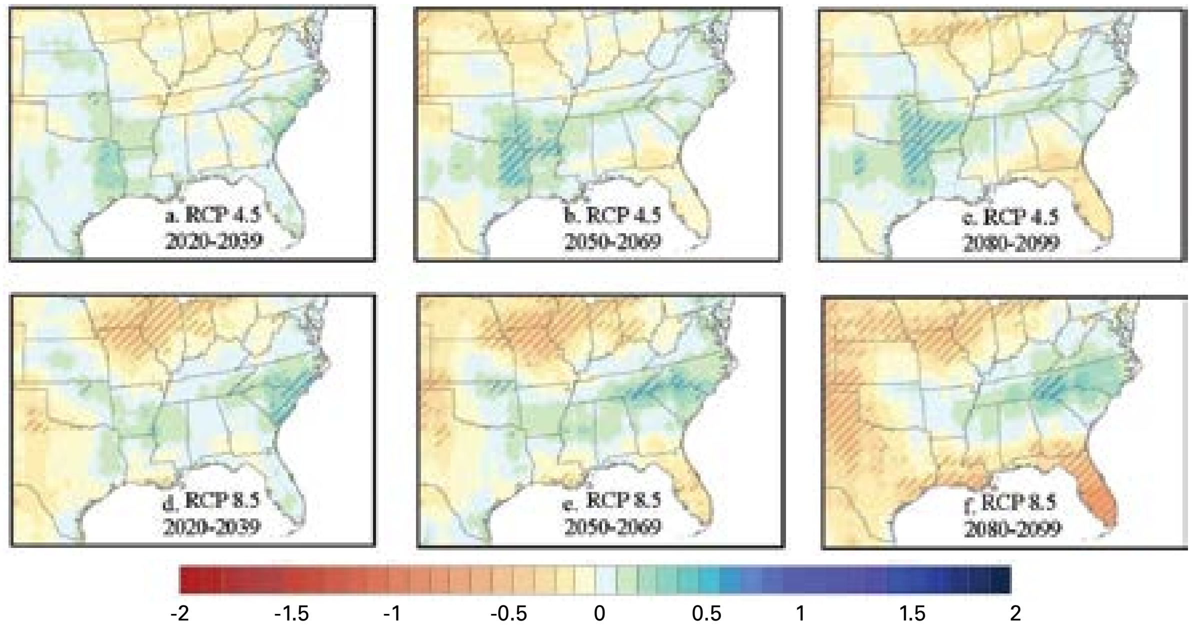

Figure 9.7—Ensemble mean Standard Precipitation Index (SPI) anomalies in summer (June, July, August) across North America at three future time periods (2020–2039, 2050–2069, and 2080–2099) and under two emissions scenarios (RCP 4.5 and RCP 8.5). Anomalies were calculated as the future minus a historical base period of 1971–2000. Blue hatched areas are projected to experience significantly higher SPI (wetter). Red hatched areas are projected to experience significantly lower SPI (drier). RCP = representative concentration pathways. (Source: Swain and Hayhoe 2015)

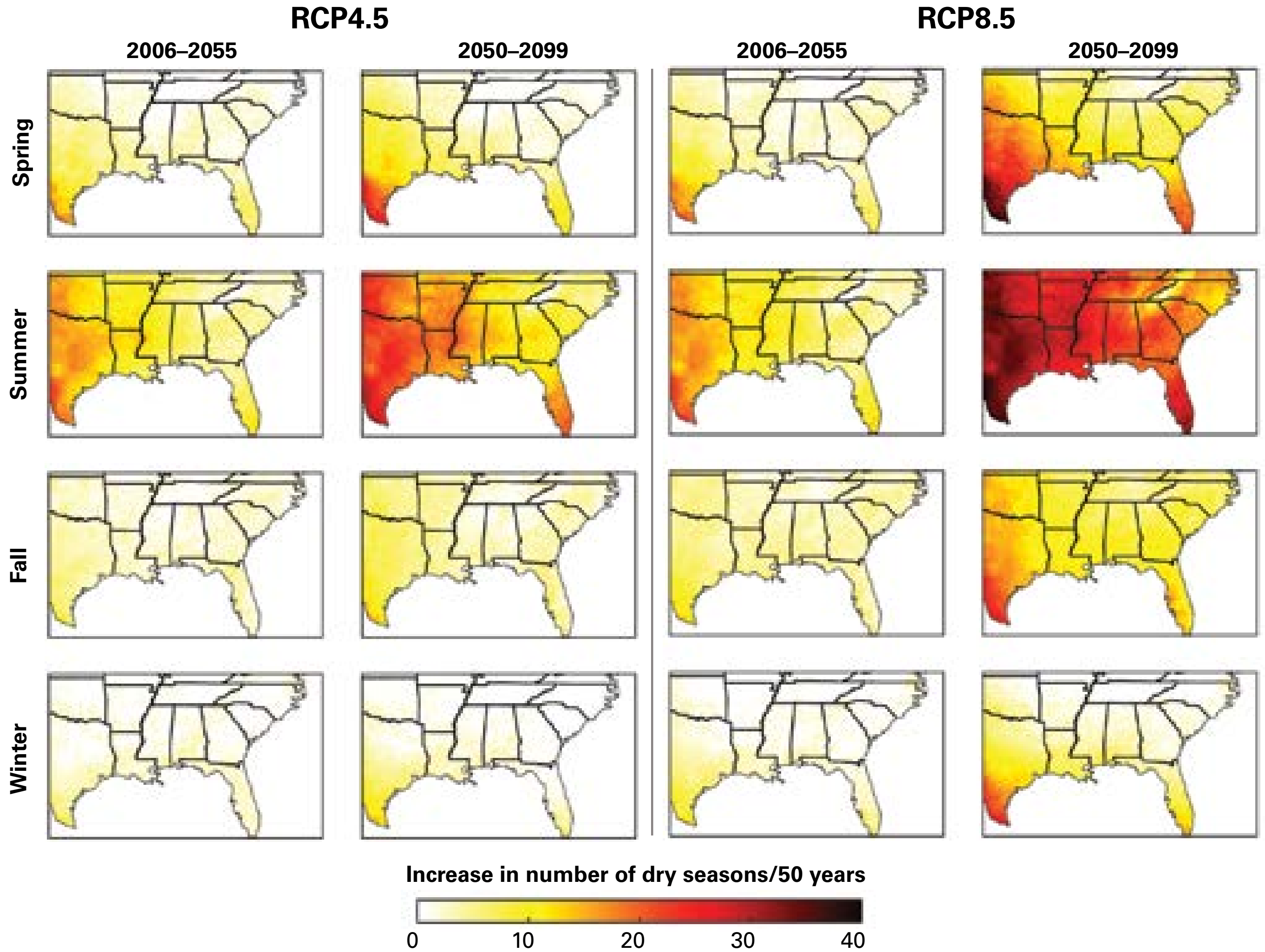

Figure 9.8—Predicted increases in the number of moderate or worse drought events in the Southeast by season according to the 3-month Standard Precipitation Index. Predictions are shown for two time periods (2006–2055 and 2050–2099) under two emissions scenarios (RCP 4.5 and RCP 8.5). RCP = representative concentration pathways. (Source: Ahmadalipour et al. 2017)

Although wildfires can be highly destructive to property, they are a natural component of many fire-adapted ecosystems. For example, pitch pine (*Pinus rigida*) and longleaf pine (*P. palustris*) are both fire-adapted species. Longleaf pine has a thick bark that protects the cambial layer from excessive heat, and both pine species benefit from the high temperatures associated with a fire for seed dispersal (Burns and Honkala 1990).

Drought is critical to wildfire occurrence and management. A drought requires several weeks or months to develop and can last for weeks or years. During these periods, forest rates of ET exceed rates of precipitation, and over time the soils lose moisture. With sufficiently severe loss, forest trees will lose leaves and could even die. Dead trees will begin to dry out, with smaller diameter material drying out first. This dry material becomes a potential source of wildfire fuel. For example, a 0.5-cm diameter stem can achieve a tissue moisture content of 15 percent within 2 days. As the fuel load dries out, fire risk increases. Once started, a fire can generate enormous amounts of heat and further decrease surrounding fuel moisture. As the fire grows, previously wet fuel and green living vegetation can dry out and become flammable sources of ignition.

Wildfire suppression activities aim to prevent loss of human life and destruction of natural and human-made assets. Severe droughts increase the risk of catastrophic and costly wildfires. The cost of wildfire suppression as a result of drought is thus a way to quantify the economic consequences of drought.

The Palmer Hydrological Drought Index (PHDI) (NOAA 2017), a widely used indicator of drought severity, represents the difference between the amount of water supplied by precipitation and the amount released by ET or lost as runoff. For the years 1995–2016, wildfire suppression in the Southeast averaged $12 million per year, but during drought years, suppression averaged $16 million, a 25-percent increase above the long-term average cost.

Insects and pathogens—Drought and the associated environmental conditions impact the population dynamics of forest insects, either through direct effects on the insects themselves or through indirect effects on their host plants, natural enemies, or environment (Bentz et al. 2010, Mattson and Haack 1987). Direct drought-related effects on insects include altered growth rates and fecundity. Indirect effects, mediated through host plants, include changes in plant palatability, attractiveness, nutrition, and defensive traits (Mattson and Haack 1987). Drought-related impacts by forest pest insects vary with the severity, timing, and duration of the drought, as well as the infestation, forest stand and site conditions, host species, insect-feeding guild, and type of plant tissue colonized (Huberty and Denno 2004, Jactel et al. 2012, Koricheva et al. 1998, Rouault et al. 2006). Discussed below are drought-related effects and management considerations with regard to forest insects of importance in the Southeast.

Pine bark beetles, such as the southern pine beetle (SPB) (*Dendroctonus frontalis*) or pine engraver beetles (*Ips* spp.), are generally secondary pests that colonize weakened trees. However, periodic outbreaks of the SPB are characterized by aggressive expansion of infestations. In periods of moderate water stress that result in decreased tree growth, more carbon is available for defensive resin production, potentially reducing pine susceptibility to SPB (Reeve et al. 1995). Under more severe drought, both growth and defense are compromised, and fewer beetles are needed to overwhelm trees, increasing the trees' mortality risk (Reeve et al. 1995, Schowalter 2012). Although local bark beetle outbreaks are often associated with drought-stressed trees, climatic variables have not been clear quantitative predictors of regional SPB outbreak dynamics. This is because outbreaks are driven by many factors, including stand density and condition, soils, and predator-prey interactions (Asaro et al. 2017, Hunter and Dwyer 1998).

Although sap-feeding insects may benefit from drought through mechanisms such as increased availability of nitrogen and other nutrients in plant tissue, they may be handicapped by decreased turgor pressure, increased sap viscosity, or inhospitable temperatures (Huberty and Denno 2004, Mattson and Haack 1987). The hemlock woolly adelgid (HWA) (*Adelges tsugae*) is an invasive sap-feeding insect in the Southeast, where it causes widespread mortality of eastern hemlock (*Tsuga canadensis*) and Carolina hemlock (*T. caroliniana*) (Vose et al. 2013). Hemlock woolly adelgid feeding induces a hypersensitive response in the tree, with physiological effects similar to water stress (Domec et al. 2013). Higher densities of HWA were found on experimentally water-stressed hemlock seedlings (Hickin and Preisser 2015), and evidence suggests that drought has exacerbated hemlock mortality in the presence of HWA in the Southern Appalachian Mountains (Ford et al. 2012). Water stress also reduces the ability of trees to take up systemic insecticide treatments, limiting HWA management options during drought conditions (Coots et al. 2015). Conversely, extreme heat may cause high summer mortality of dormant HWA (Sussky and Elkinton 2015).

Drought can affect tree pathogens and both increase and decrease tree disease (Desprez-Loustau et al. 2006). The direction and magnitude of the drought-pathogen interaction often depend on the specific host and pathogen, as well as the intensity, duration, and timing of the drought (Schoeneweiss 1986). Schoeneweiss (1986) linked pathogen aggressiveness with water stress and disease development, suggesting that nonaggressive, secondary pathogens produce disease after a threshold of water stress is reached. As pathogen aggression to primary pathogens increases, the effect of water stress on disease development decreases.

To date, most research has focused on interactions between specific hosts, pathogens, and water stress. More research is needed at the stand level on both biotic and abiotic stresses and their role in competition between trees. Two recommendations for forest management are to (1) reduce water stress to trees during drought, and (2) promote healthy trees and environments that discourage damage caused by pathogens (Breda et al. 2006).

Generally, water stress is thought to decrease damage from primary pathogens and increase damage from secondary pathogens (Desprez-Loustau et al. 2006), and this hypothesis generally seems to hold true in the Southeast. However, research is limited, and the interaction between drought and most diseases is unknown, but there are notable exceptions.

Pitch canker, caused by *Fusarium circinatum*, is more likely to infect hosts under periodic moisture stress, and trees at high stand densities are even more vulnerable (Blakeslee et al. 1999, Wingfield et al. 2008). With increasing drought in the future, damage from pitch canker is likely to increase. Heterobasidion root disease, caused by *Heterobasidion irregulare*, will also probably increase in severity with drought because water stress increases the susceptibility of loblolly pine (*Pinus taeda*) to this disease (Redfern and Stenlid 1998, Towers and Stambaugh 1968). Bacterial leaf scorch, caused by *Xylella fastidiosa*, predisposes hosts to canker-causing fungi, and both the bacterial and fungal infections are more severe during drought (Desprez-Loustau et al. 2006, Hopkins 1989, Sherald et al. 1983).

In an apparent exception to the rule, fusiform rust, caused by *Cronartium quercuum* f. sp. *fusiforme,* might cause less damage under drought conditions because drought decreases the available moisture needed for new infections (Desprez-Loustau et al. 2006, Schmidt et al. 1981).

Ink disease caused by *Phytophthora cinnamomi* interacts with drought, but how drought will affect this disease is not clear because impacts vary with the host species (Desprez-Loustau et al. 2006, Lewis and Arsdel 1978, Marçais et al. 1993).

Interactive stress—Stresses often interact because environmental conditions associated with one type of stress often contribute to another. For example, droughts often occur when stationary high-pressure systems develop that prevent moisture-laden, low-pressure systems from bringing rain to an area for an extended period (often months or longer). If nitrogen oxide levels are sufficiently high, stagnant, hot air masses are also conducive to ozone formation. Ozone can damage leaf stomata, increasing tree transpiration and reducing streamflow (Sun et al. 2012). As trees continue to evapotranspire without enough precipitation, soil moisture levels will drop. If the drought persists, soil moisture may be insufficient to maintain tree water demand. As tree moisture declines, oleoresin production may also decline, increasing tree susceptibility to insect attack of the cambial layer. Southern pine beetle outbreaks can occur during periods of tree water stress because the insects are more likely to create egg galleries in the phloem tissue without being pitched out by the resin.

Other interactive stresses may have no direct relation to drought but can predispose a forest to drought stress. For example, nitrogen is often a limiting factor in forest growth (Galloway et al. 2004). Therefore, over most forests (95 percent), the deposition of nitrogen is a benefit to forest productivity and carbon sequestration (Fenn et al. 1998). Added nitrogen can increase leaf area while reducing root mass because less root mass is required to satisfy tree nitrogen demands. As leaf area increases, so does tree water demand, while reduced root mass can reduce a tree's ability to acquire water (McNulty et al. 2014). Thus, although nitrogen deposition increases forest productivity, the morphological response to nitrogen deposition can elevate the risk of mortality during droughts.

Effect of Drought on Key Regional Resource Areas

Drought does not affect all regions or all resources in a region equally. Within the Southeast, Texas and Georgia have historically been the most drought-prone areas, and the resources in these areas will be particularly vulnerable to future drought. In addition to inequitably impacting certain areas, drought impacts also vary by ecosystem service.

To examine how historic droughts have affected forest water yield and gross primary productivity (GPP), Sun et al. (2015b) applied a validated Water Supply Stress Index model to 170 national forests (NFs) in the conterminous United States. The authors selected the top five extreme drought years during 1962–2012, defined as the top five years with the least annual SPI3 (i.e., Standardized Precipitation Index on a 3-month timescale). The extent of extreme droughts, measured by the number of NFs and total area affected by droughts, has increased during the 2000s. The extreme drought during the 2000s occurred in 2002, reducing mean water yield by 32 percent and GPP by 20 percent. On average, the five extreme droughts represented a reduction in precipitation by 145 mm yr^{-1} (22 percent), reducing water yield by 110 mm yr^{-1} (37 percent) and GPP by 65 g C m^{-2} yr^{-1} (9 percent). The responses of forest hydrology and productivity to these droughts varied spatially due to different land-surface characteristics (e.g., climatology and vegetation) as well as drought severity at each NF (figs. 9.9, 9.10). The Southeast has the highest streamflow rates in the United States, so similar losses in precipitation have less impact on streamflow in the Southeast compared to other regions (fig. 9.9).

Recreation and tourism—Recreation and tourism are integral sectors of the economy throughout the Southeast. Many outdoor activities are water-based and are therefore affected by drought. For example, about 12 million people in the Southeast participate in floating activities (e.g., canoeing, kayaking, and rafting), and another 21 million recreationists participate in motorized water activities (USDA Forest Service 2016). The amount of seasonal and annual precipitation, whether as rain or snow, can substantially impact recreational opportunities. Some recreational uses such as swimming, fishing, and boating directly depend on adequate water levels in streams, rivers, lakes, and reservoirs. Other activities such as skiing rely on adequate snowfall. Although less important in the Southeast than in other regions, limited snowfall can result in a modest snowpack, which, as it melts, provides inadequate streamflow to maintain water levels in lakes and reservoirs desirable for recreation. Drought also indirectly affects the level of recreation and tourism in forested areas through impacts on disturbance regimes. Because drought leads to increased risk of fire and forest pests, the resulting loss of forest cover and scenic beauty means fewer forest visitors (Ding et al. 2011). For areas that economically depend on recreation and tourism, the consequences of drought can be lasting. Research to date is limited on the connection between drought events and the recreation and tourism industry (Thomas et al. 2013).

Water levels in lakes and reservoirs directly impact recreational use. At four North Carolina reservoirs, higher water levels throughout the summer and fall led to more visits to the reservoirs and economic gains of millions of dollars per lake per year (Cordell and Bergstrom 1993). Studies of lowered water levels due to sedimentation (Eiswerth et al. 2000) and increased water withdrawal (Neher et al. 2013) showed similar results. Higher water levels in lakes and reservoirs were correlated with more visitation and therefore more tourism expenditures. Consistent with these findings, the 1985–1991 California droughts were correlated with fewer visits to reservoirs in the Sacramento district. As reservoir levels dropped, both day use visits and camping visits declined (Ward et al. 1996).

Although these studies do not show a causal connection between drought and tourism/recreation, the correlational evidence indicates that the conditions associated with drought (e.g., lower water levels) have had a consistent impact on this sector of the economy. The predicted increase in severity of future droughts in the Southeast could lead to a decline in tourism and recreation, and this in turn could negatively affect many areas where the regional economy depends on recreation and tourism dollars.

Water—By definition, drought limits water resources. A lack of precipitation recharge can affect any water resource: a stream, lake, reservoir, or groundwater. In vegetated landscapes in the Southeast, water use by plants (i.e., transpiration and evaporation) consumes a large proportion of precipitation (Vose et al. 2016). After plant water demand is satisfied, excess water becomes streamflow or groundwater recharge. Therefore, a moderate drought may have limited consequences to forest vegetation but a large effect on streamflow and aquatic systems (a.k.a., hydrological drought). The

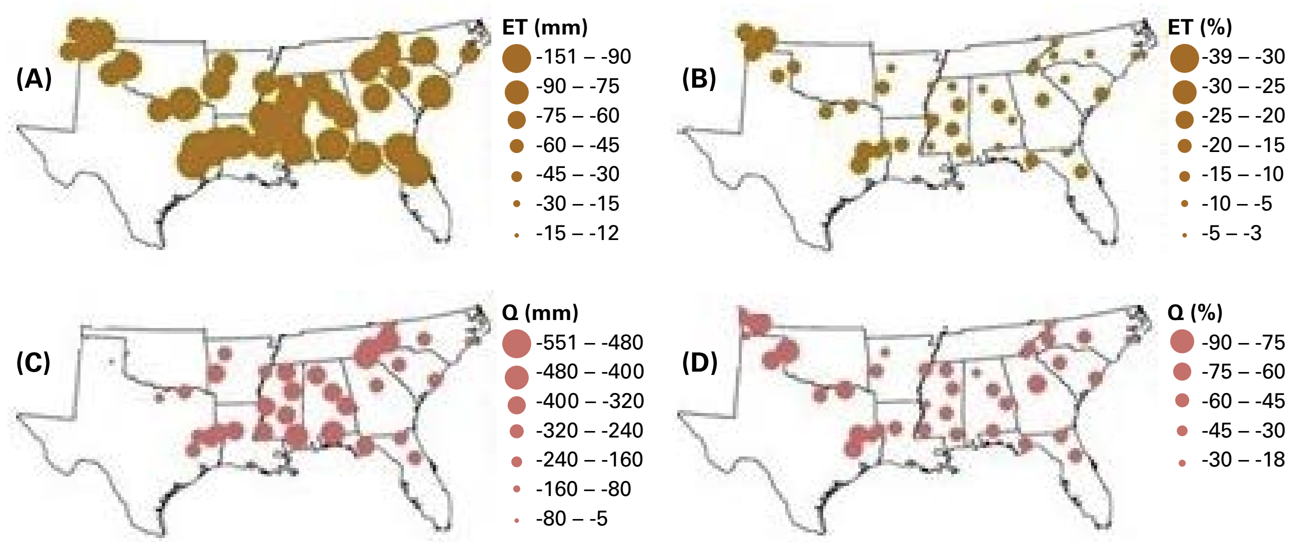

Figure 9.9—Differences in mean annual evapotranspiration (ET) and streamflow discharge (Q) between the years with five most severe droughts and the period 1962–2012. (A) ET difference (mm), (B) ET difference (%), (C) Q difference (mm), and (D) Q difference (%). (Source: Sun et al. 2015b)

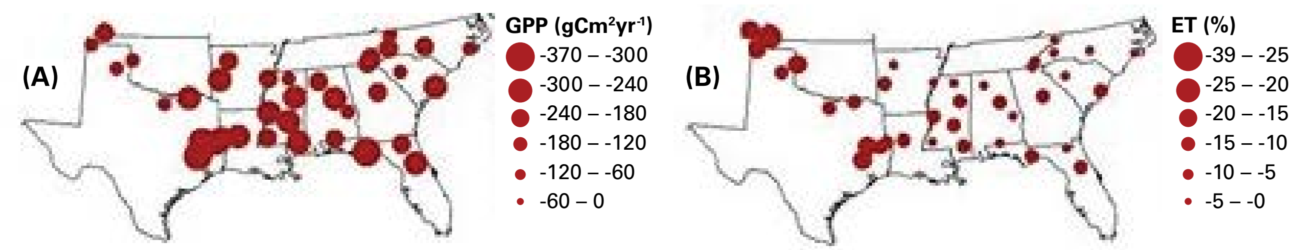

Figure 9.10—Deviations of (A) absolute values and (B) relative values of gross primary productivity (GPP) for the five most severe drought years from the long-term (1962–2012) averages. (Source: Sun et al. 2015b)

lack of precipitation recharge can also deplete shallow groundwater supplies.

Sun et al. (2015b) examined hydrological sensitivity to climatic and vegetation change in the United States using the Water Supply Stress Index (WaSSI) water balance model that runs at a monthly timestep, and a series of hypothetical scenarios. Hydrological responses to external disturbances varied greatly due to regional differences in background climate (i.e., potential ET and precipitation), vegetation (leaf areas index and species), and soils (fig. 9.11). Overall, a temperature increase of 2 °C could decrease water yield by 11 percent. Reductions of precipitation by 10 and 20 percent could decrease water yield by 20 and 39 percent, respectively. The direction and magnitude of water yield response to the combinations of leaf area index (+10 percent), climate warming (+1 °C), and precipitation change (±10 percent) were dominated by the change in precipitation. However, other evidence suggests that a large increase in air temperature (mean temperature >5 °C) due to global warming may offset the influence of precipitation on water supply in the United States by the end of the 21st century (Duan et al. 2017).

Fisheries—Historic increases in ET have resulted from land use intensification in both the agriculture and forestry sectors. These increases have already had a large effect on aquatic ecosystems during drought (Brantley et al. 2017, Golladay et al. 2007, Petes et al. 2012), and this effect may be further amplified by climate change. Streamflow is considered a 'master' variable that controls the ecological structure and function of streams and rivers (Poff and Zimmerman 2010). However, no single measurement can characterize streamflow; instead, multiple variables are used to quantify the magnitude, duration, frequency, timing, and rate of change in both common and uncommon events (e.g., low flows, base flows, and flood pulses) (McNulty et al. 2018, Olden and Poff 2003, Poff et al. 2010). The underlying assumption of this approach is that the maintenance of hydrological

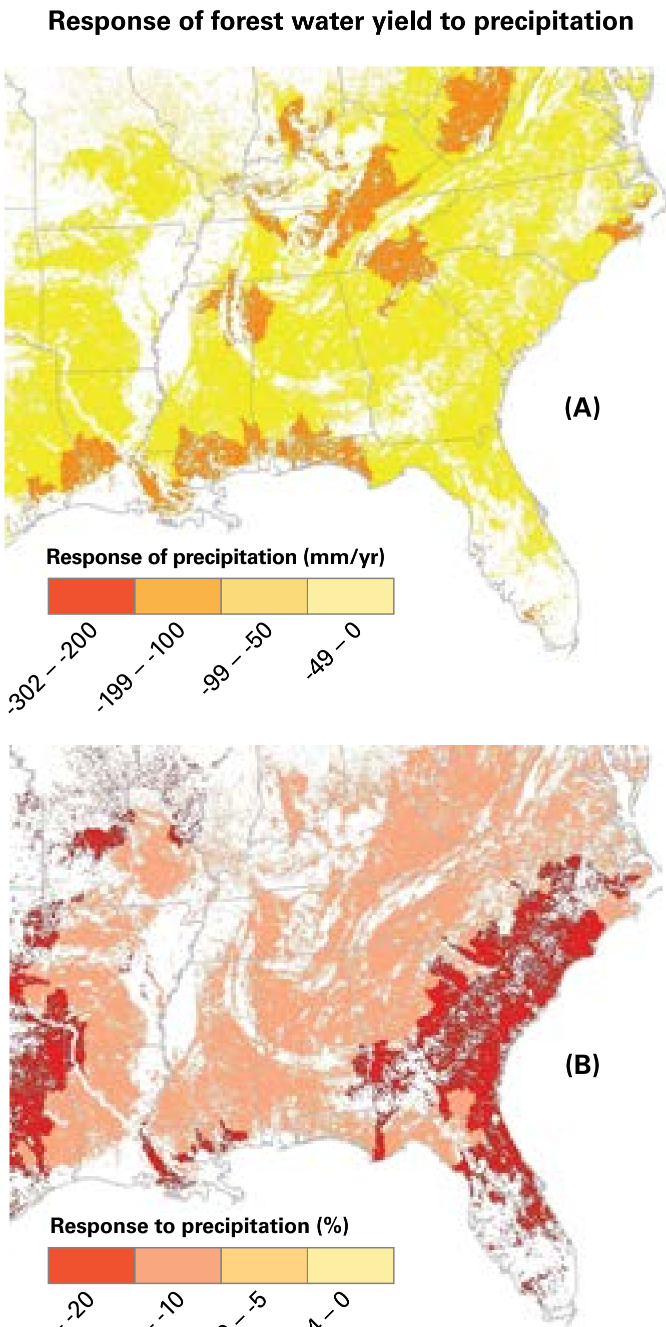

Figure 9.11—Forest water yield response across the United States to a 10-percent reduction of precipitation, as simulated by the Water Supply Stress Index model: (A) absolute values, (B) relative values. (Source: Sun et al. 2015a)

diversity conserves the structure and function of streams and rivers, even with water extraction (Poff et al. 2010). Hydrological diversity is assumed to promote ecosystem services (e.g., biological richness, assimilative capacity, recreation, fisheries) beyond simple water supply (Claassen et al. 2018).

Stream biota respond to drought and drying based on their life history characteristics, adaptations, and physiological tolerances. Traits of interest include dispersal ability, ability to find refugia during dry periods, desiccation-resistant life stages, reproductive rates, and life cycle duration (Griswold et al. 2008). Rheophilic fauna (e.g., brook trout, shoal bass, freshwater mussels) prefer perennial swift-flowing streams; they tend to have longer life cycles, poor dispersal abilities, and poor tolerances for low oxygen and high temperature (Williams 1987, 1996). As a group, rheophiles resist high flows and may even benefit from periodic flooding (Griswold et al. 2008). Rheophobes prefer less flow velocity so that they can better disperse and produce multiple generations per year (Griswold et al. 2008, Smith 2015). Some rheophobes can produce diapausing life history stages and can tolerate lower dissolved oxygen and higher water temperatures than rheophiles. As regional droughts develop, assemblages of aquatic biota may shift from dominance by rheophiles to rheophobes (Griswold et al. 2008, Smith 2015), depending on drought duration, intensity, and frequency.

Reduced summer streamflow and higher stream temperature have implications for ecological communities in rivers. The Southeast is an epicenter of global mussel diversity, and freshwater mussels, a group of regional concern, have already experienced declines in abundance associated with extended droughts (Emanuel and Rogers 2012, Golladay et al. 2004). Declines in sensitive mussel species are expected to continue. Similar drought-related changes in mussel assemblages have been observed in Oklahoma rivers (Allen et al. 2013).

Elevated stream temperatures have also been associated with the displacement of native crayfish by invasive species in the Southeast (e.g., Sargent et al. 2011). Responses of other invertebrate groups in the Southeast are less well understood, but changes in invertebrate assemblage structure, life history characteristics, and environmental tolerance have all been observed in response to drought (e.g., Griswold et al. 2008, Smith 2015). Shifts in fish assemblages would also be expected, with rheophilic species likely to show the greatest declines in response to unusual low flows (Freeman et al. 2012). Lower streamflows in the summer and during extended drought reduce access to and the availability of critical refuges from warm water. In addition to these direct ecological effects, low streamflows also reduce the seasonal volume of water available to receive permitted discharges. On top of these expected ecological changes, increased contaminant discharge may alter river assimilative capacity and increase water treatment costs for downstream users.

Droughts can impact fisheries more than terrestrial ecosystems. If water evaporation rates and outflows (natural or human-caused) exceed inputs, these systems can cause lakes and reservoirs to lose volume. The loss of volume may be accelerated because dry air associated with droughts increases water body evaporation rates. Human-centered demands for water for agriculture and residential irrigation place further stress on existing water supplies.

Wildlife—The effects of drought on upland wildlife in the Southeast are poorly studied. White-tailed deer (*Odocoileus virginianus*) were more selective of forage under drought conditions because fewer types of plants met their nutritional needs (Lashley and Harper 2012). Within a longleaf pine-dominated forest in southwestern Georgia, small mammal populations were heavily influenced by prescribed fire, with cotton rat (*Sigmodon hispidus*) abundance declining precipitously following fire events (Morris et al. 2011). Effects of precipitation among game species are perhaps best illustrated by the northern bobwhite (*Colinus virginianus*). Recent evidence from southern Texas suggests that landscapes with prominent woody cover may buffer drought effects in northern bobwhites; shading by shrubs may increase soil moisture, providing forage and cover during droughts (Parent et al. 2016).

More evidence exists for effects of drought on semi-aquatic wildlife, which depend on seasonally inundated wetlands. Numerous species depend on wetlands for all or part of their life cycle, and many, such as amphibians, are adapted to periodic droughts. These species are able to aestivate in suitable microhabitats within wetlands, move to more permanent water bodies, or have a terrestrial stage that allows them to persist until wetlands refill. However, changes in rainfall in the Southeast, including longer dry periods in summer, may threaten amphibians that depend on seasonally inundated wetlands (Walls et al. 2013a, 2013b). Specifically, these expected changes in rainfall may alter the timing and duration of the wetland hydroperiod. If this occurs, amphibians with an aquatic larval stage cannot completely develop, and the numbers of wetlands suitable for their habitat will decline.

Forest productivity and carbon sequestration—Drought can have consequences for ecosystem services provided by forests, including timber and nontimber resources. Wood fiber in the form of timber, pulp, and fuelwood are important forest outputs across the Southeast. In addition to these traditional forest commodities, carbon sequestration is a more recent area of interest as a process by which climate change can be slowed.

Although more is known about the consequences of droughts in western U.S. forests, where large-scale dieback events have occurred, eastern U.S. forests are also vulnerable to increasing drought (Clark et al. 2016). The effects of drought on southeastern U.S. forests are not well understood, and these effects may vary by species and ecological condition.

For example, tree growth and mortality rates across the Southeast measured from 1991 to 2005 indicate that pines and mesophytic species were more vulnerable than oaks (*Quercus* spp.) to increasing drought (Klos et al. 2009). In contrast, during the worst 1-year drought recorded in Texas (i.e., 2011), pine species coped fairly well relative to oaks and other species groups (Moore et al. 2016). In a recent analysis of regional species vulnerability to increasing temperature and drought, commercially important pine species such as loblolly pine and shortleaf pine (*Pinus echinata*) responded almost as much to drought (i.e., reductions in soil moisture) as they do to availability of light (Clark et al. 2014). Drought has influenced forest regeneration in the Southeast, with larger declines in the growth rate for mesophytic and oak species than for pines (Hu et al. 2017).

Despite uncertainty about specific effects of drought on tree species in the Southeast, the influence of drought on forests is of concern because of the importance of the timber industry in this region (fig. 9.12). Plantations in the Southeast are critical to national supplies of softwood timber, and the region contains the largest area dedicated to planted pines in the United States (Robertson et al. 2011). In 2016, the Southeast provided 63 percent of the national softwood growing-stock removals (fig. 9.12A) and 53 percent of hardwood growing-stock removals (fig. 9.12B). Together, the total

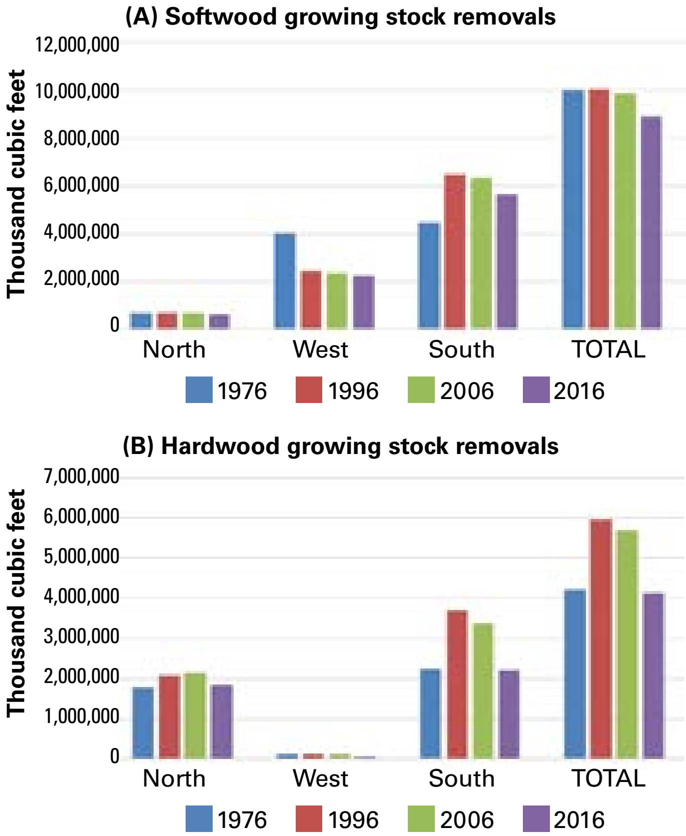

Figure 9.12—Removals of (A) softwood growing stock and (B) hardwood growing stock by region and year (Oswalt et al. 2019).

growing-stock timber removals from the Southeast accounted for 60 percent of all U.S. timber harvests (2017 RPA Database). The plantations of the Southeast are also a source of wood pellets for the European Union. In 2013, <5 percent of total timber removals in the Southeast were used for pellets (Jefferies 2016). Production of both pellets and paper products requires the same kind of timber inputs, so economic theory implies that an increase in the demand for timber in pellet production would cause an increase in small roundwood prices and thus a decrease in paper production. Due to the increased risk of drought, the Southeast timber market could be at risk for potential shortages. Drought impacts on productivity could further limit timber supplies in the upcoming decades (Clark et al. 2014).

The impact of drought on specific tree species in southern forests is uncertain, but the evidence reviewed to date suggests the possibility of declines in forest growth and inventory. For example, an estimated $558 million of standing merchantable trees were killed by the 2011 drought in Texas (Anderson et al. 2012), a substantial loss to forest landowners and roughly double the average stumpage value of timber harvested over the previous 3 years. However, economic analyses of drought impacts on forests are limited.

MANAGEMENT OPTIONS

Strategies and Tactics To Address the Impacts of Drought on Fire and Insect Outbreaks

Projections of increased drought frequency and duration in many regions of the Southeast will present challenges for land managers to reduce the likelihood of wildfire occurrences and limit area burned (Lafon and Quiring 2012, Terando et al. 2016). Fire season length has already shown a significant increase in the eastern U.S. Coastal Plain (Jolly et al. 2015), and several models using global climate scenarios, coupled with indices of fire danger, predict significant increases in wildfire area burned and fire severity in the future (Bedel et al. 2013, Flannigan et al. 2009, Lafon and Quiring 2012, Liu et al. 2012, Mitchell et al. 2014). Wildfire risk is compounded by a growing wildland-urban interface in many areas of the Eastern United States (Wear and Greis 2012). In pine forests, prescribed fire is widely used for multiple benefits, including to reduce fuel loads and to promote fire-tolerant/fire-dependent species/ecosystems such as longleaf pine (Mitchell et al. 2014). Although less widely used, prescribed fire in hardwood forests has been advanced as a tool to favor more drought- and fire-tolerant species such as oaks (Vose and Elliott 2016). Management options to reduce fire risk in the Southeast have mostly focused on reducing fuel loads through frequent prescribed burning (Mitchell et al. 2014). However, additional actions may be required to address limits to the widespread use of prescribed fire due to air quality concerns and unfavorable burn conditions associated with climate change (e.g., too dry, too hot). Examples include reducing fuel loading through planting trees at lower densities, thinning natural stands and existing plantations, reducing live and downed fuels mechanically with mastication treatments, and reducing live fuels with herbicide (McIver et al. 2012). If wildfire becomes more frequent, managers may also need to consider allowing some of these fires to burn to reduce future risk. However, the growing wildland-urban interface will likely limit those opportunities.

Thinning or other preventive silvicultural practices that, among other benefits, reduce vegetative competition for water and improve pine vigor (Guldin 2011, Nowak et al. 2015) may help mitigate drought-related insect damage (e.g., SPB and other bark beetles). During stand establishment on drier/upland sites, planting or regenerating more drought-tolerant species (e.g., longleaf pine instead of loblolly pine) could also help reduce drought-related impacts (Schowalter 2012). However, the conversion of natural forests to pine plantations can reduce tree tolerance to long-term drought (Domec et al. 2015).

Strategies and Tactics To Address the Impacts of Drought on Key Regional Resource Areas

Hydrology—Efforts to mitigate drought impacts on water resources for either ecosystems or people have to target both supply and demand. Thinning can increase water availability for tree growth (Grant et al. 2013) by reducing both stand transpiration and canopy interception. Prescribed burning that kills forest understories may reduce competition for soil water and increase groundwater recharge (Hallema et al. 2017). A study of the effects of potential thinning (i.e., reduction of leaf biomass) on water yield across the United States predicted that, if forests are thinned 50 percent, water yield in the Southeast's low coastal plain area may increase 40–80 percent (Sun et al. 2015a) (fig. 9.13).

In some cases, converting forest cover from coniferous species to deciduous species can reduce total water loss and increase watershed water yield. Species with different xylem structures and of different ages vary in their amount of water use. For example, in the Southern Appalachian Mountains and under the same climate, red oak (*Quercus rubra*) trees with a 50-cm trunk diameter transpire an average of 30 kg of water per day, but black birch (*Betula lenta*) trees transpire as much as 110 kg of water per day (Vose et al. 2011). Thus, to anticipate water supply stress from drought, one option is to use native drought-tolerant species that need less water for growth.

Innovative adaptations are needed to reduce or adapt to severe drought in the context of climate change and variability, as well as to anticipate ecological consequences, such as water supply shortages for forests and people, habitat loss, and increased wildfires (Marion et al. 2013). As the best general adaptation approach to drought, forest management practices are recommended that enhance ecosystem resilience to climate disturbances and maintain ecosystem services, including climate moderation and mitigation.

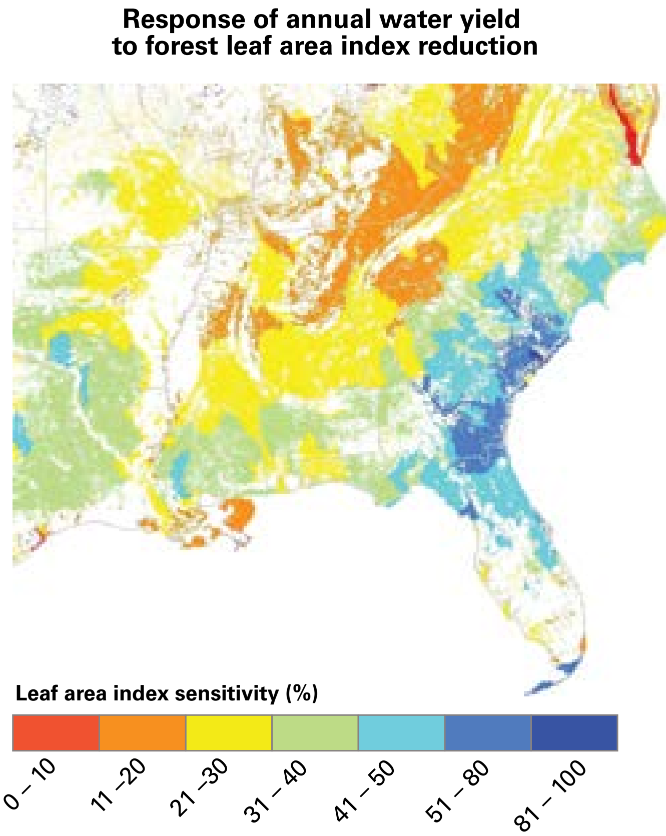

Figure 9.13—Water yield response to 50-percent reduction of leaf area index as simulated by the Water Supply Stress Index model. (Source: Sun et al. 2015a)

Streamflow, fisheries, and aquatic biodiversity—Given the projected expansion in the human population as well as changes in regional rainfall and temperature, managing forests to sustain linked aquatic ecosystems may become a higher priority (Claassen et al. 2018). Under generally accepted climate change scenarios for North America, warmer temperatures and increasingly variable rainfall will result in a trend of hydrological change in many regions. Likely changes could produce more severe drought impacts in many forested watersheds including lower growing-season streamflow. If current rates of water demand persist, then the projected increase in the human population would create even more stress on limited water resources, exacerbating climate effects, particularly during the growing season and during droughts.

To predict drought effects and develop watershed management strategies that maintain aquatic biological diversity and ecosystem function, it is critical for managers to understand and predict biological responses (Richter 2009, Richter et al. 2011). Methods for characterizing riverine hydrological regimes are well developed (e.g., Gao et al. 2009, Olden and Poff 2003). However, information about biotic responses to altered hydrological regimes is site-specific at best and is often lacking (Freeman et al. 2012). Assessment of hydrological change requires long-term streamflow records and a continuous record (typically at least 15–20 years) that spans climate variability and management efforts. Metrics for analysis must have ecological relevance to the biota of the particular stream (Olden and Poff 2003, Poff et al. 2010). What is needed is an ongoing commitment to aquatic monitoring that is equivalent to forest inventory, along with an improved modeling capability that predicts flow responses to landcover change.

Managing forests to protect linked aquatic ecosystems from drought will be challenging and will require a long-term perspective. Fortunately, existing management activities such as forest thinning and prescribed fire, which are already used to improve forest resilience, will likely also reduce total ET. Control or eradication of invasive plant species that increase water use should also be emphasized, although more research is needed on specific impacts of invasives on water budgets (Brantley et al. 2015). Finally, managing forest composition through selective harvest practices that focus on more water-dependent tree species may also be valuable (Brantley et al. 2017, Douglas 1983).

Forest mesophication, defined as the change in forest composition from drought- and fire-tolerant species to drought- and fire-intolerant tree species that use relatively more water (Nowacki and Abrams 2008), has negative effects on water yield (Caldwell et al. 2016). Reversing this trend through management would improve the resilience of linked aquatic systems by reducing ET. Tree species with higher stomatal sensitivity to drought conditions, such as longleaf pine, might also be favored in some management applications.

Although forest managers inherently focus on management activities that improve tree growth and reduce tree mortality from drought, strategies are also needed to mitigate effects of drought on linked aquatic ecosystems. Small streams that originate from forested watersheds and geographically isolated wetlands embedded within forested landscapes are intimately connected with forest processes and can be highly sensitive to drought.

The positive link between forest cover and water quality is well known, but not all southeastern forests are equal at promoting water quantity (Brantley et al. 2017, Caldwell et al. 2016). Forest management can promote higher water yield and thereby contribute to higher stream runoff and a longer wetland hydroperiod (Douglas 1983, Ford et al. 2011). Reducing forest ET through management is particularly critical during dry years. Stand-level ET tends to show relatively little interannual variation compared to rainfall (Oishi et al. 2010), and variations in precipitation tend to be reflected more strongly in water yield.

Wildlife—Management options to maintain wildlife biodiversity during drought depend on the specific habitat on which wildlife depend. Wetlands, including geographically isolated wetlands (GIWs), represent critical wildlife habitat in the Southeast. Many of the same concepts that relate forest management activities to streamflow are also relevant to maintaining wetland hydroperiod (Jones et al. 2018) and thus the quality of wetland habitat.

Geographically Isolated Wetlands may be more susceptible to surrounding landcover change than streams or other wetland types due to their relatively small volume and limited watershed area. For example, vertical water infiltration and shallow groundwater transport, rather than surface runoff from rainfall, are thought to control water levels in wetlands in undisturbed pine forests (Clayton and Hicks 2007). However, when hardwood trees become established within and around wetlands, transpiration can increase, significantly reducing subsurface flows to the wetland and shortening hydroperiod (Clayton and Hicks 2007). Upland land management may affect wetland hydroperiod in much the same way that it affects streamflow, but at more localized scales. Forest management practices (e.g., thinning, fire reintroduction, species selection) that reduce ET in the contributing area of GIWs or alter the timing of ET (e.g., favoring evergreens over hardwoods) have the potential to affect wetland hydroperiod, which may ameliorate effects of drought for wildlife dependent on these habitats.

Relationships between drought, forest management, and terrestrial wildlife are weaker. Thus, management prescriptions are harder to specify. Favoring woody plants with low ET may mitigate drought effects in some terrestrial wildlife populations in the Southeast during a drought (Parent et al. 2016). Some woody species may also redistribute groundwater to surface soils through hydraulic lift, where the water can be taken up by herbaceous vegetation (Domec et al. 2012, Espeleta et al. 2004) and possibly provide increased moisture in forage. More research is needed on drought effects on terrestrial wildlife populations and how forest management may mitigate those effects.

As climate change intensifies the length and severity of droughts in the Southeast, wildlife managers in this region may need to adopt techniques used in the Western United States to provide water to drought-stricken terrestrial wildlife (Bleich et al. 2005, 2006; Glading 1947). In addition to logistical issues, providing water sources during periods of drought may create other management concerns. For example, wildlife would be expected to congregate at watering sources, much as they concentrate at wildlife feeders. This increased concentration of wildlife may increase predation risk (Cooper and Ginnet 2000, Jones et al. 2010) and the likelihood of disease transmission (The Wildlife Society 2006). Before widespread application of artificial watering sources is considered, potential tradeoffs such as these should be identified and their risk quantified to guard against unintended consequences.

Timber resources—To mitigate economic losses, management strategies include reducing rotation age, diversifying stand species to include drought-resistant species, thinning, and intensification of stand management (Clark et al. 2016, Klos et al. 2009, Sohnhen and Tian 2016). For example, longleaf pine may confer more drought tolerance compared to loblolly or slash pine (*Pinus elliottii*) due to longleaf pine's more efficient hydraulic structure (Samuelson et al. 2012).

Longleaf pine forests were once a dominant forest ecosystem in the Southern United States, covering tens of millions of ha (Oswalt et al. 2012). During the 18th century, longleaf pine forests were valued for providing naval stores (e.g., tar, pitch, and turpentine) for the British navy (Outland 2004, Perry 1968). In the mid- to late 1800s, improved harvesting (i.e., water-powered sawmills) and timber transportation technology (i.e., steam skidders and railroads) increased the harvests of highly valued longleaf pine timber. The introduction of pulp mills in the 1950s favored trees that grew rapidly. Any second-growth longleaf pine stands were clear-cut and replanted with loblolly pine or slash pine due to their faster initial growth rates. Intensified timber production, along with the conversion of stands for agriculture and urban development, resulted in a loss of >95 percent of the initial land area of longleaf pine forests by 1990 (Oswalt et al. 2012).

There is now renewed interest in restoring longleaf pine for wood products, pine straw, wildlife, and biodiversity benefits, which has led to the creation of the America's Longleaf Restoration Initiative (ALRI). America's Longleaf Restoration Initiative is a collaboration of public and private partners who seek to create and conserve "functional, viable longleaf pine ecosystems with the full spectrum of ecological, economic, and social values inspired through a voluntary partnership of concerned, motivated organizations and individuals" (America's Longleaf 2009). The overall goal of ALRI's conservation plan is to increase longleaf pine acreage from 3.4 million to 8 million acres by 2025.

Integrating drought risk into land management planning—Efforts to restore ecological integrity are necessary strategies to increase drought resilience, particularly where current drought regimes are still within historical ranges of variation and future changes are highly uncertain. The restoration of longleaf and shortleaf pine ecosystems is a broad effort organized across the historic range of both ecosystems. Both longleaf and shortleaf pine provide numerous benefits for responding to current and future climate change, including resistance to wildfire, increased productivity during drought periods, and increased disease and pest resistance (Boensch 2016, Slack et al. 2016).

In addition to ecosystem restoration, significant effort in the Southeast focuses on improving general forest health across national forests and private lands. This effort has significant benefits for drought resilience because reducing forest density through thinning is the most common drought prevention practice. For example, the Southern Pine Beetle Program was developed after major outbreaks in 1999–2003 that caused >$1 billion of damage (USDA Forest Service 2017b). The program has since accomplished >1 million acres in SPB treatments (e.g., thinning, prescribed burning [USDA Forest Service 2005]) across private and public ownerships. This program is a successful model for how forest health strategies can be applied across large geographic areas to produce multiple benefits.

The periodic development of land management plan revision is required under the National Forest Management Act (USDA Forest Service 1976) and directed by the Planning Rule (USDA Forest Service 2012). These guidelines provide the necessary framework to assess and plan for drought, including the development of adaptive management strategies to promote ecological integrity and resiliency. The planning process is highly collaborative, with emphasis on coordinating with research and development partners to address drought and other climate-related stressors (case study; table 9.1).

As Federal land management plans are implemented through projects across the landscape, opportunities are presented to integrate drought management into the projects' purpose and need, including identifying resources that are particularly sensitive to drought. This integration is especially important in regions like the Southeast, where drought is becoming increasingly variable. Therefore, there is a need to identify change, and appropriate responses include proposed actions, development of alternatives, and analysis of effects. Sectors affected by drought that may benefit from departure analysis involve terrestrial and aquatic ecosystems; watersheds; air; soil and water resources; threatened, endangered, and proposed candidate species; social, cultural, and economic conditions; recreation; and infrastructure (USDA Forest Service 2012).

Table 9.1—Potential adaptation options for managing forest hydrological impacts (quantity, quality, timing) and ecosystem risks in response to hydrological drought

HYDROLOGICAL IMPACTS	RISK TO ECOSYSTEMS AND SOCIETY	ADAPTATION OPTIONS
Increased water supply stress	Water shortage; drying up of drinking wells; degradation of aquatic ecosystems with impacts on socioeconomics and business	Maintain watershed health; thin forests; reduce groundwater and surface water use for irrigation of croplands and lawns; enhance water conservation
Decreased transpiration	Reduced tree growth and productivity; tree mortality	Use native tree species; reduce tree stocking; irrigate
Increased soil evaporation	Hydrological droughts; wildfires; insect and disease outbreaks	Mulch; use solid waste applications in plantation forests
Decreased base flow	Water quality degradation; loss of fish habitat; reduced transportation capacity	Reduce off-stream water withdrawal; adjust water outflow from reservoirs; reclaim wastewater
Changes to wetland hydroperiod	Wildlife habitat loss; CH_4 and CO_2 emission change	Plug ditches; adjust water outflow from reservoirs
Higher streamwater temperature	Water quality degradation; loss of cold-water fish habitat	Maintain riparian buffers and shading
Increase in soil erosion from vegetation degradation; increased sedimentation	Water quality degradation; siltation of reservoirs; increased water treatment cost	Enhance forest road best management practices; redesign riparian buffers
Increased pollutant concentrations	Water quality degradation; increased water treatment cost	Maintain streamflow quantity; use forest best management practices

Source: Marion et al. (2013).

CASE STUDY
Francis Marion National Forest: Creating a master plan for drought

The Francis Marion National Forest (FMNF) in the coastal plain of South Carolina integrated drought adaptation into its recently revised land management plan (USDA Forest Service 2017a). This case study illustrates how creating a master plan to manage for drought and climate change could affect management decisions in a number of forest sectors.

The first phase of this process was to complete an assessment. Guided by the Agency's Planning Rule (USDA Forest Service 2012), the assessment consisted of three components: (1) key ecosystem characteristics, (2) developing plan components, and (3) developing monitoring. The planning team evaluated current conditions and trends using the comprehensive land management plan framework previously stated. Climate variability, in general, and drought in particular, were recognized as important ecosystem drivers and stressors. The presence of diverse native ecosystems, particularly the longleaf pine ecosystem, was recognized as a critical component of ecological integrity and sustainability. A key finding of the assessment was the need to respond to ecological challenges, including drought, thus necessitating changes to the land management plan.

Key ecosystem characteristics—The planning team recognized drought and other climate-related stressors as key ecosystem characteristics within the ecological framework required for planning. This laid the groundwork for addressing drought during the development of the plan, including through monitoring and adaptive management strategies.

Developing plan components—Drought was directly incorporated into the FMNF plan by specifying key characteristics desired for ecological integrity and explicitly identifying the influence of drought on specific ecosystems (table 9.1). These descriptions were designed to help planners and managers recognize the effects of drought as a disturbance process, which is necessary to maintain the function, structure, and composition of the ecosystem, and hence ecosystem sustainability. Although drought was identified as an important driver of forest structure and function in FMNF and the surrounding landscape, the assessment found that postdrought conditions typically return to normal quickly and vegetation recovers accordingly. Therefore, the plan supplied land managers with useful information regarding drought management, including the fact that drought management options for the FMNF are not necessary for all drought occurrences.

Developing monitoring—Given the importance of drought in the FMNF ecosystem, the plan's monitoring program described indicators of climate change, including drought, and proposed adaptive management strategies to address potential drought impacts (table 9.2). Studies (e.g., Ahmadalipour et al. 2017, Sheffield and Wood 2008) suggest that drought could become more frequent and severe in the future, therefore necessitating the need to monitor for drought impacts in the FMNF. Monitoring for drought impacts could provide early detection of change in the ecosystem and the need to implement adaptive management strategies.

Table 9.2—Plan-level monitoring question from the Francis Marion National Forest Plan that addressed climate variability and drought through indicators (I) relevant to the scale of evaluation, with relevant sources/partners and adaptive management strategies shown for each indicator

Monitoring Question: Is climate change, including changes in drought frequency and severity, influencing maintenance and ecosystem restoration?

INDICATORS (I)	SOURCES/PARTNERS	ADAPTIVE MANAGEMENT STRATEGIES
(I-1) Trends in climate, including extremes, disturbance patterns, and long-term ecological processes	National Oceanic and Atmospheric Administration (NOAA) – State of the Climate Reports NOAA – U.S. Climate Extremes Index NOAA – Severe Weather Data Inventory South Carolina Drought Response Committee Remote sensing and change detection products (e.g., ForWarn)	**Alert:** Increasing trends in frequency/magnitude of climate extremes and related disturbance **Response:** Strengthen disturbance response capabilities and assess implications during project development
(I-2) Trends in forest health status and risk	Forest Health Technology Enterprise Team (FHTET) Forest Pest Condition FHTET National Insect and Disease Risk Map University of Georgia, Center For Invasive Species and Ecosystem Health – Early Detection & Distribution Mapping System	**Alert:** Nonnative invasive species introductions/ increases in forest health risk **Response:** Rapid detection and treatment
(I-3) Trends in fire return intervals and seasonality	Monitoring Trends in Burn Severity (MTBS)	**Alert:** Inability to meet desired fire return intervals **Response:** Adjust prescribed burning schedules and take advantage of desirable conditions
(I-4) Status and trend of isolated wetlands	Natural Resources Conservation Service groundwater monitoring	**Alert:** Wood encroachment/changes in hydrology **Response:** Vegetation management if feasible/ hydrological restoration
(I-5) Status of frosted flatwood salamander habitat		**Alert:** Habitat degradation or loss due to climate influences **Response:** Promote amphibian habitat through the placement of coarse woody material piles and other features that retain moisture during dry periods
(I-6) Focal species: longleaf pine, red-cockaded woodpecker, Bachman’s sparrow, pitcher plants, and American eel		**Alert:** Declines attributable to climate influences **Response:** Species specific

Note: Measurable changes on the plan area related to climate change and other stressors.

Source: USDA Forest Service (2017a).

CONCLUSIONS

Drought has always been integral to ecosystems in the Southeast (Seager et al. 2009). Associated natural wildfires during periods of drought have helped to maintain natural open ecosystems and promote biodiversity (Christensen 2005). Since the 1900s, climate change and climate variability have added to the existing variability of regional drought. Although parts of the region experienced little or no increase in air temperature during much of the 20th century, the entire Southeast is now seeing warming air temperatures relative to historic levels (IPCC 2014). Even when precipitation does not change, higher air temperatures increase ecosystem water loss, and this is exacerbated by associated increases in ET in vegetation (e.g., forest, grassland, agricultural lands) and water body evaporation (Diffenbaugh et al. 2015).

A growing human population and the corresponding increase in water demand (McNulty et al. 2008) further complicate drought in the Southeast. Water is one of the primary ecosystem services that forests can provide, and with proper care, forest water can continue to be a resource in the future. However, even if drought conditions remain constant, water shortages will probably worsen for commercial, agricultural, residential, and industrial use. To prepare for unexpected droughts, forest management adaptation practices are needed now and will be needed even more in the future.

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