5 Future Wildfire Trends, Impacts, and Mitigation Options in the Southern United States

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Wildfire is among the most common forest disturbances, affecting the structure, composition, and functions of many ecosystems. The complex role that wildfire plays in shaping forests has been described in terms of vegetation responses, which are characterized as dependent on, sensitive to, independent of, or influenced by fire (Myers 2006). Fire is essential in areas where species have evolved to withstand burning and facilitate the spread of combustion, such as the *Pinus* spp. found in the Coastal Plain of the Southern United States. Notable fire-dependent ecosystems include many boreal, temperate, and tropical coniferous forests, eucalyptus forests, most vegetation assemblages in Mediterranean-type climates, some forests dominated by oaks (*Quercus* spp.), grasslands, savannas, and marshes, and palm forests. At the other extreme, fire is largely absent where cold, wet, or dry conditions prevail (such as tundra landscapes, some rain forests, and deserts). Fire-sensitive ecosystems that have evolved without fire as a significant process have become more vulnerable to human activities such as stand fragmentation, alteration of fuels, and increased ignitions. Fire-influenced ecosystems generally are adjacent to areas where fire-dependent vegetation facilitates ignition and spreading of wildfires.

Wildfire, meanwhile, can be a major natural disaster. From 1992 to 2001, almost 2 million ha of U.S. forests and other ecosystems were burned by hundreds of thousands of wildfires annually, costing billions (U.S. Department of Agriculture Forest Service 2005). The 1997/1998 wildfires in Indonesia burned 8 million ha (Cochrane 2003). In catastrophic wildfires in January and February of 2009 in Victoria, Australia, the greatest damages were visited on "Black Saturday" (February 7, 2009) when over 2000 homes were destroyed or damaged and 173 people were killed; 430,000 ha were burned in the region in early 2009 (Teague et al. 2010). It is notable that, as in the case of the Black Saturday fire and many other large fires, some fires are simply beyond our control, regardless of the type, kind, or number of firefighting resources deployed. In the United States, large fires and the uncontrollable "mega-fires" of the kind cited by Williams (2004) account for 90% of the area burned and 80% of suppression costs, but together represent less than 1% of all wildfires (Williams 2004).

Wildfires can also produce severe environmental consequences. Smoke particles are a source of atmospheric aerosols, which affect atmospheric radiative transfer through the scattering and absorption of solar radiation and through the modification of cloud microphysics (Charlson et al. 1992). These processes can further modify clouds, precipitation, and atmospheric circulation (Ackerman et al. 2000; Liu 2005a,b). The particulates and other air pollutants from wildfires can degrade air quality (Riebau and Fox 2001), resulting in significant human health consequences (Rittmaster et al. 2006). Wildland fires contribute an estimated 15% of total particulate matter and 8% of carbon monoxide emissions over the Southern United States (Barnard and Sabo 2003). Burned areas are prone to severe soil erosion due to loss of ground vegetation and litter cover and an accelerated overland flow. Stormflow volume and peakflow rates increase dramatically in response to reduced soil infiltration rates and soil water storage because forest evapotranspiration rates are reduced. Increases of stormflow and soil erosion carry with them the potential to degrade water quality after severe wildfire events.

Weather and climate are determinants for wildfire characteristics along with fuel properties and topography (Pyne et al. 1996). Fire activity varies from one fire season to the next. For example, the burned area in the United States increased from 0.5 million ha in 1998 to 2.3 million ha in 1999 (National Interagency Fire Center 2010). Fire weather and climate also influence wildfire behavior and account for fire variability at various time scales. Under warm and dry conditions, a fire season becomes longer, and fires are easier to ignite and spread. The interannual variability in the atmospheric circulation patterns that brought drought conditions in the past are still a driving force in the variability of fire season severity (Westerling and Swetnam 2003). Contemporary observational data indicate statistically significant relations among wildfires, atmospheric conditions, and ocean conditions (Swetnam and Betancourt 1990; Brenner 1991; Prestemon et al. 2002; Skinner et al. 2002; Liu 2004, 2006; Dixon et al. 2008; Goodrick and Hanley 2009; Hoinka et al. 2009). Research shows that wildfires, especially catastrophic wildfires, have increased in recent decades in both the

United States and other parts of the world (Piñol et al. 1998; Food and Agriculture Organization of United Nations 2001; Gillett et al. 2004; Reinhard et al. 2005; Westerling et al. 2006). Among the converging factors were extreme weather events, such as extended drought, and climate change (Goldhammer and Price 1998; Stocks et al. 2002).

A new and challenging wildfire issue is the potential increase in occurrence of wildfires due to a changing climate brought on by the greenhouse effect. Many climate models have projected that the greenhouse effect will result in significant climate change by the end of this century (Intergovernmental Panel on Climate Change 2007), including an overall increase in temperature worldwide and a drying trend in many subtropical and mid-latitude areas. Thus, it is likely that wildfires will increase in these areas. One effect could be more fires that burn more intensely and spread faster in northern California (Fried et al. 2004). A 50% increase in fire occurrence is projected in boreal forests by the end of the century (Flannigan et al. 2009). Fire potential may increase significantly in several global geographic areas, including some in the United States (Liu et al. 2009b, 2012).

The South is one of the most productive forested regions in the country, with 81 million ha or 40% of the nation's forests in an area occupying only 24% of the nation's land area (Burkett et al. 1996). Furthermore, southern forests are dynamic ecosystems characterized by rapid growth—and hence rapid accumulation of fuels within a favorable climate—and a high fire-return rate of 3–5 years (Stanturf et al. 2002). The South leads the nation in annual wildfires, averaging approximately 45,000 fires a year from 1997 to 2003 (Gramley 2005). The region is also experiencing increased droughts. For example, during the 2007 drought in the southeastern United States, the worst drought in more than a century, severe wildfires in the spring in and around the Okefenokee National Wildlife Refuge on the southern-Georgia/northern-Florida border burned approximately 243,000 ha. The frequency of droughts across the region appears to be changing and the period from the mid- to late-1990s may have been wetter than the long-term average (Seager et al. 2009).

Like many other geographic areas in the nation and in the world, the South faces the challenge of potentially increased wildfires this century, resulting from the projected warmer temperatures and more frequent droughts that would occur in response to climate change. Increased wildfire activity would have some specific ecologic, environmental, social, and economic consequences. Continued population growth increases the potential threat these fires would pose to life and property. In addition, forestry and forestry-related industry represent a significant portion of the region's economy, making each fire a potential loss to a local economy. Also, the increases in wildfire potential would require increased future resources and management efforts for disaster prevention and recovery. Projections of future wildfire trends in the South under a changing climate are essential for accurately assessing possible impacts of climate-related future wildfire trends, including human health and safety impacts and environmental impacts, and are critical to designing and implementing necessary measures to mitigate impacts.

Wildfire in the South has been identified as a priority for many research programs including those funded through the National Fire Plan, the U.S. Environmental Protection Agency Star Program, and the U.S. Departments of Agriculture and the Interior's mutually sponsored Joint Fire Science Program. The objectives of these research programs included investigating and synthesizing the current status of wildfires, projecting future trends, assessing impacts of changes in wildfires on other ecosystem processes, and providing management options to mitigate the impacts, particularly in places where wildfire activity is projected to increase. This chapter presents the findings from these studies. Background information, including climate and vegetation, wildfire, fire–weather and fire–climate interactions, fire and climate change, and research and mitigation issues, is first provided. Future fire and fuel conditions (including projection approaches, climate change scenarios, and results), the impacts of future fire changes (including impacts on emissions, smoke and air quality, forest ecosystems, socioeconomics, hydrology, and regional climate), and management options for impact mitigation are then described. Finally, major findings and knowledge gaps are summarized together with suggested future research needs.

BASICS OF WILDFIRE AND CLIMATE IN THE SOUTH

Climate

Consisting of the 13 states roughly south of the Ohio River and from Texas to the Atlantic Coast, the South can be classified by topography and ecological features into the following level II eco-regions (U.S. Environmental Protection Agency 2008): (1) Coastal Plain, consisting of the coastlines along the Atlantic Ocean and the Gulf of Mexico, including the Florida peninsula and the Mississippi Alluvial Valley; (2) Piedmont and Southern Appalachian Mountains, including the Appalachian plateaus and mountain ranges; (3) Interior Highlands, consisting of the Interior Low Plateaus of Kentucky and Tennessee and the Ozark-Ouachita Highlands; and (4) western Ranges and Plains, consisting of central and western Texas and Oklahoma. The first region of these classifications roughly corresponds to the eastern Coastal Plain, the western Coastal Plain, and the Mississippi Alluvial Valley eco-regions, while the three others roughly correspond to the Piedmont, Appalachian-Cumberland, and Mid-South eco-regions (Wear and Greis 2012).

The region primarily has a humid subtropical climate except for a tropical climate in southern Florida and a semi-arid climate in western Texas and Oklahoma [*Times* (UK) 1993]. Annual daily temperature averages range from greater than 21°C in southern Florida and Texas to 13–16°C in northern areas. Annual precipitation is 1270–1780 mm in the Mid-South including Louisiana, Mississippi, Alabama, and Tennessee, areas of Georgia and Florida, and areas along the Atlantic coastline. Precipitation reduces to 1015–1270 mm toward the Atlantic coastal areas and northern areas of the region, and to 300–500 mm toward western Texas and Oklahoma.[*] Seasonal variability is significant in most of the region, characterized by hot, humid summers and mild to cool winters. The major weather and climate extremes include tornados, hurricanes, excessive lightning, and drought, with drought the largest contributor to large wildfires.

Fuel

In the vegetation types defined by the National Fire Danger Rating System fuel models, the Coastal Plain is dominated by open pine (*Pinus* spp.) stands—with perennial grasses and forbs as the primary ground fuel—in the coastal area along the Gulf of Mexico and hardwoods in the coastal area along the Atlantic Ocean. Major pine species are longleaf (*P. palustris)*, slash (*P. elliottii*), and loblolly (*P. taeda*) pines (Wade et al. 2000). Florida has a mixture of dense live brush, agriculture, and sawgrass (*Cladium* spp.). The western Coastal Plain is dominated by natural pine stands, southern pine plantations, and hardwoods as the primary fuel. The Mississippi Alluvial Valley is dominated by agriculture, and the Piedmont by southern pine plantations and natural pine stands. Shortleaf pine (*P. echinata*) is more widespread in the Piedmont and mountains than in the Coastal Plain. The Appalachian-Cumberland highlands are dominated by pine with some perennial grasses. The central Texas and Oklahoma areas of the Mid-South are dominated by intermediate brush to the south and agriculture to the north, compared to grasses, a mixture of sagebrush (*Artemisia* spp.) and grasses, and some agriculture in western Texas.

Wildfire

The characteristics of wildfires in a geographic area are usually described in terms of fire regime and fire history. Fire regime describes the long-term presence of fire in an ecosystem (Brown 2000), mainly characterized by fire frequency (or fire return interval) and fire severity. Fire regimes can be classified as understory, stand-replacement, or mixed (Brown and Smith 2000). Understory-regime fires generally do not kill the dominant vegetation or substantially change its structure.

[*] See www.hurricane.ncdc.noaa.gov/climaps

A stand-replacement fire kills the aboveground parts of the dominant vegetation, changing the aboveground structure substantially. Mixed-regime fires can either cause selective mortality in dominant vegetation—depending on a species' susceptibility to fire—or can at some times limit effects to the understory and at other times to the dominant vegetation in a stand replacement. Fire severity depends on the type of fire regimes and is defined as the "degree to which a site has been altered or disrupted by fire; loosely, a product of fire intensity and residence time" by the National Wildfire Coordinating Group (2005). Fire severity is also often partially measured by the amount of total area burned. Burned area does not reflect the exact features of fire intensity and period. However, burned area is closely related to how intense and long-lasting a fire is: an intense and long-lasting fire usually leads to a large burned area.

The fire regimes of southern ecosystems have been described in detail (Wade et al. 2000; Stanturf et al. 2002; Fowler and Konopik 2007). Intervals between fires are primarily determined by vegetation species, which in turn depend on the physiographic characteristics of the eco-region. Intervals between fires may be as short as a year or as long as centuries. Before European settlement, frequent low severity understory fires characterized most Coastal Plain ecosystems with a return interval of 1–4 years (Table 5.1). Blowdowns and droughts led to occasional severe fires (Myers and Van Lear 1997). Mixed stands of oak and hickory (*Carya* spp.) in the Piedmont had a return interval of less than 35 years, compared to less than 200 years for Table Mountain pine (*P. pungens*). The return interval of mixed mesophytic species depended on whether they grew on the eastern or the western side of the Southern Appalachians.

The long history of fire since humans arrived in the South can be divided into five periods (Stanturf et al. 2002). (1) The pre-Columbian period, more than 500 years ago, in which Native Americans used fires extensively as a landscape management tool. (2) The early European settlement period, from 500 to about 110 years ago, in which European settlers likewise used fire

TABLE 5.1
Occurrence and Frequency of Pre-Settlement Fire Regime Types in the Southern United States, by the Society of American Foresters

	Frequency (Years) by Fire Regime		
Vegetation	**Understory**	**Mixed**	**Stand Replacement**
Longleaf pine	1–4		
Slash pine	1–4		
Loblolly pine	1–4		
Shortleaf pine	2–15		
Oak-hickory	<35		
Pond pine		6–25	
Pitch and Virginia pines		10–35	
Table Mountain pine		<200	
Mixed mesophytic		10–35 or >200	
Bottomland hardwoods		<200	
Sand pine			20–60
Bay forests			20–100
Atlantic white cedar			35–200
Northern hardwoods			300–500

Source: Modified from Wade, D.D. et al. 2000. *Wildland Fire in Ecosystems: Effects of Fire on Flora*. GTR RMRS-42. Ogden, UT: USDA Forest Service, Rocky Mountain Research Station: 53–96.

culturally but also introduced livestock and new farming practices involving widespread land clearing. (3) From the late 1890s to the 1920s, in which the remaining southern forests were extensively logged to support economic and population expansion and in which wildfires were common due to logging slash accumulations. (4) In reaction to these widespread and destructive wildfires, the fourth period, characterized by fire suppression, began in the 1920s and extended to the 1980s. (5) The current period, in which the natural role of fire is increasingly recognized and incorporated into forest management.

FIRE WEATHER AND CLIMATE

Fire weather and climate describe the atmospheric conditions that influence fires (Flannigan and Wotton 2001). Weather refers to atmospheric elements (such as temperature, humidity, pressure, winds, and precipitation) and the related processes or systems (such as fronts, cyclonic and anticyclonic circulations, troughs and ridges, and jet streams) on time scales of hours to weeks. Conversely, climate describes the statistics of weather over a long period (multiple decades). In fire research and management, however, weather conditions for fire (fire weather) often refer to atmospheric conditions and processes for individual fires on specific days and months, but climate conditions for fire (fire climate) refer to conditions during an entire fire season, inter-fire season variability, and long-term trends.

The relationship between weather and fire is often expressed in the fire environment triangle (Figure 5.1), with fire behavior in the center reflecting the degree of fire suppression difficulty based on ignition, spread, and intensity. Ignition is the process of increasing fuel temperature—often by external or internal heat energy or lightning—to a critical value (ignition temperature); that is, a temperature at which combustion starts. Heat sources can be natural (radiation, sensitive heat, chemical energy) or related to human activities (such as arson, equipment sparks, or arcing power lines). Lightning, which is of special concern when occurring in the absence of rain, initiates a series of chain reactions that generate the needed heat energy for ignition. Fire spread is the process of igniting new fuels from a single burn point. The rate of fire spread varies with time. The rate is controlled by ambient and fire-induced winds and relative humidity, which in turn determine fuel moisture. Fire intensity,* is proportional to fire spread rate, flame residence time, and reaction intensity. It is also sometimes measured by flame length.

Weather, fuel, and topography form the sides of the fire environment triangle; the role of each is described in Table 5.2. Models are available to predict the probability of ignition through heating or lightning (Latham and Williams 2001) and to calculate fire spread and intensity as a function of fuels, weather, and topography (Rothermel 1972; Finney 1998; Keane et al. 2003).

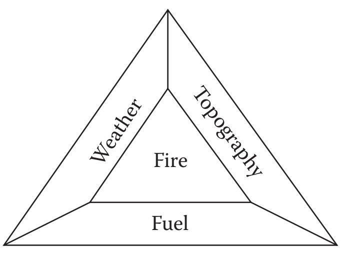

FIGURE 5.1 Fire environmental triangle. (Adapted from na.fs.fed.us/fire_poster/science_of_fire.htm)

* The literature presents a confusing array of definitions for fire intensity. According to Keeley (2009), "fire intensity represents the energy released during various phases of the fire and no single metric captures all of the relevant aspects of fire energy."

TABLE 5.2
Fire Environmental Factors, Their Elements, and Their Impacts on Fire Behavior

Factor	Parameters	Roles
Weather	Wind, temperature, relative humidity, air pressure, precipitation	High temperature reduces fuel moisture. Wind pushes a fire along. Low relative humidity dries out fuels causing them to ignite more easily. Precipitation puts out a fire and conversely a lack of precipitation can make fire more likely by drying out the fuels.
Fuels	Density (light or heavy), arrangement, moisture	The drier and lighter the fuels the more easily they will ignite. A continuous layer of fuels on the forest floor can aid in the spread of a fire.
Topography	Flat or sloped, aspect	Fire moves more rapidly up hills than down hills or over flat surfaces. Fire is more likely on southern and western aspects, which are drier.

Source: Adapted from na.fs.fed.us/fire_poster/science_of_fire.htm

Fire weather and climate conditions only provide necessary conditions rather than sufficient conditions for fire occurrence. In other words, certain weather patterns such as dry and hot weather do not guarantee the occurrence of a fire at a specific location. Rather, such conditions may confer a higher probability for a fire or fires at a location within an area of similar weather, fuel, and topography, assuming the same ignition probability. In addition, when looking at fire-climate relationships across a range of time scales (seasonal, interannual, decadal, or longer scales), the focus is often on total area burned rather than fire ignition and spread processes.

Fire potential—the measure of the chance that a fire of a certain severity will occur in an area—is often used as a surrogate for real fires. It is often estimated as a fire danger rating that is based on weather and fuel conditions. Different from fire behavior prediction, which is a property of an individual fire, fire danger rating (or fire potential) focuses on the fire situation over a geographic area. Furthermore, fire behavior prediction estimates what a fire will do, while fire danger rating is typically an ordinal index relating the probability that fires of a certain severity level will occur. Many rating systems have been developed, including the National Fire Danger Rating System. These systems often consist of a number of indices expressing fuel conditions (fuel moisture levels and energy release), weather conditions as expressed by the Keetch–Byram Drought Index (KBDI) or Fire Weather Index, and potential fire behavior (spread component and burning index).

Fire–weather and fire–climate relations have been studied extensively, including a review of studies in the last century by Flannigan and Wotton (2001) and a systematic study for the South by Heilman et al. (1998). Cold frontal passage, dry spells, and low relative humidity were found to be the most important weather determinants of area burned. These elements influence fuel moisture and associated fire danger components. Fire season variability is mainly governed by the interannual variability of atmospheric conditions, with fires often occurring during periods of drought, abnormal ocean conditions, and other anomalies of weather and climate. The anomalies in the sea-surface temperature (SST) of the equatorial eastern Pacific Ocean such as El Niño and La Niña can change the atmospheric circulation patterns in the Southern United States through atmospheric teleconnection and can modify fire weather in this region.

FIRE AND CLIMATE CHANGE

The features of fire regimes in the South described above evolved based on the climate and fuel conditions in the past. Because fire environmental conditions are expected to change this century, fire regimes could change as well. Environmental changes will occur in response to changes in climate, land use, and socioeconomic and environmental variables affecting ignitions by people, as well as change in wildfire management approaches. Understanding the possible change in fire regimes is essential to assessing the potential impact of future wildfire trends.

One among many variables affecting fire regimes, a changing climate could have various impacts on fires in the South (Table 5.3), but the relationships are complex. Projected temperature increases across the South would contribute to longer fire seasons and increases in fire frequency, intensity, and total burned area. Temperature change also could indirectly impact fires by changing fuel conditions. Increased temperature would likely increase evaporation, thereby reducing fuel moisture and increasing fire occurrence. Higher temperatures also could affect ignition rates. The impact on fuel loading is more complex. Longer growing seasons associated with temperature increases can increase fuel loading by increasing productivity, but temperature increases can also decrease vegetation growth and thereby fuel loading because of reduced water availability due to increased rates of evaporation and transpiration.

The contributions of precipitation and humidity are also complex. Precipitation is projected to decrease in many subtropical and mid-latitude areas, reducing fuel moisture and increasing fire potential. At the same time, a reduction in precipitation would reduce water availability for plant growth, leading to less fuel and lower fire potential. Clearly, projecting the effects of altered precipitation is accompanied by more uncertainty than projecting the effects of increased air temperature. Additional uncertainty comes from the atmospheric models: projected precipitation change often shows no clear trends, even over large areas. Along with changes in average precipitation, most general circulation models (GCMs) also project more frequent precipitation anomalies, such as drought, that would increase fire activity. Although increased temperature would reduce relative humidity locally, it would also increase evaporation from ocean and land surfaces, thereby producing an overall increase in relative humidity. Effects on relative humidity are also difficult to predict because of the dependence of atmospheric humidity on precipitation, which removes water vapor from the atmosphere.

Surface wind is determined by surface roughness and spatial differences in atmospheric heating, which in turn are influenced by complex thermal and dynamic processes in the atmosphere. The strong winds that have the biggest impact on fires are related to cold fronts and other weather systems that are expected to change in frequency and intensity in the future. Thus, winds and their fire impacts will likely change as well, although projections of changes in these features of climate are even more uncertain than projections of changes in precipitation, especially in areas with complex topography.

TABLE 5.3
Response of Fire and Fuel Properties to Possible Changes in Various Atmospheric Elements and Processes

	Prediction	Fire Response			Fuel Response		
Change	**Confidence**	**Frequency**	**Intensity**	**Season**	**Area**	**Loading**	**Moisture**
Increased temperature	High	+	+	+	+	+/–	–
Decreased precipitation	Low	+	+	+	+	–	–
Increased drought	High	+	+	+	+	–	–
Changed relative humidity	Low	+/–	+/–	+/–	+/–	+/–	+/–
Increased wind strength	Low	+	+	+	+	No change	No change
Increased lightning	Low	+	+	+	+	No change	No change

Lightning currently accounts for a small share of wildfire ignitions in the South compared to human ignitions but played an important ecological role in the past (Myers and Van Lear 1997; Outcalt 2008) and could play an increasingly important role in the future. Lightning is another complex process that could become more frequent due to warming and increased trends in atmospheric instability, despite the projected precipitation decreases in many places of subtropical and mid-latitude areas (Shankar et al. 2009).

ROLE OF MITIGATION

The role of forest management is illustrated in Figure 5.2 using an example of prescribed burning to reduce frequency of wildfire occurrence by removing accumulated understory fuels. Assuming that the current fire potential is at a moderate level of the KBDI of 250 and that prescribed burning is conducted every four years, the corresponding wildfire frequency is assumed to be twice every 100 years. Under a changing climate, fire potential is projected to increase to a higher level (KBDI of 350). If prescribed burning remains once every four years, wildfire frequency would increase to three times every 100 years. One of the mitigation options could be to double the rate of prescribed burning, to every two years. As a result, wildfire frequency would remain at twice per 100 years.

PROJECTIONS OF FUTURE FIRE AND FUELS

Use and Limitations of KBDI

The KBDI is used by fire managers in the South and modelers as an indicator of current and future fire potential. A detailed description of the development and application of this index was presented in Keetch and Byram (1968) and summarized in Liu et al. (2009b). The maximum value for KBDI is 800. KBDI is classified into eight drought stages by increments of 100 (Keetch and Byram 1968). Two adjacent stages represent a change of one level in fire severity potential (Table 5.4). The KBDI depends on its historical values; in other words, it has "memory" in the sense that current values depend on previous values. For example, if a drought has occurred for one month, reduced rainfall

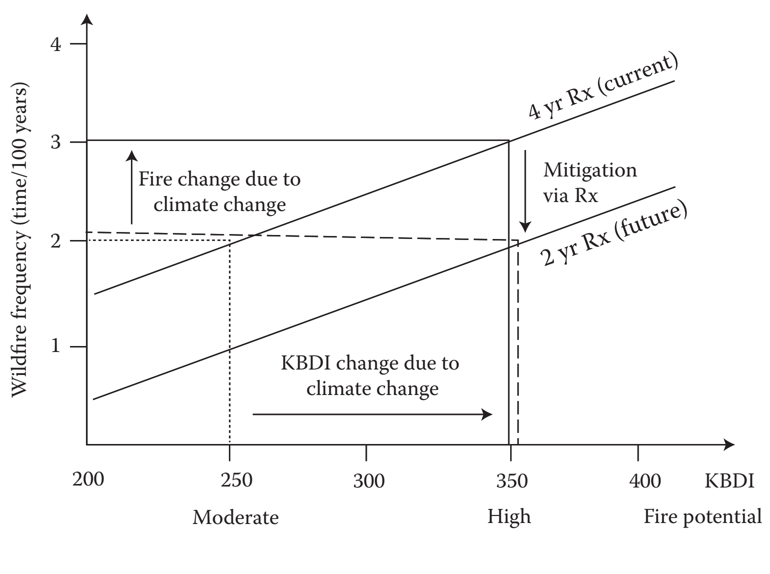

FIGURE 5.2 Schematic showing how prescribed burning can mitigate the impacts of climate change on wildfire.

TABLE 5.4
Fire Potential Classifications, Based on KBDI

Level	KBDI	Condition	Typical Period
Low	0–200	Soil moisture and large class fuel moistures are high and do not contribute much to fire intensity.	Spring dormant season following winter precipitation.
Moderate	200–400	Lower litter and duff layers are drying and beginning to contribute to fire intensity.	Late spring, early growing season.
High	400–600	Lower litter and duff layers actively contribute to fire intensity and will burn actively.	Late summer, early fall.
Extreme	600–800	Intense, deep burning fires with significant downwind spotting can be expected. Live fuels can also be expected to burn actively at these levels.	Often associated with periods of severe drought.

Source: Reorganized from U.S. Department of Agriculture Forest Service, 2005. Wildland Fire Assessment System www.wfas.net/index.php/keetch-byram-index-moisture-drought-49.

will impact the KBDI in future months. For this reason, KBDI is a fire index more suitable than most other indices to measure long-term fire potential.

The KBDI has some limitations. First, the peak values of KBDI often lag the peak of the fire season in the South. Second, the range of a specific fire potential level could vary slightly with area and season (Goodrick 1999) and fire type (Melton 1989, 1996). And third, specific KBDI values cannot be directly compared between locations with different climates because the drying rate in the index is a function of the average annual precipitation for a given location. Despite the potential limitations of the functional form used in the KBDI to parameterize evapotranspiration, the index is still a viable means of assessing the potential impacts of a changing climate on fire potential because it focuses on the relative changes produced by changes in temperature and precipitation.

STATISTICAL DOWNSCALING OF CLIMATE CHANGE SCENARIOS

To make wildfire projections based on climate change projections at a spatial scale of relevance to management (e.g., 30 × 30 km), the coarse spatial and temporal scales of projections produced by GCMs need to be downscaled to the spatial scale of inference. One option for obtaining fine scale projections from coarser scale GCMs is statistical downscaling. Statistical downscaling requires the estimation of statistical relationships among observational data and the coarse model data, and then combining these relationships using spatial interpolation. Although limited by the assumption that the factors influencing the finer spatial scale climate will remain constant throughout the projection period, these techniques are able to provide a first approximation of regional climatic conditions without the computational expense of higher resolution physical modeling.

We employed county-level temperature and precipitation data derived from an ensemble average of four GCMs [Canada General Circulation Model, version 3 (CGCM3), Geophysical Fluid Dynamic Laboratory (GFDL) model, Community Climate System Model Version 3 (CCSM3), and Hadley Center Climate Model, version 3 (HadCM3)] for three greenhouse gas emissions scenarios used by the Intergovernmental Panel on Climate Change (A1B, A2, and B1) to produce values for every month from 2010 to 2060 (Intergovernmental Panel on Climate Change 2007). Using the ensemble average of four climate models limits the impact of bias from individual models. Making projections under three different emissions scenarios allows us to sample a range of potential future conditions, possibly revealing how sensitive simulated futures are to the emissions scenario used.

Emissions scenarios combine two sets of divergent tendencies: one set varies between strong economic values and strong environmental values, and the other set between increasing globalization and increasing regionalization (Nakicenovic et al. 2000). The A1 scenario family describes a future of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and entails the supposed rapid introduction of new and more efficient technologies. Within that family, A1B represents a balance between fossil fuels and alternative energy sources. The A2 scenario differs in that population is assumed to continuously increase, economic development is more regionally focused, and the introduction of new technologies is slower and more fragmented, limiting the adoption of alternative fuels. The B1 scenario is similar to the A1 family but describes a more integrated world characterized by an emphasis on global approaches to economic, social, and environmental stability. The atmospheric CO_2 concentration in 2008 was about 360 ppmv* for all scenarios. It would increase to about 700 for A1B (950 for A1F1), 850 for A2, 550 for B1, and 600 for B2 by 2100. For the A1B scenario, GCMs estimate the global average temperature to rise by approximately 2.8°C by the end of this century, the A2 by 3.4°C, and the B1 by 1.8°C.

The temperature and precipitation data for our analysis were derived from the bias-corrected and spatially downscaled climate projections originally derived from the Climate Model Intercomparison Program (CMIP3) data by Maurer et al. (2007).† To achieve county level detail, the data were resampled using a nearest-neighbor approach: the value for each county was assigned based on the grid point nearest the county centroid. Temperature information was in the form of average daily temperature, and precipitation values reflected the average rainfall per day for each month. These values were not ideal for calculating KBDI, which normally uses daily maximum temperatures and total rainfall. This data limitation was overcome by assuming that the daily maximum temperature is 15% higher than the daily average temperature, that rain falls every two days, and that soil moisture begins each month at saturated conditions (zero KBDI). The use of a 15% increase from daily average temperature to achieve the daily high temperature is arbitrary, but it provided a generally good approximation in the South based on an application of the model to historical data. The assumption of rain every other day maximized the daily drying to align with the KBDI assumption that the first 6.5 mm of rainfall is insufficient to lower the drought index. Starting the KBDI calculations from zero each month provided an indicator of how quickly the soil could dry out each month based solely on the meteorological conditions of that month and not on any residual dryness.

In analyzing how climate change could impact the KBDI for all three emission scenarios across the South, we first established data for the baseline decade of 2000–2009 by examining KBDI patterns in the months of January, March, May, July, September, and November for those years. Next, we examined departures from these baseline patterns for 2010–2019, 2030–2039, and 2050–2059. Our goals were to identify eco-regions where fire potential is changing substantially from current conditions, gauge the level of uncertainty in the projections by noting differences among emissions scenarios, and translate these changes into impacts on fire season duration and severity.

For January during the baseline period, conditions are consistent across the scenarios (Figure 5.3). Cold temperatures throughout most of the region strongly limit drying except in the Florida peninsula and along the Texas coastline. Precipitation is more than sufficient to counter drying and keep the soil near saturation. By the 2010 to 2019 period, drying is expected to begin spreading up the Florida peninsula and into the Eastern Atlantic and Southern Gulf sections of the Coastal Plain as well as from the Texas coastline to the Western Gulf section of the Coastal Plain. Few differences are expected among the scenarios, with the A2 scenario projecting the most drying followed by A1B, and B1 projecting the least. By the 2030 decade, drying is expected to spread along the Gulf of Mexico with the A1B scenario projecting strong drying along southern areas of the Deltaic Plain section of the Mississippi Alluvial Valley. Overall, the A1B scenario projects the most drying along the Gulf of Mexico, while the B1 scenario projects the least. In summary, the changes are expected to be relatively minor because the most severe drying, found in the A2 scenario, would only change the KBDI by about 40 units by the 2050 decade.

* ppmv = parts per million by volume.

† Data available at gdo-dcp.ucllnl.org/downscaled_cmip3_projections/

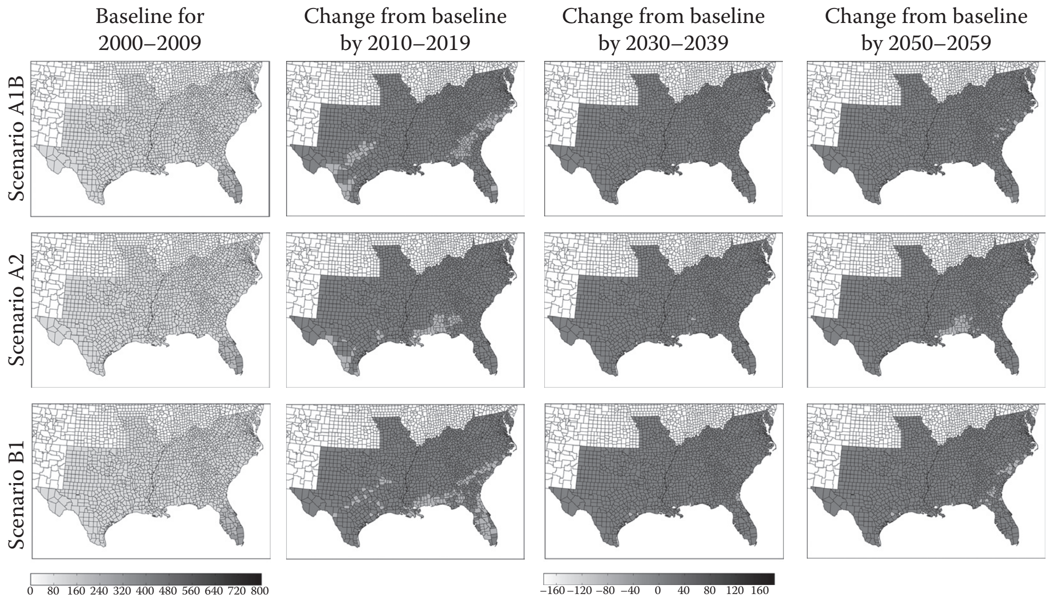

FIGURE 5.3 January fire potential for the baseline decade followed by ensemble, statistically downscaled projections of changes in fire potential for three subsequent decades assuming different Intergovernmental Panel on Climate Change (2007) emissions storylines: A1B, A2, and B1.

By March of the baseline period, dryness has begun to spread northward from the Florida peninsula and Texas coastline (Figure 5.4) with decadal averages of KBDI rising to 250–300 in some areas. As with the January baseline period, the emission scenarios have little impact on baseline conditions. By 2010, however, differences are expected among the emissions scenarios. Although projecting overall drying across most of the South, the B1 scenario projects that drying will be most severe in the Deltaic Plain section of the Mississippi Alluvial Valley, will spread across the Southern Gulf section of the Coastal Plain by 2030, and then expand into the Eastern Atlantic section by 2050. In the Blue Ridge, Northern/Southern Ridge Valley, and into the Cumberland Plateau regions, few changes in KBDI are expected, with perhaps slightly wetter conditions regardless of scenario or decade—suggesting a slight preference of the Ohio River Valley for storm tracks in the models.

In May, very slight differences among the scenarios are evident for the baseline period (Figure 5.5). Drying spreads throughout the South, except for the northernmost areas. May typically marks the peak of the spring fire season, particularly with regard to area burned. The May peak is likely to continue in the future, with all scenarios indicating that late spring will become even drier in most areas. As early as 2010, significant differences among the scenarios are expected. A1B and B1 project the most significant drying, particularly in the Texas/Oklahoma Cross Timbers section of the Mid-South and the western and eastern Middle Gulf sections of the Coastal Plain. All three scenarios project a tendency for wetter conditions in the Southern Gulf and Eastern Atlantic sections of the Coastal Plain in 2010. However, these wet areas are not expected to persist through the 2030 and 2050 decades. By 2050, the A1B scenario projects more substantial drying, an increase in KBDI of over 150 points, with the highest values centered over Louisiana and spreading throughout the Western and Middle Gulf sections of the Coastal Plain. Even the scenario with the smallest projected changes for May, those of the A2 scenario, indicates significant drying and hence longer spring fire seasons by 2050.

During the baseline period for July, high temperatures and limited rainfall result in dry conditions across much of the South (Figure 5.6). The most severe drying is projected to be centered

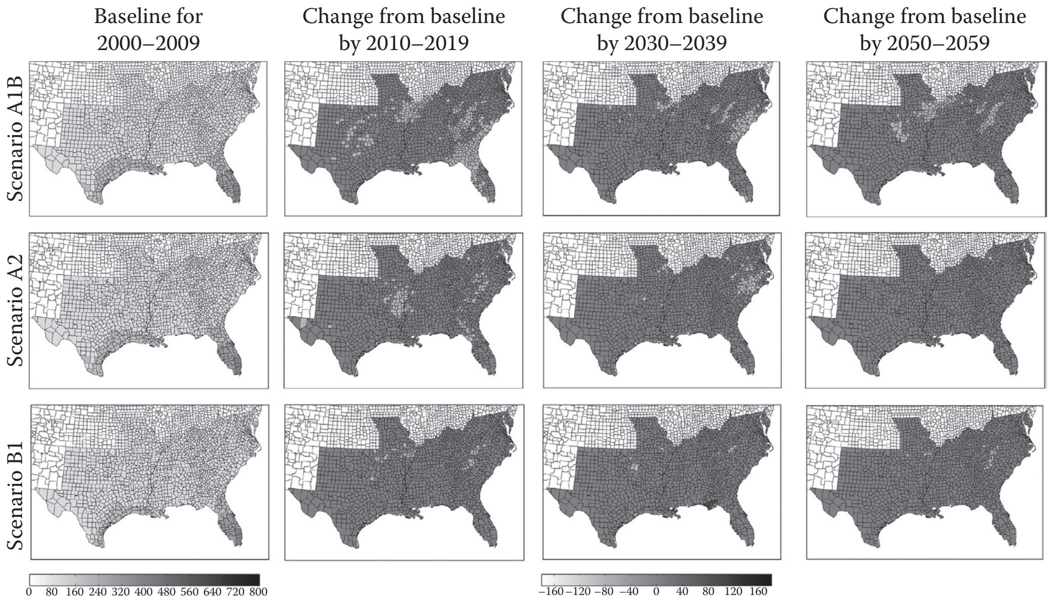

FIGURE 5.4 March fire potential for the baseline decade followed by ensemble, statistically downscaled projections of changes in fire potential for three subsequent decades assuming different Intergovernmental Panel on Climate Change (2007) emissions storylines: A1B, A2, and B1.

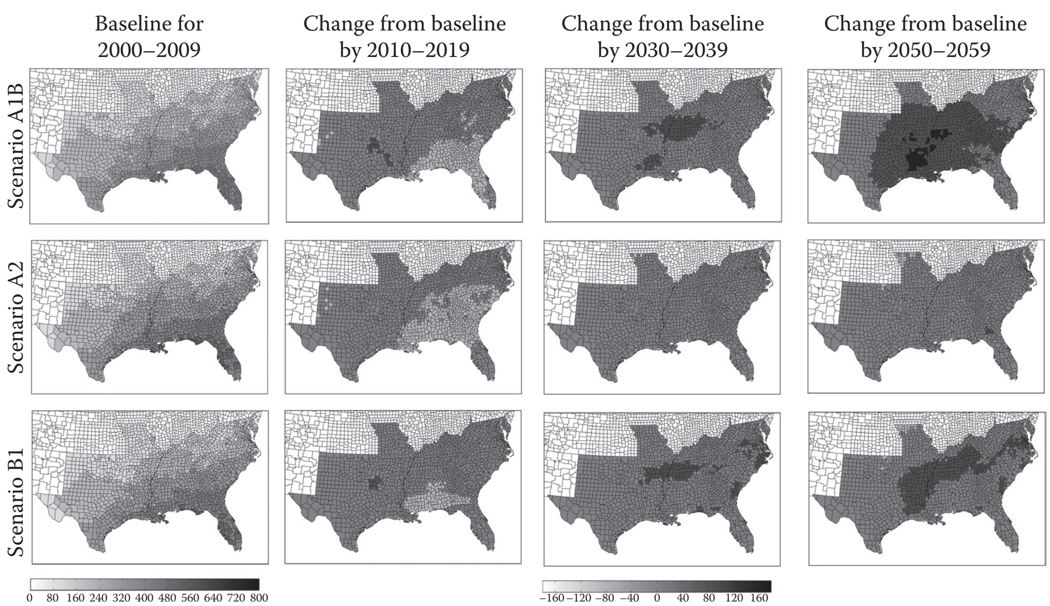

FIGURE 5.5 May fire potential for the baseline decade followed by ensemble, statistically downscaled projections of changes in fire potential for three subsequent decades assuming different Intergovernmental Panel on Climate Change (2007) emissions storylines: A1B, A2, and B1.

FIGURE 5.6 July fire potential for the baseline decade followed by ensemble, statistically downscaled projections of changes in fire potential for three subsequent decades assuming different Intergovernmental Panel on Climate Change (2007) emissions storylines: A1B, A2, and B1.

over Louisiana, Mississippi, and Arkansas, but with most coastal areas noticeably wetter from sea-breeze-induced thunderstorms. As with projections of baseline conditions for early months of the year, only subtle differences separate the three scenarios. Differences are projected to begin appearing as soon as 2010, when the A2 scenario indicates wetter conditions for the Southern Appalachians, Piedmont, Southern Gulf, and Eastern Atlantic. The A1B and B1 scenario projections are very similar across the region, except for the northern half of the Florida peninsula, where B1 projects more pronounced drying. By 2030, no areas of increased moisture are projected to remain, and all scenarios indicate conditions becoming drier, although the spatial pattern varies by scenario; for example, the A2 projects the lowest increase in dryness. By 2050, the A1B and A2 scenarios indicate KBDI increases of about 100 units across the majority of the South. The A1B projects the most intense drying in northern Alabama and Mississippi. Even the coastal areas with relatively moist conditions are projected to experience intense drying by 2030 and 2050. These results should be viewed with some level of skepticism because such local phenomena are generated based only on statistical downscaling of the coarser scale GCM projections, which do not show such small scale variations.

The area of dry conditions begins to contract by September for the baseline period (Figure 5.7) and is still centered over Louisiana. The extent of the dry area varies slightly among scenarios, with A2 being the wettest. September is the month that displays the greatest variability among the emissions scenarios for all future time periods. For 2010, the B1 scenario projects increased moisture along the Texas coastline and across the Florida peninsula as well as across the northern half of the region, with only slight drying in other areas. A1B introduces strong drying along the Atlantic coastline and the Southern Gulf section of the Coastal Plain, with wetter conditions along the Texas coastline and slightly wetter conditions along the northern half of the region, but not to the same spatial extent as in B1. The A2 projects a combination of features from the other two scenarios, but overall is drier for much of the region, with drying along the Atlantic coastline (although more spatially limited than in A1B) and wetter conditions in the Florida peninsula and along the Texas coastline. By 2030, all emissions scenarios project similar spatial patterns but vary in their intensity. The North Atlantic section of the Coastal Plain and the Central Appalachian Piedmont are projected to

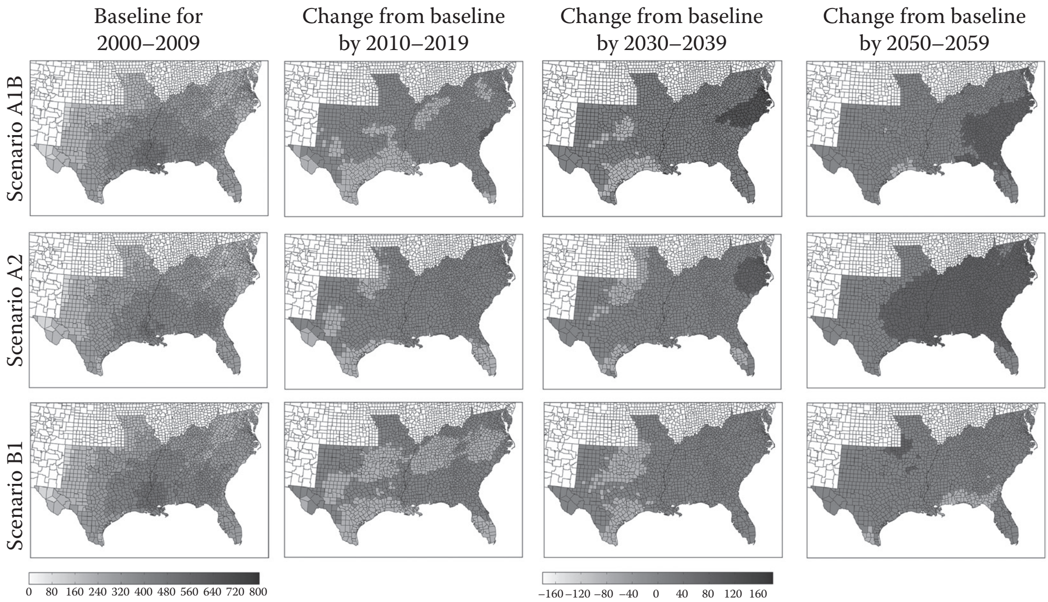

FIGURE 5.7 September fire potential for the baseline decade followed by ensemble, statistically downscaled projections of changes in fire potential for three subsequent decades assuming different Intergovernmental Panel on Climate Change (2007) emissions storylines: A1B, A2, and B1.

become a center of drying that varies in intensity from weak for B1 to strong for A1B. Although A2 does not project as high a peak in KBDI as does A1B, the spatial extent of the strong drying is larger. The Texas coastline and an area along the Texas–Oklahoma border are expected to become a center of wetter conditions, with a 40-unit decrease in KBDI. By 2050, the A2 scenario projects significant drying; much of the region experiences increases of at least 80 units in KBDI and most of the Northern Atlantic section of the Coastal Plain increasing by approximately 160 units. The A1B scenario projects a similar, although less extreme, drying trend that intensifies the dryness in eastern areas and largely eliminates the wetter conditions in the western half of the region. By 2050, the B1 scenario projects a spatial pattern that is different from the other scenarios, with region-wide drying that is centered in the Ozark-Ouachita Highlands. For those areas of the region that typically experience an autumn fire season, these results suggest an earlier start of the fire season and more severe conditions during the fire season.

The overall impact of climate change on fire potential in the South, as reflected by projected changes in the KBDI, is a gradual shift toward more severe fire conditions. The lengths of the spring and autumn fire seasons are projected to increase, and the extent of the drying is likely to be more severe. The early spring fire season is projected to be concentrated in eastern reaches of the Gulf of Mexico coast; however, the increase in severity is likely to be more widespread in coming decades. The projected dryness during the summer may mean new areas of the South that are subject to a summer fire season (or at least a later end to the spring season and earlier start of the autumn season).

The impact of the different emissions scenarios on fire potential is not large through 2060; the differences among model results are generally small. However, the consistency in emissions impacts shows that a dramatic decrease in fire potential is not likely, based on scenarios that all suggest an increase in fire potential in the coming decades. Although the models are in agreement, several factors give reason to advise caution in interpreting and applying these results, especially for any type of regional assessment. Large-scale global models are not currently run at a resolution capable of resolving all important weather phenomena. Features such as sea breezes—a mechanism for significant rainfall in coastal areas—and topographic modification of frontal systems by the Appalachian

Mountains are not adequately represented. Instead, the regional projections presented in this section rely on statistical information relating global model information to local observations; they assume that these relationships will remain constant in the future. The choice of emissions scenario drives the general circulation model, but the same statistical relations are used to translate output from all models to the region level. The statistical commonalities may limit the degree of variability that we observed in the projections. Using a regional climate model to dynamically downscale the global information may result in more variability among scenarios.

DYNAMICAL DOWNSCALING OF CLIMATE CHANGE SCENARIOS

An alternative to the statistical downscaling of climate change scenarios is the dynamical downscaling produced by the North America Regional Climate Change Assessment Project (NARCCAP). NARCCAP is an international program established to produce high-resolution simulations that describe uncertainties in regional scale projections of future climate and generate scenarios for use in impacts research (Mearns et al. 2009). The NARCCAP regional climate change scenarios were obtained by running a set of regional climate models that were driven by general circulation models over North America in conjunction with the A2 emissions scenario. The simulations were conducted for the current (recent historical) period 1971–2000 and for the future period 2041–2070, and the spatial resolution was 50 km.

These scenarios have several features different from the statistical downscaling approach. First, they provide daily output. Second, maximum temperature data are available, which is one of the variables needed for KBDI calculations. Third, other variables such as relative humidity and wind are also available, which can be used together with temperature and precipitation to calculate other fuel and fire indices in addition to the KBDI. These additional variables and the calculated indices are useful when projecting weather conditions critical to prescribed burning (see Management Options for Mitigation).

We used downscaling of HadCM3 with the Hadley Regional Model, version 3 (HRM3), which has been used for projecting fire potential trends in North America (Liu et al. 2010, 2012). The spatial scope of NARCCAP is North America. For this chapter, however, we only used the data at grid points within the South. Figures 5.8 through 5.10 show averages of temperature, precipitation, and KBDI. The simulated current maximum temperature shows a clear seasonal cycle for the region as

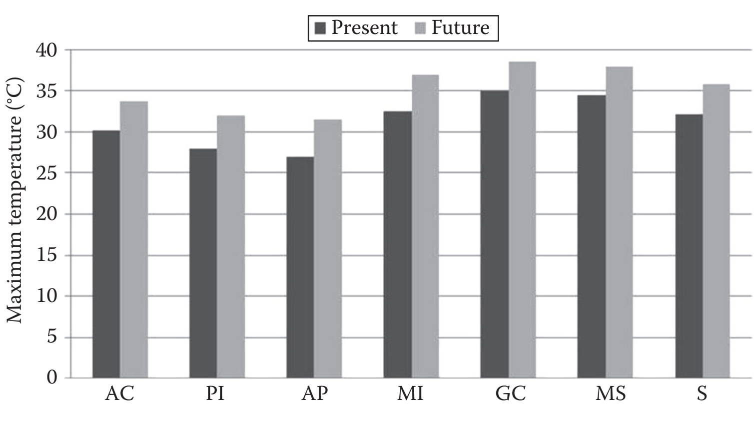

FIGURE 5.8 Current (1971–2000, left bar) and future (2041–2070, each right bar) change in seasonal temperature averaged over the Atlantic Coast (AC), Piedmont (PI), Appalachian Mountains (AP), Mississippi Alluvial Valley (MI), Gulf Coast (GC), Mid-South (MS), and entire Southern United States (S). (Adapted from Liu, Y.-Q., Goodrick, S.L., Stanturf, J.A. 2012. *Forest Ecology and Management.* 294: 120–155. doi: 10.1016/j.foreco.2012.06.049.)

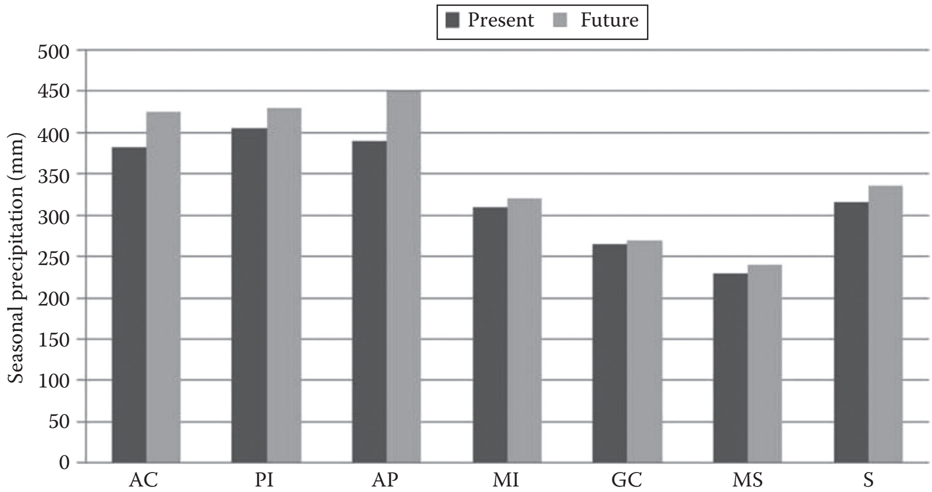

FIGURE 5.9 Same as Figure 5.8 except for precipitation.

a whole (Figure 5.8), increasing from about 10°C in winter to 20°C in spring, and 32°C in summer, and then decreasing to 22°C in autumn. Temperature decreases from the Atlantic Coastal Plain to the Piedmont and to Appalachian-Cumberland highlands for all four seasons; it generally increases from the Mississippi Alluvial Valley and southern Coastal Plain to the Mid-South. Regional maximum temperatures are projected by the middle of this century to increase by about 3–4°C during all seasons, with the largest increases projected for summer. There are no significant intraregional differences projected. The HadCM3 and HRM3 project the same spatial pattern but the HRM3 projections are slightly lower, especially in the western areas of the South.

The simulated current precipitation in the South (Figure 5.9) also shows the same seasonal cycle as that of temperature, increasing from winter (240 mm) to spring and summer (320 mm), and then decreasing in autumn (200 mm). In the western areas of the region, however, precipitation peaks in spring rather than summer. Precipitation is projected to increase for the region, by greater than 50 mm during summer in some areas. HRM3 precipitation projections for western areas are

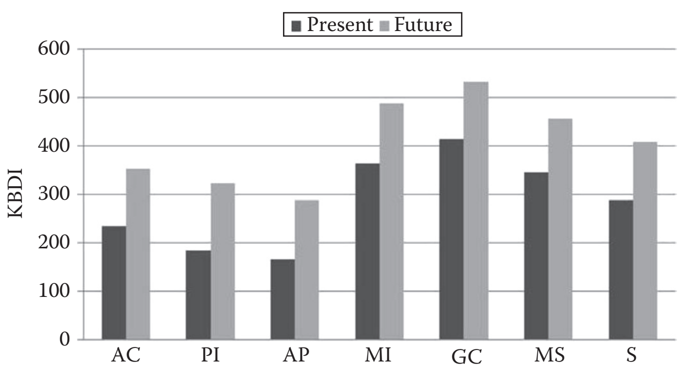

FIGURE 5.10 Summer KBDI in the Southern U.S. eco-regions for the present period of 1971–2000 and future change by 2041–2070. The regions below each panel are Atlantic Coast (AP), Piedmont (PI), Appalachian (AP), Mississippi (MI), Gulf Coast (GC), Mid-South (MS), and entire Southern U.S. (S). (Adapted from Liu, Y.-Q., Goodrick, S.L., Stanturf, J.A. 2012. *Forest Ecology and Management.* 294: 120–155. doi: 10.1016/j.foreco.2012.06.049.)

substantially different from the decrease projected by HadCM3. This divergence in precipitation projections should have a significant effect on the future KBDI calculations.

Current KBDI values are usually small in winter and spring and large in summer and autumn in all eco-regions (Figure 5.10). Present summer and autumn KBDI values are around 200 (considered in the upper KBDI range for low fire potential or the lower range for moderate fire potential) in the three eastern eco-regions, and future values rise to 350–400 (the upper KBDI range for moderate fire potential or the lower range for high fire potential). Meanwhile, present summer and autumn KBDI values are around 400 (the upper KBDI range for moderate fire potential or the lower range for high fire potential) in the three western eco-regions, and future values change to about 500 (the middle KBDI range for high fire potential). For the entire South, summer and autumn fire potential changes from moderate at present to high fire potential in future.

Figure 5.11 shows monthly variations of current and projected future KBDI for the South.

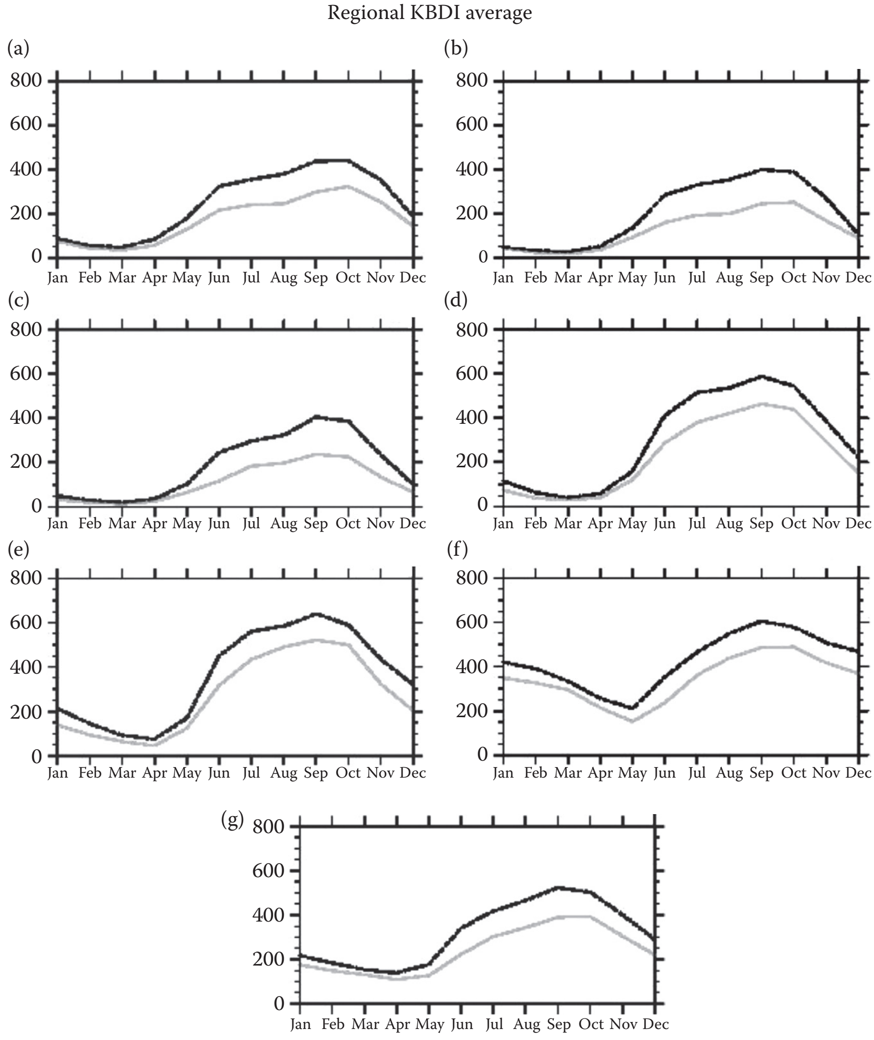

FIGURE 5.11 Monthly current and predicted fire potential, based on KBDI, averaged over the (a) Atlantic Coast, (b) Piedmont, (c) Appalachian Mountains, (d) Mississippi Alluvial Valley, (e) Gulf Coast, (f) Mid-South, and (g) entire Southern United States.

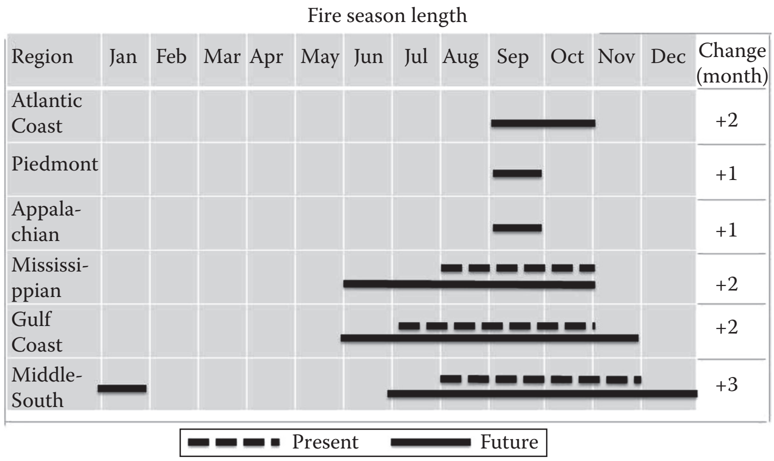

FIGURE 5.12 Current and predicted length of fire season within the Southern United States, based on KBDI ratings of moderate or high fire potential. (Adapted from Liu, Y.-Q., Goodrick, S.L., Stanturf, J.A. 2012. *Forest Ecology and Management*. 294: 120–155. doi: 10.1016/j.foreco.2012.06.049.)

Current KBDI starts with a low value of about 170 in January. It gradually decreases to less than 100 units in April, increases to about 350 in September and October, and then decreases again to about 190 in December. The corresponding fire potential is low from December to May and moderate from June to November. The future KBDI is projected to increase for all months, substantially after May, and with the largest increase of about 150 in September. Future fire potential is expected to remain low from January to May but to change from moderate to high during the July to October period. Intraregional changes in future fire potential are similar, although actual KBDI values vary.

The projected increase in fire potential suggests that fire seasons might become longer in the future (Figure 5.12). The length of a fire season, measured by the number of the months with high or extreme fire potential level, might increase by 1–3 months.

TRENDS AND PROJECTIONS FOR FIRE EXTENT

Wildfire in a Changing Climate and Societal Environment

If climate changes as projected and society continues to develop in the coming decades, then wildfire activity in the South will also change. Research has shown that wildfire responds to weather, fuels, and inputs from people. Human inputs have included intentional activities, such as prevention, fuels management, and suppression, designed to reduce wildfire occurrence and spread. They also include intentional and unintentional human fire starts and land use changes that can influence the frequency, location, and size of wildfires.

Recent research has shown that fire prevention efforts can be effective (Butry et al. 2010; Prestemon et al. 2010), that law enforcement can reduce the frequency of arson wildfires (Prestemon and Butry 2005), and that residential and commercial development patterns affect the severity and extent of wildfires in the South (Prestemon et al. 2002; Mercer and Prestemon 2005; Mercer et al. 2007). With respect to development patterns, research has shown that accumulations of forest fuels from fire suppression encourage the spread and increase the intensity of wildfires when they occur; wildfires burning in heavy fuels tend to be harder to extinguish. Human populations themselves seem to present positive risk factors for wildfire (Donoghue and Main 1985); human-ignited wildfires tend to be clustered around places with human populations (Zhai et al. 2003; Genton et al. 2006), confirming that as human populations grow, wildfire ignitions by people are more frequent, all other factors considered.

Because of the links between fuels and fuel conditions, weather and climate, as climate in the South warms or dries, wildfires could become larger and more intense—again, all other factors considered. The conclusion by Westerling et al. (2006) that wetter weather, which may be experienced in some places with climate change, would result in less frequent, smaller, and less intense wildfires is supported by much research in the South for both human- and lightning-caused fires (Donoghue and Main 1985; Prestemon et al. 2002; Mercer et al. 2007; Prestemon and Butry 2005; Butry et al. 2010).

Many natural resource scientists, land managers, and policy makers have expressed concern about the implications of climate change on wildfire activity. Other sections of this chapter document how climate change may lead to higher fire potential due to drying, warming, and longer fire seasons. Complicating questions of climate change, however, is the likelihood that society is also projected to change significantly in the coming decades. Human populations are growing, including in the South, and most economists predict continued economic expansion. Therefore, projections of future wildfire activity would be incomplete unless they considered societal change. Because of the link between greenhouse gas emissions and economic activity, climate can be said to partly depend on how society changes; Nakicenovic et al. (2000) provide a number of scenarios that describe this kind of dependence.

Results from the various scenarios described by Nakicenovic et al. (2000) and later projections in the Intergovernmental Panel on Climate Change (2007), fourth assessment, indicate that climate in the South will be warmer and, in many areas, drier. The effects of those changes on wildfire, however, are likely to be complex. Humans affect ignition processes, spread processes, and land uses—all of which have a bearing on wildfire projections. In an initial attempt to understand the effects of such changes, we developed statistical models of wildfire in the South, based on historical data, that relate wildfire activity to fuel conditions, broad descriptions of ecological conditions (ecological classification), weather, human populations, and economic activity. Climate, land use, and socioeconomic variables were then projected. This effort was part of larger effort to understand the air quality implications of altered fire activity in the South as a result of climate change (Shankar et al. 2009). An A1B scenario projection paired with the CESM3 (Community Earth System Model 2011) was used as the basis for projections of weather, fire, demographics, timber harvesting activity, and land use. Projections ran from 2002 (the base year) to 2050 and for two intervening years: 2020 and 2030.

Fire Projection Methods

We projected fire area burned on grid cells measuring 12 × 12 km for most of the South (southern Kentucky to southern Virginia, Florida to Texas). The base year for wildfire data—distinguished by cause (human or lightning)—and associated population, economic, fuels, and weather data was 2002. Cross-sectional sample selection models (Greene 1997) by cause were estimated for human-caused wildfire and lightning-caused wildfire. The modeling occurred in two stages: the first stage used a Probit model to predict whether fire occurred in the spatial unit of observation during 2002, and the second stage made a least-squares estimate of area burned using only the observations of fires recorded in 2002. In this second stage equation, the amount of fire recorded in the grid cell was regressed on a factor that measured the probability of having fire as well as a set of other predictors. The threshold used in this model for determining whether fire occurred in the grid cell was whether at least 5 ha burned in the cell. The model domain included 13,956 grid cells; hence 13,956 observations in both sample selection models. Of these, 450 grid cells had at least 5 ha burned by lightning-caused wildfires and 3882 cells had at least 5 ha burned by human-ignited wildfires.

In the first stage of the selection model, the fire occurrence was expressed as a function of income (economic output per unit area), population per unit area, forest land per unit area, fuel levels, and average wind speeds. Intercept shifting dummies reflecting ecological and states' boundaries were included to allow for absolute fire probability differences across these geographical units. The second stage of the model was expressed as a function of the same variables, predicting burned area given that a fire occurred in that grid cell in 2002. Detailed results are available in Shankar et al. (2009).

The statistical models' predicted area burned for 2002 was calibrated to match the region-wide total of area burned for 2002 by cause. The calibration factors for lightning- and human-ignited wildfires were then used in the projection years of 2020, 2030, and 2050. Projections of area burned in these future years were done by applying the estimated statistical models to the predictors. Projections of county and state level variables (forest, income, population, climate variables) were derived from the 2010 Resources Planning Act Assessment (U.S. Department of Agriculture Forest Service 2012). Forest area projections were based on work by Wear (2011), but adjusted for the base year 2002 using the National Land Cover Data from the U.S. Department of the Interior, U.S. Geological Survey. Assignment of grid cells within the region was based on work by Rudis (1999).

Fire Projections Results

Results of the wildfire projections in the South are illustrated in Figure 5.13. Lightning fires are projected to rise from base year (2002) levels. The base-year burned area levels for lightning might have been usually low in 2002, but the projections clearly show an increase, from about 18,000 ha in 2002 to 51,000 ha by 2050, with slightly higher levels expected in 2030 than 2050. Conversely, area burned in human-ignited wildfires by 2050 is projected to decrease by 35%, from about 141,000 ha in 2002 to 92,000 ha in 2050. In aggregate, the decrease in area burned by human-ignited wildfires outweighs the increase in area burned by lightning-ignited wildfires, producing a projected total

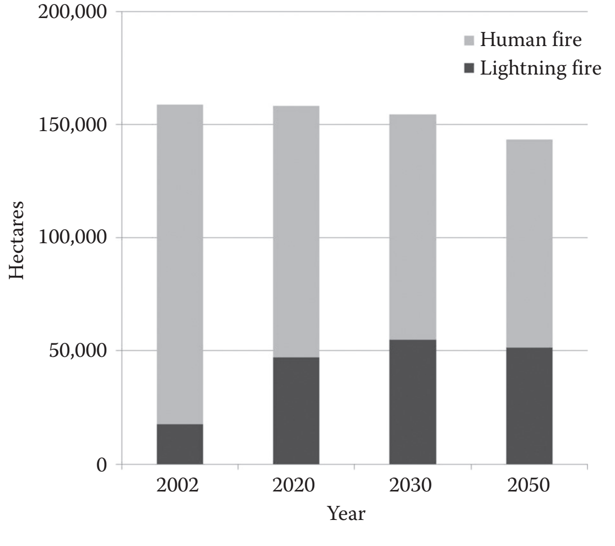

FIGURE 5.13 Area affected by human- versus lightning-caused wildfire in the Southern United States, 2002 (baseline) to 2050 (projected) assuming the Intergovernmental Panel on Climate Change (2007) A1B emissions storyline of rapid economic growth, global population that peaks in mid-century and declines thereafter, rapid introduction of new and more efficient technologies, and a balance between fossil fuels and alternative energy sources.

decrease in area burned of about 10% by 2050 (about 144,000 ha in 2050, compared to 159,000 ha in 2002).

The effects and importance of the variables used in the projection can be appreciated by examining the statistical modeling results (Shankar et al. 2009). One general result of the modeling is that, in aggregate, forest area is positively related to the area burned by both lightning fires and human-ignited fires. As forest area increases, the number of wildfires and area burned would increase. Land use projections used in this study show an aggregate loss in forest land, a change that therefore would be expected to lower overall wildfire activity. Furthermore, income increases have negative effects on both the occurrences of human-ignited wildfires in our statistical models and on the area burned by such wildfires. Therefore, as incomes rise in aggregate across the South, human-ignited wildfires would be expected to decline in both frequency and size. This effect would be expected: as values at risk increase, communities have been shown to devote greater resources toward both preventing fires (Prestemon et al. 2010) and extinguishing them more quickly. Conversely, climate changes projected under scenario A1B with the CESM3 generally show higher winter and summer temperatures and lower overall humidity in the South by 2050. These trends are likely to lead to higher overall burn probabilities and areas burned. These effects, even adding in the effects of higher populations, apparently are less important for human-caused fires compared to changes in forest area and income.

For lightning fires, however, wildfire frequencies are more heavily influenced by trends in temperatures (upward) and fuel moisture. Although the size of such fires would be expected to decline because of greater suppression efforts enabled by higher incomes (attempts to protect values at risk), the tendencies for lightning fires to be larger under a warmer and drier climate outweigh the efforts to control their extent.

TRENDS IN FUEL LOADING

To generate high-resolution datasets that reflect the spatial–temporal dynamics of fuel loads from 2002 to 2050; Zhang et al. (2010) used a global dynamic vegetation model to incorporate simulated ecosystem dynamics into the default (contemporary) fuel loading map developed by the Fuel Characteristic Classification System. Current fuel loading increases from about 6.7 Mg/ha in the coastal areas along the Atlantic Ocean and Gulf of Mexico to 11 Mg/ha or larger in the Appalachian-Cumberland and Ozark-Ouachita highlands; and is less than 2.2 Mg/ha in western Texas. Future fuel loading is expected to be reduced from current level in the central areas of the region, with the largest reduction of about 3.4 Mg/ha in the northern areas. In contrast, the projected fuel loading would increase in Atlantic coastal areas and the Piedmont, with the largest increase of about 3.4 Mg/ha. Fuel loading is expected to be slightly reduced in the central area of western Texas and Oklahoma and increased in the northern and southern areas.

IMPACTS OF PROJECTED FIRE CHANGES

Fire Emissions

Understanding the potential impact of climate change on fire emissions requires an analysis of the weather and the fuel components of the fire triangle, because both contribute to the total amount of fuel consumed. The most critical factors in determining fuel consumption are the initial amount of available fuel and its moisture content. Climate change could alter fuel loading by changing plant productivity and decomposition rates, as well as by causing shifts in species distribution. Warmer and drier conditions would result in more fuel being consumed. For a more complete picture of climate impacts on fire emissions in the South, we must expand our scope beyond wildfires to also include prescribed fires—the primary tool for preventing wildfires. Although climate may shift toward warmer and drier conditions, these conditions may not be acceptable for prescribed fires because such conditions may be outside the parameters under which land managers can safely conduct a prescribed burn to accomplish their management objectives.

On an annual basis across the South, generally more area is burned due to prescribed fires than wildfires (Figure 5.14). Although the prescribed fire data shown are limited to what was reported for the 2002 emissions inventory, prescribed fire acreage generally shows less interannual variability than wildfires. The wildfire data shown reflect a 5-year average for 1997 to 2002 (Southern Group of State Foresters 2010). Most prescribed burns are accomplished during the first half of the year before the spring wildfire season peaks. For this assessment of the impact of climate change on fire emissions, we assumed that this annual distribution of area burned remains constant.

Climate information is supplied by two models: the Model for Interdisciplinary Research on Climate (the MIROC3.2 model), obtained from the Center for Climate System Research, University of Japan (K-1 Model Developers 2004); and the Commonwealth Scientific and Industrial Research Organization Mk3.5 (the CSIROMK3.5 model), provided by the Commonwealth Scientific and Industrial Research Organization in Australia (Gordon et al. 2002)—both forced by the A1B emissions scenario. These model/scenario combinations were selected from among those used in the Southern Forest Futures Project because CSIROMK3.5 model reflects well the ensemble average that we used in our statistical downscaling analysis, while the MIROC3.2 model projects a future that is among the driest. The average KBDI projected by the CSIROMK3.5 model show modest changes between 2010 and 2060 (Figure 5.15a). The principal distinction of the CSIROMK3.5 compared to the MIROC3.2 is that the former projects a drying that begins in the spring and extends through the summer. In contrast, the MIROC3.2 model exhibits a much stronger summer drying that begins later in the year and persists until later in autumn (Figure 5.15b).

Climate models that provide only maximum temperature and average daily precipitation information are of limited use in supplying the fuel moisture information required for most methods of calculating fuel consumption; and KBDI by itself is not directly useful. To circumvent this limitation, we used a simple equation based on the National Fire Danger Rating System burning index to calculate fuel consumption (Goodrick et al. 2010). Burning index values were not developed by direct calculation (because, as stated above, we did not have all the information required for such calculations). Instead, observed burning index values calculated for weather stations across the South were used to create a set of burning index distributions as a function of KBDI.

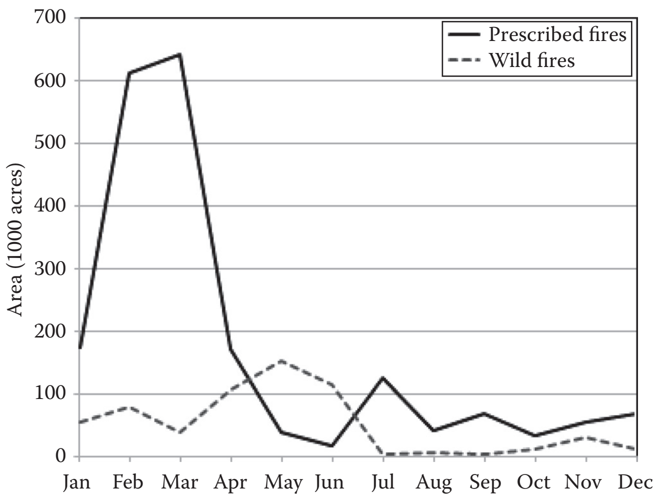

FIGURE 5.14 Average area burned by month for prescribed fires and wildfires from 1997 to 2002 in the Southern United States.

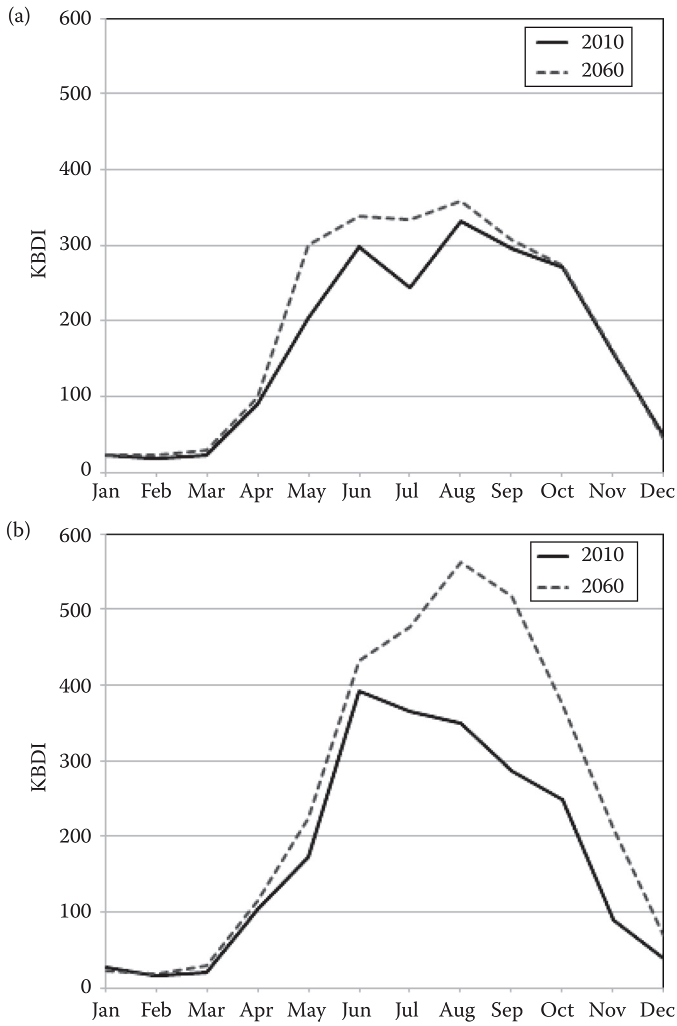

FIGURE 5.15 Monthly KBDI averages for the Southern United States in 2010 and projected for 2060, assuming the Intergovernmental Panel on Climate Change (2007) A1B emissions storyline (a) CSIROMK3.5 and (b) MIROC3.2.

For each month, the burned area of prescribed fires and wildfires was divided into 500-acre (approximately 202 ha*) fires labeled *p* for prescribed fires and *w* for wildfires. Fuel consumption was calculated following Goodrick et al. (2010) using a (1) fuel loading assigned by random draw from the spatially weighted distribution of southern fuel types from the Fuel Characteristic Classification System (with nonflammable types excluded), and (2) burning index value assigned by random draw from the observed burning index distribution that corresponded to the projected KBDI for that month. The primary difference between wildfires and prescribed fires in the analysis was that wildfires are allowed to occur for any burning index value, but prescribed fires are restricted to burning index values less than 35 points. The threshold of 35 was chosen because it reflects a flame length of 1.07 m, which is below the upper limit for which hand crews can safely work a fire-line (1.22 m). Carbon dioxide emissions were determined by simply multiplying the total fuel consumed by an emissions factor.

* The original English units were used in the calculation to avoid introducing artifacts into the data.

For the CSIROMK3.5 model, predicted changes in average fuel consumption (expressed as tons per acre) between 2010 and 2060 only occur from April through July (Figure 5.16a).

Although the MIROC3.2-based predictions are quite similar to the CSIROMK3.5 values, averaging around 6 tons/acre (approximately 13.4 Mg/ha; Figure 5.16b), the changes occur throughout the summer and into autumn.

The monthly carbon dioxide emissions for the CSIROMK3.5 projections for prescribed fires and wildfires in 2010 and 2060 are shown in Figure 5.17a. Although prescribed fire emissions change only slightly, the springtime peak in dryness coinciding with the peak in wildfire activity is expected to result in increased wildfire emissions. This increase is solely caused by the change in climate, with changes in fuel loading not included. The MIROC3.2 projections produce very little change in overall fire emissions because predicted drying occurs in summer, the time of historically low fire activity (Figure 5.17b). These results suggest that the timing of increased drying is potentially more important than the amount of drying, and that drying at times of peak fire occurrence will have a greater impact than drying at other times of the year.

In addition to the influence of fire properties, a change in fuel loading would also influence the effect of climate change on fire emissions (Liu et al. 2011). The predicted changes in fuel loading would lead to an increase in prescribed fire emissions of 500 tons (~454 Mg) from 2002 to 2050 in the eastern areas of the region, compared to a decrease in the central areas, assuming that total area burned remains unchanged.

Land cover change, another cause for changes in future fuel loading, is also expected to contribute to emissions. For prescribed fire emissions when fuel loading is combined with the land cover changes resulting from scenario A1B, instead of increasing the effect of fuel loading alone, emissions in central and northwest Florida would decrease—indicating that the amount of fuel loading reduced by urbanization would outweigh the amount of fuel loading increased by climate change.

Smoke and Air Quality

Future increases in fire activity would produce more smoke and lead to severe air quality impacts, a more far-reaching problem than just changes in fire occurrence and severity. Smoke is produced when wood and other organic material combust, producing a mixture of gases, solid particles, and droplets. Smoke impacts can generally be characterized into two classes—visibility related and health related. Visibility impacts range from regional haze that obscures general visibility and degrades scenic vistas, to dramatic visibility reductions that create a hazard to air and ground transportation. Smoke can cause safety problems when it impedes visibility, a motor vehicle hazard.

Health-related impacts negatively change or limit human habitation or activity (Achtemeier et al. 2001), which is of special concern for those with respiratory problems and other smoke-sensitive illnesses (Naeher et al. 2007). Health-related impacts are regulated through the National Ambient Air Quality Standards (NAAQS) outlined in the Clean Air Act. Wildfire emissions are important sources for particulate matter sizes above 2.5 μm ($PM_{2.5}$) and are precursors of ozone, both of which are subject to monitoring. One recent example is the smoke plume that was transported to Atlanta and other metropolitan areas during the 2007 Okefenokee wildfires that straddled the Georgia-Florida border (Odman et al. 2007). The resulting concentrations of particulate matter exceeded the danger threshold for 2.5 μm and caused significant human health problems in those areas. Prescribed fire emissions are also the source of air pollutants, as Liu et al. (2009a) found in a study on smoke incursion into urban areas of a prescribed burn in central Georgia, USA, on February 28, 2007. Using a smoke simulation system, model results indicated that the smoke invaded metropolitan Atlanta during the evening rush hour. The plumes caused severe air quality problems in Atlanta. Some hourly ground $PM_{2.5}$ concentrations at three metropolitan Atlanta locations were three to four times as high as the daily (24-h) NAAQS level.

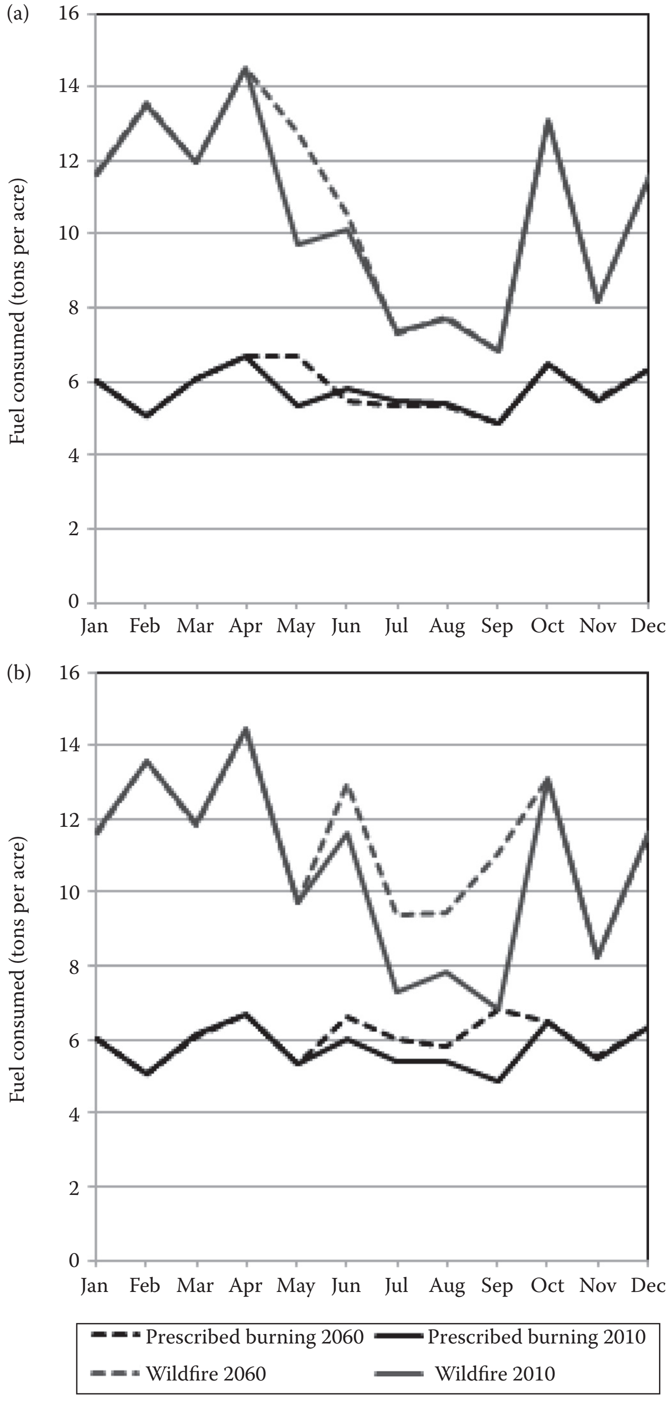

FIGURE 5.16 Average fuel consumption by month for prescribed fires and wildfires in the Southern United States in 2010 and projected for 2060, assuming the Intergovernmental Panel on Climate Change (2007) A1B emissions storyline (a) CSIROMK3.5 and (b) MIROC3.2.

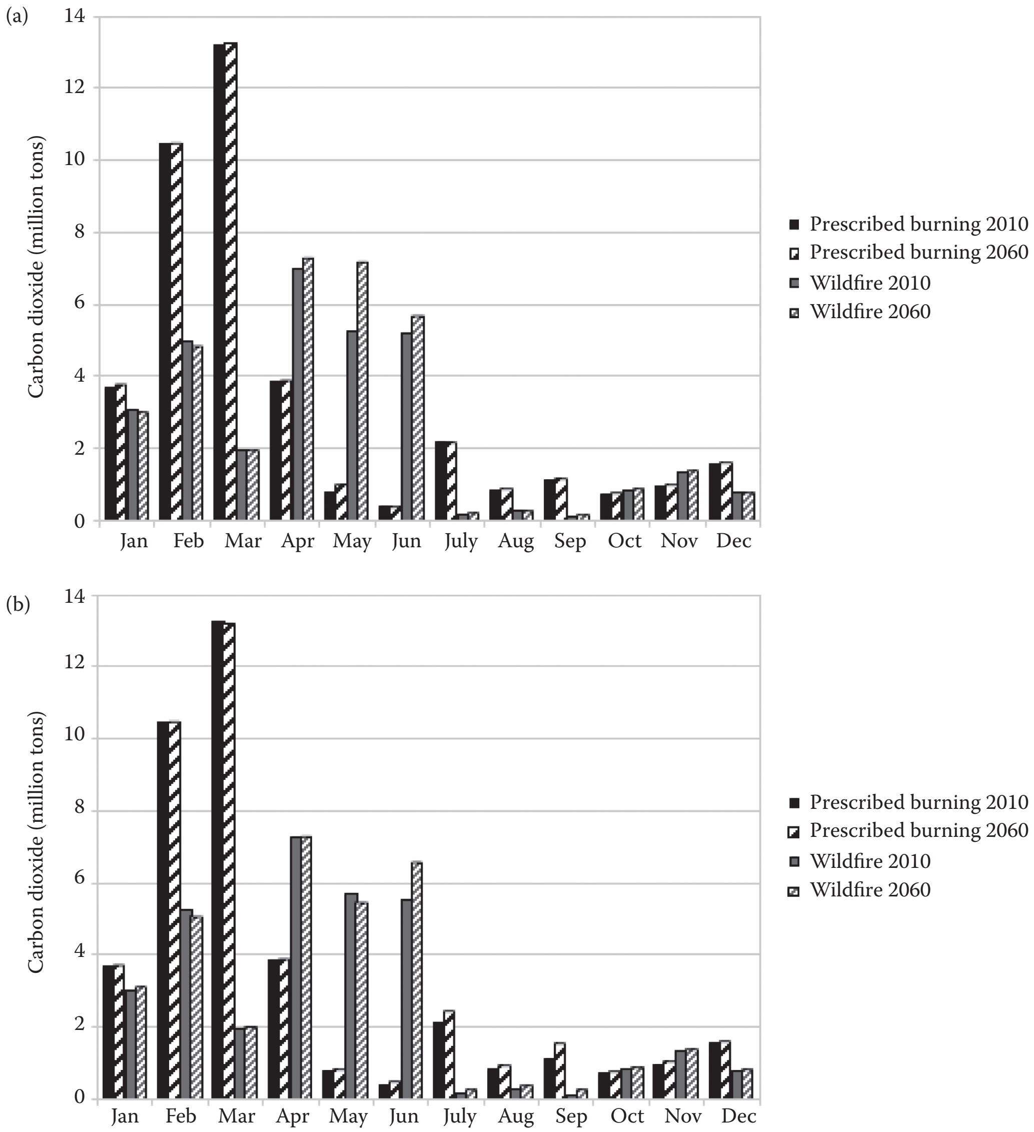

FIGURE 5.17 Monthly carbon dioxide emissions for prescribed fires and wildfires in the Southern United States in 2010 and projected for 2060, assuming the Intergovernmental Panel on Climate Change (2007) A1B emissions storyline (a) CSIROMK3.5 and (b) MIROC3.2.

Public tolerance for smoke has diminished over time, increasing the frequency of complaints about smoke impacts from prescribed burning, fire used to manage wildlands, and wildfires (National Science and Analysis Team 2012). In some situations, lawsuits have affected regional prescribed burning programs, prompting greater emphasis to be placed on smoke impacts when management options are considered (Stanturf and Goodrick 2011).

Water and Soil

Although both wildfires and prescribed burning can have negative impacts on water and soil (Neary et al. 2005), most studies have focused on prescribed burning because of ease in comparing changes before and after treatment. Opportunities to monitor large fire impacts have been rare in the Southern United States.

The impacts of fires on water quality and nutrient cycling include a reduction of total ecosystem nitrogen availability as a result of volatilization and leaching (Knoepp and Swank 1993) and increased sediment loading (Knoepp and Swank 1993; Vose et al. 1999). The magnitude of the effects varies greatly and depends on fuels, soil properties, topography, climate, weather, and fire frequency and intensity (Richter et al. 1982). A single fire occurring after an extended period of fire suppression and fuel accumulation may have a greater impact on water quality, nutrient cycling, and sedimentation than would multiple fires occurring at more frequent intervals. Fire impacts on sediment movement are also more pronounced on sloping than level landscapes.

Ursic (1969) described the effects of prescribed burning on hydrology and water quality at two abandoned fields in the Gulf Coastal Plain in Mississippi. Stormflow during the first year increased 48% in one catchment, and continued to increase in the second and third years. Treatment of the second catchment, which had a fragipan that impeded deep recharge, did not change the volume of stormflow but significantly increased peak discharges and overland flow. Sediment production increased from 0.11 to 1.9 Mg/ha in the first catchment and by 7.5 Mg/ha in the second catchment during the first year, but dropped to <0.56 Mg/ha the third year.

Douglass and Van Lear (1983) reported responses of nutrient and sediment exports to prescribed burning for a Piedmont site at the Clemson Experimental Forest in South Carolina. Four loblolly pine watersheds were burned twice at an 18-month interval. The first burn took place in March and the second in September. The prescribed burns did not change water quality of the streams.

Clinton et al. (2000) summarized the results of four experiments that examined stream nitrate (NO_3^-) responses to forest fires at the Nantahala National Forest in western North Carolina: an autumn fell-and-burn fire (Jacob's Branch) and two spring stand-replacement fires (Wine Spring Creek and Hickory Branch) implemented to improve degraded xeric oak-pine forests, and an autumn arson-related wildfire (Joyce Kilmer) that burned the understory in an old-growth mesic and xeric forest. Stream nitrate was elevated by 0.03 mg/L for eight months following the burn on Jacob's Branch and by 0.06 mg/L for six weeks following Joyce Kilmer fire. The two spring burn sites experienced no change in stream nitrate. The authors concluded that nitrogen released during the spring burns was immobilized by vegetation uptake, but that nitrogen released during the autumn burns was not.

Vose et al. (2005) used a combination of field studies and modeling to assess the impacts of varying fire regimes on water quality across a geographic gradient in North Carolina. Field study sites were located in the Nantahala National Forest in the Southern Appalachians, the Uwharrie National Forest in the Piedmont region, and the Croatan National Forest in the Coastal Plain region. This study suggested that nitrogen (NO_3^-, NH_4^+) was not affected by prescribed fires of any intensity or severity.

Neary and Currier (1982) monitored stream chemistry (nitrate nitrogen, ammoniacal nitrogen, orthophosphate, sodium, potassium, calcium, and magnesium) and total suspended solids for five streams burned by wildfires in the Blue Ridge Mountains of South Carolina. Increases in stream water nitrate were attributed to fertilizer applications. Elevated concentrations of nitrate and orthophosphate in stream water occurred mostly during stormflow events, and average concentrations were not significantly higher than those observed on undisturbed watersheds. Concentrations of anions (sodium, potassium, calcium, and magnesium) ranged from 12% to 82% above background levels during the monitoring period.

Forest fires can burn significant amounts of forest understory canopy, litter, and duff layers, leaving soils unprotected against raindrop impact. The combustion of forest litter and plants in high-intensity forest fires can create and concentrate long-chained organic compounds that induce water repellency in soils (Doerr et al. 2000). This combination of factors reduces infiltration and increases runoff and soil erosion, especially in the Western United States (Tiedemann et al. 1979; Wright and Bailey 1982; Wolgemuth 2001). However, Wohlgemuth (2001) found that during fire events on southern California chaparral watersheds, forests that had been treated with prescribed fires had erosion rates lower than previously unburned forests. Water repellency has not been found to occur in soils of the Southern United States.

Literature suggests that fire generally has less effect on sediment loading in the South than in the West (Goebell et al. 1967; Van Lear and Waldrop 1986; Van Lear and Danielovich 1988; Shahlee et al. 1991; Marion and Ursic 1992; Swift et al. 1993). Increased soil erosion following fires is frequently associated with forest floor disturbances caused by mechanical site preparation during fire controlling activities, and least with direct fire influences. Similarly, operationally disturbed sites and especially skid trails have been found to be more susceptible to postfire erosion (Ursic 1970; Van Lear et al. 1985). However, because most fire research in the Southern Appalachian Mountains has involved fires of low to moderate intensity (Van Lear and Waldrop 1989; Swift et al. 1993), their results have limited applications.

Socioeconomic Impacts

Future wildfires may induce a variety of socioeconomic consequences for people living in fire-prone areas, including loss of life, increased morbidity, loss of property, and the necessity of making investments to reduce fire-related risks. Although socioeconomic impacts are likely to occur principally in communities located in the wildland–urban interface (WUI; the area where residential development is in close proximity to private and public wildlands), urban populations will not be immune to impacts, particularly smoke-related impacts. At the national scale, the area in the WUI increased by over 50% between 1970 and 2000, and is anticipated to increase another 10% by 2030 (Theobald and Romme 2007). Similar to national trends, the WUI area in the South (roughly 88 million acres) is growing rapidly (Southern Group of State Foresters 2008).

Wildfires emit fine particulate matter in smoke, and epidemiological studies have shown that high levels of particulate matter can adversely affect human health. Some evidence exists that high particulate matter levels produced by wildfires increase mortality risk, especially for elderly populations (Sastry 2002; Kochi et al. 2012). Additional research demonstrates a strong association between particulate matter generated by wildfire and various sources of morbidity such as asthma and general respiratory effects (Rittmaster et al. 2006; Kochi et al. 2010).

Health-related impacts of wildfires generate economic impacts through losses in productivity, defensive expenditures taken to lessen health impacts, and a general loss of well-being (utility). Although only a few studies have attempted to estimate the economic losses associated with the health effects of wildfires, these studies indicate that economic impacts can be substantial. For example, a study conducted in Alberta, Canada, reported that the loss in utility associated with smoke from a large wildfire that impacted people living in Edmonton caused economic losses that were only second to timber losses associated with the fire (Rittmaster et al. 2006). Kochi et al. (2012) calculated that excess cardiorespiratory deaths due to smoke exposure during the severe 2003 wildfire season in California in 2003 was approximately $1 billion. Further, Richardson et al. (2012) estimated that people exposed to the Station Fire of 2009 in Los Angeles County, California, spent about $85.00 per day for defensive expenditures (such as wearing a face mask, running the air conditioner more than usual, or taking medications). As citizens in five California cities were exposed to smoke from that fire, which lasted several weeks, it is clear that the economic costs associated with defensive expenditures can be very large.

In addition to health impacts, wildfires pose a direct threat to lives and property. An extreme example is provided by the California fires of late October 2003, which burned over 300,000 ha in one week, destroyed over 3000 homes, and killed 26 people (Keely et al. 2004). Kochi et al. (2012) estimated that 133 additional deaths from wildfire smoke exposure occurred in southern California as a result of these 2003 wildfires. Although the impacts of the 1998 wildfires in Florida were less extreme, these wildfires nonetheless destroyed 336 homes, 33 businesses, and several cars and boats (Butry et al. 2001).

The increasing frequency and severity of wildfires in forested residential neighborhoods in the United States has caused fire managers and policymakers to emphasize the role of homeowner and community mitigation activities to reduce the hazards associated with wildfires. The Firewise Communities program was initiated in 2002 to respond to this need. During 2011, 713 communities were active in this program, having invested over $103 million in wildfire risk mitigation activities (Firewise Communities/USA 2012). The popularity of these programs is growing rapidly, with nearly one-third of the investment made in 2010 alone. More than half of the active communities are located in the Southern United States.

Within the United States, nearly one-third of the WUI occurs in either loblolly-shortleaf pine or longleaf-slash pine forest types, in which wildfires often burn at high intensity and are difficult to control (Theobald and Romme 2007). Although it is logical that communities located in these forest types might be interested in investing in Firewise Communities or similar activities, recent research suggests that poorer communities living in and near high fire risk landscapes are less likely to invest in fire risk mitigation programs (Gaither et al. 2011). These communities appear to be especially vulnerable to potential changes in fire regimes due to climate change.

Regional Climate

Carbon dioxide and aerosol particles emitted into the atmosphere during wildfires can alter climate—an effect that would increase with increased fire activity. The greenhouse effect from increased carbon dioxide gases in the atmosphere is one of the major contributors for climate change at long-term (decade and century) scales and is among the most important and challenging environmental issues facing world leaders. Greenhouse gases in the atmosphere can absorb long-wave radiation emitted from the ground, which reduces heat energy lost into space. As a result, the temperature of the earth–atmosphere system increases and the water cycle is accelerated. Many atmospheric general circulation models have projected an increase in global temperature by 4°C to about 6°C and significant changes in precipitation by the end of this century.

Smoke particles from wildland fires can affect climate by scattering and absorbing short-wave (solar) radiation (direct radiative forcing) and by modifying cloud microphysics (indirect radiative forcing), with further consequences to cloud formation and precipitation processes and atmospheric circulation (Ackerman et al. 2000; Liu 2005a). In contrast, smoke aerosols have much shorter life spans, but much larger spatial variabilities. Thus, they mainly affect short-term (daily, monthly, seasonal) regional climate variability. For example, smoke aerosols from the Yellowstone National Park wildfires may have played a role in a drought experienced later in 1988 in the Northern United States. Simulations showed the Northwest experiencing the most widespread precipitation decreases in response to radiative forcing of smoke aerosols, with large reductions (about 30 mm) in the northeastern Midwest (Liu 2005b). Meanwhile, precipitation increased in the Southwest, the southeastern Midwest, and the Northeast, but it decreased in the South. The simulated spatial pattern of precipitation anomalies was similar to the observed pattern, suggesting that the smoke particles from the wildfire may have enhanced the drought.

Carbon emitted from biomass burning from all causes contributes significantly to global carbon emissions. Average annual global fire carbon emissions were estimated at about 2 Pg in the 1990s, about one-third of the total global carbon emissions. This contribution could be exceptionally large over a short period of time, before being offset by carbon uptake from vegetation regrowth in burned areas. For example, carbon emissions during the 1997–1998 Indonesian wildfires were the equivalent to the total global carbon uptake by the terrestrial biosphere in a typical year (Page et al. 2002; Tacconi et al. 2007). Although wildfires in many forest ecosystems occur naturally, large amounts of carbon stored in forest ecosystems are lost permanently by deforestation in many regions such as the Amazon, where forest biomass is burned in the conversion to agriculture or pasture (e.g., Van der Werf et al. 2010).

MANAGEMENT OPTIONS FOR MITIGATION

Prescribed Burning

Prescribed burning is among the set of critical forest management tools that can be used to mitigate the impacts of climate change on wildfires in the South, but it has many potential benefits. Aside from potentially reducing the overall economic and negative ecological impacts of wildfires, prescribed fire can be used to enhance forage opportunities for wildlife and livestock (Waldrop and Goodrick 2012) and help to restore and maintain the fire-adapted ecosystems that many species depend on (e.g., Brockway et al. 2005). In recognition of these potential benefits, land managers in the South prescribe burn approximately 3.2 million ha annually—more than in all other regions of the United States combined (Wade et al. 2000). Broad evidence of prescribed fire's effects at reducing understory fuels and therefore wildfire risks in the South is revealed by the fact that the total prescribed area burned in the South is about 60% of the prescribed area burned for the United States, much larger than its 20% share of wildfire area burned (Figure 5.18).

Prescribed burning can also be a management option for reducing the impacts of any future increases in wildfire potential emanating from climate change. Wildfires typically occur under drier conditions that favor higher-intensity and more complete fuel consumption. Instead, prescribed burning in the South is conducted at higher fuel moistures under meteorological conditions that favor low-intensity fires with lower fuel consumption. Therefore, prescribed burning potentially results in lower emissions than wildfires (Urbanski et al. 2009). Recent studies have provided quantitative estimates of the role of prescribe fire in other U.S. regions. For example, Wiedinmyer and Hurteau (2010) used a regional fire emissions model to estimate daily carbon dioxide fire emissions for 2001–2008 for the West and found that wide-scale prescribed fire application reduces carbon dioxide fire emissions by 18 to 25% generally and by as much as 60% in specific forest systems. Robertson (2007) pointed out that managers could choose certain weather conditions to conduct prescribed burning under which fire emissions could be minimal. Narayan (2007) showed that prescribed burning can significantly reduce carbon dioxide emissions in European countries that experience high fire occurrence. This author estimated that wildfire emissions were about 11 million Mg/year over a 5-year period, compared to about 6 million Mg/year for prescribed burning.

Wildfire potential is projected to rise under some climate scenarios (perhaps especially from lightning), so more frequent prescribed burning could be used in the future to mitigate some

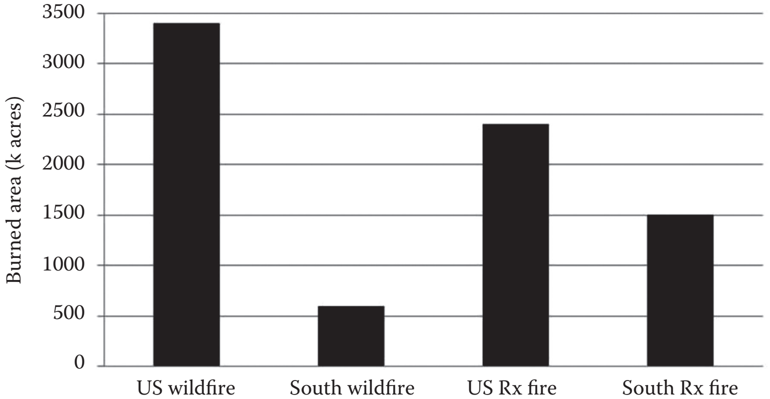

FIGURE 5.18 Burned areas in 2010 for the South and the United States by wildfire and prescribed fire.

of the negative impacts of wildfires. The challenges that southern fire and land managers may face in the future include a reduced burning window caused by changes in weather conditions (Liu 2012), higher risk of prescribed fire escape into the wildland–urban interface and other developed landscapes, and greater constraints in use because of air quality concerns. These constraints to action by managers imply that aggressive fuel load management will be needed where and when possible if future wildfire risks are to be reduced. The size of prescribed burns may be increased so that more area can be burned during the smaller number of favorable days. Burning fewer larger areas will require somewhat fewer resources than more, smaller fires would require. Greater preplanning and coordination of resources will be needed so that open windows for prescribed burning are efficiently utilized. Maintaining or increasing first attack response times will be required, posing logistical challenges in the face of more frequent ignitions and a longer fire season. Fire suppression efforts will have to adjust in order to maintain or increase firefighter safety. Fuel loads may need to be managed at reduced levels, requiring more frequent prescribed burning.

Growing urbanization of the landscape will increase the area of land at the interface with wildlands, indicating that greater engagement between fire managers and communities would be another strategy for mitigating the effects of higher wildfire potential. Prescribed burning can be conducted safely in the interface zone, but more skilled personnel will be needed. Policy and regulatory changes may be needed to provide liability protection for burners. Effective communication with the public will be critical to gaining acceptance for prescribed burning (e.g., Shindler et al. 2009), and personnel may require enhanced communication training. Educational efforts aimed at reducing arson and accidental ignitions as well as fire-wise landscaping around residences could receive increased support as prevention measures (Butry et al. 2010). Support could be provided by state forestry agencies as technical assistance or subsidies. Alternatively, regulatory approaches to risk reduction, including mandated insurance coverage for wildfires, could be another avenue toward reducing some of the negative impacts of future wildfires (Haines et al. 2008). Mechanical and chemical fuel reduction techniques may become more economically feasible under certain conditions (Prestemon et al. 2012), at least in creating buffers between structures and forests in the wildland–urban interface.

Forest Restoration

Another climate change-related wildfire mitigation option is to convert vegetation to more fire-tolerant species (e.g., replacing loblolly pine with longleaf pine or with broadleaved species). Altering forest stand structure, especially by planting at wide spacing to reduce fuel mass per unit area, may alter fire behavior in a way that produces several net benefits for ecosystems, landowners, and society. Fire behavior models may need revision to account for novel fuel types if vegetation changes significantly (e.g., planting *Eucalyptus* species; Goodrick and Stanturf 2012). This strategy, however, would not be without risks or controversy (e.g., McLachlan et al. 2007), but its viability as a wildfire risk mitigation measure merits additional study (Millar et al. 2007).

Smoke Management

Finally, as wildfire potential rises with climate change, managers, modelers, and planners could work jointly to reduce the many negative impacts from wildfire and prescribed fire-related smoke. Effective smoke management would entail the development and deployment of advanced smoke transport models. Wildfire managers seeking to expand the use of prescribed fire will need to pay increasing attention to air quality constraints, particularly if larger areas are burned within an airshed on a given day. This more concentrated prescribed fire activity will need careful management to avoid impacting urban areas.

DISCUSSION

Information on southern wildfire, potential future wildfire trends under a changing climate; the ecological, environmental, and socioeconomic impacts of southern wildland fires; and the forest management mitigation options available to fire managers and policy makers in the South have been presented in this chapter. Major findings include:

Future fire potential: Fire potential is expected to increase in the South in this century as a result of increased concentrations of greenhouse gases.

- The hotspot for the largest projected increase in future fire potential is the western coastal area, along the Gulf of Mexico, in the early spring. This hotspot extends to the central areas of the region in late spring, and spreads farther east, to the Atlantic coastline in summer and early autumn.
- The most significant increase in future fire potential is projected to occur during summer and autumn, when fire potential would increase roughly from the current low level to the moderate level in eastern areas, and from the current moderate level to the high level in western areas of the South.
- The length of fire seasons in the South will likely increase by a few months.
- Projected fire potential is unlikely to increase significantly until 2030–2040.

Burned area: Actual burned areas for a specific landscape would not necessarily increase even with a projected increase in fire potential. A decline in human-ignited wildfire area and an increase in lightning-ignited wildfire area from 2002 to 2050 are projected under a single climate change scenario. Reductions in forest area and changes in other societal factors linked to wildfire activity result in a net reduction in overall fire activity for the region as a whole.

Fuel loading: Fuels may increase or decrease through the effects on productivity and decomposition rates; higher precipitation will increase productivity and thus fuel loading. Conversely, higher temperatures will increase respiration and possibly decomposition rates, thereby lowering fuel loading. Such changes will depend upon vegetation type, soils, and anomalies from current conditions. Future fuel loading is projected to decrease in the western areas of the region and increase in the eastern areas.

Impacts: The projected changes in future wildfire occurrences are expected to have some substantial impacts on forest ecosystems, the environment, and society in the South.

- Future emissions from wildfires could increase in forested areas, especially during late spring and early summer; emissions from prescribed burning, assuming that the current level continues, are likely to decrease in most areas because of projected reductions in fuel loading.
- Increased wildfire emissions could have important smoke and air quality impacts at regional and local scales.
- With the projected increases in wildland–urban interface, wildfire and smoke are expected to result in increased wildfire economic damages and higher wildfire management costs.
- Increased wildfire occurrence in forested areas could reduce total ecosystem nitrogen and increase sediment loading.
- Increased emissions of smoke particles could reduce solar radiation absorbed by forest plants and soils, leading to a cooling effect, changes in heat and water fluxes, and potential changes in regional circulations and precipitation.
- Increased productivity and higher fuel loading, combined with fire weather changes, will favor longer wildfire seasons, increasing the need for prescribed burning to reduce hazardous fuels.

- Longer wildfire seasons may decrease the number of days when prescribed burning may be safely conducted; thus, a greater area will require prescribed burning within a shorter season.
- Increasing urbanization will expand the wildland–urban interface zone but may reduce the opportunities for conducting prescribed burning.
- Regulatory constraints on smoke driven by air quality concerns could decrease opportunities for prescribed burning.

Mitigation:

- Prescribed burning is a forest management tool that has been used extensively in the South to reduce wildfire risks by reducing understory fuel accumulation. It may be among the most useful options for mitigating the impacts of potential increases in wildfire under a changing climate.
- Higher rates of prescribed burning would bring new challenges to fire and land managers, whose use of the tool is restricted by many factors, including weather conditions, risk of escape into developed areas, and smoke-related safety and air quality regulations. Because weather, ambient air quality conditions, and values at risk are likely to change with an enhanced greenhouse effect and population and economic growth in the region, understanding how prescribed fire options may change along with them is critical.
- Altering forest stand structure, especially by planting at wide spacing to reduce fuel mass per unit area, may alter fire behavior in a way that produces several net benefits for ecosystems, landowners, and society.
- As wildfire potential rises with climate change, managers, modelers, and planners could work jointly to reduce the many negative impacts from wildfire and prescribed fire related smoke.

FUTURE RESEARCH NEEDS

The results provided in this chapter are largely preliminary and further research on the issues below is needed to improve our understanding of future fire trends, their impacts, and mitigation options that might be available:

1. The advantages, disadvantages, strengths, and weaknesses of statistical versus dynamic downscaling of projected climate variables need to be clarified with respect to wildfire. Regional climate change scenarios require comparison and interpretation. Two types of downscaled climate change scenarios were presented in this chapter. Statistical downscaling, which includes projections from multiple models and ensemble projections with multiple emissions scenarios, has a higher spatial resolution and provides outputs over various projection periods but is limited to monthly temperature and precipitation projections. Conversely, dynamical downscaling provides daily values for more variables, but has a lower spatial resolution and, for our analysis, was limited to a single general circulation model and emissions scenario for projections of fire potential and total burned area. Comparing the impacts of the differences between the two types of downscaling techniques and using multiple general circulation models and emissions scenarios for dynamic downscaling would improve projections.
2. It is critically important to develop long, consistent historical wildfire datasets for the South that can be used to develop robust statistical models. Very limited fire occurrence and burned area data were used in the analyses reported here: wildfire data for only 5 years for the fire emissions calculation and a single year for projections of future burned areas

and prescribed burning. Wildfires have significant interannual variability. Thus, using the limited fire data increases uncertainty and may obscure significant trends.

3. Alternative statistical models are needed for fire projections, including alternative functional forms, which would enable identification of the modeling framework most likely to accurately predict wildfire given a climate change scenario and expected changes in society. Also, in light of limitations with the KBDI, applications and comparisons of other fire indices, especially those that include wind and humidity factors, would be useful for a more complete understanding of future wildfire potential but would also require improved climate modeling capability.
4. Scientific understanding of fire emissions effects on climate change merits significant advancement, in multiple dimensions. Although some quantitative estimates of the impacts of future fires on emissions were made, other impacts of wildfires were only approached by synthesizing existing studies. For more extensive and reliable quantitative estimates of fire impacts, additional work is needed in a number of areas. The first is to develop more detailed spatial projections of future fires, including frequency, intensity, and burned areas in specific landscapes and ecosystems. Although finer scale resolution of climate variables and fire present statistical challenges associated with false precision, especially at the finest time and spatial scales, it is hoped that more scientific study can provide analysts with real improvements in the reliability of such fine scale projections. The second is to develop more complete datasets of ecological, environmental, and socioeconomic processes along with their interactions with wildfires. The third is to improve our capacity in data processing and computation, which is especially important to modeling the regional air quality impacts of future wildfires.
5. Fuel loading under alternative climate change scenarios needs additional study. In addition to weather and climate, fuel is a critical element in understanding wildfire trends and the potential impacts on emissions and air quality. The projections of future changes in fuel loading described in this chapter were made using a single climate change scenario. This projection approach could be improved by using multiple scenarios. A more refined understanding of fuel loading changes would be enabled by understanding better how climate change would affect vegetation types, representing a challenging but important task for the vegetation and fire modeling communities.
6. More specific understanding is needed of the dynamics of fuel loading under altered climate, productivity, and vegetation types and of the changes needed in burning frequency. Much of our exploration of climate change related wildfire mitigation options was focused on managing fuel loads by prescribed burning. But climate change's likely impacts on burning windows and smoke production and transport may limit its viability under many circumstances. Given these potential limitations, more science is needed on how other fuel reduction strategies could be affordably and effectively implemented. Included in this science would be enhanced understanding of the trade-offs between prescribed fire, nonfire fuel management, provision of ecosystem services, and wildfire risk mitigation. Wildfire in forest ecosystems contributes significantly to carbon emissions. Hence, an elucidation of the trade-offs among carbon emitted from periodic low-intensity prescribed fire, other kinds of fuel reduction treatments, and infrequent but high-intensity wildfire would improve analysts' and managers' ability to recommend and implement the combination of management actions that yielding the greatest possible benefits.

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