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

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I. INTRODUCTION

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 coniferous-boreal, temperate, and tropical forests, eucalyptus forests, most vegetation types 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 fires

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annually, costing billions (U.S. Department of Agriculture Forest Service 2005). The 1997/1998 fires in Indonesia burned 8 million ha (Cochrane 2003). In the latest catastrophic wildfires in January and February of 2009 in Victoria, Australia, a fire whose greatest damages were visited on “Black Saturday” (February 7, 2009), 2430,000 hectare were burned, over 2,000 homes were destroyed or damaged, and 173 people were killed (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 percent of the area burned and 80 percent of suppression costs, but together represent less than 1 percent 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 scattering and absorbing solar radiation and through modifying cloud microphysics (Charlson et al. 1992). These processes can further modify clouds and precipitation and atmospheric circulation (Ackerman et al. 2000, Liu 2005a, 2005b). The particulates and other air pollutants from wildfires can degrade air quality (Riebau and Fox 2001), resulting in significant health consequences (Rittmaster et al. 2006). Wildland fires contribute an estimated 15 percent of total particulate matter and 8 percent of CO emissions over the Southern United States (Barnard and Sabo 2003). Burned areas are prone to severe soil erosion due to lose of ground vegetation and litter covers and accelerated overland flow. Stormflow volume and peakflow rates increase dramatically in response to reduced soil infiltration rates and soil water storage since forest evapotranspiration rates are reduced. Increases of stormflow and soil erosion have potential to degrade watershed water quality in severe wildfire events.

Weather and climate are determinants for wildfire characteristics along with fuel properties and topography (Pyne et al. 1996). Fire activities vary 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 inter-annual 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 (Food and Agriculture Organization of United Nations 2001, Gillett et al. 2004, Piñol et al. 1998, 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 to project future trends under a changing climate. 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 and fires that burn more intensely and spread faster in northern California (Fried et al. 2004). A 50-percent increase in fire occurrence is projected in boreal forests by the end of the century (Flannigan et al 2009). Fire potential will likely increase significantly in several global geographic areas, including some in the United States (Liu et al. 2009, 2012).

The South is one of the most productive forested regions in the United States, with 81 million ha or 40 percent of the nation's forests in an area occupying only 24 percent of its 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 to 5 years (Stanturf et al. 2002). The South leads the nation in annual wildfires, averaging approximately 45,000 fires a year from 1997 through 2003 (Gramley 2005). The region is also experiencing increased droughts. For example, during the worst drought in more than a century, severe wildfires in and around the Okefenokee National Wildlife Refuge on the southern-Georgia/northern-Florida border in the spring of 2007 burned approximately 243,000 ha.

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. This 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 to accurately assessing the potential impacts of climate related trends, including human and environmental losses, 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 the 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, respectively. Finally, major findings and knowledge gaps are summarized together with suggested future research needs.

II. BASICS OF WILDFIRE AND CLIMATE IN THE SOUTH

A. CLIMATE AND FUELS

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: (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 of these classifications roughly corresponds to the eastern Coastal Plain, 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 21ºC in southern Florida and

Texas to 13 ~ 16 ºC 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 towards Atlantic coastal areas and northern areas of the region, and to 300 ~ 500 mm towards western Texas and Oklahoma. (http://www.ncdc.noaa.gov/oa/ncdc.html). 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.

In the vegetation types defined by the National Fire Danger Rating System (Figure 5.1) 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 (Model K). 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.

B. 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. 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, which depends on the type of fire regimes, is often measured by the amount of total area burned.

The fire regimes of southern ecosystems have been described in detail (Fowler and Konopik 2007, Stanturf et al. 2002, Wade et al. 2000). Intervals between fires, which may be as short as a year or as long as centuries, are primarily determined by vegetation species, which in turn depend on the physiographic characteristics of the eco-region. Before European settlement, frequent low severity surface fires characterized most Coastal Plain ecosystems with a return interval of 1 to 4 years (Table 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 extensively used fire as a landscape management tool. (2) The early European settlement period, from 500 to about 110 years ago, in which European settlers also used fire 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.

C. FIRE WEATHER AND CLIMATE

Fire weather and climate describe the atmospheric conditions that influence fires. Weather refers to atmospheric elements (such as temperature, humidity, pressure, winds, and precipitation) and the related processes or systems (such as front, cyclonic and anti-cyclonic circulation, trough and ridge, and jet stream) on time scales of hours to weeks. Conversely, climate describes the statistics of weather over a long period (usually 30 years). 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 environmental triangle (Figure 5.2), 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), i.e., 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 arched 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, reaching an equilibrium or quasi steady-state rate after a period of buildup (or acceleration). The rate is controlled by winds and relative humidity, which in turn determines fuel moisture. Fire intensity, the amount of heat released per unit of time, 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 environmental triangle; the role of each is described in Table 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).

Fire weather and climate conditions only provide necessary conditions rather than sufficient conditions for fire occurrence. This means, for example, certain weather patterns such as dry and hot weather do not guarantee the occurrence of a fire at a specific location; instead, such conditions may confer a higher probability for a fire or fires at a location within an area of similar weather, fuel, and topography. In addition, when looking at fire-climate relationships across a range of time scales (seasonal, inter-annual, 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 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 of the occurrence of fires of a certain severity level. 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 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 has mainly resulted from the inter-annual variability of atmospheric condition, with fires often occurring during periods of drought, abnormal ocean conditions, and other anomalies of weather and climate.

D. FIRE AND CLIMATE CHANGE

The features of the 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 in response to changes in climate, land use, socioeconomic and environmental variables affecting ignitions by people, and wildfire management approaches, fire regimes could change as well. Understanding the possible change in the fire regimes is essential to assessing the potential impact of future wildfire trends.

One of the many changing variables affecting fire regimes, climate could have various impacts on fires in the South (Table 3). 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 can indirectly impact fires by changing fuel conditions. Increased temperature increases evaporation, thereby reducing fuel moisture contributing to increasing fires. Temperature also can affect ignition rates. The impact on fuel loading is more complex. Increased air temperature can increase fuel loading, through its effect of increasing growing season length, but it can also decrease it by reducing water availability because of increased evaporation.

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 to plant growth, leading to less fuel and lower fire potential. Clearly, projecting the effects of reduced precipitation is much less certain than projecting the effects of increased air temperature. Projected precipitation change often shows no clear trends in atmospheric models, even over large spatial scales. Along with changes in average precipitation, most general circulation models also project more frequent precipitation anomalies such as drought, which 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 whose frequency and intensity are expected to change 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 such changes for precipitation in some areas such as those with complex topography.

Lightning, another complex process currently producing a small share of wildfires in the South, 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.

E. ROLE OF MITIGATION

The role of forest management is illustrated in Figure 5.3 using as 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 (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.

III. PROJECTIONS OF FUTURE FIRE AND FUELS

A. USE AND LIMITATIONS OF KBDI

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. (2009). The maximum value for KBDI is no higher than 800. KBDI is classified into eight drought stages by an increment of 100 (Keetch and Byram 1968). Two adjacent stages represent one severe fire potential level (Table 4). The KBDI depends on its historical values. In the other words, it has “memory,” in the sense that current values depend on previous values. For example, if a drought has occurred for one mouth, reduced rainfall 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 occur at a time later than that of a fire season in the South. Second, the range of a specific fire potential level could slightly vary with area and season (Goodrick 1999) and fire type (Melton 1989, 1996). And third, direct comparison of specific KBDI values for locations with different climate is often problematic because the drying rate in the index is a function of the average annual precipitation for a 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.

B. STATISTICAL DOWNSCALING OF CLIMATE SCENARIOS

To make wildfire projections at some spatial scale of inference (e.g., 30 x 30 km) based on climate change projections, the coarse spatial and temporal scales of projections produced by general circulation models (GCMs) need to be downscaled to the spatial scale of inference. One option for obtaining fine scale projections from coarser GCMs is statistical downscaling. Statistical downscaling requires the estimation of statistical relationships between 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 provide a first approximation of regional climatic conditions that do not require the computational expense of higher resolution physical modeling.

We employed county-level temperature and precipitation data derived from an ensemble average of four GCMs (CGCM3, GFDL, CCSM3, HadCM3) for three Intergovernmental Panel on Climate Change (2007) greenhouse gas emissions storylines (A1B, A2, and B1) for every month from 2010 to 2060. Using the average of four climate models limits the impact of individual model biases. Making projections under three different emissions storylines allows us to sample a range of potential future conditions, possibly revealing how sensitive simulated futures are to the emissions storyline used.

Emissions storylines 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 storyline family describes a future of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and it 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 storyline 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 storyline 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. For the A1B storyline, general circulation models 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 CMIP3 data by Maurer et al (2007) and served at: http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/ (Date accessed: June 14, 2012). 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 KBDI calculation, which is normally calculated based on daily maximum temperatures and total rainfall. This limitation was overcome by assuming that the daily maximum temperature is 15 percent higher than the daily average temperature, that rain falls every two days, and that each month's soil moisture begins at saturated conditions (zero KBDI). The use of a 15 percent increase from daily average temperature to achieve the daily high temperature is rather 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 may impact the KBDI across all three emissions storylines across the South, we first established data for the baseline decade of 2000 to 2009 by examining KBDI patterns in the months of January, March, May, July, September, and November for those years. Next, we examine departures from these baseline patterns for 2010 to 2019, 2030 to 2039, and 2050 to 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 storylines, and translate these changes into impacts on fire season duration and severity.

For January during the baseline period, conditions are consistent across the storylines (Figure 5.4). 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 storylines, with the A2 storyline predicting the most drying followed by A1B, and B1 predicting the least. By the 2030 decade, drying is expected to spread along the Gulf of Mexico with the A1B storyline predicting strong drying along southern areas of the Deltaic Plain. Few changes are expected by the 2050-decade. Overall, the A1B storyline predicts the most drying along the Gulf of Mexico, while B1 predicts the least. The changes are expected to be relatively minor because the most severe drying would only change the KBDI by roughly 40 points.

By March of the baseline period, dryness has begun to spread northward from the Florida peninsula and Texas coastline (Figure 5.5) with decadal averages rising to 250 to 300 in some areas. As with January, the storylines have little impact on the baseline conditions. By 2010 however, differences are expected among the emissions storylines. Although predicting overall drying across most of the South, the B1 storyline predicts that drying will be most severe in the Deltaic Plain section of the Mississippi Alluvial Valley; and will spread across the Southern Gulf section of the Coastal Plain by 2030 and then on to the Eastern Atlantic section by 2050. In the Blue Ridge, Northern/Southern Ridge Valley and into the Cumberland Plateau few changes in KBDI are expected, with perhaps slightly wetter conditions regardless of storyline or decade—suggesting a slight preference of the Ohio River Valley for the storm track in the models.

In May very slight differences between among the storylines become evident for the base period (5.6). Drying has spread throughout the South except for the northernmost areas. May typically marks the peak of the spring fire season, particularly with regard to acres burned. In the future this is likely to be even truer, with all storylines indicating that late spring will become drier. As early as 2010, significant differences among the storylines are expected. A1B and B1 predict the most significant drying, particularly in the Texan/Oklahoma Cross Timbers section of the Mid-South and the western and eastern Middle Gulf sections of the Coastal Plain. All three storylines predict a tendency for wetter conditions in the Southern Gulf and Eastern Atlantic sections of the Coastal Plain in 2010, although these wet areas are not expected to persist through the 2030 and 2050 periods. By 2050, the A1B storyline 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 storyline with the smallest projected changes for May, those of the A2 storyline, 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 5.7), with the most severe drying centered over

Louisiana, Mississippi, and Arkansas, but with most coastal areas noticeably wetter from sea-breeze induced thunderstorms. As with projections of conditions for early months of the year, only subtle differences separate the three storylines. Differences are predicted to begin appearing as soon as 2010, when the A2 storyline indicates wetter conditions for the Southern Appalachians, Piedmont, Southern Gulf and Eastern Atlantic. A1B and B1 storyline predictions are very similar across the region, except for northern half of the Florida peninsula, where B1 predicts more pronounced drying. By 2030, no areas of increased moisture are predicted to remain, and all storylines indicate conditions becoming drier, although the spatial pattern varies by storyline; for example, the A2 predicts the lowest increase in dryness. By 2050, the A1B and A2 storylines indicate KBDI increases of about 100 points across the majority of the South. The A1B predicts the most intense drying in northern Alabama and Mississippi. Even the coastal areas with relatively moist conditions are predicted 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 months of September for the baseline period (Figure 5.8) and is still centered over Louisiana. The extent of the dry area varies slightly among storylines, with A2 being the wettest. September is the month that displays the greatest variability among the emissions storylines for all future time periods. For 2010, the B1 storyline predicts 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. A2 predicts a combination of features from the other two storylines, 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 storylines predict similar spatial patterns but vary in their intensity. The North Atlantic section of the Coastal Plain and Central Appalachian Piedmont are predicted to become a center of drying that varies in intensity from weak for B1 to strong for A1B. Although A2 does not predict 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 40-points decreases in KBDI. By 2050, the A2 storyline predicts significant drying, with much of the region experiencing 80-increases of at least 80 points in KBDI and most of the Northern Atlantic section of the Coastal Plain increasing by approximately 160 points. A1B predicts 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 storyline predicts a spatial pattern that is different from the other storylines, 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 changes in the KBDI, is predicted to be a gradual shift towards more severe conditions. The length 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 coastal areas along the Gulf of Mexico; however, the increase in severity is likely to be more widespread in coming decades. The projected dryness during the summer may introduce a summer fire season to new areas of the South (or at least a later end to the spring season and earlier start of the autumn season).

The impact of the different emissions storylines is not large through 2060 as the differences among model results are generally modest. However, this consistency shows that a dramatic decrease in fire potential is not likely, based on storylines that all suggest an increase in the coming decades. Although the models are in agreement several factors give reason to question 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 storyline drives the general circulation model, but the same statistical relations are used to translate output from all models to the region level; this 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 storylines.

C. DYNAMICAL DOWNSCALING OF CLIMATE CHANGE SCENARIO

An alternative to the statistical downscaling of climate change scenarios is the dynamical downscaling produced by the North America Regional Climate Change Assessment Project (Mearns et al. 2009), 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.

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 storyline. We used downscaling of HadCM3 with HRM3, which has been used for projecting fire potential trends in North America (Liu et al. 2010, 2012). The simulation periods for the current period 1971 to 2000 and for the future period 2041 to 2070, and the spatial resolution was 50 km.

These scenarios have several features different from the statistical downscaling approach. First, they are provided at daily frequency. Second, maximum temperature data are available, which is one of the variables for KBDI calculation. Third, some 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, which is useful when projecting future weather conditions for prescribed burning (described in the section on management options, below).

The scope of the North America Regional Climate Change Assessment Project extends throughout North America. For this chapter, we use the data at the grid points within the South. Figures 5.9 to 5.11 show averages of temperature, precipitation, and KBDI. The simulated current maximum temperature shows a clear seasonal cycle for the overall region (Figure 5.9), 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. In the future, the region's maximum temperature is predicted to increase by 3°C to about 4°C during all seasons, with the largest increase during summer and with no significant intra-regional differences. HadCM3 and HRM3 predict the same spatial pattern but the HRM3 predictions are slightly lower, especially in the western areas of the region.

The simulated current precipitation in the South (Figure 5.10) 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 predicted to increase for the region, greater than 50 mm during summer in some areas. HRM3 projections for western areas are substantially different from the decrease predicted by HadCM3. This difference should have a significant effect on the future KBDI calculation.

Current KBDI values are usually small in winter and spring and large in summer and autumn in all eco-regions (Fig. 11). Present summer and autumn KBDI values are around 200 (upper KBDI range for low fire potential or lower range for moderate fire potential) in the three eastern eco-regions, and future values change to about 350 ~ 400 (upper KBDI range for moderate fire potential or lower range for high fire potential). Meanwhile, present summer and autumn KBDI values are around 400 (upper KBDI range for moderate fire potential or lower range for high fire potential) in the three western eco-regions, and future values change to about 500 (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 5.12 shows monthly variations of current and future KBDI for the South. Current KBDI starts with a low value of about 170 points in January. It gradually decreases to less than 100 points in April, increases to about 350 points in September and October, and then decreases again to about 190 points in December. The corresponding fire potential is low from December to May and moderate from June to November. Future KBDI is predicted to increase for all months, substantially after May, and with the largest increase of about 150 points in September. Future fire potential is expected to remain low from January to May, but to change from moderate to high from July to October. Intra-regional changes in future fire potential are similar although actual KBDI values vary.

The increase in fire potential suggests that fire seasons might become longer in the future (Figure 5.13). The length of a fire season, measured by the number of the months with high or extreme fire potential level, will increase by 1 ~ 3 months (Fig. 12).

D. TRENDS AND PREDICTIONS FOR FIRE EXTENT

1. Wildfire in a Changing Climate and Societal Environment

If climate and society continue to evolve in the coming decades, wildfire activity in the South will also likely 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.

Research in the past several years 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 (Mercer et al. 2005, 2007; Prestemon et al. 2002). With respect to development, research has shown that forest fuels encourage the spread and increase the intensity of wildfires; 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 (Genton et al. 2006, Zhai et al. 2003), 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 condition, weather and climate, as our climate 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 (Butry et al. 2010, Donoghue and Main 1985, Prestemon and Butry 2005, Prestemon et al. 2002) both for both human and lightning caused fires (Mercer et al. 2005, Prestemon et al. 2002).

Many natural-resource scientists, land managers, and policy makers have expressed concern about the implications of climate change on wildfire activity. 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 as well as climate 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 storylines that describe this kind of dependence.

Data from the various storylines 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 projections were then projected, using projections of the variables that expected to change in the future. This effort was part of larger effort, partially funded by the U.S. Environmental Protection Agency, 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 storyline 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 run from 2002 (the base year) to 2050 and for two intervening years: 2020 and 2030.

2. Methods of Fire Projections

We projected fire area burned on grid cells measuring 12 by 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. These models have a first stage that is a Probit model, which predicted whether fire occurred in the spatial unit of observation during 2002. The second stage is a least squares equation done with just 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 exogenous regressors. The threshold used in this model for determining whether fire occurred in the grid cell was whether greater than or equal to 5 ha of wildfire 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 greater than or equal to 5 ha of lightning caused wildfire and 3,882 had greater than or equal to 5 ha of human-ignited wildfires.

In the first stage of the selection model, the probability of a fire occurrence was expressed as a function of income (economic output per unit area), population per unit area, forest land per unit area, fuels 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).

Predicted area burned for the selection model were calibrated to match the region-wide total of area burned for 2002; 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 were made using projections of changes in fuel, wind, forest area, population, and income in each grid cell for three future years (2020, 2030, and 2050). Projections of county and state level variables (forest, income, population, climate variables) were derived from data made available by 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 using a 2002 base year based on 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).

3. Results of Fire Projections

Results of the wildfire projections in the South are illustrated in Figure 5.14. Lightning fires are projected to rise from base year (2002) levels. The base-year burned levels for lightning might have been usually low in 2002, but the projections clearly show an increase, from about 43,000 ha in 2002 to 124,000 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 percent. In aggregate, the decrease in human-ignited area burned outweighs the increase in lightning ignited area burned, producing an overall decrease of about 10 percent by 2050 (about 350,000 ha, compared to 385,000 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 forest area is, in aggregate, 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 would be expected to lower overall wildfire activity. Also, income increases have strong 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 storyline 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.

E. TRENDS OF FUEL LOADING

To generate high-resolution datasets that reflect the spatial-temporal dynamics of fuel load from 2002 to 2050, Zhang et al. (2009) 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 3 tons/acre in the coastal areas along the Atlantic Ocean and Gulf of Mexico to 5 tons/acre or larger in the Appalachian-Cumberland and Ozark-Ouachita highlands (Figure 5.15); and is less than 1 ton/acre in western Texas. Future fuel loading is expected to be reduced from current in central areas of the region, with the largest reduction of about 1.5 tons/acre in the northern areas. In contrast, fuel loading would increase in Atlantic coastal areas and the Piedmont, with the largest increase of about 1.5 tons/acre. 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.

IV. IMPACTS OF PROJECTED FIRE CHANGES

A. 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 would alter fuel loading by changing plant productivity and decomposition rates, as well as causing shifts in species distribution. The impact of climate change on fuel moisture is less complex: 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 towards warmer and drier conditions, these conditions may not be acceptable for prescribed fire 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, prescribed fire impacts more area than wildfires (Figure 5.16). Although the prescribed fire data shown are limited to what was reported for the 2002 emissions inventory, prescribed fire acreage generally shows less inter-annual variability than wildfires. The wildfire data shown reflect a 5-year average for 1997 to 2002 (SGSF 2010). Most prescribed burning is 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—MIROC3.2 from the Center for Climate System Research, University of Japan and CSIROMK3.5 from the Commonwealth Scientific and Industrial Research Organization in Australia—both forced by the A1B emissions storyline. These model/storyline combinations were selected from among those used in the Southern Forest Futures Project because CSIROMK3.5 reflects well the ensemble average that we used in our statistical downscaling analysis and the MIROC3.2 projects a future that is one of the driest. The changes in average KBDI projected by the CSIROMK3.5 model show modest changes between 2010 and 2060 (Figure 5.17a). The principle difference is a drying that begins in the spring and extends through the summer. In comparison, the MIROC3.2 model exhibits a much stronger summer drying that begins later in the year, but with more of a lasting impact in autumn (Figure 5.17b).

Climate models that provide only high 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 (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.

For each month, the number of prescribed-fire and wildfire acres were divided into 500-acre fires labeled *p* for prescribed fire 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) a 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 3.5 feet, which is below the upper limit for which hand crews can safely work a fire-line (4 feet). Carbon dioxide emissions were determined by simply multiplying the total fuel consumed by an emissions factor.

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 5.18a). Although the MIROC3.2-based predictions are quite similar to the CSIROMK3.5 values, averaging around 6 tons/acre (Figure 5.18b), 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 5.19a. 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 5.19b). 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). Figure 5.20 shows the predicted changes in March emissions from prescribed burning due to the change in fuel loading from 2002 to 2050 assuming that total area burned remains unchanged. The predicted changes in fuel loading shown in Figure 5.15 would lead to an increase in emissions of 500 tons in the eastern areas of the region, compared to a decrease in the central areas.

Land cover change, another cause for future fuel loading change, is also expected to contribute to emissions. Figure 5.20 predicts changes in emissions when fuel loading is combined with the land cover changes resulting from storyline A1B (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 emissions storyline). 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.

B. SMOKE AND AIR QUALITY

Increased fire activity in the future would increase the occurrence of smoke and lead to more 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 combusts, 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 problem when it impedes visibility and creates hazards for drivers of motor vehicles.

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 outlined in the Clean Air Act. Wildfire emissions are important sources for particulate matter above 2.5-μm 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 fires that straddled the Georgia-Florida border. The resulting concentrations of particulate matter exceeded the danger threshold for 2.5 μm and caused severe health problems in those areas.

Also, 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. 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, In Press).

C. 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 U.S.

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 an increase of sediment loading (Knoepp and Swank 1993, Vose et al. 1999). The magnitude of 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 will have greater impact than fires that occur at more frequent intervals.

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 percent 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 t/ha to 1.9 t/ha in the first catchment and by 7.5 t/ha in the second catchment during the first year, but dropped to <0.56 t/ha the third year.

Douglas and Van Lear (1983) reported responses of nutrient and sediment export to prescribed burning for a Piedmont site at the Clemson Experimental Forest in South Carolina. Four loblolly pine watersheds were burned twice at 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 (nitrate nitrogen) 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) were 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, nitrate nitrogen, were attributed to fertilizer applications.

Elevated concentrations of nitrate nitrogen 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 percent 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 petroleum-based compounds that induce water repellency in soils. This reduces infiltration and increases runoff and soil erosion, especially in the Western United States (Tiedemann et al. 1979, Wolgemuth 2001, Wright and Bailey 1982). 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, Marion and Ursic 1992, Shahlee et al. 1991, Swift et al. 1993, Van Lear and Danielovich 1988, Van Lear and Waldrop 1986). Increased soil erosion following fires is frequently associated with forest floor disturbances caused by mechanical site preparation during fire controlling activities, and most with direct fire influences. Similarly, operationally disturbed sites and especially skid trails have been found to be more susceptible to post-fire 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 (Swift et al. 1993, Van Lear and Waldrop 1989), their results have limited applications.

D. SOCIO-ECOMONICS

Future wildfires can induce a variety of socio-economic 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 socio-economic 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 percent between 1970 and 2000, and is anticipated to increase another 10 percent 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. Although only limited evidence exists that high particulate matter levels produced by wildfires increase mortality risk, especially for elderly populations (Sastry 2002), previous research has demonstrated a strong association between wildfire generated PM 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). Further, it was recently reported 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) (Richardson et al. 2012). 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 hectares in one week, destroyed over 3,000 homes, and killed 26 people (Keely et al. 2004). Although the impacts of the 1998 wildfires in Florida were less extreme, these fires none-the-less 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 policy-makers 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 and, to date, communities participating in this program have invested over $77 million in wildfire risk mitigation activities (Firewise Communities/USA 2011). The popularity of these programs is growing rapidly, with nearly one-third of the investment made in 2010 alone. Nearly 800 communities have invested in these activities, of which more than half are located in the Southern U.S.

Within the U.S., nearly one-third of the WUI occurs in either loblolly-shortleaf pine or longleaf-slash pine forest types, in which fires often burn at high intensity and are difficult to control (Theobald and Romme 2007). Although it is logical that Southern U.S. communities located in these forest types might be interested in investing in Firewise Communities type 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.

E. 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 one of the most important and challenging environmental issues facing world leaders. Greenhouse gasses in the atmosphere can absorb long-wave radiation emitted from the ground, which prevents release of heat energy into space. As a result, the temperature of the earth-atmosphere system increases. 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. Average annual global fire carbon emissions were estimated at about 2 Pg in the recent decade, about a third of total carbon emissions. This contribution could be extremely significant over a short period of time before carbon uptake resulting from regrowth of burned area vegetation. Carbon emissions during the 1997-98 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). The contribution could be significant also over a longer period because a large portion of carbon stored in forest and other ecosystems could be lost permanently in many regions such as the Amazon region where deforestation achieved using biomass burning.

The smoke particles from wildfires 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 span, but much larger spatial variability. Thus, they mainly affect short-term (daily, monthly, seasonally) regional climate variability. In modeling the role that smoke aerosols from the Yellowstone National Park wildfires may have played in the 1988 drought in the Northern United States, simulations (Liu 2005b) 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. Meanwhile, precipitation increases in the Southwest, southeastern Midwest, and Northeast, but decreases in the South. The simulated spatial pattern is similar to the observed pattern of precipitation anomalies, suggesting that the smoke particles from the wildfire might have exacerbated the drought.

V. MANAGEMENT OPTIONS FOR MITIGATION

Prescribed burning is one of the critical forest management tools that can be used to mitigate the impacts of climate change on wildfires in the South. Prescribed burning is a forest management tool for hazardous fuel reduction and for wildlife and range management. Also, an increasing number of acres are burned for ecosystem restoration and maintenance. Prescribed burning has been widely used in the South, with approximately 3.2 million ha treated each year—more than in all other regions of the United States combined (Wade et al. 2000). Figure 5.21 daily totals for the 27,000 prescribed burns that were applied on about a million acres in Florida during 2002—burning, which was yearlong, averaged 3,000 acres at 75 locations daily.

Prescribed burning has long been recognized as a useful technique for reducing the accumulation of understory fuels and therefore reducing wildfire risks in the South, more so than for the United States as a whole (Figure 5.22). The burned areas by prescribed fires in the South are about 60 percent of those in the United States, much larger than the 20-percent ratio for wildfires. Prescribed burning also can reduce wildfire risks indirectly by maintaining the health of fire-resistant species such as longleaf pine (Brockway et al. 2005).

Prescribed burning can also be a management option for reducing the impacts of any future increases in wildfires, which 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 wildfire (Urbanski et al. 2009). Some studies provide 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 to 2008 for the West and found that wide-scale prescribed fire application reduces carbon dioxide fire emissions by 18 ~ 25 percent generally and by as much as 60 percent in specific forest systems. Narayan (2007) showed that prescribed burning can significantly reduce carbon dioxide emissions in the European countries that experience high fire occurrence, estimating that wildfire emissions were about 11 million t/year over a 5-year period compared to about 6 million t/year for prescribed burning (a potential reduction of almost 50 percent).

The importance of prescribed burning as a mitigation option suggests that more frequent prescribed burning would be required in the future. This would bring new challenges to fire and land managers, who are restricted by many factors including weather conditions, escape risks into developed landscapes, 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 (Stanturf and Goodrick 2012).

The impacts of future climate change on the environmental conditions for prescribed burning was estimated in a recent study (Liu 2012). The preferred weather conditions for prescribed burning in the South include: 6 to 20 mile/hour wind speed at 20 feet above ground, 30 to 55 percent relative humidity, less than 60 ºF temperature in winter, 10 to 20 percent fine fuel (1-hour) moisture, and 250 to 400 points on the KBDI (Georgia Forestry Commission 2011, U.S. Department of Agriculture Forest Service Southern Research Station 1989). One end of each of the above ranges represents a critical value for risk moving from controlled to burning that is out-of-control; and the other end represents potential for efficient removal of fuel. For example, fuel moisture less than or equal to 10 percent is dry enough to create a high risk that a prescribed burn would escape and become a wildfire. Conversely, fuel moisture greater than or equal to 20 percent wet enough to prevent efficient removal of fuel.

In projecting the changes in future weather conditions under which a prescribed burning would be unlikely to escape controls or become a wildfire, we found that only one end of the preferred range for each condition needs to be considered as criteria. For KBDI, for example, the value is 400. However, we made three slight modifications. First, a temperature of 90ºF was used as a maximum during the non-winter seasons; this maximum was adopted from the preferred weather conditions for the northern Great Plains (Northern Prairie Wildlife Research Center 2011). Second, because fuel moisture (calculated based on the approach used in National Fire Danger Rating System) measures the worst-case scenario for wildfire risk and impact, our calculated values are systematically lower than the stick measurements and we decide that a lower fuel moisture value of 7.5 percent would be more accurate. Third, for maximum wind speed, we substituted 10-m instead of the 20 feet provided by the North America Regional Climate Change Assessment Project dynamical downscaling.

Figure 5.23 shows ideal weather conditions for prescribed burning, expressed as the ratio of days when a prescribed burning is unlikely to become a wildfire compared to total days. For the region as a whole, the ratio—or risk—is currently smallest during winter (about 30 percent) and largest during spring (about 80 percent), with few variations in pattern (but some variations in magnitude) from one area to the next. Under a changing climate the largest reduction in ideal conditions is predicted for summer and early autumn (greater than 60 percent), and the smallest reduction is predicted for spring (10 percent).

VI. CONCLUSIONS AND DISCUSSION

A. MAJOR FINDINGS

The results on current status of wildfire, future wildfire trends under a changing climate, the ecological, environmental, and socioeconomic impacts, and forest management mitigation options in the South have been presented in the chapter. The major findings include:

Fire potential—Fire potential is expected to increase in the South in this century as a result of increased concentrations of greenhouse gasses.

- The hotspot where the largest projected increase in future fire potential is the eastern coastal areas along the Gulf of Mexico in the early spring, extending to the central areas of the region in the late spring, and spreading further to the Atlantic coastline in summer and early autumn.
- The most significant increase in future fire potential is predicted for summer and autumn, when fire potential would increase roughly from the current low level to a moderate level in eastern areas, and from the current moderate level to a high level in western areas of the South.
- The length of fire seasons in the South will likely increase by a few months.
- Fire potential is unlikely to increase significantly until 2030 to 2040.

Burned area—Actual burned areas for a specific landscape would not necessarily increase even with a projected increase in fire potential. Based on the statistical relationships between wildfire occurrence and area burned, a decline in human-ignited wildfire area and an increase in lightning wildfire area from 2002 to 2050 are projected, based on expected reductions in forest coverage and changes in other societal factors that have been statistically linked to wildfire activity. Under one IPCC scenario evaluated, A1B, the projected decline in wildfires ignited by humans is greater than the increase in lightning ignited wildfires, resulting in an aggregate reduction in area burned.

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 are expected to have some substantial impacts on forest ecosystems, the environment, and society in the South.

- Future emissions from wildfires are likely to increase in forested areas especially during late spring and early summer; emissions from prescribed burning, assuming that the current level continues, are likely decrease in most areas because of reduced fuel loading.
- Increased wildfire emissions would 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 damages and wildfire management costs.
- Increased wildfire in forested areas would reduce total ecosystem nitrogen and increase sediment loading.
- Increased fire emissions of smoke particles would reduce solar radiation absorbed by forest plants and soils, leading to a cooling effect, changes in heat and water fluxes, and even 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 prescribe 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 extensively used in the South to reduce wildfire risks by reducing understory fuel accumulation. It promises to be among the most useful options for mitigating the impacts of potential increases in wildfire under a changing climate. If wildfire activity is projected to rise, then more frequent prescribed burning could be used in the future to mitigate some of the negative impacts of wildfires. Managers will have to aggressively manage fuel loads in order to reduce wildfire risk. 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 fire fighter safety; fuel loads may need to be managed at reduced levels, requiring more frequent prescribed burning. Fire behavior models may need revision to account for novel fuel types if vegetation changes significantly.

The challenges that southern fire and land managers could face would include a reduced burning window caused by changes in weather conditions, higher prescribed fire escape risks into wildland-urban interface and other developed landscapes, and greater constraints in use because of air quality concerns. The number of days when a prescribed burn has low escape risk could be reduced by about 40 to 60 percent during summer and autumn, 30 percent during winter, and 10 percent during spring.

Vegetation may be converted 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. The size of prescribed burns may be increased so that more acres can be burned in a day and remain within safety prescriptions. Burning fewer larger areas will require somewhat fewer resources than more, smaller fires would require. Greater pre-planning and coordination of resources will be needed so that open windows for prescribed burning are efficiently utilized.

Smoke management will be critical and effective use of smoke transport models will be essential in order to meet air quality constraints. If larger areas are burned within an airshed on a given day, the cumulative effects will need careful management to avoid impacting urban areas.

Increasing urbanization of the landscape will increase the land at the interface with wildlands. 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 gain acceptance for prescribed burning and personnel may require enhanced communication training. Alternatively, mechanical and chemical fuel reduction techniques may become more feasible economically, a least in creating buffers between structures and forests in the wildland urban interface. Educational efforts aimed at reducing arson and accidental ignitions as well as Firewise landscaping around residences could receive increased support as prevention measures. Support could be provided by state forestry agencies as technical assistance or subsidies. Alternatively insurance companies could require certain practices as a condition of acquiring homeowner policies.

B. 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) Regional climate change scenarios require comparison and interpretation. Two types of downscaled climate change scenarios were used. Statistical downscaling, which includes projections from multiple models and ensemble projections with multiple emissions storylines, 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 storyline for projections of fire potential and total burned area. Comparing of the impacts of the differences between the two types of downscaling techniques and using multiple general circulation models and emissions storylines for dynamic downscaling would improve projections.

(2) Very limited fire data were used: wildfire data for 5 years for fire emissions calculation and a single year for projections of future burned areas and prescribed burning. Wildfires have significant inter-annual variability. Thus, using the limited fire data would lead to certain uncertainty. It is critically important to develop long, consistent historical wildfire datasets for the South that can be used to develop robust statistical models.

(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 Keetch-Byram Drought Index, 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.

(4) Although some quantitative estimation of future fire's impacts on emissions was made, other impacts of wildfires were only approached by synthesizing existing studies. For a more extensively quantitative estimation of fire impacts, additional work is needed in a number of areas. The first is to develop more detailed projections of future fires, including frequency, intensity, and burned areas at specific landscapes and ecosystems. 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 the regional air quality impacts of future wildfires.

(5) In addition to weather and climate, fuel is a critical element in understanding wildfire trends and their impacts on emissions and air quality. The projection of future fuel loading change described in this chapter was made using a single climate change scenario. This can be improved by using multiple scenarios. In addition, changes in vegetation types under a changing climate would alter fuel loading. This is a challenge but important task for vegetation and fire modeling communities.

(6) The discussion on mitigation options was focused on prescribed burning. The investigation of this option could be improved by, for example, expressing the needs for prescribed fire in terms of actual changes in burning frequency. Moreover, other management options need to be explored in the event that the health and safety costs of prescribed burning are deemed unacceptable.

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TABLES

Table 5.1 Occurrence and frequency of pre-settlement fire regime types in the Southern United States, by the Society of American Foresters. (modified based on Wade et al. 2000)

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

Table 5.2 Fire environmental factors, their elements, and their impacts on fire behavior (Source: na.fs.fed.us/fire_poster/science_of_fire.htm)

Factor	Parameters	Roles
Weather	Wind, temperature, relative humidity, air pressure, winds, 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 dryer 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 dryer.

Table 5.3. Response of fire and fuel properties to possible changes in various atmospheric elements and processes

Change	Prediction confidence	Fire response				Fuel response	
		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

Table 5.4 Fire potential classifications, based on Keetch-Byram Drought Index (reorganized based on U.S. Department of Agriculture Forest Service, Wildland Fire Assessment System http://www.wfas.net/index.php/keetch-byram-index-moisture-drought-49)

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.

FIGURES

5.1. National Fire Danger Rating System fuel models for the Southern United States (Burgan 1988).

5.2. Fire environmental triangle (source: na.fs.fed.us/fire_poster/science_of_fire.htm)

5.3. Schematic showing how prescribed burning can mitigate the impacts that climate change has on wildfire.

5.4. 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.

5.5. 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.

5.6. 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.

5.7. 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.

5.8. 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.

5.9. Current (1971-2000, bottom portion of each bar) and future (2041-2070, top portion) 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).The unfilled or filled top portion of each bar represents positive or negative future change Liu et al., 2012).

5.10. Same as Fig.5.9 except for precipitation.

5.11. Same as Fig.5.9 except for the Keetch-Byram Drought Index (KBDI).

5.12. Monthly current and predicted fire potential, based on the Keetch-Byram Drought Index (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.

5.13. Current and predicted length of fire season within the Southern United States—based on Keetch-Byram Drought Index ratings of moderate or high fire potential (Liu et al., 2012).

5.14. 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.

5.15. Current fuel loading in the Southern United States for (A) baseline of 2002, (B) simulated for 2050 with a global dynamic vegetation model, and (C) change from baseline to projection (Zhang et al. 2010).

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

5.17. Monthly Keetch-Byram Drought Index (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.

5.18. 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.

5.19. 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.

5.20. Carbon dioxide emissions from prescribed burning in the Southern United States in March 2002 (kton) (a), future change by 2050 due to change in fuel loading alone (b) and due to changes in both fuel loading and land cover (c).

5.21. Daily prescribed burns in Florida during 2002, by number and total area burned (Liu et al. 2008).

5.22. Burned areas in 2010 for the South and the United States by (A) wildfire and (B) prescribed fire.

5.23. Current weather conditions for prescribed burning without escape and predictions for reductions in days suitable for burning under climate change in 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.

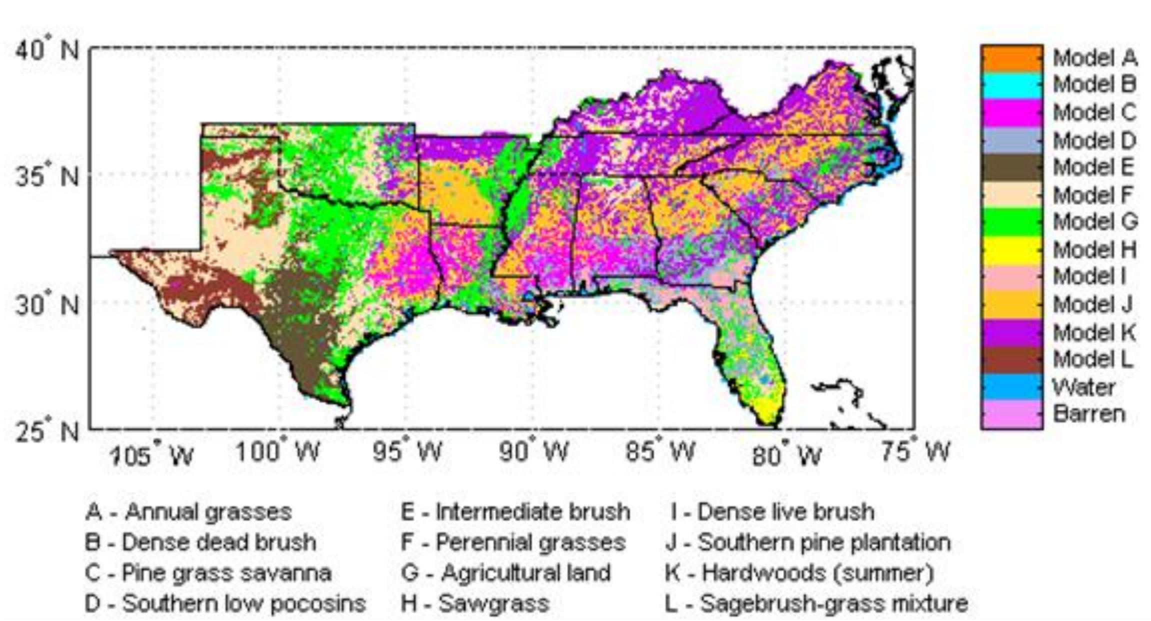


Figure 5.1. National Fire Danger Rating System fuel models for the Southern United States (Burgan 1988).

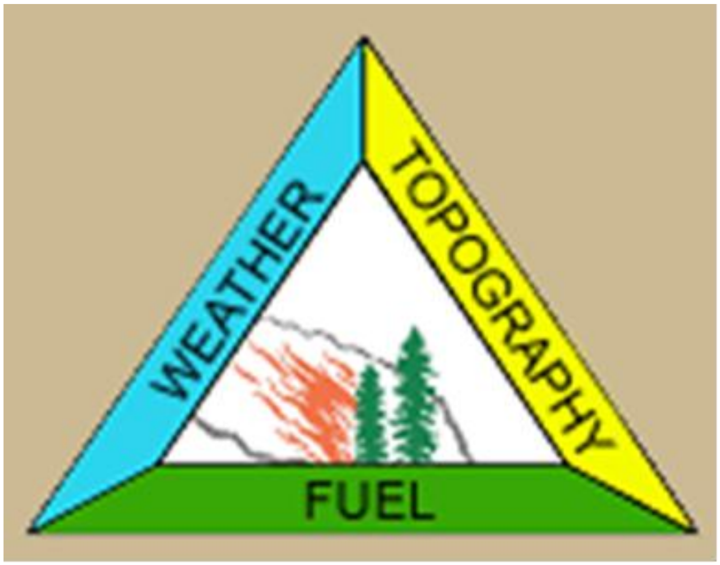


Figure 5.2. Fire environmental triangle (source: na.fs.fed.us/fire_poster/science_of_fire.htm)

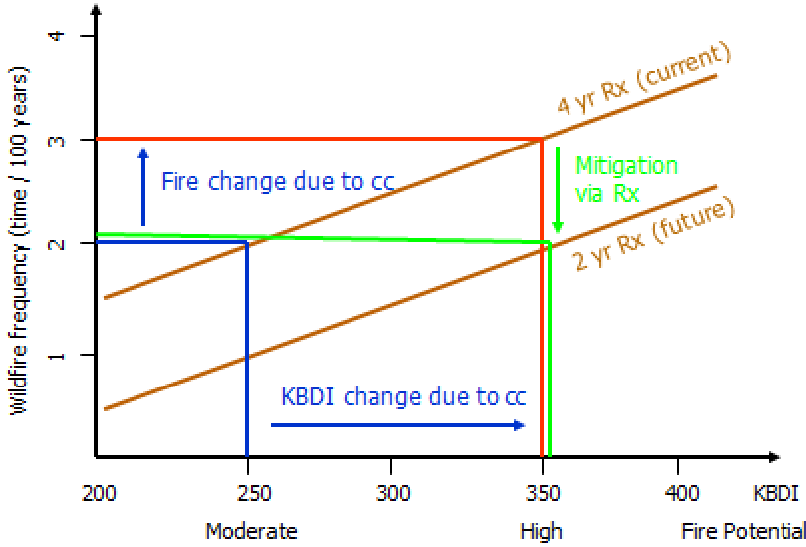


Figure 5.3. Schematic showing how prescribed burning can mitigate the impacts that climate change has on wildfire.

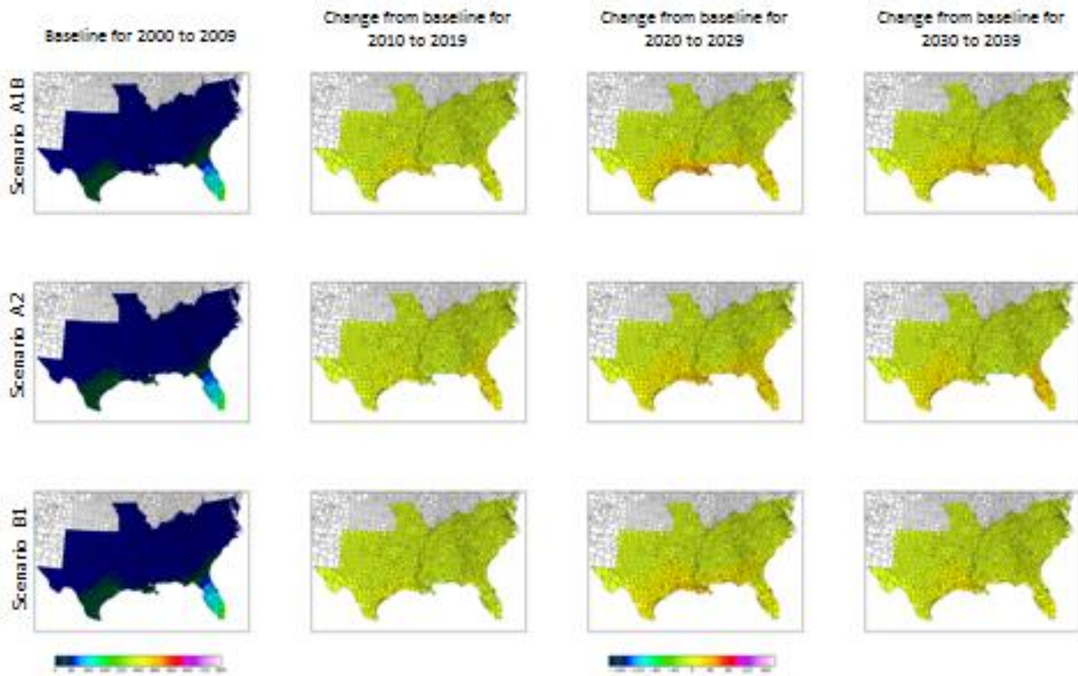


Figure 5.4 January fire potential for the baseline decade followed by ensemble, statistically downscaled projections of changes in fire potential for three subsequent decades assuming different Intergovernmental Panel on Climate Change (2007) emissions storylines: A1B, A2 and B1.

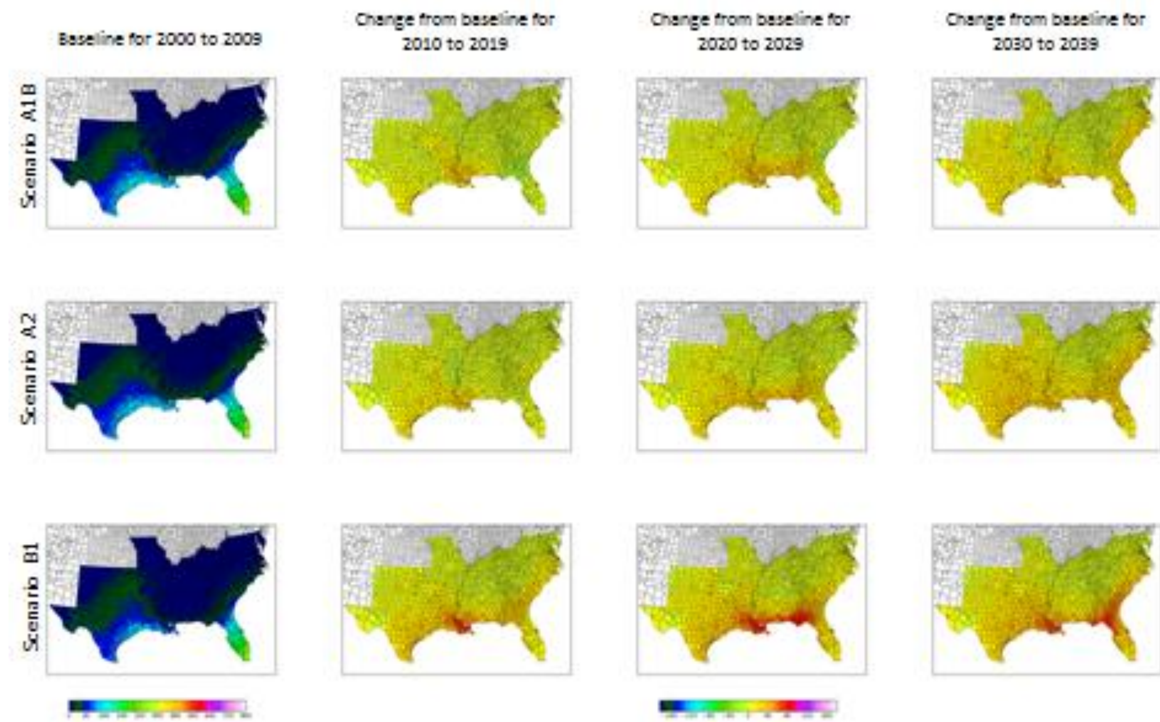


Figure 5.5. March fire potential for the baseline decade followed by ensemble, statistically downscaled projections of changes in fire potential for three subsequent decades assuming different Intergovernmental Panel on Climate Change (2007) emissions storylines: A1B, A2 and B1.

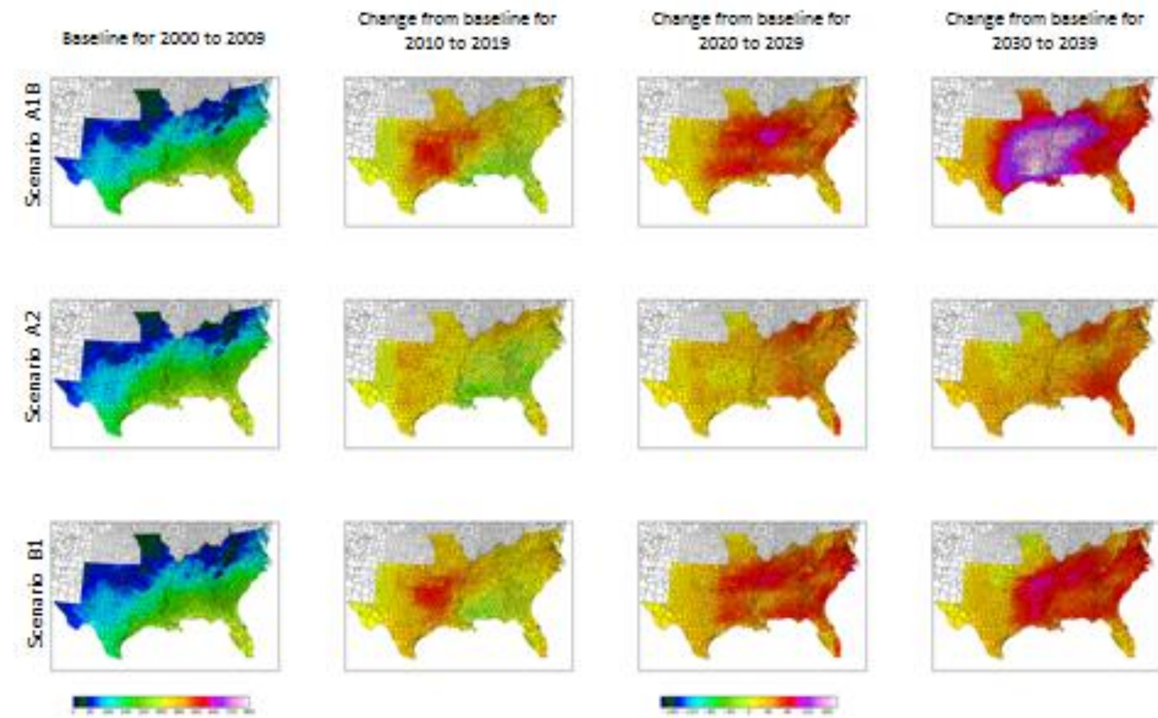


Figure 5.6. May fire potential for the baseline decade followed by ensemble, statistically downscaled projections of changes in fire potential for three subsequent decades assuming different Intergovernmental Panel on Climate Change (2007) emissions storylines: A1B, A2 and B1.

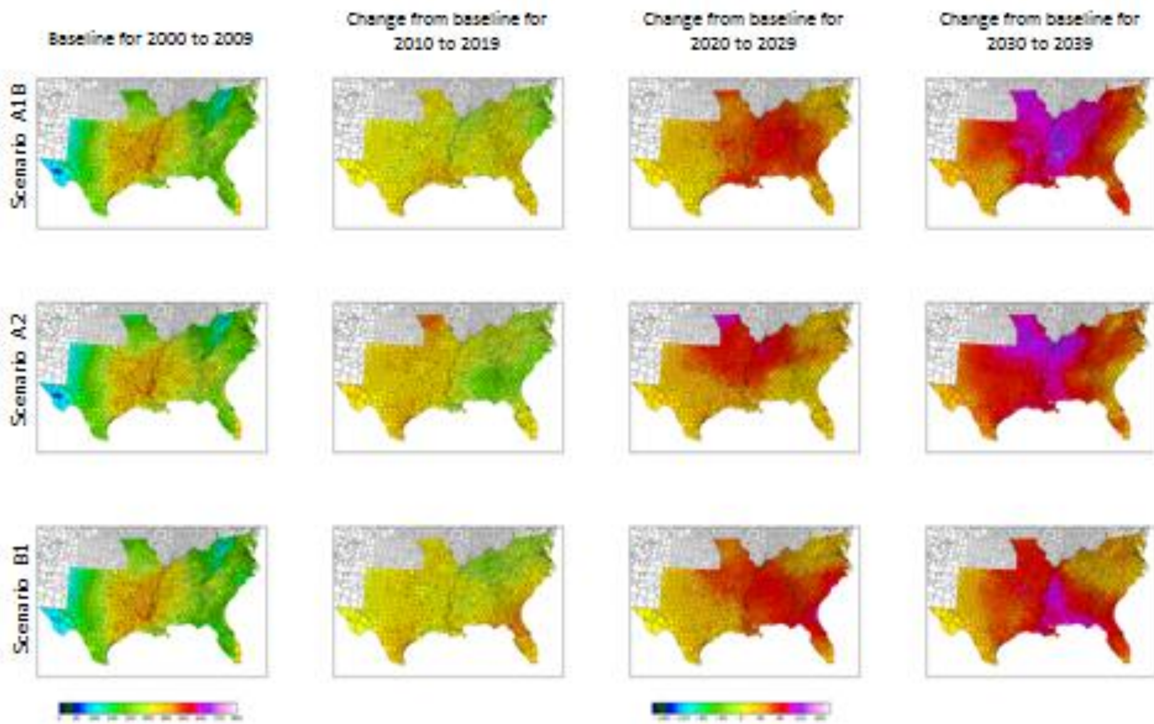


Figure 5.7. July fire potential for the baseline decade followed by ensemble, statistically downscaled projections of changes in fire potential for three subsequent decades assuming different Intergovernmental Panel on Climate Change (2007) emissions storylines: A1B, A2 and B1.

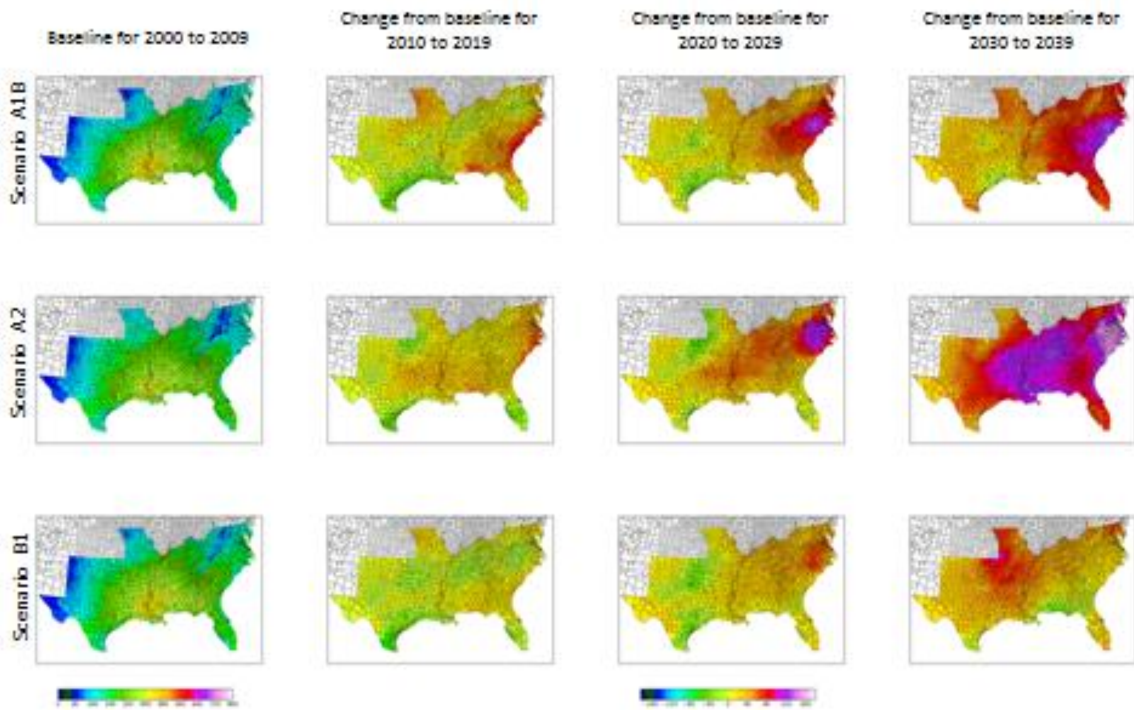


Figure 5.8. September fire potential for the baseline decade followed by ensemble, statistically downscaled projections of changes in fire potential for three subsequent decades assuming different Intergovernmental Panel on Climate Change (2007) emissions storylines: A1B, A2 and B1.

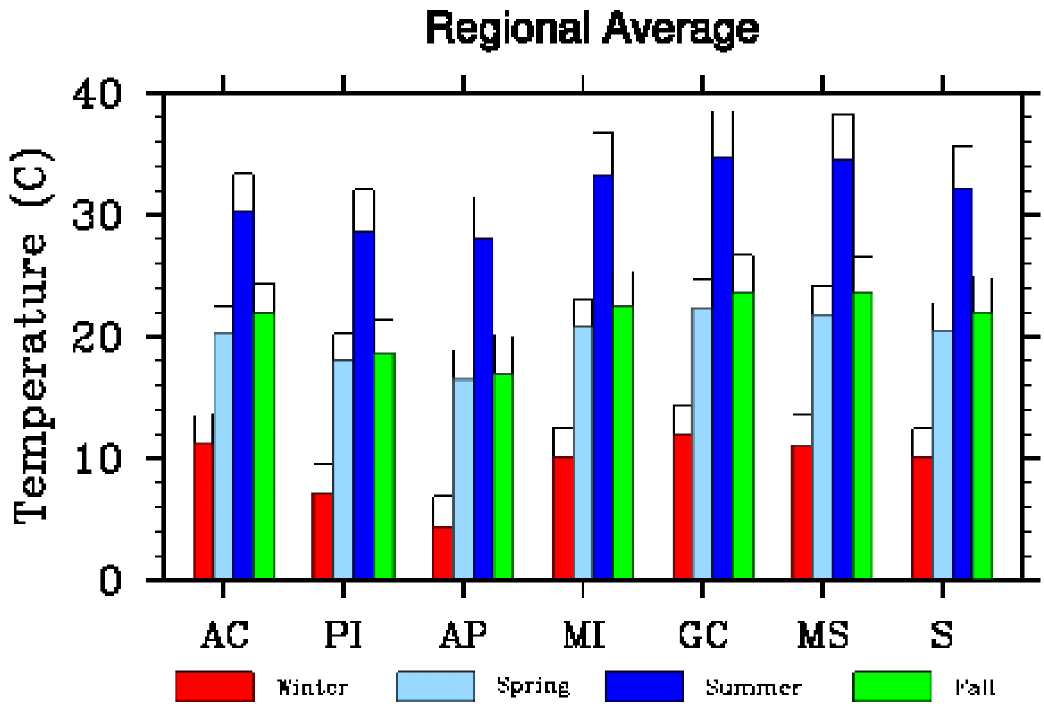


Figure 5.9 Current (1971-2000, filled bottom portion of each bar) and future change by 2041-2070 (top portion; positive if unfilled or negative if filled) in seasonal temperature averaged over the Atlantic Coast (AC), Piedmont (PI), Appalachian Mountains (AP), Mississippi Alluvial Valley (MI), Gulf Coast (GC), Mid-South (MS), and entire Southern United States (S).

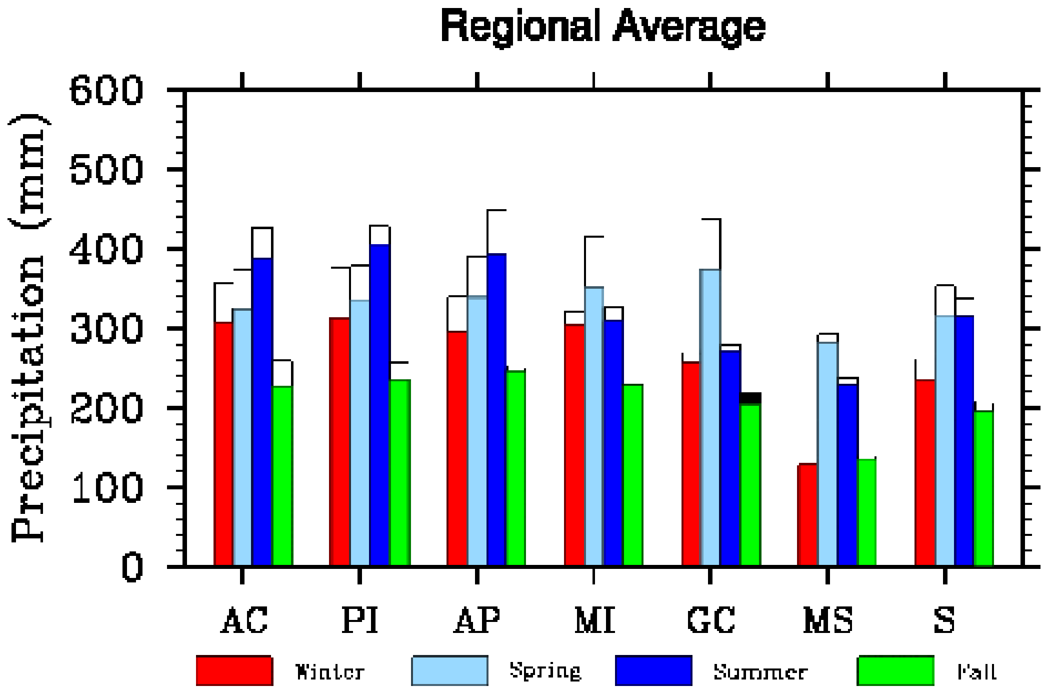


Figure 5.10 Same as figure 5.9 except for precipitation.

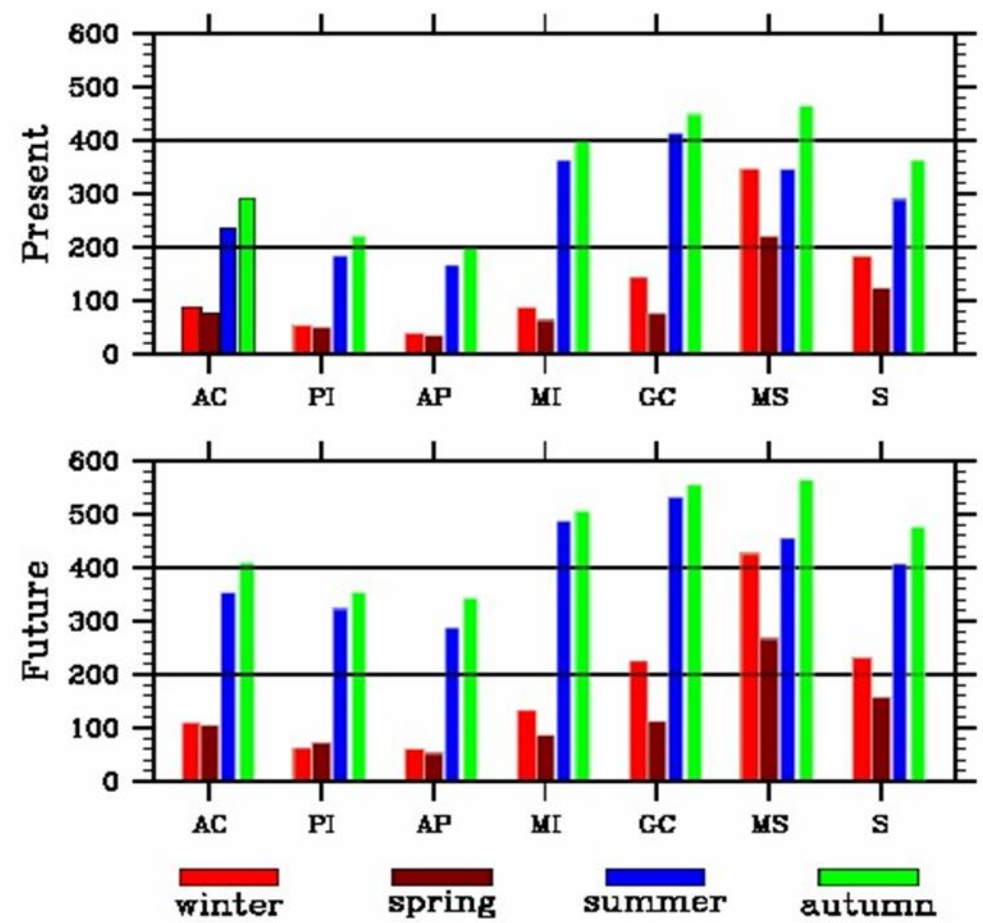


Figure 11 KBDI in the southern U.S. eco-regions. The top and bottom panels are for the present period of 1971-2000 and future period of 2041-2070. The regions below each panel are Atlantic Coast (AP), Piedmont (PI), Appalachian (AP), Mississippi (MI), Gulf Coast (GC), Mid-South (MS), and entire southern U.S. (US). (from Liu et al. 2012)

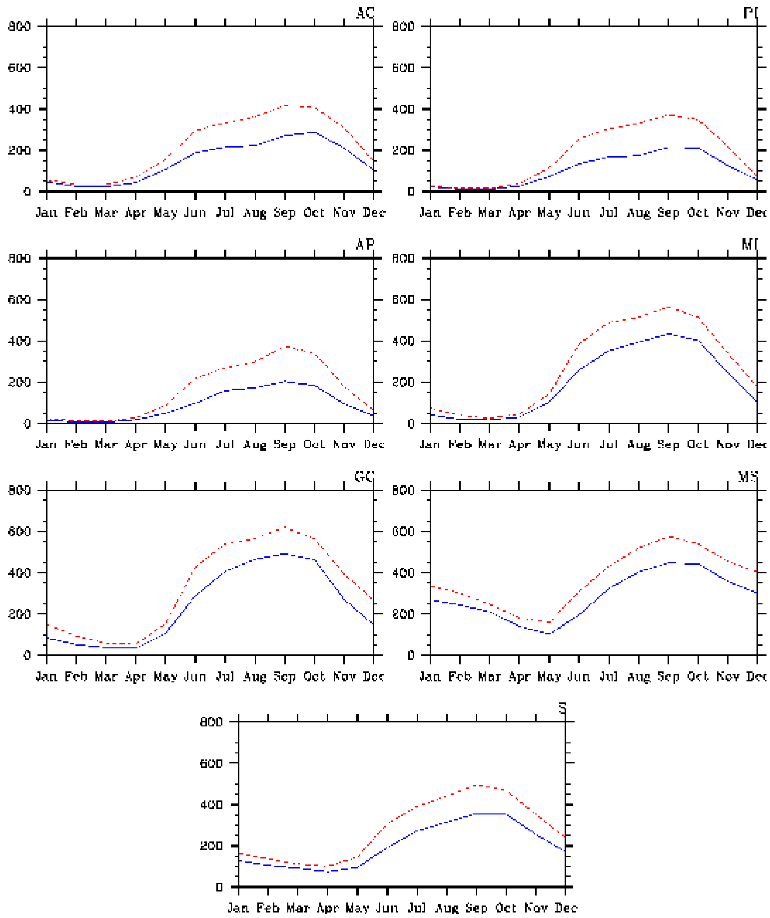


Figure 12 Monthly current and predicted fire potential, based on the Keetch-Byram Drought Index (KBDI), averaged over the (A) Atlantic Coast, (B) Piedmont, (C) Appalachian Mountains, (D) Mississippi Alluvial Valley, (E) Gulf Coast, (F) Mid-South, and (G) entire Southern United States.

Figure 13 Fire season lengths. The rows are the southern U.S. eco-regions and columns are months of a year. The numbers in the right-hand table are future change in the number of months for a fire season (high or extreme fire potential) between 2041-2070 and 1971-2000. (from Liu et al. 2012)

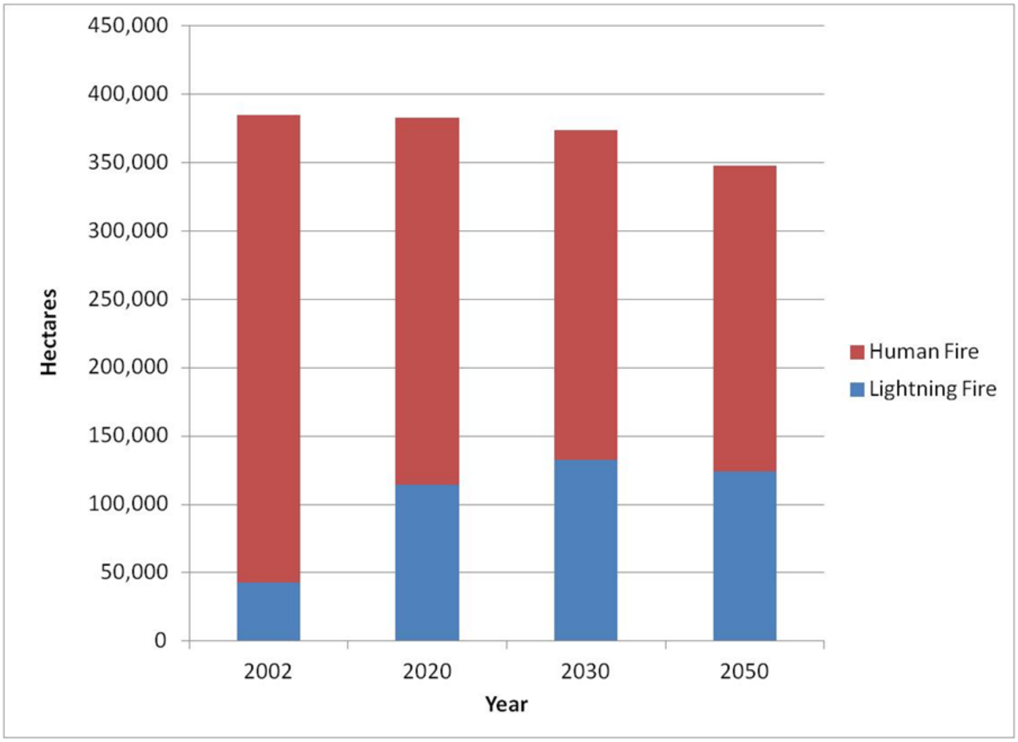


Figure 5.14. Area affected by human versus lightning caused wildfire in the Southern United States, 2002 (baseline) to 2050 (projected) assuming the Intergovernmental Panel on Climate Change (2007) A1B emissions storyline of rapid economic growth, global population that peaks in mid-century and declines thereafter, rapid introduction of new and more efficient technologies, and a balance between fossil fuels and alternative energy sources.

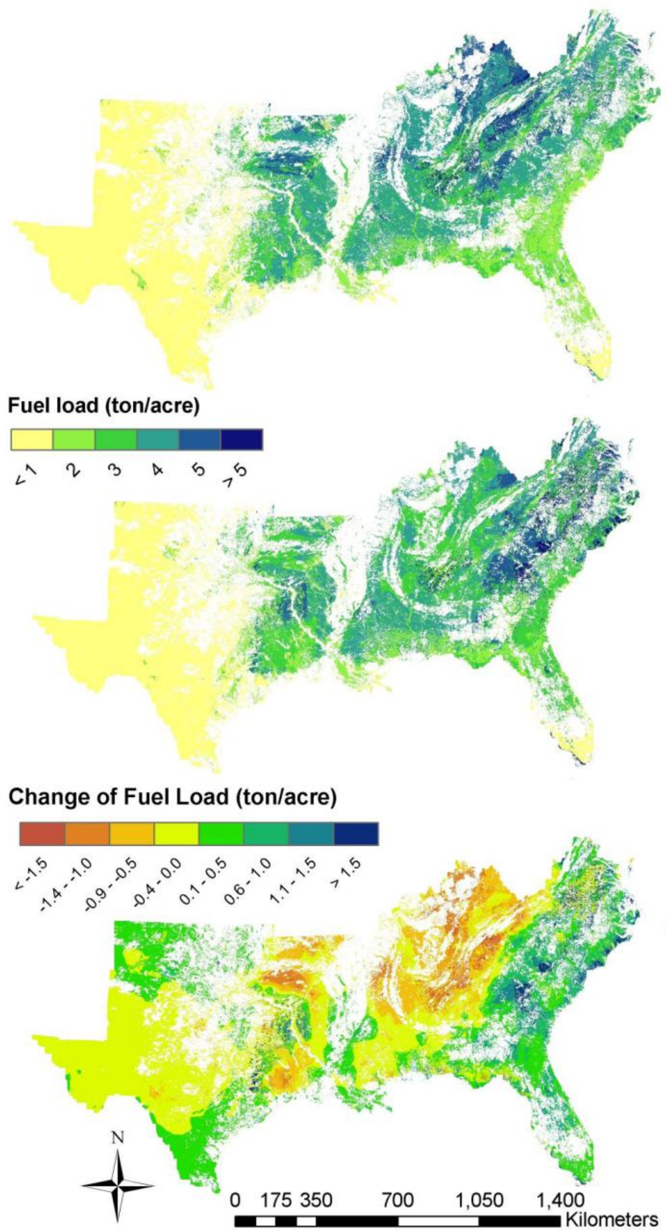


Figure 15 Current fuel loading in the Southern United States for (A) baseline of 2002, (B) change by 2050 with a global dynamic vegetation model. (Zhang et al. 2010)

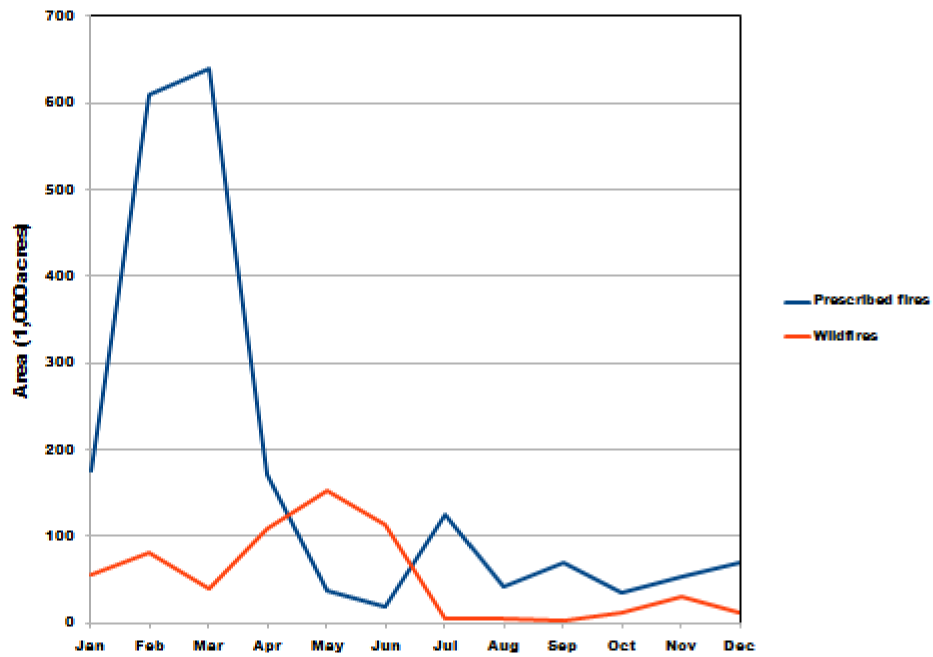


Figure 16 Average area burned by month for prescribed fires and wildfires from 1997 to 2002 in the Southern United States.

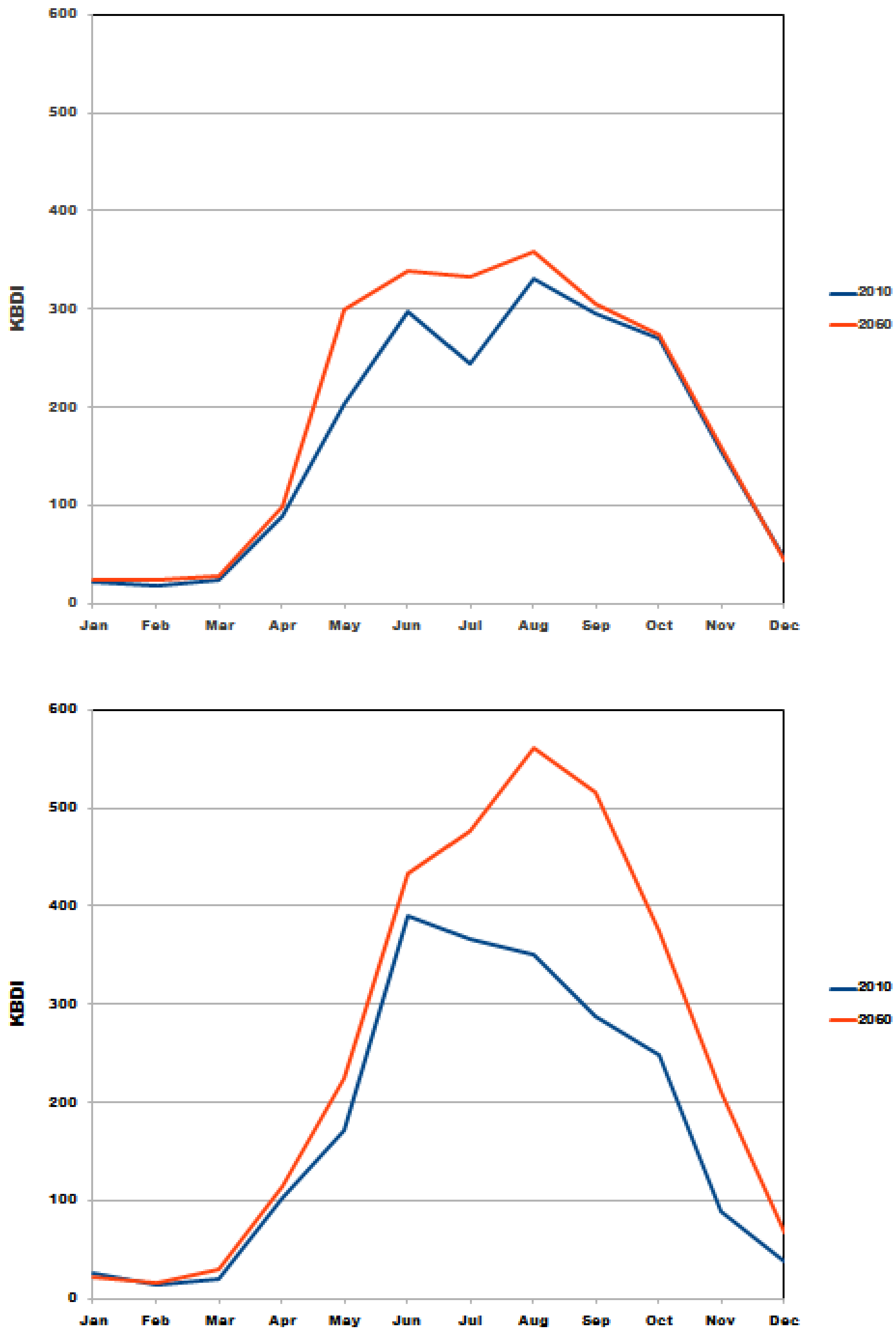


Figure 17 Monthly Keetch-Byram Drought Index (KBDI) averages for the Southern United States in 2010 and projected for 2060, assuming the Intergovernmental Panel on Climate Change (2007) A1B emissions storyline (A) CSIROMK3.5 and (B) MIROC3.2.

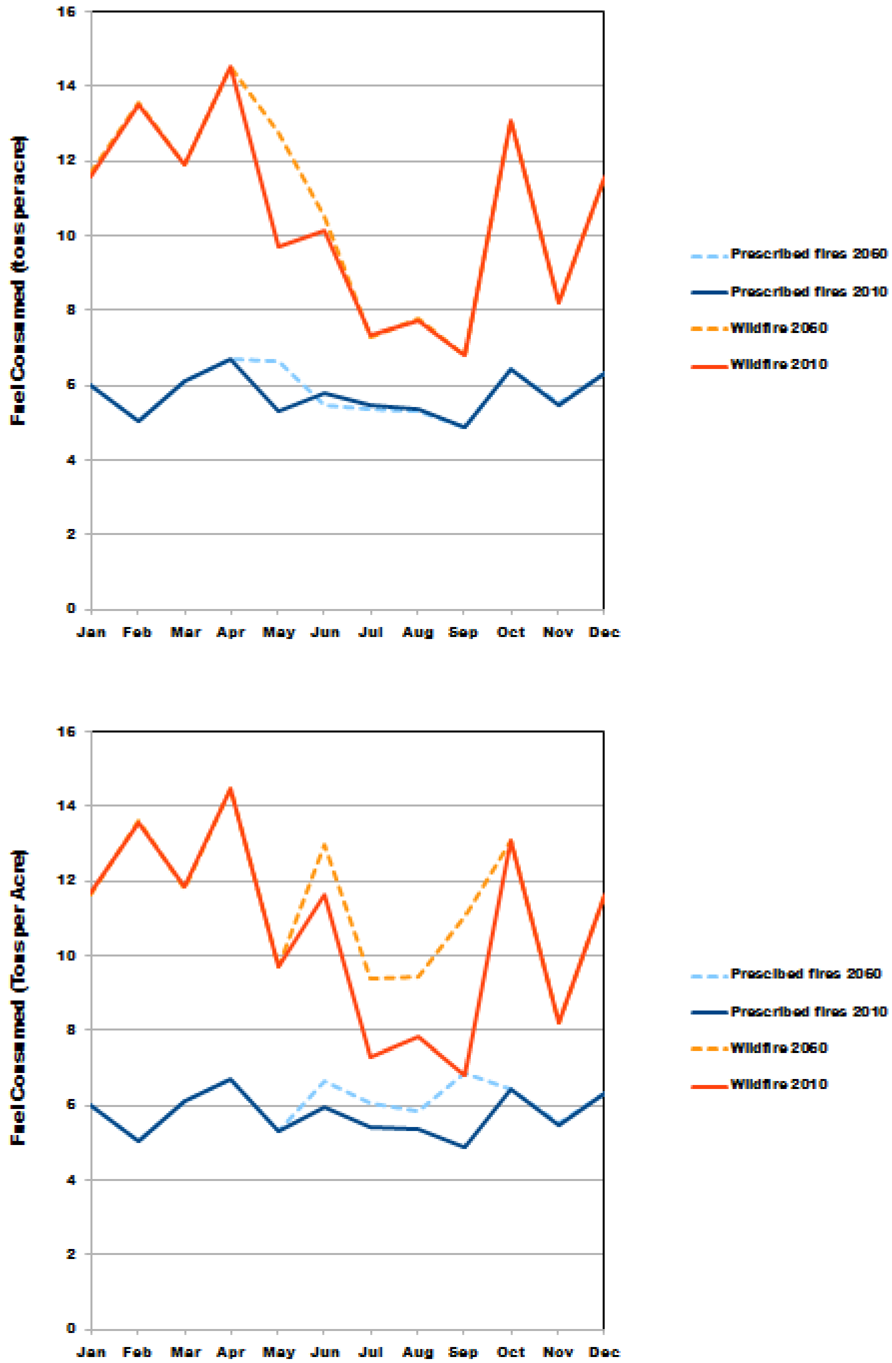
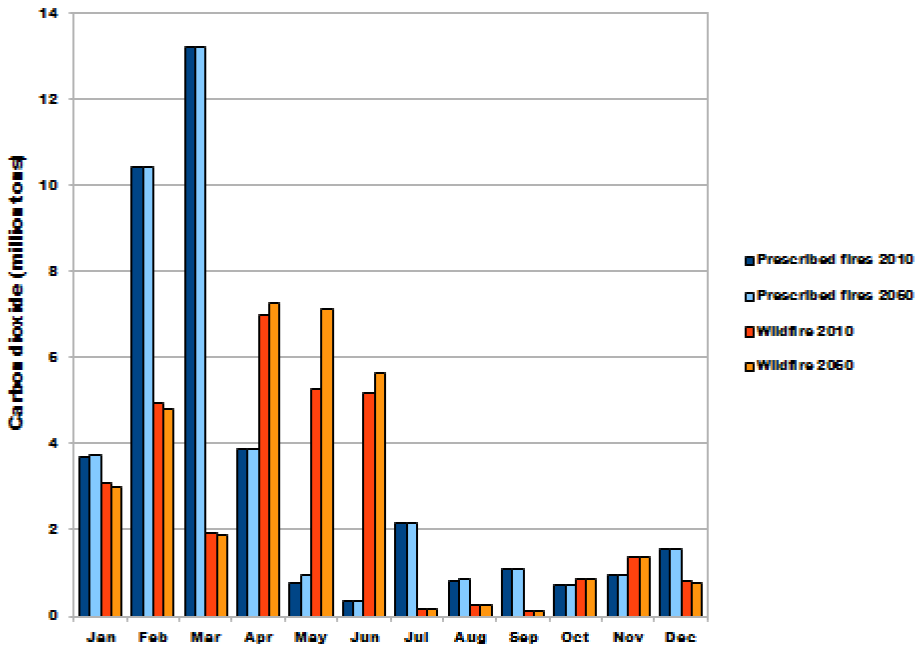


Figure 18 Average fuel consumption by month for prescribed fires and wildfires in the Southern United States in 2010 and projected for 2060, assuming the Intergovernmental Panel on Climate Change (2007) A1B emissions storyline (A) CSIROMK3.5 and (B) MIROC3.2.



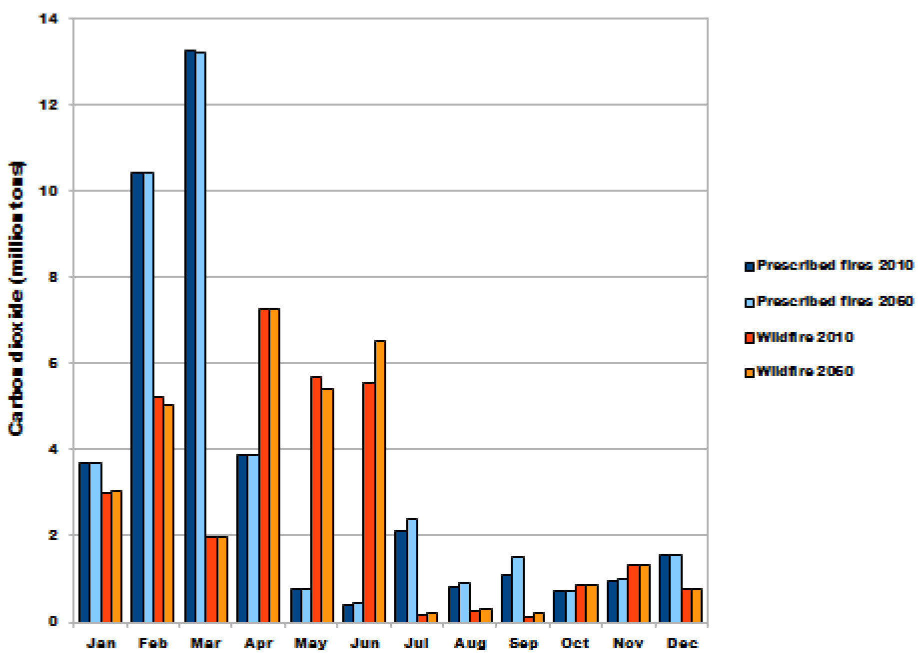


Figure 19 Monthly carbon dioxide emissions for prescribed fires and wildfires in the Southern United States in 2010 and projected for 2060, assuming the Intergovernmental Panel on Climate Change (2007) A1B emissions storyline (A) CSIROMK3.5 and (B) MIROC3.2.

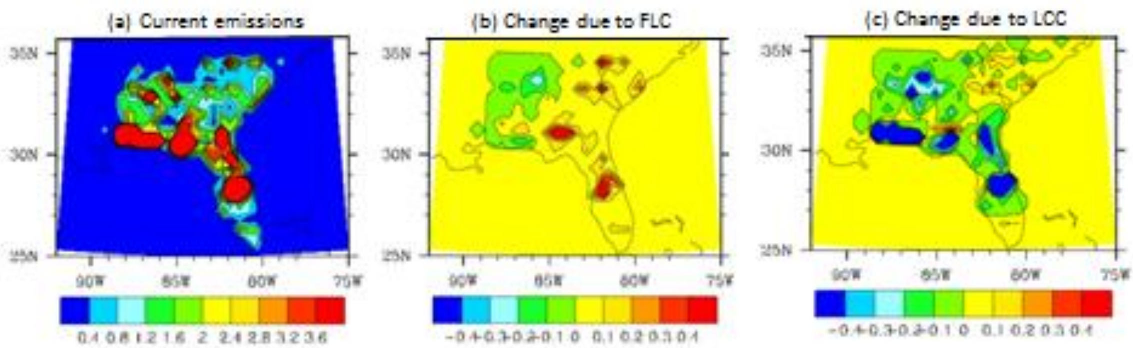


Figure 20. Carbon dioxide emissions from prescribed burning in the Southern United States in March 2002 (kton) (a), future change by 2050 due to fuel loading change (FLC) alone (b) and due to changes in both fuel loading and land cover (c).

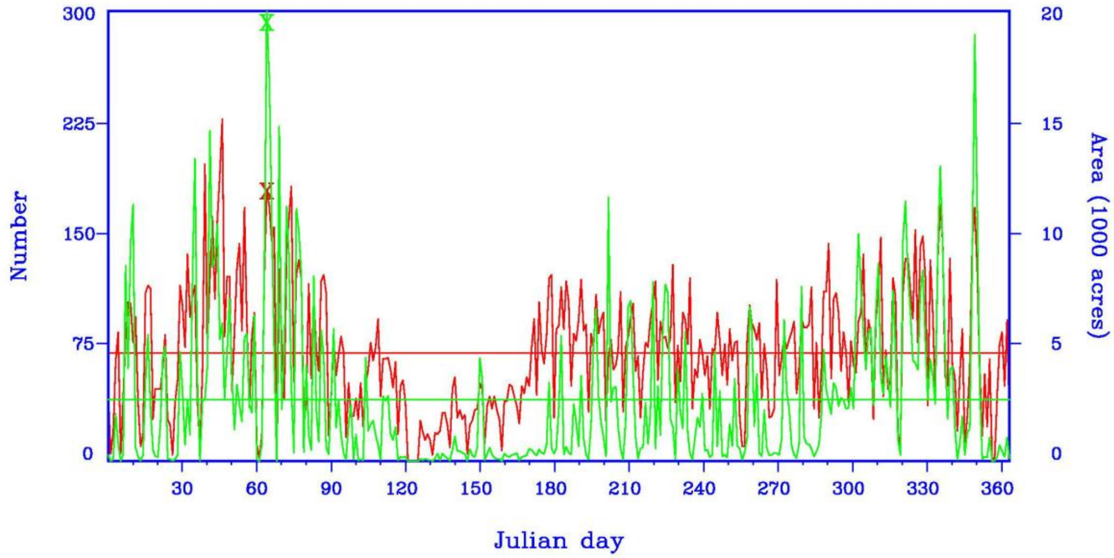


Figure 5.21 Daily prescribed burns in Florida during 2002, by number and total area burned (Liu et al. 2008).

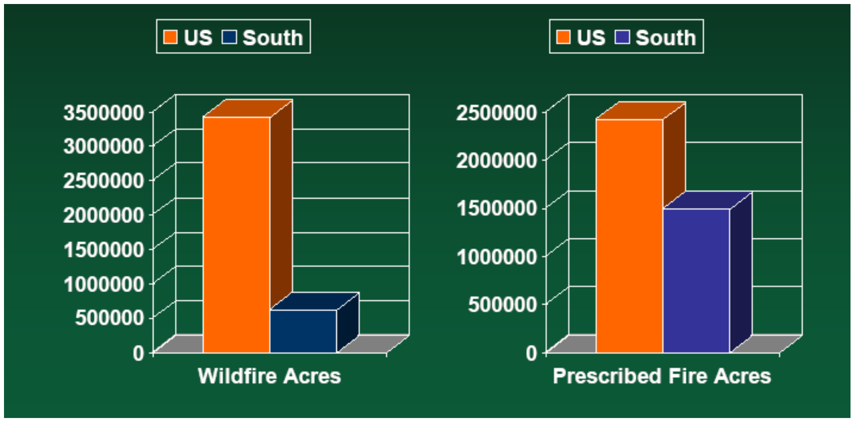


Figure 5.22 Burned areas in 2010 for the South and the United States by wildfire and prescribed fire (source:).

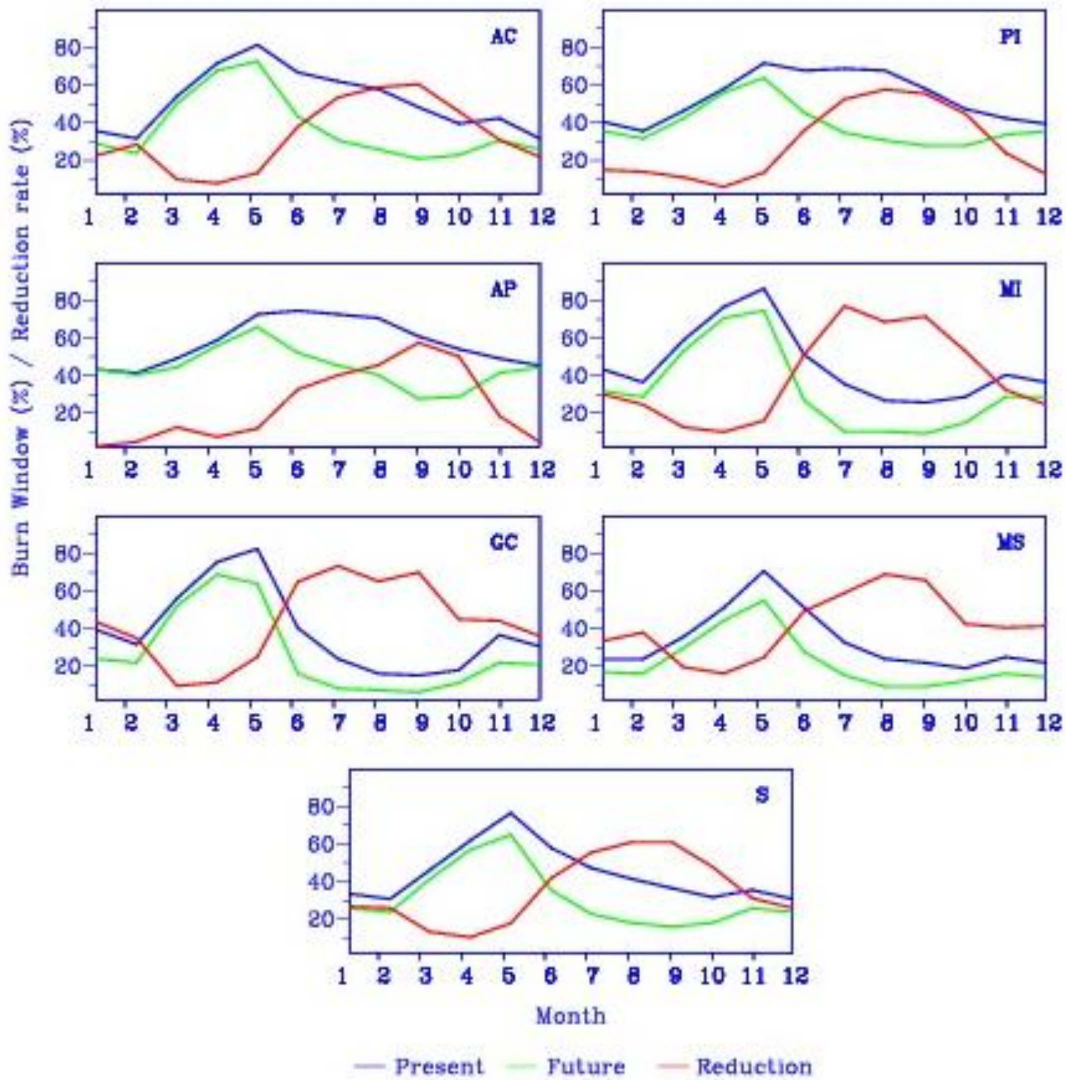


Figure 5.23 Current weather conditions for prescribed burning without escape and predictions for reductions in days suitable for burning under climate change in the (A) Atlantic Coast, (B) Piedmont, (C) Appalachian Mountains, (D) Mississippi Alluvial Valley, (E) Gulf Coast, (F) Mid-South, and (G) entire Southern United States. (from Liu 2012)