

Wildland Fire Occurrence and Emissions in the Eastern United States From 2001 Through 2050

By Todd Hawbaker and Zhiliang Zhu

Chapter 4 of

Baseline and Projected Future Carbon Storage and Greenhouse-Gas Fluxes in Ecosystems of the Eastern United States

Edited by Zhiliang Zhu and Bradley C. Reed

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Chapter 4. Wildland Fire Occurrence and Emissions in the Eastern United States From 2001 Through 2050

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4.1. Highlights

- During the baseline period of the wildland fire part of the assessment (2001 through 2008), the median of area burned by wildland fires was 1,355 square kilometers per year (km^2/yr), and the 95th percentile was 4,092 km^2/yr .
- During the baseline period of the wildland fire part of the assessment, the median of emissions from wildland fires was 5.2 teragrams of carbon dioxide equivalent per year ($\text{TgCO}_2\text{-eq/yr}$; 1.4 TgC/yr), and the 95th percentile was 17.3 $\text{TgCO}_2\text{-eq/yr}$ (4.7 TgC/yr).
- During the baseline period of the wildland fire part of the assessment, the median of wildfire emissions in the Eastern United States was equivalent to 0.51 percent of the average NEP (279 TgC/yr ; chap. 7), and the 95th percentile was 1.59 percent of the average NEP.
- During the baseline period of the wildland fire assessment, the median of wildfire emissions in the Eastern United States was equivalent to 0.09 percent of fossil fuel emissions for the United States, and the 95th percentile was 0.31 percent of fossil fuel emissions for the United States.
- For the projected period (2009 through 2050), wildland fire occurrence and greenhouse-gas emissions increased in the Eastern United States under all of the climate-change scenarios considered in this assessment.
- For the projected period, there was substantial variability in the direction and magnitude of change among ecoregions, and not all ecoregions experienced increases in wildland fire occurrence and emissions under all climate-change scenarios.
- The projected median amount of area burned annually from 2041 through 2050 was as much as 51 percent greater than the median amount of area burned annually during the baseline years. The median annual emissions were projected to increase by as much as 41 percent from the baseline median annual emissions.
- Extreme fire years (years in which the amount of area burned are ranked the 95th percentile) are projected to become more extreme. The annual area burned in extreme fire years was projected to increase by 43 to 122 percent from the early conditions, and the 95th percentile of annual wildland fire emissions was projected to increase by 41 to 111 percent from the baseline 95th percentile estimate.
- Prescribed fire is an important land management tool in the Eastern United States; however, the lack of accurate and consistent data about prescribed fires limits understanding of their contributions to GHG emissions.

4.2. Introduction

The methodology for this assessment (Zhu and others, 2010) explicitly addressed ecosystem disturbances, including human- and natural-caused wildland fires, as required by the EISA (U.S. Congress, 2007). Estimates for the baseline and projected biomass combustion emissions from wildland fires and effects in long-term carbon balance were components of the assessment (fig. 1–2). Biomass combustion emission results are presented in this chapter. The baseline burned areas and the projected future potential burned areas for wildland fires and their severity, described in this chapter, were used as input into the assessment of the long-term effects of ecosystem carbon balances (chap. 5).

Wildland fires are a critical component of the global carbon cycle because they produce an immediate release of GHGs— CO , CO_2 , and CH_4 —when biomass is consumed through combustion (Seiler and Crutzen, 1980). However, previous estimates of emissions from wildland fires in the United States were highly variable, and after converting the reported emissions to carbon-dioxide equivalents, they were as follows:

- from 15 $\text{TgCO}_2\text{-eq/yr}$ in 2001 to 73 $\text{TgCO}_2\text{-eq/yr}$ in 2008 (Giglio and others, 2010; van der Werf and others, 2010; Oak Ridge National Laboratory, 2012),
- from 29 $\text{TgCO}_2\text{-eq/yr}$ in 2001 to 199 $\text{TgCO}_2\text{-eq/yr}$ in 2008 (French and others, 2011; Michigan Tech Research Institute, 2012), and

- from 157 TgCO₂-eq/yr in 2002 to 283 TgCO₂-eq/yr in 2006 (Wiedinmeyer and Neff, 2007).

When compared with the 2010 estimate of 1,075 TgCO₂-eq/yr of net carbon flux from ecosystems in the continental United States reported by the EPA (U.S. Environmental Protection Agency, 2012), the annual emissions from wildland fires were equivalent to 1 to 26 percent of the ecosystem's total annual net carbon flux. In contrast, the combustion of fossil fuels produced 5,642 TgCO₂/yr from 2001 to 2008 (U.S. Environmental Protection Agency, 2012), and emissions increased at a rate of 1 percent per year (Pacala and others, 2007). Based on these rates, the annual emissions from wildland fires were equivalent to 0.3 to 5.1 percent of the emissions from fossil-fuel consumption.

The differences among the variability and quality of these results, the spatial and temporal resolution of the data, and assumptions about variations in combustion efficiency were the primary sources of uncertainties in wildland fire emissions estimates (Larkin and others, 2009; French and others, 2011). The assumptions about the proportion of aboveground biomass consumed by wildland fire, especially aboveground woody biomass in forests, can have a substantial influence on emission estimates (Campbell and others, 2007; Meigs and others, 2009). The methods used to calculate emissions relied on estimates of the area that was burned, fuel loads (volume of live and dead biomass available for burning), combustion efficiency, and emission factors (Seiler and Crutzen, 1980; Albin and others, 1995; Wiedinmeyer and Neff, 2007; Ottmar and others, 2008). For example, the Global Fire Emissions Database (GFED; Giglio and others, 2010; van der Werf and others, 2010) estimates biomass consumption and emission at fire locations (including agricultural fires) detected by the National Aerospace and Space Administration's (NASA) moderate resolution imaging spectroradiometer (MODIS; Roy and others, 2002; Giglio and others, 2003) based on land-cover types, combustion completeness, soil moisture, and land-cover-specific emission factors. The GFED also incorporates changes in fuel loads using the Carnegie Ames Stanford approach to characterize biomass production (Potter and others, 1993, 2012). Wiedinmeyer and Neff (2007) also used active wildland fire observations from MODIS satellite sensors (Giglio and others, 2003), but calculated the emissions based on static land-cover types, percentage of land cover, and biomass at 1-kilometer (km) resolution. French and others (2011) used the Forest Service Consume model (Ottmar and others, 2008), which calculated fuel consumption and emission using fuel loads derived from the Forest Service Fuel Characteristic Classification System (FCCS; Ottmar and others, 2007) and fuel moistures derived from weather-station data.

Wildland fires also have long-term effects on ecosystem carbon balance by influencing the rate of carbon sequestration after combustion, through the decomposition of dead vegetation (which can provide nutrients to help establish new vegetation), and by reducing the rate of photosynthesis

per unit area. Because of those effects, years to decades can pass before carbon stocks return to conditions before the fire (Turner and others, 1998; Cleary and others, 2010; Hurteau and Brooks, 2011; Kashian and others, 2012). If fire regimes are stable and assuming no other land management, the long-term effects of wildland fires on ecosystem carbon balance are typically negligible because carbon sequestration through growth of new vegetation and carbon loss through wildland fire emissions cancel out each other over long periods (Balshi and others, 2009a,b; Flannigan and others, 2009). However, if a fire regime changes, then the vulnerability for carbon storage is high because the amount of carbon stored in the ecosystem can be altered or lost through emissions.

Substantial evidence is available to document that fire regimes have not been static in modern times. For example, the frequency of wildland fires has been greatly reduced since settlement of the United States began mainly due to land-use changes and the success of fire suppression in the past century (Cleland and others, 2004). In the Western United States, the frequency of wildland fires has been increasing since the 1990s because of climate changes leading to an increasingly earlier snowmelt (Westerling and others, 2006). Wildland fires and emissions to carbon cycling are likely to be less important in the Eastern United States than in the Western United States, but limited research has been conducted quantifying relationships between wildfire occurrence and climate change in the Eastern United States. If the climate shifts to warmer and drier conditions, then increases in fire frequency and emissions are likely. Therefore, any comprehensive assessment of carbon storage and fluxes in ecosystems through time must account for the potential changes in wildland fire occurrence and emissions.

Wildland fire regimes are a function of the interactions between vegetation, land use, and ultimately, the climate (Swetnam and Betancourt, 1990; Gedalof and others, 2005; Westerling and others, 2006; Falk and others, 2007). A changing climate may result in changes in wildland fire regimes, including their occurrence and severity. Hessl (2011) outlined the primary pathways through which climate change may alter wildland fire regimes, including (1) altered fuel conditions, such as a change in fuel moisture; (2) altered fuel loads; and (3) changes in ignition patterns. The effects of climate change on wildland fires in the Eastern United States are expected to be significant and result in changes in weather patterns that would alter (1) ignition patterns, (2) wildland fire behavior, and (3) to a lesser extent, the distribution of vegetation. No single study, however, has addressed all three types of changes simultaneously at the scale required by this assessment (Flannigan and others, 2009).

Previous studies provided an estimate of the effects of wildland fires on carbon balance at a national scale but lacked the regional detail required by this assessment. Furthermore, there were few projections of future potential wildland fire emissions that were consistent with the existing baseline emission estimates. Therefore, a set of baseline emissions and projected future potential emissions was developed to ensure consistency throughout this and other regional assessments.

The primary questions addressed in this chapter include: (1) what were the patterns of wildland fire occurrence and emissions in the Eastern United States? (2) what may be the potential changes in wildland fire occurrence and emissions for the Eastern United States under climate change? (3) how did recent wildland fire occurrence and emissions vary temporally and spatially among the ecoregions of the Eastern United States? and (4) which ecoregions of the Eastern United States have the greatest potential for changes in fire-occurrence and emissions?

4.3. Methods and Data

The wildfire modeling and estimation study for the carbon sequestration assessment of ecosystems of the Eastern United States had two tasks: (1) calculating the baseline quantities for wildland fire occurrence and emissions and (2) simulating future (2009–2050) projections of wildland fire occurrence and emissions under climate-change scenarios. The methods used for this study are the same methods (Hawbaker and Zhu, 2012) used in the USGS western ecosystem carbon sequestration assessment (Zhu and Reed, 2012). Some specific technical processes are common to both parts of the study; other methods are specific for a single task. The baseline estimates for the number of wildland fires, the area burned, and emissions were derived from the Wildland Fire Leadership Council's Monitoring Trends in Burn Severity (MTBS) database (Eidenshink and others, 2007) and the Forest Service's First Order Fire Effects Model (FOFEM; Reinhardt and others, 1997) for the major GHGs CO_2 , CO , and CH_4 . This method was applied to each wildland fire in the region that was in the MTBS database to produce estimates of CO_2 , CO , and CH_4 emissions (converted to CO_2 equivalents).

The wildland fire modeling approach used for the future projections in this assessment incorporated three primary components: wildfire ignitions, spread, and effects. The parameters for the ignition and spread components were selected through a calibration process using the baseline observed data, which were used to simulate future potential wildfires and burned areas and then FOFEM was used to estimate emissions for the simulated burned areas. Results of the baseline and future projections of wildland fires were aggregated to produce estimates of emissions for the Eastern United States as a whole and for each level II ecoregion within it (fig. 1–1; as described in detail in chapter 2 of this report). The datasets and methods used by the various wildland fire modeling components are described briefly in Hawbaker and Zhu (2012) and in more detail in the following sections.

4.3.1. MTBS Wildland Fire Data

The locations of wildland fires were taken from MTBS data (Eidenshink and others, 2007) and were used for baseline observations and to calibrate the ignition and spread components of the wildland fire modeling system. The MTBS data

described fires that occurred from 1984 to 2008 and covered areas that were larger than 404 hectares (ha; 1,000 acres) in the Western United States and 202 ha (500 acres) in the Eastern United States. The MTBS data did not include small fires but captured the majority of the area burned because they included the largest fires, which contributed most to total area burned (Strauss and others, 1989; Stocks and others, 2002). Some prescribed fires are included in the MTBS database; however, they were excluded from this assessment because the completeness of prescribed fire coverage in the MTBS database was uncertain and likely underestimated actual prescribed fire use in the Eastern United States. Each wildland fire detailed in the MTBS database was identified in State or Federal fire records, and its burn scar and severity were manually mapped using Landsat imagery from before and after the fire. Because of the MTBS methodology, there was a high degree of confidence in the spatial and temporal accuracy of the wildland fire data, whereas other wildland fire databases had known problems, including duplicate records and erroneous locations (Brown and others, 2002), which would require laborious error checking before use.

4.3.2. Fuels and Topography

The methodology for the baseline and projected wildfires relied on vegetation, fuels, and topography data from the Landscape Fire and Resource Management Planning Tools (LANDFIRE) Program (Rollins, 2009) of the U.S. Department of the Interior (DOI) and the U.S. Department of Agriculture (USDA). These data included information about existing vegetation, fire-behavior fuel models, and tree canopy fuels (cover, height, base height, and bulk density), as well as the elevation, slope, and aspect of the terrain. To calculate emissions from wildland fires, the Fuel-Loading Model (FLM; Lutes and others, 2009) data layer of the LANDFIRE program was used. Vegetation and fuels were held static throughout the simulations for future wildfires and were not altered by simulated disturbances and other types of LULC change. All raster data were aggregated to 250-meter (m) resolution in order to improve the processing efficiency using a nearest-neighbor rule (Lillesand and others, 2007). The nearest-neighbor aggregation was desirable because it preserved the proportion of vegetative-cover types within the study area, whereas other aggregation methods were more likely to result in common vegetative-cover types being overrepresented and uncommon vegetative-cover types being underrepresented.

4.3.3. Weather and Climate Data

The assessment methodology required daily weather data, including temperature, precipitation, relative humidity, and wind speeds, for the baseline and future periods. For the baseline period, gridded daily weather data for the conterminous United States with 0.125-degree ($^{\circ}$) spatial resolution (approximately 12 km) were used (Maurer and others, 2002).

These data were interpolated from weather stations and included the minimum and maximum daily temperature and daily precipitation from 1950 to 2010. The data on afternoon wind speed and direction from the 0.333° (approximately 32 km) North American regional reanalysis (Mesinger and others, 2006) were joined to the 0.125° daily temperature and precipitation data.

In order to simulate the effects of the climate-change scenarios on wildland fire occurrence and emissions, downscaled monthly climate data provided by the World Climate Research Programme (WCRP) Coupled Model Intercomparison Project phase 3 (CMIP3) multimodel dataset were used. The CMIP3 data were corrected for bias and spatially downscaled to match the 0.125°-resolution baseline weather data (Maurer and others, 2007). For this analysis, the downscaled data from the Climate Research Branch of Environment Canada’s Canadian Centre for Climate Modelling and Analysis (CCCma) third generation coupled global climate model (CGCM 3.1; Flato and Boer, 2001), the Australian Bureau of Meteorology’s Commonwealth Scientific and Industrial Research Organisation Mark 3.0 (CSIRO Mk3.0; Gordon and others, 2000) climate model, and the Model for Interdisciplinary Research on Climate version 3.2 medium resolution (MIROC 3.2-medres; Hasumi and Emori, 2004) for each of climate-change scenarios A1B, A2, and B1 (chap. 2) were downloaded from the bias corrected and downscaled WCRP CMIP3 climate projections archive (Maurer and others, 2007; Meehl and others, 2007). The GCMs and scenarios were selected on the basis of their ability to capture past climate patterns (Balshi and others, 2009a,b). Additionally, the range of variability among the projections generally bracketed the extremes of temperature and precipitation projections for the conterminous United States (Gonzalez and others, 2010). Seasonal summaries of the climate projections were generated for the 1991 through 2020 and 2031 through 2060 periods. These 30-year periods

are after the baseline period (2001–2008) and the last decade of the projections (2041–2050) used in this assessment. Differences in temperature and precipitation among the 1991 through 2020 and 2031 through 2060 periods for the different climate-change scenario and GCMs used in this assessment are shown in figure 4–1.

The downscaled climate data only provided monthly temperature and precipitation values, so a temporal disaggregation algorithm (Wood and others, 2002) was implemented to produce the daily values necessary for wildland fire simulations. This algorithm randomly rearranged year-long sequences of the baseline weather data for each future year and then adjusted the disaggregated daily values of temperature and precipitation so that the monthly means matched the values provided by the monthly climate forecasts. Using this methodology, three replicate weather sequences were generated for each GCM and climate-change scenario combination for a total of 27 simulation runs. The number of GCMs used and replicate runs was ultimately limited by computing power and processing times.

For the baseline and future climate change scenarios, additional processing steps were taken to produce the live and dead fuel moisture variables required for simulating wildland fire spread and behavior. First, the University of Montana mountain climate simulator (MT–CLIM) algorithms (Glassy and Running, 1994) were used to calculate relative humidity based on minimum and afternoon daily temperatures (Kimball and others, 1997). Once humidity was estimated, the National Fire Danger Rating System (NFDRS) algorithms were used to estimate daily values for live and dead fuel moistures, as well as wildland fire behavior indices, such as an energy release component (ERC; Deeming and others, 1977; Bradshaw and others, 1983; Burgan, 1988). The NFDRS algorithms required information about the beginning of spring (green, up) and fall (brown, down) to estimate live fuel moistures. To account for potential shifts in phenology, a technique was implemented that determined the dates of seasonal

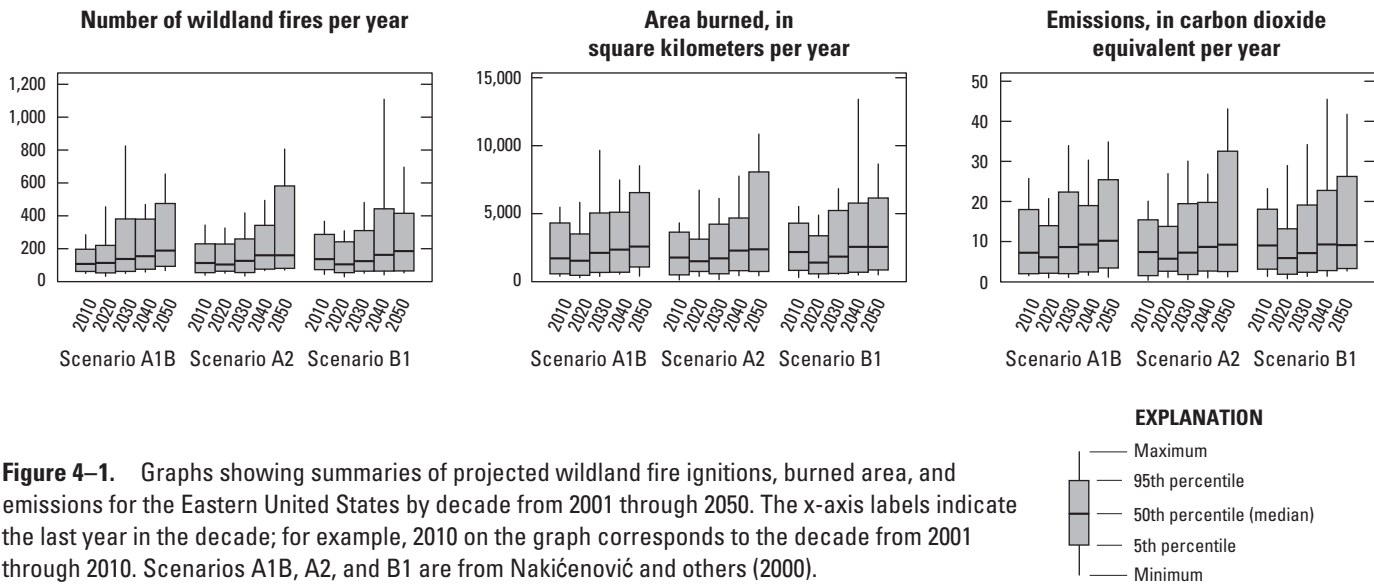


Figure 4–1. Graphs showing summaries of projected wildland fire ignitions, burned area, and emissions for the Eastern United States by decade from 2001 through 2050. The x-axis labels indicate the last year in the decade; for example, 2010 on the graph corresponds to the decade from 2001 through 2010. Scenarios A1B, A2, and B1 are from Nakićenović and others (2000).

changes based on green-up and brown-down dates using an index that incorporated the daily photoperiod, minimum temperature, and the vapor-pressure deficit (Jolly and others, 2005).

4.3.4. Baseline Wildland Fire Occurrence and Emissions

Baseline wildland fire emissions were calculated for each burned pixel in the MTBS database using FOFEM, which used fuel loads along with fuel moistures to estimate the amount of forest litter and downed deadwood that was consumed (Albini and Reinhardt, 1995, 1997; Albini and others, 1995). The consumption of duff (decaying forest litter), trees, plants, and shrubs was estimated as a function of the region, season, fuel moistures, and fuel loads. Canopy fuel consumption was estimated as a function of the burn severity provided by the MTBS data. The emissions of CO, CO₂, and CH₄ were then calculated based on the amount of fuel consumed, the organic-matter content of the fuel, and how efficiently it burned. The required input data for FOFEM included fuel loads, burn severity, and dead and live fuel moistures. To simplify the reporting of results, the emission estimates were summarized for all carbon-containing constituents to CO₂ equivalents using the following equation:

$$\text{CO}_2\text{-eq} = \text{CO}_2 + (2.33 \times \text{CO}) + (21 \times \text{CH}_4). \quad (4-1)$$

Fuel-load data provided an estimate of the amount of biomass that was available for consumption and were derived from the LANDFIRE Project's FLM data layer (Lutes and others, 2009). These fuel-load data were categorized by 1-, 10-, 100-, and 1,000-hour fuel classes for dead, decaying (duff and forest litter), and live (grass, shrubs, and tree canopy) biomass. In the FOFEM, the amount of tree canopy that was consumed was a direct function of burn-severity values from the MTBS data. The amounts of canopy foliage consumed in the high, moderate, and low burn-severity categories were assumed to be 100 percent, 60 percent, and 20 percent, respectively. Similarly, the consumption of the canopy's branch wood in the high, moderate, and low burn-severity categories was set at 50 percent, 30 percent, and 10 percent, respectively. These values were based on previously published estimates (Spracklen and others, 2009; Zhu and others, 2010) and on a comparison of FOFEM emissions with previously published results for selected wildland fires. The emissions were calculated for wildland fires between 2001 and 2008. Wildland fires before 2001 were excluded because the LANDFIRE fuels data were derived from Landsat imagery from about 2001.

After calculating emissions, summaries of the wildland fire data for each level II ecoregion and for the entirety of the Eastern United States were generated for the baseline period. These summaries include the minimum, mean, median, 95th percentile, and maximum values for number of fires per year, area burned per year, and emissions per year. The median and

95th percentile summary statistics were assumed to represent typical and extreme fire years, respectively.

4.3.5. Projected Future Wildland Fire Occurrence and Emissions

Past studies generally suggest that the area affected by large wildland fires and emissions from the fires was a function of ignition patterns and fire behavior, primarily spread; ignition patterns and fire behavior were largely influenced by weather conditions, fuels, and topography (Cary and others, 2009) and in some regions, ignitions were influenced by human activity (Cardille and others, 2001; Syphard and others, 2007). Projecting the potential changes in wildfire patterns, therefore, required an understanding and accurate characterization of the drivers that created the observed patterns of ignitions, spread, and emissions (Keane and others, 2003; Flannigan and others, 2009; Hessl, 2011). Accordingly, the wildland fire modeling approach used for this assessment incorporated three primary components: wildfire ignitions, spread, and effects. The parameters for the ignition and spread components were selected through a calibration process using the baseline observed data, which were used to simulate future potential wildfires.

4.3.5.1. Ignitions

General linear models (GLMs) with a binary response were constructed to predict daily ignition probabilities within each 0.125° weather grid cell. From the data described above, a suite of potential predictor variables was compiled that included daily weather statistics (minimum and maximum temperature and ERC), monthly weather summaries (temperature and precipitation), seasonal weather summaries (temperature and precipitation), and monthly and seasonal regional summaries of temperature and precipitation. Also included within the 0.125° weather grid cells as potential predictors in the GLM modeling were the proportions of land area classified as public or urban and existing vegetation type groups from the LANDFIRE database.

Most observations (grid cells with daily weather data) had no data on ignitions; therefore, a subsample was selected using a case-control sampling design. Any observation with precipitation greater than 0.25 centimeters (cm) was removed; this was done to ensure that ignition probabilities were zero on days with substantial precipitation that would limit fire spread. All observations with ignition data were retained along with a randomly selected set of observations without ignition data. The number of observations without ignition data was 10 times the number of observations with ignition data. The choice of design was somewhat arbitrary, but justified because the predictive performance of models using case-control sampling designs has been shown to increase with the ratio of cases to controls (Hastie and others, 2009). The intercept of the GLM was adjusted using equation 4-2 to account for unequal proportions of cases (ignitions) and controls

(non-ignitions) in the sample compared with the population (Preisler and others, 2004; Hastie and others, 2009).

$$\log \left(\frac{\text{non-ignitions}_{\text{sample}}}{\text{non-ignitions}_{\text{population}}} \right) - \log \left(\frac{\text{ignitions}_{\text{sample}}}{\text{ignitions}_{\text{population}}} \right) \quad (4-2)$$

To build the GLMs, an initial set of predictor variables was selected using forward stepwise regression, including only variables with *p*-values less than or equal to 0.05 and limiting the number of predictors to one-tenth the number of wildland fire observations. Each GLM was then evaluated and modified as needed to ensure that the selected predictor variables accurately described weather and climate conditions known to affect wildland fire occurrence in a given ecoregion. The overall performance of the final GLM was judged using the area under the curve (AUC) of a receiver-operator characteristic plot (Hanley and McNeil, 1982). The AUC measured the probability of correctly classifying a random pair of fire and nonfire observations; an AUC value of 0.5 indicated that the model predictions were equivalent to a random guess, and an AUC value of 1.0 indicated perfect predictions. AUC values greater than 0.8 were generally considered to be good.

4.3.5.2. Spread

During the simulations, the minimum travel time (MTT) algorithm (Finney, 2002) was used to simulate the spread of wildland fires after ignition. The MTT algorithm has been used extensively for local- and national-scale simulations of burn probability (Calkin and others, 2011; Finney and others, 2011). In addition to an ignition location, the MTT algorithm relied on fuels (surface and canopy), topography (elevation, slope, and aspect), weather (wind speed and direction), and live and dead fuel moisture data. The MTT algorithm also required a specified number of days and minutes per day that a wildland fire can spread. The outputs produced by the MTT algorithm included the arrival time (duration of the wildland fire since ignition) of every pixel representing burned area, as well as wildland fire-behavior metrics, such as fire line intensity and crown-fire activity.

4.3.5.3. Emissions

To calculate emissions, the FOFEM (Reinhardt and others, 1997; Reinhardt and Keane, 2009) was applied to each pixel burned by the simulated wildland fires using the same processing steps that were used for the baseline emissions.

4.3.5.4. Calibration

A number of calibration simulations were required to determine the appropriate number of days and minutes per day to allow wildland fires to spread using the MTT algorithm. The initial values for the minimum and maximum number of days to allow the spread and minutes of spread

per day were selected based on values derived from Federal fire records. Nine replicate simulations were run using the available weather data (1984–2008). After the simulations were complete, a two-sided *t*-test was used to determine if the annual average area burned during the simulations differed significantly from the annual average area burned based on observations from the MTBS database. If the differences were significant, the number of days of fire spread and the minutes of spread per day were altered and the calibration process was repeated until the *p*-value of the *t*-test was less than 0.05, indicating that the calibration simulations reproduced the baseline fire patterns.

4.3.5.5. Simulations of Future Fires

After calibration, future potential wildland fire ignitions, spread, and emissions were generated for three replicate simulations for each of the climate-change scenarios and GCMs, starting in 2001 and ending in 2050. The replicate simulations were run to help quantify uncertainty because of the stochastic nature of the models; more replicate simulations would have been ideal, but processing times limited the number of replicates to three. The simulated annual number of wildland fires, area burned, and emissions were summarized across the GCMs and replicates and were shown as the median and 95th percentile for each climate-change scenario for each decade, which represented typical and extreme fire years, respectively. The relative change between 2001–2010 and 2041–2050 were reported. Significance of each change was assessed at a 0.05-alpha (α) level using Monte Carlo permutation test with 1,000 permutations (Hesterberg and others, 2012).

4.3.6. Limitations and Uncertainties

The results generated for this assessment for baseline wildfire emissions differed and were generally lower than estimates of emissions from the peer-reviewed literature for the Eastern United States. The highest estimates of emissions from peer-reviewed literature were from Wiedinmyer and Neff (2007), who used the active fire product from the MODIS sensors from 2002 to 2006 and estimated the mean of annual emissions to be 71 TgCO₂-eq for Alabama, Connecticut, Delaware, Florida, Georgia, Illinois, Indiana, Kentucky, Louisiana, Maine, Maryland, Massachusetts, Michigan, Mississippi, New Hampshire, New Jersey, New York, North Carolina, Ohio, Pennsylvania, Rhode Island, South Carolina, Tennessee, Vermont, Virginia, West Virginia, and Wisconsin. The area used in Wiedinmyer and Neff (2007) is not the same as the area used for this analysis of the Eastern United States.

French and others (2011) calculated emissions using the MTBS data and Consume model (Ottmar and others, 2008) for wildland fires occurring from 2001 to 2008; the results are available as ecoregion-level summaries (Michigan Tech Research Institute, 2012). When the results from French and

others (2011) were summarized across the Eastern United States, the average and standard deviation of annual emissions were 20.5 TgCO₂-eq and 12 TgCO₂-eq, respectively. The emission estimates from these analyses were substantially greater than the estimates produced for this assessment. The differences among results are likely due to differences in methods, data, and the resolution of the data used. Wiedinmyer and Neff (2007) relied on 1-km-resolution active wildland fire data from MODIS and fuel data from the FCCS (U.S. Department of Agriculture, Forest Service, 2012a), which typically have higher fuel loads than the FLM data used for this assessment. They also assumed that all the available biomass could potentially burn, and that is often not the case, especially for woody fuels (Campbell and others, 2007; Meigs and others, 2009). French and others (2011) also used the 1-km-resolution FCCS fuels data and aggregated 1-km-resolution MTBS data. The fuel data in their report differed from the data layer used in this assessment in terms of information and resolution. The methods used in this assessment made use of fuel moistures, which are based on gridded daily weather data. The methods used by French and others (2011) also made use of fuel moistures, but recommended 10 percent levels for 1,000-hour availability and duff moistures, which are very favorable conditions for combustion. The full effects of the differences in fuel maps and moisture levels on the accuracy of fire modeling were difficult to assess, but these comparisons suggest that the results in this assessment are more conservative than previously published estimates of wildland fire emissions.

The MTBS data used in this assessment did not include small wildland fires, but they still captured the majority of the area burned because they included the largest wildland fires that contributed most to the amount of area burned (Strauss and others, 1989; Stocks and others, 2002). A comparison of the MTBS data with the Federal wildland fire-occurrence database (U.S. Department of Interior, 2012) showed that the MTBS listed only 3 percent of all wildland fires but accounted for 88 percent of the area burned in the Eastern United States. Therefore, the results of this assessment captured the general patterns and trends of wildland fires in the Eastern United States, but in all likelihood, underestimated wildland fire emissions.

In this assessment, the baseline and projected estimates of area burned and emissions also did not include the influence of prescribed and agricultural fires (for example, burning crop residues); however, the emissions produced by those types of fires were suspected to be low relative to the wildland fire emissions (Liu, 2004; van der Werf and others, 2010). The influence of prescribed fires on emissions was difficult to assess because the data characterizing prescribed fires were generally poor based on inconsistent reporting about them across the country. The existing estimates of emissions from prescribed fires suggested that they produced only 10 percent of the emissions from wildland fires (Liu, 2004), in part because prescribed fires usually burn under less extreme meteorological conditions than wildland fires. The influence of agricultural fires was also estimated to be about 10 percent of the wildland fire emissions in the GFED database.

In the Eastern United States, the relative amount of emissions produced by prescribed and agricultural fires is likely to be more substantial than in other parts of the United States, because agricultural fires are common in the region (Korontzi and others, 2006; Tulbure and others, 2011). Prescribed fires in the Eastern United States, especially those in the Southeast, accounted for 70 percent of the area burned by prescribed fires nationwide, and area burned by prescribed fires in the study area was more than 2.5 times the area burned by wildfires (based on 2002 to 2008 data from the National Interagency Fire Center, 2012). Unfortunately, records for many prescribed fires are not entered into national-level databases, so accurate data characterizing the individual locations of each prescribed fire are not available. In the MTBS database, the area burned by prescribed fires was only 18 percent of the total area burned in the Eastern United States. Because prescribed fires burn under less extreme meteorological conditions, severity and emissions are expected to be lower than wildfires (Liu, 2004; Outcalt and Wade, 2004; van der Werf and others, 2010). However, speculating about the locations of prescribed fires, the fuels they burn though, and the conditions under which they burn would likely introduce a greater amount of uncertainty into the emission estimates provided in this assessment. These uncertainties will remain difficult to resolve until better information is available on the timing and location of prescribed fires.

In spite of the uncertainties about the timing and location of prescribed fires in the Eastern United States, emission estimates have been included in the EPA's National Greenhouse Gas Emissions Inventory (U.S. Environmental Protection Agency, 2012) and can provide some indication of the impact of prescribed fires on emissions. The EPA methods for wildland and prescribed fire emissions focus on forests and apply emission factors to carbon stock-changes. The EPA estimates for 2005, 2007, and 2008 for wildfire emissions averaged 144.3 TgCO₂-eq/yr and for prescribed emissions averaged 20.3 TgCO₂-eq/yr for the conterminous United States. Assuming that 70 percent of prescribed fires occur in the Eastern United States (National Interagency Fire Center, 2012), then average annual emissions from prescribed fires would be 14.2 TgCO₂-eq/yr, a value substantially larger than the median wildfire emissions from the baseline period of this assessment (5.2 TgCO₂-eq/yr). However, the EPA's wildfire estimates for the continental United States (144.3 TgCO₂-eq/yr) are also substantially larger than those produced for this assessment, the Great Plains assessment (Zhu and others, 2011), and the Western assessment (Hawbaker and Zhu, 2012), which collectively had a median value of 56.0 TgCO₂-eq/yr and a maximum value of 101.4 TgCO₂-eq/yr.

Throughout the wildland fire simulations, vegetation and fuels remained static, which introduced some limitations into the assessment. Because of succession and disturbances (especially anthropogenic, such as LULC change), the composition and structure of vegetation may change substantially during the 50-year span used in this assessment (Foster and others, 1998; Gallant and others, 2004; Rhemtulla and others, 2009).

These changes could result in altered surface and canopy fuels that influence wildland fire behavior and emissions. By holding land use, vegetation, and fuels static, the interactions among wildland fire and LULC change were oversimplified, which are limitations that are shared by many broad-scale studies of projected climate change and wildland fires.

Vegetation dynamics have often been ignored in climate-change projections in part because of the difficulty of parameterizing the successional trajectories of each individual ecosystem type and the lack of information about how ecosystems may shift across the landscape under climate change. The influence that vegetation dynamics might have had on the results of this assessment is uncertain. In spite of the projected increases in wildland fire ignitions and area burned simulated for this assessment, the extent of the area burned each year was projected to be quite small relative to the extent of area that could potentially burn in an ecoregion. Thus, in the ecoregions included in this portion of the assessment, it is unlikely that the amount and arrangement of burnable vegetation on the landscape will limit wildland fires. Shifts in vegetation, however, might affect the type of vegetation and the amount of fuel available to burn; thus, past wildland fires and LULC change might alter the fuels, behavior, and emissions of future wildland fires (Bachelet and others, 2001, 2003).

Specifically, in the Eastern United States these processes could include the mesophication of forests in the mid-Atlantic throughout southern Appalachia that is reducing understory vegetation density and the flammability of litter fuels (Nowacki and Abrams, 2008). In the Southeastern USA Plains and the Mississippi Alluvial and Southeast USA Coastal Plains ecoregions, crown fire occurrence and wildland fire emissions could potentially increase with shifts in the acreage of short-rotation pine forests, with little fire management. Defoliation and mortality following insect outbreaks can affect substantial areas in the Eastern United States. The effects of insect outbreaks on carbon cycling in the Eastern United States could include short-term decreases in primary productivity and increases in respiration through altered decomposition rates (Hicke and others, 2012). However, the effects of insect disturbances on carbon cycling at ecoregional scales are not well understood, and models to predict where future outbreaks are likely are not currently available, thus the effects of insect disturbances were not incorporated into this assessment. These processes and vegetation dynamics into the ecosystem-disturbance model component should be considered for incorporation into future carbon assessments (Running, 2008; Goetz and others, 2012).

4.4. Results

Results for the baseline and future potential projections of wildland fire occurrence and emissions are presented using summary statistics of the median and 95th percentile values. These were assumed to represent typical and extreme fire years respectively.

4.4.1. Baseline Wildland Fires and Emissions

During the baseline period (2001–2008) in the Eastern United States, the number of wildland fires per year in a typical fire year was 112, but year-to-year variability was high, and as many as 186 wildfires occurred during extreme fire years (fig. 4–2; table 4–1). The area burned by wildfires in a typical fire year was 1,355 km², but was more than twice that in extreme fire years (4,092 km²). Annual emissions from wildfires were 5.2 teragrams of carbon dioxide equivalent (TgCO₂-eq) during typical fire years, but more than four times that amount in extreme fire years (17.3 TgCO₂-eq).

Combined, the Mixed Wood Shield and Mixed Wood Plains ecoregions had the least amount of fire activity among

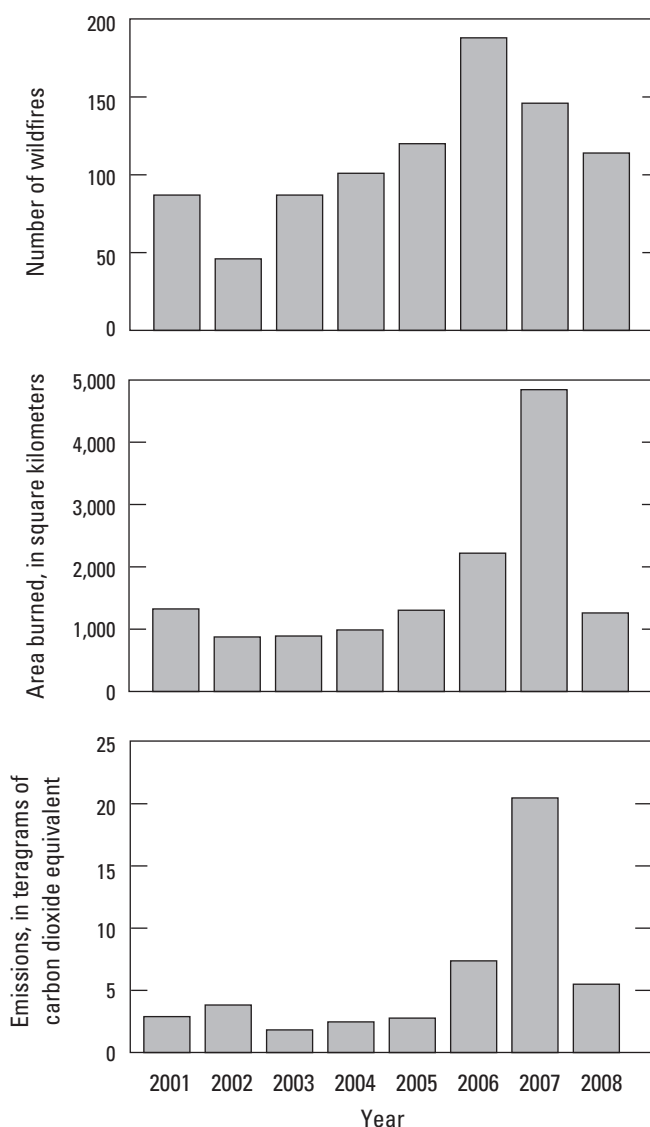


Figure 4–2. Graphs showing the annual number of wildland fires, area burned, and emissions for the baseline (2001–2008) period of the carbon flux and storage assessment of the Eastern United States.

Table 4-1. Summary statistics for the number of wildland fires, area burned, and emissions.

Metric	Mixed Wood Shield and Mixed Wood Plains	Southeastern USA Plains	Ozark, Ouachita-Appalachian Forests	Mississippi Alluvial and Southeast USA Coastal Plains ¹	Eastern United States
Number of wildfires per year					
Mean	9	17	37	58	121
Minimum	1	2	13	24	60
Median	9	10	41	49	112
95th percentile	17	49	54	97	186
Maximum	18	57	59	110	200
Area burned, in square kilometers per year					
Mean	173	137	311	1,225	1,851
Minimum	3	21	60	499	974
Median	81	52	382	746	1,355
95th percentile	497	417	462	3,164	4,092
Maximum	523	526	470	4,035	5,048
Emissions, in teragrams of carbon dioxide equivalent per year					
Mean	2.0	0.3	0.8	4.2	7.3
Minimum	0.0	0.0	0.2	0.6	2.9
Median	1.2	0.1	0.9	2.8	5.2
95th percentile	5.8	1.0	1.3	11.9	17.3
Maximum	6.0	1.3	1.3	15.6	22.3

¹Includes the Everglades and Texas-Louisiana Coastal Plain level II ecoregions for the analysis of this assessment.

the four ecoregions analyzed in the Eastern United States (fig. 4-3A; table 4-1). The median number of wildfires per year was 9, and the 95th percentile of wildfires per year was 17. Area burned during typical fire years was 81 km² and was as high as 497 km² in extreme fire years. Emissions were very low at 1.2 TgCO₂-eq/yr in a typical fire year. However, in spite of having the least amount of wildfires and area burned, emissions during extreme fire years were relatively high in this ecoregion at 5.8 TgCO₂-eq/yr.

In the Southeastern USA Plains ecoregion, the median values for wildfire occurrence, area burned, and emissions were 10 wildfires per year, 52 km²/yr, and 0.1 TgCO₂-eq/yr, respectively (fig. 4-3B; table 4-1). The number of wildfires, area burned, and emissions were much greater during extreme fire years at 49 wildfires per year, 417 km²/yr, and 1 TgCO₂-eq/yr, respectively.

Fire occurrence in the Ozark, Ouachita-Appalachian Forests ecoregion during typical fire years was greater than in the Southeastern USA Plains, Mixed Wood Shield, and Mixed Wood Plains ecoregions (fig. 4-3C; table 4-1). The number of wildfires, area burned, and emissions were 41 per year, 382 km²/yr, and 0.9 TgCO₂-eq/yr, respectively. Rates of wildfire occurrence and emissions were not substantially different during extreme fire years when the number of wildfires, area burned, and emissions were 54 per year, 462 km²/yr, and 1.3 TgCO₂-eq/yr, respectively.

Among the four ecoregions of the Eastern United States, the Mississippi Alluvial and Southeast USA Coastal Plains ecoregion had the greatest number of wildfires, area burned, and emissions (fig. 4-3D; table 4-1). During typical fire years, the number of wildfires, area burned, and emissions were 49 per year, 746 km²/yr, and 2.8 TgCO₂-eq/yr, respectively. During extreme fire years, there were nearly twice as many

wildfires (97 per year), with more than four times as much area burned (3,164 km²/yr) and emissions (11.9 TgCO₂-eq/yr).

4.4.2. Climate-Change Trends in the Eastern United States

In the Eastern United States, general warming trends were projected across all seasons and almost all GCMs between the 1991 through 2020 and 2031 through 2060 periods (fig. 4-4). As noted before, to compare results of baseline and future projection years, these intervals were used because they were centered over the adjusted baseline period (2001 through 2010, ± 10 years) and the last decade of the projections (2041 through 2050, ± 10 years). Temperatures were projected to increase by 1 to 2 degrees Celsius (°C) for all ecoregions and all seasons across the Eastern United States. Precipitation changes were more variable, but appeared to have a decreasing trend (drier) in the summer and fall. Patterns of winter and spring precipitation varied depending on the ecoregion and scenario, but tended toward increased moisture in the Northeast, Upper Great Lakes, and the Ozark and Appalachian Mountains and decreased in the Southeastern USA Plains and Mississippi Alluvial and Southeast USA Coastal Plain ecoregions (fig. 4-4). For temperature and precipitation, the spatial patterns of change were generally similar for a given GCM across scenarios, but appeared to be more variable across the GCMs than the scenarios.

In the Mixed Wood Shield ecoregion, average seasonal temperature change was projected to be 1.9 °C, 1.4 °C, 1.4 °C, and 1.2 °C for the winter, spring, summer, and fall seasons, respectively. Precipitation changes were more variable and depended on the specific scenario and GCM. In general,

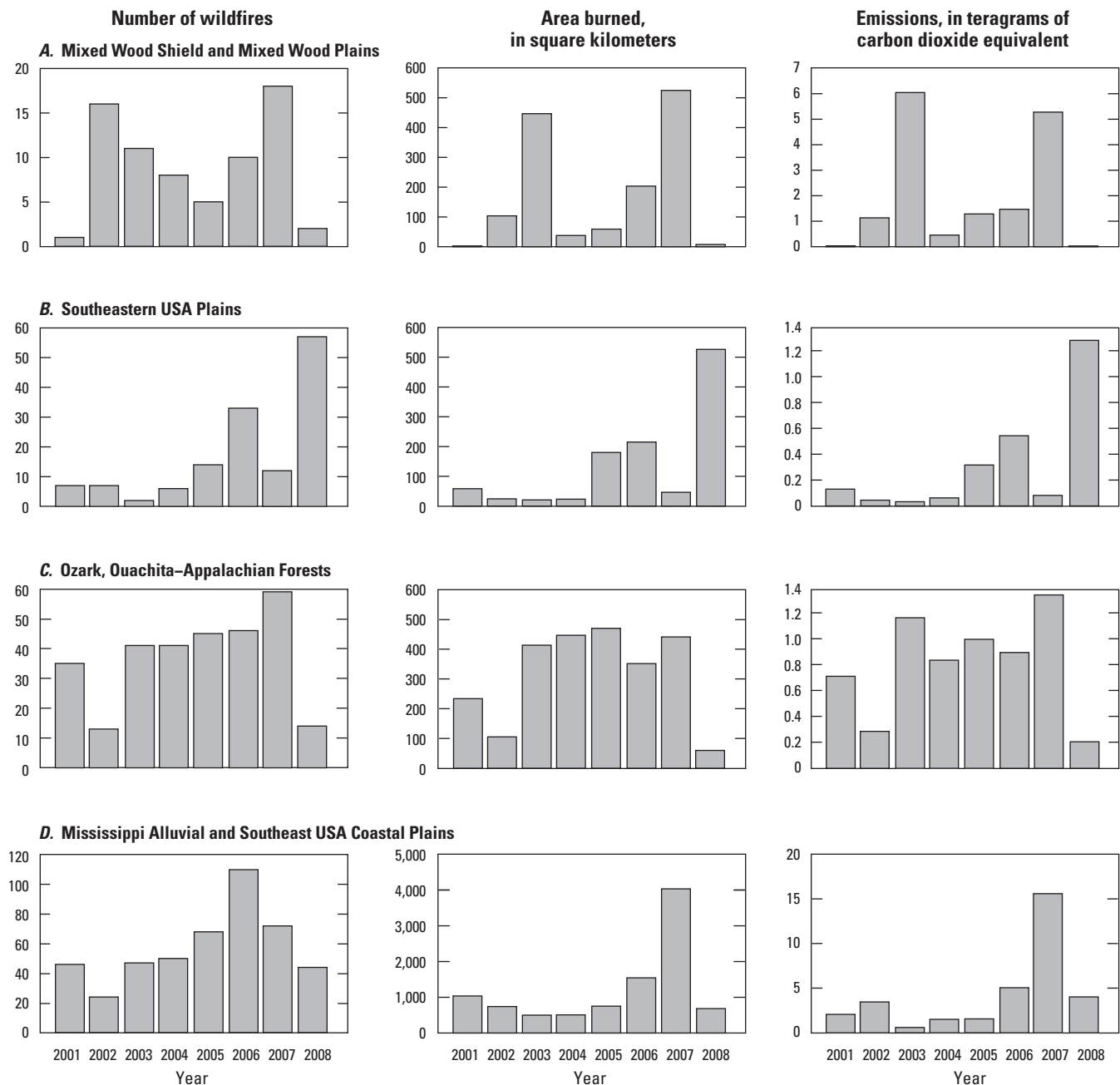


Figure 4–3. Graphs showing the annual number of wildland fires, area burned, and emissions for the baseline (2001–2008) period for the *A*, Mixed Wood Shield and Mixed Wood Plains, *B*, Southeastern USA Plains, *C*, Ozark, Ouachita–Appalachian Forests, and *D*, Mississippi Alluvial and Southeast USA Coastal Plains ecoregions (U.S. Environmental Protection Agency, 2013a) in the Eastern United States.

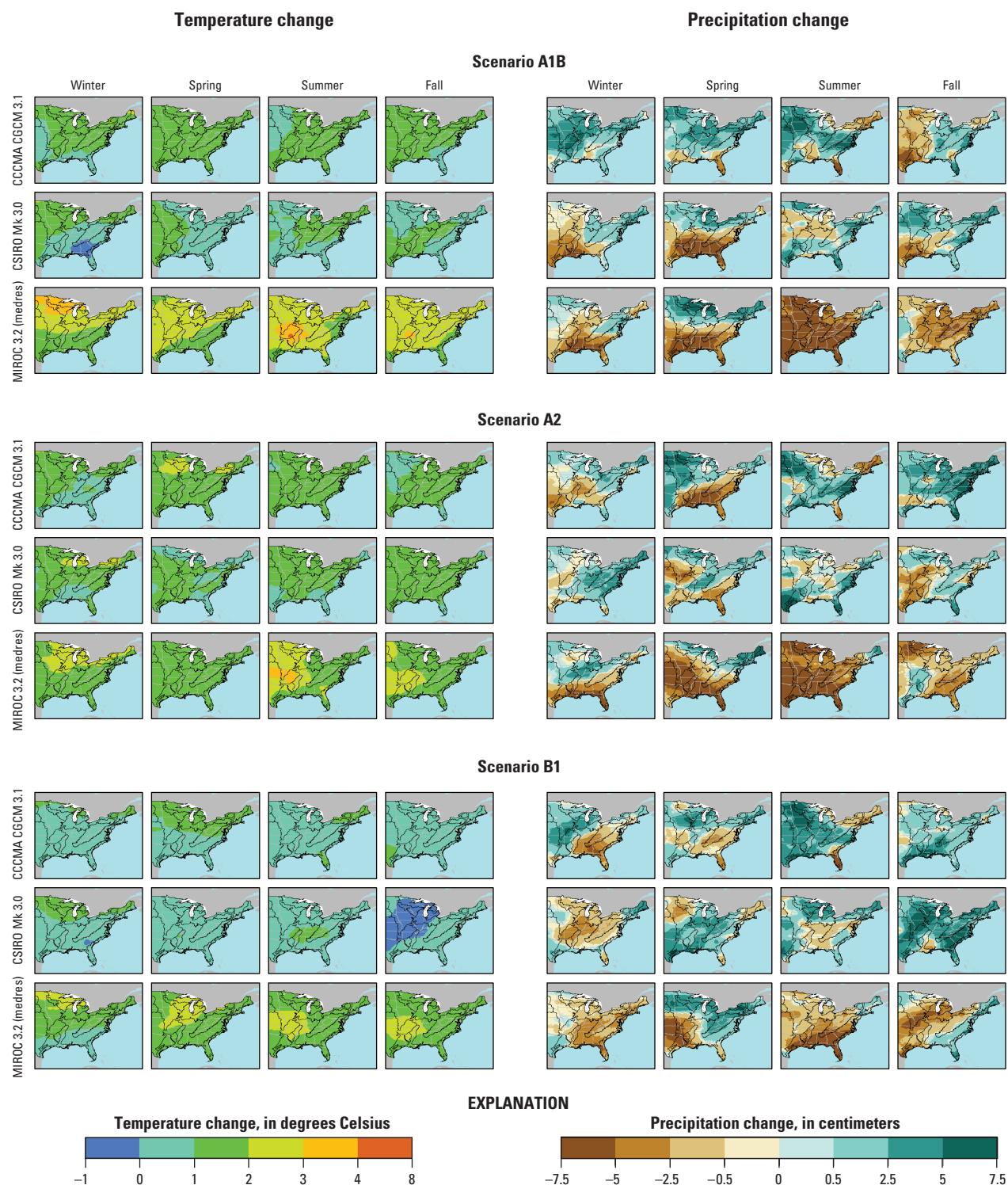


Figure 4–4. Maps showing the projected changes in mean daily temperature and total precipitation by season, calculated using the difference in mean values from 2031 through 2060 and from 1991 through 2021. Climate data are from Maurer and others (2007). Scenarios A1B, A2, and B1 are from Nakićenović and others (2000). CCCMA CGCM 3.1, Canadian Centre for Climate Modelling and Analysis third generation coupled global climate model; CSIRO Mk 3.0, Commonwealth Scientific and Industrial Research Organisation Mark 3.0; MIROC 3.2 (medres), Model for Interdisciplinary Research on Climate version 3.2 medium resolution.

winter and spring seasons were projected to have increases in precipitation of 0.5 cm and 2.4 cm, respectively. Precipitation decreased in the summer season by 0.5 cm, and fall precipitation changed little.

Warming trends were also projected by most scenarios and GCMs in the Southeastern USA Plains ecoregion. Average winter, spring, summer, and fall temperatures were 1 °C, 1.3 °C, 1.4 °C, and 1.3 °C, respectively, greater in the 2031 through 2050 period than they were in the 1991 through 2020 period. Winter and spring precipitation decreased by 1.1 cm and 1.9 cm, respectively. Summer and fall projections were more mixed depending on the GCM and scenario. Average summer precipitation decreased by 0.9 cm, but average fall precipitation increased slightly by 0.3 cm.

Similar to the Southeastern USA Plains ecoregion, temperature changes in the Ozark, Ouachita-Appalachian Forests ecoregion increased the least in winter (1.2 °C) and the most in spring (1.4 °C), summer (1.5 °C), and fall (1.3 °C). In all seasons, the GCMs and scenarios were evenly split with about how precipitation would change: about half of the simulations projected drier conditions, and half projected wetter conditions. When the precipitation change projections were averaged across GCMs and scenarios, winter precipitation decreased minimally by 0.04 cm, spring precipitation decreased by 0.5 cm, summer precipitation decreased by 0.9 cm, and fall precipitation increased slightly by 0.3 cm.

Projected changes in temperature for the Mississippi Alluvial and Southeast USA Coastal Plains ecoregion were the smallest among all ecoregions in the Eastern United States. Winter, spring, summer, and fall temperatures were projected to increase by 0.9 °C, 1.2 °C, 1.3 °C, and 1.2 °C, respectively, between the 1991 through 2020 and 2031 through 2050 periods. Precipitation changes were consistently drier in the winter and spring seasons (decreases of 1.4 cm and 2.5 cm, respectively) and to some extent in the summer season (decrease of 1.6 cm), but precipitation increased slightly in the fall season (0.6 cm).

4.4.3. Projected Future Wildland Fires and Emissions

GLMs were fit to each level III ecoregion and used to generate daily ignition probabilities in the simulations. In general, the model fits were good with the AUC values averaging 0.87 and ranging from 0.72 to 0.93. The best model fits were in the level III ecoregions within the Ozark, Ouachita-Appalachian Forests and the worst model fit was for the Southern Florida Coastal Plain level III ecoregion (reported with the Mississippi Alluvial and Southeast USA Coastal Plains ecoregion in this report). Most models included the energy release component (ERC) or 10- or 100-hour dead fuel moistures as a predictor as well as monthly and seasonal weather summaries (which captured seasonal and year-to-year variability). Most ecoregions also included at least one vegetation predictor. Developed land (which included

high- and low-density urban areas, golf courses, urban parks, and highways), public lands, and (or) area of wildland vegetation and agriculture were often included as predictors too. When included, developed land and agriculture had negative relationships with wildfire ignition probability, and public lands and wildland vegetation area had positive relationships with ignition probability.

Calibration simulations were run for each level III ecoregion to ensure that the patterns of wildland fire occurrence from 1984 through 2008 could be reproduced. For all the ecoregions, there was no significant difference in the average annual burned area between the calibration simulation and the observed values from the MTBS database, assuming that differences were not significant when a *p*-value of 0.05 or greater was calculated using a two-sided t-test that assumed unequal variance. After the calibration process, the simulated wildland fires were allowed to spread between 4 to 24 hours per day, and the burn durations ranged from 1 to 6 days, depending on the ecoregion.

For the entire Eastern United States and across all the climate-change scenarios, the projection simulations resulted in an increase in wildland fire ignitions, area burned, and emissions between the first (2001–2010) and last (2041–2050) decades (fig. 4–1; table 4–2). In typical fire years, the median number of ignitions was projected to increase, ranging from 36 percent under scenario B1 to 42 percent under scenario A2 and 75 percent under scenario A1B. The area burned was projected to increase, ranging from a 17 percent increase in scenario B1 to a 51 percent increase in scenario A1B. Wildland fire emissions followed similar patterns, with projected increases of 41 percent under scenario A1B, 25 percent under scenario A2, and 1 percent under scenario B1. However, the changes in median area burned and emissions were not statistically significant at a 0.05 α level under scenario B1. Characteristics of scenarios A1B, A2, and B1 are provided in chapter 2.

The simulated changes in ignitions, area burned, and emissions were significantly greater in extreme fire years (95th percentile); across the Eastern United States, ignitions were projected to increase by 45 to 153 percent, the area burned was projected to increase by 43 to 122 percent, and emissions were projected to increase by 41 to 111 percent (fig. 4–1; table 4–2). The rate of change was generally nonlinear, and the greatest increases in ignitions, area burned, and emissions were projected in 2021 to 2030 for scenario A1B, 2041 to 2050 in scenario A2, and 2031 to 2040 in scenario B1.

There was a large amount of variability in the projections of future potential wildfires, area burned, and emissions in the Mixed Wood Shield and Mixed Wood Plains ecoregions (fig. 4–5A; table 4–2) and not all the changes were statistically significantly different from zero. Ignitions increased by as much as 71 percent during typical fire years and as much as 43 percent during extreme fire years. Area burned and emissions did not necessarily increase even though ignitions did under all scenarios. During typical fire years, the change



- Maximum
- 95th percentile
- 50th percentile (median)
- 5th percentile
- Minimum

in the amount of area burned ranged as much as 234 percent in scenario A2, and in emissions, as much as 246 percent in scenario A2. The large amount of change is likely an artifact of the small amount of area burned and emissions during the baseline period (5 km² and 0.04 TgCO₂-eq, respectively), so that even small increases resulted in large relative change. The projected changes for ignitions, area burned, and emissions were less in extreme fire years than in typical fire years and were mostly not statistically significant. Ignitions increased by as much as 43 percent, area burned changed by as much as 65 percent, and emissions changed by as much as 26 percent, but only changes in ignitions under scenario A2 were statistically significant.

In the Southeastern USA Plains ecoregion, projected changes were only statistically significant for typical fire years under scenario A1B (fig. 4–5B; table 4–2), during which ignitions increased by as much as 40 percent, burned area increased by as much as 36 percent, and emissions increased by as much as 72 percent. Projected changes for the number of wildfires, area burned, and emissions were not statistically significant for scenario A1B for extreme fire years and for scenarios A2 and B1 for typical and extreme fire years.

The Ozark, Ouachita-Appalachian Forests ecoregion experienced the greatest amount of change in the Eastern United States in fire occurrence and emissions in typical and extreme fire years, and the all the projected changes were substantial (fig. 4–5C; table 4–2). The number of ignitions was projected to change by 56 to 123 percent in typical fire

years and 55 to 207 percent in extreme fire years. Projected changes in burned area were similar and increased by 66 to 133 percent in typical fire years and 49 to 197 percent in extreme fire years. Changes in emissions largely followed changes in burned area and increased by 64 to 132 percent in typical fire years and 48 to 209 percent in extreme fire years.

Projected changes in fire occurrence and emissions in the Mississippi Alluvial and Southeast USA Coastal Plains ecoregion generally increased (fig. 4–5D; table 4–2). Decreases were projected under some climate-change scenarios, but were not statistically significant. In typical fire years, the amounts of change ranged by as much as 30 percent for ignitions, 47 percent for area burned, and 36 percent for emissions. The decreases occurred under scenario B1, and increases were projected for scenarios A1B and A2. In extreme fire years, fire occurrence and emissions increased under all scenarios. Changes ranged by as much as 51 percent for ignitions, 55 percent for area burned, and 67 percent for emissions.

4.4.4. Summary of Wildland Fire Occurrence and Emissions of Carbon Fluxes

From 2001 through 2008, wildland fire activity in the Eastern United States was less substantial than other regions of the United States. Large wildland fires numbered between 60 and 200 per year and burned 974 to 5,048 km² each year. These wildland fires in the Eastern United States

Table 4–2. Relative projected changes in the 50th and 95th percentiles for wildfire ignitions, area burned, and emissions between 2001–2010 and 2041–2050.

Scenario	Metric	Mixed Wood Shield and Mixed Wood Plains	Southeastern USA Plains	Ozark, Ouachita-Appalachian Forests	Mississippi Alluvial and Southeast USA Coastal Plains ¹	Eastern United States
Percentage of number of wildfires per year						
A1B	Median	50*	40*	123*	26*	75*
A2	Median	71*	18	64*	30*	42*
B1	Median	20	8	56*	12	36*
A1B	95th percentile	5	15	198*	41*	141*
A2	95th percentile	43*	28	207*	51*	153*
B1	95th percentile	16	42	55*	25*	45*
Percentage of area burned per year						
A1B	Median	–10	36*	133*	47*	51*
A2	Median	234*	27	66*	12	34*
B1	Median	79	–4	70*	–2	17
A1B	95th percentile	–2	–16	162*	19	52*
A2	95th percentile	65*	–9	197*	55*	122*
B1	95th percentile	1	–5	49*	22	43*
Percentage of emissions per year						
A1B	Median	9	72*	132*	36*	41*
A2	Median	246*	20	64*	9	25*
B1	Median	127	2	70*	–17	1
A1B	95th percentile	–16	–8	209*	10	41*
A2	95th percentile	26	5	164*	67*	111*
B1	95th percentile	20	–12	48*	12	45*

¹Includes the Everglades and Texas-Louisiana Coastal Plain level II ecoregions for the analysis of this assessment.

*Change was significant at 0.05 alpha levels in permutation tests.

represented 23 percent of all wildland fires that occurred in the conterminous United States from 2001 through 2008 and are mapped in the MTBS database and accounted for 10 percent of all the area burned. The median of annual emissions was 5.2 TgCO₂-eq/yr, which was equivalent to 0.48 percent of NEP (chap. 5). The interannual variability in emissions was high and ranged from 2.9 to 22.3 TgCO₂-eq in the Eastern United States, which was equivalent to 0.27 to 2.05 percent of NEP. In 2010, the median of annual wildfire emissions was 5,594 TgCO₂-eq/yr, equivalent to 0.09 percent of nationwide fossil-fuel emissions (U.S. Environmental Protection Agency, 2012); minimum wildfire emissions were 0.13 percent and maximum wildfire emissions were 0.40 percent of the nationwide fossil-fuel emissions. The relative contribution of wildland fires of the Eastern United States to nationwide greenhouse-gas emissions was small when compared that of other regions of the United States (Zhu and others, 2010; Hawbaker and Zhu, 2012) and to the contribution of fossil-fuel emissions.

Wildland fire ignitions and area burned were projected to increase across all the climate-change scenarios for the Eastern United States as a whole, and the changes were larger for extreme fire years than for typical fire years. The annual amount of area burned by wildfires in the Eastern United States was projected to increase by as much as 51 percent from 1,355 km² in typical fire years and as much as 122 percent from 4,092 km² in extreme fire years. The projected changes in burned area resulted in similar changes in emissions, which increased by as much as 41 percent from 5.2 TgCO₂-eq in typical fire years and between 41 and 111 percent from 17.3 TgCO₂-eq in extreme fire years. These changes were driven by the influence of climate change on live and dead fuel moisture levels, which in turn had a large influence on ignition probabilities, fire spread, fuel consumption, and emissions.

The magnitude and direction of change of the wildfire projections varied among ecoregions and climate-change scenarios. The only ecoregion that had consistent increases in the number of wildfires, area burned, and emissions across

all climate-change scenarios was the Ozark, Ouachita-Appalachian Forests ecoregion. The Mixed Wood Shield and Mixed Wood Plains ecoregions projected increases in ignitions under all scenarios and increases in area burned and emissions under scenarios A2 and B1, but not for scenario A1B where precipitation projections suggested a wetter climate. The Southeastern USA Plains ecoregion had mixed results, with typical fire years experiencing mostly increases in ignitions, area burned, and emissions, but with extreme fire years experiencing decreases in area burned and emissions. The Mississippi Alluvial and Southeast USA Coastal Plains ecoregion experienced increases in fire occurrence and emissions under scenarios A1B and A2, but not under scenario B1.

In this study area, wildfire emissions were relatively low compared with carbon sequestered in terrestrial ecosystems (chap. 5), but this does not necessarily mean that wildfires do not have important effects on carbon balance in the Eastern United States. Instead, the largest effects of wildfires on carbon balance in the Eastern United States might be localized to specific ecosystems that currently have high carbon storage, but are at risk of losing carbon because of increased fire activities or altered fire behavior. These ecosystems may include pocosin wetlands with deep peat deposits along the Atlantic coast (Messina and Conner, 1998), southern boreal forests also with deep peat deposits and high fuel loads in the Upper Great Lakes (Heinselman, 1973), pine barrens in the Upper Great Lakes and New Jersey (Forman, 1998; Radeloff and others, 2000), and pine forests in the Southeastern USA Coastal Plains (Christensen, 1999). Management efforts designed to maintain or increase carbon storage in these ecosystems may be challenged by the potential carbon losses due to the projected climate-driven increases in wildland fire activities. In other ecosystems in the Eastern United States, wildfire plays a smaller role in carbon cycling, and other natural disturbances may be more important, for example, wind throw (Canham and Loucks, 1984; Frelich and Lorimer, 1991) and anthropogenic LULC change (chap. 3).

