Projected Future Wildland Fires and Emissions for the Western United States

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Chapter 8 of

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

Edited by Zhiliang Zhu and Bradley C. Reed

Professional Paper 1797

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
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U.S. Geological Survey
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U.S. Geological Survey, Reston, Virginia: 2012

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Suggested citation:
Hawbaker, T.J., and Zhu, Zhiliang, 2012, Projected future wildland fires and emissions for the Western United States, chap. 8 *of* Zhu, Zhiliang, and Reed, B.C. eds., Baseline and projected future carbon storage and greenhouse-gas fluxes in ecosystems of the Western United States: U.S. Geological Survey Professional Paper 1797, 12 p. (Also available at http://pubs.usgs/gov/pp/1797.)

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Chapter 8. Projected Future Wildland Fires and Emissions for the Western United States

By Todd J. Hawbaker[1] and Zhiliang Zhu[2]

8.1. Highlights

- Wildland-fire occurrence and greenhouse-gas emissions increased in the Western United States under all of the climate-change scenarios considered in this assessment.
- The projected median amount of area burned annually from 2041 to 2050 was 31 to 66 percent greater than the median amount of area burned annually during the baseline years from 2001 to 2008 (12,136 km^2, reported in chapter 3). The median annual emissions were projected to increase 28 to 56 percent from the baseline median annual emissions, which were approximately 41.0 $TgCO_{2\text{-eq}}$/yr (11.2 TgC/yr) (reported in chapter 3).
- Extreme fire years are projected to become more extreme. The 95th percentile of the amount of area burned annually was projected to increase 79 to 95 percent from the baseline conditions of 2001 to 2008 (23,261 km^2, reported in chapter 3), and the 95th percentile of annual wildland-fire emissions was projected to increase 73 to 150 percent from the baseline 95th percentile estimate, which was approximately 65.0 $TgCO_{2\text{-eq}}$ (17.7 TgC/yr) (reported in chapter 3).

8.2. Introduction

An assessment of the area burned by, the severity of, and the emissions from wildland fires during the baseline period (2001 to 2008) for the Western United States is presented in chapter 3 of this report; this chapter focuses on the projected future extent and severity of, and emissions from wildland fires for the period 2041 to 2050. Modeling of future wildland-fire characteristics required input from the baseline wildland-fire assessment (chapter 3) and projected future climate changes (chapter 7). The wildland-fire projections described in this chapter were provided as input into the modeling of projected future terrestrial carbon storage and greenhouse-gas fluxes described in chapter 9. The relations between this chapter and others are depicted in figure 1.2 of chapter 1 of this report.

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, severity, and frequency. 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 ignitions. The effects of climate change on wildland-fires in the Western 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).

Potential shifts in weather patterns and wildland-fire behavior, as indicated by variables such as the Keetch-Byram Drought Index (Y. Liu and others, 2010), the seasonal severity rating computed by Flannigan and others (2000), and an energy-release component (ERC) (T.J. Brown and others, 2004), are influenced by climate change and could increase the duration of the wildland-fire season and the severity of conditions under which fires may burn. Climate-driven changes in ignition patterns are not as well understood, but lightning ignitions were projected to increase as much as 44 percent across the United States under a scenario where the atmospheric carbon-dioxide concentration was doubled (Price and Rind, 1994). Regional changes may be greater; for

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instance, Westerling and Bryant (2008) examined wildland-fire risk (the probability of a >200-hectare (ha) fire) in California, Nevada, and parts of neighboring States. They compared the observed risk from 1961 to 1990 with the projected risk for 2070 to 2099 using a logistic regression under the A2 and B1 climate-change scenarios (Nakicenovic and others, 2000) with data from the Geophysical Fluid Dynamics Laboratory (GFDL; Delworth and others, 2006) model and the Parallel Climate Model (PCM; Washington and others, 2000) general circulation models (GCMs). The results indicated a projected increase in wildland-fire risk that ranged from 12 to 40 percent for the entire region and ranged from 15 to 90 percent for California alone; the results also indicated that there was substantial spatial variability among the GCMs and scenarios where the changes in risk occurred.

Projections of the extent of the burned area under climate-change scenarios have been made using climate data, sometimes with derived wildland-fire-behavior indices, at national and regional scales. The aforementioned Price and Rind (1994) study of climate change and fires ignited by lightning also suggested that a 44 percent increase in lightning ignitions may result in a 78 percent increase in the extent of the burned area across the conterminous United States. Bachelet and others (2003) suggested a 4 to 31 percent increase in the extent of the burned area by 2100, and Lenihan and others (2008) suggested a 9 to 15 percent increase in the extent of the burned area by 2100 on the basis of simulations made with the MC1 Dynamic General Vegetation Model (DGVM) model (Bachelet and others, 2001) under various climate-change scenarios for the conterminous United States. Multiple regional analyses also suggested that the extent of the burned area is likely to increase under the climate-change scenarios. Littell and others (2010) projected the annual area burned within ecosections defined by Bailey (1995) in Washington State under the A1B climate-change scenario and data from the Third Generation Coupled Global Climate Model of the Canadian Centre for Climate Modelling and Analysis (CCCma CGCM3.1; Flato and Boer, 2001) and the Hadley Centre for Climate Prediction and Research Couple Model 3 (HadCM3; Gordon and others, 2000); their results suggested that the annual extent of area burned may more than double by the 2040s and triple by the 2080s. Interannual variability also increased and the probability of having an extreme fire year (defined as a year in which the area burned is greater than the 95th percentile of the long-term distribution of total areas burned) increased from 0.05 to 0.48 by the 2080s. A study by Rogers and others (2011) yielded similar results for area burned and also demonstrated that burn severity was projected to increase in the Pacific Northwest. Litschert and others (2012) used an approach that was similar to Littell and others (2010) in the Southern Rocky Mountains and fit models to project the percent of area burned each year under the A2 and B1 climate-change scenarios using data from the HadCM3 model and the Max Planck Institute for Meteorology's European Centre for Medium-Range Weather Forecasts—Hamburg 5 (ECHAM5; Roeckner and others, 2003) model; their projections suggested that the median annual area burned may increase up to 500 percent between 1970 and 2006 and between 2010 and 2070. These studies demonstrated that the extent of the area affected by wildland fires in the Western United States was projected to increase under a range of climate-change scenarios and GCMs; however, the studies do not provide the necessary information to estimate changes in wildland-fire emissions.

Few studies have addressed how wildland-fire emissions might change with the projected increases in the extent of burned areas under climate-change scenarios for the conterminous United States, but there has been an extensive amount of work completed for boreal regions (Flannigan and others, 2005; Balshi, McGuire, Duffy, Flanigan, Kicklighter, and Melillo, 2009). Most of the existing estimates demonstrated that emissions usually changed in proportion to the amount of area burned (Spracklen and others, 2009), unless disturbances or climate change caused substantial shifts in vegetation. For instance, work by Spracklen and others (2009) used climate-change projections from the Goddard Institute for Space Studies (GISS; Russell and others, 2000) GCM under a scenario in which the concentration of carbon dioxide was doubled ($2 \times CO^2$); the simulation indicated a projected increase in mean annual area burned of 50 percent and a projected near doubling of carbonaceous aerosol emissions by 2050 across the Western United States, with the majority of the change projected to occur in the Pacific Northwest and Rocky Mountain regions. An earlier study by Bachelet and others (2004) used the MC1 DGVM model (Bachelet and others, 2001) to simulate past (1905–1995) and future (1996–2100) carbon stocks and fluxes with climate data from the HadCM2Sul (Johns and others 1997) and the CCCma CGCM1 (Flato and others, 2000) models; their results showed that biomass consumed by wildland fires steadily increased from 110 teragrams of carbon per year (TgC/yr) to 180 TgC/yr in the Western United States (specifically, Arizona, California, western Colorado, western New Mexico, Nevada, western Texas, and Utah) and from 100 TgC/yr to 160 TgC/yr in the Northwestern United States (specifically, Oregon, Washington, Idaho, and western Montana). A more recent study by Lenihan and others (2008) using the MC1 DVGM model suggested that carbon stocks in the Western United States are projected to remain stable, largely because projected increases in primary productivity would result in the storage of additional carbon, which would outweigh the carbon losses from the projected increase in wildland fires.

In spite of the large amount of research linking wildland fires to climate change, there is no existing framework that fully incorporates the mechanisms through which climate change will influence wildland-fire occurrence, behavior, and effects (Flannigan and others, 2009; Hessl, 2011); therefore, a model was developed for this assessment to simulate the influence of climate change on patterns of wildland-fire ignitions, spread, and emissions. This simulation model was calibrated using historical fire, weather, and climate data and then used to generate projections under the climate-change scenarios. The simulations were designed to address the following questions: (1) What are the potential changes in wildland-fire occurrence and emissions for the Western United States under climate change? (2) How do the potential changes vary among ecoregions and climate-change scenarios? This chapter focuses primarily on the results of the wildland-fire simulations, although wildland-fire scars for both the baseline and projection periods were also used in the analysis of projected future carbon storage and greenhouse-gas fluxes of terrestrial ecosystems (chapter 9).

8.3. Input Data and Methods

The studies described above generally indicated that the area affected by large wildland fires and their emissions was a function of both ignition patterns and fire behavior, primarily spread; both 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 wildland-fire patterns, therefore, required an understanding and accurate characterization of the drivers that created the observed, past 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: wildland-fire ignitions, spread, and effects (fig. 8.1). The parameters for the ignition and spread components were selected through a calibration process using the baseline observed data and then used to simulate future potential wildfires. The datasets and methods used by the various wildland-fire modeling components are described in the following sections.

The wildland-fire models were applied to each level III ecoregion in the Western United States. Some ecoregions that had similar fire regimes and were adjacent to each other were grouped to improve the data-processing efficiency. The following level III ecoregions were grouped together to form one region each: (1) the Cascades, North Cascades, and East Cascades—Slope and Foothills; (2) the Northern Rockies and Canadian Rockies; and (3) the Southern and Central California Chaparral and Oak Woodlands and the Southern California Mountains. In a few other level III ecoregions (the Puget Lowland, Willamette Valley, and Central California Valley), there were too few wildland fires to analyze.

After simulations were completed for the level III ecoregions, the results were aggregated to each level II ecoregion and to the entire Western United States for reporting. The simulated number of wildland fires, area burned, and emissions were summarized by climate-change scenario for each decade as the 50th and 95th percentiles, which represented typical and extreme fire years, respectively. Additionally, the relative change between the baseline decade (2001–2010) and the future decade (2041–2050) is reported.

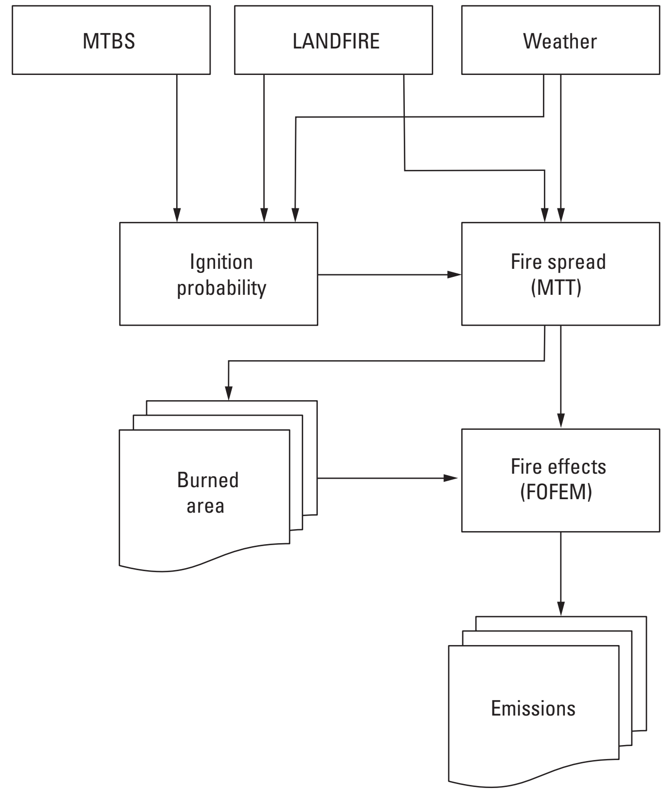

Figure 8.1. Flowchart showing the components of the disturbance model, which was used for generating projections of future potential wildland-fire ignitions, burned area, and emissions. FOFEM, First Order Fire Effects Model; LANDFIRE, Landscape Fire and Resource Management Planning Tools project; MTBS, Monitoring Trends in Burn Severity project; MTT, minimum travel time.

8.3.1. Wildland-Fire Data

The locations of wildland-fire scars were taken from the Monitoring Trends in Burn Severity data (MTBS; Eidenshink and others, 2007) 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 that were greater than 404 ha (1,000 acres) and 202 ha (500 acres) in the Western and Eastern United States, respectively. 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). 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 pre- and post-fire Landsat scenes. 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 (T.J. Brown and others, 2002), which would require laborious error checking before use.

8.3.2. Weather and Climate Data

The assessment methodology required daily weather data, including temperature, precipitation, relative humidity, and wind speeds, for both the baseline and future time periods. For the baseline time period, gridded daily weather data for the conterminous United States with 1/8° spatial resolution (approximately 12 km) were used (Maurer and others, 2002). These data, which span the period from 1950 to 2010, were interpolated from weather stations and included the minimum and maximum daily temperature and daily precipitation. The data on afternoon wind speed and direction from the 1/3° (approximately 32 km) North American Regional Reanalysis (Mesinger and others, 2006) were joined to the 1/8° 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's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multimodel dataset were used. The CMIP3 data were corrected for bias and spatially downscaled to match the 1/8°-resolution baseline weather data (Maurer and others, 2007). For this analysis, the downscaled data from the CCCma CGCM 3.1 (Flato and Boer, 2001), Australia's Commonwealth Scientific and Industrial Research Organisation Mark 3.0 (CSIRO–Mk3.0; Gordon and others, 2002) 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 the A1B, A2, and B1 climate-change scenarios were downloaded from the Bias Corrected and Downscaled WCRP CMIP3 Climate Projections archive (Maurer and others, 2007; Lawrence Livermore National Laboratory, 2012). The GCMs and scenarios were selected on the basis of their ability to capture past climate patterns (Balshi, McGuire, Duffy, Flanigan, Walsh, and Melillo, 2009). Additionally, the range of variability among the projections generally bracketed the extremes of temperature and precipitation projections for the conterminous United States (Gonzalez, Neilson, and others, 2010). Climate-change summaries for temperature and precipitation are provided in chapter 7 of this report.

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 their monthly means matched the values provided by the monthly climate forecasts. Using this methodology, 3 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 somewhat arbitrary but limited by computing power and processing times.

For both 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 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 the energy release component (ERC) (Deeming and others, 1977; Bradshaw and others, 1983; Burgan, 1988). The NFDRS algorithms required information about the beginning of both spring ("green-up") and fall ("brown-down") to estimate live fuel moistures. To generate green-up and brown-down dates, a methodology was implemented that determined the dates of seasonal changes based on the daily photoperiod, minimum temperature, and the vapor-pressure deficit (Jolly and others, 2005).

8.3.3. Fuels and Topography

In addition to daily weather sequences, the methodology relied on the LANDFIRE vegetation, fuels, and topography data (Rollins, 2009). 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 LANDFIRE fuel-loading model data layer (FLM; Lutes and others, 2009) was also used. Vegetation and fuels were held static throughout the simulations and were not altered by simulated disturbances and other types of land-use and land-cover (LULC) change. All raster data were aggregated to 250-m resolution in order to improve the processing efficiency using a nearest-neighbor rule. 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.

8.3.4. Model Components

8.3.4.1. Ignitions

General linear models (GLMs) with a binary response were constructed to predict daily ignition probabilities within each 1/8° 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 energy release component), monthly weather summaries (temperature and precipitation), seasonal weather summaries (temperature and precipitation), as well as regional summaries of temperature and precipitation, both at monthly and seasonal time steps. Also included within the 1/8° weather grid cells as potential predictors in the GLM modeling were the proportions of land area classified as public or urban, as well as 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 cm was removed. 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 1 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).

$$\log\left(\frac{\textit{non-ignitions}_{sample}}{\textit{non-ignitions}_{population}}\right) - \log\left(\frac{\textit{ignitions}_{sample}}{\textit{ignitions}_{population}}\right) \quad (1)$$

To build the GLMs, an initial set of predictor variables was selected using forward stepwise regression, including only variables with p-values ≤ 0.05 and limiting the number of predictors to 1/10 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 non-fire 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 above 0.8 were generally considered to be good.

8.3.4.2. Spread

During the simulations, the 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 moistures 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 fireline intensity and crown-fire activity.

8.3.4.3. Emissions

To calculate emissions, the First Order Fire Effects Model (FOFEM; Reinhardt and others, 1997; Reinhardt and Keane, 2009) was applied to each pixel that indicated burned area in the simulated wildland fires. The FOFEM used fuel loads along with fuel moistures to estimate the amount of forest litter and downed deadwood that was consumed (Albini and others, 1995; Albini and Reinhardt, 1995, 1997). 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. The emissions of carbon monoxide (CO), carbon dioxide (CO_2), and methane (CH_4) were then calculated on the basis of the amount of fuel consumed, the organic content of the fuel, and how efficiently it burned.

The FOFEM also required estimates about the proportion of the tree canopy affected by crown fires. In the simulated wildland fires, burn severity estimates were used to quantify the proportion of canopy fuels consumed; the burn-severity categories (low, medium, and high) were assigned randomly on the basis of their observed frequencies in LANDFIRE's existing vegetation groups. When calculating emissions with the FOFEM, 20-, 60-, and 100-percent canopy consumption was assumed for low, moderate, and high burn severity, respectively, on the basis of published literature (Spracklen and others, 2009; Zhu and others, 2010).

To simplify the reporting of results, the emission estimates were summarized for all carbon-containing constituents to carbon dioxide equivalent ($CO_{2\text{-eq}}$) using equation 2.

$$CO_{2-eq} = CO_2 + (2.33 \times CO) + (21.0 \times CH_4) \quad (2)$$

8.3.4.4. 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 on the basis of values derived from Federal fire records. Nine replicate simulations were run using the baseline weather data (1984–2008). After the simulations were complete, a 2-sided t-test was used to determine if there was a significant difference in the annual average area burned between the simulated fires and observed fires in the MTBS data. 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.

8.3.4.5. 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 results of each simulation were summarized in terms of area burned and amount of carbon emissions per year.

8.4. Results

General linear models were fit to each level III ecoregion and used to generate daily ignition probabilities in the simulations. In general, the model fits were quite good with the AUC values averaging 0.90 and ranging from 0.80 to 0.93. The best model fits were in the level III ecoregions within the Cold Deserts and the worst model fit was for the Mediterranean California ecoregion. Most models included the ERC as a predictor (which captured day-to-day variability in fuel moistures) and 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) typically was not included, except in the Wyoming Basin and Mediterranean California ecoregions.

Calibration simulations were run for each level III ecoregion to ensure that the patterns of wildland-fire occurrence from 1984 to 2008 could be reproduced. For all of 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 2-sided t-test that assumed unequal variance. After the calibration process, the simulated wildland fires were allowed to spread 240 minutes/day, and the burn durations ranged from 1 to 21 days, depending on the ecoregion.

Across all of the climate-change scenarios, the simulations resulted in a projected increase in wildland-fire ignitions, area burned, and emissions between the first and last decades (2001–2010 and 2041–2050; fig. 8.2 and table 8.1). In typical years (50th percentile), the number of ignitions was projected to increase 39 to 70 percent. The greatest projected increases in ignitions were observed under the A2 (70 percent) and A1B (58 percent) scenarios and the smallest projected increase was observed under the B1 (39 percent) scenario. The area burned was projected to increase, ranging from a 31 percent increase in the B1 scenario to a 66 percent increase in each of the A1B and A2 scenarios. Wildland-fire emissions followed similar patterns, with projected increases of 56 percent, 54 percent, and 28 percent under the A1B, A2, and B1 scenarios, respectively. The simulated changes in ignitions, area burned, and emissions were greater in extreme fire years (95th percentiles), and across the Western United States, ignitions were projected to increase between 62 and 74 percent, area burned was projected to increase between 79 and 95 percent, and emissions were projected to increase between 73 and 150 percent (fig. 8.2 and table 8.1). The rate of change was generally nonlinear and the greatest increases in ignitions, area burned, and emissions were projected to occur in from 2031 to 2040 and from 2041 to 2050.

Projected increases in ignitions, area burned, and emissions were simulated for all three climate-change scenarios in the Western Cordillera ecoregion (fig. 8.3 and table 8.2). The number of ignitions per year was projected to increase between 21 and 38 percent in typical fire years, and between 39 and 99 percent in extreme fire years. The changes in the extent of area burned were more variable but generally were projected to increase in typical fire years under the A1B (34 percent) and A2 (55 percent) scenarios, but decrease slightly under the B1 (−5 percent) scenario. The extent of the area burned in extreme years was projected to change at much greater rates than typical fire years, up to 167 percent under the A2 scenario. Emissions were projected to increase in both typical (15–64 percent) and extreme (28–188 percent) fire years. The projected increases were greatest for the A2

Table 8.1. Projected relative change (increases) in the 50th and 95th percentiles for wildland-fire ignitions, area burned, and emissions between the first and last decades (2001–2010 and 2041–2050), by climate-change scenario, for the Western United States.

[Climate-change scenarios are from the Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (Nakicenovic and others, 2000)]

Climate-change scenario	Percentile	Relative change (percent)		
		Ignitions	Area burned	Emissions
A1B	50th	58	66	56
	95th	74	95	73
A2	50th	70	66	54
	95th	62	84	150
B1	50th	39	31	28
	95th	73	79	118

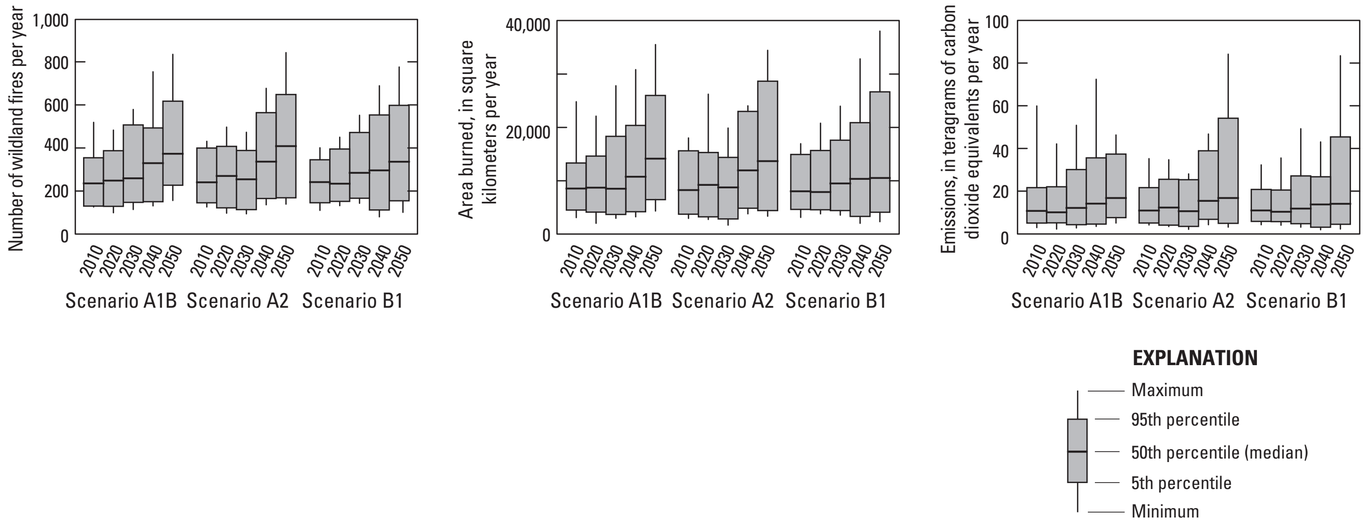

Figure 8.2. Graphs showing summaries of projected wildland-fire ignitions, area burned, and emissions for the Western United States for each decade between 2001 and 2050. The X-axis labels indicate the last year in the decade; for example, "2010" corresponds to the decade from 2001 to 2010. Scenarios are from the Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (Nakicenovic and others, 2000).

scenario but were also high for the B1 scenario. The projected changes under the A1B scenario tended to be smaller than under the other two scenarios, in part because fewer ignitions were projected to occur and a smaller area was projected to burn during the 2041 to 2050 decade under the A1B scenario.

Of the five level II ecoregions, the least amount of wildland-fire activity was observed in the Marine West Coast Forest and the simulated changes in wildland-fire occurrence and emissions were minimal (fig. 8.3 and table 8.2). The projected number of ignitions did not change in both typical and extreme years, except under extreme years in the A2 scenario, where ignitions actually declined. The projected extent of area burned and emissions were less stable, and there were no clear patterns in the projected changes (fig. 8.3), sometimes increasing (A1B and B1 scenarios) and other times decreasing (A2 scenario, extreme years).

In the baseline analysis (chapter 3 of this report), there was substantial wildland-fire activity in the Cold Deserts ecoregion. The simulations of future wildland fires projected a substantial increase in wildland-fire activity across all three climate-change scenarios (fig. 8.3 and table 8.2). The projected increases in wildland-fire ignitions ranged from 39 to 85 percent and from 72 to 103 percent for typical and extreme fire years, respectively. These projected increases in ignitions resulted in (1) projected increases in burned area of 34 to 95 percent in typical fire years and 58 to 101 percent for extreme fire years and (2) projected increases in emissions of 44 to 87 percent in typical years and 88 to 129 percent in extreme years. The projected changes in burned area and emissions were generally greatest under the A1B and A2 scenarios.

In the Warm Deserts ecoregion, ignitions were projected to increase by 5 to 64 percent (typical years) and 19 to 133 percent (extreme years), the area burned was projected to increase by 1 to 80 percent (typical years) and 22 to 155 percent (extreme years), and emissions were projected to increase by 3 to 69 percent (typical years) and –12 to 98 percent (extreme years) (fig. 8.3 and table 8.2). The projected changes in ignitions, area burned, and emissions were consistently high under the A1B climate-change scenario for both typical and extreme fire years, respectively. Under the B1 scenario, wildland-fire activity was limited in the decade between 2001 and 2010, and the changes relative to that decade were large. The changes projected under the A2 scenario were minimal, but ignitions, area burned, and emissions tended to be greater in all decades under the A2 scenario than they were under both the A1B and B1 scenarios.

In the Mediterranean California ecoregion, wildland fire ignitions, area burned, and emissions were projected to increase under all three climate-change scenarios (fig. 8.3 and table 8.2), but the differences between typical and extreme fire years were less pronounced than in other ecoregions. The projected number of wildland-fire ignitions for the decade between 2041 and 2050 was 36 to 62 percent greater than in the decade between 2001 and 2010 in typical years and 43 to 67 percent greater in extreme years. The projected increase in the number of ignitions resulted in a projected increase in burned area of 47 to 86 percent in typical years and 48 to 61 percent in extreme years. Emissions were projected to increase up to 80 percent in typical fire years and up to 55 percent in extreme years.

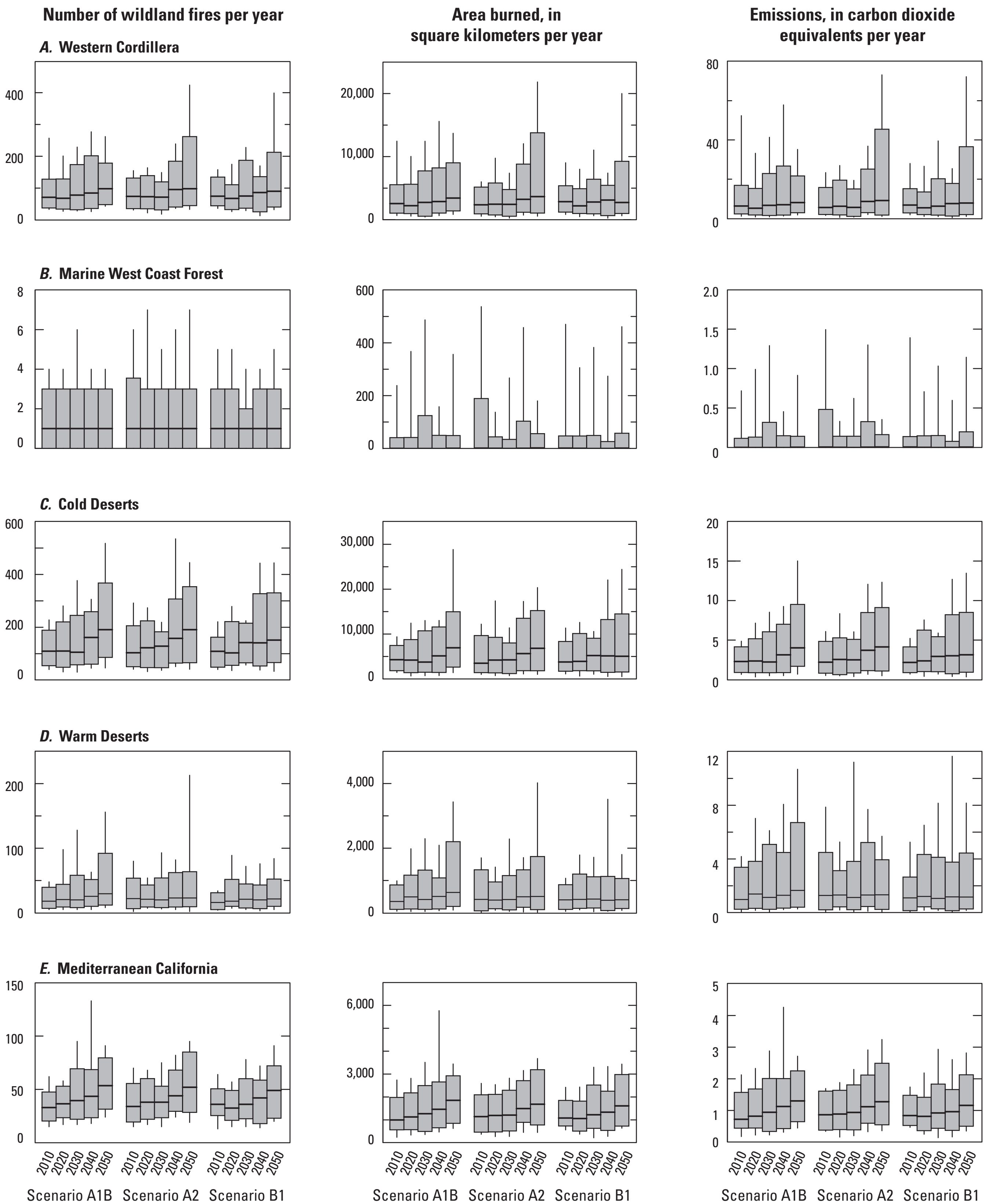

Figure 8.3. Graphs showing summaries of projected wildland-fire ignitions, area burned, and emissions by level II ecoregion, for each decade between 2001 and 2050. The X-axis labels indicate the last year in the decade; for example, “2010” corresponds to the decade from 2001 to 2010. Scenarios are from the Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (Nakicenovic and others, 2000). See figure 8.2 for an explanation of the bars.

Table 8.2. Relative projected changes in the 50th and 95th percentiles for wildland-fire ignitions, area burned, and emissions per year between the 2001-to-2010 decade and the 2041-to-2050 decade, by scenario and level II ecoregion.

[Climate-change scenarios from the Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (Nakicenovic and others, 2000)]

Climate-change scenario	Percentile	Level II ecoregion (percent)				
		Western Cordillera	Marine West Coast Forest	Cold Deserts	Warm Deserts	Mediterranean California
Ignitions						
A1B	50th	38	0	74	64	62
	95th	39	0	95	133	67
A2	50th	32	0	85	5	53
	95th	99	−15	72	19	53
B1	50th	21	0	39	34	36
	95th	58	0	103	68	43
Area burned						
A1B	50th	34	53	62	80	86
	95th	63	19	101	155	48
A2	50th	55	29	95	22	47
	95th	167	−70	58	31	52
B1	50th	−5	0	34	1	49
	95th	72	22	74	22	61
Emissions						
A1B	50th	28	42	75	69	80
	95th	28	22	129	98	43
A2	50th	64	13	87	3	48
	95th	188	−66	88	−12	55
B1	50th	15	−12	44	6	38
	95th	141	44	105	68	44

8.5. Discussion

Wildland-fire ignitions and area burned were projected to increase across all the climate-change scenarios for the Western United States as a whole and in almost all of the climate-change scenarios in each of the five ecoregions in the Western United States. Emissions were also projected to increase, but the pattern was more variable, possibly because the projected increase in the area burned may have resulted in relatively more light fuels (grass and shrub) and less heavy fuels (coniferous forest) being consumed. The projected increases in emissions were greater in extreme fire years (73–150 percent) than in typical fire years (28–56 percent). Given that the baseline wildland-fire emissions were roughly equivalent to 11.6 (7.9–87.0) percent of the mean sequestered carbon in terrestrial ecosystems (chapter 3), future efforts to increase carbon storage in ecosystems may be challenged by the potential carbon losses due to the projected climate-driven increases in wildland-fire occurrence.

The projected changes in wildland-fire patterns in the Western Cordillera ecoregion were most likely a result of the projected increases in temperatures during most of the seasons and the projected decreases in precipitation during the spring and summer, the seasons in which wildland fires are most common. In terms of the entire Western United States, the Western Cordillera ecoregion accounted for a large proportion of the baseline area burned and the majority of wildland-fire emissions (chapter 3). The results of the simulations made for this assessment indicate that wildland-fire ignitions, area burned, emissions, and associated management challenges, will likely increase in the future compared to other regions in the nation.

In the Marine West Coast Forest, wildland-fire activity has been historically infrequent and minimal changes were projected under the climate-change scenarios modeled in this assessment. The climate-change projections indicated a warming trend in this ecoregion; however, this ecoregion was also projected to have the greatest increase in precipitation under all of the climate-change scenarios among all the ecoregions of the Western United States, especially during the winter, spring, and fall. Because of the lag effects in fuel moistures, these projected changes could limit and even reduce wildland-fire activity. Because vegetation in this region historically has been highly productive, the wildland fires were extensive and severe when they occurred during droughts. This phenomenon most likely produced the highly variable projected trends in wildland-fire activity in the simulations.

The climate-change projections were variable for the Cold Deserts. As with most of the ecoregions in the Western United States, the temperatures were projected to increase. Drying patterns were projected in the southern and western portions of the ecoregion, especially in the spring, but increased precipitation in the summer was projected in the northern parts of the ecoregion. The exception was the simulation by the MIROC 3.2-medres model, which largely projected a drier climate across the entire ecoregion. These projected climate changes resulted in consistent projected increases in wildland-fire ignitions, area burned, and emissions, regardless of the climate-change scenario.

The Warm Deserts ecoregion was projected to have a consistently drier climate than the other ecoregions for most seasons under all scenarios, except under the B1 scenario during the summer (when projected by the CSIRO–Mk3.0 model) and winter (when projected by the CCCma CGCM3.1 model). Higher summer and fall temperatures were also projected. Wildland-fire activity and emissions were projected to increase under the A1B and A2 scenarios, although they were projected to be somewhat reduced under the B1 scenario. Similarly, the projected warmer temperatures (especially in the summer and fall) and drier spring and fall seasons in the Mediterranean California ecoregion corresponded to the projected increases in wildfire ignitions, area burned, and emissions.

The projected increases in fire activity that were simulated in the Cold Desert, Warm Deserts, and Mediterranean California ecoregions for this assessment were likely to be conservative estimates because vegetation types and fuel loads were static throughout the 50-year simulation period. There were strong and positive correlations between wildland-fire activity and the presence of invasive species after fire in all three ecoregions. These correlations suggest that as wildland-fire frequency increases, native ecosystems may be at risk of invasion by exotic grasses, which in turn may further increase the likelihood of wildland fires by providing fuel under some climate conditions (D'Antonio and Vitousek, 1992; Brooks and others, 2004; Keeley, 2006; Brooks and Chambers, 2011). The results of the wildland-fire simulations produced for this assessment may have been amplified if those feedback relations had been included.

The methods used here to simulate wildland fires were quite different than those used in most of the previously published studies that examined the effects of climate change on wildland-fire occurrence. Previous studies did not explicitly simulate the wildland-fire ignition locations, spread, or the effects on ecosystems; instead, they projected the probability that a grid cell contained a wildland-fire ignition (Westerling and Bryant, 2008) or the proportion of an ecoregion that burned (Littell and others, 2010; Litschert and others, 2012). The one exception is the recent paper by Westerling and others (2011), which projected wildland-fire ignition locations and size separately but did not explicitly simulate ignition locations and spread on the landscape. In spite of the differences in the methods used in this assessment, the results presented here were somewhat similar to past studies in that all of them projected an increase in the area burned in the near future; however, this assessment projected a smaller, more conservative increase in area burned than did the previously published estimates.

8.6. Limitations and Uncertainties

The MTBS database does not typically include wildland fires less than 404 ha (1,000 acres) in size in the Western United States, and because the simulation models used for this assessment were calibrated using the MTBS data, they were not influenced by smaller fires. Smaller fires are not likely to change the baseline results by much, but there is the possibility that ignitions which historically resulted in a small burned area and emissions could grow into large fires under different climate conditions. Thus, for this assessment, the simulated changes in wildland-fire occurrence and emissions may yield conservative estimates.

Throughout the wildland-fire simulations, vegetation and fuels remained static, which introduced some limitations into the assessment. Because of succession and disturbances, the composition and structure of forest vegetation may change substantially over the 50-year time span used in this assessment (Cooper, 1960; Aplet and others, 1988; Moore and others, 2004). These changes were often projected to result in altered surface and canopy fuels that determined potential wildland-fire behavior and emissions. Disturbances were especially important to consider because they were projected to reduce fuel loads and effectively act as fire breaks for future wildland fires. By holding 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 Western United States, 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 might alter the fuels, behavior, and emissions of future wildland fires (Bachelet and others, 2001, 2003). Incorporating vegetation dynamics into the ecosystem-disturbance model component is a priority task for future carbon assessments (Running, 2008; Goetz and others, 2012).

There was a large amount of variability in wildland-fire ignitions, area burned, and emissions in the simulations under the three climate-change scenarios. For each of the 3 GCMs, 3 replicate simulations were run, resulting in 9 simulations for each climate-change scenario, or 27 simulations total. It is uncertain whether those simulations fully characterized the variability in the simulated changes. Ideally, more simulations for different GCMs would have been incorporated to better characterize the variability, but practical limitations on computing resources and processing times effectively restricted the number of simulations that were run in this assessment. As a test in this study, additional GCMs were used in simulations for the Southern Rockies level III ecoregion with a greater number of replicates. The results suggested that the general projected patterns reported here will not change substantially.

8.7. Management Implications

Wildland-fire emissions produce greenhouse gases that may contribute to and accelerate climate change (Crutzen and Andreae, 1990; Andreae and Merlet, 2001) and may alter the structure and function of ecosystems (Bachelet and others, 2003; Lenihan and others, 2008). Fire-management strategies may need to be reassessed to determine whether and how best to counteract the projected increases in wildland-fire area burned and greenhouse-gas emissions, especially because managing wildland fires to reduce greenhouse-gas emissions might be at odds with other fire-management objectives, such as maintaining the historical range of variability in ecosystem disturbance regimes (McKenzie and others, 2004; Fule, 2008).

In certain cases, increased fire suppression efforts might be appropriate. Past simulation studies suggested that fire suppression in some ecosystems in the Western United States may increase carbon stocks by as much as 10 percent because of the unchecked woody encroachment and increased vegetation growth rates (Lenihan and others, 2008). In ecosystems where wildland-fire frequency has increased beyond the historical range of variability because of the influence of human development (Syphard and others, 2007) and invasive species (Brooks and others, 2004; Keeley, 2006), increased fire suppression might be a management strategy that meets the multiple goals of reducing greenhouse-gas emissions while maintaining ecosystem dynamics. The potential success of increasing wildland-fire suppression efforts remains unknown, however; fire suppression and containment efforts may become more difficult as the results of this assessment suggested that fires in both typical and extreme fire years were projected to be more severe in the future.

In other ecosystems, especially the dry forests in the Western United States, years of wildland-fire suppression have led to increased fuel loads and more severe fires, and increasing the suppression efforts in these areas may lead to additional undesirable effects (Stephens, 1998; Keane and others, 2002; Agee, 2003; Stephens and Ruth, 2005). These same ecosystems have been the targets of restoration efforts designed to reduce fuel loads and fire severity to historical conditions (Agee and Skinner, 2005; Reinhardt and others, 2008), and fuel treatments have been shown to benefit both ecosystem restoration and efforts to reduce greenhouse-gas emissions (Stephens and others, 2009; Reinhardt and Holsinger, 2010; Wiedinmyer and Hurteau, 2010; North and Hurteau, 2011). In forests at higher elevations, where the effects of suppression have not substantially altered fire regimes, the usefulness of fuel treatments to reduce wildland-fire severity and greenhouse-gas emissions is questionable (Schoennagel and others, 2004; Sibold and others, 2006; Mitchell and others, 2009). Some authors, however, have indicated that a more active management approach should be considered in forests at higher elevations in order to encourage ecosystem migration under changing climates and wildland-fire regimes (Hansen and others, 2001; Fule, 2008).

Uncertainty about the short- and long-term advantages and disadvantages of wildland-fire management and fuel treatments is high even without considering climate change, but may increase when climate change is considered. Additional analyses would be required to assess the effects of various management scenarios. Even though wildland-fire emissions in the Western United States are greater than in other parts of the country, they are still relatively small when compared to fossil-fuel emissions, and it is questionable whether any strategy designed to reduce wildland-fire emissions will have a measureable effect at a national scale.

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