esa ECOSPHERE

Mid-21st-century climate changes increase predicted fire occurrence and fire season length, Northern Rocky Mountains, United States

KARIN L. RILEY[1],† AND RACHEL A. LOEHMAN[2]

[1]Forestry Sciences Lab, USDA Forest Service, Rocky Mountain Research Station, 800 East Beckwith, Missoula, Montana 59801 USA
[2]Alaska Science Center, US Geological Survey, 4210 University Drive, Anchorage, Alaska 99508 USA

Citation: Riley, K. L., and R. A. Loehman. 2016. Mid-21st-century climate changes increase predicted fire occurrence and fire season length, Northern Rocky Mountains, United States. Ecosphere 7(11):e01543. 10.1002/ecs2.1543

Abstract. Climate changes are expected to increase fire frequency, fire season length, and cumulative area burned in the western United States. We focus on the potential impact of mid-21st-century climate changes on annual burn probability, fire season length, and large fire characteristics including number and size for a study area in the Northern Rocky Mountains. Although large fires are rare they account for most of the area burned in western North America, burn under extreme weather conditions, and exhibit behaviors that preclude methods of direct control. Allocation of resources, development of management plans, and assessment of fire effects on ecosystems all require an understanding of when and where fires are likely to burn, particularly under altered climate regimes that may increase large fire occurrence. We used the large fire simulation model FSim to model ignition, growth, and containment of wildfires under two climate scenarios: contemporary (based on instrumental weather) and mid-century (based on an ensemble average of global climate models driven by the A1B SRES emissions scenario). Modeled changes in fire patterns include increased annual burn probability, particularly in areas of the study region with relatively short contemporary fire return intervals; increased individual fire size and annual area burned; and fewer years without large fires. High fire danger days, represented by threshold values of Energy Release Component (ERC), are projected to increase in number, especially in spring and fall, lengthening the climatic fire season. For fire managers, ERC is an indicator of fire intensity potential and fire economics, with higher ERC thresholds often associated with larger, more expensive fires. Longer periods of elevated ERC may significantly increase the cost and complexity of fire management activities, requiring new strategies to maintain desired ecological conditions and limit fire risk. Increased fire activity (within the historical range of frequency and severity, and depending on the extent to which ecosystems are adapted) may maintain or restore ecosystem functionality; however, in areas that are highly departed from historical fire regimes or where there is disequilibrium between climate and vegetation, ecosystems may be rapidly and persistently altered by wildfires, especially those that burn under extreme conditions.

Key words: burn probability; climate change; climatic fire season length; fire occurrence; FSim; Northern Rocky Mountains.

Received 16 August 2016; accepted 22 August 2016. Corresponding Editor: Debra P. C. Peters.

† **E-mail:** kriley@fs.fed.us

INTRODUCTION

Climate changes are projected to profoundly influence wildfire regimes in forests of the western United States, particularly in mountainous ecosystems such as those found within the Northern Rocky Mountain region ("Northern Rockies"; Fagre and Peterson 2000, McKenzie et al. 2004, Higuera et al. 2015). Many forest types in the Northern Rockies, where fire is ubiquitous and was historically the most important and extensive landscape disturbance (Hejl et al. 1995), are fire adapted, meaning that fire is an integral part of their maintenance and ecological functioning (Agee 1993). As part of their ecological history, wildfires strongly influence vegetation structure, plant species composition, productivity, carbon (C) storage, water yield, nutrient retention, and wildlife habitat of fire-prone forest ecosystems (Agee 1993).

Despite major human influences on wildfires in the western United States since Euro-American settlement, climate is generally considered to be the primary control on fire regimes, influencing vegetation production and condition as well as the physical environment (Marlon et al. 2008, Morgan et al. 2008, Higuera et al. 2015). Annual area burned by western wildfires in the 20th century was greater in years with low precipitation, high drought severity, and high temperatures (Littell et al. 2009). Fire history reconstructions have linked regionally synchronous fire years to warm springs and warm and dry summers (Heyerdahl et al. 2008, Morgan et al. 2008, Littell et al. 2009), suggesting that projected regional climate changes may result in increased fire activity. Climate changes are likely to increase fire frequency, fire season length, and cumulative area burned in the coming decades in the western United States, in response to warmer, drier conditions (McKenzie et al. 2004, Flannigan et al. 2006, Barbero et al. 2015). For example, prolonged dry weather conditions (about 40 d without precipitation) can dry live and dead fuels enough to carry large, intense fires once they are ignited (Schoennagel et al. 2004, Riley et al. 2013). Potential mid- to late 21st-century climate-driven changes in regional fire regimes include longer climatic fire seasons (time when fires are prone to spread due to weather and fuels conditions) and increases in fire frequency, annual area burned, the number of days with high fire danger, and fire severity as compared with current fire patterns (Bachelet et al. 2003, Brown et al. 2004, Westerling et al. 2006, Krawchuk et al. 2009, Dillon et al. 2011, Rocca et al. 2014, Jolly et al. 2015). Lengthening of the climatic fire season impacts fire patterns by increasing the likelihood that ignitions—natural or human-caused—will occur during conditions conducive to fire spread; more spreading ignitions and longer periods of burning are likely to result in larger fires and increased annual area burned relative to contemporary recorded fire activity (McKenzie et al. 2004, Miller et al. 2011). This shift may be especially pronounced in middle- to high-elevation forested systems where fuels are abundant (Westerling et al. 2006, Littell et al. 2009).

Projections of future climate-driven changes in fire activity and fire impacts in the Northern Rockies have been developed using a variety of models including coarse-scale dynamic global vegetation models (DGVMs), fine-scale mechanistic landscape fire succession models, and statistical climate-fire models (Keane et al. 2004, 2015*b*, Loehman et al. 2011*a*, 2016, Seidl et al. 2011, Abatzoglou and Brown 2012; Bachelet et al., *in press*). Simulations of climate, fire, and vegetation dynamics using the MC2 DGVM showed a substantial increase in fire frequency and a loss of subalpine plant communities (Sheehan et al. 2015). Additional studies found larger, more frequent fires and changes in vegetation composition and structure with warming future climates using the mechanistic, ecosystem-fire process model FireBGCv2 to simulate landscape-scale climate, fire, and vegetation interactions (Loehman et al. 2011*a*, Holsinger et al. 2014, Keane et al. 2015*a*). Westerling et al. (2011) developed statistical models predicting increased fire activity by mid-century in the Greater Yellowstone Ecosystem by relating climate data to the occurrence and size of large fires (>200 ha).

Although large fires—generally, those that escape initial attack—are rare, they account for most of the area burned in western North America (Finney et al. 2010, Werth et al. 2011). These fires burn under the most extreme weather conditions and exhibit behaviors that preclude methods of direct control because of high rates of spread, prolific crowning, strong convective involvement, or erratic behavior (Werth et al. 2011). Fire management in the Northern Rockies, where fires are likely to become more frequent and burn across larger areas with a changing climate (Running 2006, Marlon et al. 2009), is thus likely to become even more challenging. Allocation of resources, development of land management plans, and assessment of fire effects on resources require an understanding of when and where fires are likely to burn (exposure), particularly under altered climate regimes that may increase large fire occurrence. For planning purposes, a broad-scale assessment of wildfire risk offers a means of understanding and comparing threats to valued resources across management units, as well as predicting and prioritizing investments in activities that mitigate those risks (Finney et al. 2011). However, models that realistically simulate fire spread and fire behavior over very large landscapes have rarely been implemented in the context of potential future, altered climates.

Here, we take a unique approach to predicting future fire exposure using the probabilistic large fire simulation model FSim (Finney et al. 2011) to compare estimated burn probabilities, fire characteristics, and climatic fire season length under contemporary and projected future climate, for a study area in the Idaho Panhandle. In previous work, FSim has been used to simulate continental burn probabilities as an input to national-level fire suppression budgeting (Finney et al. 2011), as the basis for risk assessment from wildland fire (Calkin et al. 2011), and as a component of a probabilistic model for estimating fire suppression costs for U.S. Forest Service lands (Thompson et al. 2015). FSim simulates large fire ignitions based on fuel moisture and weather and fire spreads in the model according to properties of fuel moisture, weather, topography, and vegetation; the model is therefore sensitive to changes in climate and can be used to assess climate change impacts on large fire probability. This manuscript responds to a need identified by Northern Rockies regional land managers for more information on future fire activity in the context of climate change. Our methods can be applied to other ecosystems or regions to project climate impacts on burn probability and fire characteristics.

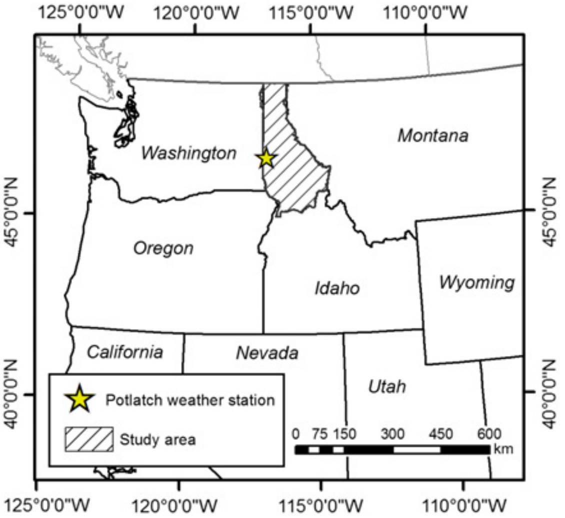

Fig. 1. Northern Rocky Mountains study area, encompassing the Nez Perce-Clearwater and Idaho Panhandle National Forests. The study area boundary matches the Northern Idaho Fire Planning Unit (NR_ID_001) used by fire program analysis (FPA), a fire budget determination tool. Daily weather recorded at the Potlatch weather station was used as a baseline (contemporary climate).

METHODS

Study area

Our study area is a 5-million-hectare region of northern Idaho that encompasses the Nez Perce-Clearwater and Idaho Panhandle National Forests (Fig. 1). We selected this region as our focal area because it is a largely forested area with a large proportion of U.S. Forest Service lands that are currently undergoing forest plan revisions. The boundaries of the study area are identical to those of the Northern Idaho Fire Planning Unit (NR_ID_001) used by fire program analysis (FPA), allowing for comparisons between our study and FPA products (Finney et al. 2011). The study area is mainly forested (76%), with smaller agricultural (9%), grassland (8%), shrubland (5%), water (2%), developed (1%), recently burned (<1%), and herbaceous (<1%) components, as characterized by the LANDFIRE assessment (LANDFIRE 2008*a*, Rollins 2009; Figs. 2 and 3a). These vegetation communities manifest a range of historical fire regimes along frequency and severity gradients of frequent (1–35 yr), moderately frequent (35–200 yr), and infrequent (200+ yr) fire return intervals and low, mixed, and replacement severities (LANDFIRE 2008*b*; Fig. 4). The majority (64%) of the study area consists of areas of historically moderate-frequency, low- and mixed-severity fires that replaced up to 75% of the overstory vegetation (LANDFIRE 2008*b*).

FSim model

The FSim model simulates ignition and growth of large fires in response to topography, fuel, and

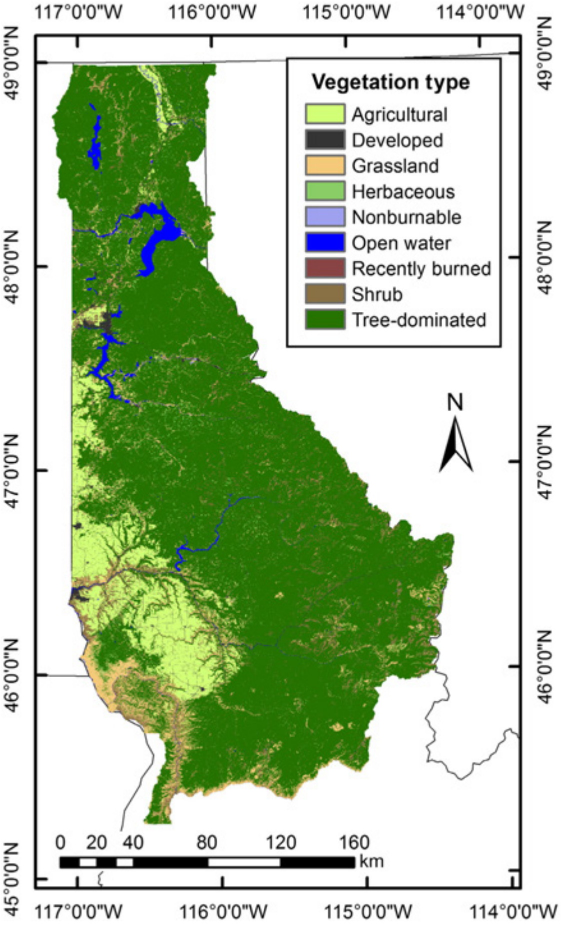

Fig. 2. Vegetation communities (summarized by ecotype), as mapped by LANDFIRE (2008*b*, version 1.3.0).

weather conditions. A key feature of the FSim model is its ability to predict the probability of fire at any given point on the landscape, accomplished via four modules: weather generation, fire ignitions, fire growth, and fire suppression. Predicting large fire burn probability using existing fire occurrence data is challenging because large fires are rare; in addition, weather records that describe fire weather conditions typically extend over only a few decades, and records of fires are reliable only for the period beginning in 1992 (Short 2014). Therefore, burn probability cannot be calculated based on fire records alone, as these records are too sparse and short in duration to capture the range of expected combinations of fire weather and ignition patterns; thus, a modeling approach is necessary. The FSim model relies on artificially generated sequences of thousands of years of daily weather in order to produce stable and repeatable estimates of burn probability (Finney et al. 2011). Each year of daily weather is a statistically plausible weather sequence for a simulation period (often 1992–2012 in order to match the period for which reliable fire records are available). Annual burn probability for each pixel is calculated as the number of times a pixel burns, divided by the total number of simulation years.

In FSim, daily large fire ignition probability is based on the statistical relationship between the daily Energy Release Component (ERC) for fuel model G of the National Fire Danger Rating System, a proxy for fuel dryness or heat per unit area available to the flaming front (Cohen and Deeming 1985), and large fire ignitions drawn from the historical record, modeled via logistic regression (Andrews et al. 2003, Finney et al. 2011). The ERC-G fuel model is used because it includes fuels from larger-diameter fuel size classes and therefore captures the seasonal trend in fuel conditions (Finney et al. 2011). In general, the probability of ignition increases with ERC. Ignition locations are determined using a density grid that allocates ignitions proportionally across a simulation landscape, based on where they have occurred in the contemporary record (Short 2014).

Daily weather records of temperature, humidity, solar radiation, and precipitation are used to calculate fuel moistures for four dead fuel timelag classes (1, 10, 100, and 1000 h) and live woody and live herbaceous components as required by fire behavior calculations (Fosberg and Deeming 1971, Deeming et al. 1984, Andrews 1986), which are used to calculate the daily ERC-G. We utilized FireFamily Plus software (Bradshaw and McCormick 2000) for these calculations. Using these inputs, FSim simulates thousands of years of statistically plausible ERC streams based on the average daily ERC and the daily standard deviation and temporal autocorrelation (Grenfell et al. 2010). Daily values for wind speed and direction are randomly drawn from the historical monthly distributions at the chosen weather station.

FSim uses the daily ERC, wind speed, and direction in combination with landscape topography and fuel characteristics to calculate fire

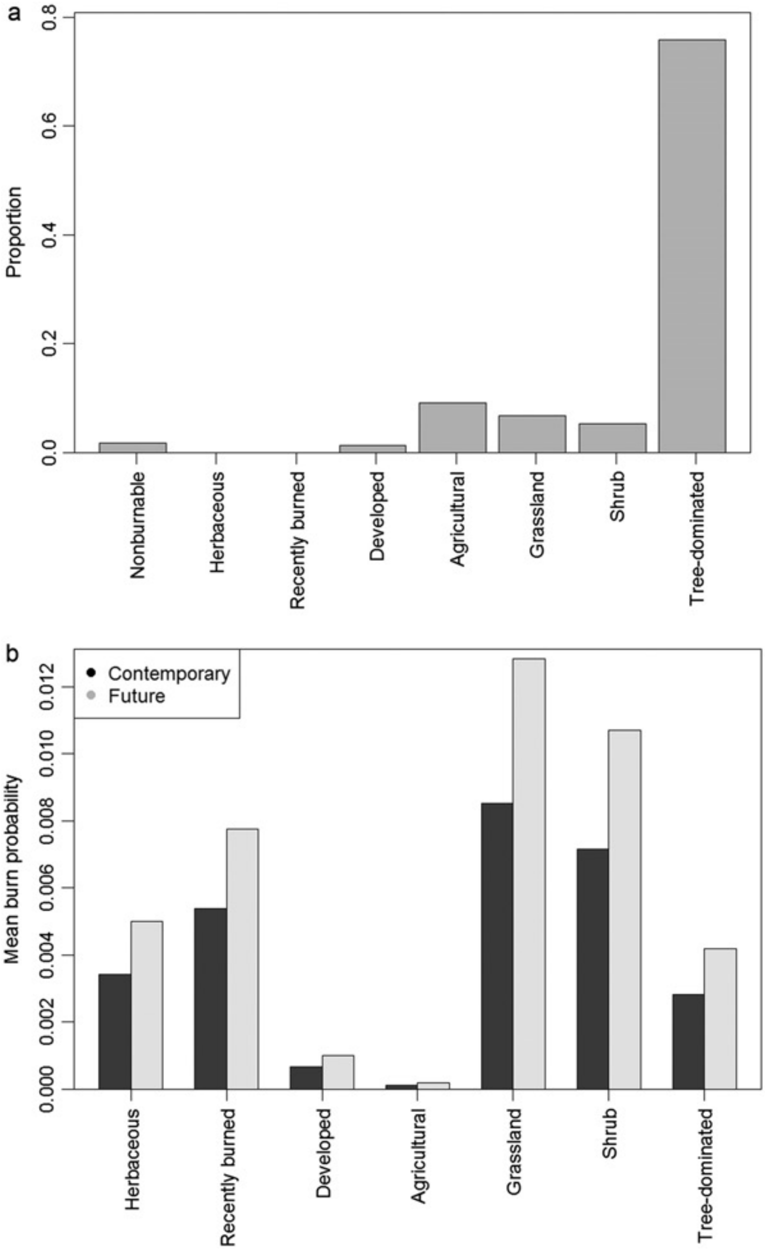

Fig. 3. (a) Proportional representation of vegetation communities within the study area; (b) Mean burn probabilities by vegetation community for contemporary (dark gray) and projected future 2030–2059 (light gray) periods.

spread, modeled via a minimum travel time algorithm that identifies paths with most rapid fire spread based on a set of gridded topographic and vegetation parameters (Finney 2002). Fires in FSim can be extinguished by sustained wet and cool weather, and we also enabled the optional fire suppression algorithm that calculates a daily containment probability based on vegetation type, time since ignition, and fire behavior (Finney et al. 2009). FSim outputs raster grids of annual burn probabilities and text files logging fire sizes and dates of ignition. We calculated projected changes in annual burn probability from the burn probability grids and projected

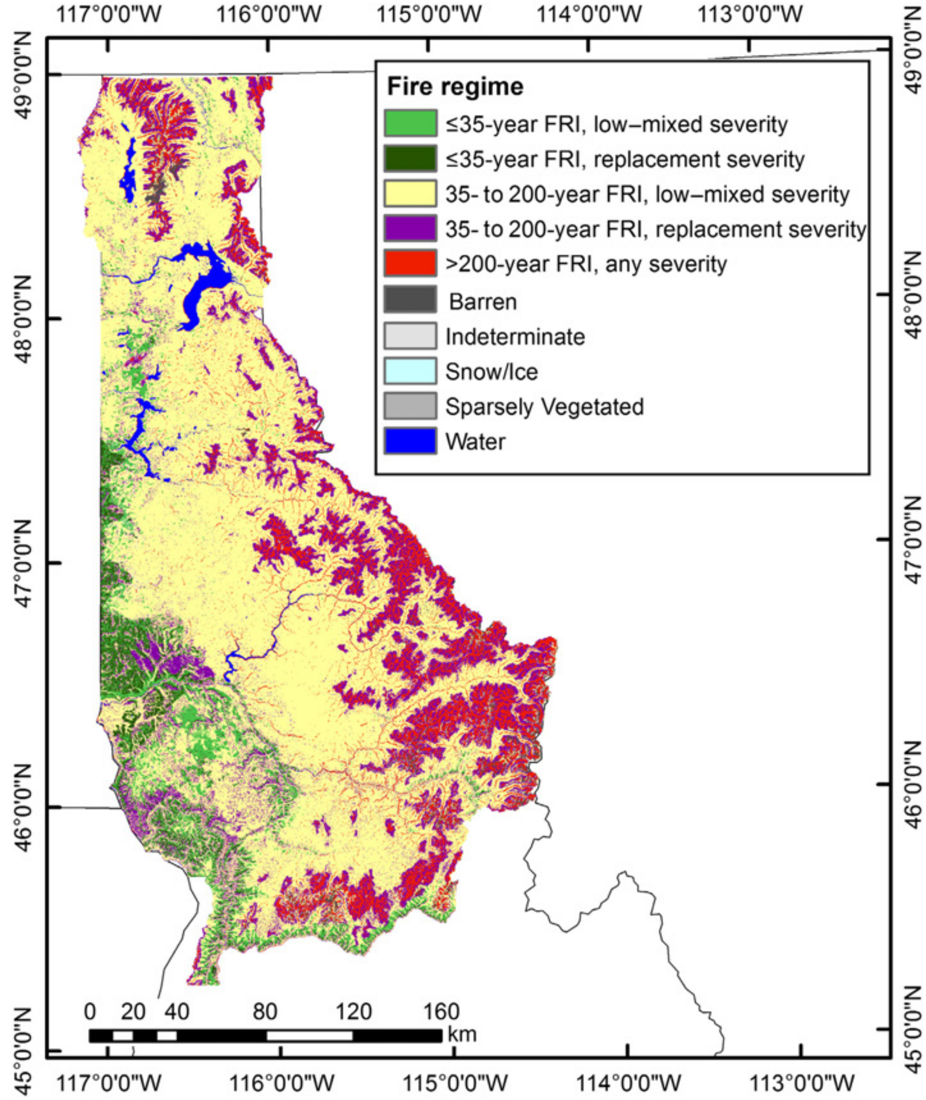

Fig. 4. Fire regime groups within the study area, as mapped by LANDFIRE (2008*b*, version 1.3.0).

changes in fire size, the number of fire-free years, annual area burned, and fire seasonality from the fire size lists.

Model inputs

Weather and climate.—We obtained weather records for the Potlatch weather station (Fig. 1) from the FAMWEB fire and weather data warehouse (https://fam.nwcg.gov/fam-web/). The Potlatch station is used by FPA and was chosen because of its length of record, minimal missing or incorrect data, and assessment by local fire managers that the station captures extreme weather events associated with large fires. We selected weather observations from the period 1992–2010 to represent contemporary conditions, which were then used by FSim to create 20,000 annual iterations ("years") of simulated weather as described above. These iterations each are statistically plausible sequences for the contemporary period and do not represent projected changes in weather for the next 20,000 yr.

We used projected monthly mean precipitation, relative humidity, and average temperature for the period 2030–2059 to create "future" daily weather streams for the FSim model, as described

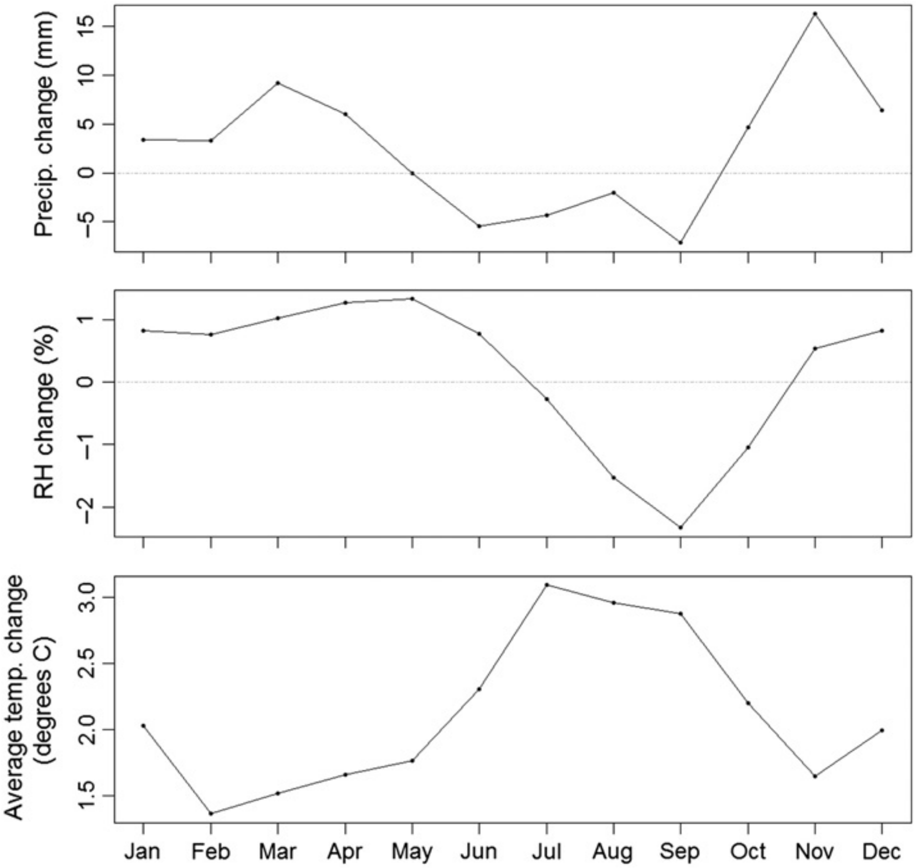

Fig. 5. Predicted average monthly changes in climate at the Potlatch weather station for the years 2030–2059 by month. RH, relative humidity (%).

below. Climate data were an ensemble average of ten best-performing global climate models (GCMs) for the Pacific Northwest/Columbia Basin region (41.5 to 49.5 N, −124.0 to −111.0 W), driven by the A1B SRES emissions scenario (Nakicenovic et al. 2000), and spatially downscaled to 6 km (Littell et al. 2011*a*). We selected the 2030–2059 (mid-century) timeframe because it provides an assessment window that is sufficiently forward-looking to capture potentially novel fire patterns but is proximate enough to be useful for management planning. Generally, the ensemble model describes decreased summer season (June to September) precipitation, lower relative humidity (July through October), and increased average monthly temperature in all months (Fig. 5).

Climate projections were used to modify the observed daily weather to represent future climate. For example, if mean July temperature was projected to increase by 1.3°C, we increased all daily observed temperatures for all months of July in our 1992–2010 weather stream by that amount. This method retains the temporal autocorrelation between daily weather values, which is an important input to the weather generation algorithm. To preserve daily correlations between temperature, relative humidity, and precipitation in the observed weather, monthly offsets of precipitation amount and duration were calculated proportionally to the observed precipitation, a method that assumes that precipitation intensities stay the same in the future. For instance, assume that 18 cm of total monthly precipitation for July 2005 was produced by two storms: a 15 July, two-hour event that delivered 6 cm of precipitation at 3 cm/h and a 22 July, 3-h event that delivered 12 cm of precipitation at 4 cm/h. We allocated one-third of the 9-cm increase in projected precipitation for July 2030–2059 to the first storm and two-thirds to the second storm, using the same intensities as in the observed events. Projected daily weather was then used to calculate "future" daily ERC values and to generate statistically plausible weather sequences using the same methods as for the contemporary period. Reliable estimates of future wind speed were not available, so the observed wind values were used.

Fuels and topography.—We obtained required landscape inputs of 30-m raster grids of slope, aspect, elevation, fuel model (Scott and Burgan 2005), canopy bulk density, canopy base height, and canopy height from the Landscape Fire and Resource Management Planning Tools, or LANDFIRE program (LANDFIRE 2013). Data layers were upscaled from 30-m to 270-m pixel size for modeling efficiency. We used the same landscape inputs for both the contemporary and future modeling periods.

Model calibration.—FSim was calibrated until the mean burn probability was near that observed in the historical record. Calibration consisted primarily of adjusting the large fire size threshold, which determines which fires from the historical record are considered to be "large" and are thus included in the logistic regression between ERC-G and large fire ignition probability. This parameter varies regionally based on characteristics of the fire regime including fire size distribution (Finney et al. 2011). Our calibration produced a large fire size threshold of 61 ha. The observed burn probability for the period 1992–2010 was calculated based on the observed fires that ignited in the study area, as recorded in the FPA Fire Occurrence Database (Short 2014). The mean modeled burn probability was calculated by averaging the burn probability of each pixel in the study area. Fire size distributions in the model output resembled those from the historical record, following a power law distribution (Finney et al. 2011). This indicates that important drivers of fire size (including spatial patterns in topography and fuels, and temporal burning windows provided by hot, dry, windy weather) are well represented in the model. The average annual burn probability in the calibrated FSim run closely matched the observed contemporary (1992–2010) burn probability in the study area: 0.0031 (modeled) versus 0.0033 (observed). The large fire size threshold and other settings from the calibrated, contemporary climate simulation were used in the future climate simulation.

Data analysis

Burn probability.—We report the average burn probabilities by ecotype (summarized from LANDFIRE existing vegetation type or EVT) and fire regime group (FRG). We calculated (1) absolute differences in burn probability between contemporary and future climates by subtracting contemporary burn probabilities from future burn probabilities and (2) percentage difference ($\mathrm{bp}_{\%\mathrm{diff}}$) in burn probability between contemporary ($\mathrm{bp}_{\mathrm{con}}$) and future ($\mathrm{bp}_{\mathrm{future}}$) periods:

$$\mathrm{bp}_{\%\mathrm{diff}} = \frac{(\mathrm{bp}_{\mathrm{future}} - \mathrm{bp}_{\mathrm{con}})}{\mathrm{bp}_{\mathrm{con}}}$$

Fire characteristics.—We calculated the mean and median size of all large fires (≥61 ha) for contemporary and future time periods. We consider both statistics to be informative; the median is considered the proper descriptive statistic of a power law distribution, and the mean is related to the annual burn probability (which is necessarily a mean of annual burned area). Fire-free years were those that elapsed without a large fire (≥61 ha), based on the ignition day and year of each simulated fire. We calculated the total area burned for each simulation year and computed the mean annual area burned during the 20,000 model iterations for both contemporary and future time periods.

Climatic fire season length.—We compared the trend in average daily ERC for contemporary and future time periods. In addition, we compared daily ERC values recorded at the Potlatch weather station with the calculated future ERCs to detect differences in the number of days at moderate (>80th percentile), high (≥90th percentile), and extreme (≥97th percentile) ERCs. The 80th percentile is often considered as a threshold value by land managers, with values above the 80th percentile indicating onset of the climatic fire season; thus, FSim simulates large fire growth only when ERCs are above the 80th percentile. Previous work (Riley et al. 2013) indicates that area burned in the western United States increases exponentially when ERCs are above the 80th percentile (Fig. 6).

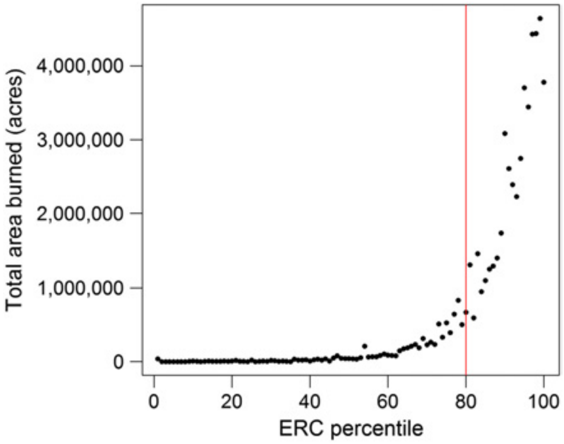

Fig. 6. Total area burned by energy release component (ERC) percentile in the western United States, 1984–2008 (modified from Riley et al. 2013).

Results

Burn probability

Modeled annual burn probabilities for the contemporary period varied across the study area by geography, vegetation type, and FRG from a low of zero (for nonburnable areas) to a high of 0.0385, equivalent to about a 4% annual occurrence probability of a large fire (Fig. 7a). Burn probabilities were highest in the southern part of the study area, where grasses and shrubs are the dominant vegetation and FRG indicates short fire return intervals (Figs. 4 and 7a, Table 1; LANDFIRE 2008*b*). Burn probabilities were lowest for agricultural and developed areas, followed by tree-dominated portions of the landscape, also congruent with expected fire

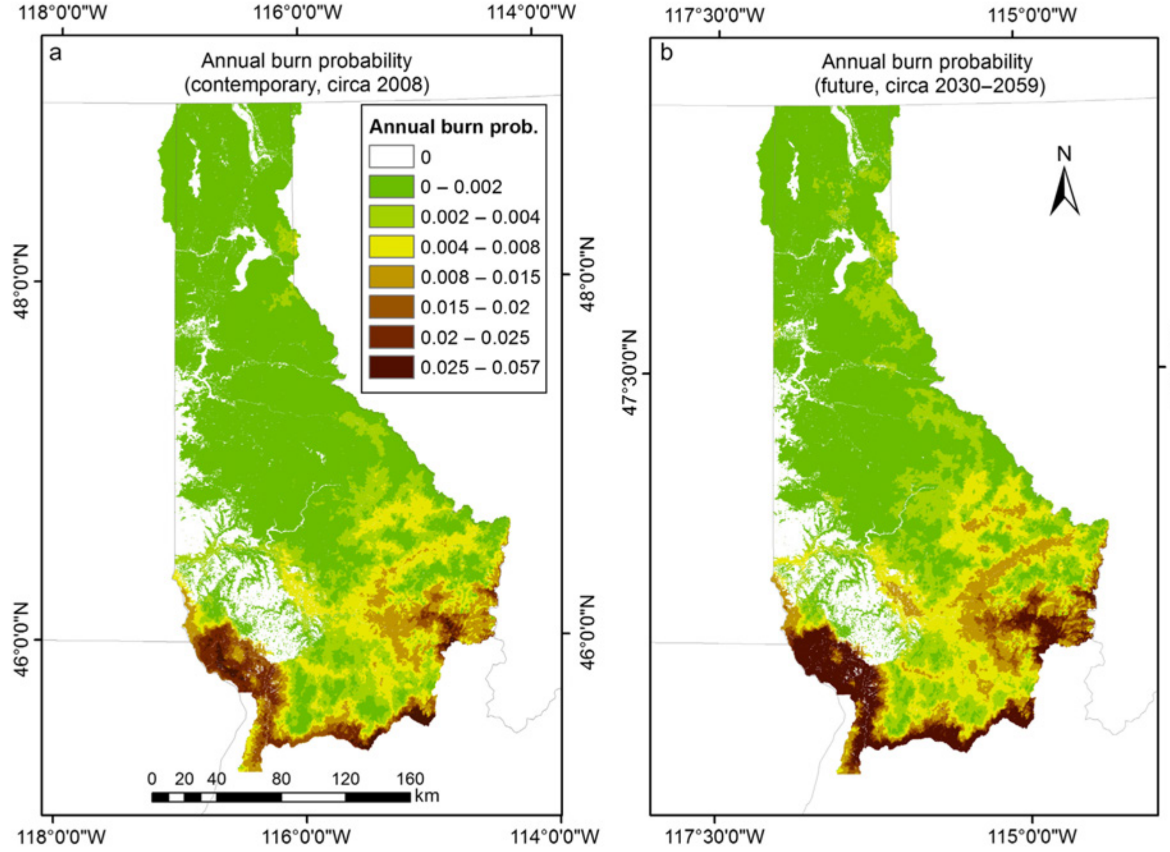

Fig. 7. Annual burn probabilities for the study area, (a) circa 1992–2010 and (b) circa 2030–2059.

Table 1. Mean burn probability for the entire study area and by vegetation community for the contemporary (1992–2010) and future (2030–2059) periods, with absolute differences and percentage change in mean burn probability.

Community	Contemporary (1992–2010)	Future (2030–2059)	Difference	Percentage change
Study area	0.0031	0.0046	0.0015	48
Grassland	0.0085	0.0128	0.0043	51
Shrub	0.0072	0.0107	0.0035	49
Recently burned	0.0054	0.0077	0.0024	44
Herbaceous	0.0034	0.0050	0.0016	47
Tree-dominated	0.0028	0.0042	0.0014	48
Developed	0.0007	0.0010	0.0003	52
Agricultural	0.0001	0.0002	0.0001	53

frequency based on FRG. This result is consistent with the geographic pattern of recent large fires, most of which have occurred in the southern part of the study area. Modeled future burn severity patterns were similar to the contemporary period (Fig. 7b); however, mean annual burn probability for the study area increased from 0.0031 to 0.0046, or 48%. Annual burn probability increased across all vegetation classes by 44% to 54% (Table 1, Fig. 3b). Burn probabilities varied by fire regime for both contemporary and future scenarios, with the highest probabilities generally occurring in areas with more frequent fire return intervals (Table 2, Figs. 4 and 7). The modeled percentage change in burn probability was similar across FRGs, from 48% to 53% increase.

Based on the percentage difference between contemporary and future periods, the largest increases in burn probability for all nondeveloped lands were modeled for grasslands (51%) and shrublands (49%), followed by tree-dominated (48%) and herbaceous (47%) vegetated areas (Table 1). In the southern part of the study area increases in burn probability of 0.001 to 0.036 were predicted, with annual burn probability values falling frequently between 0.02 and 0.03, equivalent to an annual occurrence probability of 2% to 3% (Fig. 8). In the northern half of the study region, where contemporary annual burn probabilities were much lower, burn probability slightly increased or decreased (on the order of 0.00005 to 0.003, or of 1 to 60 fires occurring during the 20,000-year simulation period).

While larger *absolute* changes in burn probability are projected for the southern half of the study area, larger percentage changes in annual burn probability are projected for the northern half of the study area, where burn probabilities were relatively low. Large percentage changes correspond to only a small increase in the simulated number of fires; for example, an increase of 0.00005 to 0.00015 amounts to a 300% increase in burn probability, but only 1 to 3 additional fires within the 20,000-iteration simulation period. In general, small increases in burn probability can result from stochasticity of ignition location (thus an area that burned once in one simulation may burn twice or no times in the next run, even if no program settings are changed), but in some portions of the northern study area the percentage increase in burn probability is large enough that we infer a climate response; for example, an increase from 0.00015 to 0.0008 is equivalent to an additional 3 to 16 fires. While the predicted changes in the northern part of the study area tended to be smaller in magnitude than in the southern half of the study area, it is important to recognize that small changes in burn probability can amount to increases of 50% to 500% in this area, which could drive ecological changes resulting from increases in burned area and decreases in fire return intervals, or strain existing management and fire suppression resources in the near future.

Fire characteristics

Projected future climate increased the median size of individual large fires by about 7% (28 ha) over modeled contemporary median fire size. Mean fire size was predicted to increase by about 11%, with disproportionate growth in the largest

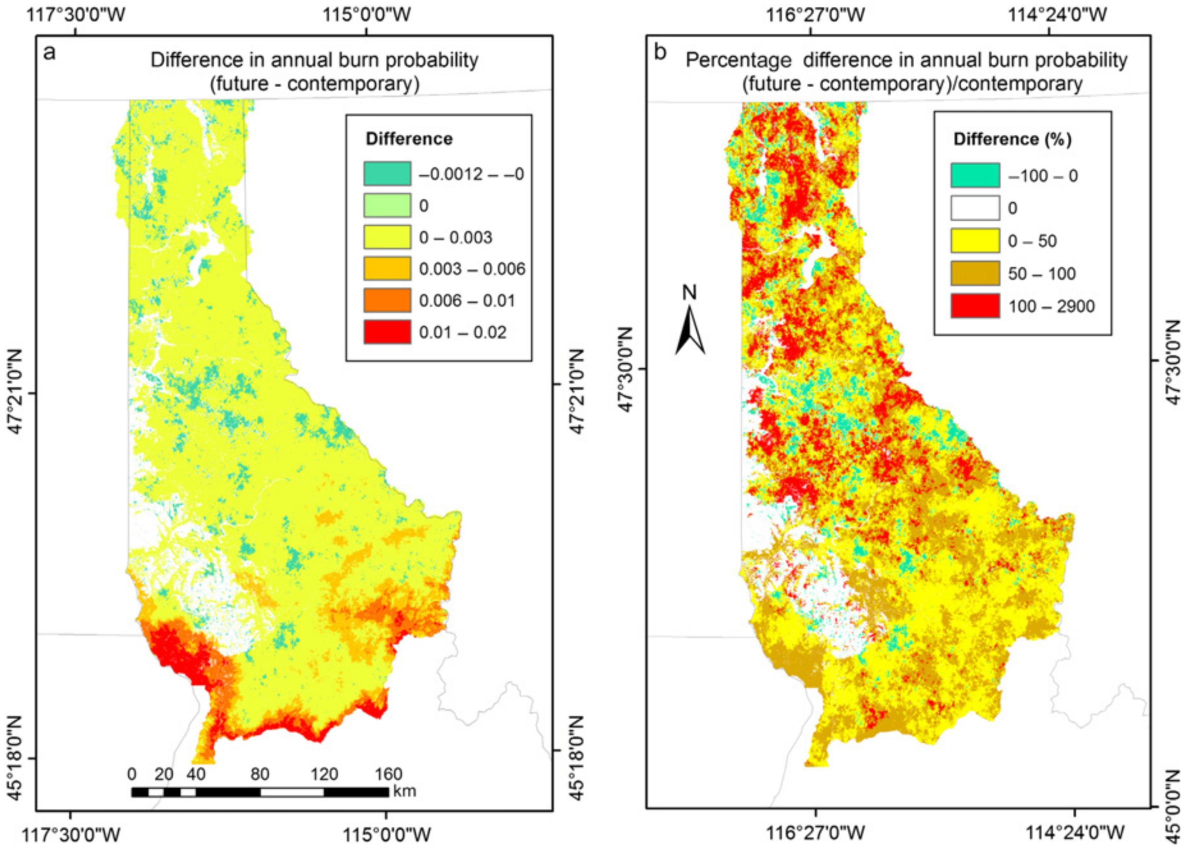

Fig. 8. Predicted changes in burn probabilities for the study area, (a) absolute change in burn probability and (b) percentage change in burn probability.

fires. The number of years without a large fire ("fire-free years") decreased with projected future climate, from about 25% to 17%. This modeled increase in large fire activity likely occurred because there are more days in the 2030–2059 weather sequence with ERCs above the 80th percentile, amounting to more frequent occurrence and longer duration of weather conditions conducive to large fire growth.

Increased mid-century burn probability resulted from increased fire size and number of fires as compared with the contemporary period. In the study area as a whole, the total area burned by all fires occurring in a single year was modeled to increase with future climate by roughly 46% or about 6800 ha/yr on average, as compared with contemporary mean annual area burned of about 14,750 ha. The number of large fires increased because weather conditions conducive to large fire ignition and growth were more common and lasted longer in the mid-century weather stream. In addition, because daily ignition probability in FSim is a function of ERC and there are more days at elevated ERC represented in the future weather stream, the number of ignitions increased.

No marked change in the seasonality of fires was observed. Increased numbers of fires (summed daily over 20,000-iteration simulation period) occurred between June and October in mid-century, with the greatest increases between July and September (Fig. 9). Little or no change in the number of fires was observed between November and May.

Climatic fire season length

The number of days above the 80th percentile ERC is projected to increase by approximately 12 d/yr in mid-century, with a projected increase of 8 d/yr above the 90th percentile ERC and

Table 2. Mean burn probability for study area by fire regime group (FRG).

FRG	Percentage of study area	Contemporary (1992–2010)	Future (2030–2059)	Raw difference	Percentage difference
1. ≤35-year fire return interval, low and mixed severity	5	0.00615	0.00924	0.00309	50
2. ≤35-year fire return interval, replacement severity	3	0.00614	0.00931	0.00317	52
3. 35- to 200-year fire return interval, low and mixed severity	64	0.00269	0.004	0.00131	49
4. 35- to 200-year fire return interval, replacement severity	15	0.00353	0.00525	0.00172	49
5. >200-year fire return interval, any severity	9	0.00255	0.00377	0.00122	48
Indeterminate	1	0.00687	0.0105	0.00363	53

Note: We do not report burn probabilities for the approximately 3% of the study area that is water or barren, because those areas are classified as nonburnable in the FSim model.

5 d/yr above the 97th percentile (Table 3). Because fire seasons are variable in length and severity, the number of days above these thresholds will also vary from year to year; these figures represent the mean.

Due to seasonal differences in projected climate, ERCs increased during some parts of the year and decreased during others (Fig. 10). Future ERCs decreased or showed no change over contemporary trends between November and June and increased between July and October. During the climatic fire season (when ERCs were above the 80th percentile), ERCs increased by about 7%.

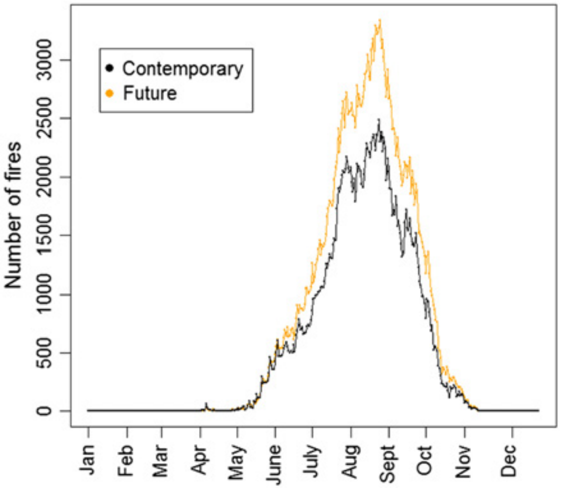

Fig. 9. Total daily number of ignitions (summed over the simulation period of 20,000 yr) for contemporary (black) and projected future 2030–2059 (orange) simulations.

Higher ERCs during the shoulder seasons (driven by projected elevated temperatures, decreased RH, and lower precipitation) increased the length of the climatic fire season. Because burned area increases sharply around the 80th percentile ERC in the western United States (Fig. 6; Riley et al. 2013), a projected increase in the number of days spent above the 80th percentile is a likely indicator of future increases in area burned.

DISCUSSION

The composition and structure of forests in the Northern Rockies is largely determined by climate, elevation, topographic position, and history of fire (Schoennagel et al. 2004). However, fire history can no longer be the sole predictor of future fire patterns or fire behavior: A combination of management factors (e.g., timber harvest, fire exclusion and associated increased surface fuel loads, tree densities, and ladder fuels) and climate drivers (earlier snowmelt, higher summer temperatures, and longer climatic fire season) has recently produced increased wildfire activity compared to the mid-20th century, particularly in the Northern Rockies (Westerling et al. 2006, Littell et al. 2009, Naficy et al. 2010, Loehman et al. 2014). As demonstrated in this study, climate-driven changes in temperature and precipitation regimes are likely to increase wildfire activity in the future, via the effects on fuel moistures and increased length of the climatic fire season.

The climate projections used in this analysis describe warmer and drier summers for the

Table 3. Annual percentage and mean number of days with moderate or high fire danger for contemporary and future periods.

Period	≥80th percentile ERC (moderate)	≥90th percentile ERC (high)	≥97th percentile ERC (extreme)
Contemporary (1992–2010)	11% (40 d/yr)	6% (23 d/yr)	2% (7 d/yr)
Future (2030–2059)	14% (53 d/yr)	9% (31 d/yr)	3% (12 d/yr)
Mean difference	3% (12 d/yr)	2% (8 d/yr)	1% (5 d/yr)

Note: ERC, energy release component.

mid-century period 2030–2059, resulting in a modeled increase in the number of large fires, the area of individual fires, and changes in landscape burn probability. The mechanism for increased fire activity was the combination of decreased precipitation, decreased or static relative humidity, and increased average temperature during the climatic fire season (approximately June–September), which drove low fuel moistures and provided conditions conducive for successful ignitions and rapid fire spread. Increases in fire activity were particularly pronounced in areas dominated by grass and shrubland vegetation, such as in the southern part of the study area where grasses, sagebrush, and open ponderosa pine dominate, as compared with areas dominated by closed-canopy mesic mixed-conifer forests.

FSim models the location of fires as a stochastic process. Ignition locations vary among simulations, so that an area that burns once in one simulation may not burn again in another model run even if all other settings are the same. Regions within the simulation area that show small increases or decreases in burn probability with future climate may be reflecting this stochasticity, rather than the effects of climate-driven changes in fuels or daily weather. In contrast, larger magnitude changes in burn probability likely occur as the result of projected changes in climate.

Modeled changes in fire characteristics—increased fire size, annual area burned, the number of large fires, and decreased fire intervals—may pose some of the greatest ecological and management challenges of the future. Dry forests, shrublands, and grasslands in the study region exist in a state of "fire deficit" (Marlon et al. 2012). The exclusion of fire from the region's fire-prone, forested biomes has increased surface and canopy fuel loads and canopy cover in forested systems, shifted the composition of mature forests toward late seral, shade-tolerant, nonfire-adapted species, and hindered the regeneration of fire-adapted species

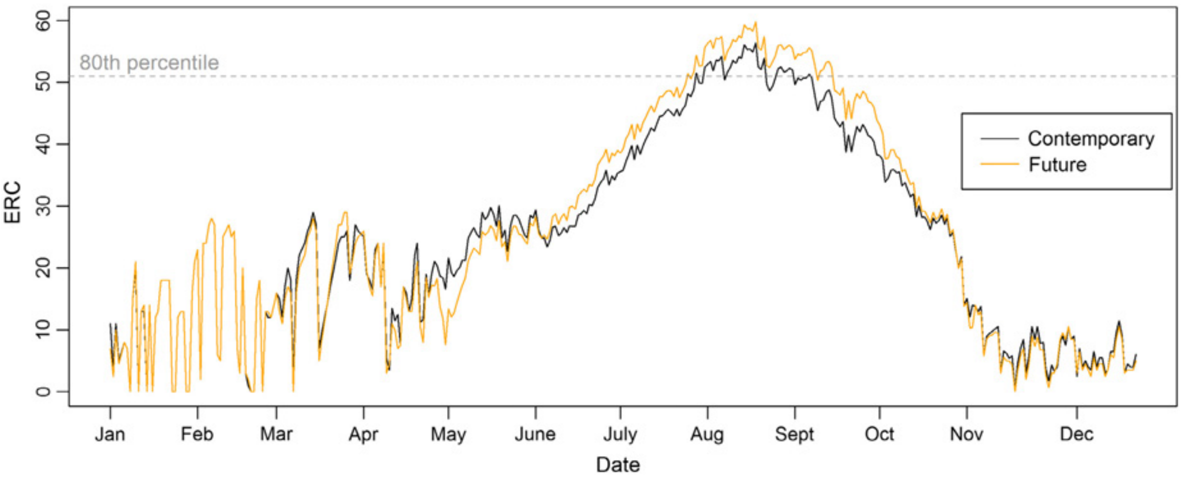

Fig. 10. Mean daily energy release component (ERC) based on contemporary weather at the Potlatch weather station (black) and predicted future ERCs (orange).

such as ponderosa pine, which requires exposed mineral soil for regeneration (Agee 1998, Taylor and Skinner 2003, Peterson et al. 2005). In shrubland and grassland areas, historically frequent surface fires prevented encroachment by trees and maintained heterogeneous plant communities (Heyerdahl et al. 2006). Thus, fire-prone, fire-adapted ecosystems from which fires have been excluded for 100-plus years may be considered highly stressed systems that are potentially at risk for the replacement of fire-adapted species, decreased heterogeneity and altered landscape composition, high-severity fire as the result of increased fuel loads, and increased tree mortality from drought, insects, and other stressors (Loehman et al. 2011*b*, 2014, Keane et al. 2015*a*). Reintroduction of fire to these systems may reduce future crown fire potential and tree mortality by reducing surface fuel loads and increasing vertical and horizontal canopy separation (Stephens et al. 2009), thereby restoring historical climate–fire–vegetation relationships. However, areas that are highly departed from historical fire regimes, fuels, and canopy structure or where climate changes and/or human activities have introduced disequilibrium conditions (i.e., where changes in vegetation composition and fuel load lag behind directional changes in climate; Sprugel 1991, Parks et al. 2016) may be rapidly and persistently altered by wildfires, especially those that burn under extreme conditions (e.g., hot and dry weather, high winds).

At the wildland–urban interface (WUI), higher population density and altered fuels and forest structure have already created forest conditions that are likely to experience an increase in area burned and potentially more high-severity fire than in the historical record (Dillon et al. 2011). Future expansion of the WUI and its resident population, further changes in fuels and forests, and increased frequency and duration of weather conducive to large fires will likely further increase large fire risk in WUI areas by mid-century (Williams 2015). Existing fire suppression resources are likely to be strained, especially in years with regionally synchronous fires, and unless operational capacity is increased the current system will not likely be able to handle increased numbers of fires (Wotton and Stocks 2006, Calkin et al. 2015). Should a disproportionate number of fires escape initial attack under the extreme weather conditions modeled here, area burned may increase more dramatically and at a faster rate than suggested by fire danger ratings (Flannigan et al. 2009).

We modeled a mid-21st-century increase in climatic fire season length (12 d/yr, ERCs above the 80th percentile), days with high fire potential (8 d/yr, ERCs above the 90th percentile), and extreme fire potential (5 d/yr, ERCs above the 97th percentile). Future ERCs were elevated earlier in spring and later in fall, lengthening the climatic fire season and increasing the potential for fire spread and larger annual area burned. For fire managers, ERC is an indicator of fire intensity potential and is used in fire planning and economics. Higher ERCs are often associated with larger, more expensive fires (Gebert et al. 2007). Increased fire activity and more extreme fire behavior associated with periods of elevated ERC may significantly increase the cost and complexity of future fire management activities, requiring new strategies to maintain desired ecological conditions and limit fire risk (Brown et al. 2004, Ager et al. 2010).

Model assumptions and limitations

Projections of future climate are uncertain because trajectories of climate change and the severity of its impacts depend strongly on societal policies and actions (Mach et al. 2016). Further, global climate models and their downscaled products may not accurately represent climate and weather at the regional and local scales that influence fire occurrence and behavior. For example, although associations between fire and quasiperiodic patterns such as ENSO and PDO have been identified, there is incomplete understanding of how these will respond to climate warming (McKenzie et al. 2004, Chen et al. 2016). In addition, precipitation trends are highly variable and projections of future precipitation reflect both high uncertainty and high variation (Murphy et al. 2004). However, ensemble mean estimates of future climate are often considered more robust than single model estimates, especially where the membership of the ensemble has been limited to models that perform best for a particular region (Littell et al. 2011*b*). Wind greatly affects fire spread, and future work could be enhanced by using downscaled projections of wind speed and direction under future projected climate if those become available. Lightning, an important ignition source for wildland fires, may increase in the future, thus increasing the potential for fire activity; for example, recent projections suggest that lightning strikes in the continental United States may increase by about 50% over the 20th century as the result of global warming-induced increase in updraft speeds and atmospheric water content (Romps et al. 2014). However, others have concluded that confidence in projections of increased thunderstorms and severe local weather events is low (Seneviratne et al. 2012).

The FSim results presented here are subject to these and a number of other assumptions and limitations. Our results presume that the relationship between ERC and ignition probability will be the same in the future, although this relationship varies across different climate and vegetation regimes and must be parameterized for local conditions. We assumed that the effectiveness of fire suppression forces will be similar in the future, but a number of factors could affect suppression effectiveness including changes in availability of suppression resources, new suppression technologies, or different suppression policies. Extreme weather conditions not observed in the historical record and climate- and human-induced changes to vegetation and fuels can influence suppression effectiveness, fire patterns, and fire behavior. Because we used the same landscape file (topography, fuels, and vegetation structural information) for contemporary and mid-century simulations, our results do not reflect potential reciprocal interactions among climate, vegetation, and wildfire, although we acknowledge the importance of these complex and potentially nonlinear relationships and feedbacks (Falk et al. 2007, Kitzberger et al. 2012, Svenning and Sandel 2013, Loehman et al. 2016). However, given the strong observed relationships between wildfire and climate in the Northern Rockies, and the tight coupling of fire danger (ERC) and area burned, our projections of increased fire activity under warmer, drier fire season conditions projected for mid-century are reasonable, at least until sufficient fire activity limits fuel amount and vertical and horizontal continuity. These results highlight potential shifts in timing, extent, and spatial arrangement of increased fire activity that may impact or overwhelm fire management capacity to manage future landscapes using the same strategies and tactics currently in place.

Conclusions

Simulations of wildfire ignition and growth under projected mid-21st-century climate indicated an increase in annual burn probability of about 48% for the Northern Rockies study area. Increased burn probability was driven by several factors: (1) an increased number of ignitions due to an annually longer period of hot, dry weather, (2) lower fuel moistures and resulting rapid fire growth, and (3) an increased number of days with moderate to extreme fire weather. Here, we develop a method that facilitates simulation of large fire spread under future climates using the FSim model (chosen for its strengths in realistically simulating fire ignition, spread, and containment). This method can be easily replicated in other study areas or using alternative climate change scenarios. Modeled increases in burn probability, the number of large fires, and climatic fire season length have implications for land management planning and national fire suppression budgets and indicate possible shifts in vegetation assemblages. This study furthers current knowledge about future changes in the occurrence of large wildfires, but more work is needed in order to incorporate the impact on fire occurrence of potential changes in vegetation assemblies, ecological impacts of increased fire activity or more severe fires, and potential changes in ignition patterns, wind speeds, and other climate uncertainties.

Acknowledgments

We thank Jessica Haas for in-depth discussions that contributed to the methods presented here. Region 1 of the U.S. Forest Service provided partial funding for the project. We appreciate comments by Dr. Faith Ann Heinsch and two anonymous reviewers who helped improve this manuscript. Any use of trade names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Literature Cited

Abatzoglou, J. T., and T. J. Brown. 2012. A comparison of statistical downscaling methods suited for wildfire applications. International Journal of Climatology 32:772–780.

Agee, J. 1993. Fire ecology of Pacific Northwest forests. Island Press, Washington, D.C., USA.

Agee, J. K. 1998. The landscape ecology of western forest fire regimes. Northwest Science 72:24–34.

Ager, A. A., N. M. Vaillant, and M. A. Finney. 2010. A comparison of landscape fuel treatment strategies to mitigate wildland fire risk in the urban interface and preserve old forest structure. Forest Ecology and Management 259:1556–1570.

Andrews, P. L. 1986. BEHAVE: fire behavior prediction and fuel modeling system-BURN subsystem, Part 1. General Technical Report INT-194. U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, Utah, USA.

Andrews, P. L., D. O. Loftsgaarden, and L. S. Bradshaw. 2003. Evaluation of fire danger rating indexes using logistic regression and percentile analysis. International Journal of Wildland Fire 12:213–226.

Bachelet, D., R. P. Neilson, T. Hickler, R. J. Drapek, J. M. Lenihan, M. T. Sykes, B. Smith, S. Sitch, and K. Thonicke. 2003. Simulating past and future dynamics of natural ecosystems in the United States. Global Biogeochemical Cycles 17:1045.

Bachelet, D., T. Sheehan, K. Ferschweiler, and J. Abatzoglou. In press. Simulating vegetation change, carbon cycling and fire over the western US using CMIP5 climate projections. Pages 257–276 *in* K. L. Riley, M. P. Thompson, and P. Webley, editors. Uncertainty in natural hazards: modeling and decision support. Wiley and American Geophysical Union Books, New York, New York, USA.

Barbero, R., J. T. Abatzoglou, N. K. Larkin, C. A. Kolden, and B. Stocks. 2015. Climate change presents increased potential for very large fires in the contiguous United States. International Journal of Wildland Fire 24:892–899.

Bradshaw, L., and E. McCormick. 2000. FireFamily Plus user's guide, version 2.0. Gen. Tech. Rep. RMRS-GTR-67WWW. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ogden, Utah, USA.

Brown, T. J., B. L. Hall, and A. L. Westerling. 2004. The impact of twenty-first century climate change on wildland fire danger in the western United States: an applications perspective. Climatic Change 62: 365–388.

Calkin, D. E., A. A. Ager, M. P. Thompson, M. A. Finney, D. C. Lee, T. M. Quigley, C. W. McHugh, K. L. Riley, and J. Gilbertson-Day. 2011. A comparative risk assessment framework for wildland fire management: the 2010 Cohesive Strategy Science Report. RMRS-GTR-262. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado, USA.

Calkin, D. E., M. P. Thompson, and M. A. Finney. 2015. Negative consequence of positive feedbacks in US wildfire management. Forest Ecosystems 2:9.

Chen, Y., D. C. Morton, N. Andela, L. Giglio, and J. T. Randerson. 2016. How much global burned area can be forecast on seasonal time scales using sea surface temperatures? Environmental Research Letters 11:045001.

Cohen, J. D., and J. E. Deeming. 1985. The national fire-danger rating system: basic equations. Gen. Tech. Rep. PSW-82. U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, California, USA.

Deeming, J. E., R. E. Burgan, and J. D. Cohen. 1984. The 1978 national fire-danger rating system: technical documentation. U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, Utah, USA.

Dillon, G. K., Z. A. Holden, P. Morgan, M. A. Crimmins, E. K. Heyerdahl, and C. H. Luce. 2011. Both topography and climate affected forest and woodland burn severity in two regions of the western US, 1984 to 2006. Ecosphere 2:1–33.

Fagre, D. B., and D. L. Peterson. 2000. Ecosystem dynamics and disturbance in mountain wildernesses: assessing vulnerability of natural resources to change. Pages 74–81 *in* S. F. McCool, D. N. Cole, W. T. Borrie, and J. O'Loughlin, editors. Wilderness science in a time of change. Vol. 3: wilderness as a place for scientific inquiry. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ogden, Utah, USA.

Falk, D. A., C. Miller, D. McKenzie, and A. E. Black. 2007. Cross-scale analysis of fire regimes. Ecosystems 10:809–823.

Finney, M. A. 2002. Fire growth using minimum travel time methods. Canadian Journal of Forest Research 32:1420–1424.

Finney, M., I. C. Grenfell, and C. W. McHugh. 2009. Modeling containment of large wildfires using generalized linear mixed-model analysis. Forest Science 55:249–255.

Finney, M. A., C. W. McHugh, I. Grenfell, and K. L. Riley. 2010. Continental-scale simulation of burn probabilities, flame lengths, and fire size distribution for the United States. Page 12 *in* D. X. Viegas, editor. Proceedings of the VI International Conference on Forest Fire Research. University of Coimbra, Coimbra, Portugal.

Finney, M. A., C. W. McHugh, I. C. Grenfell, K. L. Riley, and K. C. Short. 2011. A simulation of probabilistic wildfire risk components for the continental United States. Stochastic Environmental Research and Risk Assessment 25:973–1000.

Flannigan, M. D., B. D. Amiro, K. A. Logan, B. J. Stocks, and B. M. Wotton. 2006. Forest fires and climate change in the 21st century. Mitigation and Adaptation Strategies for Global Change 11:847–859.

Flannigan, M. D., M. A. Krawchuk, W. J. de Groot, B. M. Wotton, and L. M. Gowman. 2009. Implications of changing climate for global wildland fire. International Journal of Wildland Fire 18:483–507.

Fosberg, M. A., and J. E. Deeming. 1971. Derivation of the one-and ten-hour timelag fuel moisture calculations for fire-danger rating. 207. U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Research Note RM-207, Fort Collins, Colorado, USA.

Gebert, K. M., D. E. Calkin, and J. Yoder. 2007. Estimating suppression expenditures for individual large wildland fires. Western Journal of Applied Forestry 22:188–196.

Grenfell, I. C., M. Finney, and M. Jolly. 2010. Simulating spatial and temporally related fire weather. Page 9 *in* Proceedings of the VI International Conference on Forest Fire Research. University of Coimbra, Coimbra, Portugal.

Hejl, S. J., R. L. Hutto, C. R. Preston, and D. M. Finch. 1995. Effects of silvicultural treatments in the Rocky Mountains. Page 220 *in* T. E. Martin and D. M. Finch, editors. Ecology and management of Neotropical migratory birds, a synthesis and review of critical issues. Oxford University Press, New York, New York, USA.

Heyerdahl, E. K., R. F. Miller, and R. A. Parsons. 2006. History of fire and Douglas-fir establishment in a savanna and sagebrush–grassland mosaic, southwestern Montana, USA. Forest Ecology and Management 230:107–118.

Heyerdahl, E. K., P. Morgan, and J. P. Riser. 2008. Multi-season climate synchronized historical fires in dry forests (1650–1900), northern Rockies, USA. Ecology 89:705–716.

Higuera, P. E., J. T. Abatzoglou, J. S. Littell, and P. Morgan. 2015. The changing strength and nature of fire-climate relationships in the northern Rocky Mountains, USA, 1902–2008. PLoS ONE 10: e0127563.

Holsinger, L., R. E. Keane, D. J. Isaak, L. Eby, and M. K. Young. 2014. Relative effects of climate change and wildfires on stream temperatures: a simulation modeling approach in a Rocky Mountain watershed. Climatic Change 124:191–206.

Jolly, W. M., M. A. Cochrane, P. H. Freeborn, Z. A. Holden, T. J. Brown, G. J. Williamson, and D. M. Bowman. 2015. Climate-induced variations in global wildfire danger from 1979 to 2013. Nature Communications 6:1–11.

Keane, R. E., G. J. Cary, I. D. Davies, M. D. Flannigan, R. H. Gardner, S. Lavorel, J. M. Lenihan, C. Li, and T. S. Rupp. 2004. A classification of landscape fire succession models: spatial simulations of fire and vegetation dynamics. Ecological Modelling 179:3–27.

Keane, R. E., R. Loehman, J. Clark, E. A. Smithwick, and C. Miller. 2015*a*. Exploring interactions among multiple disturbance agents in forest landscapes: simulating effects of fire, beetles, and disease under climate change. Pages 201–231 *in* A. H. Perera, T. K. Remmel, and L. J. Buse, editors. Simulation modeling of forest landscape disturbances. Springer International Publishing, Cham, Switzerland.

Keane, R. E., D. McKenzie, D. A. Falk, E. A. Smithwick, C. Miller, and L.-K. B. Kellogg. 2015*b*. Representing climate, disturbance, and vegetation interactions in landscape models. Ecological Modelling 309:33–47.

Kitzberger, T., E. Aráoz, J. H. Gowda, M. Mermoz, and J. M. Morales. 2012. Decreases in fire spread probability with forest age promotes alternative community states, reduced resilience to climate variability and large fire regime shifts. Ecosystems 15:97–112.

Krawchuk, M. A., M. A. Moritz, M. A. Parisien, J. Van Dorn, and K. Hayhoe. 2009. Global pyrogeography: the current and future distribution of wildfire. PLoS ONE 4:e5102.

LANDFIRE. 2008*a*. Existing vegetation type layer, LANDFIRE 1.1.0. U.S. Department of Agriculture, Forest Service and U.S. Department of Interior, U.S. Geologic Survey. http://www.landfire.gov/index.php

LANDFIRE. 2008*b*. Fire regime group layer, LANDFIRE 1.1.0. U.S. Department of Agriculture, Forest Service and U.S. Department of the Interior, U.S. Geologic Survey. http://www.landfire.gov/index.php

LANDFIRE. 2013. Homepage of the LANDFIRE Project. U.S. Department of Agriculture, Forest Service and U.S. Department of the Interior, U.S. Geologic Survey. http://www.landfire.gov/index.php

Littell, J. S., M. M. Elsner, G. Mauger, E. Lutz, A. F. Hamlet, and E. Salathé. 2011*a*. Regional climate and hydrologic change in the northern US Rockies and Pacific Northwest: internally consistent projections of future climate for resource management. Climate Impacts Group, College of the Environment, University of Washington, Seattle, Washington, USA.

Littell, J. S., D. L. McKenzie, B. K. Kerns, S. Cushman, and C. G. Shaw. 2011*b*. Managing uncertainty in climate-driven ecological models to inform adaptation to climate change. Ecosphere 2:102.

Littell, J. S., D. McKenzie, D. L. Peterson, and A. L. Westerling. 2009. Climate and wildfire area burned in western US ecoprovinces, 1916–2003. Ecological Applications 19:1003–1021.

Loehman, R. A., J. A. Clark, and R. E. Keane. 2011*a*. Modeling effects of climate change and fire management on western white pine (*Pinus monticola*) in the northern Rocky Mountains, USA. Forests 2:832–860.

Loehman, R. A., A. Corrow, and R. E. Keane. 2011*b*. Modeling climate change and disturbance interactions: effects on whitebark pine (*Pinus albicaulis*) and implications for restoration, Glacier National Park, Montana, USA. Pages 176–189 *in* R. E. Keane, D. F. Tomback, M. P. Murray, and C. Smith, editors. The future of high-elevation, five-needle white pines in western North America: Proceedings of the High Five Symposium. Proceedings RMRS-P-63. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado, USA.

Loehman, R. A., R. E. Keane, L. M. Holsinger, and Z. Wu. 2016. Interactions of landscape disturbances and climate change dictate ecological pattern and process: spatial modeling of wildfire, insect, and disease dynamics under future climates. Landscape Ecology. http://dx.doi.org/10.1007/s10980-016-0414-6

Loehman, R. A., E. Reinhardt, and K. L. Riley. 2014. Wildland fire emissions, carbon, and climate: seeing the forest and the trees – A cross-scale assessment of wildfire and carbon dynamics in fire-prone, forested ecosystems. Forest Ecology and Management 317:9–19.

Mach, K. J., M. D. Mastrandrea, T. E. Bilir, and C. B. Field. 2016. Understanding and responding to danger from climate change: the role of key risks in the IPCC AR5. Climatic Change 136:427–444.

Marlon, J. R., P. Bartlein, C. Carcaillet, D. Gavin, S. Harrison, P. Higuera, F. Joos, M. Power, and I. Prentice. 2008. Climate and human influences on global biomass burning over the past two millennia. Nature Geoscience 1:697–702.

Marlon, J. R., P. J. Bartlein, D. G. Gavin, C. J. Long, R. S. Anderson, C. E. Briles, K. J. Brown, D. Colombaroli, D. J. Hallett, and M. J. Power. 2012. Long-term perspective on wildfires in the western USA. Proceedings of the National Academy of Sciences 109:E535–E543.

Marlon, J. R., et al. 2009. Wildfire responses to abrupt climate change in North America. Proceedings of the National Academy of Sciences 106: 2519–2524.

McKenzie, D., G. Ze'ev, D. Peterson, and P. Mote. 2004. Climatic change, wildfire, and conservation. Conservation Biology 18:890–902.

Miller, C., J. Abatzoglou, T. Brown, and A. D. Syphard. 2011. Wilderness fire management in a changing environment. Pages 269–294 *in* The landscape ecology of fire. Springer, New York, New York, USA.

Morgan, P., E. Heyerdahl, and C. Gibson. 2008. Multi-season climate synchronized forest fires throughout the 20th century, northern Rockies, USA. Ecology 89:717–728.

Murphy, J. M., D. M. Sexton, D. N. Barnett, G. S. Jones, M. J. Webb, M. Collins, and D. A. Stainforth. 2004. Quantification of modelling uncertainties in a large ensemble of climate change simulations. Nature 430:768–772.

Naficy, C., A. Sala, E. G. Keeling, J. Graham, and T. H. DeLuca. 2010. Interactive effects of historical logging and fire exclusion on ponderosa pine forest structure in the northern Rockies. Ecological Applications 20:1851–1864.

Nakicenovic, N., et al. 2000. Special report on emissions scenarios: a special report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Parks, S. A., C. Miller, J. T. Abatzoglou, L. M. Holsinger, M.-A. Parisien, and S. Z. Dobrowski. 2016. How will climate change affect wildland fire severity in the western US? Environmental Research Letters 11:035002.

Peterson, D. L., M. C. Johnson, J. K. Agee, T. B. Jain, D. McKenzie, and E. D. Reinhardt. 2005. Forest structure and fire hazard in dry forests of the western United States. Gen. Tech. Rep. PNW-268. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, Oregon, USA.

Riley, K. L., J. T. Abatzoglou, I. C. Grenfell, A. E. Klene, and F. A. Heinsch. 2013. The relationship of large fire occurrence with drought and fire danger indices in the western USA, 1984–2008: the role of temporal scale. International Journal of Wildland Fire 22:894–909.

Rocca, M. E., P. M. Brown, L. H. MacDonald, and C. M. Carrico. 2014. Climate change impacts on fire regimes and key ecosystem services in Rocky Mountain forests. Forest Ecology and Management 327:290–305.

Rollins, M. G. 2009. LANDFIRE: a nationally consistent vegetation, wildland fire, and fuel assessment. International Journal of Wildland Fire 18:235–249.

Romps, D. M., J. T. Seeley, D. Vollaro, and J. Molinari. 2014. Projected increase in lightning strikes in the United States due to global warming. Science 346:851–854.

Running, S. W. 2006. Is global warming causing more, larger wildfires? Science 313:927–928.

Schoennagel, T., T. T. Veblen, and W. H. Romme. 2004. The interaction of fire, fuels, and climate across Rocky Mountain forests. BioScience 54:661–676.

Scott, J. H., and R. E. Burgan. 2005. Standard fire behavior fuel models: a comprehensive set for use with Rothermel's surface fire spread model. Gen. Tech. Rep RMRS-GTR-153. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado, USA.

Seidl, R., P. M. Fernandes, T. F. Fonseca, F. Gillet, A. M. Jönsson, K. Merganicová, S. Netherer, A. Arpaci, J. D. Bontemps, and H. Bugmann. 2011. Modelling natural disturbances in forest ecosystems: a review. Ecological Modelling 222:903–924.

Seneviratne, S. I., N. Nicholls, D. Easterling, C. Goodess, S. Kanae, J. Kossin, Y. Luo, J. Marengo, K. McInnes, and M. Rahimi. 2012. Changes in climate extremes and their impacts on the natural physical environment. Pages 109–230 *in* C. Field, V. Barros, T. Stocker, D. Qin, D. Dokken, K. Ebi, M. Mastrandrea, K. Mach, G.-K. Plattner, S. Allen, M. Tignor, and P. Midgley, editors. Managing the risks of extreme events and disasters to advance climate change adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK.

Sheehan, T., D. Bachelet, and K. Ferschweiler. 2015. Projected major fire and vegetation changes in the Pacific Northwest of the conterminous United States under selected CMIP5 climate futures. Ecological Modelling 317:16–29.

Short, K. 2014. A spatial database of wildfires in the United States, 1992–2011. Earth System Science Data 6:1–27.

Sprugel, D. G. 1991. Disturbance, equilibrium, and environmental variability: What is 'natural' vegetation in a changing environment? Biological Conservation 58:1–18.

Stephens, S. L., J. J. Moghaddas, C. Edminster, C. E. Fiedler, S. Haase, M. Harrington, J. E. Keeley, E. E. Knapp, J. D. McIver, and K. Metlen. 2009. Fire treatment effects on vegetation structure, fuels, and potential fire severity in western US forests. Ecological Applications 19:305–320.

Svenning, J.-C., and B. Sandel. 2013. Disequilibrium vegetation dynamics under future climate change. American Journal of Botany 100:1266–1286.

Taylor, A. H., and C. N. Skinner. 2003. Spatial patterns and controls on historical fire regimes and forest structure in the Klamath Mountains. Ecological Applications 13:704–719.

Thompson, M. P., J. R. Haas, M. A. Finney, D. E. Calkin, M. S. Hand, M. J. Browne, M. Halek, K. C. Short, and I. C. Grenfell. 2015. Development and application of a probabilistic method for wildfire suppression cost modeling. Forest Policy and Economics 50:249–258.

Werth, P. A., B. E. Potter, C. B. Clements, M. Finney, S. L. Goodrick, M. E. Alexander, M. G. Cruz, J. A. Forthofer, and S. S. McAllister. 2011. Synthesis of knowledge of extreme fire behavior: Volume I for fire managers. Gen. Tech. Rep. PNW-GTR-854. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, Oregon, USA.

Westerling, A. L., H. G. Hidalgo, D. R. Cayan, and T. W. Swetnam. 2006. Warming and earlier spring increase western U.S. forest wildfire activity. Science 313:940–943.

Westerling, A. L., M. G. Turner, E. A. H. Smithwick, W. H. Romme, and M. G. Ryan. 2011. Continued warming could transform Greater Yellowstone fire regimes by mid-21st century. Proceedings of the National Academy of Sciences 108:13165–13170.

Williams, H. L. 2015. Economic efficiency of fuel reduction treatments in the home ignition zone to mitigate wildfire risk in Montana, USA. Master's thesis. College of Forestry and Conservation, University of Montana, Missoula, Montana, USA.

Wotton, B., and B. Stocks. 2006. Fire management in Canada: vulnerability and risk trends. Pages 49–55 *in* Canadian wildland fire strategy: background synthesis, analysis, and perspectives. Canadian Council of Forest Ministers, Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, Edmonton, Alberta, Canada.