Direct and indirect effects of climate change on projected future fire regimes in the western United States

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ABSTRACT

We asked two research questions: (1) What are the relative effects of climate change and climate-driven vegetation shifts on different components of future fire regimes? (2) How does incorporating climate-driven vegetation change into future fire regime projections alter the results compared to projections based only on direct climate effects? We used the western United States (US) as study area to answer these questions. Future (2071-2100) fire regimes were projected using statistical models to predict spatial patterns of occurrence, size and spread for large fires (> 400 ha) and a simulation experiment was conducted to compare the direct climatic effects and the indirect effects of climate-driven vegetation change on fire regimes. Results showed that vegetation change amplified climate-driven increases in fire frequency and size and had a larger overall effect on future total burned area in the western US than direct climate effects. Vegetation shifts, which were highly sensitive to precipitation pattern changes, were also a strong determinant of the future spatial pattern of burn rates and had different effects on fire in currently forested and grass/shrub areas. Our results showed that **c**limate-driven vegetation change can exert strong localized effects on fire occurrence and size, which in turn drive regional changes in fire regimes. The effects of vegetation change for projections of the geographic patterns of future fire regimes may be at least as important as the direct effects of climate change, emphasizing that accounting for changing vegetation patterns in models of future climate-fire relationships is necessary to provide accurate projections at continental to global scales.

Keywords: disturbance; fire; Western United States; model; climate change; Random Forests; vegetation dynamics

1 Introduction

Climate is a major control on fire regimes in many terrestrial ecosystems (Bowman *et al.*, 2009), and climatic variation interacts with fire over multiple temporal scales (Bradstock, 2010; Hessl, 2011). Short-term climatic anomalies directly affect subsequent fire behavior and effects through their influences on fuel moisture and fine fuel accumulation. Direct climate-fire linkages with lagged effects ranging from a few weeks to multiple years have been documented in studies of the temporal patterns of historical fire occurrence in the western US (Westerling *et al.*, 2006; Littell *et al.*, 2009; Abatzoglou & Kolden, 2013; Morton *et al.*, 2013), and these types of relationships have provided the basis for predictive models that have almost ubiquitously projected increased fire frequency and burned area in coming decades as a result of future warming (Flannigan *et al.*, 2009; Moritz *et al.*, 2012). However, such projections typically do not consider the effects of climate-driven vegetation change, which represents a more gradual, indirect influence of climate on fire regimes (Bowman *et al.*, 2014). Paleoecological research has shown that vegetation strongly mediates climate-fire relationship by altering landscape patterns of vegetation and fuels (Hu *et al.*, 2006; Higuera *et al.*, 2009; Belcher *et al.*, 2010). Studies of fire regimes in boreal Canada have also showed strong indirect effects of vegetation on climate-fire relationships, even where fuel amount and continuity were not expected to be limiting factors in these systems (Heon *et al.*, 2014; Parisien *et al.*, 2014; Wang *et al.*, 2014b). Disentangling the relative influences of direct climate effects from climate-driven vegetation change on fire regimes represents an important first step toward a more comprehensive understanding of climate-vegetation-fire interactions and improved projections of future fire regimes (Bowman *et al.*, 2014).

The rate of burning, commonly expressed as a fire return interval or area burned per unit time, is a common metric to characterize the variability of fire regimes in space and time (Gill & Allan, 2008). Both the fire frequency and fire size distribution influence the rate of burning, with the largest fires often making a disproportionately large contribution to the total area burned. Westerling *et al.* (2006) showed that increased frequency of large fires (>400 ha) was a major driver of the increase in total burned forest area from 1970 - 2003 in the western United States (US). Luo *et al.* (2013) found that August 2012 had the largest burned area of any August since 2000 in the western US because of the occurrence of several particularly large fires, even though fire frequency was relatively low. In contrast, Balch *et al.* (2013) found that changes in both fire frequency and size substantially influenced the regional fire regime across the Great Basin of the western US. Kasischke *et al.* (2002) also found that both numbers and sizes of large fire (>400 ha) increased substantially during high fire years in Alaska. A recent analysis of wildfires in the western US from 1984-2010 found that short-term climate anomalies were most strongly associated with large (> 400 ha) fire frequency, whereas vegetation types was strongly associated with the fire size distribution (Liu & Wimberly, 2015). Taken as a whole, these studies suggested that fire frequency and size can respond independently to different aspects of climate change, and thus result in future fire regimes that have no historical analog (Whitman *et al.*, 2015). Therefore, modeling how multiple components of the fire regime respond to direct and indirect climate change, as well as other landscape controls, can enhance our ability to anticipate future fire regimes (Krawchuk & Moritz, 2014).

In this study we developed an empirically-calibrated, individual-fire model that simulated the effects of climate and vegetation change on fire occurrence, size distributions, and spread patterns. The western US was selected as a study area because fire is an important component of most ecosystems and also has significant socioeconomic impacts within the region (Keane *et al.*, 2008). Dramatic changes in climate, vegetation, and fire regimes are expected in the next several decades (McKenzie *et al.*, 2004), and high-resolution geospatial data on historical wildfires, climate change, and other relevant biophysical and human influences are available for the region. Our overarching hypothesis was that the indirect effects of climate change on the distribution of major vegetation types will have a substantial effect on regional patterns of future fire regimes. Specific research questions included: (1) What are the relative effects of climate change and climate-driven vegetation shifts on different components of future fire regimes, including fire frequency, size, and total burned area? and (2) How does incorporating climate-driven vegetation change into future fire regime projections alter the results compared to projections based only on direct climate effects?

To address these questions, we conducted a modeling experiment to study the responses of fire regime components to climate change and climate-driven shifts in major vegetation types while holding other biophysical and human determinants of fire constant. We used ecological niche models to establish the present-day correlative relationships between current climate and vegetation distributions, and then projected climate-driven shifts of vegetation ranges based on predicted future climate conditions. The aim of the modeling exercise was to explore the sensitivity of projected fire regime patterns to direct and indirect effects of climate change at regional scales rather than to make precise prediction of the future fire regimes. Results showed that projections of future burned areas were indeed sensitive to the indirect effects of climate-driven vegetation change, which substantially increased the amount of future burned area compared to projections based only on direct climate change effects. This finding highlights the need to continue integrating climate effects with changes in vegetation and other landscape characteristics to provide a better understanding and generate more accurate projections of how fire and other ecosystem processes will respond to continuing global change.

2 Material and methods

2.1 Study region

The study area encompassed the Western US, and covered 2 707 515 km^2 (Figure A1). The climate of this region is generally semiarid, although there are maritime climates along the Pacific Coast and abundant precipitation in many inland mountainous areas. Geographic variability in geology, landform, and precipitation supports a high diversity of vegetation types and fire regimes across the region (Hardy *et al.*, 2001). The coastal Pacific Northwest is characterized by high annual precipitation that supports productive forests dominated by large conifers that experience relatively infrequent, high-severity, large wildfires under occasionally extreme drought conditions (Wimberly & Liu, 2014). In contrast, the drier forests ranging from southern Oregon to the Sierra Nevada of California are covered by a variety of forest types dominated by various conifer species with a mixture of different fire regimes (Perry *et al.*, 2011). These forests are characterized by low-severity fires at lower elevations, high-severity stand replacing fires at higher elevations, and mixed-severity fires in between. Significant portions of southern California are characterized by chaparral vegetation that experiences relatively frequent, high severity fires that are strongly influenced by fuel load and connectivity, human development patterns and ignitions, and the occurrence of extreme weather (Jin *et al.*, 2014). The Rockies and other mountain ranges of the interior west have a variety of forest types with species composition and fire regimes strongly influenced by elevation gradients, ranging from frequent, low severity surface fires in more open ponderosa pine and mixed-conifer forests at lower elevations to infrequent, high severity crown fires in denser subalpine forests at higher elevations (Noss *et al.*, 2006). Pinyon pine-juniper woodlands dominate much of the southwestern US and are characterized by infrequent, high-severity wildfires (Romme *et al.*, 2009). Lower elevations in the intermountain West are dominated by drought-adapted vegetation, such as shrubs and grasses, which support a diversity of fire regimes (Knapp, 1998). Fire regimes in the intermountain West are largely fuel-limited, and large fires and higher burn rates are often associated with abundant precipitation in antecedent seasons or years (Littell *et al.*, 2009).

2.2 Fire modeling framework

We developed a spatially-explicit, empirically-calibrated, statistical fire simulation model to examine the sensitivity of fire regimes to direct climate effects and climate-driven vegetation change. This approach used statistical relationships between fire characteristics (i.e., fire occurrence, size and patterns of spread) and environmental drivers to simulate individual fires (Figure 1) and then aggregated individual-fire characteristics to project how fire regimes will respond to environmental change. The fire simulation was driven by three statistical models of fire occurrence probability, fire spread probability, and fire size. These models were based on 1 km gridded datasets of environmental variables, including 30-year climate normals, short-term climate anomalies, major vegetation types, and other biophysical and human variables (Table 1). A modeling experiment was designed to elucidate the direct and indirect effects of climate change on future fire regimes (Table 2). For historical baseline simulations from 1981-2010, we used a regional fire frequency of 230 large fires per year based on the Monitoring Trends in Burn Severity (MTBS) project dataset (Eidenshink *et al.*, 2007). Future fire frequencies under various climate change scenarios were estimated by calculating the mean ratio of projected future fire occurrence probabilities to historical fire occurrence probabilities and multiplying this value by the historical fire frequency (Table 3).

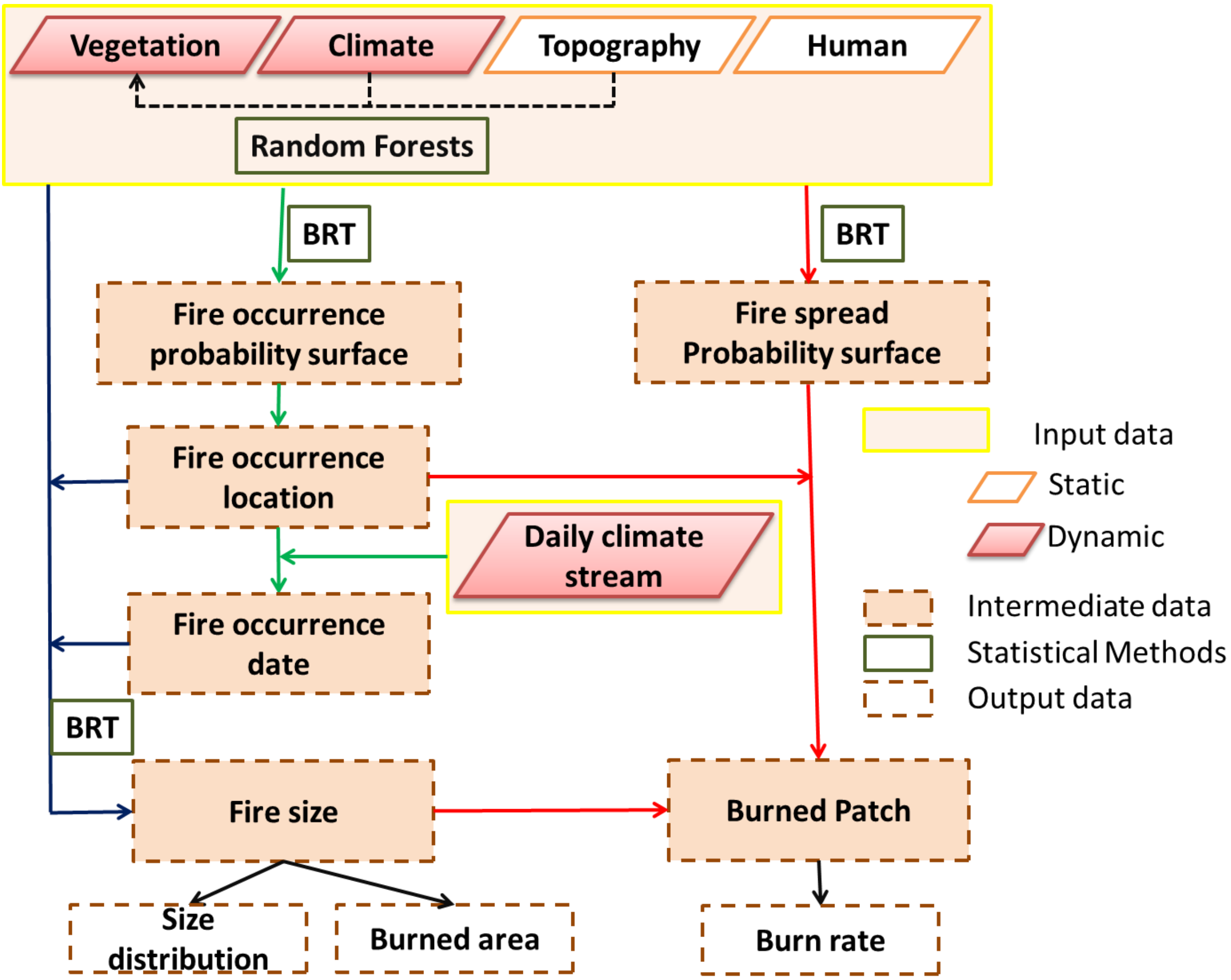

Figure 1: Fire simulation flowchart. Topography and climate data were used to predict current and future vegetation type distributions using the Random Forests algorithm. Processes related to fire occurrence simulations are shown in solid green lines. Processes related to fire size simulations are shown in solid blue lines. Processes related to fire spread simulations are shown in solid red lines.

Table1: Variables used to construct the fire occurrence probability surface, fire size model, and fire spread probability surface using boosted regression tree analysis, and to model the future vegetation type distribution using Random Forests.

Variable	Description
[1,*]TMx (degree)	Maximum temperature during fire spread period
[1,*]TAo (degree)	Temperature anomaly during fire spread period
[1,*]PM (mm)	Mean precipitation during fire spread period
[1,*]PAo (mm)	Precipitation anomaly during fire spread period
[1,*]WMx (m/s)	Maximum wind during fire spread period
[1,*]T90Ao (degree)	Temperature anomaly of 90 days preceding fire start date
[1,*]P90Ao (mm)	Mean precipitation anomaly of 90 days preceding fire start date
[1,*]W90d (m/s)	Mean wind speed of 90 days preceding fire start date
[1,*]TPAo (degree)	Previous year growing season temperature anomaly
[1,*]PPAo (mm)	Previous year growing season precipitation anomaly
[1,*]TWAo (degree)	Previous winter temperature anomaly
[1,*]PWAo (mm)	Previous winter precipitation anomaly
[1,*]TP2GAo (degree)	Growing season temperature anomaly 2 years prior
[1,*]PP2GAo (mm)	Growing season precipitation anomaly 2 years prior
[1,†,‡]Tavg	Mean annual temperature
[1,†,‡]Tjan	Mean January temperature
[1,†,‡]Tmaysep	Mean temperature from May to September

[1,†,‡]PPTavg	Annual precipitation
[1,†,‡]PPTjan	January precipitation
[1,†,‡]PPTmaysep	Precipitation from May to September
[2,‡]TSI	Terrain shape index
[2,‡]Slop (in percent)	Mean slope within fire patch
[2,‡]DEM (m)	Mean elevation within fire patch
[2,‡]RiverD(km*km^{-2})	Mean river density within fire patch
[3,]D2Rd (m)	Distance to nearest road within fire patch
[3,]D2WUI (m)	Distance to Wildland Urban interface within fire patch
[3,]LandOnShp	Land ownership: private, public non-wilderness, wilderness
Vegetation type	Aggregated to 14 vegetation types with distinctive species composition and vegetation structure

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*Fire-specific short-term climate variable used in the fire size models; [†] Long-term climate normals only used for fire occurrence and fire spread probability surface models; [‡] used for vegetation type projection. Land ownership and vegetation type are categorical variables. 1: Climate variables. 2: Topographic variables, 3: Human influence variables.

Table 2: Modeling experiment scenarios in this study

	Baseline (Scenario 1)	Climate change only (Scenario 2)	Climate change plus vegetation shift (Scenario 3)
Purpose	Baseline	Compare with scenario 1 to show the effects of climate change on future fire regime	Compare with scenario 2 to show the effects vegetation change and on future fire regime
Vegetation	Historical	Historical	Future, updated based on future climate normal
Climate	Historical	Future	Future
Fire occurrence probability map	Historical	Future, updated based on future climate normal	Future, updated based on future climate normal and vegetation
Fire size variables	Historical	Future, based on short-term climate variables updated from future daily climate	Future, based on short-term climate variables updated from future daily climate and future vegetation
Fire spread probability map	Historical	Future, updated based on future climate normal	Future, updated based on future climate normal and vegetation

Historical refers to 1981 to 2010; future refers to 2071 to 2100.

Table 3: Simulated fire frequency (number of fires per year), fire size (ha) distribution, and annual total burned area (ha) of different scenarios under GFDL and CNRM climate models.

scenarios	Frequency		Size median± SD		Total burned area median± SD	
	Value	Change (%)	Value	Change (%)	Value	Change (%)
Historical baseline	230		1777±140		650860	
Climate change only (GFDL)	251	+9.1	2365±187	+33	991538±81409	+52
Climate change plus vegetation shift (GFDL)	320	+39.1	2567±177	+45	1405858±132154	+116
Climate change only (CNRM)	244	+6.1	1951±156	+10	833100 ± 102048	+28
Climate change plus vegetation shift (CNRM)	251	+9.1	2311±169	+30	1223610 ± 111598	+88

Fire occurrence was modeled using a two-stage approach. The first stage simulated the spatial location of fires using a fire occurrence probability surface. The fire occurrence probability surface was modeled using boosted regression trees (BRT) (Elith *et al.*, 2008) based on a suite of predictors characterizing long-term climate, vegetation, and other human and physiographic drivers. The second stage simulated the seasonal timing of fire occurrences based on the temporal patterns of fire weather at the fire location. The purpose of this step was to ensure the simulated fires occurred during periods with extreme fire weather conditions. Candidate fire ignition dates were those where temperature was above the 95th percentile and precipitation was below the 1st percentile for a 40-day temporal window because a previous study found that about 40 days with no precipitation and higher-than-normal temperature can reduce live and dead fuel moisture enough to support large fires in the forests of the Rocky Mountains (Schoennagel *et al.*, 2004). When multiple candidate dates were available for a fire occurrence location, the fire starting date was randomly selected from the candidate dates. When no candidate date was available, the temporal window was shortened until a candidate date was available.

Once the location and date of a fire were determined, its size was predicted by the fire size model which was constructed using BRT with a suite of predictors characterizing short-term climate anomalies before the fire and weather conditions during the period of fire spread as well as vegetation, human, and physiographic drivers. Fire spread was then modeled using a probabilistic algorithm, which was based on a weighted spread distance surface calculated from the distance to the fire ignition point and the fire spread probability surface, which characterized the probability of fire spreading into each cell based on historical data. Fire propagated to surrounding cells with the lowest weighted spread distances using an eight-neighbor rule, and extinguished once the predicted size was reached. After all fires were simulated, a burn rate map was generated to describe the spatial pattern of fire by overlaying all the burned patches. A complete description of fire modeling approach can be found in Appendix A.

2.3 Datasets

Wildfire dataset. The perimeters of all large wildfires (>=400 ha) in the western US between 1984 and 2012 were obtained from the MTBS dataset. The dataset was split into training data (1984 – 2010, 6071 fires) and validation data (2011-2012, 594 fires). We used validation data beyond the period of training data because we were interested in the predictive performance of the fire simulation model. The training data were used to produce the fire occurrence probability surface, fire size model, and fire spread probability surface. The validation data were used to evaluate the capabilities of the simulation model to predict spatial and temporal patterns of fires.

Topographic, human influence, vegetation dataset. Topographic variables related to fuel moisture and fire behavior included elevation (meters), slope (percent), terrain shape index, and river density. Human influence factors related to fire ignitions, fire suppression, and forest management policies included major road density, the wildland urban interface (interface and intermix), and land ownership. Vegetation types related to fuel characteristics were derived from Biophysical Setting data from the LANDFIRE project (Rollins, 2009), and were aggregated into 14 major vegetation types with distinctive species composition, vegetation structure, fuels, and fire regimes. These data were resampled to 1 km resolution using the nearest neighbor method for continuous data and the majority rule for categorical data.

Historical Climate (1981 – 2010). Historical daily gridded climate variables included daily maximum and minimum temperature, precipitation, and wind speed at 4 km spatial resolution (Abatzoglou, 2013). Two climate datasets were derived: long-term climate normals and short-term climate variability (Table 1). Long-term climate normals, including annual, January, and growing season temperature and precipitation, were calculated as 30-year averages from 1981 – 2010 and were used to model fire occurrence and spread probability surfaces and vegetation types (Figure B1). Short-term climate variables used in the fire size model included temperature and precipitation anomalies for the 90 days before fires, previous winters (Oct-Mar), and the previous two growing seasons (May-Sep) along with mean and maximum wind speed, temperature, and precipitation during the fire spreading period. The length of the fire spreading period, defined as the time period from fire ignition to extinction was estimated using data from the MTBS project and followed a log-normal distribution with a mean length of 12 days.

Future Climate (2071 - 2100). Future daily gridded climate variables were obtained from the same source as the historical climate data. These projections were bias-corrected and can be used to make direct comparisons with historical climate (Abatzoglou, 2013). Preliminary analysis from 48 climate models resulting from 16 GCMs and 3 CO2 emission scenarios (A2, A1B, B2) based on the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR4) showed a consistent warming trend, but projected future precipitation varied in sign and magnitude in the western US (Figure B2), and similar results have previously been documented (Notaro *et al.*, 2012; Jiang *et al.*, 2013). The projected mean annual temperature increase was 3.32 degree (median = 3.23, 1st quantile = 1.74, 3rd quantile = 4.87), while the projected mean annual precipitation change was 1.32% (median = 1.65, 1st quantile = -3.99, 3rd quantile = 6.97). To capture the uncertainty in future precipitation, we selected two representative GCM projections forced with an A1B emission pathway: Geophysical Fluid Dynamics Laboratory (GFDL) CM 2.1, and Centre National de Recherches Météorologiques (CNRM) CM 3.0. Mean annual temperature increased by 3.67 and 3.33 degrees under GFDL and CNRM, respectively. In contrast, annual precipitation decreased by 25.5 mm (-4.9%) under GFDL but increased by 29.4 mm (5.7%) under CNRM. These two climate models encompassed the range of variation of future precipitation, and therefore its potential effects on vegetation shifts and fire regimes. Comparatively, the CNRM climate projection is hot and wet whereas GFDL is hot and dry (Appendix B). Similar to the historical climate data, long-term climate normals were summarized as 30-year averages from 2071-2100 and used to project the future fire occurrence and spread probability surfaces, as well as future vegetation types. Short-term climatic variables were used to project future fire sizes.

2.4 Future vegetation (2071-2100)

We projected future vegetation type distributions using machine-learning based ecological niche models. Previous studies have suggested that vegetation communities will likely be reassembled under future climate conditions due to individual species’ responses to climate change (Iverson *et al.*, 2008; Iverson & McKenzie, 2013). However, our aim here was to use a relatively straightforward modeling approach to generate a first approximation of future vegetation shifts in order to assess the potential sensitivity of future fire regimes to these changes. The Random Forests algorithm was used to project future vegetation types due to its strong predictive ability when applied to multi-class vegetation modeling problems (Cutler *et al.*, 2007) and its recent successful application for biome shift projection in North America (Rehfeldt *et al.*, 2012). Selection of climatic factors followed previous studies (Iverson *et al.*, 2008; Notaro *et al.*, 2012). Detailed description of the Random Forests algorithm, predictors, parameter settings, and model performance can be found in Appendix C. Cohen's Kappa index, which measures agreement between two multi-class images while taking into account agreement that occurs by chance, was reported to assess the predictive performance (Carletta, 1996).

2.5 Modeling experiment scenarios

Scenario 1: historical baseline (1984-2010): Historical climate data from 1981-2010 and modeled historical vegetation were used to simulate the historical baseline fire size distribution, total burned area, and spatial patterns of burn rate. Fire occurrence year was drawn randomly from 1984 – 2010, which corresponds to the time period of the MTBS training dataset.

Scenario 2: climate change only: This scenario was similar to scenario 1, except (1) fire occurrence location and spread were based on the future long-term climate normals, (2) fire occurrence years were drawn from randomly from 2071 – 2100, and (3) fire sizes were predicted using short-term climate variables from future daily climate data. Vegetation remained unchanged from scenario 1.

Scenario 3: climate change plus vegetation shift: This scenario was similar to scenario 2, except (1) fire occurrence location and spread were based on future long-term climate normal combined with modeled future vegetation, and (2) fire size was predicted from short-term climate variables from future daily climate data combined with modeled future vegetation.

To account for stochasticity of the simulated fire regimes, each scenario was repeated for 500 one-year periods (500 years in total). Direct climate change effects were evaluated by comparing scenarios 1 and 2. Indirect climate change effects resulting from climate-driven vegetation shifts were evaluated by comparing scenarios 2 and 3. The annual fire frequency, fire size distributions, annual total burned area, and spatial pattern of burn rate (number of times burned per 500 years, spatial resolution = 1 km^2) were used as descriptive summaries of the fire regimes. The relative influences of climate and climate-driven vegetation shifts on fire regimes were tested by comparing the difference in burn rate between scenarios 2 and 1, and the difference in burn rate between scenarios 3 and 2 with a Welch's t-test using a random sample of 5000 points on the burn rate map, based on the null hypothesis that their effects are equal at a 0.05 significance level. These tests were made separately for each climate model (GFDL and CNRM) and were compared to assess sensitivity to the different climate models.

2.6 Model validation

We evaluated the capabilities of the fire simulation model to predict spatial and temporal pattern of fire using validation fires that occurred in 2011-2012 (n = 594). To evaluate the spatial pattern of fire occurrence, we divided the historical fire occurrence probability surface into eight equal interval bins and evaluated whether validation fires were more likely to be located in areas of higher occurrence probability. Fire size was evaluated by comparing validation fires with predicted fire sizes generated at the same locations and times as the validation fires. Seasonal patterns of fire were evaluated by comparing simulated fire dates with the dates of the validation fires. Finally, we overlaid validation fire patches on the historical burn rate map to assess the overall ability of the fire simulation model to capture the spatial pattern of fire resulting from fire occurrence, size, and spread over the landscape. To assess the spatial variability of model performance, we divided the study area into forest and nonforest regions based on EPA ecoregion (Figure A1), and examined whether modeled historical burn rates was significantly higher within validation fire patches than outside the validation fire patches.

3 Results

3.1 Historical baseline

Vegetation. The Random Forests algorithm predicted the spatial pattern of vegetation types with moderate accuracy (kappa = 0.65) (Figures 2 a&b). The simulated vegetation distribution tended to have larger and more contiguous patches than the actual distribution. This likely occurred because the predictors did not capture finer-scale environmental heterogeneity and climate variability. Also, shrubland vegetation (e.g., Desert scrub, Sagebrush) was overestimated in southwestern arid and semi-arid regions (Figure 2b). Modeled historical burn rates did not differ significantly between the actual and modeled vegetation type distributions (t = -0.03, df = 6771, p = 0.97). To avoid confounding the effects of vegetation misclassification and vegetation change, we used modeled historical vegetation types in scenarios 1 and 2 as the baseline to examine the effects of climate and vegetation on future fire regimes.

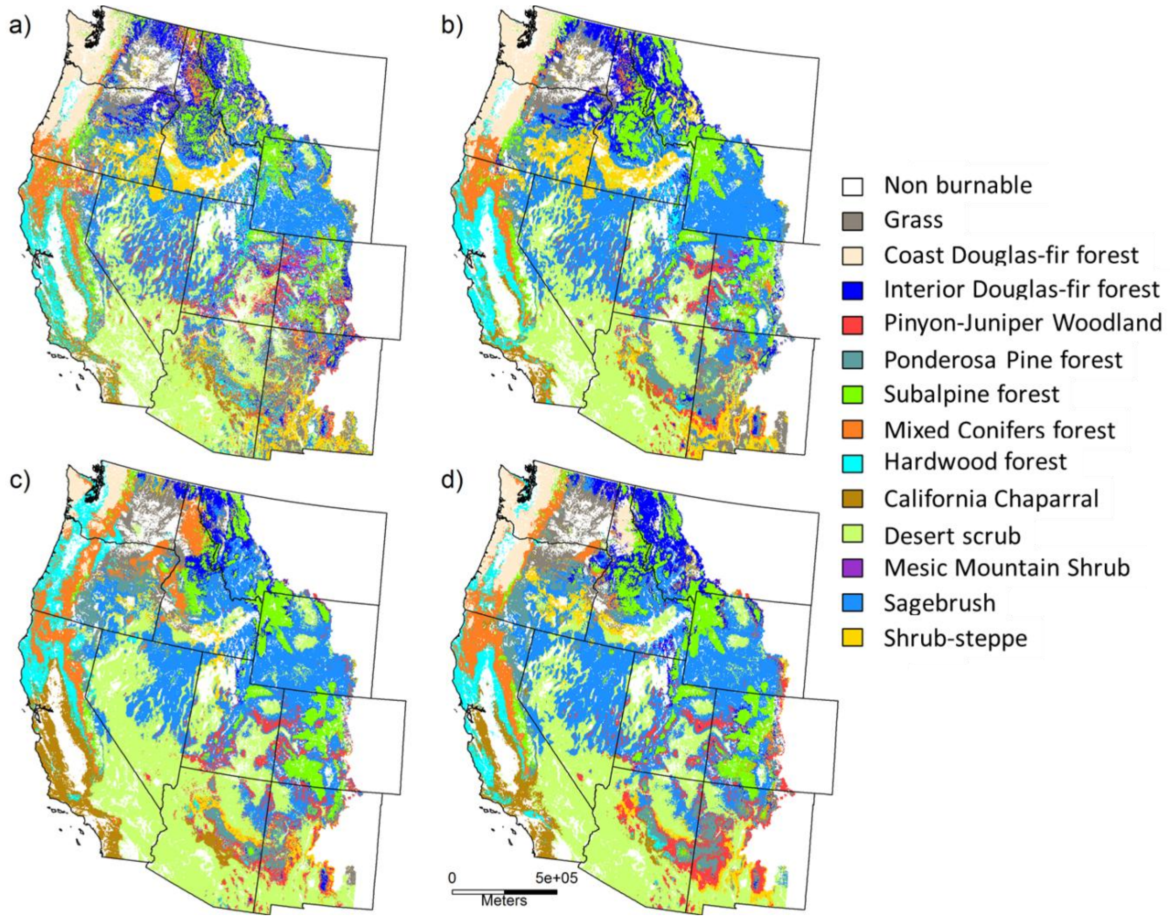

Figure 2 Vegetation type distributions from a) the LANDFIRE dataset; b) predicted historical vegetation using Random Forests (RF); c) predicted future vegetation under the GFDL climate model using RF; d) predicted future vegetation under the CNRM climate model using RF.

Fire simulations. Short-term climate variations, vegetation type, human activities, and topographic factors all had significant influences on fire occurrence and size. The best fire occurrence model yielded an area under the receiver operating characteristic curve (AUC) value of 0.82. Vegetation type had the strongest influence on fire occurrence, and explained 26.3% of the variation, and fires tended to occur in relatively hot and dry locations (Figure A2). Validation fires were more likely to be located in cells with higher fire occurrence probability (Figures A3&3a). The best fire size model explained 76% of the variation. Vegetation type had a strong influence on fire size and explained 9.8% of the variation (Figure A4). Fires tended to be larger when weather was hot and windy during the fire spreading period and when there were periods of drought prior to the fire (Figure A4). The predicted fire size distribution captured the shape of the validation fire size distribution, but had a slightly higher median fire size (Figure 3b). Simulated seasonal patterns of fire provided a reasonable representation of the validation fire distributions in which most fires occurred between May and September (Figure 3c). The spatial distribution of historical burn rate also captured the patterns of burning, with validation fires having significantly higher burn rates than random patches ($t = 2.85$, $df = 323$, $p<0.001$) (Figures 3d & A5). The historical burn rate was also significantly higher within validation fire patches than outside validation fire patches for both forest ($t = 3.50$, $df = 259$, $p<0.001$) and nonforest ($t = 6.18$, $df = 232$, $p<0.001$) regions. These results indicate that our fire simulation model predictions were robust across regions and vegetation types in the western US.

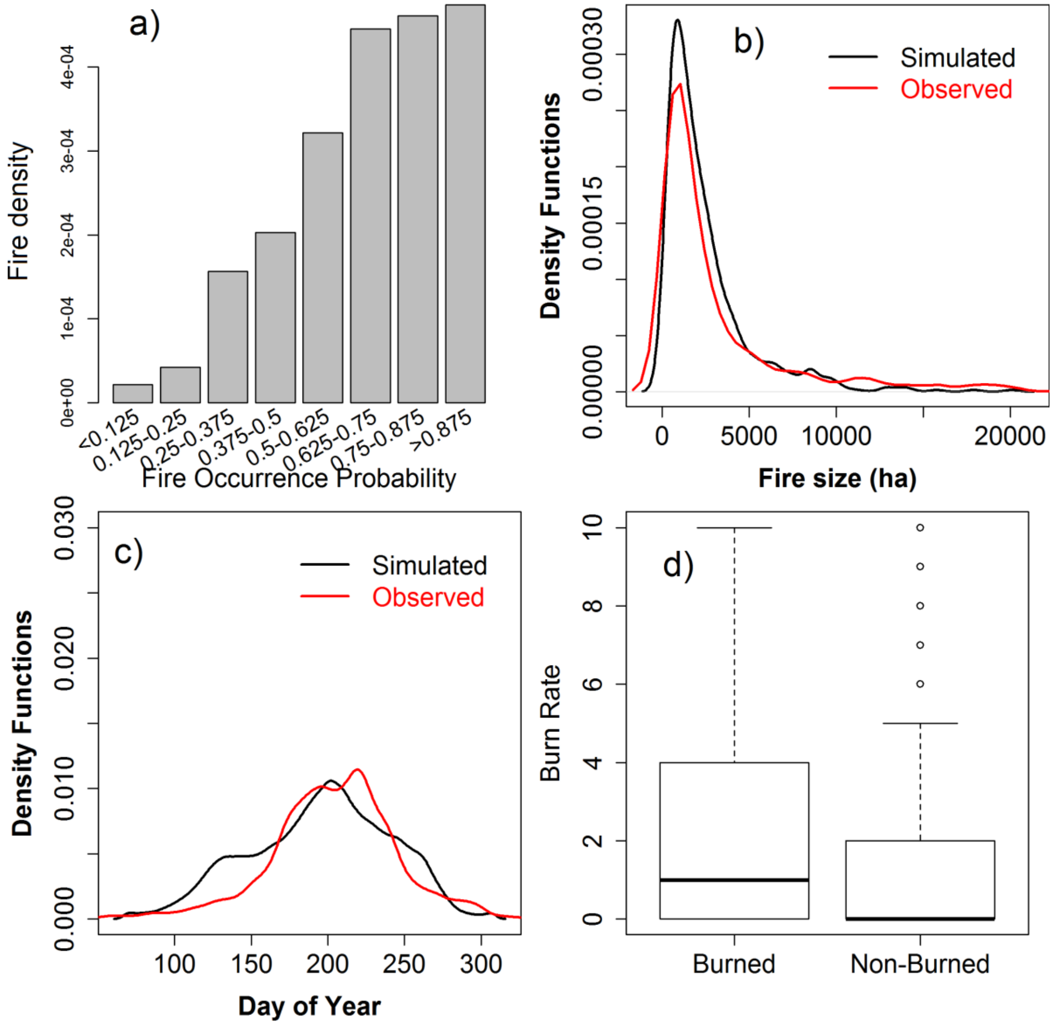

Figure 3: Validation results for (a) fire density by fire occurrence probability; (b) Predicted versus observed size distributions for simulated fires and observed validation fires; (c) Distribution of fire dates for simulated fires versus observed validation fires; and (d) simulated historical (1981 - 2010) burn rates for burned validation fires and non-burned random patches .

3.2 Future vegetation

Overall, 41% and 34% of the study area was projected to experience vegetation type change under GFDL and CNRM climate models, respectively (Figure 4). Both climate models projected significant increases for Desert scrub (from Grass and other Shrubland), California Chaparral (from Hardwood forest), Mixed Conifers forest (from Douglas fir forest), and Pinyon-Juniper Woodland (from Ponderosa Pine forest and Mesic Mountain shrub). There were also significant decreases for Shrub-steppe (to other Shrubland), Coast Douglas-fir forest (to Hardwood and Mixed Conifer forest under the GFDL climate), and Subalpine forest (Figure 4 and Figure C3). Generally, areas of drought-adapted vegetation increased in response to drier future conditions. Similar regional trends were also projected by other studies using different approaches under multiple climate models in the western US (Notaro *et al.*, 2012; Jiang *et al.*, 2013; Hansen & Phillips, 2015).

The spatial pattern of vegetation change was similar between the two climate models, but there were some regional differences (Figures 2 c&d). Along the Pacific Coast, a dramatic expansion of Hardwood forest was projected under the GFDL climate model, but not the CNRM model. In the southern parts of northern Rockies, inland Douglas fir forest was replaced by Mixed Conifers forest under the GFDL climate model, and by Pacific Coastal Douglas fir forest under the CNRM climate model. An examination of the spatial pattern of projected precipitation changes for the GFDL and CNRM models suggested that these disparities were due to differences in precipitation (Figure B3).

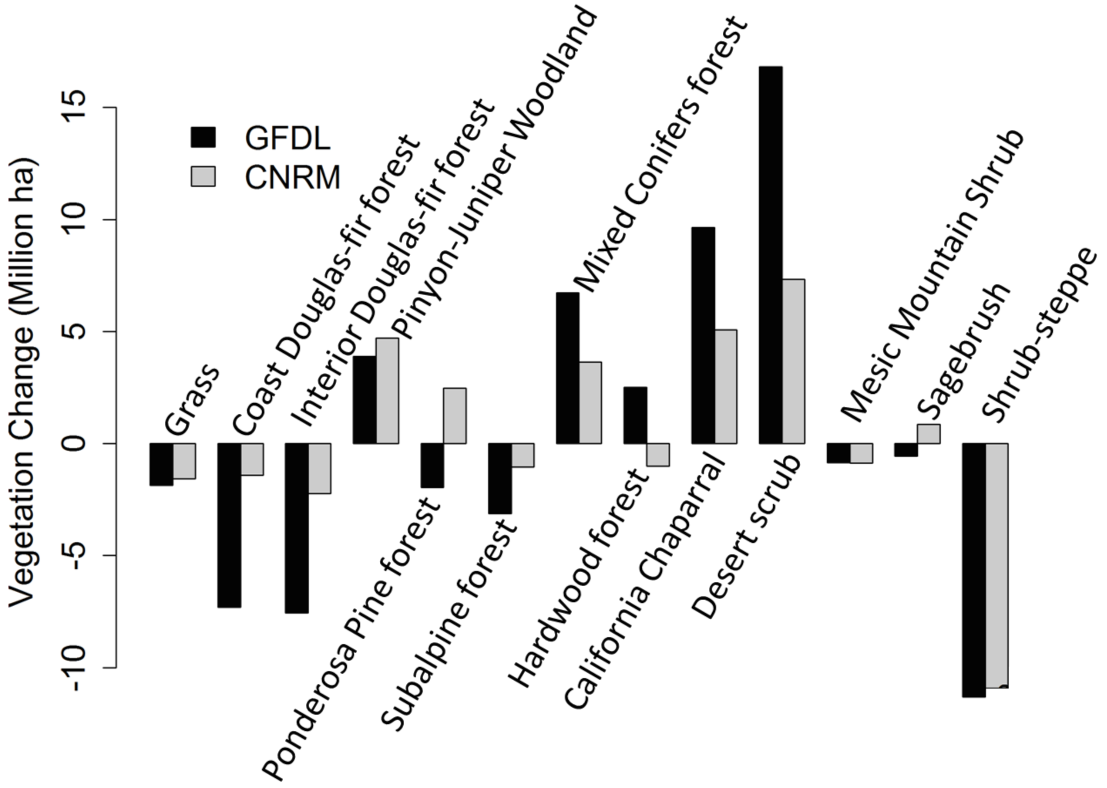

Figure 4: Projected vegetation type change from historical (1981-2010) to future (2071-2100) time periods under Geophysical Fluid Dynamics Laboratory (GFDL) CM 2.1 and Centre National de Recherches Météorologiques (CNRM) CM 3.0 climate models.

3.3 Effects of vegetation and climate change on fire regimes

Fire frequency and median size were higher under the projected future climates (scenario 2), and this increase was further amplified by climate-driven vegetation change (scenario 3) (Table 3). Fire frequency increased more dramatically under the hot and dry GFDL model than under the hot and wet CNRM model. However, the increase of fire occurrence was not uniform across the landscape, and the change in spatial patterns of fire occurrence probability under scenario 3 was primarily driven by vegetation change (Figure B5). Consequently, the total burned area increased much more dramatically when vegetation change was included. Under the GFDL climate model, annual burned area increased from about 6 508 km^2 in the historical period to 9 915 km^2 (52% increase) under the climate change only scenario and further to 14 059 km^2 (116% increase) when vegetation change was also included. Under the CNRM climate model, the annual burned area increased to 8 331 km^2 (28% increase) under the climate change only scenarios and further to 12 236 km^2 (88% increase) when vegetation change was also included (Table 3).

The projected changes in burn rate were spatially heterogeneous (Figure 5). The climate change only scenario (scenario 2) had a similar spatial pattern of burn rates as the historical scenario (Figures 5b&d vs. e). The historical mean burn rate was 1.42 fires per 500 years. About 17% of the western US (about 476 000 km^2) was projected to have at least double the historical burn rate, whereas only 9.5% of western US (255 000 km^2) was projected to decrease to half of the historical burn rate or less under the GFDL climate model (Figures 6b&d).

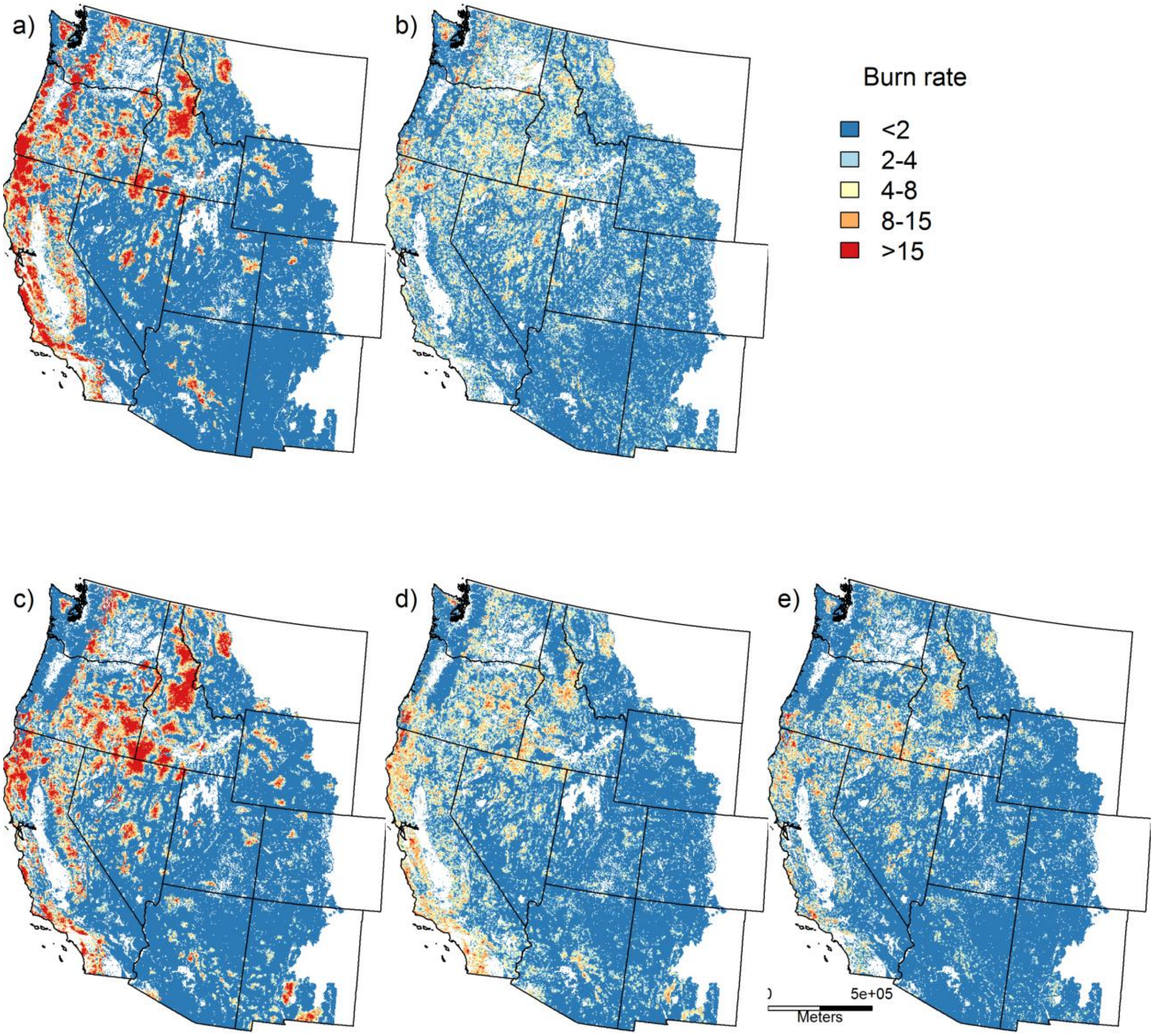

Figure 5: Simulated spatial pattern of burn rate under a) climate change plus vegetation shift under the GFDL climate model (scenario 3); b) climate change only under the GFDL climate model (scenario 2), c) climate change plus vegetation shift under the CNRM climate model (scenario 3); d) climate change only under the CNRM climate model (scenario 2), and e) the historical baseline (scenario 1).

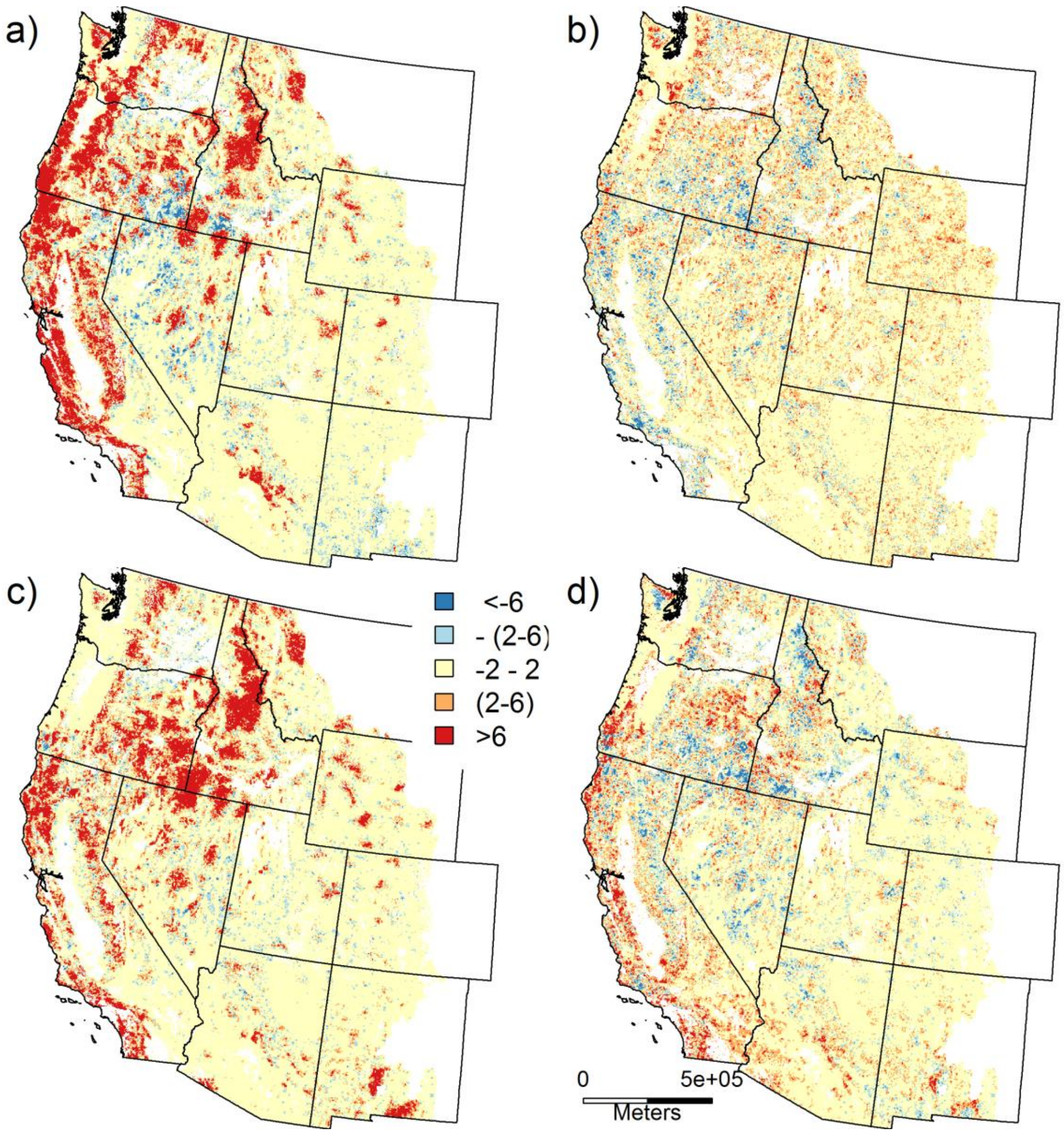

Figure 6: Simulated spatial pattern of difference in burn rate for a) the difference between climate change plus vegetation shift under the GFDL climate model (scenario 3) and the historical baseline (scenario 1); b) the difference between climate change only under the GFDL climate model (scenario 2) and the historical baseline (scenario 1); c) the difference between climate change plus vegetation shift under the CNRM climate model (scenario 3) and the

historical baseline (scenario 1); d) the difference between climate change only under the CNRM climate model (scenario 2) and the historical baseline (scenario 1).

Incororporating vegation type altered the spatial pattern of burn rate substantially (Figures 5a&c vs. e) and these patterns of fire regime change followed the patterns of vegetation change closely (Figures 6a&c). The effect of climate-driven vegetation shifts on burn rate was significantly stronger than the effect of climate only for both GFDL ($t = 9.36$, $df = 6750$, $p < 0.001$) and CNRM ($t = 12.48$, $df = 8409$, $p < 0.001$) climate models. Many of the areas with projected increases in burn rate were concentrated along the Pacific coast and inland northwest, areas with projected vegetation change in the future under GFDL climate model (Figure 6a). However, including vegetation change had varied effects on burn rates in forest and non-forest. For example, under the GFDL climate model, the percent of current forest that was projected to at least double in burn rate was 7.2% in the climate only scenario and 12.9% in the climate change plus vegetation change scenario. In contrast, the percent of current grass/shrub projected to at least double in burn rate was 10.4% under the climate only scenario but was only 6.5% under the climate change plus vegetation change scenario. In general, vegetation change amplified the direct climate change effects on fire in currently forested vegetation types, but reduced direct climate change effects in currently grass/shrub dominated vegetation types in the western US under both climate models.

To quantify potential emerging fire regimes and associated vegetation change, we calculated the vegetation transition in area with most dramatic burned rate increase (burn rate > 6 in Figure 6a&c). Most of the areas with an increase of burn rate greater than 6 were in the forested regions of Pacific Northwest resulting from an expansion of Mixed Conifers forest from Douglas-fir forest, and in California resulting from expansion of chaparral from Hardwood forest (Figure C4).

4 Discussion

These projections suggest that climate-driven vegetation change, in addition to direct climate change effects, may have a substantial influence on future total burned area and the spatial pattern of burn rate. In this study, we found that vegetation change amplifies climate-driven increases in fire frequency and size because vegetation types with higher fire occurrence and spread probability, such as California Chaparral and Mixed Conifers, were projected to replace vegetation types with lower susceptibility to fire, such as Coast Douglas-fir, hardwood and subalpine forest, under future warmer climates (Figure 2). One important implication of this finding is that projections based only on direct climate change effects may underestimate the magnitude of increased burning under future climates in the western U.S. In our simulations, incorporating the indirect effects of climate-driven vegetation change resulted in 4 143 km^2 per year of additional burned area under the GFDL climate model projections and 3 905 km^2 per year of additional burned area under the CNRM climate model projections compared to projections based only on direct climate effects. Because the spatial pattern of temperature change was similar between the two climate models that were examined, differences in the spatial pattern of precipitation explained the majority of the differences in projected vegetation patterns and their effects on fire regimes. Better projections of future spatial and temporal pattern of precipitation will be needed to improve projections of vegetation change and its effects on fires.

Our projection that wildfires will become more frequent, larger, and burn more area under future climates is consistent with many previous assessments that have been carried out in various parts of the western U.S. (Westerling *et al.*, 2011; Litschert *et al.*, 2012; Stavros *et al.*, 2014). The results of our study further suggested that changes in both fire frequency and fire size distribution will contribute to increases in total burned area in the western US, but their relative contributions to the increase in total burned area in particular regions will depend on the magnitude and spatial pattern of climate-driven vegetation change. This finding underscores the value of studying multiple components of the fire regime and their different sensitivities to climate change (Liu & Wimberly, 2015). Our approach of modeling fire regime components separately in this study is consistent with previous paleorecord studies that have shown that different fire regime components respond independently to long-term environmental change (Kelly *et al.*, 2013; Higuera *et al.*, 2014). The model projections demonstrated the potential for these independent responses of fire regime components to climate change at different spatio-temproal scales to result in novel fire regimes (Whitman *et al.*, 2015), similar to plant community reassembly that results from individualistic responses of tree species to climate change (Davis & Shaw, 2001).

Previous studies have suggested that the relative influences of climate and fuels on future fire regimes will vary along the productivity and aridity gradients (Pausas & Paula, 2012; Pausas & Ribeiro, 2013). In dry and unproductive regions dominated by grassland and shrubland, fuel availability and connectivity due to vegetation type change was considered more relevant in driving fire regime change. For example, recent increases in fire frequency and size in US Great Basin have been driven by the replacement of shrub-dominated types by invasive annual grasslands, dominated by species such as cheatgrass (*Bromus tectorum*) which have higher fine fuel biomass, increased fuel connectivity and greater flammability (Balch *et al.*, 2013). The invasive cheatgrass is better adapted to more frequent burning than native vegetation, thus maintaining a novel ‘grass-fire’ cycle. Our results showed that climate-driven vegetation change may reduce the rate of burning in these regions if current vegetation is replaced with vegetation types with sparser fuel under warmer and drier climate. In wetter and more productive regions dominated by forests, climatic variability was considered as more important than vegetation biomass in driving fire regime change (Pausas & Ribeiro, 2013). However, our projections demonstrated that changes in fuels due to climate-driven vegetation type shifts can also increase rates of burning in these regions. This is because many current forest types are projected be replaced by other vegetation types with higher fire occurrence and spread probability. In many parts of world, vegetation change is occurring rapidly due to climate change (Feng & Fu, 2013; Jiang *et al.*, 2013), land use and management (Pausas & Fernández-Muñoz, 2012), biological invasions (Balch *et al.*, 2013), and increases in CO_2 (Bond & Midgley, 2012). Depending on the type of vegetation transition occurring and the ecological context, these changes can have a wide range of effects on fire regimes at continental to global scales.

Our ecological niche modeling approach predicted an increase of drought-adapted vegetation in response to future warmer climates and related increases in water deficits in the western US. For example, forest area was projected to decrease 7.6% by 2071 – 2100 under the warmer and drier GFDL climate model. Other evidence also tends to support reduced forest area and increased nonforest area under future climates. Jiang *et al.* (2013) used a coarse-scale dynamic global vegetation model and projected a reduction in the evergreen needle leaf plant functional type and an increase in the shrub plant functional type in the western US. Notaro *et al.* (2012) used both dynamic modeling and bioclimatic-envelope approaches and projected a partial replacement of evergreen trees with grasses in the mountains of Colorado and Utah under future climates. Hansen and Phillips (2015) analyzed five published studies on climate suitability for forest species in US Northern Rocky Mountains and found a substantial loss of area of climate suitability for the subalpine species and an expansion of climate suitability for mixed conifer species in montane areas by 2070 – 2100. Generally, the vegetation transitions identified in this analysis were consistent with other studies in the western US, suggesting that future increases in fire-susceptible vegetation types will amplify the effect of climate change on fire regime in the future warmer climate. However, our results were not consistent with a recent analysis in Canadian boreal forest which found that changes in tree composition toward an increasing deciduous component under warming climate has the potential to offset the direct effects of climate warming because deciduous forests have lower ignition rates than coniferous forests (Girardin *et al.*, 2013; Terrier *et al.*, 2013). Taken as a whole, these finding suggest that the indirect effects of climate-driven vegetation change on fire regimes will be ecosystem dependent.

Our projection of future vegetation shifts only considered climatic suitability for broad vegetation types, and more localized vegetation changes driven by other processes such as natural disturbances, succession, biological invasions, and human land activities were not considered (Keane *et al.*, 2013). We also did not incorporate the time-lag associated with growth and recruitment in response to climate change and assumed unlimited dispersal ability of plant species. The future vegetation projected in these simulations should thus be interpreted as a maximum possible vegetation shift under a particular future climate projection. Comparing these projections with the static vegetation scenarios in the framework of a simulation experiment enabled us to highlight the potential effects of vegetation change on future fire regimes while limiting the confounding effects of other processes and driving variables.

We also did not incorporate the feedback effects of fires on vegetation structure and composition in our fire simulation approach (Liu & Yang, 2014). Instead, we made the assumption that broad vegetation types would remain unchanged following fires. An imporant next step in evaluating the interactive effects of changing climate and vegetation on fire regimes will be to incorporate more detailed vegetation dynamics models that incorporates disturbance effects as well as post-fire succession. An alternative approach to investigate feedbacks between climate, vegetation, and fire at global and continental scales is the use of process-based dynamic global vegetation models (Kloster *et al.*, 2012; Li *et al.*, 2012). However, these models are typically implemented at much coarser spatial scales (> 0.5º) and do not incorporate the finer spatial scale details of vegetation, topography, and human effects that influence fire occurrence and spread. At landscape scales, vegetation succession and disturbance models can be used to study the climate, vegetation succession, and fire feedbacks (Loudermilk *et al.*, 2013; Wang *et al.*, 2013; Wang *et al.*, 2014a), but the tradeoff between model realism and computational demand limits their applicability at regional to continental scales. The simulation model presented here offers a complementary empirical approach that leverages available datasets to project environment influences on fire regimes at a relatively fine spatial grain across a regional extent.

Future climate projections are burdened with uncertainty which may affect our quantitative estimates. For example, our ecological niche model projections of future vegetation distribution may respond differently if future climate conditions are out of the projected ranges used in current analysis and consequently influence the resultant fire regimes. Although our fire simulation model realistically produced historical burned patterns across the western US, it may not capture all of the finer-scale details of fire spread, fire effects, and the resulting patterns of burning. Also, human development patterns can modify fire regimes by changing ignition patterns and burn probabilities (Liu *et al.*, 2012; Liu *et al.*, 2015). Given the uncertainties associated with the various assumptions of ecological niche models and fire simulation models, these results should be seen as first estimates of the relative impacts of climate and climate-driven vegetation change on regional fire regime of western US in the context of global warming. The local accuracy of the current analysis is limited by its regional scope, and future studies can expand on it by including feedback effects of fire on vegetation distribution, human fire interaction, a wider range of climate projections, and more mechanistic dynamic vegetation models.

5 Conclusion

This study used a simulation approach based on a set of statistical models to assess the relative influences of climate and vegetation change on future fire regimes under two climate models. We found that changes in vegetation can have strong localized effects on fire occurrence probabilities, fire sizes, and fire spread rates, which in turn have large influences on broad scale fire regime patterns. Regional projections of climate-driven fire regime change have the potential to be strongly mediated by landscape-scale constraints, highlighting the critical importance of vegetation dynamics for understanding and quantifying the fire-climate relationship. Depending on the nature and extent of climate-driven vegetation change, its effect on future fire regimes may be at least as important, if not more important, than direct effects of climate change. Our findings thus support the argument of Bowman *et al.* (2014) that vegetation dynamics models need to be integrated with climate-fire association models for better projections of future fire regimes at broad spatial scales.

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Figure legends

Figure 1: Fire simulation flowchart. Topography and climate data were used to predict current and future vegetation type distributions using the Random Forests algorithm. Processes related to fire occurrence simulations are shown in solid green lines. Processes related to fire size simulations are shown in solid blue lines. Processes related to fire spread simulations are shown in solid red lines.

Figure 2: Vegetation type distributions from a) the LANDFIRE dataset; b) predicted historical vegetation using Random Forests (RF); c) predicted future vegetation under the GFDL climate model using RF; d) predicted future vegetation under the CNRM climate model using RF.

Figure 3: Validation results for (a) fire density by fire occurrence probability; (b) Predicted versus observed size distributions for simulated fires and observed validation fires; (c) Distribution of fire dates for simulated fire versus observed validation fires; and (d) simated historical (1981 - 2010) burn rate for burned validation fires and non-burned random patches.Figure 5: Simulated spatial pattern of burn rate under a) climate change plus vegetation shift under the GFDL climate model (scenario 3); b) climate change only under the GFDL climate model (scenario 2), c) climate change plus vegetation shift under the CNRM climate model (scenario 3); d) climate change only under the CNRM climate model (scenario 2), and e) the historical baseline (scenario 1).

Figure 6: Simulated spatial pattern of difference in burn rate for a) the difference between climate change plus vegetation shift under the GFDL climate model (scenario 3) and the historical baseline (scenario 1); b) the difference between climate change only under the GFDL climate model (scenario 2) and the historical baseline (scenario 1); c) the difference between

climate change plus vegetation shift under the CNRM climate model (scenario 3) and the historical baseline (scenario 1); d) the difference between climate change only under the CNRM climate model (scenario 2) and the historical baseline (scenario 1).

Appendices

Appendix A: Detailed description of fire modeling framework.

Appendix B: Supplementary maps and charts.

Appendix C: Detailed description of the vegetation change model.

***Graphical Abstract**