

How will climate change affect wildland fire severity in the western US?

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Sean A Parks¹, Carol Miller¹, John T Abatzoglou², Lisa M Holsinger¹, Marc-André Parisien³ and Solomon Z Dobrowski⁴

¹ Aldo Leopold Wilderness Research Institute, Rocky Mountain Research Station, USDA Forest Service, 790 East Beckwith Ave., Missoula, MT 59801, USA

² Department of Geography, University of Idaho, 875 Perimeter Dr MS3021, Moscow, ID 83844, USA

³ Northern Forestry Centre, Canadian Forest Service, Natural Resources Canada, 5320 122nd Street, Edmonton, Alberta T5H 3S5, Canada

⁴ Department of Forest Management, College of Forestry and Conservation, University of Montana, 32 Campus Drive, Missoula, MT 59812, USA

E-mail: sean_parks@fs.fed.us

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Abstract

Fire regime characteristics in North America are expected to change over the next several decades as a result of anthropogenic climate change. Although some fire regime characteristics (e.g., area burned and fire season length) are relatively well-studied in the context of a changing climate, fire severity has received less attention. In this study, we used observed data from 1984 to 2012 for the western United States (US) to build a statistical model of fire severity as a function of climate. We then applied this model to several ($n = 20$) climate change projections representing mid-century (2040–2069) conditions under the RCP 8.5 scenario. Model predictions suggest widespread reduction in fire severity for large portions of the western US. However, our model implicitly incorporates climate-induced changes in vegetation type, fuel load, and fire frequency. As such, our predictions are best interpreted as a *potential* reduction in fire severity, a potential that may not be realized due human-induced disequilibrium between plant communities and climate. Consequently, to realize the reductions in fire severity predicted in this study, land managers in the western US could facilitate the transition of plant communities towards a state of equilibrium with the emerging climate through means such as active restoration treatments (e.g., mechanical thinning and prescribed fire) and passive restoration strategies like managed natural fire (under suitable weather conditions). Resisting changes in vegetation composition and fuel load via activities such as aggressive fire suppression will amplify disequilibrium conditions and will likely result in increased fire severity in future decades because fuel loads will increase as the climate warms and fire danger becomes more extreme. The results of our study provide insights to the pros and cons of resisting or facilitating change in vegetation composition and fuel load in the context of a changing climate.

Introduction

Fire regimes in North America are expected to change over the next several decades as a result of anthropogenic climate change (Dale *et al* 2001). Fire activity (i.e., annual area burned and fire frequency) is expected to increase in many regions (Krawchuk *et al* 2009, Littell *et al* 2010) and new research shows that fire seasons are now starting earlier and ending

later compared to previous decades (Jolly *et al* 2015). However, the effect of climate change on one very important fire regime characteristic—*fire severity*—is not well-studied or understood (Flannigan *et al* 2009, Hessl 2011). In the context of this paper, we define severity as the degree of fire-induced change to vegetation and soils one year post-fire (Key and Benson 2006, Miller and Thode 2007). For example, a stand-replacing fire in upper-elevation conifer forest is

considered high severity because the site has drastically changed one year post-fire compared to pre-fire conditions, whereas a surface fire in a grass-dominated ecosystem is considered low severity because the vegetation is nearly fully recovered one-year post fire.

The severity at which a site burns influences vegetation response and successional trajectory (Barrett *et al* 2011), faunal response (Smucker *et al* 2005), carbon emissions (Ghimire *et al* 2012), and erosion rates and sedimentation (Benavides-Solorio and MacDonald 2005). Furthermore, human safety and infrastructure are influenced by the severity at which a site burns (Miller and Ager 2013), and management responses to fire and allocation of firefighting resources are also influenced by the expected fire severity (e.g., Calkin *et al* 2011). As such, there is a need to better understand how fire severity will respond to a changing climate (e.g., Miller *et al* 2009).

At fine temporal scales, fire severity depends on factors that are highly variable over time, such as fire spread rate and direction (e.g., heading versus backing fire) and weather (Finney 2005, Birch *et al* 2015). At broader temporal scales, however, climate (in terms of climatic normals) is a major influence through its interactive effect on productivity (and hence amount of biomass) and moisture availability (i.e., wet versus dry ecosystems) (Parks *et al* 2014b, Whitman *et al* 2015). Consequently, because fire regimes are intrinsically defined by the characteristics of fires that occur over extended periods of time (years to centuries) (Morgan *et al* 2001), evaluations of fire severity over gradients of observed and predicted climatic normals allows for a formal assessment of how fire severity may respond to climate change.

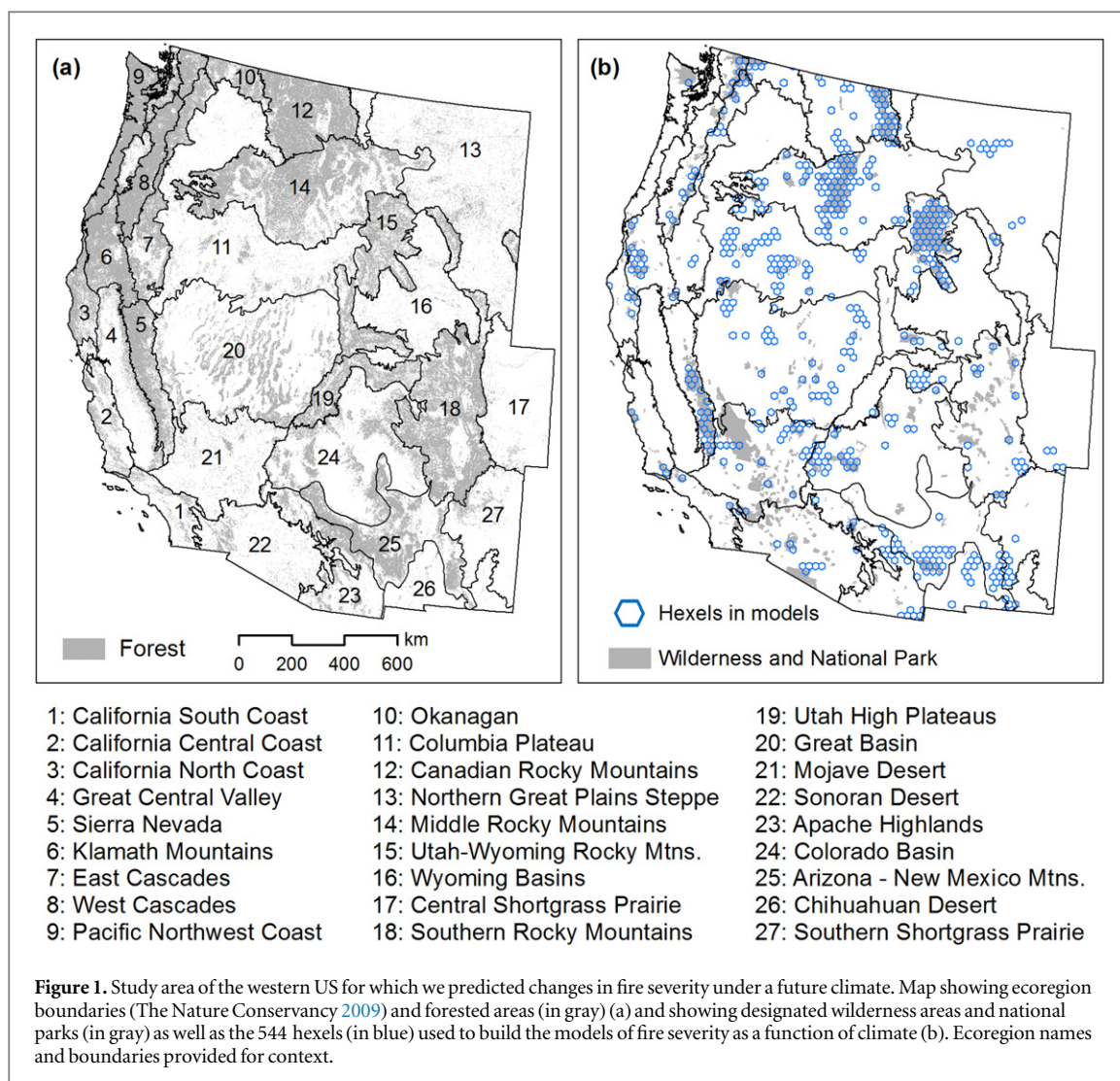
We seek to quantify how fire severity in the contiguous western United States (US) (hereafter the 'western US') may respond to climate change. We use statistical relationships between observed climatic normals and fire severity (Parks *et al* 2014b, Kane *et al* 2015) to conduct a formal evaluation of future fire severity patterns. Because the relationship between climate and fire regimes is known to be weak in areas of high human impact (Parks *et al* 2014b), we used data from areas with low anthropogenic influence to build a statistical model of fire severity as a function of climatic normals over the 1984–2012 time period. We then predicted contemporary (1984–2012) and future (mid-century; 2040–2069) fire severity using climate data from numerous global climate models (GCMs) for the western US. As far as we know, this study is the first to examine how fire severity may respond to a changing climate over such a broad spatial extent. The results of this study will advance our understanding of fire regimes in the western US in the context of a changing climate and will assist policy makers and land managers to better manage for resilient landscapes.

Methods

Consistent with major fire severity mapping efforts (Key and Benson 2006, Eidenshink *et al* 2007), we define fire severity as the degree of fire-induced change to vegetation and soils. We built a statistical model of fire severity as a function of climate by first partitioning our study area (the western US; figures 1(a) and (b)) into 500 km² hexagonal polygons (i.e., 'hexels'). Within each hexel, we summarized fire severity using the delta normalized burn ratio (dNBR) (Key and Benson 2006), a satellite index (resolution: 30 m) that differences pre- and post-fire Landsat TM, ETM+, and OLI images and has a high correspondence to field-based measures of severity such as the composite burn index (CBI; $R^2 \geq 0.65$) (van Wagtenonk *et al* 2004, Parks *et al* 2014a). The CBI is a post-fire assessment in which individual rating factors in each of several vertically arranged strata (soil and rock, litter and surface fuels, low herbs and shrubs, tall shrubs, and trees) are assessed on a continuous 0–3 scale indicating the magnitude of fire effects. A rating of 0 reflects no change due to fire, whereas 3 reflects the highest degree of change. Factors assessed include soil char, surface fuel consumption, vegetation mortality, and scorching of trees. Ratings are averaged for each stratum and then across all strata to arrive at an overall CBI rating for an entire plot. The CBI indicates that, as dNBR values increase, there is generally an increase in char and scorched/blackened vegetation and a decrease in moisture content and vegetative cover (Key and Benson 2006). Measurements of fire severity (dNBR and CBI) are generally conducted one year after fire, so any regrowth that occurs within one year will result in reduced severity compared to assessments conducted immediately post-fire; this is particularly relevant for species that recover quickly after fire (e.g., resprouting shrubs, grasses).

Fire severity (i.e., dNBR) data were obtained from the Monitoring Trends in Burn Severity project (Eidenshink *et al* 2007) for all fires ≥ 400 ha for the 1984–2012 time period. Raw dNBR values obtained from MTBS were adjusted using the 'dNBR offset' (Key 2006), which accounts for differences due to phenology or precipitation between the pre- and post-fire images by subtracting the average dNBR of pixels outside the burn perimeter. This adjustment can be important when comparing severity among fires (Parks *et al* 2014a). A mean dNBR was calculated using all pixels of all fires that intersected each 500 km² hexel; pixels classified as nonfuel were excluded in the calculation of the mean. We square-root transformed mean dNBR values to linearize the relationship to the CBI (figure S1).

We summarized climate normals within each hexel using five variables with known links to fire regimes (e.g., Littell and Gwozdz 2011, Abatzoglou and Kolden 2013, Parks *et al* 2015b): actual evapotranspiration (AET), water deficit (WD), annual



precipitation (PPT), soil moisture (SMO), and snow water equivalent (SWE). Gridded monthly temperature and PPT data were obtained from the parameter-elevation regression on independent slopes model (PRISM; Daly *et al* 2002), which uses weather station data and physiographic factors to map climate at a spatial resolution of ~ 800 m. In addition, daily and sub-daily surface meteorological variables (~ 4 km resolution) describing temperature, humidity, winds, solar radiation, and precipitation were produced following Abatzoglou (2013). These data were collectively used to compute climatic water balance following Dobrowski *et al* (2013) to estimate AET, SWE, SMO, and WD. This water balance model operates on a monthly time-step and accounts for atmospheric demand (via the Penman–Monteith equation), soil water storage, and includes the effect of temperature and radiation on snow hydrology via a snow melt model. Each variable was averaged within each hexel for the years 1984–2012, thereby matching the years of the fire severity data. We similarly summarized these five climate variables representing mid-21st century (2040–2069) conditions using 20 global

climate models (GCMs) for the RCP8.5 emissions scenario (table S1). These tables were statistically down-scaled to the same grid as observed data using the multivariate adapted constructed analogs approach (Abatzoglou and Brown 2012).

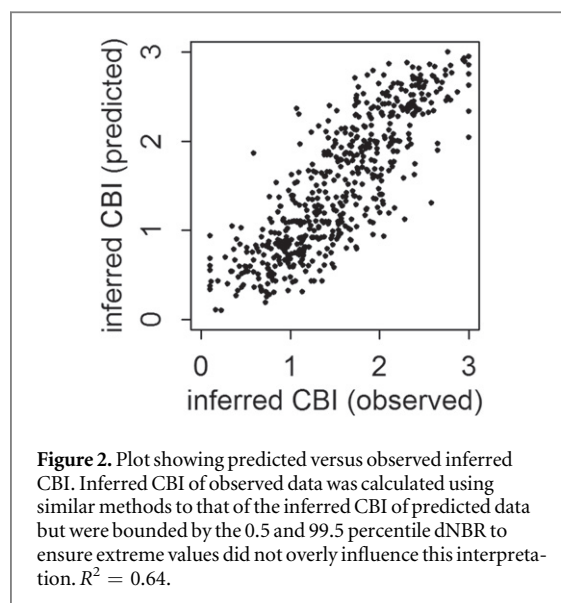
Because the relationship between climate and fire is weaker in landscapes that are highly influenced by humans (Parks *et al* 2014b), we built our model using data from a subset of hexels with low human influence (figure 1(b)). We selected only those hexels that were comprised of at least 50% designated wilderness or national park or had an average ‘human footprint’ (Leu *et al* 2008) ≤ 2.5 (on a scale of 1–10). We further limited our dataset to include only those hexels with at least 400 ha of total burned area from 1984 to 2012. These selection criteria resulted in 544 hexels that, despite representing a small proportion of our study area (8.7%), are climatically representative of much of the western US, with the notable exception of the wet regions of the Pacific Northwest (figure S2).

Using data from the subset of 544 hexels, we modeled fire severity (dNBR) as a function of contemporary climate (1984–2012) using boosted

regression trees (BRT) ('gbm' package) in the R statistical environment (R Development Core Team 2007). BRT is a nonparametric machine-learning approach that does not require *a priori* model specification or test of hypothesis (De'ath 2007). The BRT algorithm fits the best possible model to the data structure, including complex interactions among variables. It does so by building a large number of regression trees, whereby, through a forward stage-wise model-fitting process, each term represents a small tree built on the weighted residuals of the previous tree. The stage-wise procedure reduces bias, whereas variance is decreased through model averaging. The BRT method also employs 'bagging', the use of a random subset of samples, which typically improves model predictions. Comparisons to other modeling techniques indicate that BRT models consistently produce robust predictive estimates (Elith *et al* 2006). We followed the recommendations of Elith *et al* (2008) for selecting BRT options; we set the bagging fraction to 0.5, learning rate to 0.005, and tree complexity to three. We used a custom script from Elith *et al* (2008) to determine the necessary number of trees, thereby reducing the potential for overfitting. We evaluated the model fit using the (a) correlation between predicted and observed fire severity and (b) ten-fold cross-validated correlation between predicted and observed fire severity.

We used the model to predict contemporary (1984–2012) fire severity (dNBR) for all hexels in the western US. However, interpreting dNBR and changes in dNBR under a changing climate is challenging because dNBR units have no direct ecological interpretation. As such, we rescaled these predictions to correspond to the ecologically relevant composite burn index (hereafter 'inferred CBI') that ranges from 0 to 3 (Key and Benson 2006): the lowest predicted severity was given an inferred CBI of 0.1, which is the threshold for 'unchanged' (Miller and Thode 2007), and the highest predicted severity was given an inferred CBI of 3.0. We were then able to infer the CBI of all remaining predictions because the square-root transformation of dNBR linearized the relationship to CBI (figure S1). Consequently, we generated a map representing the inferred CBI for the western US under contemporary climate.

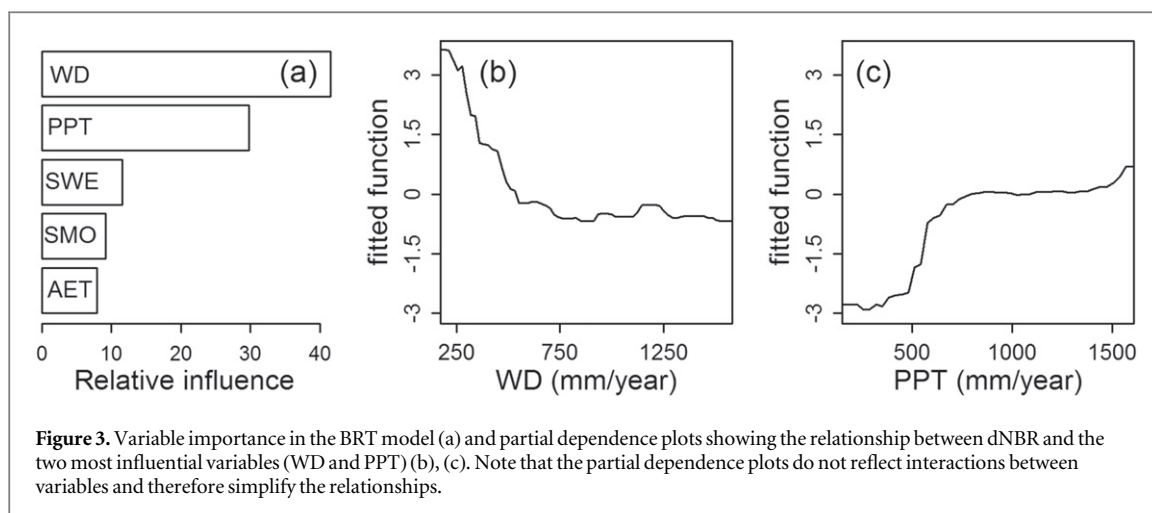
We then predicted fire severity for the mid-21st century (2040–2069) as projected by each GCM using the BRT model. We inferred CBI as previously described using the linear relationship between dNBR and CBI of the observed predictions to make the inferences. Note that the predictions for all hexels in the western US were 'clamped' to avoid predicting outside of the observed range of severity values; all predictions >3 and <0.1 were given values of 3.0 and 0.1, respectively. For each BRT prediction (one for each GCM), we then quantified the predicted change in fire severity by subtracting the inferred CBI of contemporary climate from the inferred CBI of mid-21st century



climate. We summarized the results by generating maps of (1) contemporary fire severity, (2) predicted mid-21st century fire severity (averaged over 20 GCMs) and, (3) the average change (for all 20 GCMs) in fire severity (i.e., inferred CBI) between contemporary and mid-century time periods.

Results

The correlation between predicted and observed dNBR among the 544 hexels was 0.80 and the cross-validated correlation was 0.72. A plot showing predicted versus observed inferred CBI also indicates a good fit ($R^2 = 0.64$; figure 2). Water deficit and PPT were the most influential variables (relative influence = 41.5% and 29.8%, respectively) (figure 3(a)). Fire severity generally decreased with WD and increased with PPT (figures 3(b) and (c)). The map of predicted contemporary (1984–2012) fire severity indicates that cooler and wetter forested ecoregions (e.g., Pacific Northwest, Northern Rocky Mountains, and Southern Rocky Mountains) experience more high severity fire (inferred CBI ≥ 2.25) compared to warmer and drier forested ecoregions (e.g., Arizona - New Mexico Mountains) (figure 4(a)). Non-forested ecoregions for the most part experience fairly low fire severity (inferred CBI < 1.25). The map of mid-21st century fire severity shows a similar pattern in that the cooler and/or wetter regions generally have higher severity than elsewhere (figure 4(b)), but for the most part, fire severity is predicted to decrease over much of the western US (figure 4(c)). The results of current, future, and predicted changes in fire severity are strikingly similar when we measured fire severity using a relativized metric (the relativized burn ratio; RBR) (Parks *et al* 2014a) instead of dNBR (figure S3).



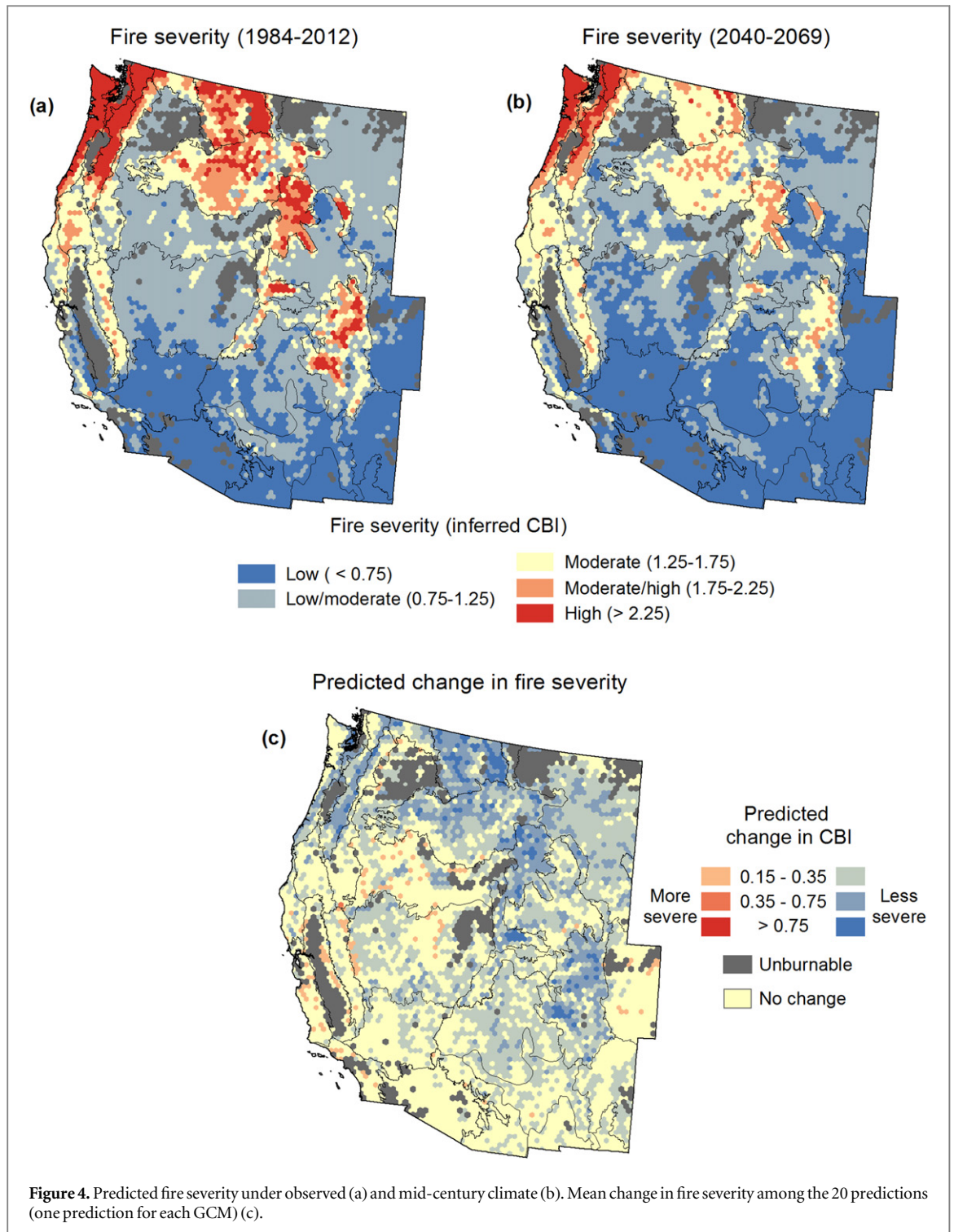
Discussion

Our models based on contemporary fire–climate relationships predict a widespread reduction in fire severity for large portions of the western US by the mid-21st century. Only a very small proportion of the western US is predicted to experience an increase in severity. Our prediction contrasts with those based on the direct influence of climate on fuel moisture and associated fire danger indices that occur at seasonal time scales (Fried *et al* 2004, Nitschke and Innes 2008). Our use of broad-scale climate as a proxy for vegetation composition and fuel load instead emphasizes the indirect influence that climate has on fire regimes (Miller and Urban 1999, Higuera *et al* 2014). Specifically, the predicted decrease in fire severity can be attributed to climatic conditions associated with higher WDs (figures 5(a) and (b)), lower productivity, and less burnable biomass (Zhao and Running 2010, Stegen *et al* 2011).

Our approach and findings are based on an implicit assumption that vegetation composition and fuel load will track changes in climate. Indeed, this is a common assumption that underlies numerous climate change studies, including those that use distribution models to project shifts in habitat ranges (Engler *et al* 2011) and fire activity (Krawchuk *et al* 2009, Moritz *et al* 2012). Specifically, our predictions of overall lower fire severity implicitly assume that vegetation composition and burnable biomass will reflect lower productivity associated with warmer and drier climates (e.g., increased WD; figure 5(b)). As such, our predictions are best interpreted as a *potential* reduction in fire severity, a potential that may not be realized where there is disequilibrium between climate and vegetation. Disequilibrium dynamics are the result of many factors and signals that directional changes in climate may not result in immediate changes in vegetation composition and fuel load (Sprugel 1991, Svenning and Sandel 2013). For example, leading-edge disequilibrium can arise when species are dispersal

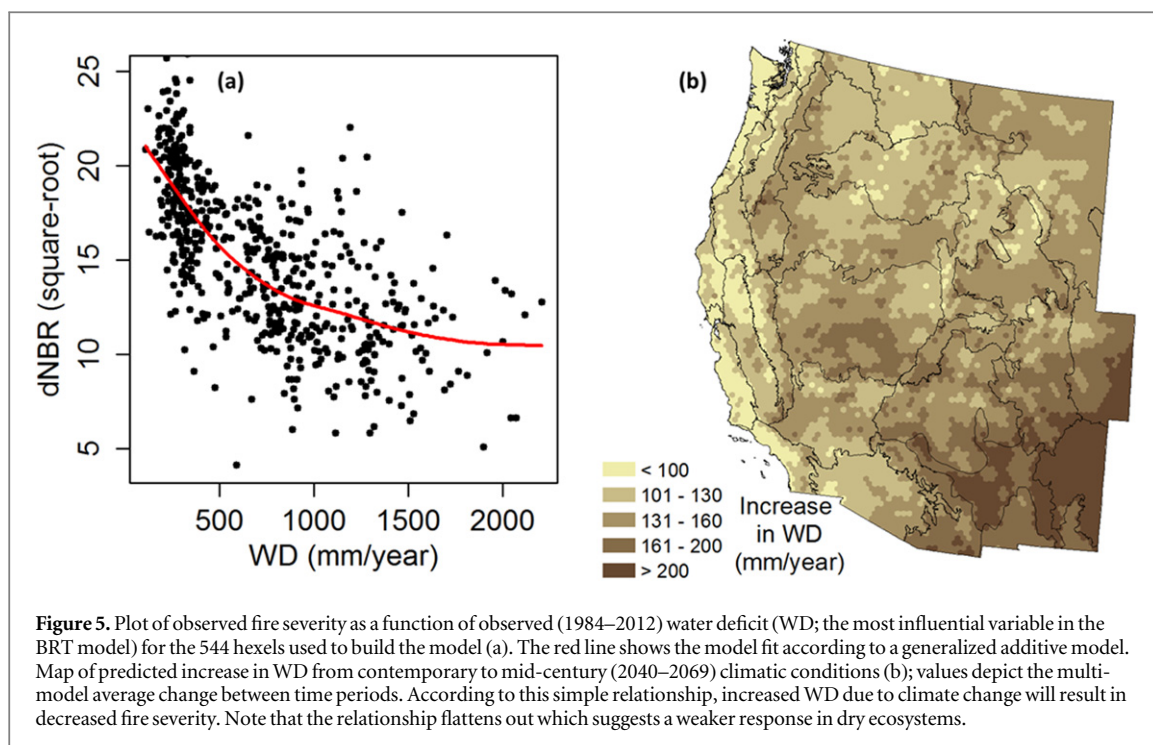
limited or don't reach reproductive maturity for many years (Svenning and Sandel 2013). Trailing-edge disequilibrium can arise because some species are long-lived and have deep roots, thereby facilitating survival and persistence under substantial inter-annual and decadal fluctuations in climate even though seedlings of the same species are unable to survive (Grubb 1977, Jackson *et al* 2009). To compound this, human-induced disequilibrium has also substantially affected most ecosystems in the western US (and globally) (Parks *et al* 2015b), in that natural disturbances such as fire have been excluded by factors such as livestock grazing, fire suppression, and landscape fragmentation (Marlon *et al* 2008). Both climate- and human-induced disequilibrium underlie present-day concerns about restoration of fire-adapted ecosystems after a century of fire exclusion (Stephens *et al* 2013, Hessburg *et al* 2015).

Consequently, our predictions are more likely to hold up in the presence of an active disturbance regime that catalyzes climatically driven changes in vegetation composition and fuel load (Flannigan *et al* 2000, Turner 2010). Disturbance catalysts are critical components for maintaining a dynamic equilibrium between vegetation and climate and appear to already be occurring with increasing frequency in some regions. For example, many studies have concluded that fire activity has increased in recent years (Westerling *et al* 2006, Kelly *et al* 2013) and widespread tree mortality has been attributed to drought and insect outbreaks (Allen *et al* 2010, Bentz *et al* 2010). In areas recently affected by these disturbances, the post-fire species and vegetation densities may be more tailored to the emerging climate (Overpeck *et al* 1990, Millar *et al* 2007). Although generally considered undesirable, disturbance-facilitated conversions from forest to non-forest vegetation are likely to occur in some situations (Stephens *et al* 2013, Coop *et al* in press), especially when compounded by human-induced disequilibrium.



Most forested regions in the western US are currently experiencing a ‘fire deficit’ (Marlon *et al* 2012, Parks *et al* 2015b) because human activities and infrastructure (e.g., fire suppression and roads) exclude fire as an important disturbance agent. Consequently, human-induced disequilibrium between vegetation and climate, coupled with a changing climate, has important implications for future fire severity. We posit that such amplified disequilibrium will likely result in *increased* fire severity in future decades as fuel loads increase, fire seasons lengthen, and fire danger becomes more extreme (Collins 2014, Jolly *et al* 2015).

This supposition is consistent with the findings of other studies that found a climate-induced increase in fire severity when assuming static vegetation (Fried *et al* 2004, Nitschke and Innes 2008). Continuing to resist catalysts of vegetation change only increases the probability of undesirable effects given that fire is inevitable (North *et al* 2009, Calkin *et al* 2015). An alternative to this unsustainable cycle is to actively facilitate transition of ecosystems to conditions that are more suited to the future climate by means of managed wildland fire or other restoration treatments (Millar *et al* 2007).



Our study complements and expands our understanding of controls on fire regimes and how they may respond to a changing climate in the western US. Specifically, predicted increases in fire activity (Littell *et al* 2010, Moritz *et al* 2012) imply that less biomass will be able to accumulate between successive fires, resulting in less biomass available for combustion and a reduction in fire severity. Furthermore, predicted increases in WD (figure 5(b)) are expected to increase water stress and decrease productivity in the generally water-limited western US (Chen *et al* 2010, Williams *et al* 2013), ultimately reducing the amount of biomass available to burn and resultant fire severity. It should be noted, however, that temperature-limited ecosystems (i.e., alpine environments) will likely experience an increase in productivity (and fire severity) under a warmer climate (Grimm *et al* 2013, Goulden and Bales 2014).

Our study relied on observed and predicted climatic normals (i.e., multi-decadal averages) to predict potential changes in fire severity. This is in contrast to other climate change fire studies that used annually or seasonally resolved climate (observed and GCM projections) and fire data to make predictions of potential changes in *fire activity* (i.e., fire frequency or area burned) (Littell *et al* 2010, Stavros *et al* 2014). The latter approach is often used because of the noted importance of climatic extremes on fire regimes (e.g., Westerling *et al* 2006). Although we could have built our model of fire severity using annually resolved data, we posit, for the purpose of predicting future fire severity, using long term averages (e.g., 1984–2012) is more appropriate for at least three reasons. First, although several studies have shown that fire severity responds to annual, seasonal, or daily variability in

climate or weather, the relative influence of this variability can be fairly weak (Dillon *et al* 2011, Birch *et al* 2015). This is in contrast to broad temporal scales where the relationship between fire severity and climate has been found to be much stronger (Parks *et al* 2014b, Kane *et al* 2015). Second, because models built at a fine temporal resolution are more focused on the direct influence of climatic variability on fire weather and fuel moisture, they generally fail to incorporate climate- or fire-induced changes in vegetation composition or fuel load (Allen *et al* 2010, Parks *et al* 2015a). We suggest that predictions based on climatic normals implicitly incorporate such changes (Kelly and Goulden 2008, Marlon *et al* 2009). Lastly, GCMs may not adequately simulate annual climatic variability and thus are better suited for predicting long term trends (Stoner *et al* 2009).

Our model used broad scale data and the predictions of widespread reduced fire severity under future climate should be interpreted accordingly. For example, fire severity and climate vary at scales finer than the spatial resolution of the hexel used in this study (Schoennagel *et al* 2004). As such, our analysis does not likely capture finer-scale changes in fire severity that could occur. For example, in alpine environments where localized upward shifts in treeline under a warmer climate are expected to contribute to increases in biomass (Higuera *et al* 2014), fire severity might be expected to increase. Although our model of fire severity (dNBR) as a function of climate performed reasonably well (see section Results), we acknowledge that further error may be introduced due to error in the relationship between CBI and dNBR. However, we posit that the improved ecological interpretation attained by converting dNBR

to CBI outweighs any increased error in our predictions.

Our measure of fire severity relied on dNBR (a unitless ratio) and CBI (a composite rating) and, consequently, there is no definable unit of measurement (e.g., grams of carbon consumed m^{-2}). Instead we infer changes in CBI, which integrates several strata (e.g., soil and shrubs) and scales severity from 0 to 3. This is admittedly a somewhat vague framework for assessing potential changes in fire severity, but takes advantage of the widespread availability of satellite-inferred metrics of fire severity and their documented correlation to the CBI. We suggest future research efforts involving fire severity and climate change aim to use more definitive and quantitative units of measurement. On a similar note, fire severity has ecological significance beyond what can be inferred from dNBR and is the result of many complex physical, biological, and ecological factors (Morgan *et al* 2014). For example, in ecosystems that are ill-adapted to fire (e.g., the Mojave Desert), dNBR values may be irrelevant, as any and all fires might be considered 'severe' (Brooks and Matchett 2006). Accordingly, although we used dNBR and CBI as a convenient and standardized way to assess fire severity, predictions for some ecoregions should be carefully interpreted.

Our model does not consider plant physiological responses to a CO_2 enriched atmosphere (e.g., improved water use efficiency and plant productivity) that could lead to increases in fire severity (Drake *et al* 1997, Keenan *et al* 2013). Given that today's atmospheric CO_2 concentration is the highest it's been for at least 650 000 years (Siegenthaler *et al* 2005), this could be a particularly important consideration for extreme water limited ecosystems such as grasslands, where woody plant encroachment could cause changes in biomass amount and structure (Morgan *et al* 2007, Norby and Zak 2011). Consequently, other research approaches using tools such as dynamic global vegetation models may predict different outcomes (Thonicke *et al* 2001).

Although we relied on data from protected areas and other areas of low human influence and thus underrepresented certain climatic environments (see Batllori *et al* 2014), these data represent a surprisingly broad range of ecosystem types in the western US ranging from warm desert (Death Valley National Park (NP) to dry conifer forest (Gila Wilderness) to cold forest (Yellowstone NP) (figure S2). As such, we suggest that under-represented climates have only a marginal effect on our results (see figure S2). Indeed, our analysis (figure S2) indicates that the data we used to build the model adequately represents the climates of most of the western US with the most notable exception being those in the Pacific Northwest where fires were historically and are currently infrequent (Agee 1993).

Conclusions

Our study predicts an overall decrease in fire severity for much of the western US by mid-century (2040–2069) due to changing climatic conditions. These predictions are best interpreted as *potential* decreases in severity that may not be realized unless vegetation composition and fuel load change in parallel with climate. Disequilibrium between plant communities and climate will only escalate, particularly in forested areas, unless natural disturbances and management activities (i.e., prescribed fire and restoration treatments) act as catalysts of vegetation change and push plant communities towards a state of equilibrium with climate. A high degree of disequilibrium between plant communities and climate is generally considered undesirable because the result may be an uncharacteristically severe wildland fire that causes abrupt ecosystem state shifts from, for example, forest to non-forest vegetation (e.g., Coop *et al* 2016).

Our findings support a passive management approach to ecosystem restoration (Arno *et al* 2000), whereby natural disturbance regimes are used to facilitate the transition of plant communities towards a state of equilibrium with the emerging climate. Active restoration treatments may also aid in facilitating these changes in certain situations (Millar *et al* 2007, Stephens *et al* 2010), but the current pace and scale of such treatments is insufficient to make a meaningful impact across the vast forested regions of the western US (North *et al* 2012). In addition, legal (e.g., designated wilderness) and logistical constraints (e.g., steep slopes) make certain activities (mechanical thinning) infeasible across a large proportion of land in the western US (North *et al* 2014). Achieving landscape resilience in a changing climate will likely require increased use of managed wildland fire, especially when weather conditions are not extreme (North *et al* 2015), and in fact, resisting change via activities such as aggressive fire suppression may be counterproductive in the long-run (Calkin *et al* 2015). As such, the results of this study provide insights to policy makers and land managers in the western US as to the pros and cons of resisting or facilitating change in vegetation composition and fuel load in the context of a changing climate.

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References

- Abatzoglou J T 2013 Development of gridded surface meteorological data for ecological applications and modelling *Int. J. Climatol.* **33** 121–31

- Abatzoglou J T and Brown T J 2012 A comparison of statistical downscaling methods suited for wildfire applications *Int. J. Climatol.* **32** 772–80
- Abatzoglou J T and Kolden C A 2013 Relationships between climate and macroscale area burned in the western United States *Int. J. Wildland Fire* **22** 1003–20
- Agee J K 1993 *Fire Ecology of Pacific Northwest Forests* (Washington, DC: Island Press)
- Allen C D *et al* 2010 A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests *Forest Ecol. Manage.* **259** 660–84
- Arno S F, Parsons D J and Keane R E 2000 Mixed-severity fire regimes in the northern rocky mountains: consequences of fire exclusion and options for the future *Wilderness Science in a Time of Change Conf.* (Rocky Mountain Research Station, Missoula, MT: USDA Forest Service) RMRS-P-15-VOL-5
- Barrett K, McGuire A D, Hoy E E and Kasischke E S 2011 Potential shifts in dominant forest cover in interior Alaska driven by variations in fire severity *Ecol. Appl.* **21** 2380–96
- Batllori E, Miller C, Parisien M-A, Parks S A and Moritz M A 2014 Is US climatic diversity well represented within the existing federal protection network? *Ecol. Appl.* **24** 1898–907
- Benavides-Solorio J D D and MacDonald L H 2005 Measurement and prediction of post-fire erosion at the hillslope scale, Colorado front range *Int. J. Wildland Fire* **14** 457–74
- Bentz B J, Regniere J, Fetting C J, Hansen E M, Hayes J L, Hicke J A, Kelsey R G, Negron J F and Seybold S J 2010 Climate change and bark beetles of the Western United States and Canada: direct and indirect effects *Bioscience* **60** 602–13
- Birch D S, Morgan P, Kolden C A, Abatzoglou J T, Dillon G K, Hudak A T and Smith A M S 2015 Vegetation, topography and daily weather influenced burn severity in central Idaho and western Montana forests *Ecosphere* **6** 17
- Brooks M L and Matchett J R 2006 Spatial and temporal patterns of wildfires in the Mojave Desert, 1980–2004 *J. Arid Environ.* **67** 148–64
- Calkin D E, Thompson M P, Finney M A and Hyde K D 2011 A real-time risk assessment tool supporting wildland fire decisionmaking *J. Forestry* **109** 274–80
- Calkin D E, Thompson M P and Finney M A 2015 Negative consequences of positive feedbacks in US wildfire management *Forest Ecosyst.* **2** 1–10
- Chen P-Y, Welsh C and Hamann A 2010 Geographic variation in growth response of Douglas-fir to interannual climate variability and projected climate change *Glob. Change Biol.* **16** 3374–85
- Collins B M 2014 Fire weather and large fire potential in the northern Sierra Nevada *Agric. Forest Meteorol.* **189–190** 30–5
- Coop J D, Parks S A, McClernan S R and Holsinger L M 2016 Influences of prior wildfires on vegetation response to subsequent fire in a reburned southwestern landscape *Ecol. Appl.* in press
- Dale V H *et al* 2001 Climate change and forest disturbances: climate change can affect forests by altering the frequency, intensity, duration, and timing of fire, drought, introduced species, insect and pathogen outbreaks, hurricanes, windstorms, ice storms, or landslides *Bioscience* **51** 723–34
- De'ath G 2007 Boosted trees for ecological modeling and prediction *Ecology* **88** 243–51
- Dillon G K, Holden Z A, Morgan P, Crimmins M A, Heyerdahl E K and Luce C H 2011 Both topography and climate affected forest and woodland burn severity in two regions of the western US, 1984–2006 *Ecosphere* **2** 130
- Dobrowski S Z, Abatzoglou J, Swanson A K, Greenberg J A, Mynsberge A R, Holden Z A and Schwartz M K 2013 The climate velocity of the contiguous United States during the 20th century *Glob. Change Biol.* **19** 241–51
- Drake B G, Gonzalez-Meler M A and Long S P 1997 More efficient plants: a consequence of rising atmospheric CO₂? *Annu. Rev. Plant Physiol. Plant Mol. Biol.* **48** 609–39
- Eidenshink J, Schwind B, Brewer K, Zhu Z L, Quayle B and Howard S 2007 A project for monitoring trends in burn severity *Fire Ecol.* **3** 3–21
- Elith J, Leathwick J R and Hastie T 2008 A working guide to boosted regression trees *J. Animal Ecol.* **77** 802–13
- Elith J *et al* 2006 Novel methods improve prediction of species' distributions from occurrence data *Ecography* **29** 129–51
- Engler R *et al* 2011 21st century climate change threatens mountain flora unequally across Europe *Glob. Change Biol.* **17** 2330–41
- Finney M A 2005 The challenge of quantitative risk analysis for wildland fire *Forest Ecol. Manage.* **211** 97–108
- Flannigan M D, Krawchuk M A, de Groot W J, Wotton B M and Gowman L M 2009 Implications of changing climate for global wildland fire *Int. J. Wildland Fire* **18** 483–507
- Flannigan M D, Stocks B J and Wotton B M 2000 Climate change and forest fires *Sci. Total Environ.* **262** 221–9
- Friedl J S, Torn M S and Mills E 2004 The impact of climate change on wildfire severity: a regional forecast for northern California *Clim. Change* **64** 169–91
- Ghimire B, Williams C A, Collatz G J and Vanderhoof M 2012 Fire-induced carbon emissions and regrowth uptake in western US forests: documenting variation across forest types, fire severity, and climate regions *J. Geophys. Res.—Biogeosci.* **117** G03036
- Goulden M L and Bales R C 2014 Mountain runoff vulnerability to increased evapotranspiration with vegetation expansion *Proc. Natl Acad. Sci. USA* **111** 14071–5
- Grimm N B *et al* 2013 The impacts of climate change on ecosystem structure and function *Front. Ecol. Environ.* **11** 474–82
- Grubb P J 1977 The maintenance of species-richness in plant communities: the importance of the regeneration niche *Biol. Rev.* **52** 107–45
- Hessburg P F *et al* 2015 Restoring fire-prone Inland Pacific landscapes: seven core principles *Landscape Ecol.* **30** 1805–35
- Hessl A E 2011 Pathways for climate change effects on fire: models, data, and uncertainties *Prog. Phys. Geogr.* **35** 393–407
- Higuera P E, Briles C E and Whitlock C 2014 Fire-regime complacency and sensitivity to centennial-through-millennial-scale climate change in Rocky Mountain subalpine forests, Colorado, USA *J. Ecol.* **102** 1429–41
- Jackson S T, Betancourt J L, Booth R K and Gray S T 2009 Ecology and the ratchet of events: Climate variability, niche dimensions, and species distributions *Proc. Natl Acad. Sci. USA* **106** 19685–92
- Jolly W M, Cochrane M A, Freeborn P H, Holden Z A, Brown T J, Williamson G J and Bowman DMJS 2015 Climate-induced variations in global wildfire danger from 1979 to 2013 *Nat. Commun.* **6** 7537
- Kane V R, Lutz J A, Cansler A C, Povak N A, Churchill D J, Smith D F, Kane J T and North M P 2015 Water balance and topography predict fire and forest structure patterns *Forest Ecol. Manage.* **338** 1–13
- Keenan T F, Hollinger D Y, Bohrer G, Dragoni D, Munger J W, Schmid H P and Richardson A D 2013 Increase in forest water-use efficiency as atmospheric carbon dioxide concentrations rise *Nature* **499** 324–7
- Kelly A E and Goulden M L 2008 Rapid shifts in plant distribution with recent climate change *Proc. Natl Acad. Sci. USA* **105** 11823–6
- Kelly R, Chipman M L, Higuera P E, Stefanova I, Brubaker L B and Hu F S 2013 Recent burning of boreal forests exceeds fire regime limits of the past 10 000 years *Proc. Natl Acad. Sci. USA* **110** 13055–60
- Key C H 2006 Ecological and sampling constraints on defining landscape fire severity *Fire Ecol.* **2** 34–59
- Key C H and Benson N C 2006 Landscape assessment (LA) FIREMON: Fire Effects Monitoring and Inventory System ed D Lutes *et al* (Fort Collins, CO: Department of Agriculture, Forest Service, Rocky Mountain Research Station) RMRS-GTR-164, 55
- Krawchuk M A, Moritz M A, Parisien M-A, Van Dorn J and Hayhoe K 2009 Global pyrogeography: the current and future distribution of wildfire *Plos One* **4** e5102
- Leu M, Hanser S E and Knick S T 2008 The human footprint in the west: a large-scale analysis of anthropogenic impacts *Ecol. Appl.* **18** 1119–39

- Littell J S and Gwozdz R B 2011 Climatic water balance in regional fire years in the Pacific Northwest, USA: linking regional climate and fire and at landscape scales *The Landscape Ecology of Fire* ed D McKenzie *et al* (Netherlands: Springer) vol 213, p 177–139
- Littell J S, Oneil E E, McKenzie D, Hicke J A, Lutz J A, Norheim R A and Elsner M M 2010 Forest ecosystems, disturbance, and climatic change in Washington State, USA *Clim. Change* **102** 129–58
- Marlon J R, Bartlein P J, Carcaillet C, Gavin D G, Harrison S P, Higuera P E, Joos F, Power M J and Prentice I C 2008 Climate and human influences on global biomass burning over the past two millennia *Nat. Geosci.* **1** 697–702
- Marlon J R *et al* 2009 Wildfire responses to abrupt climate change in North America *Proc. Natl Acad. Sci. USA* **106** 2519–24
- Marlon J R *et al* 2012 Long-term perspective on wildfires in the western USA *Proc. Natl Acad. Sci. USA* **109** E535–43
- Millar C I, Stephenson N L and Stephens S L 2007 Climate change and forests of the future: managing in the face of uncertainty *Ecol. Appl.* **17** 2145–51
- Miller C and Ager A A 2013 A review of recent advances in risk analysis for wildfire management *Int. J. Wildland Fire* **22** 1–14
- Miller C and Urban D L 1999 A model of surface fire, climate and forest pattern in the Sierra Nevada, California *Ecol. Modelling* **114** 113
- Miller J D, Safford H D, Crimmins M and Thode A E 2009 Quantitative evidence for increasing forest fire severity in the Sierra Nevada and Southern cascade mountains, California and Nevada, USA *Ecosystems* **12** 16–32
- Miller J D and Thode A E 2007 Quantifying burn severity in a heterogeneous landscape with a relative version of the delta normalized burn ratio (dNBR) *Remote Sens. Environ.* **109** 66–80
- Morgan J A, Milchunas D G, LeCain D R, West M and Mosier A R 2007 Carbon dioxide enrichment alters plant community structure and accelerates shrub growth in the shortgrass steppe *Proc. Natl Acad. Sci. USA* **104** 14724–9
- Morgan P, Hardy C C, Swetnam T W, Rollins M G and Long D G 2001 Mapping fire regimes across time and space: understanding coarse and fine-scale fire patterns *Int. J. Wildland Fire* **10** 329–42
- Morgan P, Keane R E, Dillon G K, Jain T B, Hudak A T, Karau E C, Sikkink P G, Holden Z A and Strand E K 2014 Challenges of assessing fire and burn severity using field measures, remote sensing and modelling *Int. J. Wildland Fire* **23** 1045–60
- Moritz M A, Parisien M-A, Batllori E, Krawchuk M A, Van Dorn J, Ganz D J and Hayhoe K 2012 Climate change and disruptions to global fire activity *Ecosphere* **3** 49
- Nitschke C R and Innes J L 2008 Climatic change and fire potential in South-Central British Columbia, Canada *Glob. Change Biol.* **14** 841–55
- Norby R J and Zak D R 2011 Ecological lessons from free-air CO₂ enrichment (FACE) experiments *Annu. Rev. Ecol., Evol. Systematics* **42** 181–203
- North M, Brough A, Long J, Collins B, Bowden P, Yasuda D, Miller J and Sugihara N 2014 Constraints on mechanized treatment significantly limit mechanical fuels reduction extent in the Sierra Nevada *J. Forestry* **113** 40–8
- North M, Collins B M and Stephens S 2012 Using fire to increase the scale, benefits, and future maintenance of fuels treatments *J. Forestry* **110** 392–401
- North M, Hurteau M and Innes J 2009 Fire suppression and fuels treatment effects on mixed-conifer carbon stocks and emissions *Ecol. Appl.* **19** 1385–96
- North M P, Stephens S L, Collins B M, Agee J K, Aplet G, Franklin J F and Fulé P Z 2015 Reform forest fire management *Science* **349** 1280–1
- Overpeck J T, Rind D and Goldberg R 1990 Climate-induced changes in forest disturbance and vegetation *Nature* **343** 51–3
- Parks S A, Dillon G K and Miller C 2014a A new metric for quantifying burn severity: the relativized burn ratio *Remote Sens.* **6** 1827–44
- Parks S A, Holsinger L M, Miller C and Nelson C R 2015a Wildland fire as a self-regulating mechanism: the role of previous burns and weather in limiting fire progression *Ecol. Appl.* **25** 1478–92
- Parks S A, Miller C, Parisien M-A, Holsinger L, Dobrowski S Z and Abatzoglou J T 2015b Wildland fire deficit and surplus of the western United States, 1984–2012 *Ecosphere* **6** 275
- Parks S A, Parisien M-A, Miller C and Dobrowski S Z 2014b Fire activity and severity in the western US vary along proxy gradients representing fuel amount and fuel moisture *Plos One* **9** e99699
- R Development Core Team 2007 *R: A Language and Environment for Statistical Computing* (Vienna, Austria: R foundation for computing)
- Schoennagel T, Veblen T T and Romme W H 2004 The interaction of fire, fuels, and climate across rocky mountain forests *Bioscience* **54** 661–76
- Siegenthaler U *et al* 2005 Stable carbon cycle-climate relationship during the late Pleistocene *Science* **310** 1313–7
- Smucker K M, Hutto R L and Steele B M 2005 Changes in bird abundance after wildfire: Importance of fire severity and time since fire *Ecol. Appl.* **15** 1535–49
- Sprugel D G 1991 Disturbance, equilibrium, and environmental variability: what is 'Natural' vegetation in a changing environment? *Biol. Conservation* **58** 1–18
- Stavros E N, Abatzoglou J, McKenzie D and Larkin N 2014 Regional projections of the likelihood of very large wildland fires under a changing climate in the contiguous Western United States *Clim. Change* **126** 455–68
- Stegen J C, Swenson N G, Enquist B J, White E P, Phillips O L, Jorgensen P M, Weiser M D, Mendoza A M and Vargas P N 2011 Variation in above-ground forest biomass across broad climatic gradients *Glob. Ecol. Biogeogr.* **20** 744–54
- Stephens S L, Agee J K, Fule P Z, North M P, Romme W H, Swetnam T W and Turner M G 2013 Managing forests and fire in changing climates *Science* **342** 41–2
- Stephens S L, Millar C I and Collins B M 2010 Operational approaches to managing forests of the future in Mediterranean regions within a context of changing climates *Environ. Res. Lett.* **5** 024003
- Stoner A M K, Hayhoe K and Wuebbles D J 2009 Assessing general circulation model simulations of atmospheric teleconnection patterns *J. Clim.* **22** 4348–72
- Svenning J-C and Sandel B 2013 Disequilibrium vegetation dynamics under future climate change *Am. J. Bot.* **100** 1266–86
- The Nature Conservancy 2009 TNC Terrestrial Ecoregions, Arlington, VA, USA (<http://maps.tnc.org/files/metadata/TerrEcos.xml>)
- Thonicke K, Venevsky S, Sitch S and Cramer W 2001 The role of fire disturbance for global vegetation dynamics: coupling fire into a dynamic global vegetation model *Glob. Ecol. Biogeogr.* **10** 661–77
- Turner M G 2010 Disturbance and landscape dynamics in a changing world *Ecology* **91** 2833–49
- van Wageningen J W, Root R R and Key C H 2004 Comparison of AVIRIS and Landsat ETM+ detection capabilities for burn severity *Remote Sens. Environ.* **92** 397–408
- Westerling A L, Hidalgo H G, Cayan D R and Swetnam T W 2006 Warming and earlier spring increase western US forest wildfire activity *Science* **313** 940–3
- Whitman E, Batllori E, Parisien M-A, Miller C, Coop J D, Krawchuk M A, Chong G W and Haire S 2015 The climate space of fire regimes in north-western North America *J. Biogeogr.* **42** 1736–49
- Williams A P *et al* 2013 Temperature as a potent driver of regional forest drought stress and tree mortality *Nat. Clim. Change* **3** 292–7
- Zhao M and Running S W 2010 Drought-induced reduction in global terrestrial net primary production from 2000 through 2009 *Science* **329** 940–3