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Research Note

Climatic influences on interannual variability in regional burn severity across western US forests

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Abstract. Interannual variability in burn severity is assessed across forested ecoregions of the western United States to understand how it is influenced by variations in area burned and climate during 1984–2014. Strong correlations ($|r| > 0.6$) between annual area burned and climate metrics were found across many of the studied regions. The burn severity of individual fires and fire seasons was weakly, but significantly ($P < 0.05$), correlated with burned area across many regions. Interannual variability in fuel dryness evaluated with fuel aridity metrics demonstrated weak-to-moderate ($|r| > 0.4$) relationships with regional burn severity, congruent with but weaker than those between climate and area burned for most ecoregions. These results collectively suggest that irrespective of other factors, long-term increases in fuel aridity will lead to increased burn severity in western United States forests for existing vegetation regimes.

Additional keywords: climate, fire effects.

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Introduction

Wildfire activity has increased across forests of the western United States (US) over the past four decades in terms of the area burned (Westerling *et al.* 2006; Lannom *et al.* 2014; Williams and Abatzoglou 2016), number of large fires (Dennison *et al.* 2014) and fire season length (Westerling 2016). These increases have tracked with enhanced fire danger and fuel aridity during the fire season (Jolly *et al.* 2015; Abatzoglou and Williams 2016), which facilitate conditions conducive to fire ignition and spread. The legacy of fire exclusion across western US forests has increased biomass accumulation in many regions and contributed to complementary increases in fire risk (Keane *et al.* 2002; Marlon *et al.* 2012; Taylor *et al.* 2016). The interactions between fuel accumulation, climate change and trends in subsequent burn severity have not yet been widely explored, but are critical to predicting and mitigating negative fire effects.

Burn severity is a quantification of how fire affects fuel consumption and soils, vegetation mortality, successional vegetation pathways and carbon emissions (Lentile *et al.* 2006). In contrast to the body of studies documenting increasing area burned and large-fire occurrence, reported trends in burn severity are mixed. Increased burn severity (e.g. average burn severity, proportion burned at high severity) has been documented for the forests of northern California (Miller *et al.* 2009; Miller and Safford 2012), southern Rockies (Dillon *et al.* 2011; Picotte *et al.* 2016) and south-western US (Williams *et al.* 2010); however, most regions across the continental US show no detectable trend over the 1984–2010 period (Hanson and Odion 2014; Picotte *et al.* 2016).

The contrast between inconsistent trends in burn severity and widespread increases in area burned raises questions about the bottom-up and top-down processes that determine burn severity. Changes in burn severity are likely enabled and driven by dynamic, rather than time-invariant, factors. For example, burn severity generally increases with time since last fire (Parks *et al.* 2014*a*), suggesting fire exclusion and fuel accumulation as potential contributors to increased burn severity. Previous analyses have found that top-down atmospheric drivers weakly explained spatial patterns in burn severity relative to bottom-up time-invariant topographic factors (Dillon *et al.* 2011; Birch *et al.* 2015; Harvey *et al.* 2016; Bradley *et al.* 2016). However, weak relationships to climate in those studies are potentially a by-product of the scale mismatch between remotely sensed burned severity data (usually inferred at the 30-m scale of Landsat) and climate variables (usually inferred at coarser scales >1 km).

In theory, climate variability should exhibit a mechanistic link to variability in burn severity. Experimental studies find that fuel moisture and fire radiative energy density influence the completeness of burn and subsequent delayed mortality rate (Smith *et al.* 2016, 2017; Sparks *et al.* 2016, 2017). Likewise, longitudinal studies demonstrate that moisture stress enhances post-fire tree mortality (van Mantgem *et al.* 2013). Whether these relationships scale up to larger spatial scales is not well tested. Mean climatic conditions exhibit spatial relationships with burn severity (Parks *et al.* 2014*b*; Whitman *et al.* 2015), at least partly because mean climatic conditions largely control the biogeography of vegetative fuels (Kane *et al.* 2015). Weak correlations between climate variability and burn severity have been seen for individual fires in subregions of the western US (Kolden *et al.* 2015*a*) and for different vegetation classes in the Sierra Nevada (Miller *et al.* 2009). Burn severity has been shown to be higher in both larger fires and larger fire seasons (Lutz *et al.* 2009, 2011; Miller and Safford 2012; Cansler and McKenzie 2014), which tend to occur under anomalous climatic conditions characterised by low fuel moisture in forested systems (Littell *et al.* 2009; Riley *et al.* 2013; Barbero *et al.* 2014). However, a comprehensive analysis of the potential relationships between interannual variability in climate, burned area and burn severity across western US forests has not yet been undertaken. The present study aims to address these knowledge gaps across forested ecoregions of the western US from 1984 to 2014. Although this analysis focused on the western US, the methodology and findings should apply to similar biomes globally.

Data and methods

Our analysis focused on forested ecosystems of the western US defined by Bailey ecoprovinces. Shrubland and grassland ecoprovinces were excluded owing to limited field validation of remotely sensed burn severity products in those ecosystems (Sparks *et al.* 2015). We examined burn severity relationships at ecoprovince levels to account for commonality in vegetation assemblages at a geographic scale that conforms with previous climate–fire relationships (Littell *et al.* 2009). Analyses were also performed at two additional spatial scales: (i) aggregated across all forested ecoprovinces of the western US, and (ii) for a subset of ecosections (sub-ecoprovince) that had at least three large fires (>404 ha) per year for a majority of the study period.

We acquired differenced Normalized Burn Ratio (dNBR) data from all large fires (primarily >404 ha burned within the US) mapped by the Monitoring Trends in Burn Severity (MTBS) product (Eidenshink *et al.* 2007) covering the western US from 1984 to 2014. We excluded prescribed fires. MTBS uses Landsat Thematic Mapper (TM), Enhanced Thematic Mapper-Plus (ETM+) and Operational Land Imager (OLI) reflectance data to calculate dNBR, which quantifies changes between pre-and post-fire conditions. Although MTBS also provides a classified burn severity product, the classification is subjective and inconsistent (Kolden *et al.* 2015*b*), and validation of MTBS-derived products remains limited (Thode *et al.* 2011; Sparks *et al.* 2015). All fires with fire centroids outside the eight forested ecoprovinces or lacking dNBR data (i.e. containing post-fire imagery only) were removed from subsequent analysis, leaving a total of 3415 fires over the 31-year period (Fig. 1). For each fire, we extracted the distribution of dNBR values from each individual 0.09-ha Landsat pixel within the fire perimeter, the area burned within the fire perimeter and fire year.

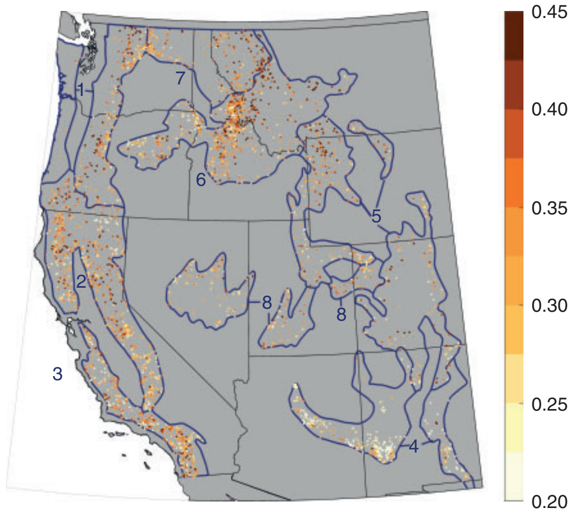

Fig. 1. Map of study area showing the severity metric (SM, coloured triangles) for 3415 fires from 1984 to 2014 within the eight ecoprovinces (outlined in blue). Numbers adjacent to each ecoprovince show the location of the (1) Cascades; (2) Sierra Nevada; (3) California coastal; (4) Arizona–New Mexico mountains; (5) Southern Rockies; (6) Middle Rockies; (7) Northern Rockies; and (8) Great Basin mountains ecoprovinces.

We used the severity metric (SM) developed by Lutz *et al.* (2011) to quantify burn severity within the perimeter of each fire. The SM is calculated from the dNBR distribution by summing all the values from –200 to 1200, resulting in a unitless value between 0 and 1. This value is strongly correlated with mean dNBR for the fire, but is a more robust representation when dNBR data are not normally distributed, a frequent occurrence for MTBS data (Picotte *et al.* 2016). Further, the SM is normalised by being bounded from 0 to 1 and made more easily comparable between fires, whereas dNBR is both unitless and unbounded, and therefore difficult to compare between fires. In addition to calculating SM for each fire, we calculated the area-weighted SM (SM_{AW}) for each ecoregion (i) and year (t) using Eqn 1:

$$SM_{AW}(i,t) = \frac{\sum_{n=1}^{nf} SM(n) \bullet A(n)}{\sum_{n=1}^{nf} A(n)} \quad (1)$$

which is the sum of the product of SM and area burned (A) for each individual fire in a given ecoprovince and year divided by the total area burned for the given ecoregion and year. We complemented this analysis by considering interannual variability in the annual proportion of area burned with dNBR exceeding the 75th percentile value. The 75th percentile was determined separately for each ecoprovince from the pooled dNBR distribution of grid cells (dNBR > -200) within all fire perimeters from 1984 to 2014. This value was comparable with published regional dNBR thresholds found between Moderate and High burn severity in previous studies (Cansler and McKenzie 2012; Kolden *et al.* 2015*b*).

Gridded surface meteorological data at a 1/24° (~4000-m) spatial resolution from 1979 to 2014 (Abatzoglou 2013) were used to calculate several metrics with demonstrated links to fire activity (Littell *et al.* 2009; Abatzoglou and Kolden 2013; Williams *et al.* 2015): (i) vapour pressure deficit (VPD); (ii) energy release component (ERC) using fuel model G (dense conifer with heavy fuels; Andrews *et al.* 2003); (iii) reference potential evapotranspiration (ETo) following Allen *et al.* (1998); (iv) Palmer Drought Severity Index (PDSI); and (v) climatic water deficit (CWD). Climate metrics i–iv were temporally aggregated over the fire season, nominally defined as May–September, despite regional differences in fire seasons across western forests. We used annual CWD (January–December) to potentially capture moisture stress during the shoulders of the primary fire season. In addition, we used spring (March–May) and summer (June–August) mean temperature and accumulated precipitation, as well as antecedent PDSI averaged over the previous fire season (May–September). Finally, we used soil moisture (Soil) averaged over the fire season (May–September) and April mean snow water equivalent (SWE) output modelled using the Variable Infiltration Capacity (VIC) model at 1/16° (~6000-m) spatial resolution from Livneh *et al.* (2013), although these data were limited to 1984–2011. Climate data for each ecoprovince were summarised by aggregating gridded climate data for cells within each ecoprovince boundary.

For each ecoprovince, we conducted a simple correlation analysis to assess relationships between SM and fire size, both on a per-fire basis and on a per-year basis, using SM_{AW} for the latter. We quantified univariate relationships (e.g. climate–SM) for each ecoprovince using non-parametric Kendall rank correlation coefficients given their simplicity and to account for the non-Gaussian distribution of some of the variables. Correlations between climate and burn severity were compared with those between climate and area burned to provide context to one another and to previous studies. Years with fewer than three large fires within an ecoprovince were excluded from the correlation analysis given the small sample size. However, we note that such years with limited fire activity typically coincide with an anomalous climate signal. Therefore, eliminating such years from correlative analysis can potentially reduce the signal strength for variables like area burned. Statistical significance was assessed at $\alpha = 0.05$.

Results

Statistically significant, positive correlations between area burned and SM were found at the per-fire level for all ecoprovinces except the California Coast range and Great Basin mountains, suggesting that large fires tend to have higher SM values. However, the correlation between fire size and SM was weak (Fig. 2*a*). The SM was significantly higher for very large fires (>5000 ha) than other large fires (<5000 ha) in each ecoprovince (using a Mann–Whitney U test), except the Great Basin mountains. Significant correlations between annual burned area and SM_{AW} were found in the Sierra Nevada, Cascades and Southern Rocky Mountains ecoprovinces, and also when aggregated across all western US forested regions (Fig. 2*b*).

Strong correlations ($|r| > 0.6$) were found between annual area burned and climate metrics for many ecoprovinces (Fig. 3*a*). The strongest correlations with area burned were typically realised between integrative proxies for fuel aridity such as VPD, ETo, CWD and ERC (Fig. 2*c*) rather than temperature or precipitation. Whereas significant correlations were found between the matrix of climate metrics and area burned in each ecoprovince, correlations were strongest across ecoprovinces in the Rocky Mountains, and notably weaker across the Great Basin mountains, California Coastal range and Cascades ecoprovinces.

Correlations between SM_{AW} and climate metrics generally showed similar, albeit weaker, relationships as to those seen for area burned (Fig. 3*b*). Moderate correlations ($|r| > 0.4$) were found between SM_{AW} and fuel aridity metrics in the Sierra Nevada, Arizona–New Mexico mountains and Great Basin mountains ecoprovinces, and also at the scale of the western US mountains. All ecoprovinces exhibited a positive relationship between interannual variability in fuel aridity and SM_{AW} (e.g. Fig. 2*d*). The largest number of significant correlations with interannual variability in SM_{AW} was seen with VPD (four of eight ecoprovinces). Antecedent conditions generally showed weaker correlation with SM_{AW}; however, spring temperature and precipitation exhibited significant correlations in the Sierra Nevada, whereas spring SWE showed significant negative correlations with SM_{AW} in the Arizona–New Mexico mountains and Great Basin mountains ecoprovinces. Additionally, drought severity during the previous fire season ($PDSI_A$) showed a significant negative correlation with SM_{AW} in Great Basin mountains, implying that antecedent drought enhances burn severity. Similar, but somewhat stronger correlations were found between climate variables and the annual percentage of area burned above the 75th percentile dNBR value (Fig. 3*c*).

Discussion and conclusions

Our results generally support the view that burn severity increases with fire extent (Lutz *et al.* 2009; Cansler and McKenzie 2014), at least at the spatial scales analysed. However, little of the overall variability of burn severity of individual fires was explained by fire size. Likewise, interannual variability in regional burn severity was weakly to moderately correlated with annual area burned at the ecoprovince level. This is in contrast to Kolden *et al.* (2015*a*), who found that burn severity and fire extent were not significantly correlated for three more localised national park study areas.

Interannual variability in burn severity was weakly to moderately correlated with climate variability, with increased fuel aridity promoting increased burn severity, similarly to that of previous studies at regional scales (Miller *et al.* 2009; Miller and Safford 2012; Kolden *et al.* 2015*a*). Relationships were congruent with, but substantially weaker than, those between area burned and climate, suggesting that top-down drivers play a much weaker role in determining regional burn severity than they do for burned area extent. No single climate variable was universally a stronger predictor of burn severity across the studied ecoprovinces. Longer-term drought severity throughout the fire season, as reflected by PDSI and soil moisture, exhibited significant relationships with SM_{AW}. Multiyear drought stress inferred through PDSI during the previous fire season showed some empirical evidence of enhancing burn severity and the proportion of area burned at high severity in the Great Basin

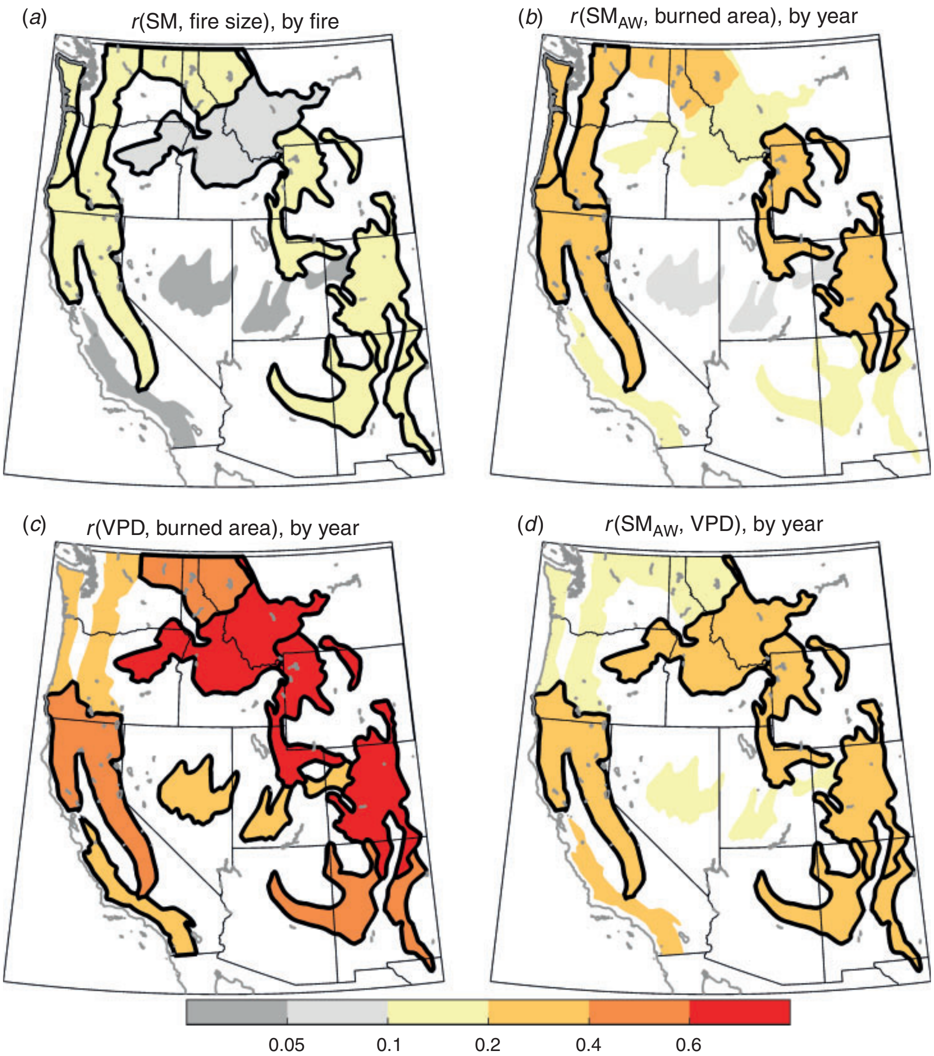

Fig. 2. Kendall rank correlation coefficient (*r*) for ecoprovinces where (*a*) shows the relationship between fire size and severity metric (SM) among individual fires; (*b*) shows the interannual relationships between area-weighted SM and annual burned area by ecoprovince; (*c*) shows the interannual relationships between May–September mean vapour pressure deficit (VPD) and annual burned area; (*d*) shows the interannual relationship between VPD and area-weighted SM. Interannual correlations shown in panels (*b–d*) cover the period 1984–2014. Statistically significant correlations are denoted by the black border across each ecoprovince.

mountains and California Coastal range ecoprovinces. By contrast, precipitation occurring during the fire season exhibited significant negative correlation with SM for the three ecoprovinces in the Rocky Mountains, suggesting that short-duration drought may also contribute. We did not explicitly consider fire weather (e.g. winds or short-term fire danger indices) coincident with the timing of fire events, which may better reflect consumption potential and fireline intensity. However, Birch *et al.* (2014, 2015) did not find that wind or wind-driven large fire runs explained patterns of burn severity.

Increased fuel aridity and potential fire intensity have demonstrated mechanistic links to vegetation consumption, plant physiology and delayed mortality from fire (van Mantgem *et al.* 2013; Smith *et al.* 2016; Restaino *et al.* 2016) and provide a basis for the statistical relationships identified in the current study. Regional relationships between burn severity and climate variability may alternatively be manifest through interannual variability in what vegetation types burn within a region and how completely the vegetation burns in individual years. For example, the more mesic portions of an ecoregion may only become flammable and burn during fire seasons with anomalously high fuel aridity (Cansler and McKenzie 2014; Schoennagel *et al.* 2004). Parks *et al.* (2014*b*) showed that burn severity is generally greater in more mesic areas across the western US. Hence, increased regional burn severity during summers with elevated fuel aridity may be due to biogeographic differences in what burns within a region, rather than wholesale changes in burn severity across the region. The aforementioned relationships are generally weaker at smaller eco-section levels (Fig. S1 in online supplementary material), yet directional relationships generally

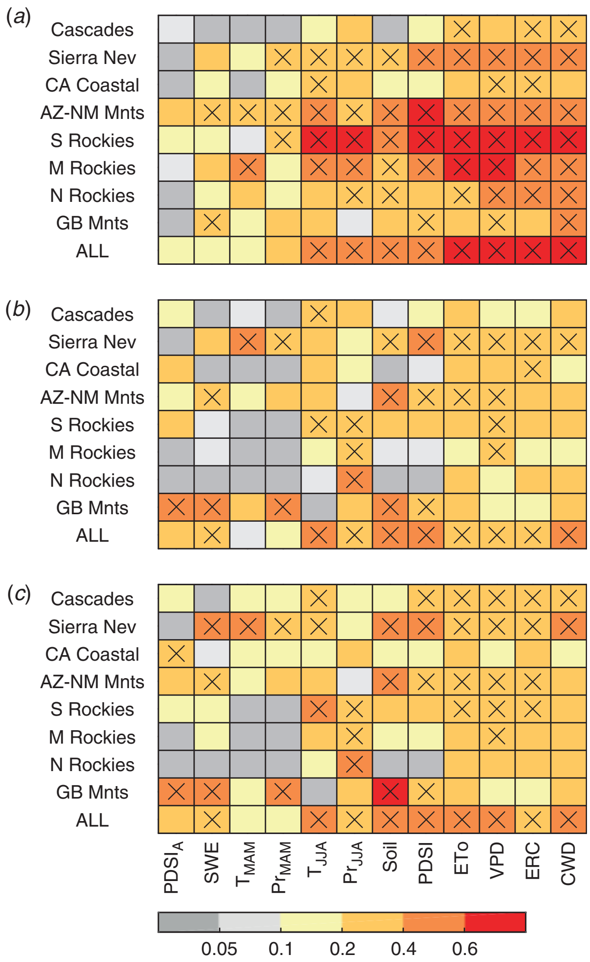

Fig. 3. Matrix of Kendall rank correlation coefficients for each ecoprovince (*y* axis, ALL represents aggregation over all eight forested ecoprovinces) and climate correlate (*x* axis) with (*a*) interannual area burned; (*b*) interannual variability in area-weighted severity metric; and (*c*) interannual variability in the proportion of burned area exceeding the 75th percentile dNBR (differenced Normalized Burn Ratio) value. Statistically significant relationships are denoted by a black X. Climate variables listed horizontally from left to right are the Palmer Drought Severity Index of the previous fire season ($PDSI_A$), April snow water equivalent (SWE), spring temperature (T_{MAM}), spring precipitation (Pr_{MAM}), summer temperature (T_{JJA}), summer precipitation (Pr_{JJA}), fire season (May–September) soil moisture (Soil), Palmer Drought Severity Index (PDSI), reference potential evapotranspiration (ETo), vapour pressure deficit (VPD), energy release component (ERC), and annual climatic water deficit (CWD). The sign of the correlation is reversed for PDSI, SWE, Pr and Soil.

persist. The reduced sampling opportunities for wildfire at smaller geographic scales limit a robust assessment of temporal variability.

The correlative relationships between fuel aridity and burn severity demonstrated here and increased fuel aridity resulting from anthropogenic climate change (Flannigan *et al.* 2013; Stavros *et al.* 2014) support prior suggestions that mean burn severity across western US forests will increase with climate change. However, this suggestion relies on stationarity of climate–fire dynamics, including stationary vegetation distributions (McKenzie and Littell 2017). When Parks *et al.* (2016) used a pyrogeographic modelling approach that did not assume vegetative stationarity under anthropogenic climate change, they modelled widespread *decreases* in burn severity. They thus inferred that warming-driven changes in vegetation distributions would yield an expansion of vegetative types that have historically burned at lower severities. However, neither the approach presented here nor that of Parks *et al.* (2016) accounts for the full range of vegetation–climate dynamics and management influences that are likely to determine future burn severity regimes, and the conflicting results suggest that these must be accounted for to improve accuracy of projected changes in burn severity.

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