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Relationships between climate and macroscale area burned in the western United States

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Abstract. Increased wildfire activity (e.g. number of starts, area burned, fire behaviour) across the western United States in recent decades has heightened interest in resolving climate–fire relationships. Macroscale climate–fire relationships were examined in forested and non-forested lands for eight Geographic Area Coordination Centers in the western United States, using area burned derived from the Monitoring Trends in Burn Severity dataset (1984–2010). Fire-specific biophysical variables including fire danger and water balance metrics were considered in addition to standard climate variables of monthly temperature, precipitation and drought indices to explicitly determine their optimal capacity to explain interannual variability in area burned. Biophysical variables tied to the depletion of fuel and soil moisture and prolonged periods of elevated fire-danger had stronger correlations to area burned than standard variables antecedent to or during the fire season, particularly in forested systems. Antecedent climate–fire relationships exhibited inter-region commonality with area burned in forested lands correlated with winter snow water equivalent and emergent drought in late spring. Area burned in non-forested lands correlated with moisture availability in the growing season preceding the fire year. Despite differences in the role of antecedent climate in preconditioning fuels, synchronous regional fire activity in forested and non-forested lands suggests that atmospheric conditions during the fire season unify fire activity and can compound or supersede antecedent climatic stressors. Collectively, climate–fire relationships viewed through the lens of biophysical variables provide a more direct link to fuel flammability and wildfire activity than standard climate variables, thereby narrowing the gap in incorporating top-down climatic factors between empirical and process-based fire models.

Additional keywords: fire danger, management, modelling.

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Introduction

Climate and weather are respective key enablers and drivers of wildfire activity including fire occurrence, area burned and fire behaviour (e.g. Swetnam and Betancourt 1990; Bessie and Johnson 1995). Knowledge gaps in isolating the temporal scales and processes through which top-down atmospheric processes influence wildfire activity have complicated the ability to model wildfire (Girardin *et al.* 2009; Macias-Fauria *et al.* 2011), and hinder the effectiveness of operational fire management who use seasonal predictions of wildfire activity to proactively allocate regional suppression resources (Kolden and Brown 2010; Owen *et al.* 2012). Increases in wildfire activity across western North America realised through increases in area burned, structure loss and suppression expenditures over the past several decades are hypothesised to be partially attributable to more favourable climatic conditions for large wildfire seasons (e.g. Gillett *et al.* 2004; Westerling *et al.* 2006) and changes in land management (e.g. Marlon *et al.* 2012). Such changes have increased the urgency to better resolve climatic controls on regional wildfire activity.

Prior studies of climate–fire relationships across the western United States suggest two general climate–fire regimes (e.g. Westerling *et al.* 2003; Littell *et al.* 2009; Gedalof 2011). A fuel-limited regime in arid and semiarid deserts and rangelands is associated with higher fuel abundance resulting from increased moisture availability that leads to heightened wildfire activity the following year through increased fuel connectivity and the ability of the landscape to carry fire. By contrast, a flammability-limited regime in forested landscapes is associated with concurrent moisture deficits that increase the availability of fuels to carry fire. This dichotomy in climate–fire relationships is realised through the preconditioning of fuels to wildfire potential via antecedent climatic conditions, defined herein as collective atmospheric conditions in the months to years before the onset of fire season. Antecedent conditions are incorporated prognostically in the development of seasonal wildfire outlooks (Brown *et al.* 2004). However, the recurrence of large regional fire seasons failing to materialise in flammability limited systems following antecedent conditions otherwise conducive to large fire years, including drought or the phase of El Niño–Southern Oscillation and its associated influence on winter and spring climate, suggests that optimal antecedent conditions alone are insufficient to promote high wildfire activity (e.g. McKenzie *et al.* 2004; Morgan *et al.* 2008). By contrast, other studies have emphasised the importance of climate during the fire season in determining area burned (e.g. Gedalof *et al.* 2005; Trouet *et al.* 2006; Morton *et al.* 2013), and the importance of concurrent weather regimes amenable to wildfire growth and subsequent area burned (e.g. Flannigan and Harrington 1988; Bessie and Johnson 1995; Moritz *et al.* 2010; Abatzoglou and Kolden 2011*a*). Finally, the various mechanisms and time-scales through which atmospheric conditions influence wildfire are contingent upon bottom-up factors of fuel types, successional stage and topography (e.g. Parks *et al.* 2012) as well as the frequency and timing of ignitions.

Most prior analyses of climate–fire relationships in the western United States have used readily available standard climate variables including monthly and seasonal temperature, precipitation and the Palmer Drought Severity Index (PDSI). Such relationships indirectly assess the abundance of fuels and availability of fuels to combust (e.g. Carcaillet *et al.* 2001), but may fail to synthesise the direct connection to processes intrinsic to facilitating wildfire. By contrast, recent studies have identified relationships between wildfire and water balance variables as proxies of vegetative moisture stress (Littell and Gwozdz 2011; Westerling *et al.* 2011; Morton *et al.* 2013), and to operational fire danger indices designed to integrate meteorological forcing into numerical ratings of fuel moisture and potential fire behaviour (e.g. Flannigan *et al.* 2009; Spracklen *et al.* 2009; Trouet *et al.* 2009; Riley *et al.* 2013). These dynamic biophysical variables (e.g. McKenzie *et al.* 2003) integrate meteorological variables in a mechanistic fashion across a range of temporal scales and yield a more direct link to fire processes (e.g. flammability, rate of spread) than any meteorological variable alone. We expand upon previous studies that have considered both standard climate variables and biophysical variables (e.g. Spracklen *et al.* 2009; Riley *et al.* 2013) by explicitly examining their ability to explain interannual variability in macroscale area burned in the western United States.

Macroscale climate–fire relationships in the western United States have typically used the monthly wildfire area burned on federal lands, as reported in the federal Fire Occurrence Database (FOD; e.g. Westerling *et al.* 2003). Unfortunately, federal fire records contain several documented inaccuracies, including published fire perimeters that significantly overestimate area burned compared with satellite-based approaches because they assume homogenous consumption within the fire perimeter and ignore unburned inclusions (Kolden and Weisberg 2007; Kolden *et al.* 2012). This within-fire heterogeneity is captured by the database developed by the Monitoring Trends in Burn Severity (MTBS) program (Eidenshink *et al.* 2007), which includes all wildfires from 1984–2010 (and continuing) greater than 404 ha in the western United States. Utilising only the true area burned from MTBS (and excluding unburned inclusions) is a new approach in climate–fire studies, and will allow for a more accurate portrayal of climate–fire relationships.

The present study builds upon prior climate–fire studies in the western United States and seeks to better characterise macroscale relationships between climate and annual area burned in forested and non-forested lands by examining two primary questions. First, we examine whether biophysical variables including fire danger indices and water balance variables are more strongly correlated with area burned than standard climate variables using univariate analysis, and how these differences are manifested geographically and in forested and non-forested lands. Second, we examine differences in the relationship between area burned and both antecedent and in-season atmospheric conditions to resolve temporal aspects of predictability of burned area. These questions have relevancy in better resolving climate–fire relationships applicable to larger scales at which operational regional fire management decisions are made in the western United States (e.g. Corringham *et al.* 2008), as well furthering statistical modelling of wildfire by incorporating a diverse set of climate and biophysical variables to better understand how the atmosphere enables and drives seasonal wildfire activity.

Data and methods

Climate–fire relationships are examined across the eight Geographic Area Coordination Centers (GACCs) in the western United States (Fig. 1), including Pacific Northwest (NW), Northern Rockies (NR), Northern California (NO, excluding Hawaii), Southern California (SO), Western Great Basin (WB), Eastern Great Basin (EB), Rocky Mountain (RM) and Southwest (SW). GACCs were created to facilitate suppression resource (e.g. firefighter crews, engines, air support) prioritisation and allocation during wildfire season. Predictive Service Areas (subsets of GACCs, acquired from http://psgeodata.fs.fed.us/data/gis_data_download/static/PSA_2009.zip, accessed 1 October 2011) in the NR, RM and SW GACCs that fell completely within the Great Plains are excluded as they include both early-season wildfire activity relative to their parent GACCs and numerous agricultural burns misclassified as wildfire. Previous studies investigating macroscale climate–wildfire relationships in western United States have typically aggregated regional fire activity by states or by ecoregions under the hypothesis that climate–fire relationships are mediated through macroscale vegetation (e.g. Westerling *et al.* 2003; Littell *et al.* 2009). However, heterogeneity in fuel type and abundance within ecoregions limit a complete isolation of fuel classes even at the ecoregion scale, and fire statistics become a limiting factor at more localised scales. We compromise these limitations of scale by separately considering ecologically relevant forested and non-forested lands within management relevant GACCs. One of the most widely utilised pre-season planning tools, the National Seasonal Assessment Workshops and their monthly follow-up publications (Owen *et al.* 2012), are developed by GACC region, with additional emphasis on forested *v.* non-forested fuels within a GACC. Our focus on resolving climate–wildfire relationships at the GACC level corresponds to the scales at which climate information is digested and interpreted by fire management operations for seasonal planning, resource allocation, financial support requests from Congress and suppression activity (Kolden and Brown 2010; Owen *et al.* 2012), thereby providing a direct application of our analysis to decision makers, particularly at the national level where fiduciary planning and suppression resource allocation occurs (Owen *et al.* 2012). Furthermore, we justify examining macroscale area burned, rather than more refined spatial scales, as widespread fire activity associated with large-scale, top-down climate drivers can strain local, regional and national resources, potentially decoupling local area burned

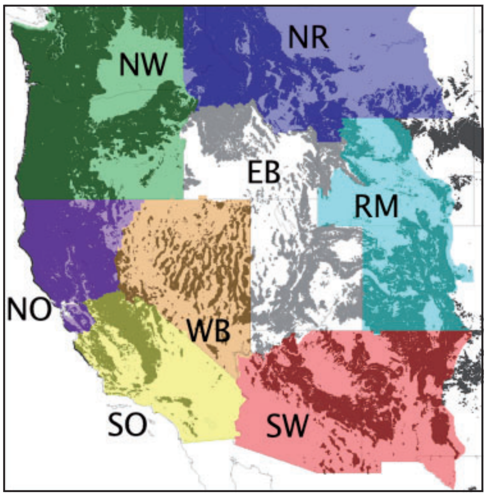

Fig. 1. Map of Geographic Area Coordination Centers in the western United States excluding Predictive Services Areas (NR11–13, RM04–06, RM23–27, SW13–14) that fell completely within the Great Plains ecoregion. Forested land (shaded) as delineated from LANDFIRE.

from localised climate drivers during periods when fire suppression resources are over-allocated and certain fires and regions gain priority for suppression resources.

Wildfire data

Area burned in the United States is reported to the federal Fire Occurrence Database in one of two ways: an expert estimate based on flight-based demarcation of fire lines on maps, or a calculated value derived from fire polygons drawn with Global Positioning System units and both airborne and spaceborne image acquisitions (Kolden and Weisberg 2007). In both cases, the area burned is calculated as the total area within the perimeter of a fire polygon. In actuality, wildfires burn in heterogeneous patterns that include significant islands of unburned area (Kolden *et al.* 2012). To circumvent known limitations of compiled area burned datasets and obtain a more accurate depiction of area burned, we used satellite-derived area burned from over 7000 individual large fires (>404 ha) from MTBS dataset (last acquired from http://www.mtbs.gov, accessed 1 October 2011) in the eight western GACCs from 1984–2010 (Eidenshink *et al.* 2007). Based on previous estimates from three dominant western US forest types, we estimate that the 404 ha threshold encompasses greater than 95% of all burned area for these regions (Kolden *et al.* 2012).

We attribute area burned in forested or non-forested vegetation utilising the Environmental Site Potential (ESP) product from LANDFIRE (www.landfire.gov, accessed 20 January 2013). ESP is deemed the most appropriate vegetation classification for long time-series analysis as it represents the climax succession stage, and does not contain the footprint of fires from recent years as most of the other available land cover products do. We delineate forest as any ESP vegetation class that contains 'forest' or 'woodland' in the class name, and quantify the proportion of forest *v.* non-forest pixels for each fire in the dataset. For purposes of delineating seasonality for forest *v.* non-forest fires, all fires where the proportion of forest pixels within a fire perimeter exceeds 50% are classified as forest fires, fires with less than 50% forest pixels are classified non-forest fires. Fig. 2 shows the proportion of large fires discovered per month and the cumulative distribution of area burned as a function of the month of the discovery date. We exclude out-of-season wildfires with discovery dates in the top and bottom 2.5% of the historical seasonal distribution for forested and non-forested GACC areas to better constrain the analysis to area burned during the primary fire season. To resolve fire–climate relationships, we produce a more accurate estimate of area burned in forested *v.* non-forested lands by multiplying the proportion of forest or non-forest pixels by the total area burned for each fire. For each fire, we exclude the area classified as 'Unburned to Low' (as delineated by MTBS) to remove unburned inclusions within the fire perimeter. The end result is a time series of fire-season area burned (FSAB) in large fires summing the actual area burned each year within the perimeter of each GACC in both forested and non-forested areas. Half of the GACCs had greater than 50% total area burned in forest (NR, RM, NO and SW), and significant correlations were observed between the FSAB for forest *v.* non-forest FSAB across the 27-year temporal period, indicating some synchronicity in large fire years between the two ecotypes (Fig. 2; Appendix Table A1).

Climate data

Long-term climate and meteorological data for the western United States have typically been derived from one of two primary sources: (i) the relatively sparse observational network (e.g. National Weather Service Cooperative Observer Program stations) or (ii) National Climatic Data Center divisional data that are not geographically consistent with ecological or management jurisdictions and may be ill-suited given the varied terrain of the region. We overcome such limitations by aggregating data from three high-resolution gridded datasets to across all pixels in forested and non-forested GACCs separately to obtain both standard climate variables and biophysical variables (Table 1). A pixel is considered forested when forested ESP occupies a majority of the area within its native resolution. The three datasets include:

1. Monthly temperature and precipitation data from Parameter-elevation Regressions on Independent Slopes Model (PRISM, Daly *et al.* 2008) at 0.0083° resolution. Monthly PDSI is calculated from these variables following Kangas and Brown (2007).
2. Daily high-resolution meteorological data at 0.0416° resolution (Abatzoglou 2013) is used to calculate fire danger indices from the National Fire Danger Rating System (NFDRS) and the Canadian Forest Fire Danger Rating System (CFFDRS) as well as reference potential evapotranspiration (ET_o) using the Penman-Montieth method (Allen *et al.* 1998) with zero canopy stomatal resistance (e.g. Littell and Gwozdz 2011; Morton *et al.* 2013).
3. Daily snow water equivalent (SWE) and soil moisture (3-layer total) data from the Variable Infiltration Capacity (VIC) model at 0.125° resolution (Liang *et al.* 1994).

Methods

Relationships between FSAB and monthly temperature and precipitation are examined across a matrix of time intervals from

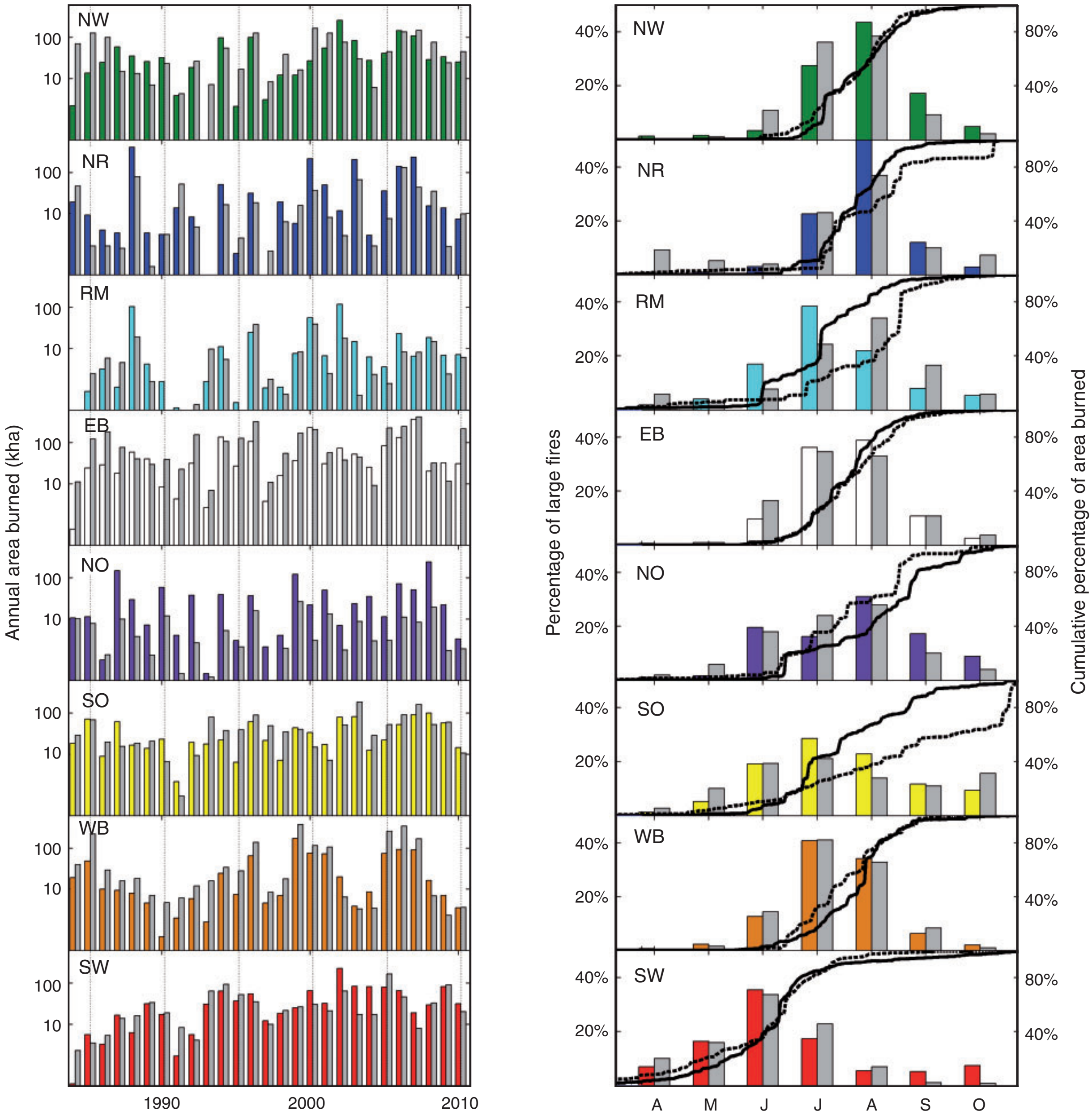

Fig. 2. (Left column) Time series of logarithmic annual fire-season area burned from 1984–2010 for each Geographic Area Coordination Center (GACC). Grey coloured bars denote non-forested area burned and coloured bars denote forested area burned. (Right column) Seasonal distribution of large fire activity (1984–2010) for each GACC. The bars show the percentage of total large fires discovered for each month of the fire season, whereas solid and dashed lines show the cumulative distribution of burned area by discovery date for forested and non-forested areas respectively.

January 1-year before the fire year through October of the fire year and for temporal averages that include the previous 1–12 months (Table 1). Monthly PDSI, and monthly averaged SWE and soil moisture are considered over the same time span. Antecedent, or pre-fire season conditions are defined as conditions accrued before the fire through the climatological start date of fire season for each region (i.e. day of year after which more than 2.5% of the historical large fires occurred), whereas concurrent or in-season conditions are liberally defined as conditions accrued following this date of the fire year. The strong temporal-autocorrelation of variables that integrate longer-lived moisture deficits (e.g. soil moisture, 1000-h fuel moisture, PDSI) limit an absolute separation between antecedent and in-season conditions; however, we consider relationships examined during the fire season as being in-season conditions, regardless of whether they incorporate atmospheric conditions before the start of fire season or the actual commencement of large fires during any particular year.

We build upon prior studies by examining both water balance variables including ET_o, soil moisture and fire danger indices from the NFDRS and CFFDRS. These biophysical variables are examined at twice-monthly time intervals ending on the 1st and

Table 1. Variables used in the analysis separated into standard climate or biophysical variables

Time interval refers to the temporal frequency for which variables were analysed over the period specified. Temporal averaging refers to the span of time ranges at each time interval. Descriptions of individual variables are provided in the text

Variable	Time interval	Temporal averaging	Period
Standard climate variables			
Temperature[A,C], Precipitation[A,C]	Monthly	1–12 months	Jan (year −1)–Oct (year)
	Twice-monthly	1, 15, 30, 45, 60, 75, 90, 105, 120, 135, 150 days	1 May–1 Nov
	Extrema		
Palmer Drought Severity Index[A]	Monthly	1 month	Jan (year −1)–Oct (year)
Biophysical variables			
Snow Water Equivalent[B], Soil moisture[B]	Monthly	1 month	Jan (year −1)–Oct (year)
Energy Release Component[C], Burning Index[C], 100-h fuel moisture[C], 1000-h fuel moisture[C], Fine Fuel Moisture Code[C], Duff Moisture Code[C], Drought Code[C], Potential Evapotranspiration[C], Water Deficit (Potential Evapotranspiration minus Precipitation)[C], Soil Moisture[B]	Twice-monthly Extrema	1, 15, 30, 45, 60, 75, 90, 105, 120, 135, 150 days	1 May–1 Nov

[A]PRISM.
[B]VIC.
[C]Abatzoglou (2013).

16th of each month from 1 May to 1 November, and consider both instantaneous observations (e.g. soil moisture on 1 September) and temporal averages of the previous 15 days (e.g. average soil moisture for previous 15-days ending 1 September) up to 150 days (e.g. average soil moisture for the previous 150 days ending 1 September) using a 15-day time step (Table 1). We additionally consider extrema of daily biophysical variables, precipitation and temperature during the fire season of each year. We consider extrema of both single-day values (e.g. lowest FM100, highest DMC) and values averaged over the aforementioned temporal windows (e.g. highest 30-day ERC). These extrema consider flexible temporal windows allowed to vary interannually, rather than a prescribed calendar window and have shown utility in prior analyses (P. Higuera, pers. comm.).

Federal, state and local fire management agencies in the United States use operational NFDRS outputs as proxies for fire danger; including Energy Release Component (ERC), Burning Index (BI) and 100-h and 1000-h fuel moisture (Deeming *et al.* 1977). NFDRS is a statistical-based system that is used both to model fire behaviour, initiation and spread and to guide suppression and fuel treatments operations. Unlike slowly evolving drought indices such as PDSI, fire danger indices can be separated from longer-term (>3 months) antecedent moisture stress and current fuel loading or conditions, thereby isolating concurrent moisture stressors. For example, the 100- and 1000-h fuel moistures explicitly correspond to the timescale of exponential decay of fuel moisture with respect to the equilibrium moisture content. ERC is a weather–climate hybrid index of daily fire energy intensity that considers the cumulative drying effect of previous daily weather conditions on the 100- and 1000-h fuel complex by integrating temperature, precipitation, humidity and solar radiation, whereas BI is a proxy for the flame length and difficulty of fire control by incorporating the ERC along with a spread component that includes wind speed. Fuel model G (dense conifer stand with heavy litter accumulation) is used in NFDRS calculations to maintain consistency with previous studies and usage by regional fire management (Andrews *et al.* 2003), and green-up dates are defined by the first day of each year when the normalised growing season index for each pixel are >0.5 (Jolly *et al.* 2005; M. Jolly, pers. comm.). The CFFDRS requires less meteorological data and has been more widely applied in research studies across boreal forests (e.g. Van Wagner 1987; Wotton 2009). The CFFDRS is designed to track fuel moisture for different layers of the forest fuel structure, including surface fuel through the Fine Fuel Moisture Code (FFMC, time lag of 2/3 day), moisture in the upper organic layer of the forest floor through the Duff Moisture Code (DMC, time lag of 15 days) and moisture in the deeper layer of organic matter through the Drought Code (DC, time scale of 52 days). Note that these biophysical variables are strongly inter-related as they integrate the same surface meteorological data, but vary in terms of which variables are assimilated, the interaction and weighting of different variables and their time-lag response time.

In addition to soil moisture and ET_o, we also calculate water deficit as ET_o minus precipitation (e.g. Morton *et al.* 2013). This differs from the climatic water deficit approach that considers soil moisture carry-over (e.g. Stephenson 1998), but may be more pertinent to dead fuels that are unable to exploit soil moisture reserves and free of uncertainties regarding the ability of vegetation to utilise soil moisture from different depths in the soil column. Additional calculations that involve soil moisture hydrology may be particularly relevant for integrating the influence of antecedent soil moisture in estimating actual evapotranspiration and the classical climatic water deficit (e.g. Westerling *et al.* 2011).

A Pearson's correlation analysis between annual log-transformed FSAB and climate and biophysical variables (Table 1) is performed for each region. This approach presumes a log-linear relationship and ignores nonlinear or threshold-based relationships that may exist. More complex relationships tied to physical processes (e.g. critical fuel moisture, specific fire-weather situation, season ending precipitation event) are likely best resolved at smaller spatial scales for individual fire events using mechanistic approaches. To increase the robustness of our results, we bootstrap resample with replacement 1000 times and recalculate linear correlations. Hereafter, we present results of the correlation using all 27 years and report statistical significance only in cases where >95% of the bootstrapped correlations are of the same sign.

Results

Correlations between antecedent climate and FSAB exhibited clear differences between forested and non-forested areas. In forested areas, several regions showed a positive correlation between FSAB and autumn-winter temperatures and a negative correlation with autumn-winter precipitation (Fig. 3). Collectively, these relationships were manifested through negative correlations between FSAB and SWE in NR, EB, RM and NO; however, the strongest correlations were observed in mid-winter rather than during spring. Spring correlations were generally weaker, except for negative correlations between spring precipitation and FSAB in RM and SO. Soil moisture and PDSI tended towards negative correlations during spring, with statistically significant negative correlations with FSAB by May in several GACCs. By contrast, a fuel-limited climate–fire signal was found in many non-forested regions through relationships between FSAB and temperature, precipitation and moisture (PDSI and soil moisture) the year before the fire season (Fig. 4). In addition, many GACCs showed negative correlations between FSAB and late-winter to spring precipitation that assist the transition between pluvial conditions the previous year to normal or below normal PDSI leading up to the fire season. Outside of a few exceptions, univariate correlations with antecedent conditions explained less than 30% of the variance in FSAB.

Correlations between FSAB and temperature, precipitation and drought concurrent to the fire season were unanimously stronger than antecedent relationships in all forested GACC areas except WB. This is reflected in the commonality of positive correlations between FSAB and temperature and negative correlations between FSAB and precipitation, PDSI and soil moisture for time intervals extending into and through the fire season consistent with flammability limited climate–fire relationships. Aggregates of monthly climate summaries explained over half of the variability in forested FSAB in several GACCs. Relationships were weaker in non-forested GACC areas; however, most non-forested areas exhibited relationships of the same sign as their forested counterparts, with warm and dry conditions during the summer linked to above normal FSAB.

Contemporaneous linkages are further elucidated through correlations between FSAB across the suite of biophysical variables and sub-monthly temperature and precipitation. Correlations in forested GACCs areas similarly showed that prolonged periods of heightened fire danger and ET_o, water-deficit and low soil and fuel moisture correlate strongly with widespread fire activity (Fig. 5, Appendix Fig. A1). Relationships were generally strongest for fire danger indices and water balance variables integrated over an extended period (60–120 days) of the fire season. At least 30% of the variance in forested FSAB was explained with a single variable in all GACCs, with more than 60% of variance explained by a single variable in the NW, NR, EB, RM and SW GACCs. Although strong correlations were also evident with temperature and precipitation, typically 10–15% more variance was explained through biophysical variables.

Similar, albeit weaker relationships were seen in non-forested FSAB (Figs 6, A2). Aside from WB and EB, significant correlations to fire danger and water-balance variables were observed during the core of the fire season and extend through to the end of the fire season. The lack of any coherent correlation during the fire season in non-forested WB and EB contrasts with the strong correlation between FSAB and antecedent moisture the year before the fire season in these regions (Fig. 4).

The strongest univariate correlation identified for each region involved biophysical variables in all forested GACC areas, with mixed results in non-forested GACC areas (Table 2). The optimal correlations in forested areas integrated fire danger indices and water-balance variables over the course of the fire season and were realised near the climatological end of fire season, and past the typical end of the fire season in RM, NO and SW. The latter likely reflect the influence of delayed onset of precipitation that allow active fires to continue growing. The temporally flexible windows exhibited strong correlations across several GACC-variable combinations with peak 75-day ERC and peak 60-day ERC being the two strongest correlates in forested areas for the NR and EB respectively. Aside from WB and non-forested areas of NO and EB, all of the strongest correlations were realised during the fire season rather than being purely antecedent. Strongest correlations to antecedent conditions all involved aspects of moisture availability the year before the fire season, rather than antecedent conditions in the winter or spring before the fire season.

Fig. 7 shows a scatterplot of FSAB anomalies (percentage of normal) between antecedent climatic factors, 1 June PDSI in forested regions and PDSI averaged over the prior growing season in non-forested areas, and in-season biophysical factors, depicted as ERC during the temporal window that exhibited the strongest correlation to FSAB for each GACC. Over 65 and 50% of all large fire years, defined as when FSAB exceeds twice the 27-year average FSAB, occurred during summers with fire danger in the upper quintile for forested areas and non-forested areas respectively. By contrast, only a few large fire years occurred during summers with below normal fire danger. Large fire years preferentially occurred with antecedent drought in forested regions (60% increase over the expected value for PDSI in the lower quintile) and with pluvial conditions the year before the fire season in non-forested regions.

Discussion and conclusions

Our study illustrates regional commonality between FSAB and biophysical variables manifested during the fire season as top-down drivers of regional wildfire activity that complement antecedent climate controls on fuels (e.g. Swetnam and Betancourt 1998; Morgan *et al.* 2008). Biophysical variables, particularly ERC and ET_o, both quantitatively and conceptually provided a more direct link to fuel flammability and conditions conducive to large fire potential and area burned than individual variables like temperature and precipitation for the 1984–2010 time period. These findings corroborate both modelling (e.g.Finney *et al.* 2011) and observational studies

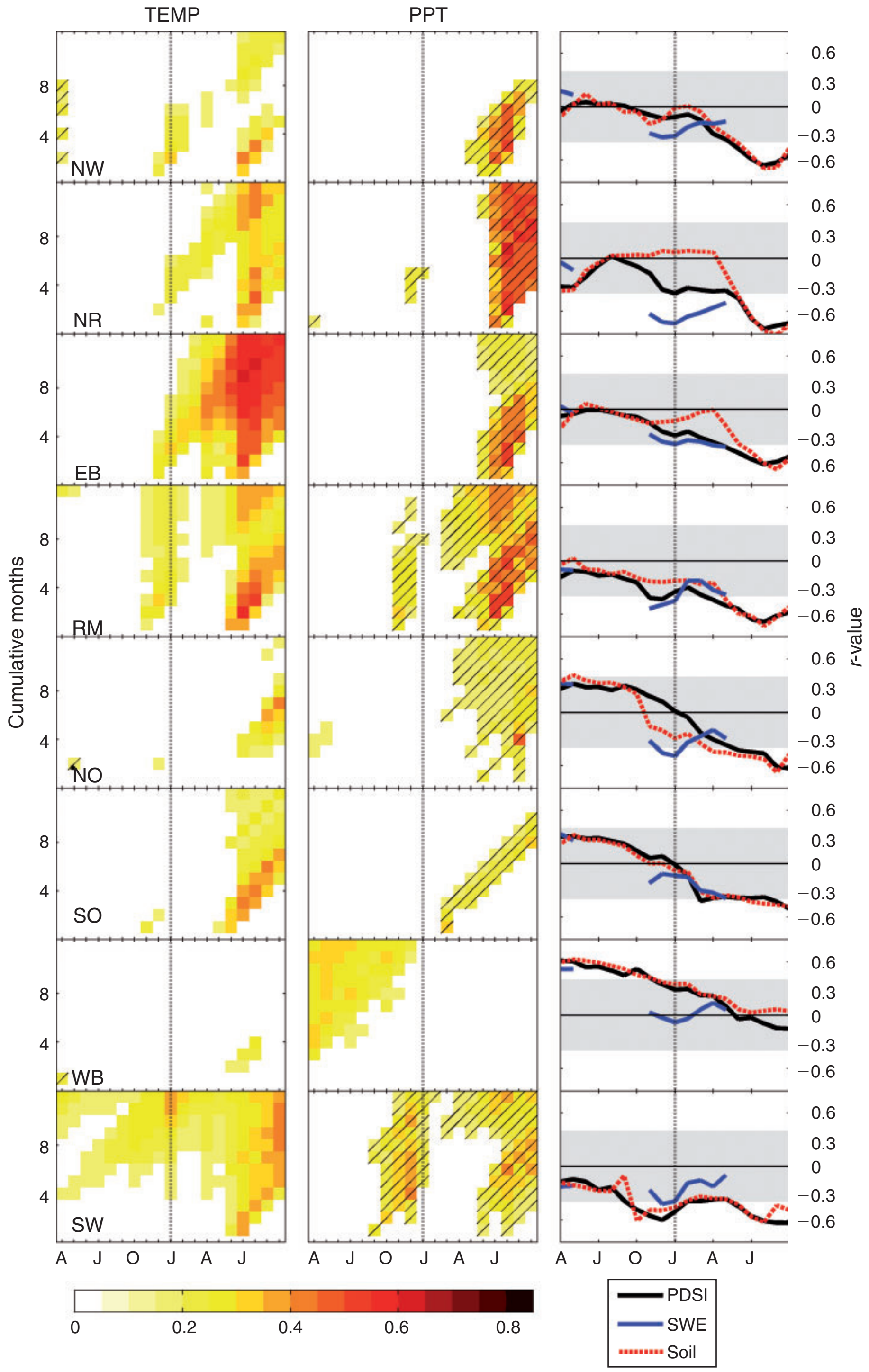

Fig. 3. Correlation matrices (R^2) of the logarithm of fire-season area burned and monthly temperature (left column) or precipitation (middle column) for forested Geographic Area Coordination Centers (GACCs). (GACC regions span each row with the name abbreviated in the lower-left hand corner of the temperature correlation matrix). Correlations are shown from January one-year prior through October of the fire year (x-axis) and averaged over the prior 1-to-12 months (y-axis). The dashed vertical line denotes January of the fire year. Values are only shown where at least 95% of bootstrapped samples were of the same sign, with hatching indicating significant negative correlations. The rightmost column shows mean correlation (r) of monthly Palmer Drought Severity Index (PDSI), soil moisture (Soil) and snow water equivalent (SWE, only shown for Nov–May) to the logarithm of fire-season area burned. The grey shading highlights the 95% confidence interval, estimated by assuming that the climate variables and the log of fire-season area burned are from a bivariate normal distribution.

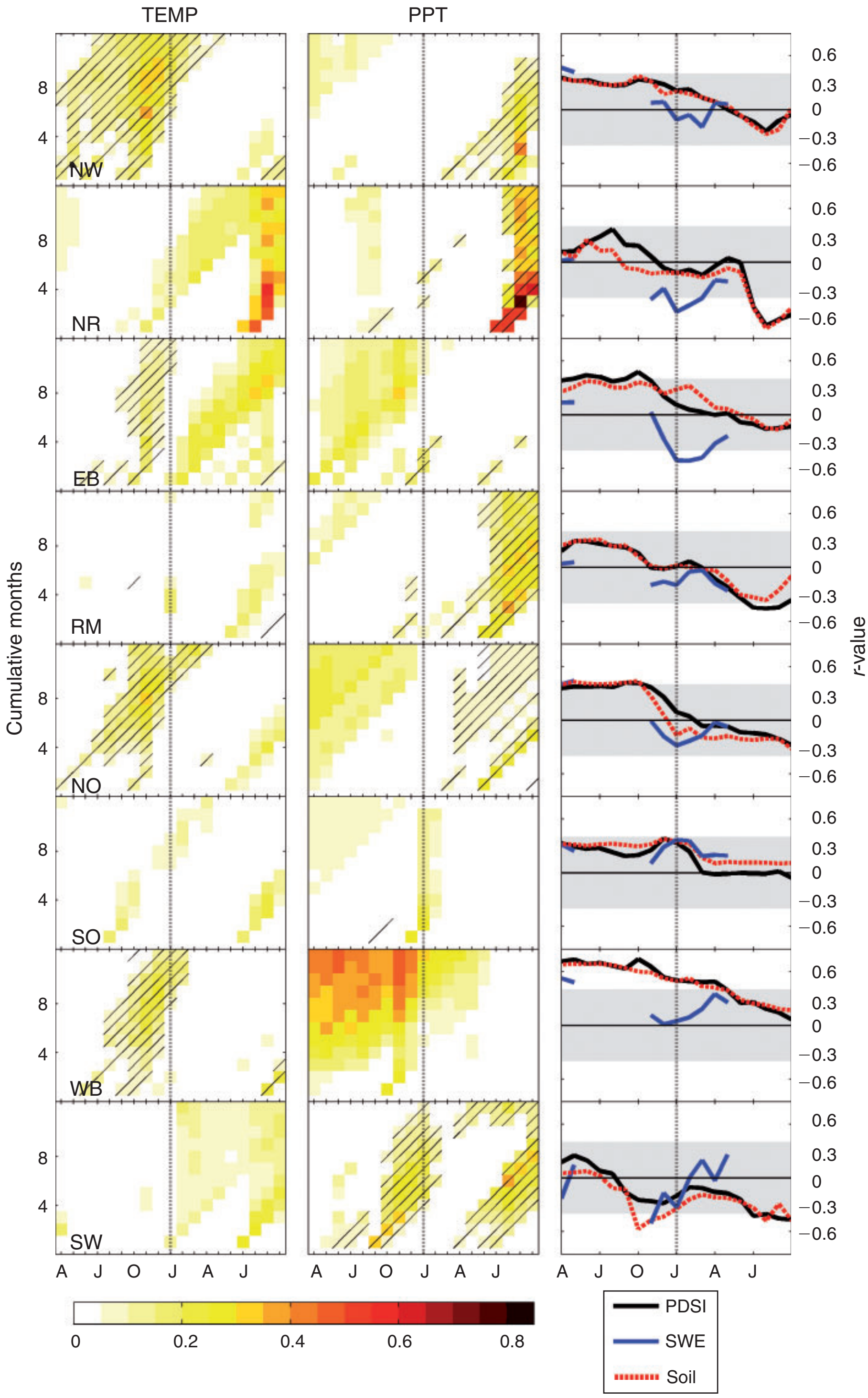

Fig. 4. As Fig. 3 but for climate–fire relationships in non-forested GACCs.

(e.g. Andrews *et al.* 2003; Girardin and Wotton 2009; Littell and Gwozdz 2011; Morton *et al.* 2013; Riley *et al.* 2013), and extend statistical relationships between actual area burned (excluding what can be substantial unburned islands) and a suite of biophysical variables across the western United States. Additional climate–fire studies at multiple spatial scales are needed to establish whether biophysical variables are robust predictors of FSAB (e.g. Parisien *et al.* 2011), as macroscale analysis may obscure localised relationships for more specific fuel classes or at smaller geographic scales. At local scales, biophysical variables can be used in a more process-based fashion for modelling ignition efficiency, fire behaviour, longevity of conditions

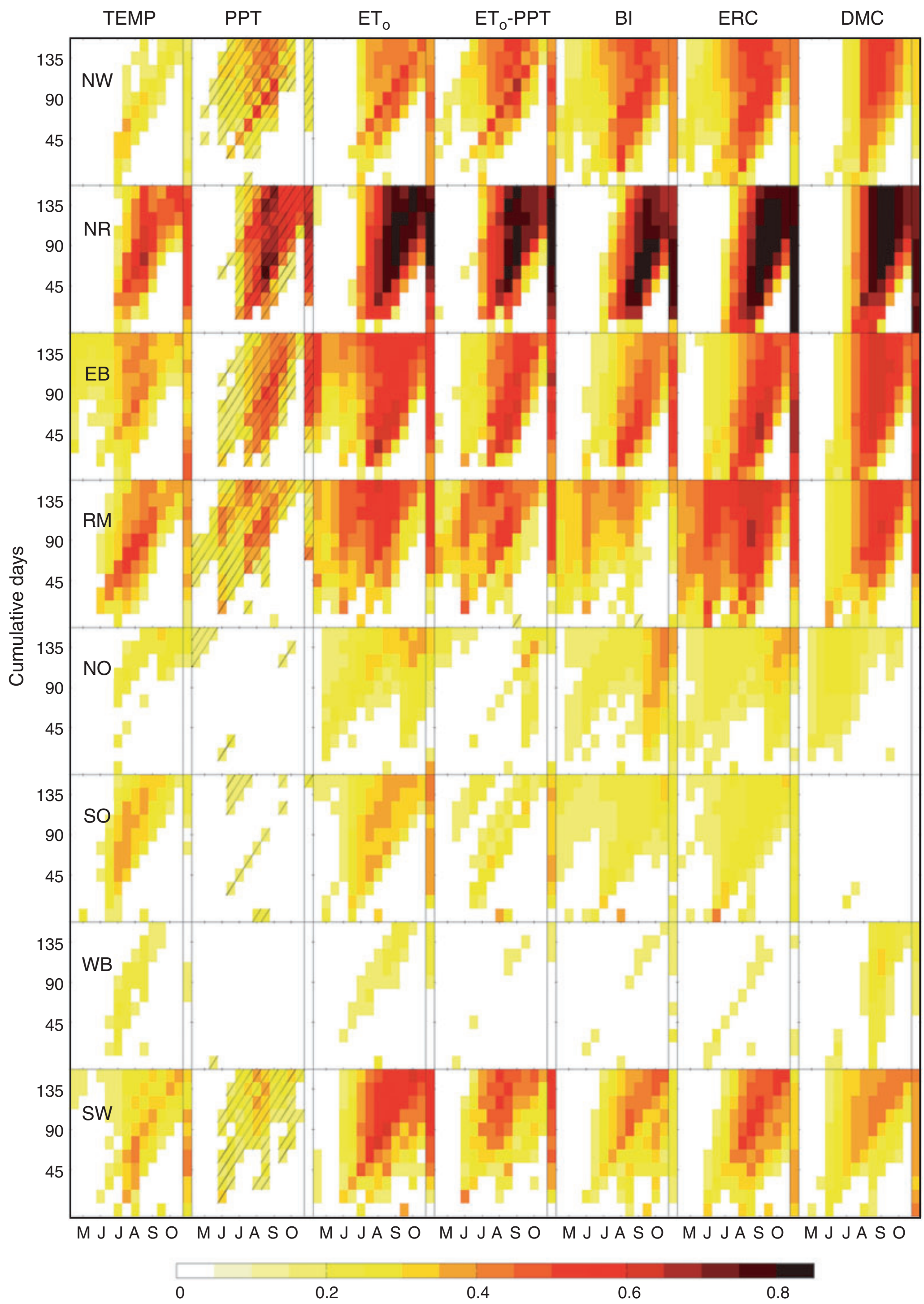

Fig. 5. Correlation matrices (R^2) of the logarithm of fire-season area burned and biophysical variables for forested Geographic Area Coordination Centers (GACCs). Biophysical variables as follows (from left to right): temperature (TEMP), precipitation (PPT), reference evapotranspiration (ET$_o$), water deficit (ET$_o$ minus Precipitation), Burning Index (BI), Energy Release Component (ERC) and Duff Moisture Code (DMC). GACC regions span each row with the name abbreviated in the lower-left hand corner of the temperature correlation matrix. Lagged correlations were calculated at twice-monthly intervals from 1 May through 1 November of the fire year (*x*-axis), integrated over the previous 1–150 days at 15-day intervals (*y*-axis). The far right column separated from the data shows (R^2) extrema of values at corresponding time spans over the fire season that were not confined to a specific calendar date. Values are only shown where at least 95% of bootstrapped samples were of the same sign, with hatching indicating significant negative correlations.

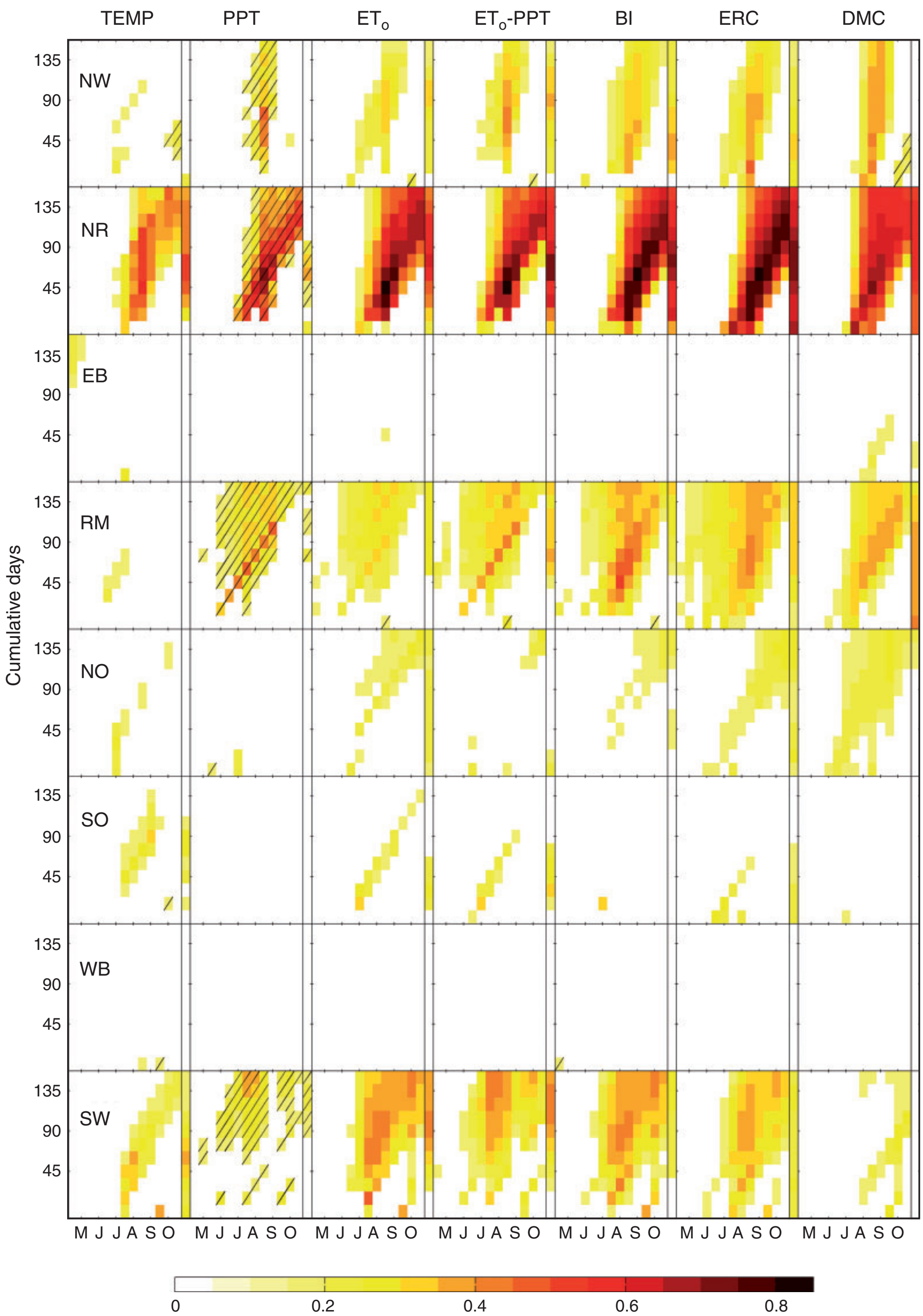

Fig. 6. As in Fig. 5, but for climate–fire relationships in non-forested Geographic Area Coordination Centers.

conducive to fire growth, periods of rapid fire spread or difficulty of containment, and hence may help bridge the gap between empirical and process-based fire modelling (e.g. Macias-Fauria *et al.* 2011). Although dynamic biophysical variables are posited to be better process-based deterministic predictors of fire behaviour and growth for individual fires, we show that the seasonal integration of such metrics is strongly correlated with regional FSAB and explained more than 60% of interannual area burned in several regions. Finally, as fire danger indices are used operationally and are familiar to managers, research studies that utilise metrics that are currently part of the management lexicon naturally lend themselves to technology

Table 2. Variable and temporal window corresponding to the maximum percentage of variance explained between fire-season area burned (1984–2010) for forested and non-forested Geographic Area Coordination Centers

Variables include: ET_o, reference evapotranspiration; ERC, energy release component; BI, burning index; FFMC, fine fuel moisture content; Soil, soil moisture; PPT, precipitation; Temp, temperature; PDSI, Palmer Drought Severity Index

Region	R^2	Variable	Temporal window
Forested area			
Pacific Northwest (NW)	0.66	ET_o – PPT	1 Jul–15 Sep
Northern Rockies (NR)	0.88	ERC	Peak 75-day
Eastern Great Basin (EB)	0.69	ERC	Peak 60-day
Rocky Mountain (RM)	0.66	ERC	1 Jun–1 Sep
North Ops (NO)	0.54	FFMC	1 Jul–1 Nov
South Ops (SO)	0.44	ET_o	1 May–1 Aug
Western Great Basin (WB)	0.39	Soil	May (year −1)
South-west (SW)	0.63	ET_o	1 Jun–15 Aug
Non-forested area			
Pacific Northwest (NW)	0.48	PPT	15 Jun–1 Sep
Northern Rockies (NR)	0.83	ET_o	15 Jul–1 Sep
Eastern Great Basin (EB)	0.31	PPT	Apr–Oct (year −1)
Rocky Mountain (RM)	0.51	BI	1 Jul–15 Aug
North Ops (NO)	0.35	Temp	Apr–Oct (year −1)
South Ops (SO)	0.44	Temp	15 Jun–15 Sep
Western Great Basin (WB)	0.54	PDSI	October (year −1)
South-west (SW)	0.47	ET_o	1 Jun–15 Aug

transfer into wildland fire decision-making, particularly at regional levels where decisions pertaining to finance and resource allocation are made (Owen *et al.* 2012).

Coherent antecedent climate–fire relationships at the macroscale levels analysed in this study are generally consistent with previous analyses in forested and non-forested systems (e.g. Westerling *et al.* 2003; Littell *et al.* 2009). The lack of significant relationships between spring (March–May) temperature and FSAB differ from previous studies (e.g. Westerling *et al.* 2006) that encompassed a period of amplified springtime warming and snowpack recession in the western United States (Abatzoglou and Redmond 2007). We do, however, find midwinter SWE was the strongest long-lead correlate to FSAB in several forested GACCs. Below-normal winter SWE may help precondition large-diameter dead fuels and contribute to the commencement of fuel availability in montane regions (e.g. Westerling *et al.* 2006; Gedalof 2011). This is further corroborated by the evolution of negative correlations with PDSI towards the end of spring that strengthen throughout the fire season in forested GACC areas. Antecedent climate–fire relationships in non-forested GACC areas exhibit a more coherent antecedent signal with moisture availability in the prior year facilitating potential increases in surface biomass accumulation that can allow for a fuel-limited landscape to carry fire (e.g. Westerling *et al.* 2003; Balch *et al.* 2013).

Strong correlations between FSAB and conditions realised during the fire season align with previous studies (e.g. Westerling *et al.* 2003; McKenzie *et al.* 2004; Gedalof *et al.* 2005; Morgan *et al.* 2008). The emergence of strong correlations during the fire season provides evidence of the importance of concurrent atmospheric conditions in fostering or inhibiting wildfire activity by compounding or superseding antecedent stressors (Fig. 7, and Bumbaco and Mote 2010). This highlights that long-term drought (>4 months) in forested areas is not a prerequisite for enabling large fire potential at macroscale levels. However, prolonged moisture deficits associated with subpar winter snowpack may be of more importance in enabling flammability at more localised scales in wetter forests with long fire-return intervals (e.g. forests west of the Cascade mountains in the Pacific Northwest or high elevation, northward facing aspects). We identified similar relationships between in-season climate and FSAB in non-forested lands, with elevated fire danger and moisture deficits favouring larger FSAB. These linkages are stronger than reported in previous studies (e.g. Westerling *et al.* 2003), potentially due to the usage of biophysical variables, a more accurate fire area burned database, or changes in fine fuel biomass in non-forested areas (e.g. invasive annual grasses) that have increased fuel connectivity, fire return intervals and the sensitivity to interannual climate variability of landscape receptiveness to fire (e.g. Balch *et al.* 2013). The strong interannual correlation between FSAB in forested and non-forested areas (Table A1), and dichotomous influences of antecedent climate in preconditioning fuels further substantiates the role of in-season conditions in unifying large regional fire years that have subsequent effects on availability of suppression resources and regional air quality. One potential non-climatic hypothesis for this relationship is that the strain on suppression resources during large fire years in forested areas diminishes resources for fire suppression in non-forested regions and may enable more non-forested FSAB.

These results place emphasis on the need for skilful seasonal climate forecasts in developing seasonal wildfire outlooks. This is particularly challenging as seasonal climate forecasts have relatively low skill during the primary fire season in the western United States. Some of the antecedent factors identified in this study as providing predictive information are currently used in seasonal strategic planning (Predictive Services, Owen *et al.* 2012), but may not be the best indicators of FSAB, with potential for inaccurate forecasts that lead to negative outcomes such as poor preparedness. Correlations between monthly SWE and forested area burned during only the first half of the fire season (as defined by wildfires with discovery dates in the first half of the historic distribution) showed significantly higher correlations (>10% variance explained) *v.* total (whole season) FSAB in the NR, EB, NO and SO GACCs (not shown), suggesting that early large fire activity is linked to early snowpack melt in montane regions. This also suggests climatic controls on area burned change throughout the fire season, with antecedent factors being more important for early season wildfire activity (e.g. Morton *et al.* 2013) whereas in-season conditions become more important for large fire growth potential in the middle and latter parts of the fire season (e.g. Abatzoglou and Kolden 2011*a*). This change in contributing factors over time is critical to recognise for planning and decision-making.

Geographic differences in climate–fire relationships and across predictor variables are apparent in both forested and non-forested areas. Several factors likely contribute to these differences including bi-modal fire regimes in a given region (e.g. autumn Santa Ana wind-driven wildfires *v.* summer wildfires in SO), sub-regional climate–fire relationships across

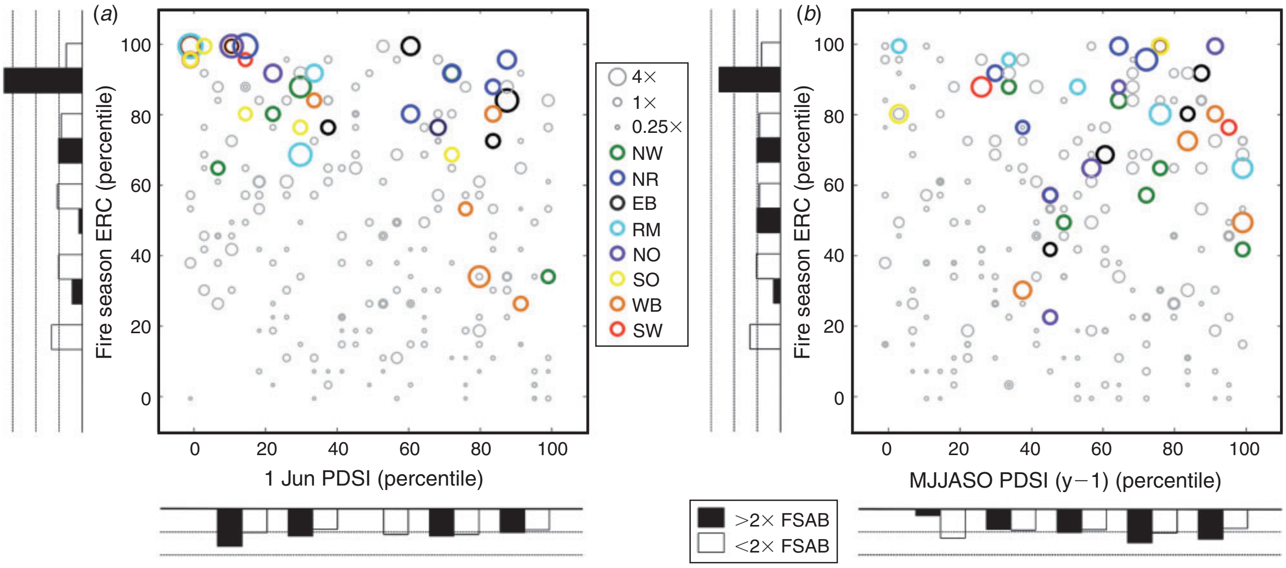

Fig. 7. Scatterplot of (*a*) 1 June Palmer Drought Severity Index (PDSI) *v.* the optimal window of in-season Energy Release Component (ERC) for all forested GACCs and (*b*) May–October PDSI averaged over the year before the fire season *v.* the optimal window of in-season ERC for non-forested Geographic Area Coordination Centers (GACCs). Variables are converted to percentiles to normalise across all regions. The radius of the circles is proportional to percentage of averaged 1984–2010 fire-season area burned in each region with coloured circles denoting years with at least double the average area burned. Histograms along the *x*- and *y*-axes correspond to the ratio of large fire seasons (black) and non-large fire seasons (white) in each quintile of the distribution with the dashed lines showing the expected value, twice the expected value and three times the expected value.

different fuel classes or abundance, the length of the fire season, sub-regional differences in climate variability and human factors associated with ignition, landscape fire spread and fire suppression. The strongest relationships between in-season predictors and forested FSAB were found in the NR, EB, RM and NW GACCs. The NR, EB and NW have well defined fire seasons with over 95% of the area burned in forested lands occurring over a 3-month period (Fig. 2) that constrains the fire season to more limited temporal window and more common set of top-down climatic drivers of fire activity. These regions are also not fuel-limited; abundant moisture drives both consistent, abundant vegetation growth and serves as a barrier to large fire growth until conditions develop that drop moisture levels below critical thresholds. By contrast, the longer fire season in NO and SO, and hence more diverse set of atmospheric drivers in addition to increased human ignitions likely dilutes climate–fire linkages. Lesser correlations in non-forested GACC areas are likely a function of bottom-up drivers of fire through fuel connectivity as well as the influence of short-lived critical fire weather patterns and dry-lightning events that can result in large areas burned over relatively short time periods, and which may not be well resolved through the metrics used in this study.

Prior studies have hypothesised that temperature is the single most important variable that influences wildland fire (e.g. Gillett *et al.* 2004). Antecedent temperature is hypothesised to advance the timing of snowmelt and green-up in forested systems, thereby potentially facilitating an earlier depletion of fuel moisture and extending the seasonal window during which fuels are receptive to fire (e.g. Westerling *et al.* 2006). We did not find strong evidence to support this hypothesis (particularly with respect to spring temperature) over the 1984–2010 period, but rather found strong correlations between FSAB and summer temperature. Temperature is indirectly associated with fuel moisture stress and flammability; however, atmospheric variables more directly tied to moisture demand (i.e. ET_o) and the amount and timing of moisture supply as incorporated in biophysical variables may more accurately synthesise fuel flammability across the weather–climate continuum during the fire season. This is demonstrated in our analysis by the unanimously stronger correlations between forested FSAB and biophysical variables *v.* temperature (e.g. Morton *et al.* 2013). This is likely partially due to the use of an integrated set of variables used in estimating equilibrium moisture content, fuel moisture and moisture demand. Temperature was strongly correlated with FSAB in many regions; however, this is partially associated with aliasing of temperature to variables more directly linked to the depletion of fuel moisture through atmospheric circulation and soil-moisture feedbacks that couple temperature to precipitation, vapor pressure deficit and solar radiation during the warm season across much of the western United States (e.g. Trenberth and Shea 2005; Trouet *et al.* 2009). Although temperature may influence fire activity, the results shown here highlight that temperature may be better contextualised through variables that biophysically link a consortium of atmospheric drivers to fuel availability and fire behaviour.

The exclusion of classified 'unburned' area burned resulted in subtle changes in climate–fire relationships when compared with using total area burned within the mapped fire perimeters. Overall, slightly more variance was explained (typically $<2\%$) by excluding unburned area. This finding is corroborated by running correlations between the percentage of annual area unburned in each vegetation type and our suite of climate variables. At the scales of the analysis we did not find any consistent and robust relationships between climate and percentage of unburned area across regions, although this may be partially attributable to unknowns surrounding the classification of unburned area by MTBS (Kolden *et al.* 2012). The percentage of unburned area within fire perimeters in forested areas of NO and SO showed significant negative correlations to growing-season temperature, and positive correlations to PDSI. However, the influence of climate and weather on burn severity at macroscales warrants further analysis to determine the roles of top-down *v.* bottom-up controls on fire effects.

The host of processes, timescales and sequences of atmospheric forcing that conspire in wildfire occurrence, behaviour and growth, varies geographically and remains challenging to integrate in both research studies and operational fire management alongside the increasingly complex human environment (Marlon *et al.* 2012). Our analyses did not include any diagnostics of management intervention or land use changes, even though such factors are an inherent component of wildfire in managed landscapes. We demonstrate strong linkages between regional fire activity and both fire danger indices and water balance variables during the fire season across much of the western United States from 1984–2010. The past three decades (1979–2012) coincide with a period of increased fire danger (e.g. Fig. A3, Abatzoglou and Kolden 2011*b*), moisture deficits and decreased soil and fuel moisture across much of the western United States during fire season that would increase both the seasonal window where fuels are receptive to wildfire and potentially increase fire-behaviour irrespective of changes in fuels or management action. Although biophysical variables were strongly correlated with FSAB, the ability to project future fire activity from such variables is an open question and contingent upon changes in fuel type and quantity, fire management and ignitions and potential non-stationary aspects of climate–fire relationships (Collins *et al.* 2006).

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References

Abatzoglou JT (2013) Development of gridded surface meteorological data for ecological applications and modeling. *International Journal of Climatology*. doi:10.1002/JOC.3413

Abatzoglou JT, Kolden CA (2011*a*) Relative importance of weather and climate on wildfire growth in interior Alaska. *International Journal of Wildland Fire* **20**(4), 479–486. doi:10.1071/WF10046

Abatzoglou JT, Kolden CA (2011*b*) Climate change in western US deserts: potential for increased wildfire and invasive annual grasses. *Rangeland Ecology and Management*. doi:10.2111/REM-D-09-00151.1

Abatzoglou JT, Redmond KT (2007) Asymmetry between trends in spring and autumn temperature and circulation regimes over western North America. *Geophysical Research Letters* **34**(18), L18808. doi:10.1029/2007GL030891

Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration, guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56, Food and Agriculture Organisation of the United Nations. (Rome, Italy)

Andrews PL, Loftsgaarden DO, Bradshaw LS (2003) Evaluation of fire danger rating indexes using logistic regression and percentile analysis. *International Journal of Wildland Fire* **12**, 213–226. doi:10.1071/WF02059

Balch JK, Bradley BA, D'Antonio CM, Gómez-Dans J (2013) Introduced annual grass increases regional fire activity across the arid western USA (1980–2009). *Global Change Biology* **19**, 173–183. doi:10.1111/GCB.12046

Bessie WC, Johnson EA (1995) The relative importance of fuels and weather on fire behavior in subalpine forests. *Ecology* **76**, 747–762. doi:10.2307/1939341

Brown TJ, Garfin G, Wordell T, Ochoa R, Morehouse B (2004) Climate, fuels, fire and decisions: the making of monthly and seasonal wildland fire outlooks. In 'Preprints, 14th Conference on Applied Climatology and 15th Symposium on Global Change and Climate Variations', Seattle, WA. Paper J.4.5. (CD-ROM) (American Meteorological Society: Boston, MA)

Bumbaco KA, Mote PW (2010) Three recent flavors of drought in the Pacific Northwest. *Journal of Applied Meteorology and Climatology* **49**, 2058–2068. doi:10.1175/2010JAMC2423.1

Carcaillet C, Bergeron Y, Richard PJH, Frechette B, Gauthier S, Prairie YT (2001) Change of fire frequency in the eastern Canadian boreal forests during the Holocene: Does vegetation composition or climate trigger the fire regime. *Journal of Ecology* **89**, 930–946. doi:10.1111/J.1365-2745.2001.00614.X

Collins BM, Omi PN, Chapman PL (2006) Regional relationships between climate and wildfire-burned area in the Interior West, USA. *Canadian Journal of Forest Research* **36**, 699–709. doi:10.1139/X05-264

Corringham T, Westerling AL, Morehouse B (2008) Exploring use of climate information in wildland fire management: a decision calendar study. *Journal of Forestry* **106**(2), 71–77.

Daly C, Halbleib M, Smith JI, Gibson WP, Doggett MK, Taylor GH, Curtis J, Pasteris PA (2008) Physiographically-sensitive mapping of temperature and precipitation across the conterminous United States. *International Journal of Climatology*. doi:10.1002/JOC.1688

Deeming JE, Burgan RE, Cohen JD (1977) The National Fire Danger Rating System – 1978. USDA Forest Service, Intermountain Forest and Range Experiment Station, General Technical Report INT-39. (Ogden, UT)

Eidenshink J, Schwind B, Brewer K, Zhu ZL, Quayle B, Howard S (2007) A project for monitoring trends in burn severity. *Fire Ecology* **3**(1), 3–21. doi:10.4996/FIREECOLOGY.0301003

Finney MA, Grenfell IC, McHugh CW, Seli RC, Trethewey D, Stratton RD, Brittain S (2011) A method for ensemble wildland fire simulation. *Environmental Modeling and Assessment* **16**, 153–167. doi:10.1007/S10666-010-9241-3

Flannigan MD, Harrington JB (1988) A study of the relation of meteorological variables to monthly provincial area burned by wildfire in Canada (1953–80). *Journal of Applied Meteorology* **27**, 441–452. doi:10.1175/1520-0450(1988)027<0441:ASOTRO>2.0.CO;2

Flannigan MD, Krawchuk MA, de Groot WJ, Wotton BM, Gowman LM (2009) Implications of changing climate for global wildland fire. *International Journal of Wildland Fire* **18**, 483–507. doi:10.1071/WF08187

Gedalof Z (2011) Climate and spatial patterns of wildfire. *Ecological Studies* **213**, 89–115. doi:10.1890/03-5116

Gedalof Z, Peterson D, Mantua N (2005) Atmospheric, climatic, and ecological controls on extreme wildfire years in the northwestern United States. *Ecological Applications* **15**, 154–174. doi:10.1890/03-5116

Gillett NP, Weaver AJ, Zwiers FW, Flannigan MD (2004) Detecting the effect of climate change on Canadian forest fires. *Geophysical Research Letters* **31**(18), L18211. doi:10.1029/2004GL020876

Girardin MP, Wotton BM (2009) Summer moisture and wildfire risks across Canada. *Journal of Applied Meteorology and Climatology* **48**, 517–533. doi:10.1175/2008JAMC1996.1

Girardin MP, Ali AA, Carcaillet C, Mudelsee M, Drobyshev I, Hély C, Bergeron Y (2009) Heterogeneous response of circumboreal wildfire risk to climate change since the early 1900s. *Global Change Biology* **15**, 2751–2769. doi:10.1111/J.1365-2486.2009.01869.X

Jolly WM, Nemani R, Running SW (2005) A generalized, bioclimatic index to predict foliar phenology in response to climate. *Global Change Biology* **11**, 619–632. doi:10.1111/J.1365-2486.2005.00930.X

Kangas RS, Brown TJ (2007) Characteristics of US drought and pluvials from a high-resolution spatial dataset. *International Journal of Climatology* **27**(10), 1303–1325. doi:10.1002/JOC.1473

Kolden CA, Brown TJ (2010) Beyond wildfire: perspectives of climate, managed fire and policy in the USA. *International Journal of Wildland Fire* **19**(3), 364–373. doi:10.1071/WF08111

Kolden CA, Weisberg PW (2007) Assessing accuracy of manually-mapped wildfire perimeters in topographically dissected areas. *Fire Ecology* **3**(1), 22–31. doi:10.4996/FIREECOLOGY.0301022

Kolden CA, Lutz JA, Key CH, Kane JT, vanWagtendonk JW (2012) Mapped versus actual burned area within wildfire perimeters: characterizing the unburned. *Forest Ecology and Management* **286**, 38–47. doi:10.1016/J.FORECO.2012.08.020

Liang X, Lettenmaier DP, Wood EF, Burges SJ (1994) A simple hydrologically based model of land surface water and energy fluxes for GSMs. *Journal of Geophysical Research* **99**(D7), 14 415–14 428. doi:10.1029/94JD00483

Littell JS, Gwozdz R (2011) Climatic water balance and regional fire years in the Pacific Northwest, USA: linking regional climate and fire at landscape scales. *Ecological Studies* **213**, 117–139. doi:10.1029/94JD00483

Littell JS, McKenzie D, Peterson DL, Westerling AL (2009) Climate and wildfire area burned in western U.S. ecoprovinces, 1916–2003. *Ecological Applications* **19**(4), 1003–1021. doi:10.1890/07-1183.1

Macias-Fauria M, Michaletz ST, Johnson EA (2011) Predicting climate change effects on wildfires requires linking processes across scales. *Wiley Interdisciplinary Reviews-Climate Change* **2**, 99–112. doi:10.1002/WCC.92

Marlon JR, Bartlein PJ, Gavin DG, Long CJ, Anderson RS, Briles ChE, Brown KJ, Colombaroli D, Hallett DJ, Power MJ, Scharf EA, Walsh MK (2012) Long-term perspective on wildfires in the western USA. *Proceedings of the National Academy of Sciences of the United States of America.* [Published online early 14 February 2012] doi:10.1890/07-1183.1

McKenzie D, Peterson DW, Peterson DL, Thornton PE (2003) Climatic and biophysical controls on conifer species distributions in mountain forests of Washington State, USA. *Journal of Biogeography* **30**, 1093–1108. doi:10.1046/J.1365-2699.2003.00921.X

McKenzie D, Gedalof ZM, Peterson DL, Mote P (2004) Climatic change, wildfire, and conservation. *Conservation Biology* **18**, 890–902. doi:10.1111/J.1523-1739.2004.00492.X

Morgan P, Heyerdahl EK, Gibson CE (2008) Multi-season climate synchronized forest fires throughout the 20th century, northern Rockies, USA. *Ecology* **89**, 717–728. doi:10.1890/06-2049.1

Moritz MA, Moody TJ, Krawchuk MA, Hughes M, Hall A (2010) Spatial variation in extreme winds predicts large wildfire locations in chaparral ecosystems. *Geophysical Research Letters* **37**, L04801. doi:10.1029/2009GL041735

Morton DC, Collatz GJ, Wang D, Randerson JT, Giglio L, Chen Y (2013) Satellite-based assessment of climate controls on US burned area. *Biogeosciences* **10**, 247–260. doi:10.5194/BG-10-247-2013

Owen G, McLeod JD, Kolden CA, Ferguson DB, Brown TJ (2012) Wildfire management and forecasting fire potential: the roles of climate information and social networks in the Southwest US. *Weather, Climate, and Society* **4**, 90–102. doi:10.1175/WCAS-D-11-00038.1

Parisien MA, Parks SA, Miller C, Krawchuk MA, Heathcott M, Moritz MA (2011) Contributions of ignitions, fuels, and weather to the burn probability of a boreal landscape. *Ecosystems* **14**, 1141–1155. doi:10.1007/S10021-011-9474-2

Parks SA, Parisien MA, Miller C (2012) Spatial bottom-up controls on fire likelihood vary across western North America. *Ecosphere* **3**, art12. doi:10.1890/ES11-00298.1

Riley KL, Abatzoglou JT, Grenfell IC, Klene AE, Heinsch FA (2013) The relationship of large fire occurrence with drought and fire danger indices in the western USA, 1984–2008: the role of temporal scale. *International Journal of Wildland Fire,* in press. doi:10.1071/WF12149

Spracklen DV, Mickley LJ, Logan JA, Hudman RC, Yevich R, Flannigan MD, Westerling AL (2009) Impacts of climate change from 2000 to 2050 on wildfire activity and carbonaceous aerosol concentrations in the western United States. *Journal of Geophysical Research, D, Atmospheres* **114**, D20301. doi:10.1029/2008JD010966

Stephenson NL (1998) Actual evapotranspiration and deficit: biologically meaningful correlates of vegetation distribution across spatial scales. *Journal of Biogeography* **25**, 855–870. doi:10.1046/J.1365-2699.1998.00233.X

Swetnam TW, Betancourt JL (1990) Fire–southern oscillation relations in the Southwestern United States. *Science* **249**, 1017–1020. doi:10.1126/SCIENCE.249.4972.1017

Swetnam TW, Betancourt JL (1998) Mesoscale disturbance and ecological response to decadal climatic variability in the American Southwest. *Journal of Climate* **11**, 3128–3147. doi:10.1175/1520-0442(1998)011<3128:MDAERT>2.0.CO;2

Trenberth KE, Shea DJ (2005) Relationships between precipitation and surface temperature. *Geophysical Research Letters* **32**, L14703. doi:10.1029/2005GL022760

Trouet V, Taylor AH, Carleton AM, Skinner CN (2006) Fire–climate interactions in forests of the American Pacific coast. *Geophysical Research Letters* **33**, L18704. doi:10.1029/2006GL027502

Trouet V, Taylor AH, Carleton AM (2009) Interannual variations in fire weather, fire extent, and synoptic-scale circulation patterns in northern California and Oregon. *Theoretical and Applied Climatology* **95**, 349–360. doi:10.1007/S00704-008-0012-X

Van Wagner CE (1987) Development and structure of the Canadian Forest Fire Weather Index System. Canadian Forestry Service, Forestry Technical Report 35. (Ottawa, ON)

Westerling AL, Brown TJ, Gershunov A, Cayan DR, Dettinger MD (2003) Climate and wildfire in the western United States. *Bulletin of the American Meteorological Society* **84**(5), 595–604. doi:10.1175/BAMS-84-5-595

Westerling AL, Hidalgo HG, Cayan DR, Swetnam TW (2006) Warming and earlier spring increases western US forest wildfire activity. *Science*. doi:10.1126/SCIENCE.1128834

Westerling AL, Turner MG, Smithwick EAH, Romme WH, Ryan MG (2011) Continued warming could transform Greater Yellowstone fire regimes by mid-21st century. *Proceedings of the National Academy of Sciences of the United States of America* **108**, 13 165–13 170. doi:10.1073/PNAS.1110199108

Wotton BM (2009) Interpreting and using outputs from the Canadian Forest Fire Danger Rating System in research applications. *Environmental and Ecological Statistics* **16**(2), 107–131. doi:10.1007/S10651-007-0084-2

Appendix

Table A1. Summary statistics of fire-season area burned (FSAB) in the eight Geographic Area Coordination Centers (1984–2010) showing the percentage of total area burned (AB) in forested lands and the squared Pearsons correlation coefficient of the logarithm of FSAB in forested areas to logarithm of FSAB in non-forested areas

Relationships are significant at $P < 0.01$ for all GACCs

GACC	Percentage of AB in forest	R^2 ($FSAB_F$, $FSAB_{NF}$)
NW	45.6	0.25
NR	71.9	0.67
EB	35.3	0.75
RM	68.2	0.51
NO	85.5	0.44
SO	43.5	0.67
WB	30.0	0.71
SW	54.9	0.66

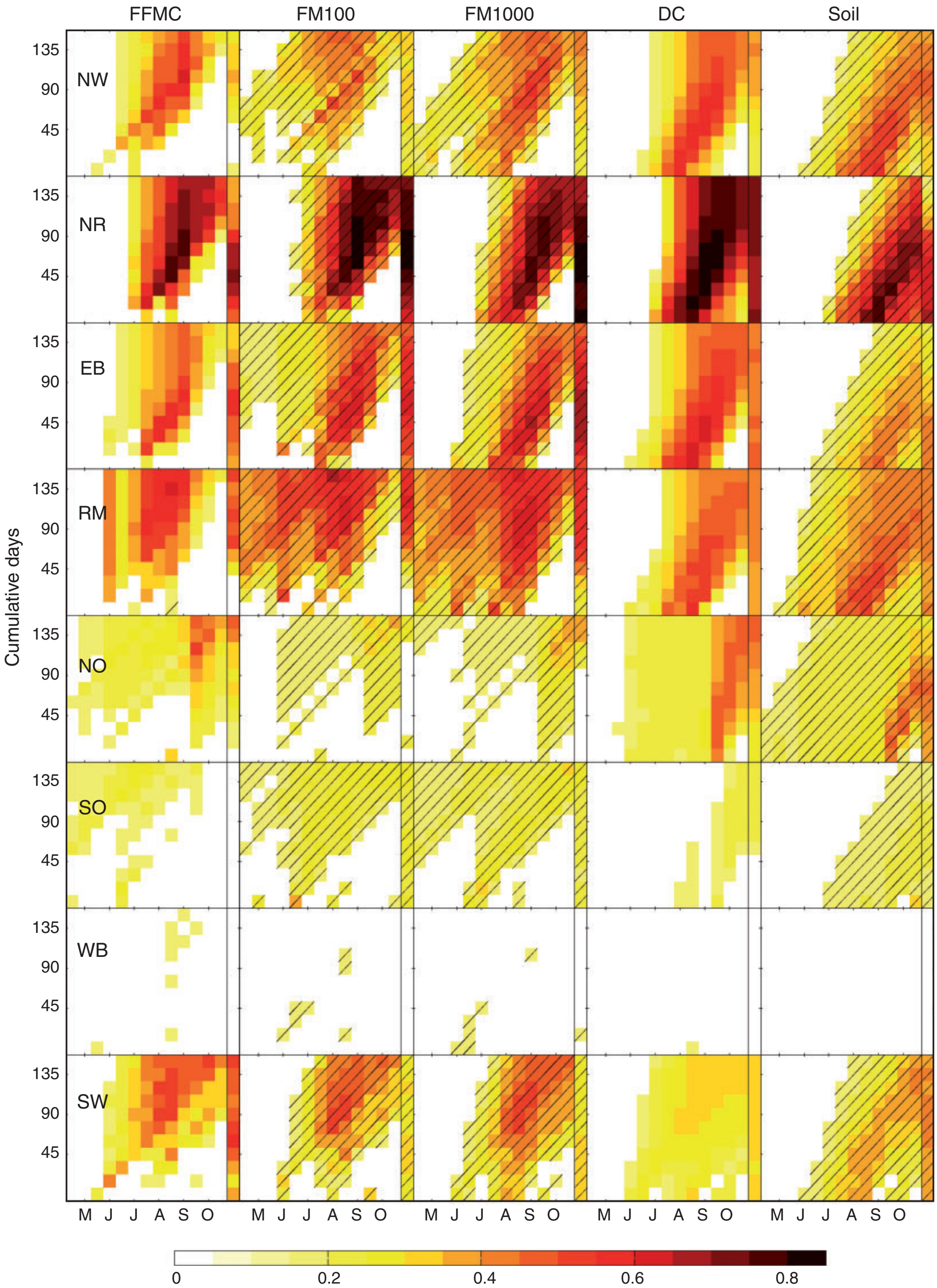

Fig. A1. As Fig. 5, but for Fine Fuel Moisture Code (FFMC), 100-h fuel moisture (FM100), 1000-h fuel moisture (FM1000), Drought Code (DC) and Soil Moisture (Soil).

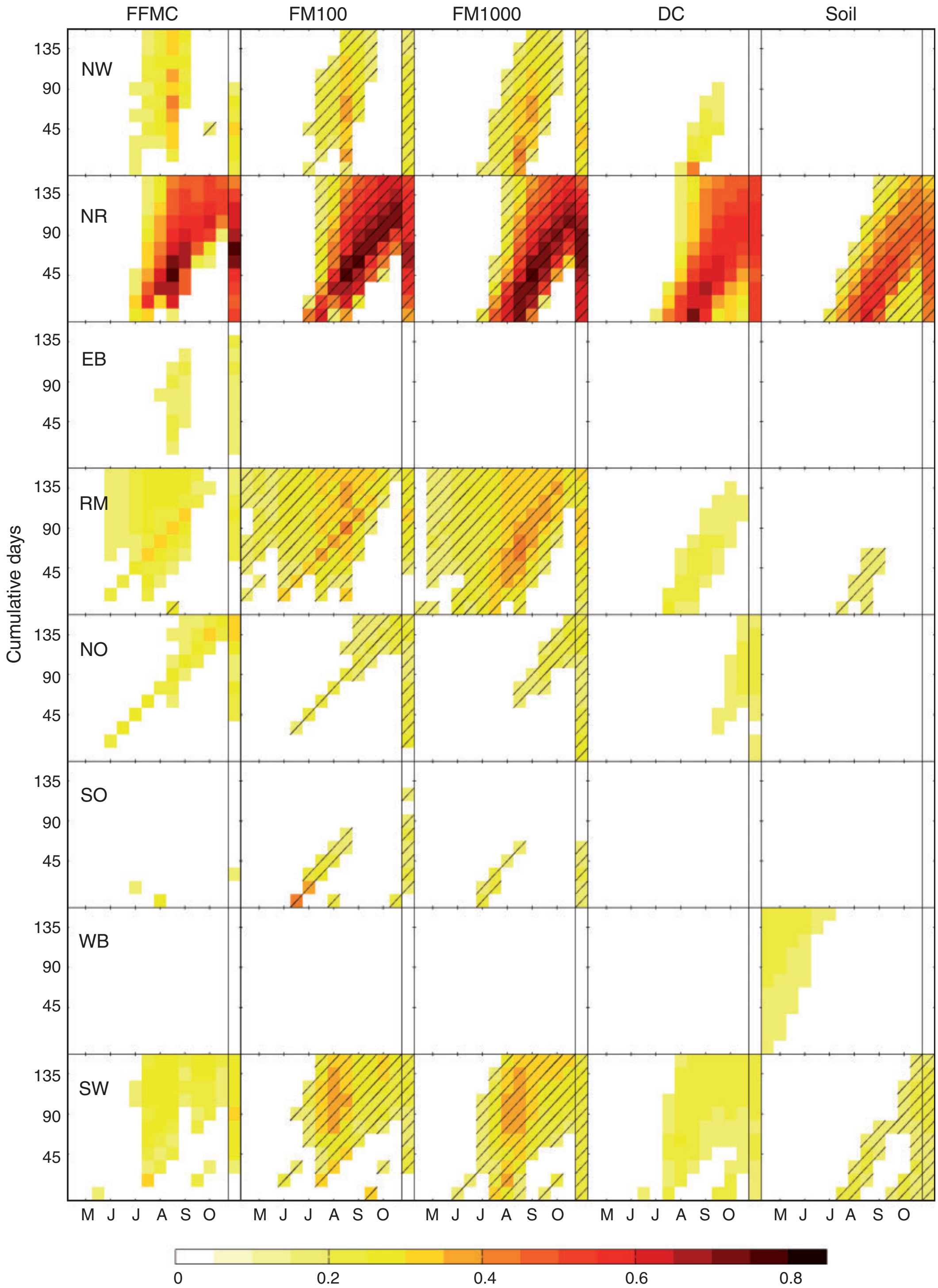

Fig. A2. As Fig. 6, but for Fine Fuel Moisture Code (FFMC), 100-h fuel moisture (FM100), 1000-h fuel moisture (FM1000), Drought Code (DC) and Soil Moisture (Soil).

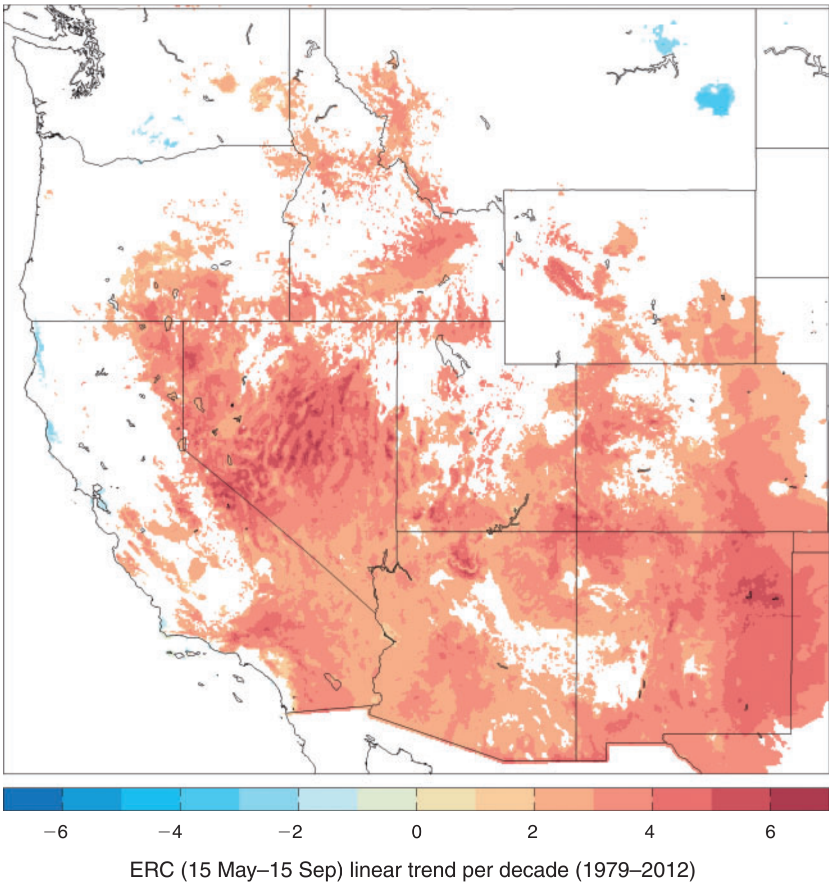

Fig. A3. Map of western United States demonstrating linear least-squares trends of Energy Release Component (fuel model G) averaged over 15 May–15 Sep (1979–2012) expressed in change per decade. Data not exhibiting statistically significant trends at the $P < 0.05$ are omitted.