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Satellite-based assessment of climate controls on US burned area

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Abstract

Climate regulates fire activity through the buildup and drying of fuels and the conditions for fire ignition and spread. Understanding the dynamics of contemporary climate-fire relationships at national and sub-national scales is critical to assess the likelihood of changes in future fire activity and the potential options for mitigation and adaptation. Here, we conducted the first national assessment of climate controls on US fire activity using two satellite-based estimates of monthly burned area (BA), the Global Fire Emissions Database (GFED, 1997–2010) and Monitoring Trends in Burn Severity (MTBS, 1984–2009) BA products. For each US National Climate Assessment (NCA) region, we analyzed the relationships between monthly BA and potential evaporation (PE) derived from reanalysis climate data at 0.5° resolution. US fire activity increased over the past 25 yr, with statistically significant increases in MTBS BA for entire US and the Southeast and Southwest NCA regions. Monthly PE was strongly correlated with US fire activity, yet the climate driver of PE varied regionally. Fire season temperature and shortwave radiation were the primary controls on PE and fire activity in the Alaska, while water deficit (precipitation – PE) was strongly correlated with fire activity in the Plains regions and Northwest US. BA and precipitation anomalies were negatively correlated in all regions, although fuel-limited ecosystems in the Southern Plains and Southwest exhibited positive correlations with longer lead times (6–12 months). Fire season PE increased from the 1980s–2000s, enhancing climate-driven fire risk in the southern and western US where PE-BA correlations were strongest. Spatial and temporal patterns of increasing fire season PE and BA during the 1990s–2000s highlight the potential sensitivity of US fire activity to climate change in coming decades. However, climate-fire relationships at the national scale are complex, based on the diversity of fire types, ecosystems, and ignition sources within each NCA region. Changes in the seasonality or magnitude of climate anomalies are therefore unlikely to result in uniform changes in US fire activity.

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1 Introduction

Climate is a fundamental constraint on fire activity. Climate conditions influence the quantity and condition of fuels (e.g., Arora and Boer, 2005; van der Werf et al., 2008b; Thonicke et al., 2010), rate of fire spread (e.g., Rothermel, 1972; Scott and Burgan, 2005), and frequency of fire ignitions from lightning (Bartlein et al., 2008; Christian et al., 2003). Globally, fires are most common in regions with intermediate levels of precipitation; fuel availability or moisture content limit fires in regions with low or high precipitation, respectively (van der Werf et al., 2008b). Human activities have amplified seasonal fire activity in temperate and tropical ecosystems (e.g., Morton et al., 2008; Giglio et al., 2006) and modified natural fire regimes through agricultural management (e.g., Le Page et al., 2010) and fire suppression efforts (Girod et al., 2007; Lenihan et al., 2008; Marlon et al., 2009). The timing, frequency, and extent of recent fires therefore reflect this complex suite of interactions among climate, ecosystems, and human societies (e.g., Thonicke et al., 2010; Giglio et al., 2006; Lavorel et al., 2007; Krawchuk et al., 2009; van der Werf et al., 2010; Kloster et al., 2010; Bowman et al., 2011; O'Connor et al., 2011).

Projections of higher fire activity under scenarios of climate change have elevated the science and policy interest in understanding climate-fire relationships (e.g., Flannigan et al., 2005; Scholze et al., 2006; Spraklen et al., 2009; Westerling et al., 2011b; Pechony and Shindell, 2010). Fires also generate feedbacks to the climate system through changes in land surface albedo (Randerson et al., 2006) and emissions of greenhouse gases (van der Werf et al., 2010) and aerosols (Tosca et al., 2010; Seiler and Crutzen, 1980). Coupled carbon cycle and climate models that include fire illustrate the potential for fires to accelerate changes in ecosystem structure and composition expected from climate change alone (e.g., Golding and Betts, 2008; Kloster et al., 2012). Climate-driven changes in fire activity are one motivating factor for the focus on forest carbon stocks in international climate negotiations (Bonan, 2008; Malhi et al., 2008). National assessments of fire activity and climate-fire interactions are needed

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to connect the science and policy objectives at a common scale (e.g., CCSP, 2008; US-GCRP, 2009).

In the US, regional relationships between climate and fire activity reflect a diversity of human and natural fire regimes. Previous studies were typically limited to regional analyses of climate-fire relationships because historic burned area (BA) data were unavailable at national scales (e.g., Swetnam and Betancourt, 1990; Westerling et al., 2011b; Kasischke et al., 2002). Most previous studies were also limited to forests, where stand age, charcoal records, or scarred trees retain evidence of historic fire activity (e.g., McKenzie et al., 2004).

Analyses of recent forest fires in the US highlight three broad patterns of climatic control on BA. First, summer temperatures are positively correlated with the extent of forest fires in Alaska (e.g., Kasischke and Turetsky, 2006; Kasischke et al., 2002; Duffy et al., 2005), the northwest US (McKenzie et al., 2004; Spraklen et al., 2009), and montane areas across the western US (Littell et al., 2009; Spraklen et al., 2009; Westerling et al., 2011b). Second, precipitation is a stronger control on fire activity than temperature in the southwest US (Littell et al., 2009; McKenzie et al., 2004), where long-term drought conditions (e.g., Westerling et al., 2002) and seasonal water deficits linked to early snowmelt (Westerling et al., 2006) increase regional fire activity. Third, coincident temperature and precipitation anomalies that synchronize regional fire activity in Alaska and the western US frequently coincide with large-scale climate modes, such as the Pacific Decadal Oscillation (Swetnam and Betancourt, 1990; Duffy et al., 2005; Trouet et al., 2006) and El Niño Southern Oscillation (e.g., Kitzberger et al., 2007; Heyerdahl et al., 2002; Veblen et al., 2000; Schoennagel et al., 2005). Large-scale studies of climate and fire activity in other US regions are less common, and no study has used a national database of fire activity to consider fire-climate relationships in forest and non-forest ecosystems.

Satellite data provide consistent information on the spatial and temporal dynamics of recent fire activity. Active fire detections from satellite sensors offer unprecedented detail about the diurnal and seasonal distribution of global fire activity (Giglio, 2007; Giglio

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et al., 2006; Mu et al., 2011; Le Page et al., 2010; Chuvieco et al., 2008). Satellite-based estimates of BA integrate fire activity over time, capturing the timing, extent, and severity of burning based on pre and post-fire imagery (e.g., Roy et al., 2008; Giglio et al., 2010). Satellite BA can be combined with land cover information to classify fires as savanna, woodland, forest, and agricultural burns, and to further distinguish forest fires between intentional deforestation and wildfires (e.g., van der Werf et al., 2010). The satellite data record of BA in savannas and woodlands is particularly valuable because the history of fire activity in these ecosystems is more difficult to determine from other proxy measures (McKenzie et al., 2004; Marlon et al., 2009; Bowman et al., 2009).

Here, we use two satellite-based estimates of monthly BA to assess climate controls on recent US fire activity. The Global Fire Emissions Database (GFED, version 3) BA product is a 14-yr record of global fire activity (1997–2010) derived from multiple satellite data sources (Giglio et al., 2010). The GFED BA product has been used previously to understand global trends in BA (Giglio et al., 2010), and GFED emissions data have been used to evaluate climate-fire relationships in equatorial Asia (van der Werf et al., 2008a) and South America (Chen et al., 2011). The Monitoring Trends in Burned Severity (MTBS) BA product (1984–2009) provides a longer record of large fire activity in the US based on pre- and post-fire Landsat imagery for large fires on federal and state lands (Eidenshink et al., 2007). The MTBS database offers an opportunity to evaluate the consistency of fire-climate relationships over the past 25 yr. The goal of this study was to conduct a national assessment of climate-fire relationships using satellite BA data for forest and non-forest fires. A baseline understanding of climate controls on BA is a critical precursor to assessing how future climate change may influence regional and sub-regional US fire activity. Potential evaporation (PE), calculated at 0.5° resolution using reanalysis climate data, was used to integrate the influence of temperature, humidity, and other climate factors that influence monthly fire weather. Our results suggest that BA has increased in the six major US fire regions over the past 25 yr, consistent with increases in fire season PE during this period.

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2 Data and methods

2.1 Study area

Relationships between monthly BA and climate variables were analysed at 0.5° resolution and summarized at national and sub-national scales (Fig. 1). The US was initially divided into seven regions, as defined in the National Climate Assessment (NCA, <http://assessment.globalchange.gov>): Alaska & Arctic (AK), Northwest (NW), Southwest (SW), Great Plains (GP), Midwest (MW), Southeast and Caribbean (SE), and Northeast (NE). For this study, the GP region was subdivided into separate regions for the northern plains (NP) and southern plains (SP) along the Kansas-Nebraska state border to better characterize latitudinal changes in climate-fire relationships in the central US. These administrative regions broadly reflect climate and vegetation zones with similar climate-fire responses. Puerto Rico and the US Virgin Islands (SE region) and the Hawaii and Pacific Islands NCA region were excluded from the analysis because complete GFED and MTBS data time series were not available for these islands.

2.2 GFED data

GFED data provide a consistent estimate of global BA on a monthly time step. Daily BA information, based on a combination of 500 m BA maps and active fire detections, were aggregated to monthly BA estimates at 0.5° resolution (Giglio et al., 2010). Briefly, the main source of BA information for the GFED BA product was the Moderate Resolution Imaging Spectroradiometer (MODIS) direct broadcast BA algorithm (MCD64A1). During 2001–2009, >90% of all global BA was mapped directly using the 500 m MODIS product (van der Werf et al., 2010). For periods without MCD64A1 data (1997–2000, and selected months during the MODIS era), BA estimates were based on the relationship between active fire detections and MCD64A1 BA (Giglio et al., 2010). Active fire detections from MODIS, Along-Track-Scanning Radiometer (ATSR), and Tropical Rainfall Measurement Mission (TRMM) Visible and Infrared Scanner (VIRS) sensors

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complemented the available MCD64A1 data to provide consistent, gridded estimates of monthly BA for 1997–2010. GFED BA and emissions data are available online (www.globalfiredata.org).

Information on fire type facilitated detailed comparisons between GFED monthly BA and climate variables for the US. Beginning with version 3, GFED BA and fire emissions were partitioned into six fire types (van der Werf et al., 2010). Four of these fire types occur in the US: forest, woodland, grassland and savanna, and agricultural fires. In this study, woodland, grassland and savanna, and agricultural fires were combined into a single “herbaceous” fire category.

2.3 MTBS data

The MTBS project maintains the longest consistent BA time series for the entire US. Large fire perimeters in the MTBS database are derived from the combination of state and federal large fire inventories with pre- and post-fire Landsat imagery (Eidenshink et al., 2007). Large fires are defined as > 500 AC (202 ha) in the eastern US and > 1000 AC (404 ha) in the western US. Many smaller fires are also included in the MTBS database, either due to differences between satellite and Incident Command System database (ICS 209) estimates of burn size, or from the National Park Service’s request for an assessment of burn severity for a small fire within a National Park.

The MTBS fire perimeter data were used to assess the consistency of fire-climate relationships in the US between 1984 and 2009. MTBS fire perimeter data for 1984–2009 were downloaded from www.mtbs.gov (December 2011 data release), and MTBS fire perimeter data were aggregated to monthly BA estimates (km^2) at 0.5° resolution. The fire start date was used to identify the burn month for each fire for comparisons with climate data.

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2.4 Climate data

Climate data for this study were derived from the National Centers for Environmental Prediction (NCEP) North American Regional Reanalysis (NARR) dataset at ~ 32 km spatial and 3-hourly temporal resolutions (Mesinger et al., 2006). Eleven NARR climate variables were used in this study: air temperature at 2 m, u/v wind speeds at 10 m, precipitation, snow depth, relative humidity, surface pressure, albedo, surface downward shortwave radiation, and surface upward and downward longwave radiation. The entire NARR data record (1979–2010) was used as the baseline from which to estimate monthly climate variable anomalies during the GFED (1997–2010) and MTBS (1984–2009) time periods. NARR data were converted from Northern Lambert Conformal Conic to geographic projection for comparisons with GFED and MTBS BA data.

2.5 Calculation of potential evaporation

In addition to individual NARR climatic variables, monthly potential evaporation (PE) was used to represent the hydrologic demand of the atmosphere (Lu et al., 2005). PE was calculated using the Food and Agriculture Organization (FAO) version of the Penman Monteith equation (Allen et al., 1998):

$$\text{PE} = \frac{\delta(R_n - G) + \rho_a C_p (V/r_a)}{\delta + \gamma(1 + r_s/r_a)} \quad (1)$$

where δ is the slope of the saturation pressure to temperature, R_n is the net radiation, (G) is ground heat flux, ρ_a is air density, C_p is the specific heat of the air, (V) is the vapor pressure deficit (VPD), γ is the psychrometric constant, and r_s and r_a are surface and aerodynamic resistance, respectively. Except for the two resistance terms, the input parameters for (1) are constants (Allen et al., 1998) or can be calculated from the 3-hourly NARR climate variables. For this study, the bulk canopy stomatal resistance (r_s) was deemed irrelevant for fuel drying and was set to zero, and aerodynamic resistance

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(r_a) was calculated using the standard reference grass canopy (Allen et al., 1998). The influence of stomatal conductance on humidity and regional fire weather, likely a second order climatic control on regional BA, could be addressed in a future study. To account for non-linear variability in PE over diurnal time scales, PE was first calculated at the native 3-hourly time step of the NARR data and then aggregated to daily and monthly time steps. The use of PE in this study represents a methodological advance over previous studies based on empirical indices of fuel condition (e.g., Littell et al., 2009; Balshi et al., 2009) or Thornthwaite PE estimates based only on monthly air temperature, latitude, and date (e.g., Girardin and Wooton, 2009). Equation (1) mechanically combines the interactions between temperature, solar radiation, humidity, and wind into a single variable for fuel drying potential.

2.6 Statistical analysis

Robust linear regression was used to calculate regional trends in BA and PE, and least-squares linear regression was used to estimate correlations and cross correlations between BA and climate anomalies. Correlation coefficients between climate anomalies and BA were calculated for the peak fire month, defined as the month with the largest fraction of annual fire activity. In addition, climate-fire relationships were assessed for a 3-month fire season. The consecutive 3-month period including the peak fire month with the highest fraction of annual BA was selected as the fire season. The significance of trends and correlations was assessed using a student's t-test and 95% confidence level.

The statistical approach in this study considered a range of lead times between climate and fire activity. Short lead times (0–3 months) were considered for all variables, with lead times relative to the peak fire month or the first month of the 3-month fire season. A moving 3-month window was used to aggregate climate variables for comparisons with fire-season BA. Lead times of up to 24 months were used to evaluate the influence of precipitation and snow depth on fire activity, since previous studies

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have shown that fuel build up and fuel drying may occur over longer time scales in water-limited systems (Westerling et al., 2003; Taylor and Beaty, 2005).

The relationships between BA and climate were initially calculated at 0.5° resolution. Results were also calculated at two coarser spatial resolutions to consider sub-regional and regional relationships between climate and BA. First, BA and climate data were aggregated to 5° resolution. BA at the coarser resolution was calculated as the sum of BA at the native 0.5° resolution, whereas climate variables at the coarser resolution were calculated as the area-weighted average of the variable at native resolution. Second, we analyzed fire-climate relationships for each NCA region. BA and climate variables for each NCA region were aggregated from 0.5° data in a similar fashion. The distributions of climate and BA at these scales supported a more robust statistical analysis, since individual 0.5° grid cells may only burn once during the study period.

3 Results

3.1 US burned area

Satellite-based BA data offer a consistent, national perspective on US fire activity. The spatial distribution of US BA was similar for the GFED and MTBS products (Fig. 1). Within each study region, areas of concentrated fire activity appear in both datasets, including interior Alaska (AK), central Idaho (NW), southern California (SW), eastern Kansas (SP), and southern Florida (SE). Spatial patterns of recent fire activity from the MTBS data record were similar between the GFED years (1997–2009) and the full BA time series (1984–2009, Fig. 1). Differences between GFED and MTBS estimates of mean annual BA highlight areas with small fires or fires on private lands, including agricultural areas in the Mississippi River Valley (MW, SE) and southern Texas (SP).

The timing of recent US fire activity also varied regionally, with monthly BA peaking early in the year in the SE and SP regions and progressively later across the western US and Alaska (Fig. 2, Table 1). The timing of peak fire activity was more

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heterogeneous in the SP and SE than in other regions with substantial fire activity (Table 1). Variability in the peak fire month is consistent with a greater diversity of fire types in these regions, including fires for agricultural and forest management that do not appear in the MTBS record (Fig. 1).

5 Together, the spatial and temporal patterns of fire activity highlight areas where climate or management exert strong control burned area (Fig. 2, Fig. 3). More than 60% of the total GFED BA for the US occurred during June–August (Fig. 3). Concentrated fire activity during warmer months highlighted the importance of climate controls on BA. Six of the eight study regions had a single 3-month fire season that accounted
10 for >70% of mean annual BA (Table 1). Fire seasons in the other three regions did not coincide with summer months. Burning occurred year-round in the SE US, and the January–March fire season accounted for only 33% of annual BA in the SE region. Fires in the SP also peaked during drier winter months (February–April). Evidence for year-round fire activity in the SE and SP regions underscores the role of management
15 for burning in these regions. Finally, fires were rare in the NE US (Fig. 1).

3.2 Burned area trends

Annual GFED BA for the US averaged $18\,800\text{ km}^2\text{ yr}^{-1}$ during 1997–2010 (Table 2). More than 70% of all burning during this period occurred in non-forest cover types, including woodlands, grasslands, and agricultural areas. The NW region had the highest
20 fractional BA, with nearly 0.5% of the region burning each year (Table 2).

Six NCA regions accounted for 98% of BA in the GFED and MTBS BA time series (Table 2). The regional distribution of GFED and MTBS BA estimates were similar in four of the six major burning regions (AK, NP, NW, and SW). Extensive fires for agricultural management may explain the two to threefold difference between GFED
25 and MTBS mean annual BA estimates for the SP and SE regions (Table 2), since small fires (<202 ha) and fires on private lands are not included in the MTBS dataset.

At the regional scale, BA exhibited strong interannual variability (Fig. 4). Positive BA trends were only statistically significant in the MTBS record (Table 2). Interestingly,

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positive MTBS BA trends were also statistically significant in the SE region and the entire US during the GFED years (1997–2009). MTBS BA trends ($\text{km}^2\text{ yr}^{-1}$) using robust linear regression were also larger in the GFED years (Table 2).

3.3 Climate and interannual variability in burned area

5 Across the US, PE anomalies explained more variance in GFED BA than anomalies in mean monthly temperature, precipitation, VPD, or incoming shortwave radiation (Fig. 5). Correlations between BA and PE in the fire season were strongest in the NW, NP, SP, and SE regions. PE anomalies were not strongly correlated with fire season BA in portions of the SW US, where average conditions during the June–August fire sea-
10 son are typically hot and dry. The relationships between BA and VPD showed a similar spatial pattern as the BA-PE relationship but with somewhat weaker correlations in AK and the NW US (Fig. 5). Shortwave radiation and temperature were better predictors of interannual variability in BA at higher latitudes, and precipitation anomalies and BA were negatively correlated during the fire season in all regions (Fig. 5). Precipitation
15 and associated cloudiness often reduce shortwave radiation, VPD, and temperature, causing substantial reductions in PE.

The regional distribution and magnitude of correlations between MTBS BA and fire season PE were similar to patterns using the GFED data (Fig. 6). The relationship between MTBS BA and PE was stronger during the GFED years than over the entire data
20 record, particularly in the NW and NP regions. The slope of the regression relationships provided an indication of the sensitivity of BA to recent climate conditions (Fig. 6). BA in the NW and AK regions showed the highest sensitivity to increases in fire season PE.

The lead times between monthly drying potential (PE) and BA illustrated the diversity
25 of time scales over which climate influences fire activity (Fig. 7). Coincident (lead = 0) relationships between PE and BA were most common in regions with abundant fuels (AK, NW, and MW). Cross correlations between PE and BA in these regions decreased steadily with longer lead times, suggesting that current drying conditions are

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more important for monthly BA than dry conditions in previous months. In contrast, PE anomalies 2–6 months prior to the fire season were strongly correlated with BA in the NP and SP regions. Extended dry periods may convert live plants into fine fuels in grassland and woodland ecosystems, increasing fire spread rates and BA.

5 Monthly relationships between MTBS BA and PE were similar to results using GFED BA data (Fig. 7). The longer MTBS data record of fires on public lands indicated shorter lead times for PE-BA cross correlations in the NP, and longer lead times for the maximum cross correlation between PE and BA in the SE US, similar to relationships in the Plains regions. The relationships between PE and MTBS BA across all regions
10 were stronger for recent years (1997–2009) than during the entire MTBS time series (1984–2009), as indicated in Fig. 6.

Across the major US fire regions, monthly cross correlations between PE and BA during the fire season were statistically significant ($p < 0.05$) based on both GFED and MTBS data, especially for months with more than 20% of annual BA for a region
15 (Fig. 7). The lack of statistically significant relationships between PE and GFED BA in two of three fire season months for the SW, SE, and MW regions suggested that other climate variables or non-climate drivers of BA such as agricultural management were more important controls on fire activity during these months.

Climate controls on PE and BA varied both within and among regions over the course of the fire season (Fig. 8). Temperature was the main driver of fire season PE in the AK and MW regions, whereas the best predictor of fire season BA in the NP, SP, and NW regions was water deficit, likely as a control on fuel availability via the conversion of live plants to fine fuels. Climatic control on monthly BA changed seasonally in the NW and NP regions, shifting from temperature to water deficit during the fire season (Fig. 8).
20 Representation of both temperature and VPD in the PE calculation integrated the combined influence of warming and drying conditions on BA (Fig. 7). Climate anomalies during the fire season were also important for fires in subsequent months (e.g., AK, NW, SP), suggesting that dry conditions early in the fire season may influence BA later in the year.

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Over longer time scales, precipitation played an important role in interannual variability of monthly BA in the SP region. Precipitation in each of the previous two growing seasons explained nearly 30% of the variability of BA (Fig. 9). This lag between climate conditions and fire activity suggests that an increase in the interannual
5 variability of precipitation could enhance fire activity in this region, especially in fuel-limited savanna or woodland ecosystems (e.g., Taylor and Beaty, 2005). In contrast, precipitation was more important for fire suppression than fuel accumulation in the SE region (Fig. 9). Similar lagged relationships between NARR snow depth and GFED BA for high-elevation areas in the western US and AK were not statistically significant
10 (data not shown).

3.4 Climate and fire risk

PE provides an integrative measure of climate-driven fire risk. Fires occurred in grid cells with above-average monthly PE values in all northern regions with substantial fire activity (AK, NW, NP, MW), with the largest difference in monthly PE between fire and non-fire grid cells in AK (Fig. 10). Higher PE values for fire cells in the first month
15 of the fire season are consistent with the need for drier conditions to accelerate the fuel drying process for early-season fires relative to later months (NP, NW, MW). The absolute value of PE in fire grid cells was less consistent than the tendency for above-average PE in cells with GFED BA. PE varied between 3 mm day^{-1} for late-season fires in AK or early-season fires in the MW region and $>10 \text{ mm day}^{-1}$ for July fires in the NP.
20

The three southern regions exhibited contrasting patterns of monthly PE for fire grid cells compared to grid cells without GFED BA (Fig. 10). In the SE, PE values were higher in fire cells despite lower PE values during the January–March fire season in this region. In the SW, PE values were also higher in fire grid cells, but the distribution
25 of monthly PE values was more similar between fire and no-fire cells. Monthly PE values in the SW region were the highest of any region in all three months of the fire season (mean $>6 \text{ mm day}^{-1}$), consistent with other evidence (i.e., Fig. 5) that BA was less sensitive to PE anomalies in this region. Finally, PE values in the SP region were

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average or below average in cells with GFED BA. Fires in these months may reflect agricultural management, rather than wildfires, given differences in climate-BA cross correlations between MTBS and GFED BA for this region (Figs. 7 and 8).

Climate controls on US burned area (expressed as PE) increased over the past 30 yr (Fig. 11). The strongest positive trends in fire season PE occurred in the NP and MW regions. In other regions, decadal differences in PE during the fire season were more pronounced than the 30-yr trends. Drying potential increased between the 1980s–1990s in the SP and SW regions, with further increases in fire season PE values between the 1990s–2000s (Fig. 12). Subtle increases in fire season PE across interior AK and the SE US were also consistent over the past 30 yr (Figs. 11 and 12). Fire season PE values increased for all US regions between the 1990s–2000s, with statistically significant PE increases in the AK, NP, MW, and NE regions. A strengthening relationship between climate and fire activity (Figs. 7 and 12) is one potential driver of recent increases in US wildfires (Table 2).

4 Discussion

Satellite BA data provide unprecedented spatial and temporal detail to assess fire-climate relationships at national, regional, and sub-regional scales. Independent BA datasets from GFED and MTBS indicate increasing fire activity across the southern and western US in recent decades, with a statistically significant increase in total US BA during 1984–2009. Interannual variability in US BA was strongly correlated with atmospheric drying potential during the fire season. Fire season PE increased from the 1980s–2000s, enhancing climate-driven fire risk in the SP, NP, NW, and AK where PE-BA correlations were strongest. This study corroborates and expands the results of previous research on climate variability and fire activity in the US (Littell et al., 2009; Westerling et al., 2006; Xiao and Zhuang, 2007; Kloster et al., 2010) using a more mechanistic approach to estimate PE (Allen et al., 1998) and satellite-based data for monthly BA in forest and non-forest cover types. Evidence in this study for

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increasing climatic control on US wildfires is also consistent with previous research on temperature-driven changes in BA for Canadian boreal forests (Balshi et al., 2009; Girardin and Wootton, 2009; Xiao and Zhuang, 2007; Gillett et al., 2004).

The US experiences a complex array of fire activity, from small agricultural management fires (McCarty et al., 2007) to large wildfires in the western US and Alaska (Westerling et al., 2003; Grissino-Mayer and Swetnam, 2000; Kasischke et al., 2002). Climate-fire relationships within each NCA region were similarly complex; no single climate variable explained more than 60% of the variance in fire season BA. The PE calculation in this study captured the interactions between humidity and temperature, in addition to wind speed and net radiation, and changes in these conditions during the fire season. Fire season PE was a good predictor of interannual variability in US BA, particularly in regions such as AK, NW, and NP where either higher temperatures or lower humidity can dry existing fuels. Precipitation-fire relationships were more variable, since precipitation can increase fire risk in fuel-limited systems in the months-years following increased rainfall (e.g., Littell et al., 2009; Westerling et al., 2003; Taylor and Beaty, 2005). Fire-climate relationships in the SW and SE regions were more difficult to generalize, given large within-region climate variability and ecosystem diversity. The distribution of peak fire month within these two regions (Fig. 2) suggests that finer spatial partitioning of fire-climate relationships may be warranted.

Differences in the climate-fire relationships between GFED and MTBS BA in this study highlight regions with human modifications of the natural fire regime. Year-round GFED fire activity in the SE US did not exhibit consistent relationships with climate variables. Seasonal differences in the timing of management fires could be used to isolate the management fire activity in BA or active fire datasets (e.g., Magi et al., 2012). Indeed, the inclusion of agricultural management fires in the GFED BA product may partially explain this variability (Giglio et al., 2010; van der Werf et al., 2010), as both climate and non-climate drivers contribute to fire activity in this region. In contrast, the MTBS record of large fires on public lands showed more consistent relationships between BA and water deficits in the SP and SE regions. Contrasting patterns of fire

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activity between the GFED and MTBS BA products underscore the importance of fire type on climate-fire relationships. One goal of this study was to highlight the diversity of climate-fire interactions at the national scale, including regions with few historic studies (MW, NE). The ability to capture the heterogeneity in fire activity at a region scale using satellite data provides a more complete baseline of contemporary US fire activity than in previous studies confined to regional scales (e.g., McKenzie et al., 2004; Westerling et al., 2006; Xiao and Zhuang, 2007).

Contemporary relationships between climate and fire provide a blueprint for assessing regional changes in US fire activity under future climate conditions. The results of this study illustrate how the spatial and temporal variability in US climate-fire relationships complicate projections of future fire activity. Increasing PE during the fire season could lead to increases in fire activity in the NP, NW, and AK. In contrast, increasing fire season PE in the SW US may have little impact on BA because mean PE values during the fire season are already favourable for fire activity. BA in the SP region responded to short-term water deficits and long-term anomalies in precipitation, such that increasing interannual variability in precipitation could lead to additional fires in the region. Thus, changes in the seasonality or magnitude of climate anomalies are unlikely to result in uniform changes in US fire activity. The results of this study could be used to identify region-specific relationships between climate and BA to improve the parameterization of models that project future fire activity.

Recent efforts to model US fire activity under scenarios of climate change project a climate-driven increase in the area and severity of wildfires (e.g., Brown et al., 2004; Spraklen et al., 2009; Westerling et al., 2011a). Different projections of future fire activity depend, in large part, on the complexity of the fire-climate feedbacks in the model. Models that simulated the response of vegetation and fire to climate warming suggest that some of the increase in net carbon losses from wildfire could be offset by enhanced vegetation growth (Bachelet et al., 2005) or by the combination of enhanced vegetation growth plus fire suppression efforts (Lenihan et al., 2008; Rogers et al., 2011). Coupled models of the climate system with projections of population, land use, and wildfires also

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highlight the likely increase in US fire activity under scenarios of land use and climate change (Pechony and Shindell, 2010). However, studies that include other direct and indirect climate feedbacks from fire are still needed, such as the impacts of aerosols and long-lived trace gases (Seiler and Crutzen, 1980; Andreae and Merlet, 2001; van der Werf et al., 2010), albedo changes (Randerson et al., 2006), and hydrological exchanges between the land surface and atmosphere (Busch and Smith, 1993; Kang et al., 2006).

Five methodological limitations in this study could be addressed in future research. First, fire activity reflects the influence of climate anomalies over a range of temporal and spatial scales (Parisien et al., 2011). The use of monthly PE values in this study does not capture synoptic events or longer-term evolution of climate phenomena, including carryover effects from anomalies in previous months such as soil water deficits. Second, climate controls on fire ignitions and the duration of fire activity may differ (Abatzoglou and Kolden, 2011), or be self-reinforcing through rainfall inhibition from biomass burning aerosols (Tosca et al., 2010; Rosenfeld, 1999). Daily BA and climate information can help isolate climate conditions that favour ignition, growth, and suppression of fire activities to better target mitigation and adaptation efforts on a regional basis. Third, other climate phenomena, such as changes in atmospheric circulation (Skinner et al., 1999; Macias Fauria and Johnson, 2006), may provide a more mechanistic representation of the evolution of warm, dry conditions that promote fire activity at mid-high latitudes. Future efforts to capture changing atmospheric circulation as a function of sea surface temperature anomalies (e.g., Duffy et al., 2005; Chen et al., 2011) may provide an alternate means to assess seasonal or long-term changes fire risk in the US and other regions. Fourth, some local interactions between climate and fire were not well captured in this study, such as the role of snowpack for fire activity at the watershed scale (Westerling et al., 2006). BA and climate data on finer spatial scales may be needed to isolate climate-fire relationships in ecosystems with complex terrain or hydrology. Finally, the use of NCA administrative regions in this study may

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have masked climate-fire relationships for specific biomes (Littell et al., 2009) or other sub-regions where land cover, land use, or fragmentation are strong controls on BA.

This study represents the first national assessment of climate-fire relationships in the US. The MTBS (26 yr) and GFED time series (14 yr) of satellite BA data provide complementary information to evaluate the consistency of climate-fire relationships on a regional basis. Spatial patterns of BA in the US are complex, based on the diversity of fire types, ecosystems, and ignition sources within each NCA region. We document a significant increase in US BA during 1984–2009. Fire season PE also increased during this period, suggesting that stronger climate control on BA is one potential driver of recent BA trends in the western US and Alaska. Non-climate drivers of regional BA were also important for the seasonal and interannual variability of fire activity across the southern US. This satellite-based assessment of US fire activity provides a foundation for future work on the regional sensitivity of US BA to climate change. Mid-term projections of future fire activity may benefit from the regional characterization of climate-fire relationships in this study, as climate-driven fire activity reflects existing fuel loads rather than the coupled response of vegetation growth and fire disturbance rates to future climate conditions.

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Table 1. Peak fire month, 3-month fire season, and the fraction of mean annual GFED BA in these months for each study region. The mean deviation in peak fire month highlights the heterogeneity of fire activity within each region.

Region	Peak Fire Month	Mean Deviation (Months)	% BA	Fire Season	% BA
AK	Jul	0.9	45.4	Jun–Aug	93.6
NW	Aug	0.8	46.4	Jul–Sep	85.7
NP	Aug	1.6	45.1	Jul–Sept	81.5
MW	Apr	1.5	39.2	Mar–May	71.7
NE	Dec	3.9	33.4	Oct–Dec	38.3
SW	Jul	1.4	27.6	Jun–Aug	70.0
SP	Apr	2.1	41.0	Feb–Apr	66.2
SE	Feb	3.1	15.0	Jan–Mar	33.1
US	Jul	1.8	25.8	Jun–Aug	62.2

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Table 2. Mean annual GFED (1997–2010) and MTBS (1984–2009) burned area (BA, km² yr⁻¹) for the US and sub-national NCA regions. Mean annual BA as a fraction of the region area and trends in annual BA (km² yr⁻¹) are also shown. Starred values indicate statistically significant BA trends based on robust linear regression ($p < 0.05$).

	AK	NW	NP	MW	NE	SW	SP	SE	US
GFED Mean Annual BA (km² yr⁻¹)	4340.9	2984.8	1461.8	345.5	53.8	4686.6	2213.5	2779.6	18 866.4
Herbaceous BA (km ² yr ⁻¹)	2407	2427.1	1126.6	254.8	34.9	3771.5	1889.1	1727.8	13 638.7
Forest BA (km ² yr ⁻¹)	1775.2	449.5	278.6	58.3	18.3	699.6	214	938.1	4431.7
GFED BA (% yr⁻¹)	0.284	0.474	0.118	0.029	0.01	0.264	0.201	0.206	0.202
GFED BA trend 1997–2010 (km² yr⁻¹)	43.7	-42.3	26.3	8.7	-3.7	138.5	155.5	48.7	831.0
Herbaceous BA Trend (km ² yr ⁻¹)	5.8	-49.7	12.6	2.4	-2.2	61.0	120.3	25.9	372.4
Forest BA Trend (km ² yr ⁻¹)	32.0	7.2	1.7	5.3	-0.7	31.7	10.4	-11.1	315.3
MTBS Mean Annual BA (km² yr⁻¹)	3679.2	2942.8	1506.3	220.7	103.9	4973.5	1375.9	1165.1	10 993.9
MTBS BA (% yr ⁻¹)	0.24	0.468	0.122	0.018	0.02	0.28	0.125	0.086	0.118
MTBS BA Trend 1984–2009 (km² yr⁻¹)	11.8	22.7	28.1	4.5	0.2	281.0*	38.9	82.6*	753.0*
MTBS BA Trend 1997–2009 (km² yr⁻¹)	505.7	162.3	58.7	11.4	0.6	355.9	123.6	209.9*	1809.8*

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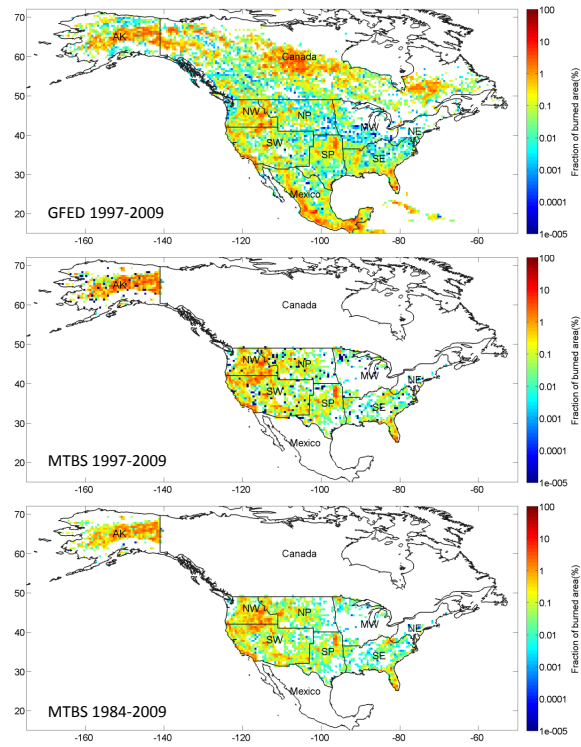


Fig. 1. Mean annual GFED BA (1997–2009, top) and MTBS BA (1997–2009, middle; 1984–2009, bottom), shown as the burned fraction of each 0.5° grid cell. Sub-national study regions are outlined in black: Alaska & Arctic (AK), Northwest (NW), Southwest (SW), Northern Plains (NP), Southern Plains (SP), Midwest (MW), Southeast (SE), and Northeast (NE).

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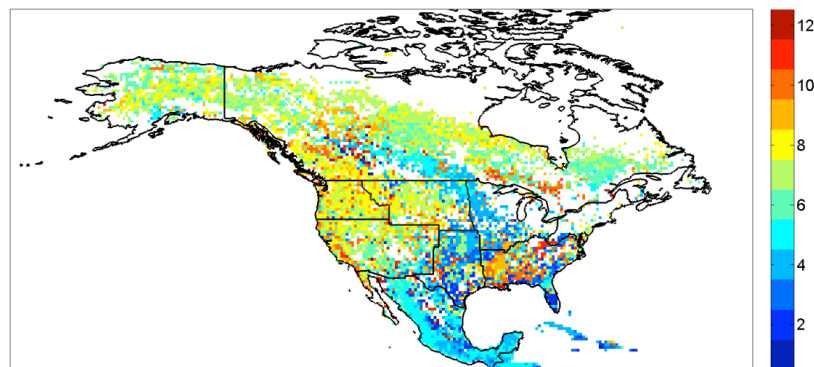


Fig. 2. Peak fire month in North America, defined as the month with the largest fraction of annual GFED burned area during 1997–2010.

7882

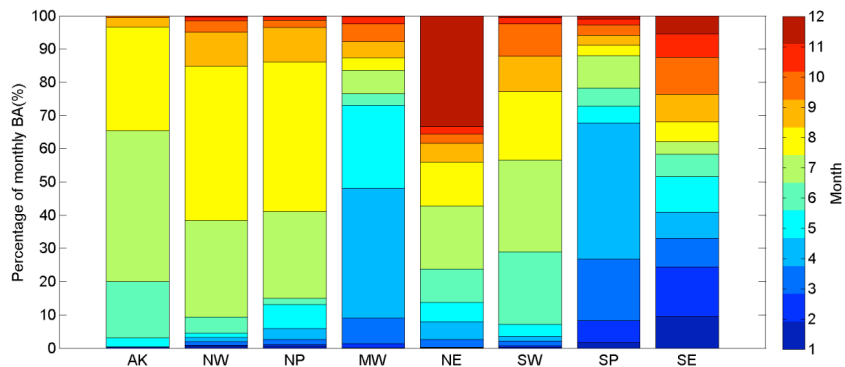


Fig. 3. Seasonal distribution of GFED BA for each US National Climate Assessment study region during 1997–2010.

7883

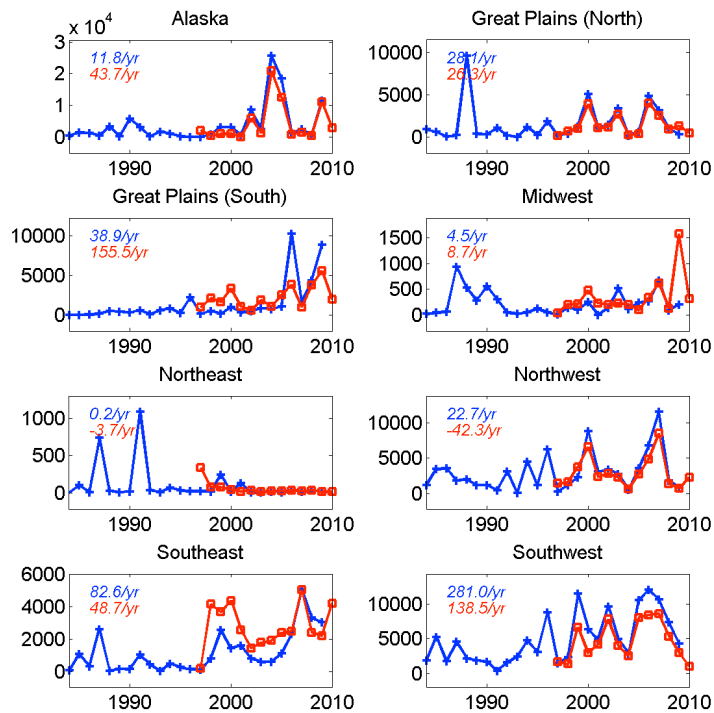


Fig. 4. Interannual variability in MTBS (blue) and GFED (red) BA for each NCA region. Values in each panel indicate the trends in annual BA (km² yr⁻¹) from robust linear regression for MTBS (1984–2009) and GFED (1997–2010) BA time series, as shown in Table 2.

7884

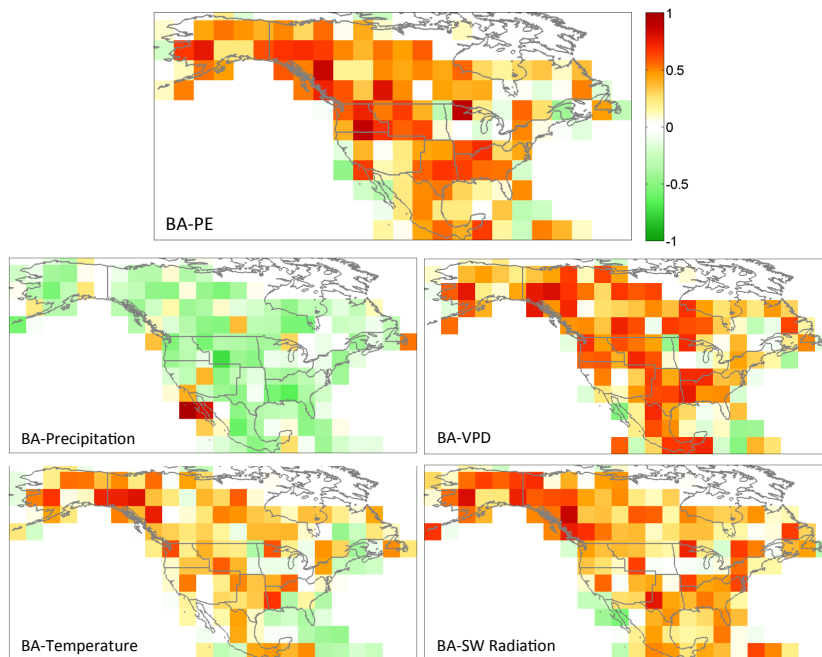


Fig. 5. Correlations between GFED BA (1997–2010) during the 3-month fire season and climate metrics for each $5^\circ \times 5^\circ$ grid cell in North America. Separate map panels show the correlation between fire-season BA and Potential Evaporation (PE), Precipitation, Vapour Pressure Deficit (VPD), mean monthly temperature, and incoming shortwave (SW) radiation from reanalysis climate data.

7885

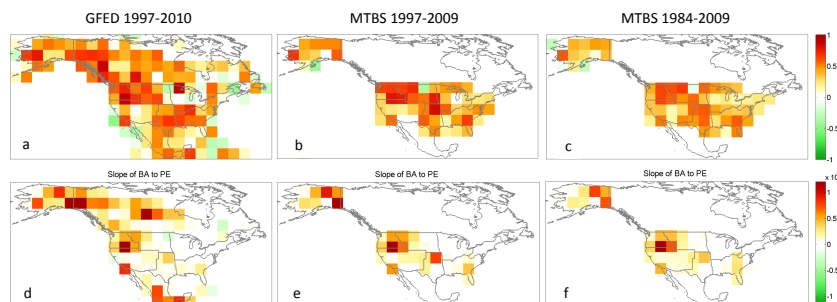


Fig. 6. Correlations between fire season PE and GFED BA (a), MTBS BA 1997–2009 (b), and MTBS BA 1984–2009 (c) for each $5^\circ \times 5^\circ$ grid cell in North America. Panels d–f show the slope of the BA-PE relationships for the fire season ($10\,000\text{ ha mm}^{-1}\text{ day}^{-1}$).

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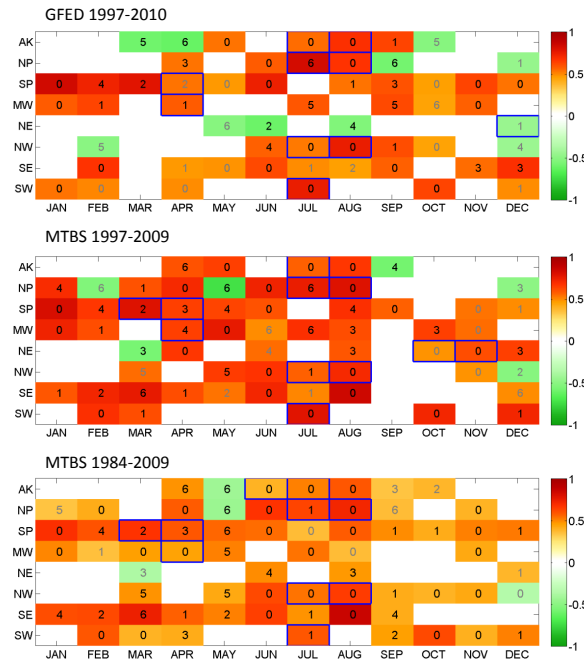


Fig. 7. Monthly cross correlation coefficients between PE and GFED BA (1997–2010, top) and MTBS BA (1997–2009, middle; 1984–2009, bottom). Numbers indicate the lead time between climate and BA in months. Black text signifies correlation coefficients with $p < 0.05$, and grey text indicates correlation coefficients with $0.05 \leq p < 0.1$. Months with $< 2\%$ of annual BA or months without statistically significant correlations between BA and climate variables ($p > 0.1$) appear white. Blue boxes outline months with $\geq 20\%$ of annual BA for each region.

7887

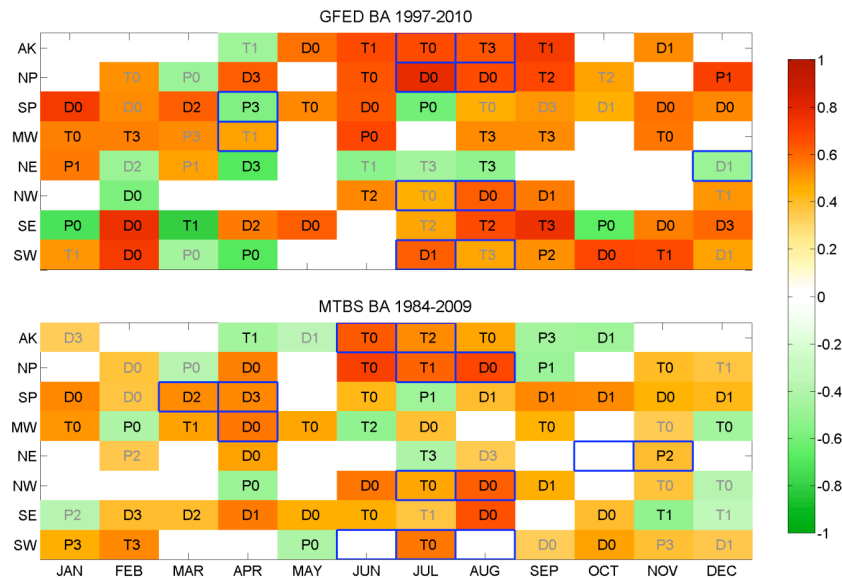


Fig. 8. Maximum monthly cross correlation coefficients between GFED (top) and MTBS (bottom) BA and alternate climate indices. Letters in each grid cell indicate the monthly mean climate variable (P : precipitation; D : water deficit, calculated as $P-PE$; T : temperature), numbers represent the lead time between climate and BA in months (max = 3), and colors represent the correlation coefficient. Black text indicates correlation coefficients with $p < 0.05$, and grey text signifies correlation coefficients with $0.05 \leq p < 0.1$. Months with $< 2\%$ of annual BA or without statistically significant correlations between BA and climate variables ($p > 0.1$) appear white. Blue boxes outline months with $\geq 20\%$ of annual BA for each region.

7888

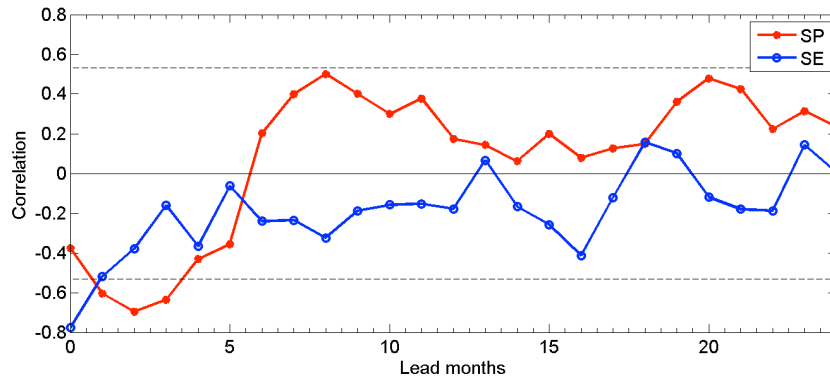


Fig. 9. Cross correlation coefficients between fire season BA and precipitation for the Southern Plains (SP) and Southeast (SE) regions for lead times of 0 to 24 months prior to the start of the fire season. Dashed lines indicate the limits for statistically significant correlation at the 95% confidence level.

7889

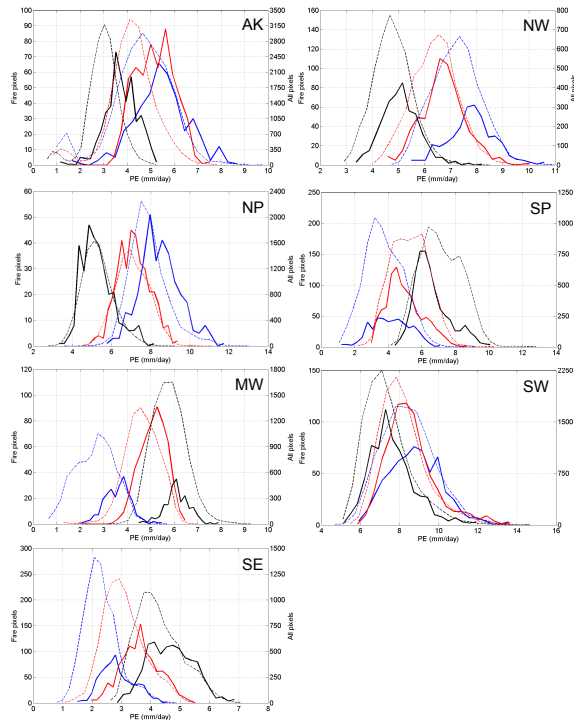


Fig. 10. Histograms of monthly PE (1997–2010) for 0.5° fire grid cells (solid lines) and all grid cells (dashed lines) by region. Blue, red, and black lines indicate the first, second, and third months of the fire season, respectively (see Table 1).

7890

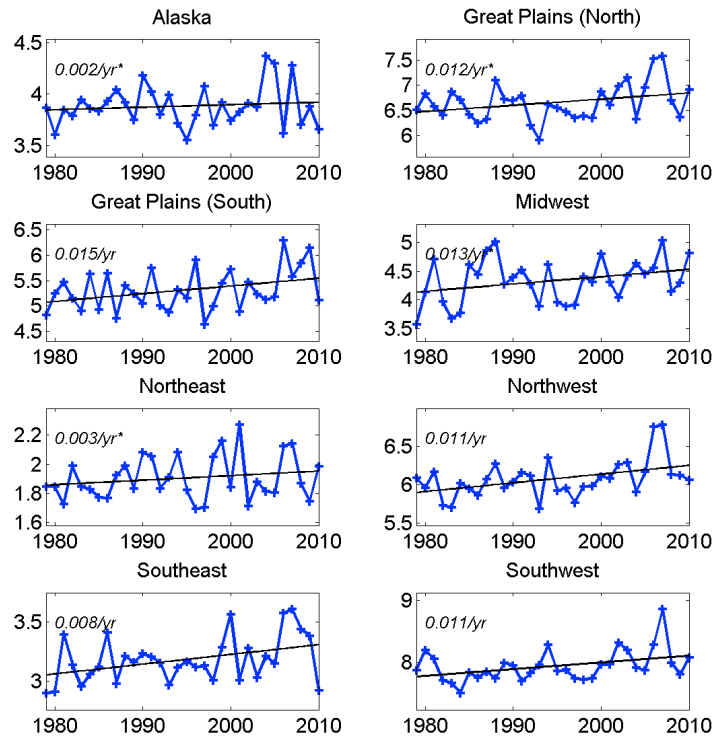


Fig. 11. Fire season PE (+) for each NCA region between 1980 and 2010. Values indicate the linear trends in fire season PE (black lines) during this period. Starred values indicate statistically significant PE trends based on robust linear regression ($p < 0.05$).

7891

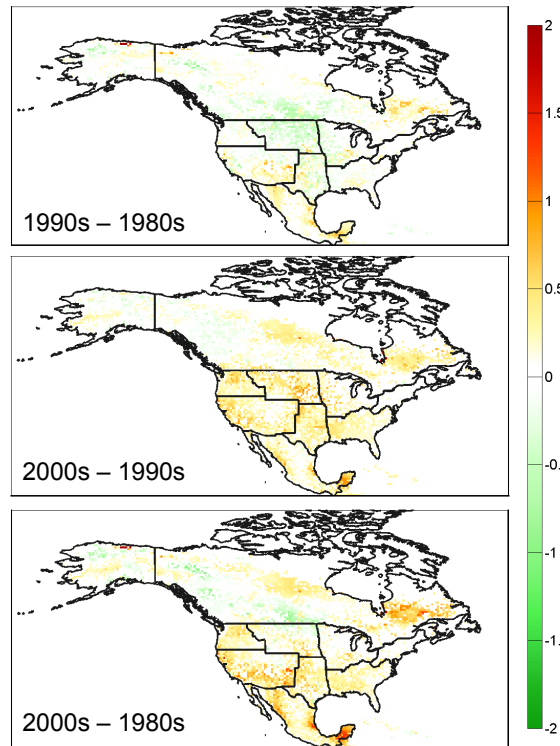


Fig. 12. Difference in decadal mean fire season PE for the 1980s, 1990s, and 2000s (mm day^{-1}). Cells without GFED BA area in any year (1997–2010) appear white.

7892