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Key Points:
- Number of large fires and large fire area have increased across the western U.S.
- Fire activity trends were most significant in southern and mountain ecoregions
- Increased fire in these ecoregions coincided with increased drought severity

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Large wildfire trends in the western United States, 1984–2011

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Abstract We used a database capturing large wildfires (> 405 ha) in the western U.S. to document regional trends in fire occurrence, total fire area, fire size, and day of year of ignition for 1984–2011. Over the western U.S. and in a majority of ecoregions, we found significant, increasing trends in the number of large fires and/or total large fire area per year. Trends were most significant for southern and mountain ecoregions, coinciding with trends toward increased drought severity. For all ecoregions combined, the number of large fires increased at a rate of seven fires per year, while total fire area increased at a rate of 355 km^2 per year. Continuing changes in climate, invasive species, and consequences of past fire management, added to the impacts of larger, more frequent fires, will drive further disruptions to fire regimes of the western U.S. and other fire-prone regions of the world.

1. Introduction

Quantification of recent historical trends in fire activity is challenging, due to a lack of spatially complete and consistently derived data sets, regional variation in fire regimes and their controls, and statistical limitations associated with the temporal extent of instrumental records. Previous efforts have found increasing fire occurrence or severity over time in the western United States but have been limited in geographic scope [*Dillon et al.*, 2011; *Miller and Safford*, 2012; *Miller et al.*, 2012] or to National Forest lands [*Calkin et al.*, 2005; *Stephens*, 2005; *Westerling et al.*, 2006] and have not assigned likelihood to observed trends. We used burn area boundaries mapped from satellite remote sensing data by the Monitoring Trends in Burn Severity Project (MTBS) [*Eidenshink et al.*, 2007] to determine wildfire trends within nine ecoregions spanning the western U.S. (Figure 1). A nonparametric linear trend estimator with low sensitivity to outliers was applied to time series of four variables describing fire activity. In addition to number of large fires and total area inside fire boundaries mapped by MTBS, the 90th percentile of large fire size was used to examine whether the size of the largest fires grew over the study period, and 10th percentile of day of year of ignition was used to test whether the earliest large fires started earlier over the study period. Since past work has demonstrated that climate is a primary control on fire activity [*Krawchuk and Moritz*, 2011; *Littell et al.*, 2009; *Westerling et al.*, 2003], seasonal trends in maximum temperature, precipitation, and Self-Calibrated Palmer Drought Severity Index (SCPDSI) [*Wells et al.*, 2004] were also assessed. Likelihood of trends was evaluated by comparison against random perturbations of each time series, and significance was determined using the Mann-Kendall trend test [*Mann*, 1945].

2. Methods

MTBS uses satellite remote sensing data to map burn area boundaries in the U.S. The project has the goal of mapping all fires larger than 405 hectares (1000 acres) in the continental U.S. west of 97° longitude [*Eidenshink et al.*, 2007]. Burn area boundary polygons are determined by analysts comparing prefire and postfire values of the normalized burn ratio [*Key and Benson*, 2006]. While MTBS data are limited in temporal extent due to a lack of 30 m resolution satellite data prior to 1984, the data have important advantages over longer, less complete fire databases previously used for trend analysis [*Calkin et al.*, 2005; *Littell et al.*, 2009; *Stephens*, 2005; *Westerling et al.*, 2006]. MTBS has complete coverage of all public and private lands rather than being limited by administrative boundaries. Since burn area boundaries are all derived using the same methodology, the data are not vulnerable to temporal and spatial variability in fire reporting methods.

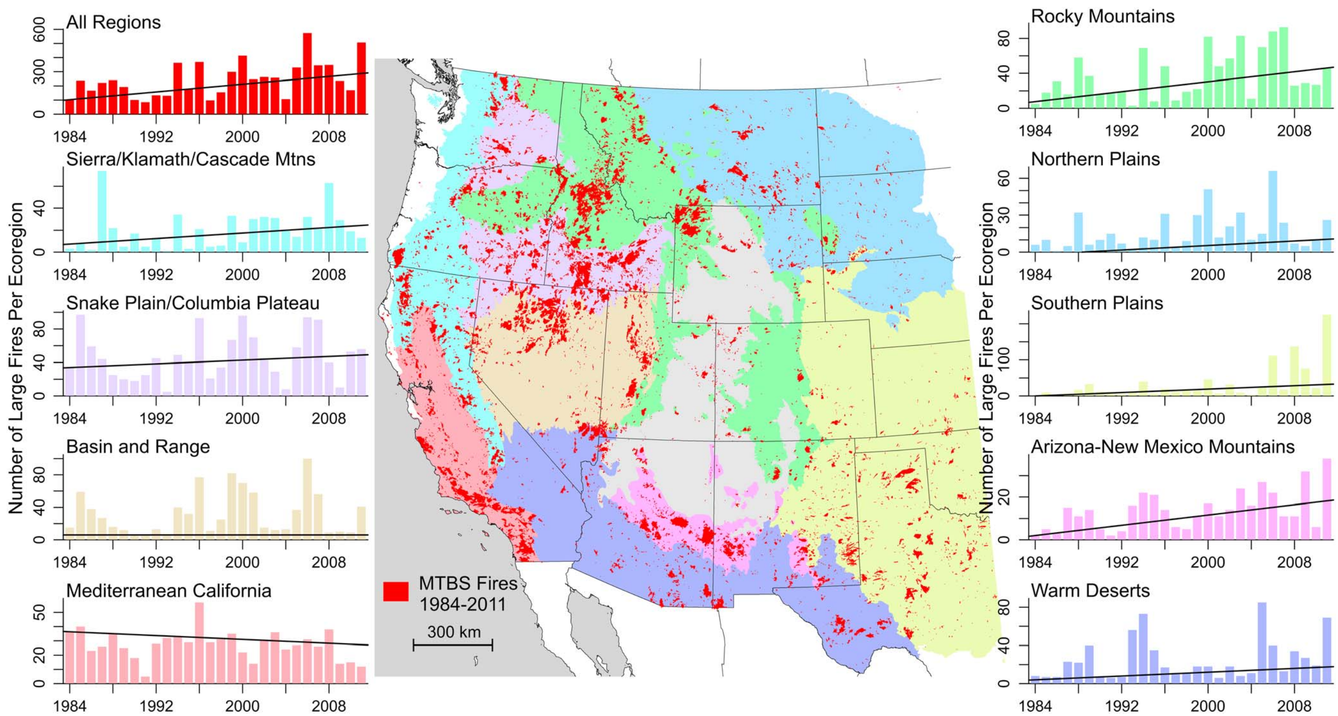

Figure 1. Western U.S. trends for number of large fires in each ecoregion per year. The center map illustrates ecoregions based on Levels II and III of the Omernik ecoregion system. The Wyoming Basin and Colorado Plateau ecoregions had too few large fires for trend analysis at the ecoregion level, and are shown in gray. MTBS-mapped fires are shown in red. The surrounding bar plots display the number of large fires in each ecoregion over the 1984–2011 study period. The black line on each plot indicates the Theil-Sen estimated slope for each ecoregion, with slope values and significance shown in Figure 2a.

All fires labeled by MTBS as “prescribed” were excluded from the analysis, and burn area boundaries were required to have a “high” confidence level as described in the MTBS metadata. A total of 6876 large fires cataloged by MTBS during the 1984–2011 study period were examined. Area contained within each burn area boundary was calculated and is referred to here as “fire area” rather than “burn area” since burn area boundaries produced by MTBS represent the maximum extent of the fire and can contain islands of unburned vegetation. Burn area boundaries also include areas burned as part of firefighting activities.

Ecoregions were used to capture areas of similar climate variability and vegetation types. The Omernik ecoregion system [*Omernik*, 1987] as adapted by the U.S. Environmental Protection Agency (http://www.epa.gov/wed/pages/ecoregions.htm) served as the basis for ecoregions used in this study. Omernik ecoregions are hierarchical, for example, providing multiple Level III subregions for each Level II ecoregion. All Level II ecoregions exceeding an average of 10 fires per year over the 28 year study period were combined for the western U.S.-scale analysis. For the ecoregion-scale analysis, Omernik Level II ecoregions were divided into groupings of Level III ecoregions where it was possible to maintain an average of 10 large fires per year. The Arizona-New Mexico Mountains ecoregion had the smallest number of fires, with 385. Two Level III ecoregions, the Colorado Plateau and Wyoming Basin, did not have a sufficient number of fires for trend analysis at the ecoregion level, leaving nine individual ecoregions (Figure 1). Data from the Colorado Plateau and Wyoming Basin ecoregions were used for the combined, western U.S.-scale analysis. Fires crossing ecoregion boundaries were counted as occurring in both ecoregions but were counted only once at the western U.S. level.

Seasonal temperature, precipitation, and SCPDSI were determined for each ecoregion over the 28 year study period. Monthly precipitation and maximum temperature with an approximate spatial resolution of 4 km were obtained from the parameter-elevation regressions on independent slopes model (PRISM) [*Daly et al*., 2000]. SCPDSI [*Wells et al*., 2004] is based on the Palmer Drought Severity Index [*Palmer*, 1965] and captures longer-term variability in water balance while using constants calculated for each grid cell. Gridded SCPDSI data provided by the Western Regional Climate Center (http://www.wrcc.dri.edu) were based on 4 km PRISM temperature and precipitation products. Seasons were defined as December, January, and February (DJF); March, April, and May (MAM); June, July, and August (JJA); and September, October, and November (SON). Mean monthly maximum temperature and SCPDSI were calculated for each ecoregion and then averaged across each 3 month period. Precipitation was summed for each season then averaged across each ecoregion.

Four fire variables and twelve climate variables were used for trend analysis. Annual number of fires and total fire area were calculated from the MTBS data for each ecoregion. Quantile regression [*Koenker and Bassett*, 1978] for the combined nine ecoregions revealed that the steepest trends in fire size and day of year of fire ignition (DOY) occurred at the highest quantiles of size and the lowest quantiles of DOY. Annual 90th percentile of fire size and 10th percentile of DOY for each ecoregion were thus added as fire variables. Ninetieth percentile of DOY was also tested as a variable but resulted in no significant ($p < 0.1$) trends in any ecoregion. Years with fewer than 10 fires within an ecoregion were excluded from trend analysis for 90th percentile fire size and 10th percentile DOY. To examine potential climate forcings over the study period, trends were also analyzed for maximum temperature, precipitation, and SCPDSI for DJF, MAM, JJA, and SON.

Rather than arbitrarily divide the study period into subperiods, linear trends were examined using the entire time series. For each variable, our null hypothesis was that the increase or decrease of a given variable cannot be distinguished from a difference arising from a random redistribution of the annual values. To accommodate nonnormal distributions of fire and climate variables, the nonparametric Theil-Sen estimator [*Wilcox*, 2012] was used to calculate slope over time for each variable. The Theil-Sen slope estimator is the median value of all pairwise differences between two time steps and is robust to outliers while still approaching an ordinary least squares estimate of slope when the distribution of values is close to normal. We estimated the likelihood of the Theil-Sen estimated slope being different from zero using 10,000 random redistributions of the time series for each ecoregion [*Wilcox*, 2012]. For increasing (decreasing) trends, the slope from the original data was compared to the upper (lower) part of the distribution of bootstrapped slopes to determine a likelihood value. A two-sided Mann-Kendall trend test was used to assess the significance of monotonic trends in fire and climate variables [*Mann*, 1945].

3. Results and Discussion

Spatial and temporal variability in fire activity is apparent at the ecoregion and western U.S. scales (Figure 1). Although fire can be reduced or even absent from an ecoregion in low-activity years, over a longer time period, positive trends in the number of fires emerge in most ecoregions. The number of large fires trended higher in seven out of nine ecoregions, and the increased trends were significant ($p < 0.05$) in the Southern Plains, Arizona-New Mexico Mountains, Rocky Mountains, and Sierra/Klamath/Cascade Mountains ecoregions (Figure 2a). The Arizona-New Mexico Mountains and Sierra/Klamath/Cascade Mountains ecoregions had slopes increasing at rates near 0.6 large fires per year, while the Southern Plains and Rocky Mountains ecoregions demonstrated increasing slopes in excess of 1 large fire per year. Across all ecoregions, the estimated slope indicated that the number of large fires increased at a rate of nearly seven large fires per year over the study period.

We found that total fire area trended higher in all nine ecoregions (Figure 2b). The Southern Plains and Arizona-New Mexico Mountains ecoregions possessed significant positive trends in both number of fires and total fire area, while the Warm Deserts ecoregion had a significant trend increase in total fire area but not number of fires. Total fire area increased by a rate of 355 km^2 per year over the study period for the combined ecoregions. The 90th percentile of fire size trended higher for eight out of nine ecoregions, with only the Sierra/Klamath/Cascade Mountains ecoregion displaying a strong negative slope that was significant at the $p < 0.1$ level (Figure 2c). The Warm Deserts, Arizona-New Mexico Mountains, and Mediterranean California ecoregions showed strong trends in the 90th percentile of large fire size, with increasing trends in excess of 2 km^2 per year. Unlike other ecoregions in the western U.S., the Mediterranean California ecoregion experienced a significant increase in the 90th percentile of large fire size without demonstrating significant trends in the number of fires or total fire area. The percentage of fire area mapped as unburned-to-low severity by MTBS decreased significantly over time, so increases in total fire area and 90th percentile of large fire size reported here may underestimate actual increases.

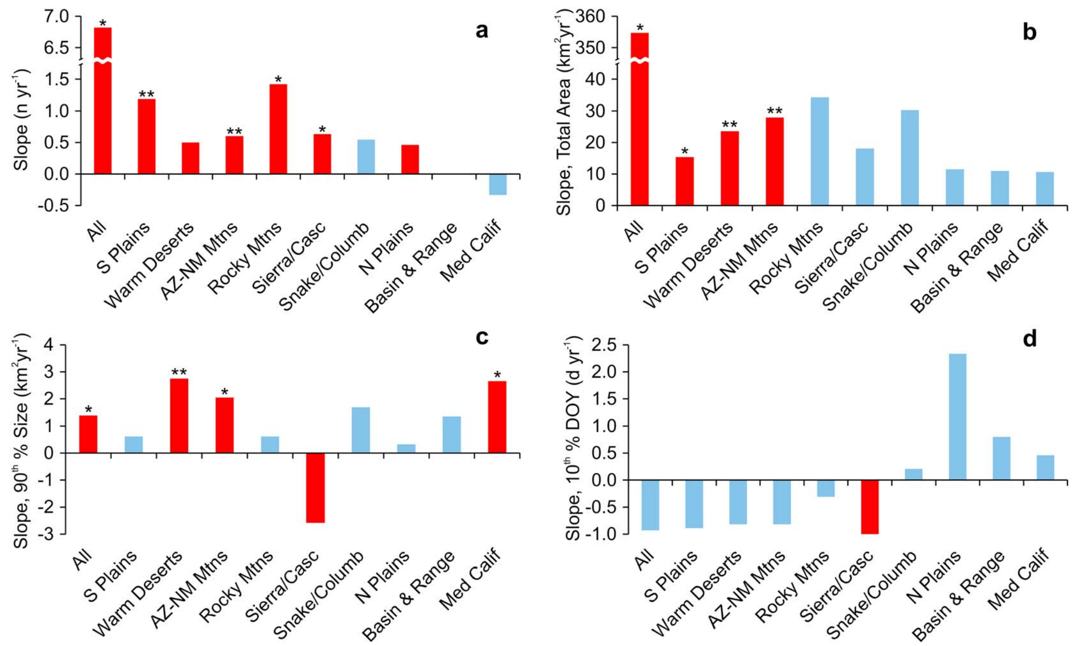

Figure 2. Fire activity trends for western U.S. ecoregions. (a) Slope in number of large fires per year. (b) Slope in total fire area per year. (c) Slope in 90th percentile large fire size per year. (d) Slope in 10th percentile day of year (DOY) per year. Significance (p) of slopes assessed using the Mann-Kendall test is shown as a red bar ($p < 0.10$), one asterisk ($0.01 < p < 0.05$), and two asterisks ($p < 0.01$).

Among ecoregions there was substantial variation in trends for the timing of early season fires (Figure 2d). Higher elevation and more southern ecoregions had trends toward earlier 10th percentile DOY, while more northern, interior ecoregions and Mediterranean California had trends toward later 10th percentile DOY. However, none of the slopes for the 10th percentile DOY trends were found to be significant at $p < 0.05$ (Figure 2d). The Sierra/Klamath/Cascade Mountains ecoregion exhibited the most significant trend ($p < 0.06$), with a slope of -1.0 days per year. This trend toward earlier large fires at higher elevation agrees with previous findings that early snowmelt may contribute to earlier fire seasons [*Westerling et al.*, 2006], but our findings did not indicate a significant western U.S. trend toward earlier fires during this study period.

The exclusion of burn area boundaries with low certainty had little effect on the trends described above. All trends described as significant ($p < 0.05$) remained significant if low-certainty fires were included, with two exceptions. In the Rocky Mountains and Sierra/Klamath/Cascade Mountains ecoregions, the trends in number of large fires per year dropped to $p = 0.08$ and $p = 0.09$, respectively.

Many ecoregions showed trends that are very unlikely to be due to random variation alone, toward a larger number of large fires, larger total fire area, and/or larger 90th percentile of large fire size (Figure 3). The five ecoregions displaying the lowest average likelihood of random variation in fire activity over the study period were Southern Plains, Warm Deserts, Arizona-New Mexico Mountains, Rocky Mountains, and Sierra/Klamath/Cascade Mountains. On average, the likelihood of these five ecoregions exhibiting such trends due to random variation was only 2% for number of fires and 4% for total fire area. For the western U.S., the likelihood that the number of fires, total fire area, and 90th percentile of fire size were random through the study period was less than 1% for all three variables.

Taken together, trends in fire variables indicate significant increases in fire activity over much of the western U.S. Notable exceptions are the Snake Plain/Columbia Plateau, Northern Plains, and Basin and Range ecoregions. While trends pointed toward increasing total area and 90th percentile fire size, none of these ecoregions demonstrated significant changes in the four fire variables (Figure 2). Remarkably, the increasing trends in fire activity span a wide range of vegetation types, latitudes, and precipitation regimes found in the western U.S. Fire regimes that dominate the nine examined ecoregions vary in prevalent fuel type, fire season, fire frequency, and fire intensity but share large increases in fire activity over the study period.

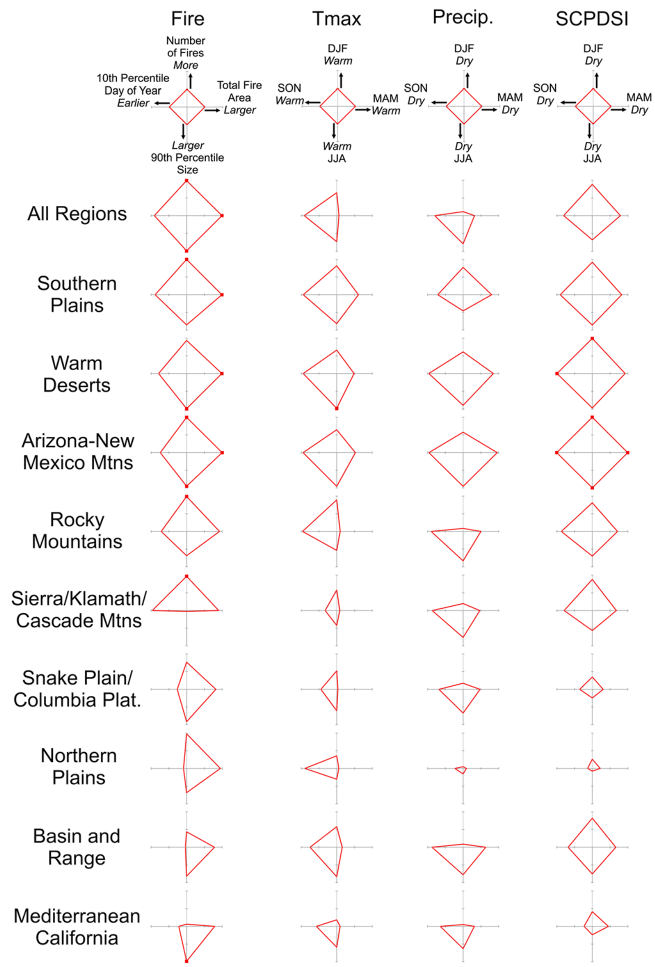

Figure 3. Likelihood for fire and climate variables. The first row of plots represents times series with no increasing or decreasing trends in variables. Movement toward the edge or center of each plot indicates decreasing likelihood of a random trend over 1984–2011. Larger diamonds indicate trends toward higher fire activity, higher temperature, lower precipitation, and higher drought severity. Likelihood from the four fire variables was averaged to sort the ecoregions from (top) lowest to (bottom) highest (bottom) average likelihood of a random trend over 1984–2011. Trends determined significant at $p < 0.05$ using the Mann-Kendall test are marked with a square.

Seasonal temperature and precipitation did not have significant trends, with the exception of significantly increasing summer temperature in the Warm Deserts ecoregion (Figure 3). For the ecoregions with the largest increases in fire activity, temperatures trended hotter and precipitation trended drier relative to ecoregions not experiencing significant changes in fire variables. SCPDSI integrates longer time periods, and trended toward higher drought severity for all four seasons in a majority of ecoregions. Likelihood of random variation over 1984–2011 in the five ecoregions showing the largest change in fire activity averaged 8% for winter (DJF) SCPDSI, 17% for spring (MAM) SCPDSI, 18% for summer (JJA) SCPDSI, and 9% for fall SCPDSI.

Ecoregions are not homogeneous in terms of fuel types, climate conditions, or fire regimes. Important trends may therefore exist at the subecoregion level, but these trends will be difficult to assess due to low sample size, as occurred for the Wyoming Basin and Colorado Plateau ecoregions. Furthermore, our seasonal climate variables only account for variation within the year each fire occurred, and previous work has shown that antecedent climate over multiple years can be correlated with fire activity [*Littell et al.*, 2009; *Schoennagel et al.*, 2004; *Westerling et al.*, 2003]. While climate trends for ecoregions with increased fire activity were toward stronger drought, wetter antecedent conditions can potentially increase fine fuels in fuel-limited ecosystems [*Krawchuk and Moritz*, 2011; *Littell et al.*, 2009; *Westerling et al.*, 2003]. Trends toward higher precipitation in the Northern Plains ecoregion (Figure 3), for example, could be responsible for the near significant increase in number of large fires in this region.

Although trends in SCPDSI coincided with trends in fire variables across a large swath of the western U.S., other factors are likely contributing to changes in fire activity. For example, invasion of nonnative annual grasses across large areas of the Great Basin [*Balch et al.*, 2013] has been linked to increases in fire frequency and area burned in recent decades. The role of past fire management practices on trends in fire variables varies by ecoregion. Past fire suppression has led to changes in fuels, fire frequency, and fire intensity in some southwestern ponderosa pine [*Fulé et al.*, 1997] and Sierran forests [*Collins and Stephens*, 2007] but has had relatively little impact on fire activity in portions of the Rocky Mountains [*Schoennagel et al.*, 2004] and in southern California chaparral [*Moritz et al.*, 2004]. Changes in firefighting practices over time (e.g., more frequent use of intentional burning to clear fuels as a fire suppression tactic) may have had impacts on mapped burn area boundaries. The effects of human development vary regionally, in some cases increasing fire activity and in others decreasing it [*Hawbaker et al.*, 2013; *Syphard et al.*, 2007].

Ecoregions with increasing trends in the number of large fires and total fire area also displayed increasing trends in drought severity. The geographically broad and coherent nature of fire and climate trends across much of the study area implicates climate as a dominant driver of changing fire activity in the western U.S. Due to complex interacting influences on fire regimes across the western U.S. and the relatively short period analyzed by this study, care must be exercised in directly attributing increases in fire activity to anthropogenic climate change. Even so, these changes in fire activity are a reflection of long-term, global fire trends that will likely occur with increased temperature and drought severity in coming decades. Studies from other parts of the world using a variety of data sources corroborate similar findings [e.g., *Giglio et al*., 2013; *Gillett et al*., 2004; *Piñol et al*., 1998]. Recent fire projections from an ensemble of global climate models for 2010–2039, a period we have already entered, show much of the Northern Hemisphere, including most of the western U.S., as being more fire prone [*Moritz et al*., 2012], consistent with the trends identified here.

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References

Balch, J. K., B. A. Bradley, C. M. D'Antonio, and J. Gómez-Dans (2013), Introduced annual grass increases regional fire activity across the arid western U.S.A. (1980–2009), *Global Change Biol.*, *19*(1), 173–183.
Calkin, D. E., K. M. Gebert, J. G. Jones, and R. P. Neilson (2005), Forest service large fire area burned and suppression expenditure trends, 1970–2002, *J. For.*, *103*(4), 179–183.
Collins, B. M., and S. L. Stephens (2007), Managing natural wildfires in Sierra Nevada wilderness areas, *Front. Ecol. Environ.*, *5*(10), 523–527.
Daly, C., G. H. Taylor, W. P. Gibson, T. W. Parzybok, G. L. Johnson, and P. A. Pasteris (2000), High-quality spatial climate data sets for the United States and beyond, *Trans. Am. Soc. Agric. Eng.*, *43*(6), 1957–1962.
Dillon, G. K., Z. A. Holden, P. Morgan, M. A. Crimmins, E. K. Heyerdahl, and C. H. Luce (2011), Both topography and climate affected forest and woodland burn severity in two regions of the western US, 1984 to 2006, *Ecosphere*, *2*(12), 130, doi:10.1890/ES11-00271.1.
Eidenshink, J., B. Schwind, K. Brewer, Z.-L. Zhu, B. Quayle, and S. Howard (2007), A project for monitoring trends in burn severity, *J. Assoc. Fire Ecol.*, *3*(01), 3.
Fulé, P. Z., W. W. Covington, and M. M. Moore (1997), Determining reference conditions for ecosystem management of southwestern ponderosa pine forests, *Ecol. Appl.*, *7*(3), 895–908.
Giglio, L., J. T. Randerson, and G. R. Van Der Werf (2013), Analysis of daily, monthly, and annual burned area using the fourth-generation global fire emissions database (GFED4), *J. Geophys. Res. Biogeosci.*, *118*, 317–328, doi:10.1002/jgrg.20042.
Gillett, N. P., A. J. Weaver, F. W. Zwiers, and M. D. Flannigan (2004), Detecting the effect of climate change on Canadian forest fires, *Geophys. Res. Lett.*, *31*, L18211, doi:10.1029/2004GL020876.
Hawbaker, T. J., V. C. Radeloff, S. I. Stewart, R. B. Hammer, N. S. Keuler, and M. K. Clayton (2013), Human and biophysical influences on fire occurrence in the United States, *Ecol. Appl.*, *23*(3), 565–582.
Key, C., and N. Benson (2006), Landscape assessment: Sampling and analysis methods *Rep*., USDA Forest Service, Rocky Mountain Research Station, Fort Collins, Colo.
Koenker, R., and G. Bassett Jr. (1978), Regression quantiles, *Econometrica J. Econometric Soc.*, *46*, 33–50.
Krawchuk, M. A., and M. A. Moritz (2011), Constraints on global fire activity vary across a resource gradient, *Ecology*, *92*(1), 121–132.
Littell, J. S., D. McKenzie, D. L. Peterson, and A. L. Westerling (2009), Climate and wildfire area burned in western U.S. ecoprovinces, 1916–2003, *Ecol. Appl.*, *19*(4), 1003–1021.
Mann, H. B. (1945), Nonparametric tests against trend, *Econometrica J. Econometric Soc.*, *13*, 245–259.
Miller, J. D., and H. Safford (2012), Trends in wildfire severity: 1984 to 2010 in the Sierra Nevada, Modoc Plateau, and southern Cascades, California, U.S.A., *Fire Ecol.*, *8*(3), 41–57.
Miller, J. D., C. N. Skinner, H. D. Safford, E. E. Knapp, and C. M. Ramirez (2012), Trends and causes of severity, size, and number of fires in northwestern California, U.S.A., *Ecol. Appl.*, *22*(1), 184–203.
Moritz, M. A., J. E. Keeley, E. A. Johnson, and A. A. Schaffner (2004), Testing a basic assumption of shrubland fire management: How important is fuel age?, *Front. Ecol. Environ.*, *2*(2), 67–72.
Moritz, M. A., M.-A. Parisien, E. Batllori, M. A. Krawchuk, J. Van Dorn, D. J. Ganz, and K. Hayhoe (2012), Climate change and disruptions to global fire activity, *Ecosphere*, *3*(6), 49, doi:10.1890/ES11-00345.1.
Omernik, J. M. (1987), Ecoregions of the conterminous United States, *Ann. Assoc. Am. Geogr.*, *77*(1), 118–125.
Palmer, W. C. (1965), Meteorological drought, Research Paper No. 45, U.S. Weather Bureau, Washington, D. C.
Piñol, J., J. Terradas, and F. Lloret (1998), Climate warming, wildfire hazard, and wildfire occurrence in coastal eastern Spain, *Clim. Change*, *38*(3), 345–357.
Schoennagel, T., T. T. Veblen, and W. H. Romme (2004), The interaction of fire, fuels, and climate across Rocky Mountain forests, *BioScience*, *54*(7), 661–676.
Stephens, S. L. (2005), Forest fire causes and extent on United States Forest Service lands, *Int. J. Wildland Fire*, *14*(3), 213–222.
Syphard, A. D., V. C. Radeloff, J. E. Keeley, T. J. Hawbaker, M. K. Clayton, S. I. Stewart, and R. B. Hammer (2007), Human influence on California fire regimes, *Ecol. Appl.*, *17*(5), 1388–1402.
Wells, N., S. Goddard, and M. J. Hayes (2004), A self-calibrating Palmer Drought Severity Index, *J. Clim.*, *17*(12), 2335–2351.
Westerling, A. L., H. G. Hidalgo, D. R. Cayan, and T. W. Swetnam (2006), Warming and earlier spring increase Western U.S. forest wildfire activity, *Science*, *313*(5789), 940–943.
Westerling, A. L., A. Gershunov, T. J. Brown, D. R. Cayan, and M. D. Dettinger (2003), Climate and wildfire in the western United States, *Bull. Am. Meteorol. Soc.*, *84*(5), 595–604.
Wilcox, R. R. (2012), *Introduction to Robust Estimation and Hypothesis Testing*, Academic Press, San Diego, Calif.