

Wildland fire deficit and surplus in the western United States, 1984–2012

SEAN A. PARKS,^{1,†} CAROL MILLER,¹ MARC-ANDRÉ PARISIEN,² LISA M. HOLSINGER,¹
SOLOMON Z. DOBROWSKI,³ AND JOHN ABATZOGLOU⁴

¹*Aldo Leopold Wilderness Research Institute, Rocky Mountain Research Station, USDA Forest Service,
Missoula, Montana 59801 USA*

²*Northern Forestry Centre, Canadian Forest Service, Natural Resources Canada, Edmonton, Alberta T5H3S5 Canada*

³*Department of Forest Management, College of Forestry and Conservation, University of Montana, Missoula, Montana 59812 USA*

⁴*Department of Geography, University of Idaho, Moscow, Idaho 83844 USA*

Citation: Parks, S. A., C. Miller, M.-A. Parisien, L. M. Holsinger, S. Z. Dobrowski, and J. Abatzoglou. 2015. Wildland fire deficit and surplus in the western United States, 1984–2012. *Ecosphere* 6(12):275. <http://dx.doi.org/10.1890/ES15-00294.1>

Abstract. Wildland fire is an important disturbance agent in the western US and globally. However, the natural role of fire has been disrupted in many regions due to the influence of human activities, which have the potential to either exclude or promote fire, resulting in a “fire deficit” or “fire surplus”, respectively. In this study, we developed a model of expected area burned for the western US as a function of climate from 1984 to 2012. We then quantified departures from expected area burned to identify geographic regions with fire deficit or surplus. We developed our model of area burned as a function of several climatic variables from reference areas with low human influence; the relationship between climate and fire is strong in these areas. We then quantified the degree of fire deficit or surplus for all areas of the western US as the difference between expected (as predicted with the model) and observed area burned from 1984 to 2012. Results indicate that many forested areas in the western US experienced a fire deficit from 1984 to 2012, likely due to fire exclusion by human activities. We also found that large expanses of non-forested regions experienced a fire surplus, presumably due to introduced annual grasses and the prevalence of anthropogenic ignitions. The heterogeneity in patterns of fire deficit and surplus among ecoregions emphasizes fundamentally different ecosystem sensitivities to human influences and suggests that large-scale adaptation and mitigation strategies will be necessary in order to restore and maintain resilient, healthy, and naturally functioning ecosystems.

Key words: climate; fire deficit; fire departure; fire exclusion; fire occurrence; fire suppression; fire surplus; invasive species; protected areas; wilderness; wildland fire.

Received 20 May 2015; revised 29 July 2015; accepted 10 August 2015; **published** 15 December 2015. Corresponding Editor: F. Biondi.

Copyright: © 2015 Parks et al. This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited. <http://creativecommons.org/licenses/by/3.0/>

† **E-mail:** sean_parks@fs.fed.us

INTRODUCTION

The arrival of Euro-American settlers in the late-1800s disrupted the natural ecological role of fire in the western US (Keane et al. 2002), thereby resulting in departures in fire activity compared to earlier periods (Safford and Van de Water

2014). These departures in fire activity have been directly linked to a decoupling of the relationship between climate and fire, which, prior to Euro-American settlement, was fairly strong (Marlon et al. 2012). Consequently, many fire-prone ecosystems in the western US have experienced a reduction in fire activity since Euro-American

settlement compared to earlier periods (e.g., Mallek et al. 2013). Such decreases in fire activity have been attributed to human activities such as fire suppression, livestock grazing, logging, land-type conversion (e.g., to agriculture), and other anthropogenic influences (e.g., roads; Savage and Swetnam 1990, Heyerdahl et al. 2001, Allen et al. 2002, Marlon et al. 2008). Conversely, *increases* in fire activity have also been documented in certain ecosystems or localized areas due to factors such as invasive species that facilitate fire ignition and spread as well as high rates of human-caused ignitions (D'Antonio and Vitousek 1992, Syphard et al. 2007, Balch et al. 2013). Although many of these studies definitively demonstrated that fire activity today is much different in the western US compared to historical conditions (e.g., pre Euro-American settlement), some have questioned the relevance of a past time period in defining reference conditions given that contemporary climate change is altering the biophysical environment (Harris et al. 2006).

At broad spatial scales, climate clearly influences fire activity, although the temporal resolution of analysis can result in different interpretations (Parisien et al. 2014). For example, fire activity has been shown to strongly correlate with climatic normals (e.g., 30 year averages; hereafter “climate;” Krawchuk et al. 2009, Parisien et al. 2011, Moritz et al. 2012). This is likely an indirect influence on fuel conditions via climate's effect on productivity, moisture, and dominant vegetation type (Krawchuk and Moritz 2011, Pausas and Ribeiro 2013, Parks et al. 2014). This climatic effect is in contrast to inter-annual *climatic variability* that also influences fire activity, whereby warm and dry years generally correspond to increased fire activity (Westerling et al. 2006, Heyerdahl et al. 2008, Littell et al. 2009). We suggest that, because climate (i.e., climatic normals) is a strong top-down control on fire activity (although it may be an indirect control), a natural level of fire activity can be defined as that which emerges from the climate. As such, the “expected” amount of fire can be statistically modeled as a function of climate. Indeed, this rationale is often invoked in studies evaluating the effect of climate change on future fire activity (Krawchuk et al. 2009, Moritz et al. 2012, Batllori et al. 2013). This rationale also allows for an evaluation of contemporary departures in fire

activity by comparing the expected and observed area burned. Where observed fire activity is less than expected, the result is a “fire deficit” because there is less fire than the climate dictates (Marlon et al. 2012). Where observed fire activity is greater than expected, the result is a “fire surplus.”

Because ecosystems with disrupted fire regimes are thought to be less resilient to environmental change (Millar et al. 2007), land managers often cite the need to restore wildland fire as a natural disturbance (NWCG 2001). To accomplish this, land managers need to better understand current departures from natural levels of fire activity, especially considering that restoring wildland fire necessitates that our communities learn to co-exist with fire (Moritz et al. 2014). However, quantifying natural levels of fire activity is challenging for two reasons. First, as climate changes, the natural level of fire activity is a moving target. Second, human activities continue to alter fire regimes (as previously described). Fortunately, protected areas and other lands with little anthropogenic impact can provide a benchmark for quantifying natural levels of fire activity as a function of climate. For example, Parks et al. (2014) found that the relationship between climate and fire activity was reasonably strong in the western US when models were built using samples primarily comprised of protected areas; the relationship was weak when models were built using samples irrespective of the protected area composition (Appendix A). Archibald et al. (2010) had a similar finding in their study of fire and climate variability in southern Africa. A comparison of expected (according to the natural benchmark) to observed fire activity then allows for a formal evaluation of fire deficit and surplus for lands of all management designations.

We sought to quantify departures from contemporary natural levels of expected fire activity and identify areas of fire deficit and surplus in the western US for the 1984–2012 time period. This was achieved by developing a boosted regression tree (BRT) model to predict area burned as a function of several climatic variables for 500 km² hexagonal polygons (hereafter “hexels”). The model was built using fire and climate data from a subset of hexels in the western US having substantial area in a protected

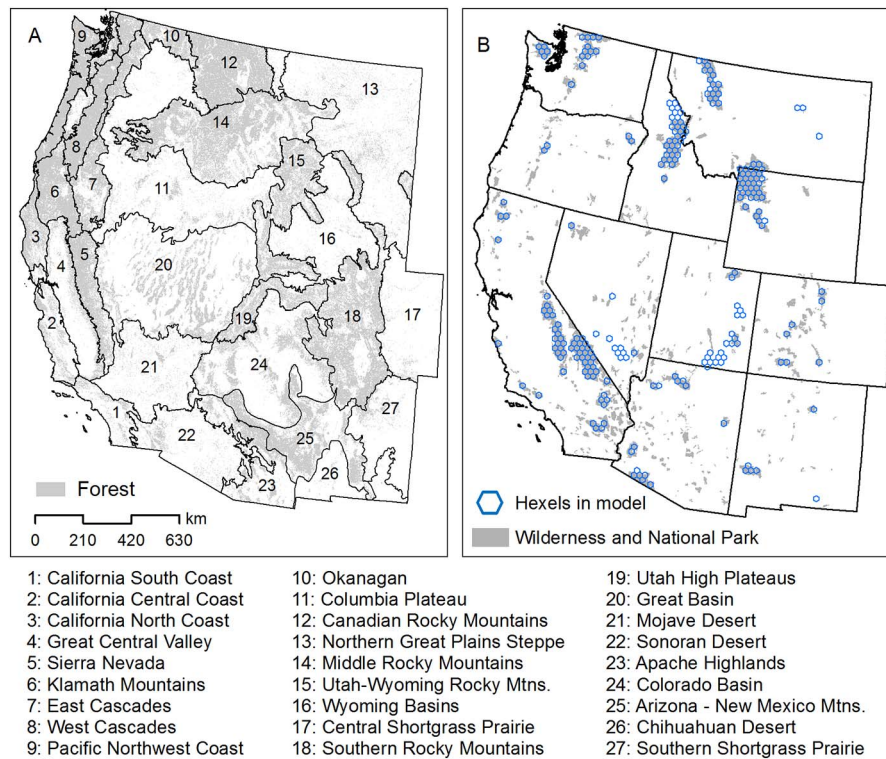


Fig. 1. Study area of the western US for which we quantify departures in expected area burned. Map showing forested areas and ecoregion boundaries (A) and showing designated wilderness areas and national parks as well as the hexels we used to build the model of area burned (B).

status (e.g., wilderness and parks) or otherwise having a low anthropogenic influence. These hexels serve as a natural benchmark (e.g., Appendix A) and are representative of a broad gradient in climate (Appendix B) and include ecosystems such as desert, dry conifer forest, and cold conifer forest. We then quantified the degree of fire deficit or surplus as the difference between expected (as predicted with the BRT model) and observed area burned from 1984 to 2012 for all hexels in the western US and provided ecoregional summaries. Our study is relevant to the contemporary time period (i.e., 1984–2012) and does not reflect prior time periods in which the climate was different or indigenous burning was common.

METHODS

We quantified departures in expected area burned from 1984 to 2012 for each 500 km² hexagonal polygon (i.e., “hexels”) in the western

US (Fig. 1). We chose this hexel size based on previous work (Parks et al. 2014), although we acknowledge that the resolution of analysis may influence the relationship between fire and its environment (Parisien et al. 2011, Parks et al. 2011). We built a model of area burned as a function of climate and then used model results to quantify fire departures.

We selected a subset of hexels with low human influence to build the model because the relationship between climate and fire is reasonably strong in areas of low human impact but weakens as anthropogenic influences increase (Archibald et al. 2009, Parks et al. 2014; Appendix A). Consequently, areas of low human impact act as “controls” and therefore characterize the expected relationship between fire and climate where human activities not an overarching influence. We selected hexels comprised of at least 75% designated wilderness and national park or had an average “human footprint” (HFP; Leu et al. 2008) ≤ 1.5 (on a scale of 1–10). We also

Table 1. Climatic variables evaluated as independent variables in the statistical model describing area burned. Only those that had a correlation coefficient <0.9 (bold) to each other were included in the final model ($n = 5$). The coefficient of variation (among years) of the five selected variables were also included in the statistical model for a total of 10 variables. These variables represent climatic conditions from 1984 to 2012.

Variable abbreviation	Description	Units
AET	Actual evapotranspiration (annual average)	mm/year
DMC†	Duff moisture code (annual average)	dimensionless
ERC‡	Energy release component (annual average)	dimensionless
PRECIP	Precipitation (annual average)	mm/year
SWE	Snow water equivalent (monthly average)	mm/month
SMO	Soil moisture (monthly average)	mm/month
TEMP	Temperature (annual average)	°C
VPD	Vapor pressure deficit (monthly average)	kPa
WD	Water deficit (annual average)	mm/year

† ERC is a fire danger index in the National Fire Danger Rating System (NFDRS; Cohen and Deeming 1985).

‡ DMC is a fire danger index in the Canadian Forest Fire Danger Rating System (CFFDRS; van Wagner 1987).

excluded hexels with more than 50% nonfuel (e.g., open water and barren). These selection criteria resulted in 235 hexels for which we built the model of area burned (Fig. 1). Despite representing only a small proportion of the western US (~4%), the hexels span broad climatic gradients ranging from warm deserts to cold forests (Appendix B). Although human-ignited fires may blur the relationship between climate and fire, only about 8% of the area burned from this subset of hexels was due to such fires (for the years 1992–2012; Short 2014).

Area burned (ha) was calculated within each hexel using a fire atlas covering all fires ≥ 400 ha from 1984 to 2012 (Eidenshink et al. 2007). Area burned was adjusted to account for unburnable areas (e.g., open water) within each hexel by dividing area burned by the proportion of the hexel that was composed of burnable fuel types (Rollins 2009). Several climatic variables known to influence fire activity were evaluated for inclusion into the model as independent variables (e.g., Littell and Gwozdz 2011, Abatzoglou and Kolden 2013, Parks et al. 2014; Table 1). Gridded monthly temperature and precipitation data were obtained from the parameter-elevation regression on independent slopes model (PRISM; Daly et al. 2002) that uses station data and physiographic factors to map climate at a spatial resolution of ~800 m. Abatzoglou (2013) combined monthly data from PRISM and hourly estimates from coarser scale analyses from the North American Land Data Assimilation System Phase 2 (NLDAS-2; Mitchell et al. 2004) to produce daily and sub-daily surface meteorolog-

ical variables at a ~4-km resolution that captures temperature, humidity, winds, solar radiation, and precipitation, which were subsequently used to estimate the energy release component (ERC; Cohen and Deeming 1985), duff moisture code (DMC; van Wagner 1987), and reference evapotranspiration. These data were collectively used to run the climatic water balance model following Dobrowski et al. (2013) to estimate monthly actual evapotranspiration (AET), snow water equivalent (SWE), soil moisture (SMO), and water deficit (WD). This model operates on a monthly time-step and accounts for atmospheric demand (via the Penman-Monteith equation), soil water storage, and includes the effect of temperature and radiation on snow hydrology via a snow melt model. All variables were characterized by averaging or summing monthly values over each year, then averaging the values over 1984–2012, and finally, averaging within each hexel. Those variables with a correlation coefficient of ≥ 0.9 (for the 235 hexels used to build the model) were excluded from the model (Table 1). For the five variables that met this correlation criterion, we also included in the model variables representing inter-annual variability (coefficient of variation).

We built our model of area burned as a function of climate using boosted regression trees (BRT) within the R statistical program (R Development Core Team 2007; “gbm” package). BRT is a machine-learning approach that does not require a priori model specification (De’ath 2007). We square-root-transformed area burned to homogenize variance in model residuals and

used a Poisson distribution. We followed the recommendations of Elith et al. (2008) for selecting BRT options; we set the bagging fraction to 0.5, learning rate to 0.0025, and tree complexity to 5. We used a custom script from Elith et al. (2008) to determine the necessary number of trees, thereby reducing the potential for overfitting the model. We evaluated model fit using 10-fold cross-validated correlation between predicted and observed values of area burned.

We quantified departures in expected area burned for each hexel in the western US by subtracting predicted from observed area burned for the 1984–2012 time period; negative values indicate less area burned than expected (i.e., a fire deficit), and positive values indicate more area burned (i.e., a fire surplus). We “clamped” predicted area burned to the maximum value in the training hexels to avoid predicting outside of the observed range of area burned. We summarized deficits and surpluses, as well as the expected and observed fire rotation, for each ecoregion (Olsen and Dinerstein 2002; Fig. 1); results for ecoregions with minimal overlap with the study area are not shown (e.g., Black Hills). Hexels on the edge of study area boundary are omitted from the ecoregional summaries if >50% of its area overlaps with the ocean, Mexico, Canada, or areas east of the study area. Hexels are defined as unburnable if $\geq 50\%$ is characterized as irrigated agriculture, barren, urban, or water (Rollins 2009) and are excluded from the ecoregional summaries.

RESULTS

The BRT performed well; the cross-validated correlation between predicted and observed area burned was 0.80 (see Appendix C for variable importance and response curves for selected variables). Departures from expected area burned from 1984 to 2012 were spatially heterogeneous across the western US (Fig. 2). Some ecoregions exhibited large fire deficits (e.g., California North Coast and Apache Highlands), others a fire surplus (e.g., California South Coast and Columbia Plateau), and others no substantial departure (e.g., West Cascades and Sonoran Desert; Fig. 2, Table 2). Most forested ecoregions experienced a fire deficit, with the notable exception of mesic forested ecoregions in the

Pacific Northwest, which showed no substantial departure from expected area burned. Large geographic expanses of fire surplus were apparent in some non-forested regions (e.g., the southern Columbia Plateau and northern Great Basin), although a fire deficit was observed in two non-forested ecoregions (i.e., Central Shortgrass Prairie and Southern Shortgrass Prairie; Fig. 2, Table 2).

DISCUSSION

Our results reveal a striking pattern of departures from expected area burned across the western US from 1984 to 2012. We found that fire deficits were more prevalent in forested ecoregions compared to non-forested ecoregions. In several non-forested ecoregions, large expanses of fire surplus were evident. The contrasting patterns of fire deficit and surplus between forested and non-forested ecoregions emphasize fundamentally different ecosystem sensitivities to human influences. However, there were also large expanses that experienced no substantial departure from expected area burned. Such areas generally corresponded to two types of ecosystems that typically experience little fire: very dry ecosystems that are biomass limited (i.e., warm and cold deserts that have not been invaded by annual grasses) and wet ecosystems (temperate rainforest) that are rarely conducive to burning (Krawchuk and Moritz 2011, Parks et al. 2014).

Most forested areas in the western US experienced a fire deficit from 1984 to 2012. These deficits strongly support the widespread notion that fire activity is reduced by human activities that exclude fire. Although our findings are only relevant to climate and fire over the 1984–2012 time period, they corroborate the findings of Marlon et al. (2012) and multiple fire history studies that indicated a sharp reduction in fire activity since the arrival of Euro-Americans, e.g., in the Sierra Nevada (Taylor 2000, Beaty and Taylor 2008), Klamath Mountains (Taylor and Skinner 2003), California North Coast (Stuart and Salazar 2000), East Cascades (Wright and Agee 2004), Southern Rocky Mountains (Grissino-Mayer et al. 2004), Middle Rocky Mountains (Heyerdahl et al. 2001), Canadian Rocky Mountains (Power et al. 2006), Utah High Plateaus (Stein 1988, Brown et al. 2008), Apache High-

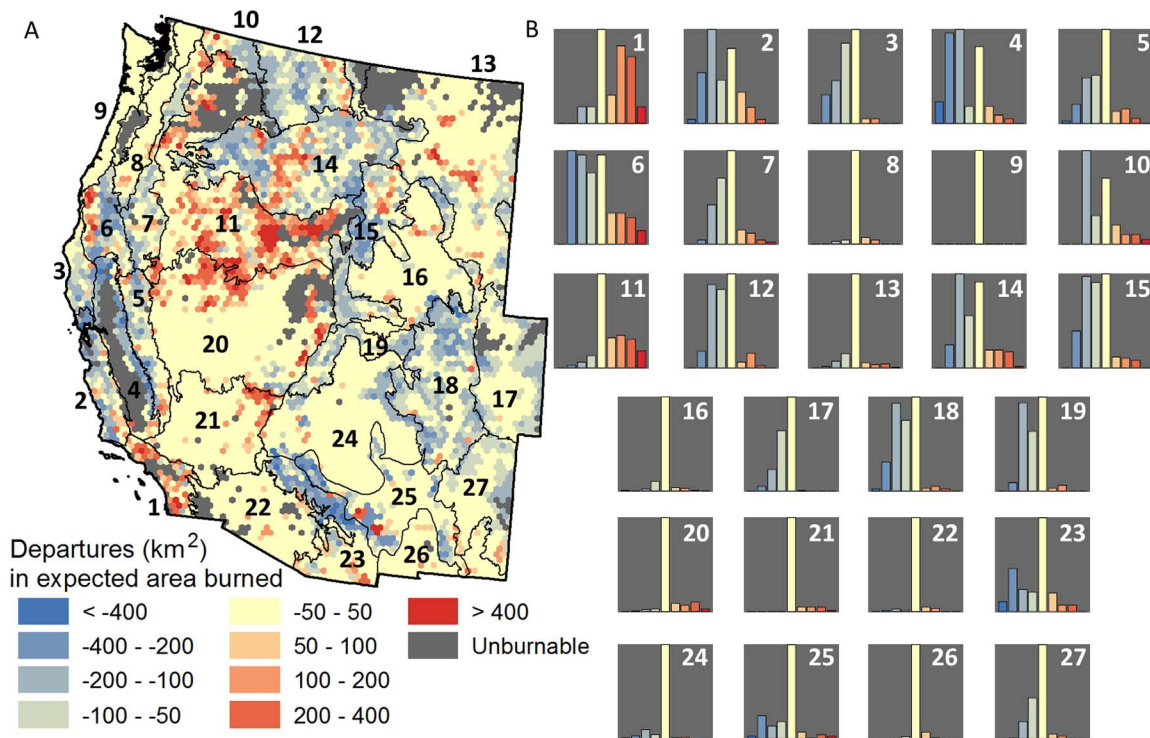


Fig. 2. Map depicting departures in expected area burned from 1984 to 2012 (A). Blue hexels represent less fire than expected (i.e., a fire deficit); red hexels represent more than expected (i.e., a fire surplus); yellow hexels indicate no substantial departure; dark gray hexels are unburnable. Histograms of each ecoregion (B) correspond to fire departure categories shown in the map legend (A).

lands (Baisan and Swetnam 1990), and Arizona-New Mexico Mountains (Swetnam and Dieterich 1985). Decreased fire activity has resulted in substantial changes to some forested ecosystems. For example, reduced rates of burning have resulted in altered species composition (i.e., increases in shade-tolerant species), increased tree density, and increased landscape homogeneity (Taylor 2000, Naficy et al. 2010, Fry et al. 2014, Stephens et al. 2015). A major concern of these site- and landscape-level ecosystem changes is the increased likelihood of uncharacteristically large and severe wildland fire in future years (Hessburg et al. 2005, Stephens 2005, Calkin et al. 2015). Although such fires may contribute to a reduction in the fire deficit, the uncharacteristic manner in which they burn can exceed ecological thresholds and result in conversion to non-forest types (Savage and Mast 2005). A few forested areas did not experience a fire deficit (i.e., Pacific Northwest Coast and West Cascades ecoregions), which is coherent with our

knowledge of the fire regime characteristics of these regions where fires are infrequent (fire return intervals of 200–1000 years; Agee 1993).

The pattern of fire surpluses and deficits in non-forested ecoregions is consistent with our knowledge of the impact of human activities on area burned. For example, in the Columbia Plateau and Great Basin ecoregions, the large expanse of fire surplus is likely the result of cheatgrass invasion (*Bromus tectorum*; Fig. 3; Knapp 1996, Bradley and Mustard 2008), a non-native annual grass that was introduced to North America during the 1800s that is known to increase fire activity (Knick and Rotenberry 1997, Balch et al. 2013). Similarly, the fire surplus in the Mojave Desert ecoregion is likely due to invasion by the annual grass red brome (*Bromus rubens*; Hunter 1991, Salo et al. 2005, Brooks and Matchett 2006), another grass introduced from Europe. In many of these affected areas, there is generally a positive feedback where fire facilitates invasive grass establishment, which in turn

Table 2. Ecoregional summary of fire departures in the western US†; values were summed across hexels within each ecoregion.

ID	Ecoregion name	Area (km ²)	Observed area burned (km ²)	Expected area burned (km ²)	Total fire departure (km ²)‡	Expected fire rotations§ (years)	Observed fire rotations§ (years)
1	California South Coast	28376	13256	6268	6987	131	62
2	California Central Coast	39505	7330	14269	-6939	80	156
3	California North Coast	27828	2798	7714	-4916	105	288
4	Great Central Valley	38340	4499	15905	-11406	70	247
5	Sierra Nevada	50000	7121	11793	-4672	123	204
6	Klamath Mountains	50144	10323	15541	-5218	94	141
7	East Cascades	65500	6095	10076	-3981	189	312
8	West Cascades	43000	1774	1992	-217	626	703
9	Pacific Northwest Coast	40177	137	1179	-1042	988	8505
10	Okanagan	24549	3308	5459	-2151	130	215
11	Columbia Plateau	234000	64668	15973	48695	425	105
12	Canadian Rocky Mountains	81230	5957	16871	-10914	140	395
13	Northern Great Plains Steppe	236458	14347	17922	-3575	383	478
14	Middle Rockies	210000	38255	59794	-21539	102	159
15	Utah-Wyoming Rocky Mountains	108500	12393	29836	-17444	105	254
16	Wyoming Basins	132000	3247	5856	-2609	654	1179
17	Central Shortgrass Prairie	108156	650	15094	-14445	208	4825
18	Southern Rocky Mountains	160000	5489	34228	-28739	136	845
19	Utah High Plateaus	45500	2685	9457	-6772	140	491
20	Great Basin	269000	31827	10853	20974	719	245
21	Mojave Desert	128500	8506	475	8031	7845	438
22	Sonoran Desert	101830	3023	2732	291	1081	977
23	Apache Highlands	83987	12359	26610	-14251	92	197
24	Colorado Plateau	197000	3505	12142	-8637	471	1630
25	Arizona-New Mexico Mountains	114572	13491	25820	-12329	129	246
26	Chihuahuan Desert	58407	1347	1221	127	1387	1257
27	Southern Shortgrass Prairie	94031	2761	11402	-8641	239	988

† Hexels are considered unburnable if $\geq 50\%$ is characterized as irrigated agriculture, barren, urban, or water and are excluded from all calculations.

‡ Negative values indicate a fire deficit and positive values a fire surplus.

§ Fire rotation is defined as the number of years necessary to burn an area the size of the ecoregion and for the 29 year record (1984–2012) is calculated as follows: $29/(\text{expected [or observed] area burned/area of the ecoregion})$.

increases fire frequency because the invading grass produces a continuous bed of flammable fine fuels (Brooks et al. 2004). Although the Sonoran Desert and Chihuahuan Desert ecoregions exhibited no substantial fire departure from 1984–2012, natural and climate-induced range expansions of invasive annual grasses could put them at risk in the future (Salo 2004, Abatzoglou and Kolden 2011). In addition to the effects from invasive and exotic plant species, the prevalence of human-caused ignitions are implicated in increased fire activity and the associated fire surplus found in the California South Coast ecoregion (Syphard et al. 2007, Keeley et al. 2011, Keeley and Brennan 2012). The fire deficits we found for the Central Shortgrass Prairie and Southern Shortgrass Prairie ecoregions are areas that naturally would support periodic fire, but fire suppression and grazing by domestic cattle has reduced fire activity in these areas (Axelrod 1985, Brockway et al. 2002).

Other studies that also evaluated potential departures in fire activity include Mallek et al. (2013), who used the results of numerous published dendrochronology studies to infer historical annual area burned for several forest types in the Sierra Nevada and made comparisons to contemporary rates of burning. Also, Ager et al. (2014) compared burn probability maps (generated with simulation models) to those of the Landfire “mean fire return interval” product (Rollins 2009) for National Forests in the western US to identify which pixels had higher or lower burn probabilities compared to presumed historical conditions. Similar to our findings, these studies found that contemporary fire activity in forested regions, for the most part, was less than that of the pre-European reference period. However, formal comparisons between our study and these previous studies are not appropriate due to differences in the reference period, spatial resolution, and spatial extent of

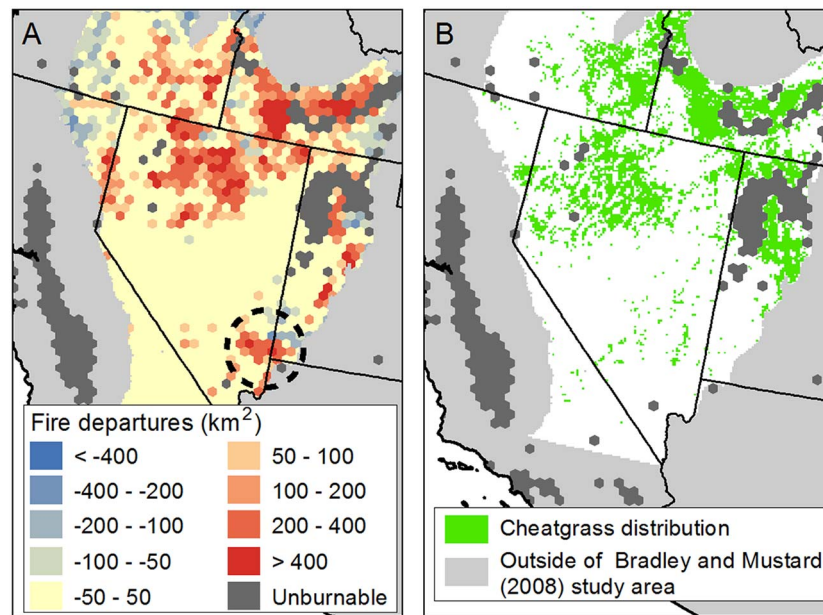


Fig. 3. Departures in expected area burned (km^2) within the Bradley and Mustard (2008) study area (A) and cheatgrass (*Bromus tectorum*) distribution according to Bradley and Mustard (2008) (B). Note the high spatial correspondence between fire surplus and cheatgrass distribution. The large expanse of fire surplus in southeastern Nevada (shown by the dashed circle) is likely due to a different invasive annual grass, red brome (*Bromus rubens*; Salo 2005).

analyses.

Multiple lines of evidence have attributed departures in fire activity between contemporary and historical (i.e., pre-Euro settlement) eras to human activities. Studies using both dendrochronology (i.e., cross-dated fire scar records; e.g., Heyerdahl et al. 2001, Mallek et al. 2013) and charcoal records (e.g., Colombaroli and Gavin 2010) have inferred that humans are at least partly responsible for reductions in rates of burning after about 1900. Our findings suggest that humans continue to influence fire activity today and show how this influence varies among ecosystems. As such, our approach to quantifying departures in fire activity complements earlier research and offers certain advantages. For example, because our model of expected area burned was built from a broad spatial extent, it incorporates all major ecosystems in the western US (e.g., shrub, forest, desert). Specifically, our method is not limited to tree-dominated ecosystems (cf. dendrochronology) or those that have permanent or ephemeral water bodies (cf. charcoal records). Furthermore, because we used

contemporary fire and climate data in our study, we defined a contemporary, climatically driven baseline for expected fire activity. As such, in quantifying departures in fire activity, we avoid the use of a past reference period in which climate and indigenous burning practices were quite different (Sheppard et al. 2002, Stephens et al. 2007).

Several factors should be considered when interpreting our results. We assume a space-for-time substitution in calibrating our model; the large sample domain ensures adequate sampling of fires and allows us to infer relationships between fire and climate. Nevertheless, the temporal window of our analysis (1984–2012) is relatively short for many ecosystems (Agee 1993). Consequently, we may not have adequately characterized departures from expected area burned in certain regions, especially in cool/wet forested areas that show an apparent fire surplus only because of large, infrequent fires (sensu Meyn et al. 2007) that have occurred during our study period (e.g., Yellowstone National Park in 1988). For this reason, it is inappropriate to focus

on any single hexel or small group of hexels to infer departures in expected fire activity. Instead, it is most appropriate to evaluate fire surplus and deficit over large geographical regions, which explains our rationale for providing ecoregional summaries (Fig. 2, Table 2). The temporal window we analyzed (i.e., 1984–2012) also coincides with increased fire activity compared to earlier decades (e.g., 1940–1970; Littell et al. 2009). Consequently, had we analyzed fire and climate data from a different time period, our results would certainly be different. Periodic updates to our model and map are clearly warranted to provide a longer-term perspective on departures in expected fire activity, especially given the heterogeneous nature of fire and that negative feedbacks associated with recurring fires will likely limit future burning in some areas (Héon et al. 2014, Parks et al. 2015). Lastly, our study relies heavily on data from protected areas, which, despite representing the majority of climates in the western US, admittedly do not represent the complete range of climatic conditions (Batllori et al. 2014). Nevertheless, the climatic variability encompassed in the data we used to build the model (Appendix B) translates into a broad range of ecosystem and vegetation types, for example, warm desert (Death Valley National Park [NP]), dry conifer forest (Gila Wilderness), and cold forest (Yellowstone NP). As such, we suggest that poorly represented climates have only a marginal effect on our results.

CONCLUSIONS

Previous studies conducted at a variety of temporal and spatial scales identified a sharp drop in fire activity with the arrival of Euro-American settlers in forest-dominated landscapes of the western US (e.g., Marlon et al. 2012, Mallek et al. 2013). Our study makes no comparisons to time periods and climates prior to 1984 but demonstrates that most forested regions continue to experience less fire than expected, or a fire deficit. Our study also demonstrates that some non-forested regions experienced more fire than expected, or a fire surplus, over the 1984–2012 time period. The findings of our study, as well as other efforts such as the Landfire “Vegetation departure” (Rollins 2009) product, suggest that

multiple large-scale adaptation and mitigation strategies will be necessary in order to restore and maintain resilient, healthy, and naturally functioning ecosystems (cf. Hessburg et al. 2015). For example, forested areas experiencing a fire deficit may be candidates for restoration treatments (e.g., mechanical fuel treatments, prescribed fire, wildland fire use) intended to promote resilience to future disturbances (Stephens and Ruth 2005, Millar et al. 2007). Conversely, areas experiencing a fire surplus may be indicative of highly altered and degraded ecosystems (Bradley and Mustard 2008, Brooks 2012) that are in need of restoration and ignition management (e.g., fire suppression and prevention). Protected areas and other areas with low anthropogenic influence served as a natural benchmark in which fire activity and climate are relatively tightly linked, and as such, are an invaluable data source for assessing perturbations to fire regimes across multiple ecosystem types.

ACKNOWLEDGMENTS

We thank two anonymous reviewers for thoughtful comments that significantly improved this manuscript. We acknowledge National Fire Plan funding from the Rocky Mountain Research Station.

LITERATURE CITED

- Abatzoglou, J. T. 2013. Development of gridded surface meteorological data for ecological applications and modelling. *International Journal of Climatology* 33:121–131.
- Abatzoglou, J. T., and C. A. Kolden. 2011. Climate change in western US deserts: potential for increased wildfire and invasive annual grasses. *Rangeland Ecology and Management* 64:471–478.
- Abatzoglou, J. T., and C. A. Kolden. 2013. Relationships between climate and macroscale area burned in the western United States. *International Journal of Wildland Fire* 22:1003–1020.
- Agee, J. K. 1993. *Fire ecology of Pacific Northwest forests*. Island Press, Washington, D.C., USA.
- Ager, A. A., M. A. Day, C. W. McHugh, K. Short, J. Gilbertson-Day, M. A. Finney, and D. E. Calkin. 2014. Wildfire exposure and fuel management on western US national forests. *Journal of Environmental Management* 145:54–70.
- Allen, C. D., M. Savage, D. A. Falk, K. F. Suckling, T. W. Swetnam, T. Schulke, P. B. Stacey, P. Morgan, M. Hoffman, and J. T. Klingel. 2002. Ecological

- restoration of Southwestern ponderosa pine ecosystems: a broad perspective. *Ecological Applications* 12:1418–1433.
- Archibald, S., A. Nickless, N. Govender, R. J. Scholes, and V. Lehsten. 2010. Climate and the inter-annual variability of fire in southern Africa: a meta-analysis using long-term field data and satellite-derived burnt area data. *Global Ecology and Biogeography* 19:794–809.
- Archibald, S., D. P. Roy, B. W. van Wilgen, and R. J. Scholes. 2009. What limits fire? An examination of drivers of burnt area in Southern Africa. *Global Change Biology* 15:613–630.
- Axelrod, D. I. 1985. Rise of the grassland biome, central North America. *Botanical Review* 51:163–201.
- Baisan, C. H., and T. W. Swetnam. 1990. Fire history on a desert mountain range: Rincon Mountain Wilderness, Arizona, USA. *Canadian Journal of Forest Research* 20:1559–1569.
- Balch, J. K., B. A. Bradley, C. M. D'Antonio, and J. Gomez-Dans. 2013. Introduced annual grass increases regional fire activity across the arid western USA (1980-2009). *Global Change Biology* 19:173–183.
- Batliori, E., C. Miller, M.-A. Parisien, S. A. Parks, and M. A. Moritz. 2014. Is U.S. climatic diversity well represented within the existing federal protection network? *Ecological Applications* 24:1898–1907.
- Batliori, E., M. A. Parisien, M. A. Krawchuk, and M. A. Moritz. 2013. Climate change-induced shifts in fire for Mediterranean ecosystems. *Global Ecology and Biogeography* 22:1118–1129.
- Beaty, R. M., and A. H. Taylor. 2008. Fire history and the structure and dynamics of a mixed conifer forest landscape in the northern Sierra Nevada, Lake Tahoe Basin, California, USA. *Forest Ecology and Management* 255:707–719.
- Bradley, B. A., and J. F. Mustard. 2008. Comparison of phenology trends by land cover class: a case study in the Great Basin, USA. *Global Change Biology* 14:334–346.
- Brockway, D. G., R. G. Gatewood, and R. B. Paris. 2002. Restoring fire as an ecological process in shortgrass prairie ecosystems: initial effects of prescribed burning during the dormant and growing seasons. *Journal of Environmental Management* 65:135–152.
- Brooks, M. L. 2012. Effects of high fire frequency in creosote bush scrub vegetation of the Mojave Desert. *International Journal of Wildland Fire* 21:61–68.
- Brooks, M. L., C. M. D'Antonio, D. M. Richardson, J. B. Grace, J. E. Keeley, J. M. DiTomaso, R. J. Hobbs, M. Pellant, and D. Pyke. 2004. Effects of invasive alien plants on fire regimes. *BioScience* 54:677–688.
- Brooks, M. L., and J. R. Matchett. 2006. Spatial and temporal patterns of wildfires in the Mojave Desert, 1980-2004. *Journal of Arid Environments* 67:148–164.
- Brown, P. M., E. K. Heyerdahl, S. G. Kitchen, and M. H. Weber. 2008. Climate effects on historical fires (1630-1900) in Utah. *International Journal of Wildland Fire* 17:28–39.
- Calkin, D. E., M. P. Thompson, and M. A. Finney. 2015. Negative consequences of positive feedbacks in US wildfire management. *Forest Ecosystems* 2:1–10.
- Cohen, J. D., and J. E. Deeming. 1985. The national fire danger rating system: basic equations. GTR-PSW-82. USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, California, USA.
- Colombaroli, D., and D. G. Gavin. 2010. Highly episodic fire and erosion regime over the past 2,000 y in the Siskiyou Mountains, Oregon. *Proceedings of the National Academy of Sciences USA* 107:18909–18914.
- Daly, C., W. P. Gibson, G. H. Taylor, G. L. Johnson, and P. Pasteris. 2002. A knowledge-based approach to the statistical mapping of climate. *Climate Research* 22:99–113.
- D'Antonio, C. M., and P. M. Vitousek. 1992. Biological invasions by exotic grasses, the grass fire cycle, and global change. *Annual Review of Ecology and Systematics* 23:63–87.
- De'ath, G. 2007. Boosted trees for ecological modeling and prediction. *Ecology* 88:243–251.
- Dobrowski, S. Z., J. Abatzoglou, A. K. Swanson, J. A. Greenberg, A. R. Mynsberge, Z. A. Holden, and M. K. Schwartz. 2013. The climate velocity of the contiguous United States during the 20th century. *Global Change Biology* 19:241–251.
- Eidenshink, J., B. Schwind, K. Brewer, Z. L. Zhu, B. Quayle, and S. Howard. 2007. A project for monitoring trends in burn severity. *Fire Ecology* 3:3–21.
- Elith, J., J. R. Leathwick, and T. Hastie. 2008. A working guide to boosted regression trees. *Journal of Animal Ecology* 77:802–813.
- Fry, D. L., S. L. Stephens, B. M. Collins, M. P. North, E. Franco-Vizcaino, and S. J. Gill. 2014. Contrasting spatial patterns in active-fire and fire-suppressed Mediterranean climate old-growth mixed conifer forests. *PLoS ONE* 9(2):e88985.
- Grissino-Mayer, H. D., W. H. Romme, M. L. Floyd, and D. D. Hanna. 2004. Climatic and human influences on fire regimes of the southern San Juan Mountains, Colorado, USA. *Ecology* 85:1708–1724.
- Harris, J. A., R. J. Hobbs, E. Higgs, and J. Aronson. 2006. Ecological restoration and global climate change. *Restoration Ecology* 14:170–176.
- Héon, J., D. Arseneault, and M.-A. Parisien. 2014. Resistance of the boreal forest to high burn rates. *Proceedings of the National Academy of Sciences*

- USA 111:13888–13893.
- Hessburg, P. F., J. K. Agee, and J. F. Franklin. 2005. Dry forests and wildland fires of the inland Northwest USA: contrasting the landscape ecology of the pre-settlement and modern eras. *Forest Ecology and Management* 211:117–139.
- Hessburg, P. F., et al. 2015. Restoring fire-prone Inland Pacific landscapes: seven core principles. *Landscape Ecology* 30: 1805–1835.
- Heyerdahl, E. K., L. B. Brubaker, and J. K. Agee. 2001. Spatial controls of historical fire regimes: a multi-scale example from the interior west, USA. *Ecology* 82:660–678.
- Heyerdahl, E. K., P. Morgan, and J. P. Riser. 2008. Multi-season climate synchronized historical fires in dry forests (1650-1900), northern Rockies, USA. *Ecology* 89:705–716.
- Hunter, R. 1991. *Bromus* invasions on the Nevada Test Site: present status of *B. rubens* and *B. tectorum* with notes on their relationship to disturbance and altitude. *Great Basin Naturalist* 51:176–182.
- Keane, R. E., K. C. Ryan, T. T. Veblen, C. D. Allen, J. A. Logan, and B. Hawkes. 2002. The cascading effects of fire exclusion in Rocky Mountain ecosystems. Pages 133–521 in J. S. Baron, editor. *Rocky Mountain futures: an ecological perspective*. Island Press, Washington, D.C., USA.
- Keeley, J. E., and T. J. Brennan. 2012. Fire-driven alien invasion in a fire-adapted ecosystem. *Oecologia* 169:1043–1052.
- Keeley, J. E., J. Franklin, and C. D'Antonio. 2011. Fire and invasive plants in California Landscapes. Pages 193–222 in D. McKenzie, C. Miller, and D. A. Falk, editors. *The landscape ecology of fire*. Springer, Amsterdam, The Netherlands.
- Knapp, P. A. 1996. Cheatgrass (*Bromus tectorum* L) dominance in the Great Basin Desert: history, persistence, and influences to human activities. *Global Environmental Change, Human and Policy Dimensions* 6:37–52.
- Knick, S. T., and J. T. Rotenberry. 1997. Landscape characteristics of disturbed shrubsteppe habitats in southwestern Idaho (USA). *Landscape Ecology* 12:287–297.
- Krawchuk, M. A., and M. A. Moritz. 2011. Constraints on global fire activity vary across a resource gradient. *Ecology* 92:121–132.
- Krawchuk, M. A., M. A. Moritz, M.-A. Parisien, J. Van Dorn, and K. Hayhoe. 2009. Global pyrogeography: the current and future distribution of wildfire. *PloS ONE* 4:e5102.
- Leu, M., S. E. Hanser, and S. T. Knick. 2008. The human footprint in the west: a large-scale analysis of anthropogenic impacts. *Ecological Applications* 18:1119–1139.
- Littell, J. S., and R. B. Gwozdz. 2011. Climatic water balance in regional fire years in the Pacific Northwest, USA: linking regional climate and fire and at landscape scales. Pages 177–139 in D. McKenzie, C. Miller, and D. A. Falk, editors. *The landscape ecology of fire*. Springer, Amsterdam, The Netherlands.
- 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. *Ecological Applications* 19:1003–1021.
- Mallek, C., H. Safford, J. Viers, and J. Miller. 2013. Modern departures in fire severity and area vary by forest type, Sierra Nevada and southern Cascades, California, USA. *Ecosphere* 4:art153.
- Marlon, J. R., P. J. Bartlein, C. Carcaillet, D. G. Gavin, S. P. Harrison, P. E. Higuera, F. Joos, M. J. Power, and I. C. Prentice. 2008. Climate and human influences on global biomass burning over the past two millennia. *Nature Geoscience* 1:697–702.
- Marlon, J. R., et al. 2012. Long-term perspective on wildfires in the western USA. *Proceedings of the National Academy of Science USA* 109:E535–E543.
- Meyn, A., P. S. White, C. Buhk, and A. Jentsch. 2007. Environmental drivers of large, infrequent wildfires: the emerging conceptual model. *Progress in Physical Geography* 31:287–312.
- Millar, C. I., N. L. Stephenson, and S. L. Stephens. 2007. Climate change and forests of the future: managing in the face of uncertainty. *Ecological Applications* 17:2145–2151.
- Mitchell, K. E., et al. 2004. The multi-institution North American Land Data Assimilation System (NLDAS): utilizing multiple GCIP products and partners in a continental distributed hydrological modeling system. *Journal of Geophysical Research, Atmospheres* 109:D07S90.
- Moritz, M. A., et al. 2014. Learning to coexist with wildfire. *Nature* 515:58–66.
- 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:art49.
- Naficy, C., A. Sala, E. G. Keeling, J. Graham, and T. H. DeLuca. 2010. Interactive effects of historical logging and fire exclusion on ponderosa pine forest structure in the northern Rockies. *Ecological Applications* 20:1851–1864.
- NWCG [National Wildfire Coordinating Group]. 2001. Review and update of the 1995 federal wildland fire management policy. National Wildfire Coordinating Group, Interagency Fire Center, Boise, Idaho, USA.
- Olsen, D. M., and E. Dinerstein. 2002. The global 200: priority ecoregions for global conservation. *Annals of the Missouri Botanical Garden* 89(2):199–224.
- Parisien, M.-A., S. A. Parks, M. A. Krawchuk, M. D.

- Flannigan, L. M. Bowman, and M. A. Moritz. 2011. Scale-dependent controls on the area burned in the boreal forest of Canada, 1980-2005. *Ecological Applications* 21:789–805.
- Parisien, M.-A., S. A. Parks, M. A. Krawchuk, J. M. Little, M. D. Flannigan, L. M. Gowman, and M. A. Moritz. 2014. An analysis of controls on fire activity in boreal Canada: comparing models built with different temporal resolutions. *Ecological Applications* 24:1341–1356.
- Parks, S. A., L. M. Holsinger, C. Miller, and C. R. Nelson. 2015. Wildland fire as a self-regulating mechanism: the role of previous burns and weather in limiting fire progression. *Ecological Applications* 25:1478–1492.
- Parks, S. A., M.-A. Parisien, and C. Miller. 2011. Multi-scale evaluation of the environmental controls on burn probability in a southern Sierra Nevada landscape. *International Journal of Wildland Fire* 20:815–828.
- Parks, S. A., M.-A. Parisien, C. Miller, and S. Z. Dobrowski. 2014. Fire activity and severity in the western US vary along proxy gradients representing fuel amount and fuel moisture. *PLoS ONE* 9:e99699.
- Pausas, J. G., and E. Ribeiro. 2013. The global fire productivity relationship. *Global Ecology and Biogeography* 22:728–736.
- Power, M. J., C. Whitlock, P. Bartlein, and L. R. Stevens. 2006. Fire and vegetation history during the last 3800 years in northwestern Montana. *Geomorphology* 75:420–436.
- R Development Core Team. 2007. R: a language and environment for statistical computing. R Foundation for Computing, Vienna, Austria.
- Rollins, M. G. 2009. LANDFIRE: a nationally consistent vegetation, wildland fire, and fuel assessment. *International Journal of Wildland Fire* 18:235–249.
- Safford, H. D., and K. P. Van de Water. 2014. Using fire return interval departure (FRID) analysis to map spatial and temporal changes in fire frequency on National Forest lands in California. Research Paper PSW-RP-266. USDA Forest Service, Pacific Southwest Research Station, Albany, California, USA.
- Salo, L. F. 2004. Population dynamics of red brome (*Bromus madritensis* subsp. *rubens*): times for concern, opportunities for management. *Journal of Arid Environments* 57:291–296.
- Salo, L. F. 2005. Red brome (*Bromus rubens* subsp. *madritensis*) in North America: possible modes for early introductions, subsequent spread. *Biological Invasions* 7:165–180.
- Salo, L. F., G. R. McPherson, and D. G. Williams. 2005. Sonoran desert winter annuals affected by density of red brome and soil nitrogen. *American Midland Naturalist* 153:95–109.
- Savage, M., and J. N. Mast. 2005. How resilient are southwestern ponderosa pine forests after crown fires? *Canadian Journal of Forest Research* 35:967–977.
- Savage, M., and T. W. Swetnam. 1990. Early 19th-century fire decline following sheep pasturing in a Navajo ponderosa pine forest. *Ecology* 71:2374–2378.
- Sheppard, P. R., A. C. Comrie, G. D. Packin, K. Angersbach, and M. K. Hughes. 2002. The climate of the US Southwest. *Climate Research* 21:219–238.
- Short, K. C. 2014. A spatial database of wildfires in the United States, 1992-2011. *Earth System Science Data* 6:1–27.
- Stein, S. J. 1988. Fire history of the Paunsaugunt plateau in southern Utah. *Great Basin Naturalist* 48:58–63.
- Stephens, S. L. 2005. Forest fire causes and extent on United States Forest Service lands. *International Journal of Wildland Fire* 14:213–222.
- Stephens, S. L., J. M. Lydersen, B. M. Collins, D. L. Fry, and M. D. Meyer. 2015. Historical and current landscape-scale ponderosa pine and mixed conifer forest structure in the Southern Sierra Nevada. *Ecosphere* 6:79.
- Stephens, S. L., R. E. Martin, and N. E. Clinton. 2007. Prehistoric fire area and emissions from California's forests, woodlands, shrublands, and grasslands. *Forest Ecology and Management* 251:205–216.
- Stephens, S. L., and L. W. Ruth. 2005. Federal forest-fire policy in the United States. *Ecological Applications* 15:532–542.
- Stuart, J. D., and L. A. Salazar. 2000. Fire history of white fir forests in the coastal mountains of northwestern California. *Northwest Science* 74:280–285.
- Swetnam, T. W., and J. H. Dieterich. 1985. Fire history of ponderosa pine forests in the Gila Wilderness, New Mexico. Pages 390–397 in J. E. Lotan, B. M. Kilgore, W. C. Fischer, and R. W. Mutch, editors. *Proceedings of the Symposium and Workshop on Wilderness Fire*. USDA Forest Service, Ogden, Utah, USA.
- 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. *Ecological Applications* 17:1388–1402.
- Taylor, A. H. 2000. Fire regimes and forest changes in mid and upper montane forests of the southern Cascades, Lassen Volcanic National Park, California, USA. *Journal of Biogeography* 27:87–104.
- Taylor, A. H. and C. N. Skinner. 2003. Spatial patterns and controls on historical fire regimes and forest structure in the Klamath Mountains. *Ecological Applications* 13:704–719.
- van Wagner, C. E. 1987. Development and structure of

- the Canadian forest fire weather index system. Forest Technical Report 35:37. Canadian Forest Service, Ontario, Canada.
- Westerling, A. L., H. G. Hidalgo, D. R. Cayan, and T. W. Swetnam. 2006. Warming and earlier spring increase western US forest wildfire activity. *Science* 313:940–943.
- Wright, C. S., and J. K. Agee. 2004. Fire and vegetation history in the eastern Cascade Mountains, Washington. *Ecological Applications* 14:443–459.

SUPPLEMENTAL MATERIAL

ECOLOGICAL ARCHIVES

Appendices A–C are available online: <http://dx.doi.org/10.1890/ES15-00294.1.sm>