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Different fire–climate relationships on forested and non-forested landscapes in the Sierra Nevada ecoregion

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Abstract. In the California Sierra Nevada region, increased fire activity over the last 50 years has only occurred in the higher-elevation forests on US Forest Service (USFS) lands, and is not characteristic of the lower-elevation grasslands, woodlands and shrublands on state responsibility lands (Cal Fire). Increased fire activity on USFS lands was correlated with warmer and drier springs. Although this is consistent with recent global warming, we found an equally strong relationship between fire activity and climate in the first half of the 20th century. At lower elevations, warmer and drier conditions were not strongly tied to fire activity over the last 90 years, although prior-year precipitation was significant. It is hypothesised that the fire–climate relationship in forests is determined by climatic effects on spring and summer fuel moisture, with hotter and drier springs leading to a longer fire season and more extensive burning. In contrast, future fire activity in the foothills may be more dependent on rainfall patterns and their effect on the herbaceous fuel load. We predict spring and summer warming will have a significant impact on future fire regimes, primarily in higher-elevation forests. Lower elevation ecosystems are likely to be affected as much by global changes that directly involve land-use patterns as by climate change.

Additional keywords: area burned, chaparral, climate change, non-forested ecosystems, spring temperature, snow pack.

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Introduction

Wildfire activity and fire severity have increased in many western USA forests over the past several decades, and these changes are widely attributed to a combination of climate change and past fire suppression (McKenzie *et al.* 2004; Westerling *et al.* 2006; Littell *et al.* 2009; Miller *et al.* 2009). However, despite the generalisations that fire activity is increasing across the western US, these patterns are not universal and some non-forested landscapes have not experienced recent increases in fire activity (Baker 2013). As the bulk of the western USA landscape comprises non-forested ecosystems, and the relationship between climate and fire activity has not been as thoroughly studied for these ecosystems, we investigated temporal patterns of fire activity on forested and non-forested landscapes and the role of annual variation in seasonal temperatures and precipitation.

Historical relationships between fire and climate are one of the few tools we have for understanding future climate change impacts on fire regimes (McKenzie *et al.* 2004; Safford *et al.* 2012). Western landscapes are highly heterogeneous with varying histories of human impacts (Parisien *et al.* 2012) and with very different fire–climate relationships from one region to the next (McKenzie *et al.* 2004; Gedalof *et al.* 2005; Collins *et al.* 2006; Littell *et al.* 2009); thus, one way to parse out climate from other influences is by narrowing the focus to a single region. The Sierra Nevada ecoregion is a good focal point because of its immense importance to California water supply, recreation, forestry and ecosystem conservation (SNEP 1996). This region represents many of the issues in understanding future fire regimes as it includes both high-elevation coniferous forests and low-elevation mixed vegetation on landscapes more heavily influenced by human interference. More importantly, a greater proportion of California burns annually than other parts of North America (Stephens 2005; Keeley *et al.* 2009), and the state has a very long, well-documented fire history for both forested and non-forested landscapes (see Methods).

Here, we examine a 101-year fire record on US Forest Service (USFS) lands and a 92-year record on California Department of Forestry and Fire Protection (Cal Fire) lands in the Sierra Nevada mountains, foothills and adjacent valleys (Fig. 1) for long-term trends in area burned and the relationship between annual fire activity and seasonal climate.

Methods

To stay within a climatically homogeneous area, we restricted our analysis to National Oceanographic and Atmospheric

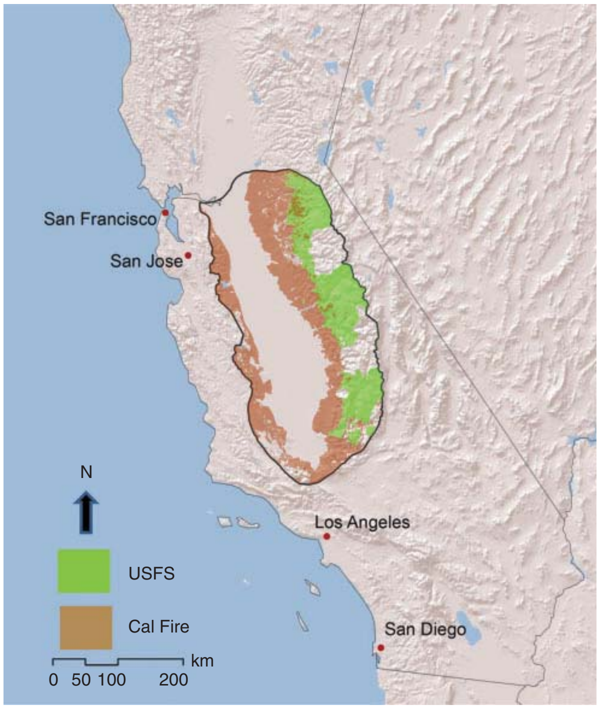

Fig. 1. California's Sierra Nevada National Oceanographic and Atmospheric Administration (NOAA) climate Division 5 with Cal Fire lands (brown) and US Forest Service (FS) lands (green) indicated. A portion of Cal Fire lands is distributed on the western sides of counties that fall outside of the Sierra Nevada ecoregion. The historical fire database does not allow these lands to be separated out; however, they represent a minor portion of Cal Fire fire activity and are climatically very similar to the eastern portion of these counties (see Abatzoglou *et al.* 2009).

Administration's (NOAA's) National Climatic Data Center (NCDC) California Climate Division 5 (http://www.ncdc.noaa.gov/temp-and-precip/time-series/index.php?parameter=pdsi&month=1&year=2008&filter=p12&state=4&div=5, verified 6 November 2014). This did not include the far northern portion of what is often included in the Sierra Nevada Mountains. California Climate Division 5 has been discussed more fully by Abatzoglou *et al.* (2009), who noted very strong correlations between low- and moderate-elevation sites; however, winter temperatures in the valleys were markedly affected by persistent winter inversion layers. As described in more detail below, we have accounted for these differences by using separate PRISM data for the montane USFS lands and the valley and foothill Cal Fire landscapes. The USFS and Cal Fire lands used in this study are illustrated in Fig. 1. This landscape comprises more than 3 million ha of largely coniferous forested USFS lands (average elevation 2200 m) and approximately equivalent-size lower-elevation (average 500 m) Cal Fire lands of grasslands, shrublands and woodlands (Fig. 2*a* and *b*).

Fire history data were obtained from two sources: (1) USFS fire data covered five national forests (north to south: Eldorado, Stanislaus, Sierra, Inyo–Mono and Sequoia) and included largely mid-elevation forested landscapes for the years 1910–2010. Annual data on numbers of fires by cause and area burned are published and available in research libraries and are spatially explicit at the level of the forest. Over the period of record, national forest area ranged from 2.4 to 3.0 million ha. (2) Cal Fire data covered direct protection areas (DPA), which are mostly state responsibility lands with small amounts of federal lands, and included eight counties with complete coverage from 1919 to 2010 (from north to south: El Dorado, Amador, Calaveras, Tuolumne, Mariposa, Madera, Fresno and Tulare). Counties that began record-keeping after 1919, and not used for the time-course analysis (discussed below) but included in the fire–climate analysis, were San Joaquin, Stanislaus, Merced, Kings, Inyo, Kern and Mono counties. Over the period of record, DPA ranged from 1.7 to 4.4 million ha. Data from 1931 to 2010 are available in the annually published *Redbook* series (available at http://www.fire.ca.gov/fire_protection/fire_protection_fire_info_redbooks.php, verified 6 November 2014), but data from 1919 to 1930 are unpublished and only available at the California State Archives in Sacramento. For each year, area burned and fire frequency were normalised to the land area protected by USFS and by Cal Fire.

Despite informal discussions that early fire records are unreliable, serious study of fire histories in California does not support that idea (Clar 1959; Cermak 2005, but cf. Stephens 2005), and personal studies of fire records in the State Library and State Archives suggest a level of thoroughness not unlike contemporary fire record-keeping. We believe there is a strong case that statistics on area burned are highly reliable throughout the period of record. As presented below, the peak in area burned on both USFS and Cal Fire lands was in the 1920s decade, which would not be consistent with the hypothesis of early records failing to record fire events adequately. Data on numbers of ignitions, particularly of lightning ignitions in remote locations, are potentially underestimated in the early part of the record owing to difficulties of detection. We estimate this potential error was ~1% on Cal Fire lands and 12% on USFS lands, based on the percentage of fires due to lightning in the first two decades compared with the last two decades of record.

To characterise the differences between USFS and Cal Fire lands, elevation, vegetation type and housing density were estimated by overlaying 500 random sample points on USFS and Cal Fire lands, then extracting and summarising spatial data for those points. Source of geographic information system (GIS) data included: National Elevation Dataset of the USGS (30 m, http://ned.usgs.gov/, verified 8 June 2014), CALVEG existing vegetation maps (http://www.fs.usda.gov/detail/r5/landmanagement/resourcemanagement/?cid=stelprdb5365219, verified 8 June 2014), and housing density from the year 2000 within census partial block groups (Hammer *et al.* 2004).

To evaluate climate impact on fire activity, we utilised PRISM climate for the USFS lands and the Cal Fire lands (Fig. 1). For every year in the analysis, we extracted 2.5-arc-minute PRISM data (PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, 2014) for areas within the boundaries of the Cal Fire and USFS regions. For each region and year, we computed area-weighted averages of monthly mean precipitation and temperature.

Snow-pack data extending back in time to cover a substantial part of our fire record were not widely available within the elevation zone prone to fires. The longest record close to the

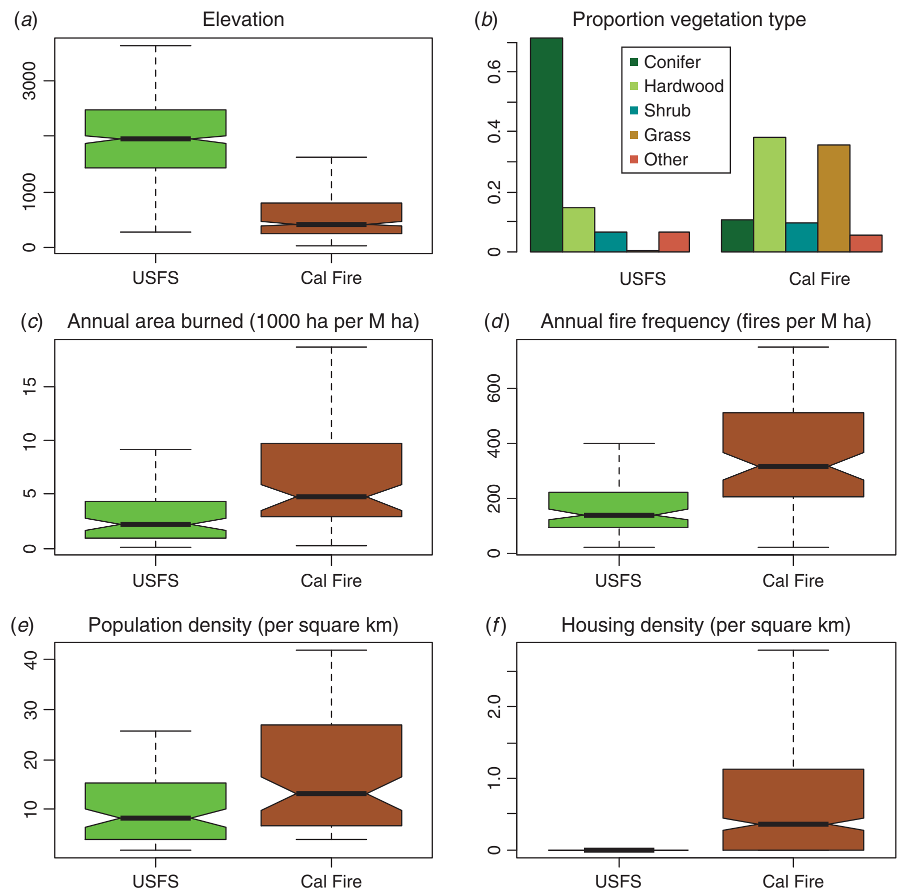

Fig. 2. Characteristics of US Forest Service (FS) and Cal Fire lands and fire statistics: (*a*) mean elevation; (*b*) major vegetation types; (*c*) average annual area burned over the period of record, per million ha protected; (*d*) average fire frequency per million ha protected; (*e*) population density; and (*f*) housing density. Box plots show the median, the first and third quartiles, and the 95% confidence interval of the median.

mean elevation of US Forest Service lands included here was from Giant Forest at 1950 m in Sequoia National Park (http://www.wrcc.dri.edu/for), latitudinally approximately mid-way in the study region (http://www.wrcc.dri.edu/).

Bivariate regressions were conducted with *Systat 11.0* software (http://www.systat.com/). We developed multiple regression models explaining area burned for USFS and Cal Fire based on seasonal temperature, precipitation and prior-season precipitation variables. We considered all possible combinations of the predictor variables and used Akaike information criterion (AICc) to rank and select the best-supported models for each region using package *MuMIn* in R (Burnham and Anderson 2002; R Development Core Team 2012). To ensure multicollinearity would not be an issue, we calculated correlation coefficients among all potential explanatory variables. No variables were correlated ($R < 0.5$), so all were considered in the analysis. Because Cal Fire lands comprised a mosaic of grasslands, shrublands, and woodlands and forests (Fig. 2*b*), and the database presented data by vegetation type, we determined models separately for these three vegetation types.

Results

Over the period of record, there were substantially more fires and more area burned on Cal Fire lands than on USFS lands (Fig. 2*c*, *d*). Direct human impacts were potentially greater on Cal Fire landscapes as population density and housing density were greater (Fig. 2*e*, *f*). This impact is also reflected in the proportion of fires ignited by humans: on Cal Fire lands, humans accounted for 97% of all fires early (1920s decade) and late in the record (2000 decade), whereas on USFS lands, humans accounted for 62% and 50% respectively. Most USFS lands were coniferous forests (Fig. 2*a*) whereas the Cal Fire landscape comprised a mosaic (Fig. 2*b*). Throughout the period of record, grasslands and shrublands were the vegetation types in which the bulk of area was burned (Fig. 3).

Historical trends

On USFS lands, total area burned peaked in the 1920s and declined over subsequent decades until the latter part of the 20th century when fire activity began to increase (Fig. 4*a*). Cal Fire lands likewise showed a peak in area burned in the 1920s but this

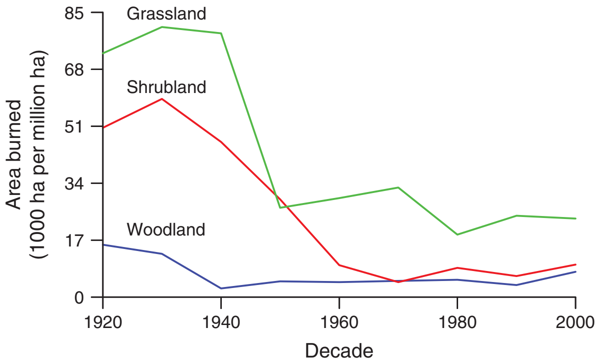

Fig. 3. Decadal burning by vegetation type on Cal Fire lands over the 90 years of record.

declined to a generally constant level of burning over the past half-century, and no subsequent increase in recent decades has been detected (Fig. 4*b*).

Very little of the variation in annual area burned is correlated with patterns of ignitions. Both landscapes had the fewest ignitions in the 1920s (Fig. 5) when the highest area burned on both USFS and Cal Fire lands. There was a highly significant increase in ignitions up through the 1980s and then a highly significant decline in the last couple of decades. Over the period of record, humans were the dominant ignition source (95%) on Cal Fire lands, whereas lightning ignitions were slightly higher (54%) on USFS lands. The decline in ignitions on USFS lands in the last two decades is due to a drop in both human-ignited and lightning-ignited fires; comparing the last two decades with the 1970s and 1980s, there was a 38% drop in human-ignited and 47% drop in lightning-ignited fires.

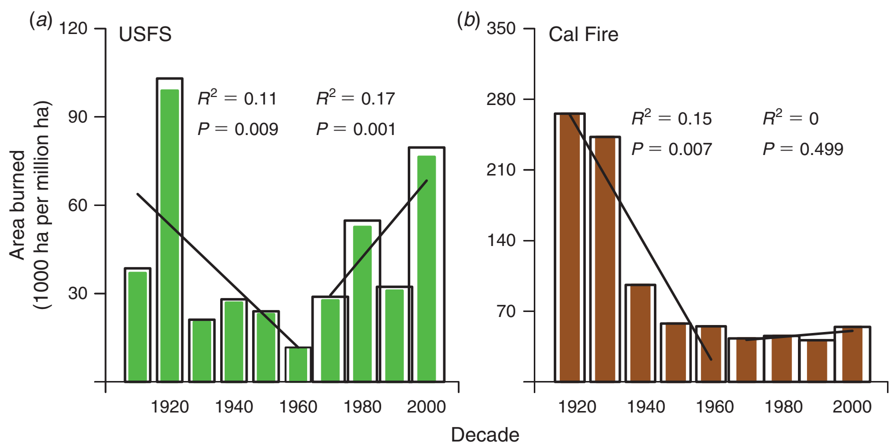

Fig. 4. (*a*) One hundred years of burning in the six US Forest Service (FS) forests of the Sierra Nevada (green bars) based on hectares protected. Because trends changed over time, regression lines are for decades 1910–50 and 1960–2000; and (*b*) 90 years of burning on lands protected by Cal Fire (brown bars) in Sierra Nevada counties with complete data for the years 1920–2009; regression lines are for decades 1920–50 and 1960–2000.

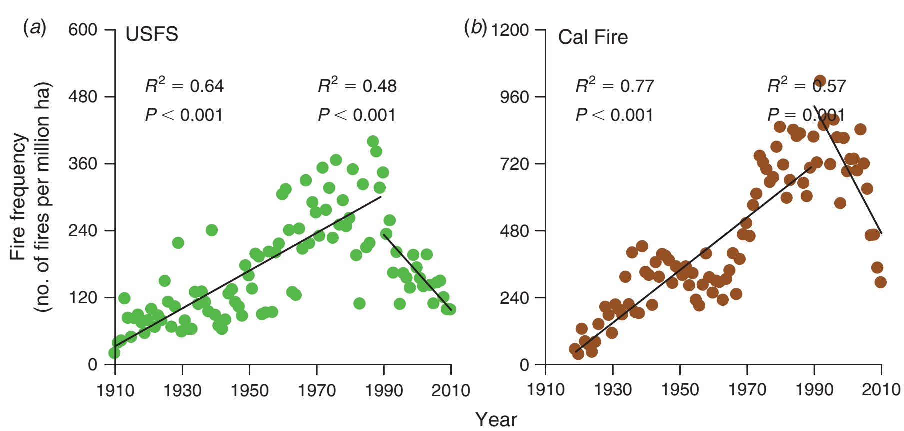

Fig. 5. Annual fire frequency for (*a*) US Forest Service (FS) data from 1910 to 2010; and (*b*) Cal Fire in counties with complete data for the years 1919–2010. Regression lines are for years 1910 or 1919 to 1989 and 1990 to 2010.

Annual fire–climate relationships

For all of these analyses, we compared annual fire activity with both seasonal climate parameters as well as monthly parameters. The monthly analysis provided results comparable with seasonal data, although R^2 values were in most cases higher than those for individual months. Thus, the presentation here will focus on fire response to seasonal patterns of temperature and precipitation.

On USFS lands, spring and summer temperatures over the past 101 years of record exhibited a highly significant positive relationship with annual area burned (Fig. 6). Neither winter nor autumn temperatures were correlated with area burned. On Cal Fire lands, area burned was only weakly related to spring temperature and exhibited no significant relationship with winter, summer or autumn temperature (Fig. 7).

Patterns of seasonal precipitation pretty much mirrored temperature effects on fire activity. On USFS lands (Fig. 8), annual area burned was most strongly tied to spring precipitation, and winter precipitation, which comprises the bulk of the annual rainfall, was only weakly related to area burned. In contrast, area burned on Cal Fire lands showed no relationship with seasonal precipitation (Fig. 9).

As spring temperature and precipitation were most strongly tied to fire activity in the higher USFS landscapes, it was hypothesised that area burned would be correlated with spring snowpack. This proved to be the case (Fig. 10*a*), and not surprisingly, fire activity in the lower-elevation Cal Fire lands was not related to spring snow pack in the higher elevations (Fig. 10*b*). The spring snow pack level was best predicted by the model: April snow depth = 1.08 (winter precipitation (ppt)) – 174 (mean winter temp) – 194 (mean spring temp); adjusted $R^2 = 0.46$, $P < 0.001$ (these independent variables were not significantly correlated at $P > 0.05$ with each other).

We investigated the consistency of the fire–climate relationship throughout the 100-year history with multiple regression models for the first half of the fire record and compared those with the second half of the record. On USFS lands during the first half of the 20th century, winter, spring and summer precipitation were the important determinants of area burned (Table 1). However, in the second half up to the present, summer temperature became a significant predictor, along with spring precipitation, of fire activity and during this most recent era, the model explained over half the variation in annual area burned. Consistent with these temporal switches in fire–climate relationships, on a monthly basis the highest R^2 was for March precipitation during the first 50 years and mean June temperature in the last 51 years.

Because Cal Fire lands comprise a mosaic of grasslands, shrublands and woodlands (including a small amount of conifer forest), we calculated models collectively for all Cal Fire

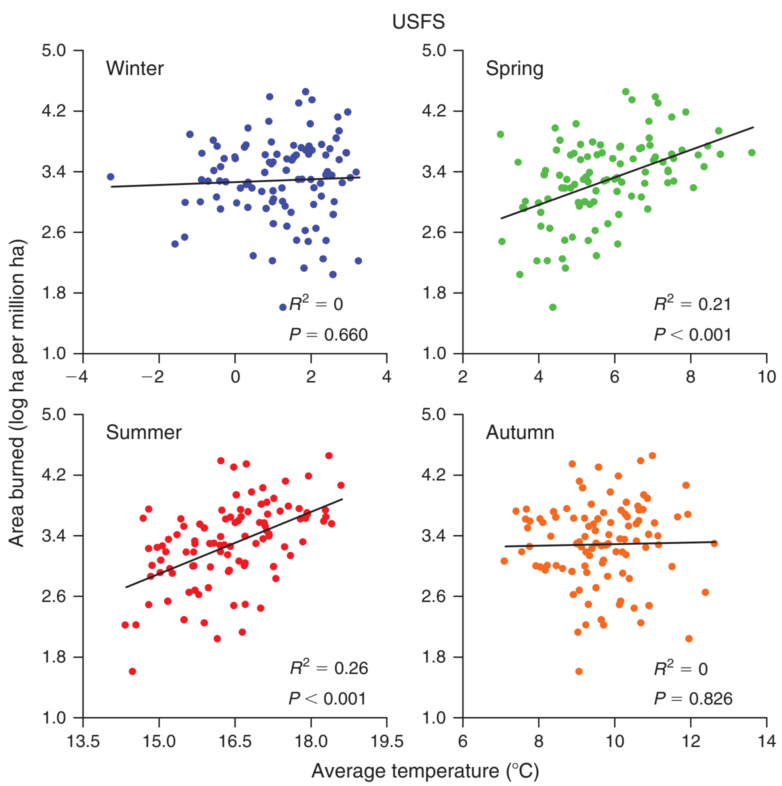

Fig. 6. Relationship of mean seasonal temperature and area burned for US Forest Service (FS) (1910–2010) lands; winter = Dec–Feb; spring = Mar–May; summer = Jun–Aug; autumn = Sep–Nov.

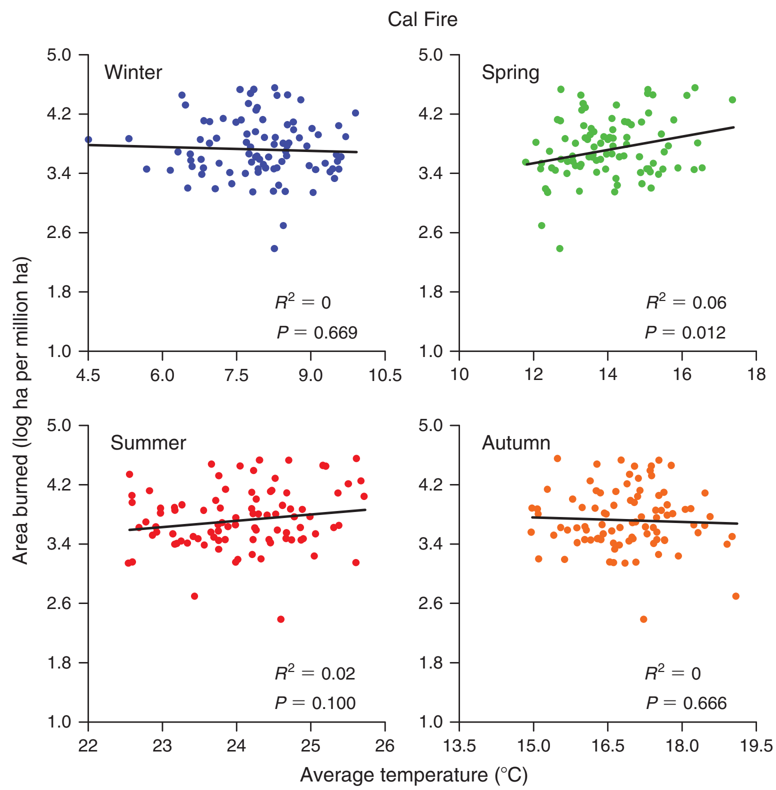

Fig. 7. Relationship of mean seasonal temperature and area burned for Cal Fire (1919–2010) lands.

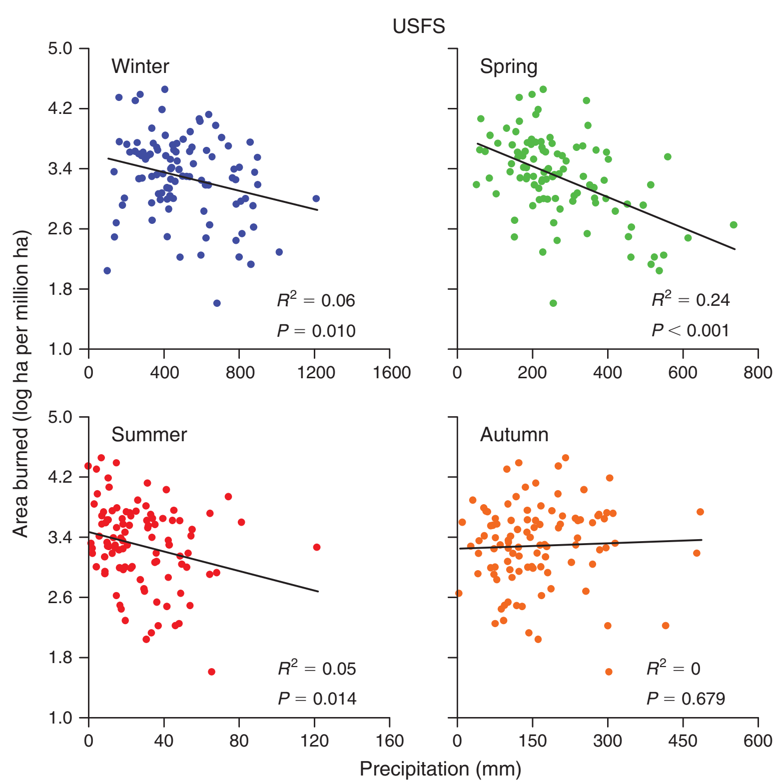

Fig. 8. Relationship of total seasonal precipitation and area burned for US Forest Service (FS) (1910–2010) lands.

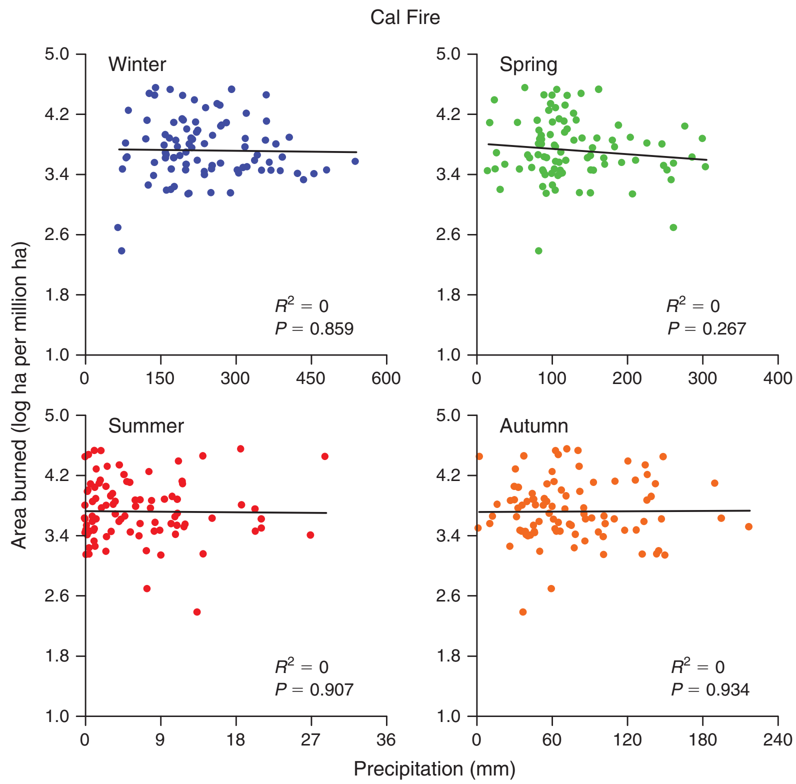

Fig. 9. Relationship of total seasonal precipitation and area burned for Cal Fire (1919–2010) lands.

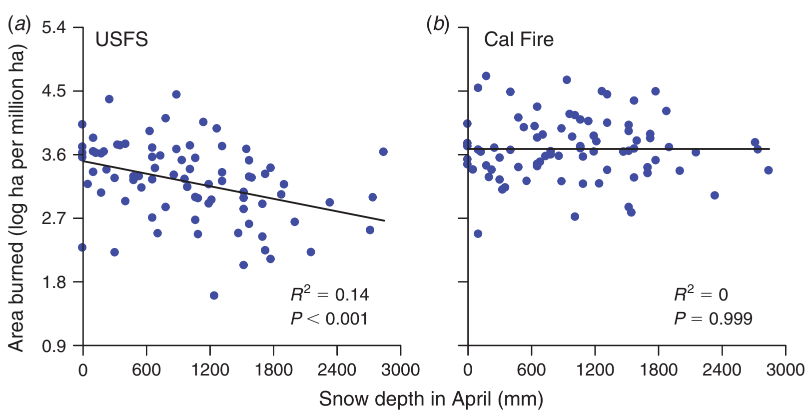

Fig. 10. Snow pack depth (mm) at Giant Forest (Sequoia National Park) for years 1930–2010 *v.* area burned on (*a*) US Forest Service (FS); and (*b*) Cal Fire lands.

landscapes, and separately by vegetation type (Table 1). The most obvious difference with USFS lands is that climate during the fire year has not been as important in determining fire activity as the level of precipitation in the year before fire activity. For total area burned, the prior year spring precipitation was an important determinant of fire activity in both the first half and second half of the records. It is of some interest that far less of the annual variation is explained by climate parameters in the last 50 years than in the first part of the record.

Discussion

20th-Century trends in fires

In this region over the past century, the peak fire activity in both the montane forests (USFS) and the lower foothills and valleys (Cal Fire) was during the 1920s decade (Fig. 4) and this 1920s peak is mirrored on USFS lands throughout the western US (Littell *et al.* 2009). Although limited fire suppression effectiveness in the early 20th century may be a factor, it is not the

Table 1. Akaike information criterion regression models of climate variables on area burned (temperatures are the seasonal mean and precipitation (ppt) the seasonal total)

	Adjusted R^2	P
US Forest Service 1910–59		
Log(ha burned) = −0.002(spring ppt) − 0.0008(winter ppt)	0.41	<0.001
US Forest Service 1960–2010		
Log(ha burned) = 0.317(summer temp) − 0.001(spring ppt)	0.53	<0.001
Cal Fire 1919–59		
Log(ha burned) = 0.002(prior year spring ppt) + 0.07(spring temp) + 0.023(summer ppt) + 0.003(autumn ppt)	0.34	<0.001
Log(grassland ha burned) = 0.002(prior year spring ppt) + 0.028(summer ppt) + 0.003(autumn ppt)	0.24	0.005
Log(shrubland ha burned) = 0.002(prior year spring ppt) + 0.023(summer ppt) + 0.003(autumn ppt) + 0.07(spring temp)	0.34	<0.001
Log(woodland ha burned) = −0.002(prior year winter ppt) − 0.003(spring ppt) + 0.021(summer ppt)	0.23	0.008
Cal Fire 1960–2010		
Log(ha burned) = 0.001(prior year spring ppt) + 0.001(prior year winter ppt) + 0.002(summer temp)	0.27	0.005

whole answer as much less area burned during the first decade of record from 1910 to 1919 in California (Fig. 4*a*), and throughout the western USA (Littell *et al.* 2009), when presumably fire suppression capabilities were as limited if not more so than in the 1920s. In Sierra Nevada USFS forests, our models for the first half of the 20th century (Table 1) support the idea that this 1920s peak may have been attributable in large part to climate; however, climate was not a strong factor in the lower-elevation Cal Fire landscapes. Human factors also may have contributed to the peak of fire activity in the 1920s as this was an era of rapid road building that brought an order of magnitude increase in automobile use and human wildfire ignitions in rural and mountainous landscapes (Keeley and Fotheringham 2003).

In the decades after the 1920s, area burned on forested and non-forested lands in the region declined markedly and a major factor was better equipped and organised fire suppression (Cermak 2005). However, in recent decades, the trajectories of area burned on these two landscapes have been divergent (Fig. 4). On USFS lands beginning in the latter quarter of the 20th century, area burned has increased steadily (Fig. 4*a*) whereas on the lower-elevation Cal Fire landscapes, there has not been a late-20th-century–early-21st-century increase in fire activity (Fig. 4*b*). This observation is important because it illustrates that the often-observed increase in area burned in recent decades in the western USA landscape (Westerling *et al.* 2006; Miller *et al.* 2009; Littell *et al.* 2009) is apparently a reflection of the fact that most studies have focussed on higher-elevation forested ecosystems and not on lower-elevation non-forested landscapes. In short, area burned has not increased in recent decades on all landscapes throughout the west (e.g. Baker 2013).

The historical pattern of ignitions (Fig. 5) does not seem to be an obvious explanation for these burning patterns. The 20th-century rise in ignitions on both landscapes (Fig. 5) is hypothesised to be largely the result of human population growth, although there was a substantial increase in lightning-ignited fires during the 1970s and 1980s. The decline in ignitions over the past couple of decades is not clearly understood, but is the result of proportionally similar drops in both lightning-ignited and human-ignited fires.

Global warming has been suggested as part of the explanation for increased area burned in western forests in recent decades (Westerling *et al.* 2006; Littell *et al.* 2009). As discussed below, this could explain our observed increase in area burned on USFS lands over the past 50 years, and consistent with this hypothesis is the weak relationship between climate and area burned on Cal Fire lands and the lack of any observed increase in fire activity on those landscapes.

Despite the evidence that climate variables affect fire activity in Sierra Nevada USFS forests (see below), it is apparent that they account for only approximately half of the annual variation in area burned (Table 1). As suggested by other authors, past fire management practices may account for some of the unexplained variation. Fuel accumulation from fire suppression has been repeatedly invoked (McKenzie *et al.* 2004; Westerling *et al.* 2006). An issue not well studied but having a potential role (Miller *et al.* 2009) is a change in fire management. The late-20th-century increase in fire activity observed across the western USA (e.g. Fig. 4*a*) began at a time of change in USFS policy (Cermak 2005). In the 1960s, in response to numerous issues, including recognition of the natural role of fire in western forests and the resource benefit from fire, the so-called '10 am policy' was replaced with a policy of 'constrain and contain'. The former policy mandated aggressive action towards immediate suppression of all fires with the goal of having the fire extinguished by 10 am the following morning, but was replaced by a change in fire response during the 1960s and 1970s that did not mandate immediate suppression. The goal of this new policy was to constrain and contain fires within a watershed or other boundaries and consequently allowed fires to increase in size beyond what might have happened under the earlier policy. This change could account for some of the unexplained increase in area burned on USFS lands over the past several decades, and similar changes in management have been invoked to explain changes in fire activity in other regions of the world (e.g. Brotons *et al.* 2013). Consistent with this model is the fact that Cal Fire has retained the aggressive '10 am policy' to the present and this region has not experienced a late-20th-century increase in area burned (Fig. 4*b*). This hypothesis deserves further examination as a factor in the late-20th-century increase in area burned on USFS lands.

Fire–climate patterns

The fire–climate relationships documented here support models published elsewhere that climate affects fires through its impact on fuels and this can occur in two ways: by changing fuel moisture and by changing fuel volume (Keeley *et al.* 2009; Littell *et al.* 2009; Batllori *et al.* 2013). Climate influences fire activity in forests through effects on fuel moisture that lead to longer and drier fire seasons (Dennison *et al.* 2008). However, in non-forested ecosystems of the foothills and valleys, it appears that year-to-year variation in area burned is influenced much less by drying conditions on fuels than by the effect of higher rainfall contributing to increased herbaceous fuel volume, which contributes to greater area burned the following year.

The role of climate in driving forest fire regimes hypothesised here is consistent with results from other studies in the western US derived through somewhat different methods. Westerling *et al.* (2006) reported that the number of fires over 4.05 km^2 was explained by the timing of peak spring stream flow; they hypothesised that this was the result of higher spring temperatures, which reduced the spring snow pack, leading to a longer and drier fire season. Our study supports the conclusion that spring and summer temperatures are important (Fig. 6), but questions whether they act primarily through effects on snow pack. This is suggested by our model of factors controlling winter snow pack, which were largely winter precipitation and winter temperature, and yet those variables were not strongly tied to area burned. The climatic water balance approach of Littell and Gwozdz (2011) would seem to hold promise for more clearly understanding the link between fire activity and climate. One of the least-emphasised limitations of the study of Westerling *et al.* (2006) was that it did not consider non-forested ecosystems, and these ecosystems dominate much of the western US landscape, yet there is much less evidence that these fire regimes are likely to be affected by global warming.

Interpretations of the Westerling paper in the media make it clear that it is widely believed that these patterns are driven by global warming, which has manifested itself during the last several decades. This conclusion is supported by the fact that temperature became an important driver of area burned in the last 50 years of record, whereas precipitation patterns during the first 50 years produced almost as a strong a relationship with area burned (Table 1). The lower-elevation Cal Fire lands have not experienced an increase in area burned over the past several decades (Fig. 4*b*), and annual variation in area burned is not strongly controlled by year-to-year variation in temperature. This may derive from the hotter, drier conditions in the lower elevations being conducive to fires most years, and factors other than climate such as ignitions, fuel condition, continuity or composition being more critical to determining the amount of area burned.

Fire–climate relationships throughout the western US differ not just between forested and non-forested ecosystems. There is extraordinary variation from region to region in the relative roles of temperature, seasonal patterns of temperature and precipitation (e.g. Gedalof *et al.* 2005; Collins *et al.* 2006; Littell *et al.* 2009; Abatzoglou and Kolden 2013; Morton *et al.* 2013). Our models suggest that over the past century, temperature and precipitation have varied in their importance to area burned and this pattern is reflected in other studies (Miller *et al.* 2009). This variation over space and in time may have resulted from a variety of factors that not only include changing interactions among climate and fuel properties, but could also stem from interactions with topography and human land use.

Implications for climate change

The variable role of climate and other factors driving fire activity underlines the importance of context when considering the impacts of climate change on future fire regimes. Nevertheless, a warmer future looks to be inevitable, as climate model projections consistently agree there will be significant temperature increases, although forecasts of precipitation change are more variable and spatially heterogeneous (Knutti and Sedláček 2013; Kumar *et al.* 2013). To this end, our historical analyses suggest that global warming will indeed increase the likelihood for further increases in fire activity in high-elevation forested landscapes, at least in the short term. Longer time periods bring greater uncertainty, however, because climate change may significantly shift fuel properties through changing species' distributions and forest structure (Chen *et al.* 2011; Keane *et al.* 2013). Increased fire activity in the short term may also decrease subsequent fire intensity through the reduction in fuels (Batllori *et al.* 2013). Predicting the effects of climate change in lower-elevation non-forested landscapes is more complicated because, climatologically, fire activity in these areas has not been keyed to temperature, but is driven instead by interactions among precipitation and fine-fuel load. Not only are future projections of average precipitation more variable, but the frequency and intensity of extreme precipitation events are also likely to change. If vegetation composition shifts to become increasingly herbaceous, changing precipitation patterns may play an even larger role in future fire activity. Beyond consideration of the role of climate, however, it will be important to account for other global change factors when predicting future fire activity, particularly the role of population growth and land-use change, which have been so influential in the past and present (Syphard *et al.* 2007).

Conclusions

After reviewing the early history of fire in California forests, Cermak (2005) concluded 'The *sine qua non* of a severe fire season in California is dry spring weather'. His conclusion has since been borne out by other studies (Westerling *et al.* 2006; Littell *et al.* 2009; present study). This has implications for understanding how future climate change will impact fire regimes and is consistent with the issues raised by Hessl (2011) in her review of climate change impacts on fire regimes. Our study shows that three issues need to be considered in making forecasts of future fire regimes. (1) Models predicting changes in annual temperature will be of limited value in understanding future fire regimes unless they pay close attention to seasonal temperature changes. The present study suggests that global warming during the winter will have less impact on future fire regimes than spring and summer warming. (2) The relationship between fire activity and climate is not static. In the present study, fires in Sierra Nevada forests were far more heavily influenced by precipitation patterns in winter, spring and summer during the first half of the 20th century than in the second half (Table 1). (3) Non-forested ecosystems appear to have a weak link between climate and fire activity, likely reflecting the over-riding influence of more direct human impacts.

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References

Abatzoglou JT, Kolden CA (2013) Relationships between climate and macroscale area burned in the western United States. *International Journal of Wildland Fire* **22**, 1003–1020. doi:10.1071/WF13019

Abatzoglou JT, Redmond KT, Edwards LM (2009) Classification of regional climate variability in the state of California. *Journal of Applied Meteorology and Climatology* **48**, 1527–1541. doi:10.1175/2009JAMC2062.1

Baker WL (2013) Is wildland fire increasing in sagebrush landscapes of the western United States? *Annals of the Association of American Geographers. Association of American Geographers* **103**, 5–19. doi:10.1080/00045608.2012.732483

Batllori E, Parisien M-A, Krawchuck M, Moritz MA (2013) Climate change-induced shifts in fire for Mediterranean ecosystems. *Global Ecology and Biogeography* **22**, 1118–1129. doi:10.1111/GEB.12065

Brotons L, Aquilue N, de Caceres M, Fortin M-J, Fall A (2013) How fire history, fire suppression practices and climate change affect wildfire regimes in Mediterranean landscapes. *PLoS ONE* **8**, e62392. doi:10.1371/JOURNAL.PONE.0062392

Burnham KP, Anderson DR (2002) 'Model Selection and Multimodel Inference: A Practical Information-Theoretic Approach.' 2nd edn (Springer: New York).

Cermak RW (2005) Fire in the forest. A history of forest fire control on the National Forests in California, 1898–1956. USDA Forest Service, Pacific Southwest Region, R5-FR-003. (Albany, CA)

Chen IC, Hill JK, Ohlemüller R, Roy DB, Thomas CD (2011) Rapid range shifts of species associated with high levels of climate warming. *Science* **333**, 1024–1026. doi:10.1126/SCIENCE.1206432

Clar CR (1959) 'California Government and Forestry from Spanish Days Until the Creation of the Department of Natural Resources in 1927.' (Division of Forestry, Department of Natural Resources, State of California: Sacramento, CA)

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

Dennison PE, Moritz MA, Taylor RS (2008) Evaluating predictive models of critical live fuel moisture in the Santa Monica Mountains, California. *International Journal of Wildland Fire* **17**, 18–27. doi:10.1071/WF07017

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

Hammer RB, Stewart SI, Winkler R, Radeloff VC, Voss PR (2004) Characterizing spatial and temporal residential density patterns across the US Midwest, 1940–1990. *Landscape and Urban Planning* **69**, 183–199. doi:10.1016/J.LANDURBPLAN.2003.08.011

Hessl AE (2011) Pathways for climate change effects on fire: models, data, and uncertainties. *Progress in Physical Geography* **35**, 393–407. doi:10.1177/0309133311407654

Keane RE, Cary GJ, Flannigan MD, Parsons RA, Davies ID, King KJ, Li C, Bradstock RA, Gill M (2013) Exploring the role of fire, succession, climate, and weather on landscape dynamics using comparative modeling. *Ecological Modelling* **266**, 172–186. doi:10.1016/J.ECOLMODEL.2013.06.020

Keeley JE, Fotheringham CJ (2003) Impact of past, present, and future fire regimes on North American Mediterranean shrublands. In 'Fire and Climatic Change in Temperate Ecosystems of the Western Americas'. (Eds TT Veblen, WL Baker, G Montenegro, TW Swetnam) pp. 218–262. (Springer: New York)

Keeley JE, Aplet GH, Christensen NL, Conard SG, Johnson EA, Omi PN, Peterson DL, Swetnam TW (2009) Ecological foundations for fire management in North American forest and shrubland ecosystems. USDA Forest Service, Pacific Northwest Research Station, General Technical Report PNW-GTR-779. (Portland, OR)

Knutti R, Sedláček J (2013) Robustness and uncertainties in the new CMIP5 climate model projections. *Nature Climate Change* **3**, 369–373. doi:10.1038/NCLIMATE1716

Kumar D, Merwade V, Kinter JL, Niyogi D (2013) Evaluation of temperature and precipitation trends and long-term persistence in CMIP5 twentieth-century climate simulations. *Journal of Climatology* **26**, 4168–4185. doi:10.1175/JCLI-D-12-00259.1

Littell JS, Gwozdz RB (2011) Climatic water balance and regional fire years in the Pacific North-west, USA: Linking regional climate and fire at landscape scales. In 'The Landscape Ecology of Fire'. (Eds D McKenzie, C Miller DA Falk) pp. 117–139. (Springer: New York)

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

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

Miller JD, Safford HD, Crimmins M, Thode AE (2009) Quantitative evidence for increasing forest fire severity in the Sierra Nevada and southern Cascade mountains, California and Nevada, USA. *Ecosystems* **12**, 16–32. doi:10.1007/S10021-008-9201-9

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

Parisien M, Snetsinger S, Greenber JA, Nelson CR, Schoennagel T, Dobrowski SZ, Moritz MA (2012) Spatial variability in wildfire probability across the western United States. *International Journal of Wildland Fire* **21**, 313–327. doi:10.1071/WF11044

R Development Core Team (2012) A Language and Environment for Statistical Computing. R Foundation for Statistical Computing. (Vienna, Austria). Available at http://www.R-project.org [Verified 1 May 2014]

Safford HD, Hayward GD, Heller NE, Wiens JA (2012) Historical ecology, climate change, and resource management: can the past still inform the future? In 'Historical Environmental Variation in Conservation and Natural Resource Management'. (Eds JA Wiens, GD Hayward, HD Safford, CM Giffen) pp. 46–62. (Wiley-Blackwell: Oxford, UK)

SNEP (1996) 'Sierra Nevada Ecosystem Report: Final Report to Congress.' (University of California: Davis, CA)

Stephens SL (2005) Forest fire causes and extent on United States Forest Service lands. *International Journal of Wildland Fire* **14**, 213–222. doi:10.1071/WF04006

Syphard AD, Radeloff VC, Keeley JE, Hawbaker TJ, Clayton MK, Stewart SI, Hammer RB (2007) Human influence on California fire regimes. *Ecological Applications* **17**, 1388–1402. doi:10.1890/06-1128.1

Westerling AL, Hidalgo HG, Cayan DR, Swetnam TW (2006) Warming and earlier spring increase western US forest wildfire activity. *Science* **313**, 940–943. doi:10.1126/SCIENCE.1128834