

Increasing elevation of fire in the Sierra Nevada and implications for forest change

MARK W. SCHWARTZ,^{1,2,†} NATHALIE BUTT,³ CHRISTOPHER R. DOLANC,^{1,4} ANDREW HOLGUIN,¹ MAX A. MORITZ,⁵ MALCOLM P. NORTH,⁶ HUGH D. SAFFORD,^{1,7} NATHAN L. STEPHENSON,⁸ JAMES H. THORNE,¹ AND PHILLIP J. VAN MANTGEM⁹

¹Department of Environmental Science & Policy, University of California, Davis, California 95616 USA

²John Muir Institute of the Environment, University of California, Davis, California 95616 USA

³School of Biological Sciences, University of Queensland, St. Lucia, Queensland 4072 Australia

⁴Department of Biology, Mercyhurst University, Erie, Pennsylvania 16546 USA

⁵University of California, Berkeley, Department Environmental Science Policy & Management, Berkeley, California 94720 USA

⁶Pacific Southwest Research Station, US Forest Service, Davis, California 95618 USA

⁷USDA Forest Service, Pacific Southwest Region, Vallejo, California 94592 USA

⁸U.S. Geological Survey, Western Ecological Research Center, Three Rivers, California 93271 USA

⁹U.S. Geological Survey, Western Ecological Research Center, Redwood Field Station, 1655 Heindon Road, Arcata, California 95521 USA

Citation: Schwartz, M. W., N. Butt, C. R. Dolanc, A. Holguin, M. A. Moritz, M. P. North, H. D. Safford, N. L. Stephenson, J. H. Thorne, and P. J. van Mantgem. 2015. Increasing elevation of fire in the Sierra Nevada and implications for forest change. *Ecosphere* 6(7):121. <http://dx.doi.org/10.1890/ES15-00003.1>

Abstract. Fire in high-elevation forest ecosystems can have severe impacts on forest structure, function and biodiversity. Using a 105-year data set, we found increasing elevation extent of fires in the Sierra Nevada, and pose five hypotheses to explain this pattern. Beyond the recognized pattern of increasing fire frequency in the Sierra Nevada since the late 20th century, we find that the upper elevation extent of those fires has also been increasing. Factors such as fire season climate and fuel build up are recognized potential drivers of changes in fire regimes. Patterns of warming climate and increasing stand density are consistent with both the direction and magnitude of increasing elevation of wildfire. Reduction in high elevation wildfire suppression and increasing ignition frequencies may also contribute to the observed pattern. Historical biases in fire reporting are recognized, but not likely to explain the observed patterns. The four plausible mechanistic hypotheses (changes in fire management, climate, fuels, ignitions) are not mutually exclusive, and likely have synergistic interactions that may explain the observed changes. Irrespective of mechanism, the observed pattern of increasing occurrence of fire in these subalpine forests may have significant impacts on their resilience to changing climatic conditions.

Key words: climate change; fire; fire suppression; forest stand structure; fuels; Sierra Nevada; subalpine.

Received 5 January 2015; revised 20 January 2015; accepted 29 January 2015; final version received 2 April 2015; **published** 23 July 2015. Corresponding Editor: D. P. C. Peters.

Copyright: © 2015 Schwartz 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:** mwschwartz@ucdavis.edu

INTRODUCTION

Increasing incidence of fire may have cascading effects on forest structure, function and biodiversity (Bowman et al. 2009, Stephens et

al. 2013). These effects might be particularly acute in forest types where fire has been historically rare, such as high-elevation forests. If vegetation is not adapted to frequent fire, increasing fire activity may alter community

composition, potentially driving further unexpected changes (“ecological surprises”) (Paine et al. 1998). We present evidence that fire is becoming increasingly frequent at higher elevations in the Sierra Nevada of California.

Fire occurrence and spread have been limited historically by sparse, relatively wet fuels in the low-productivity, high-elevation forests of the Sierra Nevada (van Wageningen and Fites-Kaufman 2006, Fites-Kaufman et al. 2007). However, empirical studies have documented increasing tree density in subalpine forests, suggesting that fuels may also be increasing (Millar et al. 2004, Dolanc et al. 2013, 2014).

Warming temperatures may also be directly reducing fuel moisture (Fried et al. 2008), while indirectly promoting fuel production by encouraging pest and pathogen attack (Raffa et al. 2008) and increasing tree mortality (van Mantgem et al. 2009, Allen et al. 2010). Ultimately, increasing fire frequency may serve as a catalyst of changing species distributions and vegetation type conversion in these forests (Lenihan et al. 2008, Moritz and Stephens 2008).

Our aim was to determine whether there is evidence of an on-going upward shift in maximum elevation of fire in California’s Sierra Nevada. We evaluated the maximum elevation of fires as recorded by the California Fire Perimeters Database version 12.1 (www.fire.ca.gov), a geodatabase of fires in California that dates from the early 20th century. Observing strong increases in the upper elevation extent of fire in the Sierra Nevada through the 20th century, we present five hypotheses that may explain this pattern and discuss what might constitute evidence for these explanations. Many of the mechanisms that may drive increasing fire elevation, however, lack adequate data to rigorously test the hypotheses. In light of this inability to conduct fair tests, and recognizing these as non-exclusive hypotheses (e.g., many may be contributing to the pattern), we focus on interpreting the ramifications of the observations. We synthesize these observations with a discussion of the implications for forest structure, composition and management in the subalpine zone of the Sierra Nevada during the coming century.

METHODS

We downloaded fire perimeters from the California Fire Perimeter Geodatabase (version 12.1, April 2014), archived by the California Department of Forestry Fire and Resource Assessment Program (FRAP), available at http://frap.fire.ca.gov/projects/fire_data/fire_perimeters_index.php (Fig. 1). The time scale of the data was 1908 to 2012. We selected all fires that occurred in California’s Sierra Nevada, spanning an elevation range from 10 to 4421 m and an area of 60,755 km² (Fig. 1).

There are several ways to evaluate potential changes in the elevation of fires through time in the Sierra Nevada. Our goal was to be thorough and test fire elevation patterns to ensure that our observation is robust to data selection. The first issue of concern is that the fire record becomes more detailed and more thorough over time. To evaluate potential spurious patterns we evaluated fires in two sets by size, all fires and all fires greater than 202 ha (500 acres) in size. We did this to account for the hypothesis that small fires early in the record would have been less frequently detected, reported and recorded within the dataset. Large fires, however, would be well-recorded throughout the data record. We arbitrarily chose 202 ha (500 acres) as a cut-off to represent large fire areas. A preliminary assessment of the frequency of fires of different sizes reported in the database suggests that fires smaller than 50 ha are much less frequent earlier in the time period. However, there is no evidence of an increasing proportion of fires larger than 50 ha reported since 1950. Hence using 1970, and 202 ha, represents conservative cut-offs that likely remove potential bias that arises from differential reporting through time.

Similarly, as record-keeping has improved through time, earlier records may be inadequate. Therefore, we ran our analysis for all fires and for larger (>202 ha) fires for the entire time series, as well as from 1970 onwards, when FRAP indicated that record keeping became much more thorough and accurate.

We also calculated two metrics of elevation for each fire: the maximum elevation within each fire boundary and the highest elevation along the fire boundary line as recorded in the fire database. The lack of data on burn coverage within a fire

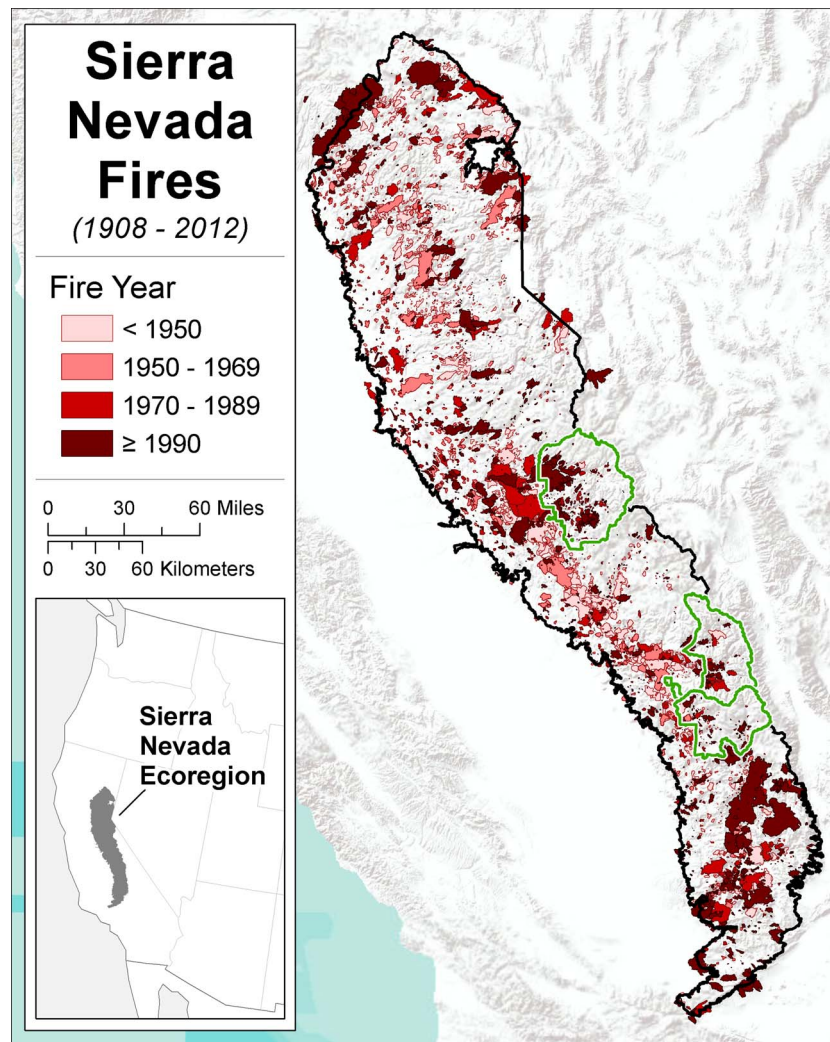


Fig. 1. California's Sierra Nevada region as defined by the Jepson Manual (Hickman 1993). Shaded gray areas represent fire boundary polygons for the period 1900 to 2012. Green boundaries represent Yosemite National Park (north) and Sequoia and Kings Canyon National Parks (south).

boundary could obfuscate what represents the highest elevation of a fire. An alternative approach is to use the highest elevation along the perimeter of a fire. We found, however, there was no substantive difference in patterns between the highest elevation within a burn or the highest point along the fire boundary (perimeter) in preliminary assessments, and the correlation between the two measures across all fires was 0.998. As a consequence, we report only the maximum elevation along the fire boundary.

We extracted these metrics for the seven fires with the highest maximum elevations for each

year and tested the correlation between elevations and year for the single, three, five and seven highest. We evaluated several of these metrics in order to reduce the stochasticity that is observed when only the single highest fire was used to represent each year, and further explore the degree to which our observation is robust. For each subset of data we calculated the slope of the prediction, the standard error of that regression coefficient, and the p-value for each. For ease of interpretation, we also calculated the fraction of the variation explained (r^2) and the predicted change in elevation across the time period

Table 1. Statistical evaluation of temporal changes in upper extent of fire in the Sierra Nevada. Analyses were run varying three attributes: (a) length of record, (b) size of fire area, and (c) fraction of the highest fires evaluated. Rationale for each is reported in the methods.

Sample set	N	Coefficient	SE	P	r ²	Rate†
1908–2012, all sizes; highest	105	6.79	1.20	<0.0001	0.238	67.9
1908–2012, all sizes, 3 highest	315	6.93	0.71	<0.0001	0.236	69.2
1908–2012, all sizes, 5 highest	525	6.81	0.59	<0.0001	0.210	68.1
1908–2012, all sizes 7 highest	726	6.44	0.54	<0.0001	0.166	64.4
1908–2012; >500 acres; highest	104	5.18	1.55	0.0012	0.099	92.7
1908–2012, >500 acres; 3 highest	301	4.86	0.97	<0.0001	0.077	48.6
1908–2012, >500 acres; 5 highest	483	3.67	0.86	<0.0001	0.037	36.7
1908–2012, >500 acres, 7 highest	641	2.52	0.78	0.0013	0.016	25.1
1970–2012, all sizes; highest	43	5.85	3.14	0.0699	0.078	50.7
1970–2012, all sizes, 3 highest	129	6.64	2.03	0.001	0.078	64.9
1970–2012, all sizes, 5 highest	215	7.53	1.83	<0.001	0.073	73.5
1970–2012, all sizes 7 highest	301	7.58	1.72	<0.0001	0.061	74.0
1970–2012; >500 acres; highest	43	9.27	4.58	0.0497	0.091	57.0
1970–2012, >500 acres; 3 highest	125	6.49	3.59	0.0734	0.026	62.6
1970–2012, >500 acres; 5 highest	204	7.76	3.63	0.0338	0.022	75.8
1970–2012, >500 acres, 7 highest	276	7.97	3.39	0.0192	0.0198	77.9

† Predicted rate of increase in elevation expressed in meters per decade.

evaluated.

Finally, we used a contingency test to evaluate changes in the frequencies of fires at different elevation bands through time. Again, because of reporting issues, we repeated our analysis using both all fires and fires larger than 202 ha that are likely to have accurate reporting throughout the temporal record of FRAP. We used a likelihood ratio test to assess the frequency of fires in early (1908–1950), middle (1951–1988) and late (1989–2012) time periods. Time periods were selected to divide the number of observed fires roughly into three groups. Fires were then grouped by their upper elevation extents into five 500-m elevation bands ranging from 1000 m to >3000 m. Although fire frequency is increasing at low elevation, we did not include fires below 1000 m as they would contribute to significant changes in the distribution of fire frequency by elevation, without being indicative of high elevation.

RESULTS

We found significant positive regression coefficients for ‘year’ on maximum fire perimeter elevation for all but two of our 16 test permutations (Table 1, Fig. 2). These strongly positive relationships resulted in a predicted increase in maximum fire elevation of over 700 m for fires generally (Table 1). Restricting the analysis to later in the time series, or to larger fires did not, in general alter the conclusion that the maximum

elevation of fire in the Sierra Nevada is increasing.

We also found strong supportive evidence of differential fractions of fires at different upper elevations across early (1908–1950), middle (1951–1988) and late (1989–2012) time periods ($n = 4545$; $df = 12$; $\chi^2 = 455.1$; $p < 0.0001$; Table 2). Similar results were produced when restricting the data to fires greater than 202 ha (Table 2). The probability of fires at elevations above 3000 m has increased through time with 30 of 1534 fires (1.95%; 1.36–2.78% CI) occurring since 1989 above 3000 m, while just 7 of 1531 (0.46%; 0.22–0.94% CI) recorded fires prior to 1950 were above this elevation (Table 2).

DISCUSSION

The important trend in our analysis is the increasing frequency of wildfire at higher elevations in the Sierra Nevada. Historically fire was rare in subalpine forests in California, with an expected fire return interval in excess of 100 years (Caprio and Lineback 2002, Safford and van de Water 2014). The observed trend suggests a fundamental change in the disturbance regime for these forests that may affect the structure, composition and function of subalpine forests. Our data are observational and cannot provide a means of identifying the potential mechanisms that may be driving this change. Below we propose five hypotheses as to what may be

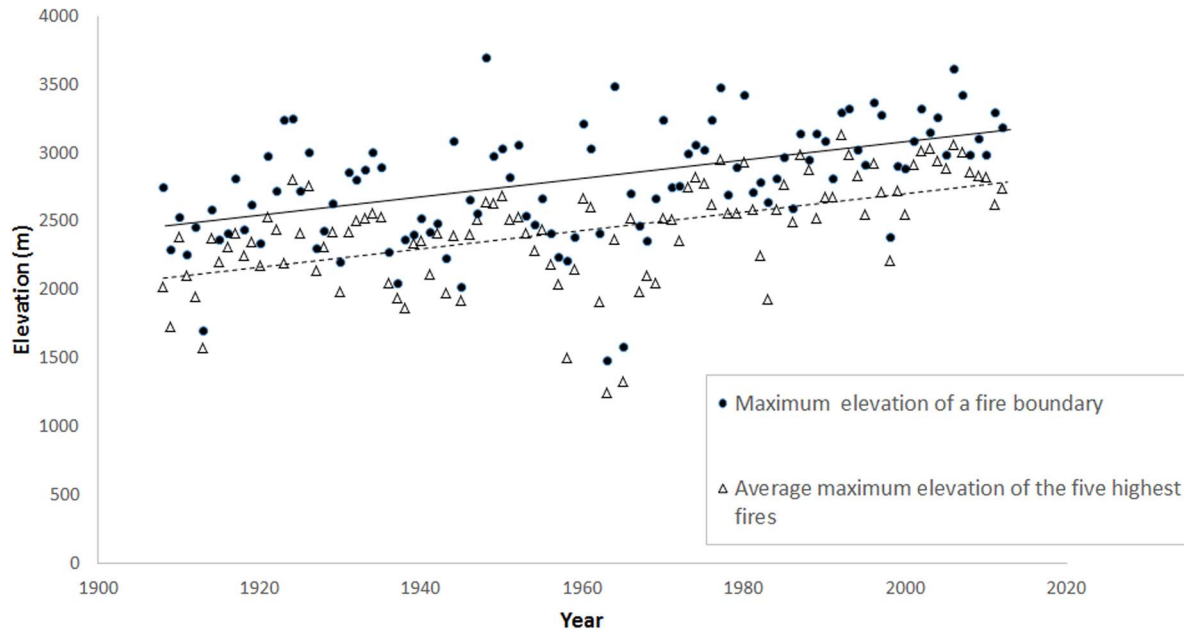


Fig. 2. Two metrics of the increasing elevation of fire in the Sierra Nevada: The upper elevation of the highest (solid circles, $r^2 = 0.24$, $p < 0.0001$); and fifth highest (triangles; $r^2 = 0.23$, $p < 0.0001$) fires by year. Each set of points shows an increasing trend.

driving the increase in fire incidence at high elevations in the Sierra Nevada. They are not mutually exclusive; each could contribute to observed patterns.

1. *Fire management strategies.*—A cessation of fire suppression at higher elevations, along with a shift toward focusing management of wildfire

risk at lower elevations may result in a pattern of increasing fire elevation. Since the beginning of the 20th century, federal and state land management agencies have generally sought to extinguish wildfire in the western United States. Accumulated evidence of the ecological roles played by fire in western US forests led to the adoption of “wildland fire use” (WFU) policies by federal land management agencies by the late 20th century (Stephens and Ruth 2005). These policies permit the management of fire for natural resource benefits in instances where threats to human life, infrastructure, and resources are minimal, particularly in some higher elevation forests (mostly >1800 m). In the Sierra Nevada, WFU-type policies have been the rule on many National Park Service lands since approximately 1970, and the US Forest Service adopted similar policies in the mid-1990s for some large high-elevation wilderness areas in the southern part of the range (Stephens and Sugihara 2006). Mallek et al. (2013) found that although more WFU is practiced in higher elevation forests, even limited application of fire suppression in these long fire-return interval ecosystems can significantly limit high-elevation

Table 2. Contingency table data for fires in the Sierra Nevada reporting observed and (expected) numbers of fires for each elevation and time class. Italicized numbers represent cells where the difference between observed and expected contributed the most to the significance of goodness of fit statistics.

Elevation	Time period		
	1908–1950	1951–1988	1989–2012
A) All Fires			
1000–1500 m	504 (452)	333 (344)	292 (333)
1500–2000 m	440 (399)	293 (304)	264 (294)
2000–2500 m	250 (269)	207 (205)	215 (198)
2500–3000 m	50 (110)	104 (84)	121 (81)
>3000 m	7 (20.8)	15 (15.8)	30 (15.3)
B) Fires > 202 ha in area			
1000–1500 m	193 (177)	111 (119)	92 (100)
1500–2000 m	144 (131)	85 (87.6)	63 (73.6)
2000–2500 m	86 (90.0)	60 (60.3)	55 (50.7)
2500–3000 m	13 (34.5)	34 (23.1)	30 (19.4)
>3000 m	3 (6.3)	4 (4.2)	7 (3.5)

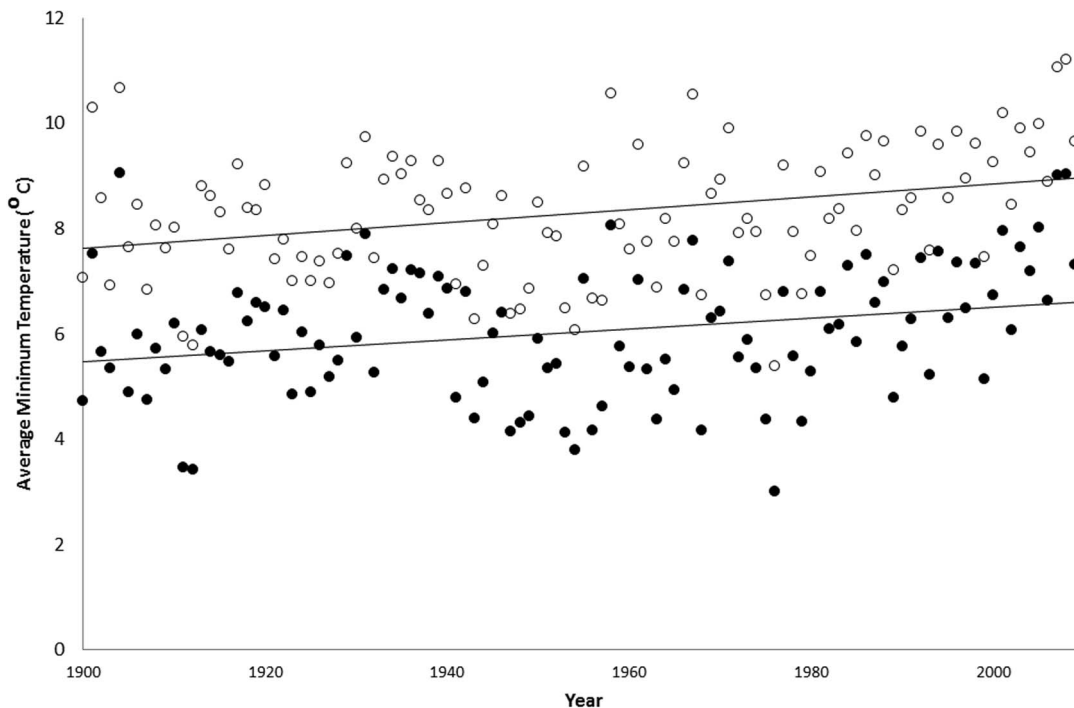


Fig. 3. Average August minimum temperatures for the Sierra Nevada bioregion (Fig. 1) within two elevation boundaries. Open circles capture average annualized daily minimum temperatures between 2000 and 2250 m in elevation within the Sierra Nevada ($n = 111$, $r^2 = 0.11$, $p = 0.0005$). Closed circles represent average minimum temperatures between 2500 and 2750 m elevation ($n = 111$, $r^2 = 0.07$, $p = 0.004$). Minimum temperature values for August were extracted from downscaled climate data used with the California Basin Characterization Model (Flint et al. 2013).

burn extent.

2. *Changing climate affects fire.*—Warming trends are likely leading to increased forest fire activity (Westerling et al. 2006), including in high-elevation forests, and this trend is predicted to continue increasing over the next several decades (Moritz et al. 2012). Climate during the fire season at higher elevations (approximately July through October) is also changing: earlier snowpack melt (Kapnick and Hall 2010) resulting in earlier dry down of soils and fuels, and longer, warmer and/or drier summers could all lead to an increase in fire, particularly at higher elevations. While high-elevation areas in the southern Sierra Nevada may resist snowpack declines (Mote et al. 2005), increasing night-time low temperature may be resulting in generally warmer and drier conditions during the fire season (Fig. 3).

We assessed changes in a climatic variable that may be associated with changing fire conditions,

average August minimum daily temperature (as the most rapid increases in temperatures have been in daily minima), from 1900 to 2010 for two elevation zones in the study area (Fig. 3). The lower elevation zone, 2000–2250 m, was defined because it captures the mean upper elevation of fires prior to 1930, whereas the upper elevation zone, 2500–2750 m, represents the normal upper elevation boundaries of the highest fires in the 21st century (Fig. 2). The upward temperature trend in both curves (Fig. 3) suggests that the upper elevation band will soon experience minimum temperatures analogous to those in the lower elevation band in the first part of the twentieth century, suggesting an upward shift of the upper montane climate zone.

3. *Increasing forest fuels.*—Increasing fuels and connectivity between fuels at high elevations may also be driving increased incidence of fire. Several mechanisms could be responsible. Fire suppression throughout most of the 20th century

has contributed to increasing stem density in forests of the Sierra Nevada, and allowed the build-up of both live and dead fuels (Vankat and Major 1978, Parsons and Debenedetti 1979, McKelvey et al. 1996, Ansley and Battles 1998). Combined with rising temperatures, this has contributed to increasing fire severity in low to mid elevation forests (Miller et al. 2009, Dillon et al. 2011, Miller and Safford 2012, Mallek et al. 2013). Historically, high-elevation forests of the Sierra Nevada, with their thin soils, sparse structure and cool climate, burned infrequently (van Wagtendonk and Fites-Kaufman 2006, Fites-Kaufman et al. 2007). However, while the significant increases in overall density experienced in these forests over the last few decades (Dolanc et al. 2013) may be driven more by climate than fire suppression, the increased fuels at high elevation may connect previously discontinuous forest stands and allow fires to carry farther upslope.

4. *Increasing ignitions.*—Fires on federal lands in the Sierra Nevada are caused both by lightning and by human ignition, at about an equal rate (Keeley 1982). There is also an elevation gradient effect, such that both lightning and human ignitions may be equally important at low to middle elevations. Records indicate that the density of lightning strikes are greatest between 1800 m and 3000 m, and reduce markedly above 3600 m (van Wagtendonk and Cayan 2008). With increasing human presence at higher elevations, however, there is the potential for increased ignitions, although data are lacking. High elevation fire has previously been limited by some combination of sparse fuels in some locations and burning conditions (weather and fuel moisture) in others. Limiting ignition sources may not have been important. However, with stand density and potentially increasing fuel contiguity in subalpine forests, the likelihood of a lightning strike starting a fire at higher elevations may be rising.

5. *Sampling bias.*—Finally, sampling bias is also a possible driver of the recorded increase in maximum fire elevation. Record keeping has improved over time, and simply keeping better track of fire in remote locations may have contributed to our observation. Based on conversations with knowledgeable FRAP experts, we consider the effect of fire sampling bias to have

made only a negligible impact on our observation. Sampling bias would have resulted in an under-reporting of older fires. This would be less likely true for larger fires. We restricted our sample to fire perimeters >202 ha (500 acres), and found a similar increasing trend through time, reducing the likelihood that this pattern is due to under reporting of fires in older records.

Our hypotheses are not mutually exclusive, and a close examination of lightning ignitions, annual snowpack estimates, seasonal temperatures increasing vegetation density, and fire may reveal linked drivers of increasing fire elevation.

MANAGEMENT IMPLICATIONS

Increased fire at high elevations could accelerate vegetation shifts by increasing mortality rates of existing vegetation, and creating opportunities for upslope migration of species from lower elevations. Climate projection models predict a demise of Sierra Nevada subalpine forests as a direct or indirect consequence of changing climate (Lenihan et al. 2008). Empirical studies evaluating forest change in this region during the 20th century have recorded a different trend: increasing densities of subalpine forests, with relatively little upward distributional shifts of upper montane tree species such as red fir (*Abies magnifica*; Millar et al. 2004, Dolanc et al. 2013, 2014). The thin soils and harsh environment of the subalpine zone (Fites-Kaufman et al. 2007) may constrain species such as red fir, which grows on deeper soils (Potter 1998, Sawyer et al. 2009). Nevertheless, the pattern of increasing density of subalpine species suggests a shift toward conditions in which disturbance may accelerate climatically-driven transitions toward upper montane forest types, as also appears to be happening along the lower edge of conifer forests, where conifers are being replaced by hardwoods (Thorne et al. 2008).

Increased mortality rates among larger trees (Lutz et al. 2009, van Mantgem et al. 2009) could contribute to proportional shifts in tree density from larger to smaller trees in the upper montane and subalpine forests of the Sierra Nevada (Dolanc et al. 2013). The build-up of dead fuel biomass is also increasing with stand density in some parts of the high Sierras (Guarin and Taylor 2005, Smith et al. 2005), potentially enabling

more intense, and larger fires, which in turn could accelerate further changes in forest structure. Indeed, proportional increases in annual area burned were greatest in Sierra Nevada subalpine communities during the period 1984–2010 (Mallek et al. 2013).

A second issue relates to forest disease and pests. Currently, several high elevation white pine (*Pinus* spp.) species in the US and Canada are threatened by white pine blister rust (*Cronartium ribicola*) (Tomback and Achuff 2010). However, so far, rates of mortality from the disease are lower in the Sierra Nevada than in other mountain ranges (Maloney 2011), which suggests the Sierra Nevada may provide refuge for some high elevation conifer populations. If this is the case, protection of such populations would have greater conservation importance and may become a focal management objective. Increased fire, if it fosters succession toward replacement of subalpine tree species by upper montane species, could run counter to this objective. To date high elevation forests in the Sierra Nevada have not suffered the catastrophic losses to pine beetles (*Dendroctonus* spp.) seen in the central and northern Rocky Mountains over the last 5–10 years. However, recent (i.e., 2014) aerial surveys by the US Forest Service found notable increases in insect-driven mortality of high elevation pines (Z. Heath, *personal communication*) and continuation of California's current drought may exacerbate this trend.

The demonstrated upward shift in high elevation fires, coupled with changes in tree mortality and stand density, and the potential of the Sierra Nevada as a refuge for disease-threatened tree species, all speak to the importance of carefully researching and monitoring the effects of increasing fire elevation on ecosystem composition, structure and function.

ACKNOWLEDGMENTS

The authors thank the USGS Southwest Climate Science Center for support. Any use of trade names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

LITERATURE CITED

Allen, C. D., et al. 2010. A global overview of drought and heat-induced tree mortality reveals emerging

- climate change risks for forests. *Forest Ecology and Management* 259:660–684.
- Ansley, J. A. S., and J. J. Battles. 1998. Forest composition, structure, and change in an old-growth mixed conifer forest in the northern Sierra Nevada. *Journal of the Torrey Botanical Society* 125:297–308.
- Bowman, D. M. J. S., J. K. Balch, P. Artaxo, W. J. Bond, J. M. Carlson, M. A. Cochrane, C. M. D'Antonio, R. S. DeFries, J. C. Doyle, and S. P. Harrison. 2009. Fire in the earth system. *Science* 324:481–484.
- Caprio, A. C., and P. Lineback. 2002. Pre-twentieth century fire history of Sequoia and Kings Canyon National Park: a review and evaluation of our knowledge. Fire in California ecosystems: integrating ecology, prevention and management. AFE Miscellaneous Publication #1. Association of Fire Ecology, Eugene, Oregon, USA.
- 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* 2:130.
- Dolanc, C. R., H. D. Safford, S. Z. Dobrowski, and J. H. Thorne. 2014. Twentieth century shifts in abundance and composition of vegetation types of the Sierra Nevada, CA, US. *Applied Vegetation Science* 17:442–455.
- Dolanc, C. R., J. H. Thorne, and H. D. Safford. 2013. Widespread shifts in the demographic structure of subalpine forests in the Sierra Nevada, California, 1934 to 2007. *Global Ecology and Biogeography* 22:264–276.
- Fites-Kaufman, J. A., P. Rundel, N. L. Stephenson, and D. A. Weixelman. 2007. Montane and Subalpine Vegetation of the Sierra Nevada and Cascade Ranges. Pages 456–501 in M. G. Barbour, T. Keeler-Wolf, and A. A. Schoenherr, editors. *Terrestrial vegetation of California*. University of California Press, Berkeley, California, USA.
- Flint, L. E., A. L. Flint, J. H. Thorne, and R. Boynton. 2013. Fine-scale hydrologic modeling for regional landscape applications: the California Basin Characterization Model development and performance. *Ecological Processes* 2:1–21.
- Fried, J., J. Gilless, W. Riley, T. Moody, C. Simon de Blas, K. Hayhoe, M. Moritz, S. Stephens, and M. Torn. 2008. Predicting the effect of climate change on wildfire behavior and initial attack success. *Climatic Change* 87:251–264.
- Guarin, A., and A. H. Taylor. 2005. Drought triggered tree mortality in mixed conifer forests in Yosemite National Park, California, USA. *Forest Ecology and Management* 218:229–244.
- Hickman, J. C., editor. 1993. *The Jepson manual: higher plants of California*. University of California Press, Berkeley, California, USA.

- Kapnick, S., and A. Hall. 2010. Observed climate–snowpack relationships in California and their implications for the future. *Journal of Climate* 23:3446–3456.
- Keeley, J. E. 1982. Distribution of lightning and man-caused wildfires in California. Pages 431–437 in C. E. Conrad and W. C. Oechel, editors. Symposium on dynamics and management of Mediterranean-type ecosystems. General Technical Report PSW-GTR-58. USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, California, USA.
- Lenihan, J. M., D. Bachelet, R. P. Neilson, and R. Drapek. 2008. Response of vegetation distribution, ecosystem productivity, and fire to climate change scenarios for California. *Climatic Change* 87:S215–S230.
- Lutz, J. A., J. W. van Wagten-donk, and J. F. Franklin. 2009. Twentieth-century decline of large-diameter trees in Yosemite National Park, California, USA. *Forest Ecology and Management* 257:2296–2307.
- 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* 4:153.
- Maloney, P. E. 2011. Incidence and distribution of white pine blister rust in the high-elevation forests of California. *Forest Pathology* 41:308–316.
- McKelvey, K. S., C. N. Skinner, C. Chang, D. C. Erman, S. J. Husari, D. J. Parsons, J. W. van Wagten-donk, and C. P. Weatherspoon. 1996. An overview of fire in the Sierra Nevada. Pages 1031–1040 in *Sierra Nevada Ecosystem Project: Final Report to Congress. Volume II: Assessments and scientific basis for management options*. University of California, Centers for Water and Wildland Resources, Davis, California, USA.
- Millar, C. I., R. D. Westfall, D. L. Delany, J. C. King, and L. J. Graumlich. 2004. Response of subalpine conifers in the Sierra Nevada, California, USA, to 20th-century warming and decadal climate variability. *Arctic Antarctic and Alpine Research* 36:181–200.
- Miller, J. D., and H. D. Safford. 2012. Trends in wildfire severity: 1984 to 2010 in the Sierra Nevada, Modoc Plateau, and southern Cascades, California, USA. *Fire Ecology* 8:41–57.
- Miller, J. D., H. D. Safford, M. Crimmins, and A. E. Thode. 2009. Quantitative evidence for increasing forest fire severity in the Sierra Nevada and Southern Cascade Mountains, California and Nevada, USA. *Ecosystems* 12:16–32.
- 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* 3:49.
- Moritz, M. A., and S. L. Stephens. 2008. Fires and sustainability: considerations for California's altered future climate. *Climatic Change* 87:S265–S271.
- Mote, P. W., A. F. Hamlet, M. P. Clark, and D. P. Lettenmaier. 2005. Declining mountain snowpack in western North America. *Bulletin of the American Meteorological Society* 86:39–49.
- Paine, R. T., M. J. Tegner, and E. A. Johnson. 1998. Compounded perturbations yield ecological surprises. *Ecosystems* 1:535–545.
- Parsons, D. J., and S. H. DeBenedetti. 1979. Impact of fire suppression on a mixed-conifer forest. *Forest Ecology and Management* 2:21–33.
- Potter, D. A. 1998. Forested communities of the upper montane in the central and southern Sierra Nevada. General Technical Report PSW-GTR-169. USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Albany, California, USA.
- Raffa, K. F., B. H. Aukema, B. J. Bentz, A. L. Carroll, J. A. Hicke, M. G. Turner, and W. H. Romme. 2008. Cross-scale drivers of natural disturbances prone to anthropogenic amplification: the dynamics of bark beetle eruptions. *BioScience* 58:501–517.
- Safford, H. D., and K. M. 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. PSW-RP-266. USDA Forest Service, Albany, California, USA.
- Sawyer, J. O., T. Keeler-Wolf, and J. Evens. 2009. A manual of California vegetation. Second edition. California Native Plant Society, Sacramento, California, USA.
- Smith, T. F., D. M. Rizzo, and M. North. 2005. Patterns of mortality in an old-growth mixed-conifer forest of the southern Sierra Nevada, California. *Forest Science* 51:266–275.
- Stephens, S., J. Agee, P. Fulé, M. North, W. Romme, T. Swetnam, and M. Turner. 2013. Managing forests and fire in changing climates. *Science* 342:41–42.
- Stephens, S. L., and L. W. Ruth. 2005. Federal forest-fire policy in the United States. *Ecological Applications* 15:532–542.
- Stephens, S. L., and N. G. Sugihara. 2006. Fire management and policy since European settlement. Pages 431–443 in N. G. Sugihara, J. van Wagten-donk, K. E. Shaffer, J. Fites-Kaufman, and A. E. Thode, editors. *Fire in California's ecosystems*. University of California Press, Berkeley, California, USA.
- Thorne, J. H., B. J. Morgan, and J. A. Kennedy. 2008. Vegetation Change over 60 Years in the Central Sierra Nevada. *Madroño* 55:223–237.
- Tomback, D. F., and P. Achuff. 2010. Blister rust and western forest biodiversity: ecology, values and outlook for white pines. *Forest Pathology* 40:186–225.

- van Mantgem, P. J., N. L. Stephenson, J. C. Byrne, L. D. Daniels, J. F. Franklin, P. Z. Fule, M. E. Harmon, A. J. Larson, J. M. Smith, A. H. Taylor, and T. T. Veblen. 2009. Widespread increase of tree mortality rates in the western United States. *Science* 323:521–524.
- Vankat, J. L., and J. Major. 1978. Vegetation changes in Sequoia National Park, California. *Journal of Biogeography* 5:377–402.
- van Wagtendonk, J. W., and D. R. Cayan. 2008. Temporal and spatial distribution of lightning strikes in California in relation to large-scale weather patterns. *Fire Ecology* 4:34–56.
- van Wagtendonk, J. W., and J. A. Fites-Kaufman. 2006. Sierra Nevada Bioregion. Pages 264–294 in N. G. Sugihara, J. W. Van Wagtendonk, K. E. Shaffer, J. A. Fites-Kaufman, and A. E. Thode, editors. *Fire in California's ecosystems*. University of California Press, Berkeley, California, USA.
- 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.