Research Article

TRENDS IN WILDFIRE SEVERITY: 1984 TO 2010 IN THE SIERRA NEVADA, MODOC PLATEAU, AND SOUTHERN CASCADES, CALIFORNIA, USA

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ABSTRACT

Data from recent assessments indicate that the annual area of wildfires burning at high severity (where most trees are killed) has increased since 1984 across much of the southwestern United States. Increasing areas of high-severity fire can occur when greater area is burned at constant proportion of high-severity fire, or when the proportion of high-severity fire within fire perimeters increases, or some combination of both. For the Sierra Nevada Forest Plan Amendment (SNFPA) area, which includes forestlands in eastern California and western Nevada, Miller *et al.* (2009*a*) concluded that the proportion of area burning at high severity in mixed-conifer forests had risen over the 1984 to 2004 period. However, no statistical assessment was made of the temporal trend in high-severity fire area because the analyzed dataset was incomplete in the early years of the study period. In this update, we use satellite-derived estimates of fire severity from the three most widely distributed SNFPA forest types to examine the trend in percent high severity and high-severity fire area for all wildfires ≥80 ha that occurred during the 1984 to 2010 period. Time-series regression modeling indicates that the percentage of total high severity per year for a combination of yellow pine (ponderosa pine [*Pinus ponderosa* Lawson & C. Lawson] or Jeffrey pine [*P. jeffreyi* Balf.]) and mixed-conifer forests increased significantly over the 27-year period. The annual area of high-severity fire also increased significantly in yellow pine-mixed-conifer forests. The percentage of high severity in fires ≥400 ha burning in yellow pine-mixed-conifer forests was significantly higher than in fires <400 ha. Additionally, the number of fires ≥400 ha significantly increased over the 1950 to 2010 period. There were no significant trends in red fir (*Abies magnifica* A. Murray bis) forests. These results confirm and expand our earlier published results for a shorter 21-year period.

Keywords: California, fire effects, fire severity, Forest Service, Sierra Nevada, wildfire

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INTRODUCTION

Recent research has concluded that, over the last four decades, wildfires have become larger, and large fires have become more frequent across the western United States (Calkin *et al.* 2005, Westerling *et al.* 2006, Miller *et al.* 2009*a*, Miller *et al.* 2012*a*). In the southwestern US, the overall annual area of high-severity fire has also been rising. Using a 1984 to 2006 dataset, Dillon *et al.* (2011) found that, of three large ecological regions in the southwestern US, increases in the area of high-severity fire were driven principally by overall increases in burned area, except in the southern Rockies of Utah, Colorado, and New Mexico, where an increase in the relative proportion of fire area burning at high severity was also apparent. A dataset analyzed by Miller and colleagues (Miller and Safford 2008, Miller *et al.* 2009*a*) from the Sierra Nevada Forest Plan Amendment (SNFPA) area of eastern California and western Nevada during the same time period showed that the proportion of fire area burning at high severity was rising over time. The area of high-severity fire also increased during the study period, but the data were not statistically analyzed due to an incomplete dataset from the early years of the study.

These contemporary assessments of fire severity were made using remotely sensed Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM) images, which first became available in 1984. The Monitoring Trends in Burn Severity (MTBS) program (http://www.mtbs.gov) provides most fire severity mapping data used in the United States. Because of the large number of wildfires that occur every year, the MTBS program restricts its severity assessments to large fires, defined as ≥200 ha in the eastern US, and ≥400 ha in the western US. Although it excludes more than 95% of all wildfires, the 400 ha restriction in MTBS western US fire severity assessments nonetheless captures about 95% of the total area burned across the western US area during 1984 to 2010 (http://www.mtbs.gov/faqs.html).

In 2009, Miller *et al.* (2009*a*) published an analysis of spatiotemporal trends of fire severity using satellite derived severity data calibrated by field data. That 1984 to 2006 assessment of the SNFPA area in California and western Nevada was completed in 2007 and mostly predated the MTBS program. The MTBS program was chartered in 2006 and did not begin to conduct severity assessments of pre-2006 Landsat images for the SNFPA area until 2007 to 2008 (Eidenshink *et al.* 2007). The Miller *et al.* (2009*a*) study formed part of the SNFPA monitoring plan, and due to limited data availability, was restricted to a large sample of fires (n = 202) ≥40 ha in size that captured approximately 60% of the burned area in the SNFPA area. In addition, only data collected up to 2004 could be classified into distinctive vegetation types, so detailed analyses could not be made for the 2005 and 2006 fire seasons (Miller *et al.* 2009*a*). With completion of the historical data assessments by MTBS, and ongoing data collection by the fire effects monitoring program of the Forest Service Pacific Southwest Region, we are now able to update our previous study using a complete catalogue of fires ≥80 ha from 1984 to 2010 for the SNFPA area. Based upon fire statistics of all fires on Forest Service (FS) lands, fires ≥80 ha account for approximately 98% of the area burned on FS lands in the SNFPA area over the 1984 to 2010 period. In this contribution, we focused on the three most widely distributed forest types in the SNFPA area, and we extended our original assessment of temporal trends in wildfire severity for the SNFPA area an additional 6 years (2005 to 2010), adding all fires ≥80 ha the occurred on FS lands. We also conducted a statistical assessment of the temporal trend in area of high-severity fire for the target forest types. Finally, we tested for differences in percentage of high severity between small and large fires to determine if fire effects were related to conditions that led to fires getting large.

METHODS

Our study area encompassed the ten national forests managed under the SNFPA (USDA 2004) and managed by the Forest Service Pacific Southwest Region. These include the Eldorado, Inyo, Lassen, Modoc, Plumas, Sequoia, Sierra, Stanislaus, and Tahoe national forests, and the Lake Tahoe Basin Management Unit. The study area included lands within three Ecological Sections (Miles and Goudey 1997): the Sierra Nevada, the Modoc Plateau including the Warner Mountains, and the southern Cascades.

Our study focused on the three most extensive conifer-dominated forest types managed by the Forest Service in the study region: yellow pine (forests and woodlands dominated by ponderosa pine [*Pinus ponderosa* Lawson & C. Lawson] or Jeffrey pine [*P. jeffreyi* Balf.]); mixed conifer (forests with ≥3 codominant conifer species, including various mixtures of ponderosa pine, Jeffrey pine, sugar pine [*P. lambertiana* Douglas], white fir [*Abies concolor* {Gord. and Glend.} Lindl. ex Hildebr.], incense cedar [*Calocedrus decurrens* {Torr.} Florin], Douglas-fir [*Pseudotsuga menziesii* {Mirb.} Franco], and other species); and red fir (forests found above the mixed-conifer belt, dominated by *Abies magnifica* A. Murray bis). Together, these forest types comprise >50 % of the forestlands in our study area. Before Euroamerican settlement, conifer forests throughout the study region primarily experienced wildfires of low and moderate severity. Yellow pine and mixed-conifer forests historically experienced predominantly low-severity fires with mean fire return intervals of 11 to 16 years; red fir forests experienced low- to mixed-severity fires with mean fire return intervals of about 40 years (Sugihara *et al.* 2006, Van de Water and Safford 2011).

The FS maintains a spatial database of fire severity data for most large fires since 1984 that have occurred at least partially on FS lands in California (available online at http://www.fs.usda.gov/main/r5/landmanagement/gis). For our study area, the database includes all wildfires ≥80 ha in size between 1984 and 2010 that occurred at least partially on the SNFPA national forests (286 fires, 190 of which were ≥400 ha). To permit inter-fire comparisons of severity, the severity data we used were developed from the relativized differenced normalized burn ratio (RdNBR) data, which compensate for different pre-fire vegetation conditions (Miller and Thode 2007). The RdNBR data were converted to units of the composite burn index (CBI), which is a field based measure of fire severity, and condensed into four categories (unchanged = 0 to 0.1, low = 0.1 to 1.24, moderate = 1.25 to 2.24, and high = 2.25 to 3.0; Key and Benson 2006, Miller and Thode 2007). Our high-severity category is equal to approximately 95 % change in canopy cover (Miller *et al.* 2009*b*). Forest Service vegetation classification standards specify that forested areas must have at least 10 % pre-fire tree canopy cover (Brohman and Bryant 2005). In forested areas, our high-severity category therefore essentially represents stand-replacing fire (i.e., that in which the forest was reset to an earlier, non-forested seral condition).

Our previous study stratified severity data by forest type using Classification and Assessment with Landsat of Visible Ecological Groupings (CALVEG) maps that are based upon existing vegetation, but also retain information on the location of dominant forest types as they occurred during the mid-1980s (Keeler-Wolf 2007, Miller *et al.* 2009*a*). When characterizing fire regime characteristics over broad scales, it may make more sense to stratify with data that describe the geographic distribution of forest types independently of their seral stage (Van de Water and Safford 2011). Therefore, for this study, we used the LANDFIRE-generated Biophysical Settings (BpS) vegetation layer to stratify our fire severity data (data available online at www.landfire.gov). The BpS data are a combination of potential vegetation modeled using biophysical environment variables (climate, soils, and topography) and the best estimate of the pre-Euroamerican fire regime (Rollins 2009). The BpS vegetation types are based on Nature Serve's Ecological Systems classification system, and are more broad in definition and scale than the National Vegetation Classification System (NVCS) floristic units that CALVEG is based upon (Comer *et al.* 2003, USDA 2008). To determine the accuracy of the BpS vegetation data, we performed an error analysis using forest inventory and analysis (FIA) intensification plots established by the FS for CALVEG map accuracy assessment (Keeler-Wolf 2007, USDA 2008). We only used FIA intensification plots that occurred on FS managed lands, and plots that fell within fires that occurred from 1984 to 2009 were eliminated from the analysis.

Although the FS manages some wildland fires for multiple benefits (habitat creation, fuel reduction, etc.), the vast majority of wildfires are subject to full suppression tactics (van Wagtendonk 2007, North *et al.* 2012). Thus, large fires are almost always the result of ignitions that escape initial attack. Based on the MTBS fire size classification, we chose 400 ha as the division between large (≥400 ha) and small fires (≥80 ha and <400 ha).

We were interested in identifying any underlying trends in percentage and area of high severity. Ordinary least squares (OLS) regression is usually used for testing of linear relationships between variables (Burt and Barber 1996). But OLS is not appropriate for trend analysis of time series because errors about the regression line will typically be autocorrelated. If autocorrelation is ignored, the estimated standard error of the regression line is incorrect, causing any formal inferences concerning trends to be underestimated (Edwards and Coull 1987). Additionally, non-parametric methods that have typically been used to test for trends in time series, such as Mann-Kendall and Spearman rho, have very little predictive power (>0.9 probability of accepting the null hypothesis that there is no trend when in reality there is one) when testing for linear trends with small slopes in short time series with high variance like our severity data (Helsel and Hirsch 2002, Yue *et al.* 2002). Autoregressive Integrated Moving Average (ARIMA) time series regression methods have long been used to develop predictive models of long time series, but have also been used to test for trends in time series on the order of 10 years (Edwards and Coull 1987). We were also not interested in developing predictive models in this manuscript, but only in identifying any underlying trend. As in our previous study, we therefore used ARIMA time series regression to model percentage and area of total high severity per year over time by forest type (Miller *et al.* 2009*a*). For percentage of high severity, we developed ARIMA models for large fires, and all fires ≥80 ha. For area of high severity, we only developed models for all fires ≥80 ha because small fires accounted for only 3 % of the area burned in the three forest types. Percentage and area of high severity sometimes vary widely between successive years. To test whether model significance only occurred for time series ending in particular years, we developed separate models for time series ending in each of the last seven years (e.g., 1984 to 2004, 1984 to 2005… and 1984 to 2010). Model goodness-of-fit was assessed using the Akaike information criterion (AIC) (Shumway 1988). Percent values were arcsine-square root transformed and area data were log-transformed prior to model development to satisfy normality requirements.

We used a Generalized Linear Mixed Model (GLMM) to test for differences in percentage of high severity between large and small fires. Fire size (i.e., large or small) crossed by forest type was the fixed effect, and fires were considered a random effect because the percentage of high severity at which a forest type will burn can differ between fire events. A *post hoc* test was used to compare differences in mean percentage of high severity per fire between large and small fires. Interactions were limited to forest types. We set $\alpha = 0.05$, and used the Tukey-Kramer adjustment to account for multiple comparisons (Kramer 1956). Percent high-severity values were arcsine-square root transformed to satisfy normality requirements.

Finally, we tested for any trend in the number of large fires that burned on FS lands in the three major forest types using ARIMA regression. Advances in wildfire suppression technology after World War II have generally been credited with ushering in the modern fire suppression era (Pyne 1982). We therefore limited our analysis of number of large fires to 1950 to 2010. For fires before 1984, we used fire perimeters from the fire history database for the state of California (available online at http://frap.cdf.ca.gov/data/frapgisdata/select.asp). For fires since 1984, we used the number of fires from our severity database.

RESULTS

Our analysis of how mapped BpS forest types correspond to CALVEG forest types as determined empirically by FIA plots indicates considerable confusion between mixed conifer and yellow pine types (Table 1). The BpS red fir vs. FIA-CALVEG red fir comparison shows slightly better correspondence, with BpS mapping error occurring mostly within the lodge-

Table 1. Confusion matrix of BpS mapped forest type to CALVEG vegetation type based upon Forest Inventory and Analysis (FIA) intensification plots.

CALVEG alliance[a]	Mixed conifer	Yellow pine	Red fir	Other	Total
Pacific Douglas-fir	26	0	0	7	33
Douglas-fir-ponderosa pine	24	3	0	5	32
Eastside pine	22	62	2	25	111
Yellow pine-western juniper	7	8	0	9	24
Jeffrey pine	11	73	20	8	112
Lodgepole pine	3	4	22	13	42
Mixed conifer-giant sequoia	21	3	0	1	25
Incense cedar	8	0	0	5	13
Mixed conifer-fir	43	40	39	16	138
Mixed conifer-pine	144	35	4	22	205
Ponderosa pine	55	34	0	8	97
Ponderosa pine-white fir	12	1	0	1	14
Red fir	0	1	68	3	72
Subalpine conifers	5	0	39	11	55
White fir	42	12	18	15	87
Other	31	17	18	64	130
Total	454	293	230	213	1190

[a] See USDA 2008 for alliance descriptions.

pole pine, mixed conifer-fir, and subalpine conifer types. To minimize any effect of BpS mapping error, we combined the yellow pine and mixed conifer types and carried out all analyses on two forest type groupings: yellow pine-mixed conifer (YPMC), and red fir (RF). Of the 318 192 ha burned from 1984 to 2010 in fires ≥80 ha, 86 % was in YPMC and 14 % was in RF (Table 2).

All ARIMA time series regression models of percent high severity per year for YPMC in fires ≥80 ha indicated a significant positive linear trend (Table 3 and Figure 1). The ARIMA models of YPMC in large fires for time series ending in years 2007 to 2010 also indicated a significant positive linear trend (Table 4 and Figure 2). The ARIMA modeling for YPMC in small fires, and all fire sizes in RF, produced no models with a significant trend (results not shown). The GLMM results indicate that the percentage of high severity per fire for YPMC in small fires was significantly smaller (adjusted $P < 0.001$) than in large fires over the 1984 to 2010 period, but for RF the percentage of high severity per fire in small fires was only marginally significantly smaller than for large fires (adjusted $P = 0.068$).

With respect to area of high-severity fire per year, YPMC in fires ≥80 ha showed a significant positive linear trend for time series ending in years 2007 to 2010 (Table 5 and Figure 3). Using a purely linear model (ARIMA modeling indicated no significant autoregressive lags), the temporal trend for high-severity fire area for RF in fires ≥80 ha was marginally significant ($P = 0.061$, $r^2 = 0.164$; data not shown).

There was a significantly positive trend ($P = 0.019$) in the number of large fires over the 1950 to 2010 period (Figure 4). From 1950 through 1993 (44 years), there were 11 years (25 %) without any large fires. Prior to 1993, eight years (1968 to 1975) was the longest period during which large fires occurred every year. Large fires occurred every year after 1993 (17 years). Three of the years without any large fires (1985, 1991, and 1993) fell into the first half of the 1984 to 2010 period over which the trends analyses were performed.

DISCUSSION

Our analyses indicate that, on FS lands in our study area, the proportion of annual wildfire burning at high severity increased significantly in YPMC forests when all fires ≥80 ha were considered (Figure 1). When only large fires were considered, the increasing trend was significant only for time series ending in the last four years (2007 to 2010). However, the trend lines for large fire time series ending in the first three years (2004 to 2006) were very similar to the significant trend lines from series ending in the last four years (Figure 2). The

Table 2. Area burned by fire size and forest type.

Fire size (ha)	Forest type	Unchanged + low (ha)	Moderate (ha)	High (ha)	Total* (ha)	Unchanged + low (%)	Moderate (%)	High (%)
<400	yellow pine-mixed conifer	4 754	2 024	1 483	8 261	57.5	24.5	18.0
	red fir	1 870	546	201	2 617	71.5	20.8	7.7
≥400	yellow pine-mixed conifer	95 309	80 291	88 615	264 255	36.1	30.4	33.5
	red fir	25 798	9 856	7 403	43 060	59.9	22.9	17.2
Total		127 732	92 717	97 702	318 192	40.1	29.1	30.7

* Includes area that could not be mapped (degree of severity was not assessed).

Table 3. Regression statistics for ARIMA time series modeling of percent of high-severity fire per year for yellow pine-mixed conifer forests, for fires ≥80 ha 1984 to 2010.

	Last year in model						
Model statistic	**2010**	**2009**	**2008**	**2007**	**2006**	**2005**	**2004**
Parameter estimates							
Model variance (sigma squared)	0.0079	0.0080	0.0082	0.0083	0.0087	0.0086	0.0092
Intercept	0.3018	0.2996	0.3014	0.3038	0.3060	0.3024	0.3030
Linear trend	0.0027	0.0030	0.0028	0.0025	0.0023	0.0027	0.0026
Autoregressive function (AR) 1	–0.9501	–0.9185	–0.9380	–0.9674	–0.9373	–0.9526	–0.9509
AR 2	–0.7800	–0.7314	–0.7777	–0.7702	–0.7352	–0.7505	–0.7429
AR 3	–0.6472	–0.5725	–0.5748	–0.5695	–0.5489	–0.5933	–0.5933
AR 4	–0.5099	–0.4937	–0.4812	–0.4897	–0.4648	–0.4707	–0.4718
P (linear)	<0.001	<0.001	0.002	0.008	0.031	0.017	0.036
P (AR 1)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
P (AR 2)	0.006	0.011	<0.001	0.011	0.019	0.017	0.022
P (AR 3)	0.014	0.038	0.041	0.045	0.060	0.044	0.052
P (AR 4)	0.016	0.021	0.026	0.025	0.041	0.038	0.046
Statistics of fit							
Number of observations	27	26	25	24	23	22	21
Number of missing actuals	0	0	0	0	0	0	0
Number of model parameters	6	6	6	6	6	6	6
Mean square error	0.007	0.007	0.007	0.007	0.007	0.007	0.007
Root mean square error	0.081	0.081	0.082	0.082	0.083	0.082	0.084
Mean absolute percent error	20.124	19.560	19.703	19.825	20.263	18.924	19.640
Mean absolute error	0.066	0.065	0.066	0.067	0.068	0.064	0.066
R^2	0.561	0.561	0.566	0.582	0.540	0.560	0.561
adjusted R^2	0.456	0.452	0.452	0.465	0.405	0.423	0.415
Akaike information criterion	–123.514	–118.436	–113.120	–108.025	–102.520	–97.849	–91.927

three years without any large fires, coupled with fewer data values in the earlier time series, led to progressively higher model variances and larger AIC values as the number of years in the time series decreased (Table 3). The ARIMA methods have normally been used for modeling densely sampled multi-year time series, with daily to quarterly time steps (De Gooijer and Hyndman 2006). It is most likely, given the AIC values and consistency of the non-significant trend lines, that the non-significance of the three shortest time series models was due to our short and sparsely sampled time series, and not to variation in the severity data. We did not find any trend in percentage of high severity for fires of any size in RF forests. Finally, our trend analyses also indicate that the annual area of high-severity fire increased during the 1984 to 2010 period in YPMC forests. The trend in the RF area was also up during this period, although it was of marginal statistical significance. These results confirm and

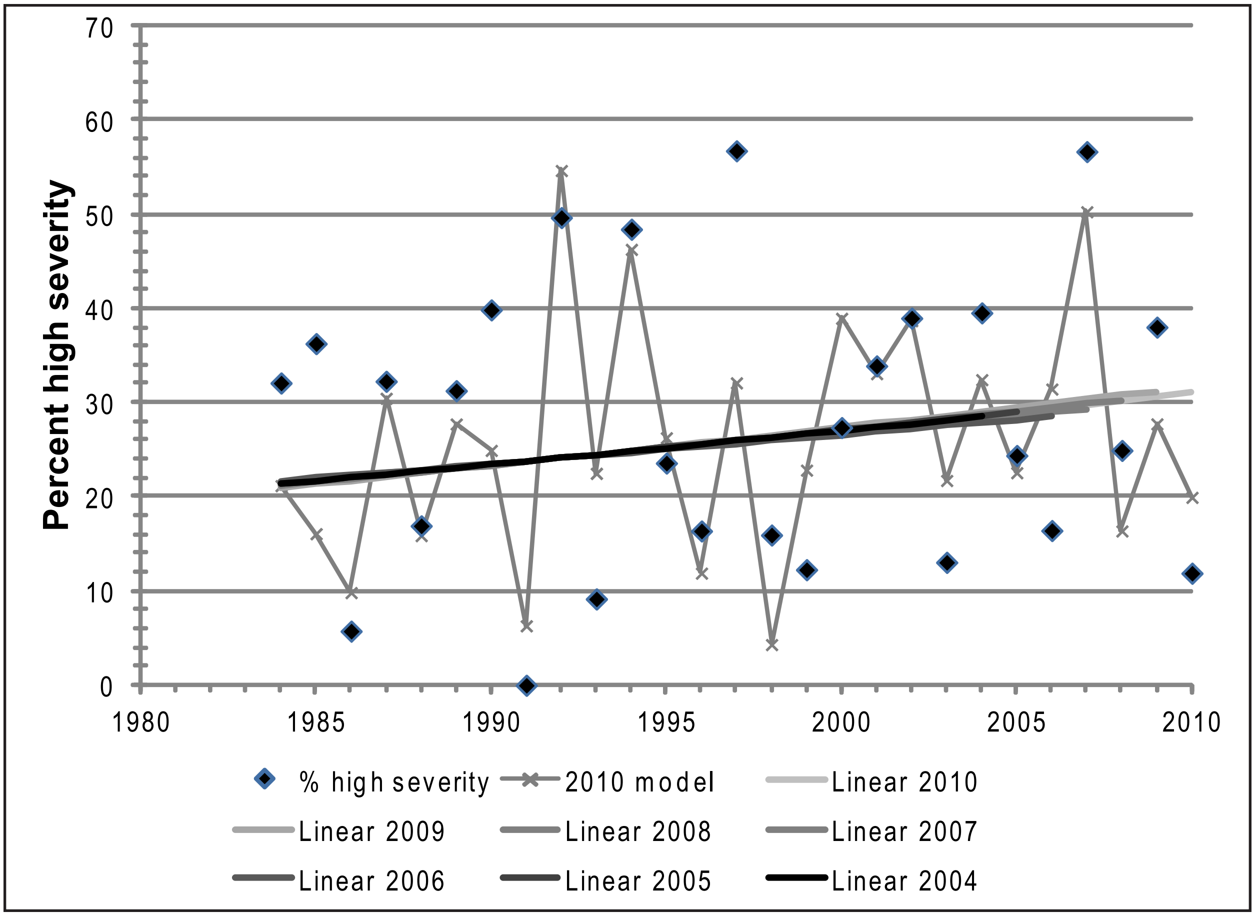

Figure 1. Temporal trends in percentage of high-severity fire for yellow pine-mixed conifer (YPMC) forest types in fires ≥80 ha in the study area between 1984 and 2010. Data shown are yearly percentages of high severity, ARIMA model for the 1984 to 2010 time series, and linear trend lines for seven time series ending in years 2004 to 2010.

temporally extend the results previously published based upon a smaller set of fires >40 ha over a shorter, 21-year period (Miller *et al.* 2009*a*).

Our results suggest that the positive trend in percentage of high severity in YPMC in our study area is due to two factors: 1) an increase in the percentage of high severity in large fires, and 2) the absence of years without any large fires after 1993. The second factor is important because we found that large fires had a significantly greater percentage of high severity in YPMC forests than did small fires. More years with large fires and increasing areas of high severity over the 1984 to 2010 period are consistent with observed increases in the number of large fires across the western US that have increasing percentages of high severity with increasing annual areas burned, and predictions of more large fires due to climate change (Westerling *et al.* 2006, Lenihan *et al.* 2008, Westerling and Bryant 2008, Littell *et al.* 2009, Lutz *et al.* 2009). If the relationship of a greater percentage of high severity in large fires compared with small fires can be assumed to apply over the whole modern suppression era, the increase in number of large fires not only indicates an overall increase in fire area, but also an increase in high-severity area over the longer 1950 to 2010 period, primarily driven by the 17 consecutive years of large fires after 1993.

Table 4. Regression statistics for ARIMA time series modeling of percent of high-severity fire per year for yellow pine-mixed conifer forests, fires ≥400 ha 1984 to 2010.

	Last year in model						
	2010	**2009**	**2008**	**2007**	**2006**	**2005**	**2004**
Parameter estimates							
Model variance (sigma squared)	0.0079	0.0078	0.0081	0.0084	0.0090	0.0088	0.0096
Intercept	0.3064	0.2986	0.3020	0.3055	0.3085	0.3009	0.3015
Linear trend	0.0028	0.0034	0.0031	0.0028	0.0026	0.0033	0.0032
Autoregressive function (AR) 1	–0.8560	–0.7972	–0.8108	–0.8302	–0.8031	–0.8228	–0.8169
AR 2	–0.6782	–0.5829	–0.6183	–0.6108	–0.5812	–0.5924	–0.5816
AR 3	–0.5713	–0.4404	–0.4414	–0.4403	–0.4232	–0.4638	–0.4583
AR 4	–0.5686	–0.5388	–0.5272	–0.5345	–0.5170	–0.5196	–0.5161
P (linear)	0.011	0.008	0.019	0.046	0.110	0.056	0.096
P (AR 1)	<0.001	0.001	0.002	0.002	0.004	0.004	0.005
P (AR 2)	0.023	0.053	0.051	0.057	0.086	0.079	0.099
P (AR 3)	0.039	0.127	0.135	0.140	0.174	0.139	0.160
P (AR 4)	0.008	0.012	0.016	0.016	0.026	0.026	0.035
Statistics of fit							
Number of observations	27	26	25	24	23	22	21
Number of missing actuals	3	3	3	3	3	3	3
Number of model parameters	6	6	6	6	6	6	6
Mean square error	0.008	0.007	0.008	0.008	0.008	0.008	0.009
Root mean square error	0.088	0.086	0.088	0.089	0.091	0.090	0.092
Mean absolute percent error	25.924	24.491	25.293	26.260	27.334	26.154	27.500
Mean absolute error	0.074	0.071	0.073	0.075	0.078	0.074	0.078
R^2	0.379	0.386	0.376	0.386	0.303	0.331	0.330
adjusted R^2	0.207	0.205	0.182	0.182	0.054	0.074	0.050
Akaike information criterion	–104.805	–100.641	–94.900	–89.444	–83.796	–79.534	–73.745

The impact that missing data values in the YPMC large fire time series had on model significance has implications for the time and geographic scales at which these types of trend analyses can be carried out. A sufficient number of data values are required in the time series to develop statistical models of trend. Thus, the geographic area needs to be large enough to record fires in all successive years, or the time series needs to be of a long duration, or both. There were no national forests in our study area in which fires ≥80 ha occurred every year during the 1984 to 2010 period, therefore performing a time series analysis at the forest level was not appropriate. Fire behavior in individual fires is influenced by local weather, topography, and vegetation, but is also influenced by regional climate patterns (Pyne *et al.* 1996, Lenihan *et al.* 2008, Westerling and Bryant 2008, Littell *et al.* 2009). As a result, we chose to cover the whole SNFPA area in one analysis, which is similar in scale

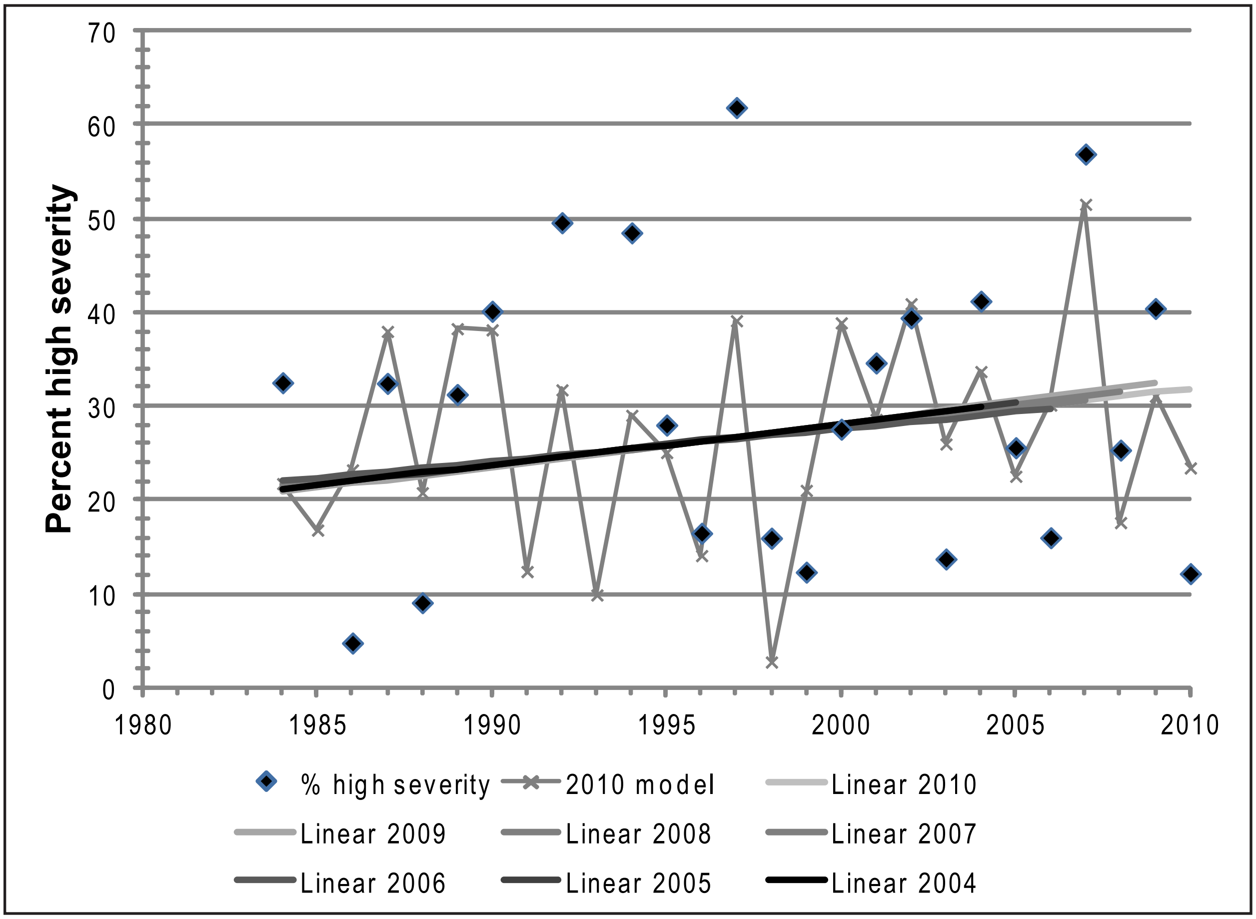

Figure 2. Temporal trends in percentage of high-severity fire for yellow pine-mixed-conifer (YPMC) forest types in fires ≥400 ha in the study area between 1984 and 2010. Data shown are yearly percentages of high severity, ARIMA model for the 1984 to 2010 time series, and linear trend lines for seven time series ending in years 2004 to 2010. Linear trends for the three shorter time series ending in 2004, 2005, and 2006 are not significant ($P > 0.05$), but they are consistent with the significant trend lines for time series ending in the last four years.

to other recent regional assessments of severity (e.g., Dillon *et al.* 2011, Miller *et al.* 2012*b*).

Two previous studies within our larger study area, conducted in Yosemite National Park (NP), with fully populated severity data time series from fires >40 ha of 22 years and 26 years, respectively, found no trend in percentage of high severity (Lutz *et al.* 2009, Lutz *et al.* 2011). However, we do not believe that differences in geographic scale led to the different results. While changing climate has likely played a part in the increasing trends on FS lands in the SNFPA area, we believe that differences in fire management policies between the FS and Yosemite NP at least partially explain current differences in percentages of high severity per fire, high-severity patch size, and fire size, all of which are significantly smaller in Yosemite NP (Miller *et al.* 2012*c*). Based upon the evidence from Yosemite, a shift in FS fire management policy similar to Yosemite's may have some effect on lowering the proportion of high severity on FS lands.

Although the FS has had a policy of managing wildland fires for multiple benefits since 1974 (when it was known as "prescribed natural fire"), immediate suppression has been, and continues to be, the most common fire man-

Table 5. Regression statistics for ARIMA time series models of area of high-severity fire per year in yellow pine-mixed-conifer forests, fires ≥80 ha, 1984 to 2010.

	Last year in model						
Model statistic	**2010**	**2009**	**2008**	**2007**	**2006**	**2005**	**2004**
Parameter estimates							
Model variance (sigma squared)	0.8409	0.8014	0.8165	0.8117	0.8221	0.8726	1.0163
Intercept	2.2390	2.1572	2.1088	2.1729	2.2357	2.2204	2.2177
Linear trend	0.0450	0.0531	0.0580	0.0508	0.0436	0.0455	0.0501
Autoregressive function (AR) 1	–0.2960	–0.3018	–0.2734	–0.3108	–0.2875	–0.2949	–0.3796
AR 2	0.1720	0.2303	0.2719	0.2857	0.3211	0.3159	
AR 3	–0.1589	–0.0998	–0.1117	–0.0676	–0.0636	–0.0628	
AR 4	–0.4137	–0.4334	–0.4715	–0.4652	–0.4556	–0.4443	
P (linear)	0.008	0.005	0.005	0.018	0.063	0.078	0.083
P (AR 1)	0.151	0.134	0.186	0.143	0.181	0.190	0.096
P (AR 2)	0.424	0.284	0.228	0.206	0.168	0.189	
P (AR 3)	0.465	0.644	0.609	0.762	0.778	0.787	
P (AR 4)	0.059	0.043	0.035	0.037	0.043	0.060	
Statistics of fit							
Number of observations	27	26	25	24	23	22	21
Number of missing actuals	0	0	0	0	0	0	0
Number of model parameters	6	6	6	6	6	6	3
Mean square error	0.673	0.639	0.649	0.635	0.634	0.661	0.873
Root mean square error	0.820	0.799	0.806	0.797	0.796	0.813	0.934
Mean absolute percent error	24.994	24.125	24.038	23.570	22.365	23.334	30.171
Mean absolute error	0.668	0.654	0.649	0.639	0.612	0.633	0.734
R^2	0.338	0.391	0.400	0.402	0.383	0.384	0.221
adjusted R^2	0.180	0.239	0.241	0.236	0.202	0.191	0.134
Akaike information criterion	1.305	0.343	1.211	1.114	1.507	2.886	3.137

agement response on FS lands in our study area (van Wagtendonk 2007, USDA-USDI 2009). When fire suppression policies such as those practiced by the FS are in force, large fires typically result under conditions in which initial attack is unsuccessful (due to, e.g., difficult weather or topographic conditions), or when firefighting resources are inadequate (Podur and Martell 2007, Finney *et al.* 2011). Severe weather conditions that characterize many escaped wildfires (dry, hot, and windy) commonly result in substantial loss of forest tree cover. Small fires on FS lands are usually the result of more moderate weather, or topographic or situational conditions that are not conducive to fire growth, allowing suppression efforts to be successful. In contrast, Yosemite NP has followed a policy since 1972 of allowing most lightning ignitions to burn unimpeded under prescribed conditions (van Wagtendonk 2007). As a result, Yosemite has had many areas burn multiple times with large proportions

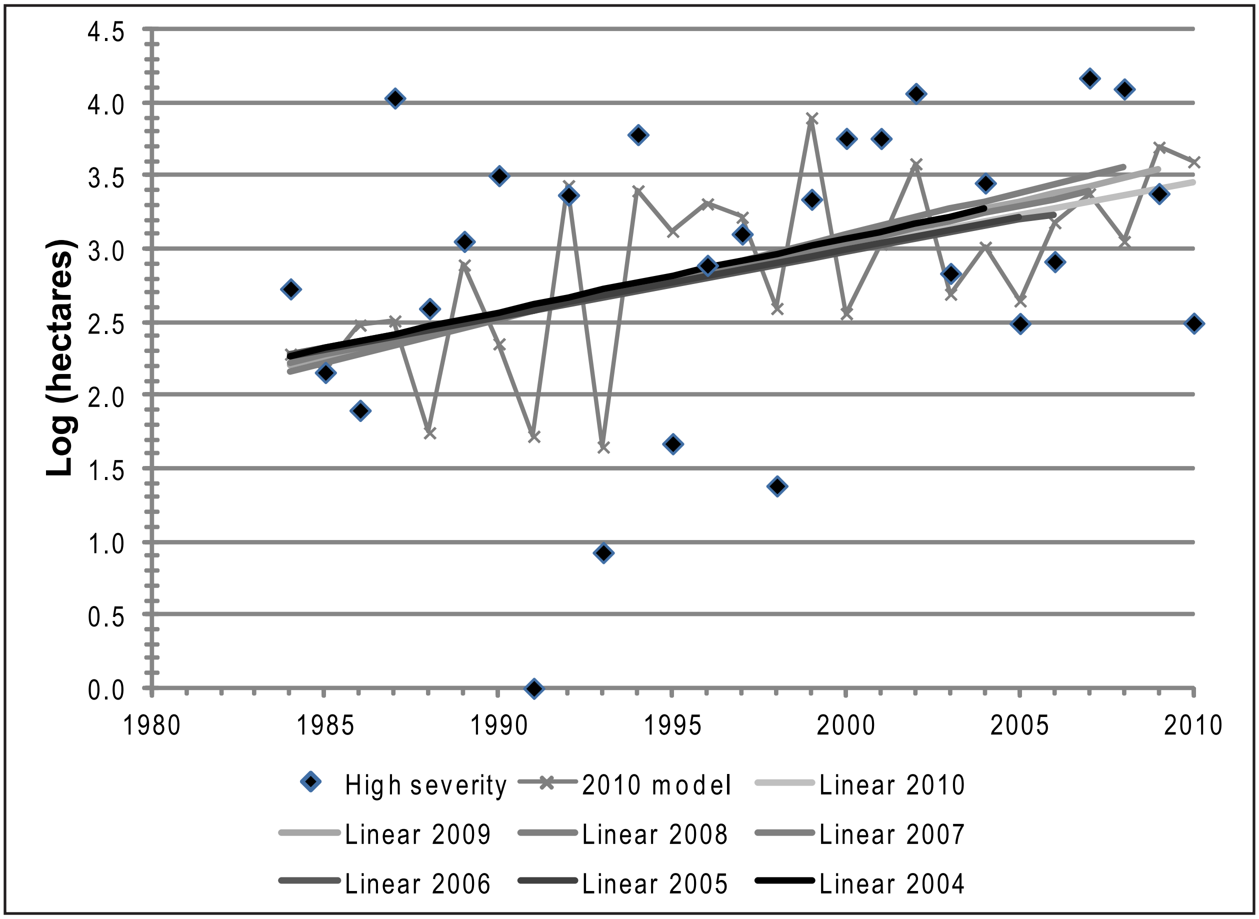

Figure 3. Temporal trends in area of high-severity fire for yellow pine-mixed-conifer (YPMC) forest types in fires ≥80 ha in the study area between 1984 and 2010. Data shown are yearly percentages of high severity, ARIMA model for the 1984 to 2010 time series, and linear trend lines for seven time series ending in years 2004 to 2010. Linear trends for the three shorter time series ending in 2004, 2005, and 2006 are not significant ($P > 0.05$), but they are consistent with the significant trend lines for time series ending in the last four years.

at low to moderate severity, and retains percentages of high severity that are more similar to the pre-Euroamerican settlement fire regime (Collins *et al.* 2009, Miller *et al.* 2012*c*, van Wagtendonk *et al.* 2012).

The difference we see in severity trends between YPMC and RF forest types is probably largely due to the different environments and natural fire regimes that characterize them. The YPMC forests in our study area historically supported fires dominated by low- and mixed-severity effects (van Wagtendonk and Fites-Kaufman 2006, Stephens *et al.* 2007, Scholl and Taylor 2010, Perry *et al.* 2011, Van de Water and Safford 2011). In these forests on FS land, >80 years of fire suppression, a century and half of timber harvest, and other management practices have led to major changes in forest composition and structure, and increases in density and fuel-loading (Scholl and Taylor 2010, Collins *et al.* 2011, Perry *et al.* 2011, Kane *et al.* 2013). Red fir forests grow at higher elevations in our study area, where winter snowpack is at its deepest and timber harvest has had much less impact on forest conditions (Potter 1998). Productivity in red fir forests is also much lower than in the YPMC (Barbour *et al.* 2007), and fire re-

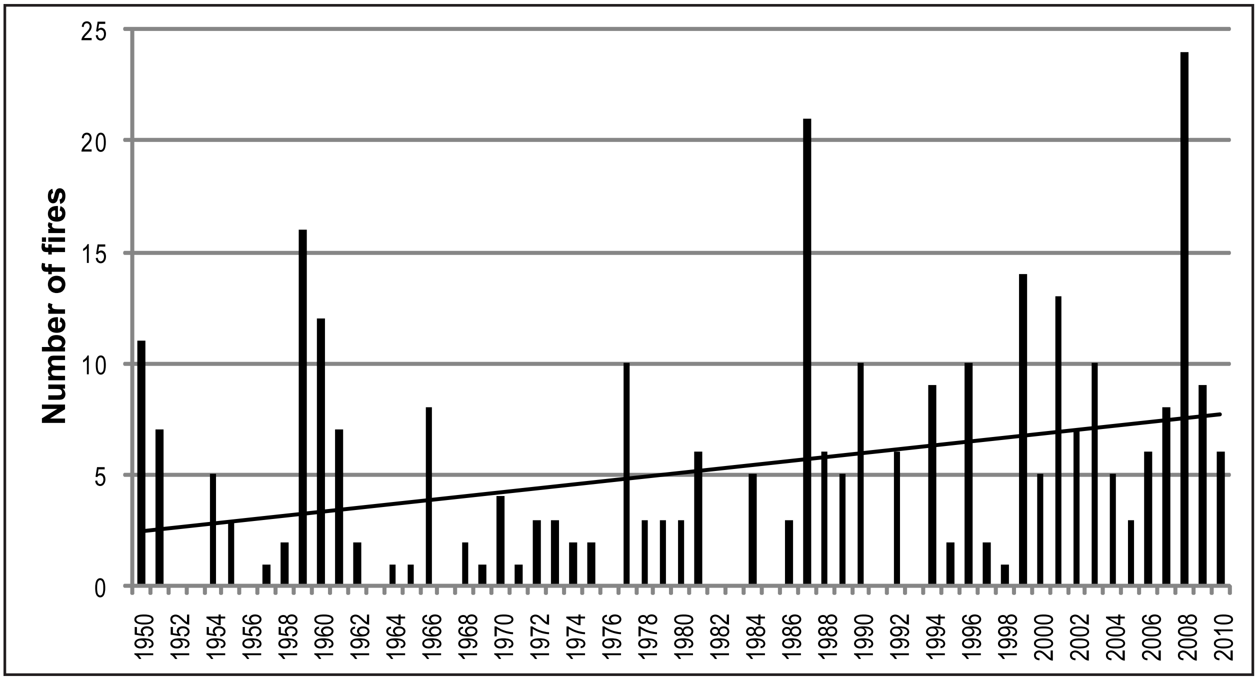

Figure 4. Number of fires >400 ha per year that burned in at least one of the three major forest types in the study area. Linear trend line (shown) for years 1950 to 2010 is significant at $P = 0.019$.

turn intervals before Euroamerican settlement were generally three to four times longer in RF than in YPMC (Van de Water and Safford 2011). As a result, most red fir forests have only missed one to three fire cycles, and therefore the ecosystem impacts of fire suppression have not been as extreme. Climate has been warming across the Sierra Nevada, and precipitation has been steady to increasing over the last century (Safford *et al.* 2012). Consultation of climate station records from the Sierra Nevada (Crimmins *et al.* 2011, WRCC 2012) provides no evidence of differential warming or changes in precipitation or climatic water deficit at elevations characteristic of YPMC vs. RF forests, however the decreasing ratio of snow to rain is likely resulting in drier fuels and less influence of snowpack on fire occurrence and behavior in the red fir belt, where precipitation is predominantly snow. By first principles, we would expect this to increase fire activity and severity in RF forests, but we did not find a statistical signal for increases in either variable in our study. The Miller *et al.* (2012*c*) study comparing fire size and severity in Yosemite NP vs. FS managed lands in the Sierra Nevada showed that the percentage of high severity fire in YPMC and RF forests was 2.4 and 2.2 times higher, respectively, on FS lands. Climates have been changing at similar rates and in similar directions in Yosemite NP and surrounding FS lands so that the very different fire patterns in the two jurisdictions are most likely due to different management histories and contemporary policies of fire management.

Overall, our results confirm that forests of eastern California and western Nevada form part of the southwestern US pattern, documented by Dillon *et al.* (2011), in which temporal trends over the last two to three decades show statistical increases in the area of high-severity fire per year. Like the southern Rockies, in some forest types in our study area, the increase in overall fire area is being compounded by a proportional increase in the high-severity component of large fires. These trends have important implications for the viability of strategies to manage SNFPA area forests for carbon storage to temper the effects of climate change (e.g., Executive Order No. 13514: "Federal Leadership in Environmental, Energy, and Economic Performance" October 5, 2009), or for animal species. Other research predicts continued warming trends, longer summer droughts, increasing forest fuels, and larger and more severe fires in our study area (Westerling *et al.* 2006, Lenihan *et al.* 2008, Westerling and Bryant 2008, Littell *et al.* 2009, Lutz *et al.* 2009). If high-severity fire continues to increase in concert with area burned, increasing areas of old forest will be lost, emissions will rise, and fewer large diameter conifers—which store the most carbon and play a variety of other keystone ecological roles—will be retained (Hurteau and Brooks 2011, National Research Council 2011, North and Hurteau 2011, Lutz *et al.* 2012).

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LITERATURE CITED

Barbour, M.G., T. Keeler-Wolf, and A.A. Schoenherr, editors. 2007. Terrestrial vegetation of California. Third edition. University of California Press, Berkeley, USA. doi: 10.1525/california/9780520249554.001.0001

Brohman, R., and L. Bryant, editors. 2005. Existing vegetation classification and mapping technical guide. USDA Forest Service General Technical Report WO-67, Washington Office, Ecosystem Management Coordination Staff, Washington, D.C., USA.

Burt, J.E., and G.M. Barber. 1996. Elementary statistics for geographers. Second edition. The Guilford Press, New York, New York, USA.

Calkin, D.E., K.M. Gebert, J.G. Jones, and R.P. Neilson. 2005. Forest Service large fire area burned and suppression expenditure trends, 1970-2002. Journal of Forestry 103: 179-183.

Collins, B.M., R.G. Everett, and S.L. Stephens. 2011. Impacts of fire exclusion and recent managed fire on forest structure in old growth Sierra Nevada mixed-conifer forests. Ecosphere 2: art51. doi: 10.1890/ES11-00026.1

Collins, B.M., J.D. Miller, A.E. Thode, M. Kelly, J.W. van Wagtendonk, and S.L. Stephens. 2009. Interactions among wildland fires in a long-established Sierra Nevada natural fire area. Ecosystems 12: 114-128. doi: 10.1007/s10021-008-9211-7

Comer, P., D. Faber-Langendoen, R. Evans, S. Gawler, C. Josse, G. Kittel, S. Menard, M. Pyne, M. Reid, K. Schulz, K. Snow, and J. Teague. 2003. Ecological systems of the United States: a working classification of US terrestrial systems. NatureServe, Arlington, Virginia, USA.

Crimmins, S.M., S.Z. Dobrowski, J.A. Greenberg, J.T. Abatzoglou, and A.R. Mynsberge. 2011. Changes in climatic water balance drive downhill shifts in plant species' optimum elevations. Science 331: 324-327. doi: 10.1126/science.1199040

De Gooijer, J.G., and R.J. Hyndman. 2006. 25 years of time series forecasting. International Journal of Forecasting 22: 443-473. doi: 10.1016/j.ijforecast.2006.01.001

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: art130.

Edwards, D., and B.C. Coull. 1987. Autoregressive trend analysis: an example using long-term ecological data. OIKOS 50: 95-102. doi: 10.2307/3565405

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(1): 3-21. doi: 10.4996/fireecology.0301003

Finney, M.A., C.W. McHugh, I.C. Grenfell, K.L. Riley, and K.C. Short. 2011. A simulation of probabilistic wildfire risk components for the continental United States. Stochastic Environmental Research and Risk Assessment 25: 973-1000. doi: 10.1007/s00477-011-0462-z

Helsel, D.R., and R.M. Hirsch. 2002. Statistical methods in water resources. Chapter A3 of book 4, Hydrologic analysis and interpretation. Techniques of water-resources investigations of the United States Geological Survey. US Geological Survey, Washington, D.C., USA.

Hurteau, M.D., and M.L. Brooks. 2011. Short- and long-term effects of fire on carbon in US dry temperate forest systems. BioScience 61: 139-146. doi: 10.1525/bio.2011.61.2.9

Kane, V.R., J.A. Lutz, S.L. Roberts, D.F. Smith, R.J. McGaughey, N.A. Povak, and M.L. Brooks. 2013. Landscape-scale effects of fire severity on mixed-conifer and red fir forest structure in Yosemite National Park. Forest Ecology and Management 287: 17-31. doi: 10.1016/j.foreco.2012.08.044

Keeler-Wolf, T. 2007. The history of vegetation classification and mapping in California. Pages 1-42 in: M.G. Barbour, T. Keeler-Wolf, and A.A. Schoenherr, editors. Terrestrial vegetation of California. University of California Press, Berkeley, USA.

Key, C.H., and N.C. Benson. 2006. Landscape assessment: ground measure of severity, the Composite Burn Index. Pages LA8-LA15 in: D.C. Lutes, editor. FIREMON: Fire Effects Monitoring and Inventory System. USDA Forest Service General Technical Report 164-CD, Rocky Mountain Research Station, Fort Collins, Colorado, USA.

Kramer, C.Y. 1956. Extension of multiple range tests to group means with unequal number of replications. Biometrics 12: 307-310. doi: 10.2307/3001469

Lenihan, J., D. Bachelet, R. Neilson, and R. Drapek. 2008. Response of vegetation distribution, ecosystem productivity, and fire to climate change scenarios for California. Climatic Change 87: S215-S230. doi: 10.1007/s10584-007-9362-0

Littell, J.S., D. McKenzie, D.L. Peterson, and A.L. Westerling. 2009. Climate and wildfire area burned in western US ecoprovinces, 1916-2003. Ecological Applications 19: 1003-1021. doi: 10.1890/07-1183.1

Lutz, J., J. van Wagtendonk, A. Thode, J. Miller, and J. Franklin. 2009. Climate, lightning ignitions, and fire severity in Yosemite National Park, California, USA. International Journal of Wildland Fire 18: 765-774. doi: 10.1071/WF08117

Lutz, J.A., A.J. Larson, M.E. Swanson, and J.A. Freund. 2012. Ecological importance of large-diameter trees in a temperate mixed-conifer forest. PLoS ONE 7: e36131. doi: 10.1371/journal.pone.0036131

Lutz, J.A., C.H. Key, C.A. Kolden, J.T. Kane, and J.W. van Wagtendonk. 2011. Fire frequency, area burned, and severity: a quantitative approach to defining a normal fire year. Fire Ecology 7: 51-65. doi: 10.4996/fireecology.0702051

Miles, S.R., and C.B. Goudey. 1997. Ecological subregions of California: section and subsection descriptions. USDA Forest Service Report R5-EM-TP-005, Pacific Southwest Region, Vallejo, California, USA.

Miller, J.D., B.M. Collins, J.A. Lutz, S.L. Stephens, J.W. van Wagtendonk, and D.A. Yasuda. 2012*c*. Differences in wildfires among ecoregions and land management agencies in the Sierra Nevada region, California, USA. Ecosphere 3: art80. doi: 10.1890/ES12-00158.1

Miller, J.D., E.E. Knapp, C.H. Key, C.N. Skinner, C.J. Isbell, R.M. Creasy, and J.W. Sherlock. 2009*b*. Calibration and validation of the Relative differenced Normalized Burn Ratio (RdNBR) to three measures of fire severity in the Sierra Nevada and Klamath Mountains, California, USA. Remote Sensing of Environment 113: 645-656. doi: 10.1016/j.rse.2008.11.009

Miller, J.D., and H.D. Safford. 2008. Sierra Nevada fire severity monitoring: 1984-2004. USDA Forest Service Report R5-TP-027, Pacific Southwest Region, Vallejo, California, USA.

Miller, J.D., H.D. Safford, M.A. Crimmins, and A.E. Thode. 2009*a*. 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

Miller, J.D., C.N. Skinner, H.D. Safford, E.E. Knapp, and C.M. Ramirez. 2012*a*. Trends and causes of severity, size and number of fires in northwestern California, USA. Ecological Applications 22: 184-203. doi: 10.1890/10-2108.1

Miller, J.D., C.N. Skinner, H.D. Safford, E.E. Knapp, and C.M. Ramirez. 2012*b*. Northwestern California national forests fire severity monitoring 1987-2008. USDA Forest Service Report R5-TP-0035, Pacific Southwest Region, Vallejo, California, USA.

Miller, J.D., and A.E. Thode. 2007. Quantifying burn severity in a heterogeneous landscape with a relative version of the delta Normalized Burn Ratio (dNBR). Remote Sensing of Environment 109: 66-80. doi: 10.1016/j.rse.2006.12.006

National Research Council. 2011. Climate stabilization targets: emissions, concentrations, and impacts over decades to millennia. The National Academies Press, Washington, D.C., USA.

North, M.P., and M.D. Hurteau. 2011. High-severity wildfire effects on carbon stocks and emissions in fuels treated and untreated forest. Forest Ecology and Management 261: 1115-1120. doi: 10.1016/j.foreco.2010.12.039

North, M.P., B.M. Collins, and S.L. Stephens. 2012. Using fire to increase the scale, benefits and future maintenance of fuels treatments. Journal of Forestry 110: 392-401. doi: 10.5849/jof.12-021

Perry, D.A., P.F. Hessburg, C.N. Skinner, T.A. Spies, S.L. Stephens, A.H. Taylor, J.F. Franklin, B. McComb, and G. Riegel. 2011. The ecology of mixed severity fire regimes in Washington, Oregon, and northern California. Forest Ecology and Management 262: 703-717. doi: 10.1016/j.foreco.2011.05.004

Podur, J.J., and D.L. Martell. 2007. A simulation model of the growth and suppression of large forest fires in Ontario. International Journal of Wildland Fire 16: 285-294. doi: 10.1071/WF06107

Potter, D.A. 1998. Forested communities of the upper montane in the central and southern Sierra Nevada. USDA Forest Service General Technical Report PSW-GTR-169, Pacific Southwest Research Station, Albany, California, USA.

Pyne, S.J. 1982. Fire in America: a cultural history of wildland and rural fire. University of Washington Press, Seattle, USA.

Pyne, S.J., P.L. Andrews, and R.D. Laven. 1996. Introduction to wildland fire. Second edition. John Wiley & Sons, New York, New York, USA.

Rollins, M.G. 2009. LANDFIRE: a nationally consistent vegetation, wildland fire, and fuel assessment. International Journal of Wildland Fire 18: 235-249. doi: 10.1071/WF08088

Safford, H.D., M.P. North, and M.D. Meyer. 2012. Climate change and the relevance of historical forest conditions. Pages 23-45 in: M.P. North, editor. Managing Sierra Nevada forests. USDA Forest Service General Technical Report PSW-GTR-237, Pacific Southwest Research Station, Albany, California, USA.

Scholl, A.E., and A.H. Taylor. 2010. Fire regimes, forest change, and self-organization in an old-growth mixed-conifer forest, Yosemite National Park, USA. Ecological Applications 20: 362-380. doi: 10.1890/08-2324.1

Shumway, R.H. 1988. Applied statistical time series analysis. Prentice Hall, Englewood Cliffs, New Jersey, USA.

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. doi: 10.1016/j.foreco.2007.06.005

Sugihara, N.G., J.W. van Wagtendonk, K.E. Shaffer, J. Fites-Kaufman, and A.E. Thode, editors. 2006. Fire in California's ecosystems. University of California Press, Berkeley, USA. doi: 10.1525/california/9780520246058.001.0001

USDA [US Department of Agriculture]. 2004. Sierra Nevada forest plan amendment final supplemental environmental impact statement. USDA Forest Service Report R5-MB-046, Pacific Southwest Region, Vallejo, California, USA.

USDA [US Department of Agriculture]. 2008. CALVEG zones and alliances—vegetation descriptions. USDA Forest Service, Pacific Southwest Region, Remote Sensing Lab, Vallejo, California, USA. <http://www.fs.usda.gov/detail/r5/landmanagement/resourcemanagement/?cid=stelprdb5347192>. Accessed 15 March 2012.

USDA-USDI [US Department of Agriculture-US Department of the Interior]. 2009. Page 20 in: Guidance for implementation of federal wildland fire management policy (February 2009). US Department of Agriculture, US Department of the Interior, Boise, Idaho, USA.

Van de Water, K., and H.D. Safford. 2011. A summary of fire frequency estimates for California vegetation before Euro-American settlement. Fire Ecology 7(3): 26-58. doi: 10.4996/fireecology.0703026

van Wagtendonk, J.W. 2007. The history and evolution of wildland fire use. Fire Ecology 3(2): 3-17. doi: 10.4996/fireecology.0302003

van Wagtendonk, J.W., and J. Fites-Kaufman. 2006. Sierra Nevada bioregion. Pages 264-294 in: N.G. Sugihara, J.W. van Wagtendonk, J.A. Fites-Kaufman, K.E. Shaffer, and A.E. Thode, editors. Fire in California's ecosystems. University of California, Berkeley, USA.

van Wagtendonk, J.W., K.A. van Wagtendonk, and A.E. Thode. 2012. Factors associated with the severity of intersecting fires in Yosemite National Park, California, USA. Fire Ecology 8(1): 11-31. doi: 10.4996/fireecology.0801011

Westerling, A., and B. Bryant. 2008. Climate change and wildfire in California. Climatic Change 87: S231-S249. doi: 10.1007/s10584-007-9363-z

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. doi: 10.1126/science.1128834

WRCC [Western Regional Climate Center]. 2012. California COOP station climate summaries. <http://www.wrcc.dri.edu/summary/Climsmcca.html>. Accessed 12 October 2012.

Yue, S., P. Pilon, and G. Cavadias. 2002. Power of the Mann-Kendall and Spearman's rho tests for detecting monotonic trends in hydrological series. Journal of Hydrology 259: 254-271. doi: 10.1016/S0022-1694(01)00594-7