Agricultural and Forest Meteorology 189–190 (2014) 30–35

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Short communication

Fire weather and large fire potential in the northern Sierra Nevada

Brandon M. Collins[a,b,*]

[a] USDA Forest Service, Pacific Southwest Research Station, 1731 Research Park Drive, Davis, CA 95618, USA
[b] Center for Fire Research and Outreach, University of California, Berkeley, Berkeley, CA, 94720, USA

ARTICLE INFO

Article history:
Received 23 October 2013
Received in revised form
21 December 2013
Accepted 3 January 2014

Keywords:
Wildfire
Fire management
Climate change

ABSTRACT

Fuels, weather, and topography all contribute to observed fire behavior. Of these, weather is not only the most dynamic factor, it is the most likely to be directly influenced by climate change. In this study 40 years of daily fire weather observations from five weather stations across the northern Sierra Nevada were analyzed to investigate potential changes or trends in the frequency of high- to extreme-fire weather. The analysis demonstrated fairly strong upward trends in the occurrence of high- to extreme-fire weather, particularly since the mid-1990s. This increased occurrence of high fire weather conditions suggests that there is more opportunity for fires to grow rapidly and overwhelm initial suppression efforts, likely resulting in greater incidence of large fires throughout the region. This is particularly problematic in the northern Sierra Nevada, where there is a complex arrangement of land ownerships, including numerous human communities.

Published by Elsevier B.V.

1. Introduction

Large fire occurrence is increasing throughout the western U.S. and climate is thought to be one of the main drivers (Miller et al., 2009; Stephens, 2005; Westerling et al., 2006). It is hypothesized that this connection with climate is due to the lengthening of the dry season, brought about by increased temperatures and decreased snowpack (Lutz et al., 2009; Westerling et al., 2006). While it is clear that inter-annual climatic patterns have an influence on regional area burned (Collins et al., 2006; Littell et al., 2009; Morgan et al., 2008; Swetnam and Betancourt, 1990; Trouet et al., 2009; Westerling and Swetnam, 2003), shorter-term fire weather has a strong influence on large fire growth for individual fire events (Finney et al., 2011). This is particularly true given the efficiency of contemporary fire suppression organizations, which are generally able to contain fires at relatively small extents under low- to moderate-fire weather conditions (Finney et al., 2009; Finney, 2007). It should be noted that multiple, co-occurring lightning ignitions in an area can also lead to large fire occurrence due to the overwhelming of suppression forces (Preisler and Westerling, 2007).

Coincident with the potential impacts of changing climatic conditions on large fire occurrence, forest structure and surface fuel conditions in dry, frequent-fire adapted forest types throughout the western U.S. are such that large fires are much more likely than they were historically (Hessburg et al., 2005). These conditions exist irrespective of climate, and are the result of the long period of fire exclusion, as well as past timber harvesting practices in many of these forests (Agee and Skinner, 2005; Naficy et al., 2010; Parsons and Debenedetti, 1979). Empirical evidence from repeated forest measurements (Stephens et al., 2012) and forest dynamics modeling (Collins et al., 2013; Collins et al., 2011) suggest that stand- and landscape-level fire hazard continues to grow over time in untreated forests. Collectively, these studies suggest that fuel conditions may also be contributing to contemporary trends of increasing large fire occurrence (Miller et al., 2012; Miller and Safford, 2012).

Predicting large fire occurrence is difficult due to the complexity associated with forecasting interactions among several contributing factors: fuels, ignitions, local fire weather, and suppression capabilities. Given this complexity and the uncertainties therein, fire managers often rely on more simplified fire weather (also referred to as fire danger) indices to capture the potential for large fire growth. These indices capture fuel and atmospheric moisture, atmospheric stability, and wind, and relate these conditions to expected fire behavior (e.g., Bradshaw et al., 1984). Of the many indices, the Energy Release Component (ERC) has been strongly connected to large fire occurrence (Andrews et al., 2003; Finney et al., 2011; Trouet et al., 2009). ERC is a measure of the potential fire intensity, and is strongly influenced by fuel moisture, particularly in larger fuels (>2.5 cm diameter) (Bradshaw et al., 1984). Despite its importance in identifying large fire potential, there has been little investigation into changes or trends in ERC values over the last several decades. Wastl et al. (2012) analyzed the occurrence of extreme fire weather days in the Alps, based on different fire danger indices, and demonstrated an increase over the last several decades in some

* Corresponding author. Tel.: +15307591701.
E-mail address: bcollins@berkeley.edu

0168-1923/$ – see front matter. Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.agrformet.2014.01.005

regions, but this was not consistent across regions. This type of investigation in western U.S. forests would provide information to land management organizations on the contributing factors for the observed increases in large fires.

The present study examined the occurrence of high- to extreme-fire weather in an area that has experienced numerous large fires (>10,000 ha) in the last 10–15 years, the northern Sierra Nevada (Fig. 1). Historical weather records from several weather stations were analyzed for potential trends in the number of days per year that exceeded station-specific weather thresholds. Based on these analyses, occurrence of high- to extreme-fire weather is projected for the near-term (through 2020). These results can provide more insight into the potential mechanisms behind observed increases in large fires in the northern Sierra Nevada, as well as inform near-term fire management planning on large fire potential (Brown et al., 2004).

2. Methods

The study area was defined by partitioning the Sierra Nevada ecoregion described by Bailey et al. (1994) based on a major river bisecting the range (Fig. 1). The intent of isolating the northern portion of the Sierra Nevada was to focus the investigation on an area that has experienced several large fires in recent years, many of which represent a much greater proportion of area burned relative to the rest of the Sierra Nevada (Fig. 1). Within the study area all Remote Automated Weather Stations (RAWS) with long observation records (40–50 years) were identified. This resulted in six stations. Five of the six stations had relatively similar longitudes and were within mixed conifer forests, while one station was on the extreme eastern edge of the study area in a shrub-dominated vegetation type. The decision was made to only perform analyses on the five more similar stations (Fig. 1). Missing data proportions among the five stations ranged from 0.03–0.26. There were three stations with missing data proportions below 0.06 (Chester, Quincy, and White Cloud), while for Duncan and Saddleback, the proportions were 0.26 and 0.24, respectively. The relatively high proportion of missing data for the latter two stations was due to 3 or 4 years in the time series in which observations were absent or largely missing (Fig. 2).

The period of analysis was 1972–2012. The starting year of 1972 was chosen because it corresponded with the onset of standardized observations among the RAWS network to inform the National Danger Fire Rating System (NFDRS) (Bradshaw et al., 1984). Note that the White Cloud station did not begin recording weather observations until 1975 (Fig. 2). Daily observations, taken once at 1300, were used to compute daily ERC values for the predominant fire season in this area, 1 June–30 September (Collins et al., 2013). ERC values are calculated using live and dead (by timelag class) fuel moistures, which are derived from daily observed relative humidity, temperature, and 10 h fuel stick moisture (Bradshaw and McCormick, 2000). Computations were performed in Fire Family Plus 4.0.2 (Bradshaw and McCormick, 2000), using a standard forest surface fuel model for all five stations, NFDRS fuel model "G". Relative to other fuel models that can be used to calculate ERC, ERC(G) resulted in consistently better predictions of large fire activity (Andrews et al., 2003; Finney et al., 2011).

Thresholds for high- and extreme- fire weather were determined based on 90th and 95th ERC(G) percentile values (Table 1). These percentile values have been widely used in fire behavior modeling to represent conditions in which fires escape initial suppression actions and grow rapidly (e.g., Collins et al., 2011; Fulé et al., 2004; Schmidt et al., 2008; Stephens et al., 2009). Additionally, these individual weather station-specific thresholds correspond well with observed ERC(G) values in past "problem" fires occurring near each station (Fig. 1, Table 1). "Problem" fires refer to actual fire events that escaped initial suppression actions and exhibited extreme fire behavior (sensu Bahro et al., 2007). For each weather station, the proportion of daily observations exceeding both 90th and 95th percentile values was computed for each year.

Annual proportions of daily observations exceeding 90th and 95th percentile values were fitted to Autoregressive Integrated Moving Average (ARIMA) time domain regressions models, (Cryer and Chan, 2008) using the Stats package in R, version 2.14.2. This procedure includes parameters to capture three processes: autoregressive, differencing, and moving average. Four levels (0–3) were examined for each parameter, with all possible combinations among processes, resulting in a total of 64 different models for each station and each threshold. Model selection was performed based on lowest Akaike Information Criteria (AIC) (Cryer and Chan, 2008). In addition to the ARIMA analysis, autocorrelation plots were generated for each station time series, and simple linear regression between time and proportion of exceedances was performed. Using coefficients from both the top ARIMA model and the linear regression model, predictions for the proportion of daily observations exceeding threshold values were made for 2013–2020.

Additional analyses were performed to: (1) describe the similarity in the annual proportion of 90th and 95th percentile exceedances among weather stations, and (2) test the correspondence between the level of annual exceedances and annual area burned. Pearson's correlation coefficients were calculated for all pair wise comparisons among the five stations ($n = 10$), for both 90th and 95th percentile exceedances. Randomization tests were then performed for each pair wise comparison, in which the time series for one station was held constant while the other was randomly organized. Correlation coefficients were calculated for each random permutation ($n = 10{,}000$). The observed correlation was compared to distribution of randomized correlations to generate a P-value for each pair wise comparison (Manly, 2007). Correspondence between aggregated (averaged across all stations) proportion of annual exceedances and area burned was analyzed using a 2×2 contingency table test for independence. Contingency criteria for annual percentage of exceedances were 20% for 90th percentile and 10% for 95th percentile exceedances, and 10,000 ha for area burned. Using these criteria, each of the 41 years in the study period was binned into one of four categories: (1) exceedances and area burned both below (low–low), (2) exceedances below and area burned above (low–high), (3) exceedances above and area burned below (high–low), and 4) exceedances and area burned both above (high–high). Chi-squared tests were performed by comparing observed and expected distributions among the four categories. Differences in observed and expected distributions were considered statistically significant if $P < 0.05$.

3. Results

Plots of all fire season ERC(G) values demonstrate subtle upward trends for all stations, particularly since the mid-1990's (Fig. 2). Splitting the time series in half revealed strong differences in the percentage of days exceeding both thresholds. From 1972–1992, on average 0–4% of the days exceeded 90th percentile thresholds, and 0–2% of the days exceeded 95th percentile thresholds. Averages for the period 1993–2012 were 17–20% and 8–12%, for 90th and 95th percentile thresholds, respectively (Table 2).

As would be expected, there was inter annual variability in the percentage of days exceeding 90th and 95th percentile thresholds (Fig. 3). This variability was considerably greater from 1994-on for all stations (Fig. 3). Prior to 1994, years with noticeable proportions of exceedances occurred infrequently. ARIMA models somewhat

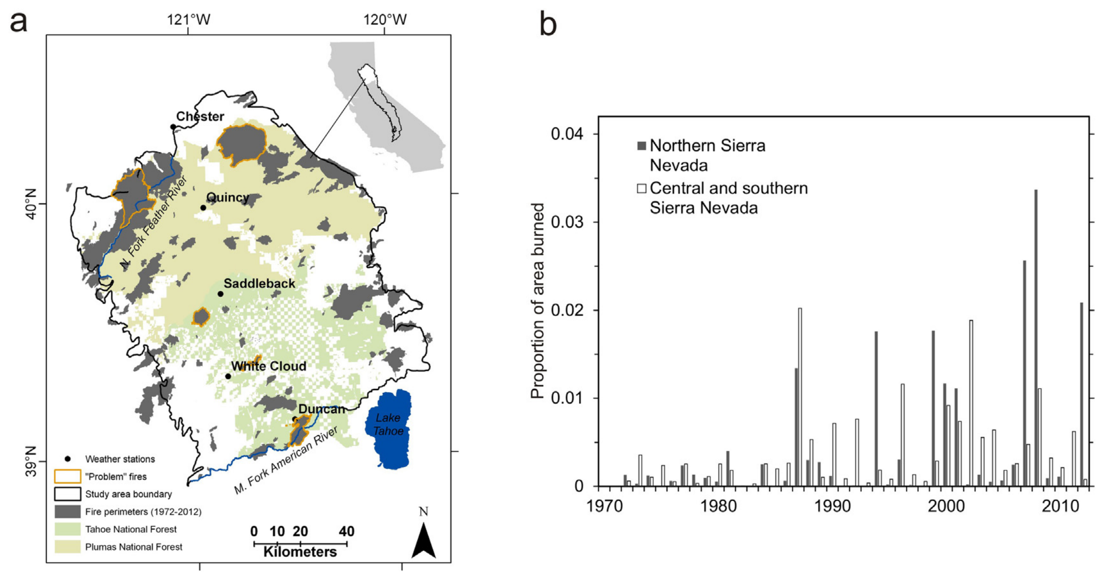

Fig. 1. (a) Northern Sierra Nevada study area with fire perimeters (1972–2012) and weather stations identified. "Problem" fires, which were used to compare to percentile fire weather thresholds, are also identified. (b) Proportion of study area burned by year in the northern Sierra Nevada, as well as for and the rest of the Sierra Nevada. For reference, 0.01 proportion of area burned corresponds to approximately 15,000 ha and 38,000 ha for the northern Sierra Nevada and the rest of the range, respectively.

tracked the observed inter annual variability, but could not account for the full amplitude in the time series for several stations (Fig. 3). For most stations/thresholds the ARIMA model chosen (lowest AIC) included no autoregressive parameters, and second order differencing and moving average parameters (Table S1). The only stations/thresholds with autoregressive parameters retained in the top model were White Cloud (90th) and Chester (95th), which is evident in the 2013–2020 predictions (Fig. 3). In all models *P*-values for the coefficients of these parameters were <0.01.

Autocorrelation plots in the time series of 90th and 95th percentile exceedances indicated very low incidence of statistical significance for lags up to 15 years for most stations/thresholds

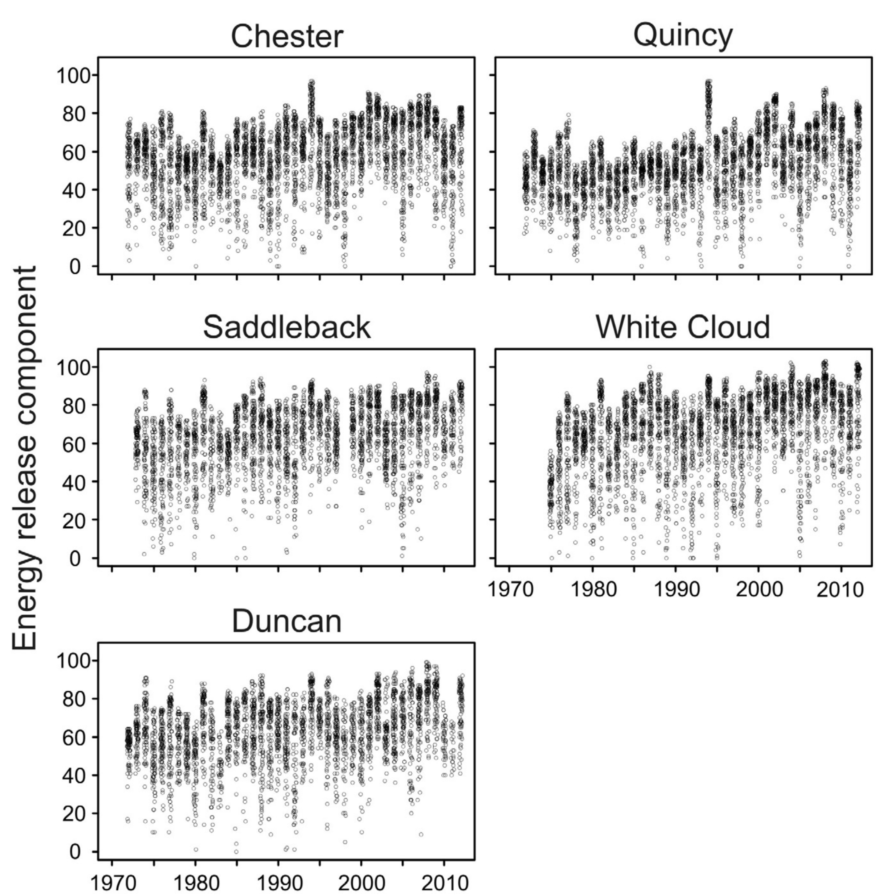

Fig. 2. Strip plots, by year, of daily energy release component values for each weather station analyzed.

Table 1
Fire weather thresholds and elevation for each northern Sierra Nevada weather station analyzed. Fire weather from local "problem" fires is also reported for comparison to percentile thresholds.

Weather station	Elevation (m)	Energy release component threshold			
		90th percentile	95th percentile	Problem fire	Problem fire name (ignition date)
Chester	1380	79	82	85	Moonlight (3 Sep 2007)
Quincy	1067	75	81	80	Storrie (17 Aug 2000)
Saddleback	2034	84	87	81	Indian (29 Aug 1987)
White Cloud	1317	89	93	84	Yuba river complex (21 Jun 2008)
Duncan	2165	83	88	79	Star (25 Aug 2001)

Table 2
Average number of days per fire season exceeding 90th and 95th percentile Energy Release Component thresholds.

Weather station	All years: 1972–2012		First half: 1972–1992		Second half: 1993–2012	
	90th	95th	90th	95th	90th	95th
Chester	10.0	6.0	1.5	0.3	18.9	12.0
Quincy	9.8	5.1	0.2	0	19.9	10.4
Saddleback	10.6	5.2	4.4	2.1	17.1	8.5
White Cloud	11.1	5.0	3.3	1.1	18.2	8.5
Duncan	10.3	4.7	2.9	1.1	18.0	8.4

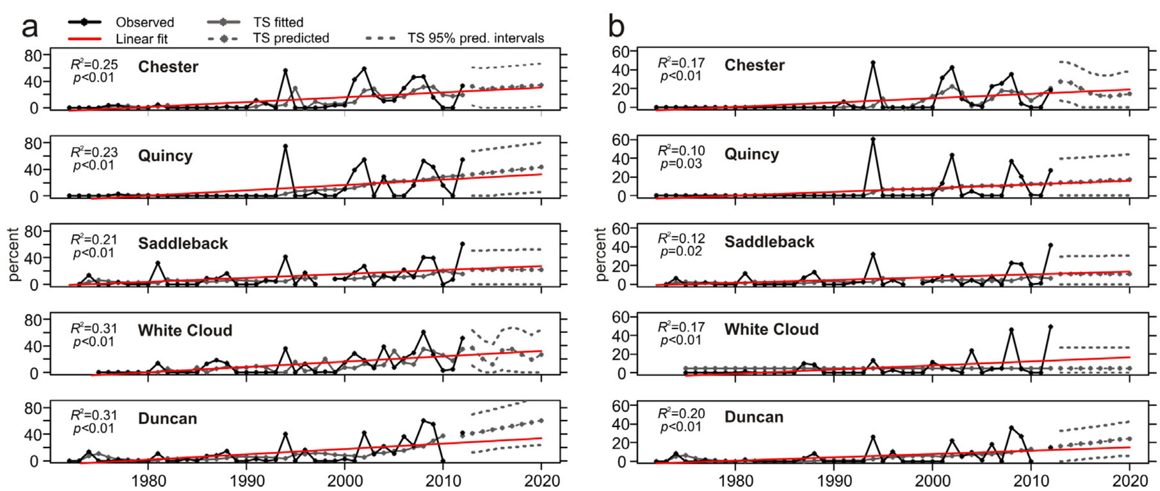

Fig. 3. Observed and fitted percent of days per fire season exceeding 90th (a) and 95th (b) percentile Energy Release Component thresholds. Statistical fits are reported for both linear regression and time series (TS) analysis using an ARIMA model. Near-term projections for 2013–2020 are also reported using both statistical methods. Reported R^2 and P-values are for the linear fits for each station/threshold.

(Fig. S1). Based on this, linear regression lines and fits are reported (Fig. 3). Using the 90th percentile threshold, P-values for time coefficients were all <0.01, and R^2 ranged between 0.21–0.31. For the 95th percentile P-values were slightly higher, but all <0.05, with R^2 values between 0.10–0.20. Both linear and ARIMA model predictions for 2013–2020 indicated continued increases in the proportion of days exceeding 90th and 95th percentile ERC(G) thresholds (Fig. 3). For Chester, Quincy, Saddleback, and White Cloud (90th), the linear and ARIMA predictions were very similar, while for Duncan ARIMA predictions have a greater rate of increase (Fig. 3).

Mean Pearson's correlation coefficients for 90th and 95th percentile exceedances among the five weather stations were 0.79 and 0.69, respectively (Table 3). P-values for the randomization tests were very low (<0.001) for all pair wise comparisons at the 90th percentile and low (0.01 or lower) for all comparisons at the 95th percentile, indicating correlations among stations were all significantly different from what would be expected by chance. Based on the reasonably good correlations the annual proportions of days exceeding 90th and 95th percentile ERC(G) thresholds were aggregated for each threshold by averaging proportions across the five stations. Contingency table tests indicated that observed and

Table 3
Summary of correlation analysis comparing percentage of fire season days exceeding 90th and 95th percentile energy release component thresholds among weather stations and contingency table relating aggregated 90th and 95th percentile exceedances to annual area burned. The number of years in which both the percentage of exceedances and area burned are consistent (below criteria values, low–low, and above values, high–high), as well as the number of inconsistent years (low–high, high–low), are reported. The Chi-square values and statistical significance (*P < 0.05,) are also reported.

		90th	95th
Pearson's correlation coefficients (n = 10 comparisons)	Mean	0.79	0.69
	Range	0.67–0.86	0.47–0.85
Contingency table			
Observed	Low–low	28	30
	Low–high	3	4
	High–low	5	3
	High–high	5	4
Expected	Low–low	24.95	27.37
	Low–high	6.05	6.63
	High–low	8.05	5.63
	High–high	1.95	1.37
Chi-square	–	9.54*	7.61*

expected distributions among the four categories analyzed were statistically different for both 90th and 95th percentile aggregated exceedances (Table 3). For both percentiles this difference was due to greater correspondence between observed annual proportion of exceedances and area burned, both low–low and high–high, than would be expected (Table 3). It is worth noting that although the observed inconsistencies were lower than would be expected, there were 7,8 years in which exceedances were low, but area burned was high (low–high), or vice-versa (high–low) (Table 3).

4. Discussion

Fuels, weather, and topography all contribute to observed fire behavior. Of these, weather is not only the most dynamic factor, it may be the most influential on fire spread and intensity. This is particularly true during periods of high- to extreme-fire weather (Bessie and Johnson, 1995). Previous studies indicating strong connections between occurrence of high- to extreme fire weather and fire extent provide further support for this assertion (Andrews et al., 2003; Trouet et al., 2009). The analysis conducted here demonstrates fairly strong upward trends in the occurrence of high- to extreme-fire weather (proportion of days exceeding 90th and 95th percentile ERC(G) values) over the last several decades. This increased occurrence is likely a strong contributor to the greater frequency of large fires observed in the northern Sierra Nevada (Fig. 1) (Wastl et al., 2012).

There were several years in which large area burned coincided with high proportions of days exceeding both ERC(G) percentile thresholds (1994, 2008, 2012). This is supported by contingency table analyses indicating greater correspondence between years with increased proportions of high- to extreme and large area burned (>10,000 ha) than would be expected (Table 3). However, there were also years with low proportions of fire weather exceedences and high area burned (1987, 1999, 2000), as well as the opposite case (2002). Clearly, fire weather is not the only factor driving large fire occurrence. Forest succession in the absence of the frequent, low- to moderate-severity fire that these forests experienced for centuries prior to Euro-American settlement is leading to increasing surface, ladder and canopy fuel loads, and overall greater fuel continuity (Hessburg et al., 2005; Perry et al., 2011; Stephens et al., 2012). These increases create more reactive forest fuel complexes, which also likely contributes to observed increases in large fire occurrence (Miller and Safford, 2012). Additionally, extensive dry lightning events, as was the case in 1987 and 1999 in the northern Sierra Nevada, contribute to episodic large fire years (Preisler and Westerling, 2007).

The increases in high- to extreme-fire weather were not steady throughout the period studied. For all weather stations, starting in the mid-1990's, years with high proportions of days exceeding both thresholds occurred more frequently (Fig. 3). This is reflected in the marked increases in average number of days per year exceeding both thresholds between the first half and second half of the analysis period (Table 2). Climate change, specifically rising mean annual surface air temperatures and longer periods with low moisture availability, is a likely contributor to these relatively recent increases (Brown et al., 2004; Saunders et al., 2008). Another potential contributor is a teleconnection with low-frequency synoptic climatic patterns (Trouet et al., 2009). The Atlantic Multidecadal Oscillation (AMO), which has been associated with climatic variability in western North America (Enfield et al., 2001), changed from cool to warm phase in the mid-1990's (Deser et al., 2010). Warm phase AMO has been associated with both long-term drought (Gray et al., 2003; McCabe et al., 2004) and greater fire occurrence throughout western North America (Collins et al., 2006; Kitzberger et al., 2007). The simple co-occurrence of an AMO phase change and the observed increases in frequency of high- to extreme-fire weather is not strong evidence of a driving mechanism, but given the connections with AMO and climate demonstrated in several previous studies, further investigation into its effects on fire weather may be warranted.

The two northernmost stations, Chester and Quincy, have the most dramatic increases in the frequency of high- to extreme fire weather from the first half to the second half of the analysis period (Table 2). The concentration of large fires is also disproportionally skewed towards the northern portion of the study area (Fig. 1). Since 1999, there have been five fires in this area that exceeded 10,000 ha. While increased occurrence of high- to extreme-fire weather does not directly translate to greater large fire incidence, it does appear that these increases may be driving the recent occurrence of large fires in this area. Given that near-term future projections for all station/threshold combinations indicate continued increases in the frequency of high fire weather years (Fig. 3), there may be greater large fire potential throughout the study area.

5. Conclusion

Future climate-fire projections predict a continuation, if not an acceleration, in large fire occurrence (Flannigan et al., 2000; Lenihan et al., 2008; McKenzie et al., 2004; Westerling et al., 2011a; Westerling et al., 2011b). These projections are largely driven by a lengthening of the dry season (Hurteau et al., 2013), which correspond with increases in the frequency of high fire weather conditions (Brown et al., 2004; Wastl et al., 2012). The results from this analysis demonstrate that these trends in fire weather are indeed being observed, at least in the northern Sierra Nevada. The increased occurrence of high fire weather conditions suggests that there is more opportunity for fires to grow rapidly and overwhelm initial suppression efforts, likely resulting in greater incidence of large fires throughout the region. This is particularly problematic in the northern Sierra Nevada, where there is a complex arrangement of land ownerships, including numerous human communities. This mix of ownerships not only complicates fire control efforts, it makes landscape-scale fire-mitigation (e.g., fuel reduction projects) more difficult to plan and coordinate (Collins et al., 2010). That said, large-scale fuel reduction/restoration strategies (e.g., Ager et al., 2013; Collins et al., 2013), coupled with increased "use" of fire under more moderate fire weather conditions (North et al., 2012), may be the only way to counteract the weather-driven increases in large fire potential. If implemented, these strategies can build resilience to uncharacteristic impacts from fire in these forests.

Acknowledgements

Jim Baldwin provided statistical expertise and helped develop specific statistical analyses. Gary Roller helped with initial data acquisition. Scott Stephens and Eric Knapp also provided helpful comments that improved the manuscript. Funding was provided by the USFS Pacific Southwest Research Station.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agrformet.2014.01.005.

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