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A 1,500-year synthesis of wildfire activity stratified by elevation from the U.S. Rocky Mountains

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A R T I C L E I N F O

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A B S T R A C T

A key task in fire-climate research in the western United States is to characterize potential future fire-climate linkages across different elevational gradients. Using thirty-seven sedimentary charcoal records, here we present a 1500-year synthesis of wildfire activity across different elevational gradients to characterize fire-climate linkages. From our results, we have identified three periods of elevated fire occurrence centered on the 20th century, 900 cal yr BP, and 1350 cal yr BP. During the 20th century, fire activity has occurred primarily in the northern Rocky Mountains, with mid-elevations experiencing the greatest increase in wildfire activity. While wildfires occurred primarily in the SRM region ~900 cal yr BP, the greatest increase in high-elevations occurred in the NRM at this time. Finally, synchronous wildfires occurred in both northern and southern Rocky Mountain mid-elevations ~1350 cal yr BP, suggesting a potential analog for future wildfire conditions in response to warmer temperatures and more protracted droughts. We conclude that wildfire activity increased in most elevations during periods of protracted summer drought, warmer-than-average temperatures, and based on modern climate analogs, reduced atmospheric humidity.

1. Introduction

Fire is considered to be an important natural disturbance because of its ecological role in releasing nutrients, influencing stand composition, reducing biomass, and increasing biodiversity in many forested ecosystems across the western United States (U.S.) (Agee, 1993; Cruzten and Goldammer, 1993; Mutch, 1994; Keane et al., 2002; Dunnette et al., 2014). Over the past 30 years, there has been an increase in the number of large wildfires, as well as an increase in the area burned across many ecoregions of the western U.S. (Dennison et al., 2014). The recent increase in wildfire activity has been linked to both longer and warmer summers, as well as increased drought severity over the past two decades (Westerling et al., 2006; Clark et al., 2016). Climate model projections suggest a minimum increase of ~2 °C in average global temperatures by the end of the 21st century, which will likely lead to more intense droughts, increased precipitation variability (Romero-Lankao et al., 2014), and increased fire frequency and fire severity (Flannigan et al., 2009; Liu et al., 2016). As forested ecosystems are expected to shift towards novel-disturbance regimes in the western U.S. (e.g. Allen et al., 2011; Westerling et al., 2011), it is important to understand which ecosystems are the most susceptible to shifts towards novel-disturbance regimes.

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A key task in fire-climate research in the western U.S. is to characterize potential future fire-climate linkages across different elevational gradients. During the past several decades, mid-elevation montane forests have been the most susceptible to temperature-driven increases in wildfire activity, particularly in the northern Rocky Mountain region (Westerling et al., 2006). Using knowledge of past fire-climate linkages during previous warm periods, such as during the Medieval Climate Anomaly (MCA; 1000–700 cal yr BP) (Mann et al., 2009), reveals greater incidence of wildfires (i.e., biomass burning) under warmer temperatures and drought conditions across much of the western U.S. (Marlon et al., 2012). However, because temperature variability appears to be a significant control on wildfire activity at both mid- and high-elevations (Schoennagel et al., 2004), projected future warming in mid-elevation montane forests may represent one of the most vulnerable ecosystems to novel-disturbance regimes.

Reconstructed fire-climate indices using primarily fire-scars and tree rings have shown that large wildfires in the northern Rocky Mountains have occurred during years of warmer-than-average spring temperatures, and warm and dry summers (Kitzberger et al., 2007; Heyerdahl et al., 2008). However, these fire histories are typically limited to low elevations where moderate-to-high severity fire regimes generally do not occur. Lake sediment records provide the only reliable method to obtain quantitative information about long-term ecological processes (Willis et al., 2010). Of these data, sedimentary charcoal are the most widespread proxy for reconstructing fire occurrence and regional trends in wildfire activity on varying time and spatial scales, and provide information regarding the potential impacts of climate variability on fire activity (Power et al., 2008; Marlon et al., 2012). However, regional paleofire reconstructions are limited to geographic regions with higher record densities (Power et al., 2008). For example, merging charcoal records on regional-to-continental scales and across different vegetation types, climate zones, and human population densities could dilute the importance of climate versus vegetation and human controls on wildfire activity through time (Blarquez and Aleman, 2015). However, when compared to the early Holocene, vegetation composition has remained relatively stable in the U.S. Rocky Mountains over the past 1500 years until the modern period (Anderson et al., 2008; Brunelle et al., 2005; Carter et al., 2013; Higuera et al., 2014), and provides an opportunity to explore the importance of fire-climate linkages. Additionally, prior-to Euro-American settlement (~1850 CE), indigenous human populations likely had minimal impact on mid-to-high elevation fire regimes in the U.S. Rocky Mountains (Schoennagel et al., 2004), thus making this region an ideal study region to understand fire-climate relationships.

Here, we present a regional-scale reconstruction of paleofire history from different elevational gradients from the northern Rocky Mountains (NRM) and southern Rocky Mountains (SRM) over the past 1500 years inferred from a new compilation of sedimentary charcoal records. Specifically, we explore sedimentary charcoal records across elevational gradients to determine whether the recent increase in wildfire activity at mid-elevation forests is unprecedented in both time and space. We hypothesize that over the past 1500 years, periods with significant changes in fire activity occurred in response to warmer-than-average temperatures and lower-than-average seasonal moisture in mid-to-high elevation Rocky Mountain montane forests. We focus on three periods of extreme fire activity; the mid-20th century, ~900 cal yr BP, and ~1350 cal yr BP.

2. Regional setting

2.1. NRM and SRM climate

The U.S. Rocky Mountains are typically partitioned into the NRM and SRM units based on the major winter climate boundaries identified by Mitchell (1976). Here, we used the original boundaries identified by Mitchell (1976), as well as used 42°N latitude as a geographic transition point between the two climate regions that generally correspond with the El Niño Southern Oscillation (ENSO) transition zone (Dettinger et al., 1998; Wise, 2010) (Fig. 1).

Due to the complex topography of the U.S. Rocky Mountains, climate and vegetation communities are influenced by local orographic effects, which promote steep precipitation gradients, rain shadows, and differences in insolation receipt (i.e., aspect). Broadly, winter storms originating from the Pacific Ocean are moisture laden, which result in a winter snow-dominant precipitation regime in the NRM region, with 50–80% of the annual precipitation falling during the winter months of December, January, and February (DJF) (Fig. 1). In the SRM region, winter storms generally lose much of their moisture crossing the Sierra Nevada range and Intermountain West (Kittel et al., 2002). However, while the SRM region does receive winter moisture in mountainous areas due to orographic effect, the SRM are generally more influenced by summer precipitation than the NRM region (Fig. 1). In the NRM, the timing of peak precipitation generally varies between February and May (Shinker, 2010), while the timing of peak precipitation in the SRM varies between May and August, depending on the geographical position and influence of the North American Monsoon (Shinker, 2010).

2.2. Modern fire-vegetation-climate linkages in the NRM and SRM regions

Throughout the NRM and SRM, low-to-mid-elevation conifer forests are generally dominated by Ponderosa pine (*Pinus ponderosa*), quaking aspen (*Populus tremuloides*) and Douglas-fir (*Psuedotsuga menziesii*). Ponderosa pine forests typically experience frequent, low-to-moderate severity wildfires, while Douglas-fir forests typically experience infrequent, yet variable severity wildfires (Baker, 2009). Fire-climate linkages in low-to-mid-elevation conifer forests of the SRM can be attributed to oscillating teleconnection patterns associated with ENSO (Swetnam and Betancourt, 1998). Generally, La Niña years are associated with lower-than-average winter precipitation and increased fire activity during the summer in the SRM (Schoennagel et al., 2005), while in the NRM, La Niña years are associated with high snowpack and reduced wildfire activity (Heyerdahl et al., 2008). However, the opposite pattern occurs during El Niño years, which delivers high snowfall to the SRM, and lower-than-average snowfall in the NRM. In general, wet antecedent conditions promote the buildup of fuels in low-elevation grasslands, woodlands, and forests, which facilitate the spread of wildfires in both the NRM (Morgan et al., 2008) and SRM. Therefore, low-to-mid-elevation conifer forests can be characterized as being 'fuel-limited' systems (Schoennagel et al., 2004).

High-elevation conifer forests that generally include lodgepole pine (*Pinus contorta*), subalpine fir (*Abies lasiocarpa*), and Engelmann spruce (*Picea engelmannii*) across both regions typically experience a fire regime characterized by infrequent, stand-replacing burns. These forests are abundant in fine fuels, particularly among the duff layer. As a result of a limited snow-free

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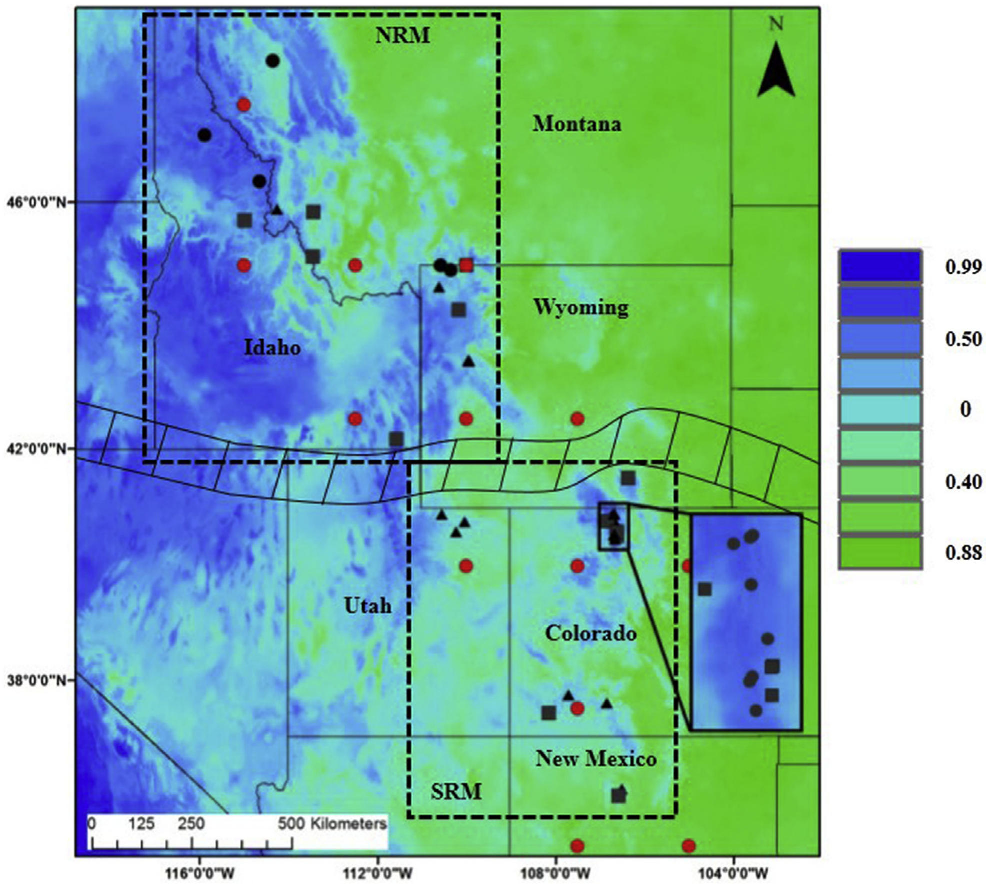

Fig. 1. Map of January:July precipitation using 30-year normal monthly precipitation PRISM data (www.prismclimate.org). Black dashed boxes indicate the NRM and SRM regions. Black triangles indicate high-elevation charcoal records (<500 m from timberline), black squares indicate mid-elevation charcoal records (>500 m, <1000 m from timberline), and black circles indicate low-elevation charcoal records (>1000 m from timberline) used in this study. The long dashed black line indicates the boundary of major winter potential temperature boundaries and climatic regions, adapted from Mitchell (1976). PDSI grid points <200 km from any charcoal record was used to reconstruct drought (red circles). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

period, fine fuels and soil moisture may not sufficiently dry out in high elevation forests. Additionally, high-elevation conifer forests are abundant in ladder fuels, which promote stand-replacement fires through transmission of the forest canopy. Large wildfires in both NRM and SRM high-elevation conifer forests typically occur under persistent, higher pressure systems that promote regional drought conditions (Schoennagel et al., 2004; Sibold and Veblan, 2006; Morgan et al., 2008), suggesting the importance of broad scale synoptic climate in wildfire occurrence in high-elevations forests (Kipfmueller and Baker, 2000; Veblen, 2000). Large wildfires typical of high-elevation conifer forests are usually influenced by an intensification of summer drought linked to reduced seasonal snowpack (Westerling et al., 2003; Sibold and Veblan, 2006; Power, 2006; Westerling et al., 2006; Diaz and Swetnam, 2013).

3. Material and methods

3.1. Charcoal data source and classification

The regional analysis of fire activity across the NRM and SRM over the past 1500 years presented here was accomplished by examining records within the Global Charcoal Database (GCD) (Table 1, GCD version 3, http://gpwg.org). A total of 37 sedimentary charcoal records were analyzed for this study. Charcoal records were obtained from the GCD (n = 18), the National Oceanic and Atmospheric Administration (NOAA) (n = 12), and from co-authors (n = 7) (Table 1). A total of 11 charcoal records from the region were excluded from this analysis because of several factors; 1) the records had too low of resolution of charcoal samples (<5 charcoal samples over the past 1500 years); 2) the records had chronological issues; or 3) the records had significant portions of time missing from the past 1500 years (Table 1). Because most of the sites used in this study are from mid-to-high elevations, most of the records are located within mixed-conifer and/or subalpine forests dominated with lodgepole pine, and/or Engelmann spruce-fir forests (Fig. 2).

To help control for regional variables that impact orographic and climatic treelines (Holmeir and Broll, 2005), and the related elevational changes in forest composition, we classified each charcoal record based on elevation below timberline from the primary regions where charcoal records were clustered; Bitterroot Mountains, Yellowstone National Park (YNP), Wasatch Mountains, Medicine Bow Mountains, White River Plateau, Uinta Mountains, West Elk Mountains, San Juan Mountains, and near the Sangre de Cristo Mountains (Table 1). We determined the average timberline elevation from each clustered region, then subtracted the actual elevation of each charcoal record to determine whether each charcoal record was classified as high-elevation (<500 m from timberline), mid-elevation (<1000 m - >500 m from timberline), or low-elevation (>1000 m from timberline) (Table 1) (Figs. 1 and 2).

Table 1
List of charcoal records used in the analysis, including latitude/longitude of each record, the number of charcoal samples each record contributed to the regional composite curve, elevation and classification (low, mid, or high), vegetation type, and the author of publication of each record used in this study. Charcoal records with a '*' or '**' symbol next to the number of samples indicates records that did not span the entire 1500 year interval, or did not capture the modern era (20th century). Charcoal records <500 m from timberline were classified as high-elevation records. Charcoal records >500 m and <1000 m from timberline were classified as mid-elevation records, while records >1000 m from timberline were classified as low-elevation records.

Site Name	Lat. (N)/Long. (W)	# of samples & resolution	Elevation (m) & Classification	Regional Vegetation	Author of Publication
NRM region					
Foy Lake	48.16, −114.35	245, ~15 yrs/cm	1006, Low[a]	Forest-steppe border	Power et al., 2005
Foy L. F.C.	48.16, −114.35	89*, ~3 yrs/cm	1006, Low[a]	Forest-steppe border	Power et al., 2005
Upper Rocket	47.04, −115.88	30, ~52 yrs/cm	1710, Low[a]	Sub-alpine forest	S.Mensing unpublished data
Hoodoo Lake	46.32, −114.65	30, ~23 yrs/cm	1770, Low[a]	Montane forest	Brunelle et al., 2005
Baker Lake	45.89, −114.26	50, ~32 yrs/cm	2300, High[a]	Sub-alpine forest	Brunelle et al., 2005
Pintlar Lake	45.84, −113.44	137**, ~10 yrs/cm	1912, Mid[a]	Montane forest	Brunelle et al., 2005
Burnt Knob L.	45.70, −114.98	44, ~25 yrs/cm	2250, Mid[a]	Sub-alpine forest	Brunelle et al., 2005 and Whitlock et al., 2003
Crevice Lake	45.00, −110.47	136, ~25 yrs/cm	1713, Low[b]	Lodgepole pine forest	Whitlock et al., 2008
Crevice L. F.C.	45.00, −110.47	108*, ~3 yrs/cm	1713, Low[b]	Lodgepole pine forest	M.J. Power unpublished data
Slough C. Pond	44.91, −110.34	107, ~17 yrs/cm	1884, Low[b]	Montane forest/forest-steppe	Millspaugh, 1997
Cygnet Lake	44.66, −110.61	35, ~51 yrs/cm	2530, High[b]	Montane forest	Millspaugh et al., 2000
Trail Lake	44.28, −110.17	259, ~6 yrs/cm	2362, Mid[b]	Montane forest	Whitlock et al., 2003
Forest Pond 1	43.47, −109.93	10, ~137 yrs/cm	2797, High[b]	Lodgepole pine-park	Lynch, 1998
Park Pond 1	43.46, −109.95	7, ~87 yrs/cm	2705, High[b]	Lodgepole pine-park	Lynch, 1998
Park Pond 2	43.45, −109.94	8, ~74 yrs/cm	2714, High[b]	Lodgepole pine-park	Lynch, 1998
Plan B Pond	42.15, −111.58	72, ~24 yrs/cm	2250, Mid[c]	Sub-alpine forest	Lundeen and Brunelle, 2016
SRM region					
Long Lake	41.50−106.36	81, ~20 yrs/cm	2700, Mid[d]	Lodgepole pine mixed forest	Carter et al., 2013
Lake Eileen	40.90, −106.67	95, ~20 yrs/cm	3135, High[e]	Subalpine forest	Calder et al., 2015
Salamander P.	40.90, −110.55	51, ~33 yrs/cm	3079, High[f]	Subalpine forest	Carter, 2016
Seven Lake	40.89, −106.68	79, ~39 yrs/cm	3276, High[e]	Alpine forest/meadow	Calder et al., 2015
Gem Lake	40.88, −106.73	188, ~17 yrs/cm	3101, High[e]	Subalpine forest	Calder et al., 2015
Gold Creek	40.78, −106.67	84, ~20 yrs/cm	2917, High[e]	Subalpine forest	Calder et al., 2015
Hinman Lake	40.77, −106.82	92, ~20 yrs/cm	2501, Mid[e]	Subalpine forest	Calder et al., 2015
Reader Fen	40.77, −110.04	37, ~45 yrs/cm	3300, High[f]	Subalpine forest/meadow	Koll, 2012
M. Rainbow	40.64, −106.62	86, ~21 yrs/cm	3001, High[e]	Subalpine forest	Calder et al., 2015
Heller Gulch	40.60, −110.23	47**, ~46 yrs/cm	2870, High[f]	Mixed forest meadow	Turney, 2014
Teal Lake	40.58, −106.60	92, ~17 yrs/cm	2689, Mid[e]	Subalpine forest	Calder et al., 2015
Tiago Lake	40.57, −106.61	156, ~20 yrs/cm	2700, Mid[e]	Subalpine forest	Calder et al., 2015
Whale Lake	40.55, −106.67	74, ~22 yrs/cm	3059, High[e]	Subalpine forest	Calder et al., 2015
Summit Lake	40.54, −106.61	94, ~34 yrs/cm	3149, High[e]	Alpine forest/meadow	Calder et al., 2015
Hidden Lake	40.51, −106.61	156, ~21 yrs/cm	2710, Mid[e]	Subalpine forest	Calder et al., 2015
Round Lake	40.47, −106.66	146, ~21 yrs/cm	3071, High[e]	Subalpine forest	Calder et al., 2015
DeHerrera Lake	37.74, −107.70	67, ~17 yrs/cm	3343, High[g]	Subalpine forest	Anderson et al., 2008
Little Molas L.	37.74, −107.70	55, ~26 yrs/cm	3370, High[g]	Subalpine forest	Toney and Anderson, 2006
Hunter's Lake	37.60, −106.84	67, ~24 yrs/cm	3516, High[g]	Subalpine forest	Anderson et al., 2008
Beef Pasture	37.41, −108.15	13, ~12 yrs/cm	3060, Mid[h]	Meadow/Montane forest	Petersen, 1988
Chihauhueños B.	36.04, −106.50	71, ~17 yrs/cm	2925, Mid[i]	Mixed-conifer forest	Brunner Jass, 1999
Alamo Bog	35.91, −106.58	139, ~9 yrs/cm	2630, Mid[i]	Mixed-conifer forest	Brunner Jass, 1999

[a] Charcoal records near the Bitterroot Mountains, Montana used the average timberline elevation of 2800 m. Mehringer et al., 1977.
[b] Charcoal records near Yellowstone National Park, Wyoming used the average timberline elevation of 2900 m. Romme and Turner, 1991.
[c] Charcoal record located near the Wasatch Range, Utah used the average timberline elevation of 3100 m. Richmond, 1964.
[d] Charcoal record in the Medicine Bow Mountains, Wyoming used the average timberline elevation of 3350 m. Billings, 1969.
[e] Charcoal records near the White River Plateau region of Colorado used the average timberline elevation of 3400 m. Feiler et al., 1997.
[f] Charcoal records located in the Uinta Mountains, Utah used the average timberline elevation of 3300 m. Monroe, 2003.
[g] Charcoal records located near the West Elk Mountains, Colorado used the average timberline elevation of 3400 m. Fall, 1997.
[h] Charcoal record located in the San Juan Mountain, Colorado used an average timberline elevation of 3600 m. Carrara et al., 1991.
[i] Charcoal records located near the Sangre de Cristo Mountains, New Mexico used an average timberline elevation of 3500 m. Jiménez-Moreno et al., 2008.

3.2. Charcoal data analysis

Accurate chronologies are essential for sedimentary paleoecological work. As each version of the GCD is released, new age-depth models are constructed for each individual charcoal record so that each record has an up-to-date age chronology. This study extracted sedimentary charcoal records from latest version, version 3 (Marlon et al., 2016). For sedimentary charcoal records obtained by colleagues, age-depth models were constructed for each individual charcoal record using the classical age-depth model (CLAM) with a smoothing spline and a smoothing parameter of 0.3 (Blaauw, 2010). The approximate sedimentation rate for each record is listed in Table 1.

Because each charcoal record varies in sampling resolution (i.e., sampled contiguously or not) (Fig. 3), the record must be standardized in order to examine the relative change in charcoal influx over time (Power et al., 2010). Standardization occurred after individual records were classified by region and elevation. Once the records are standardized, charcoal influx anomalies can be averaged from multiple records to create charcoal composite series in which trends can be identified and interpreted (Marlon et al., 2016). The most widely used standardizing protocol includes 1) transforming non-influx values (e.g., raw charcoal counts or concentration values), 2) homogenizing the variance using a Box-Cox transformation; and 3), standardizing to z-scores using a base period (Power et al., 2010). In this study, we used a base period between 150 and 1500 cal yr BP to avoid the influence of 20th century land cover changes. Charcoal records were compiled to create regional and elevational composite charcoal curves for each region (Table 1). Each record was sampled at 20-year intervals to

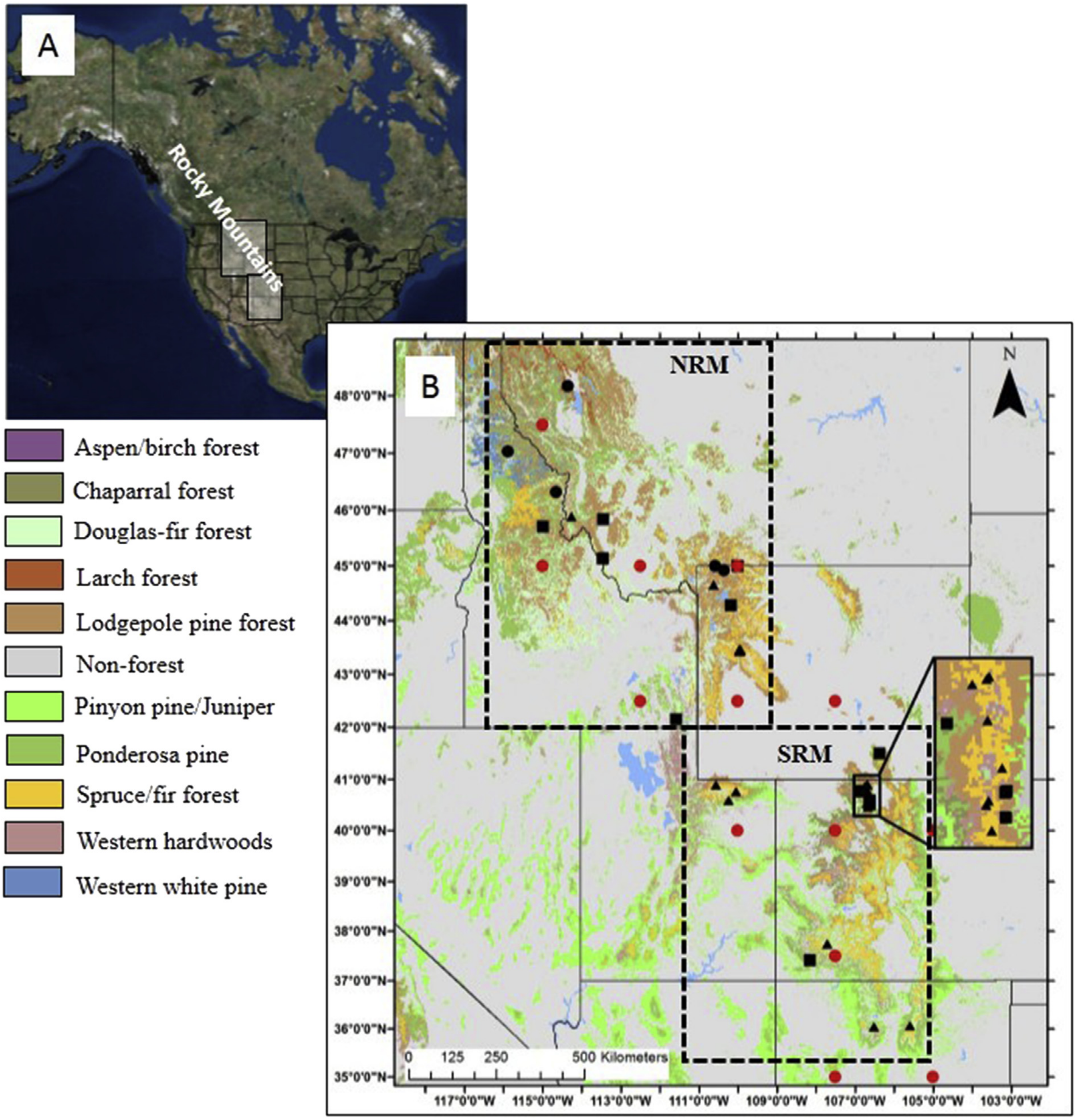

Fig. 2. Map of the study region. A) Map of North America showing the extent of the Rocky Mountains. Shaded white boxes indicate both the Northern Rocky Mountain (upper) and Southern Rocky Mountain (lower) regions, as defined in this study. B) Regional map of the charcoal records used in this study, and their location within the main forest types of the U.S. Rocky Mountains (Zhu and Evans, 1994). PDSI grid-points <200 km from any charcoal record was used to reconstruct drought (red circles). Black triangles indicate high-elevation charcoal records (<500 m from timberline), black squares indicate mid-elevation charcoal records (>500 m, <1000 m from timberline), and black circles indicate low-elevation charcoal records (>1000 m from timberline). Black dashed boxes indicate the NRM and SRM regions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

reduce the bias of high-resolution records used in the study (Marlon et al., 2013). Once standardized, the records were smoothed using a lowess curve with 250- and 500-year moving window widths. In general, variability in the regional composite curves reflects changes in the average amount of wildfire activity, whereas variability in the width of the confidence intervals reflects the degree of dissimilarity between charcoal influxes from different records for the period of interest (Marlon et al., 2013). Bootstrapping generated the 95th confidence intervals. Charcoal transformations were implemented in the Paleofire R Package (Blarquez et al., 2014). Finally, we applied a regime shift index (RSI) algorithm (Rodionov, 2004) to the regional and elevational composite charcoal curves to statistically quantify shifts in mean fire activity through time. The RSI was calculated using student's *t*-test (Huber's WF = 1, $P < 0.0001$, cut-off = 10 yr) with a IP4 red noise estimation.

To visualize the different spatial patterns of wildfire activity at specific time windows, a weighted spatio-temporal interpolation was used to produce gridded maps from the NRM and SRM regions using all 37 charcoal records. A spatial grid of 1600 km^2 pixels was used to interpolate charcoal values for three defined temporal time slices of interest, determined through inspection of the time series analysis; the 20th century, 900 cal yr BP, and 1350 cal yr BP. Spatial interpolation involved searching for charcoal records located at a

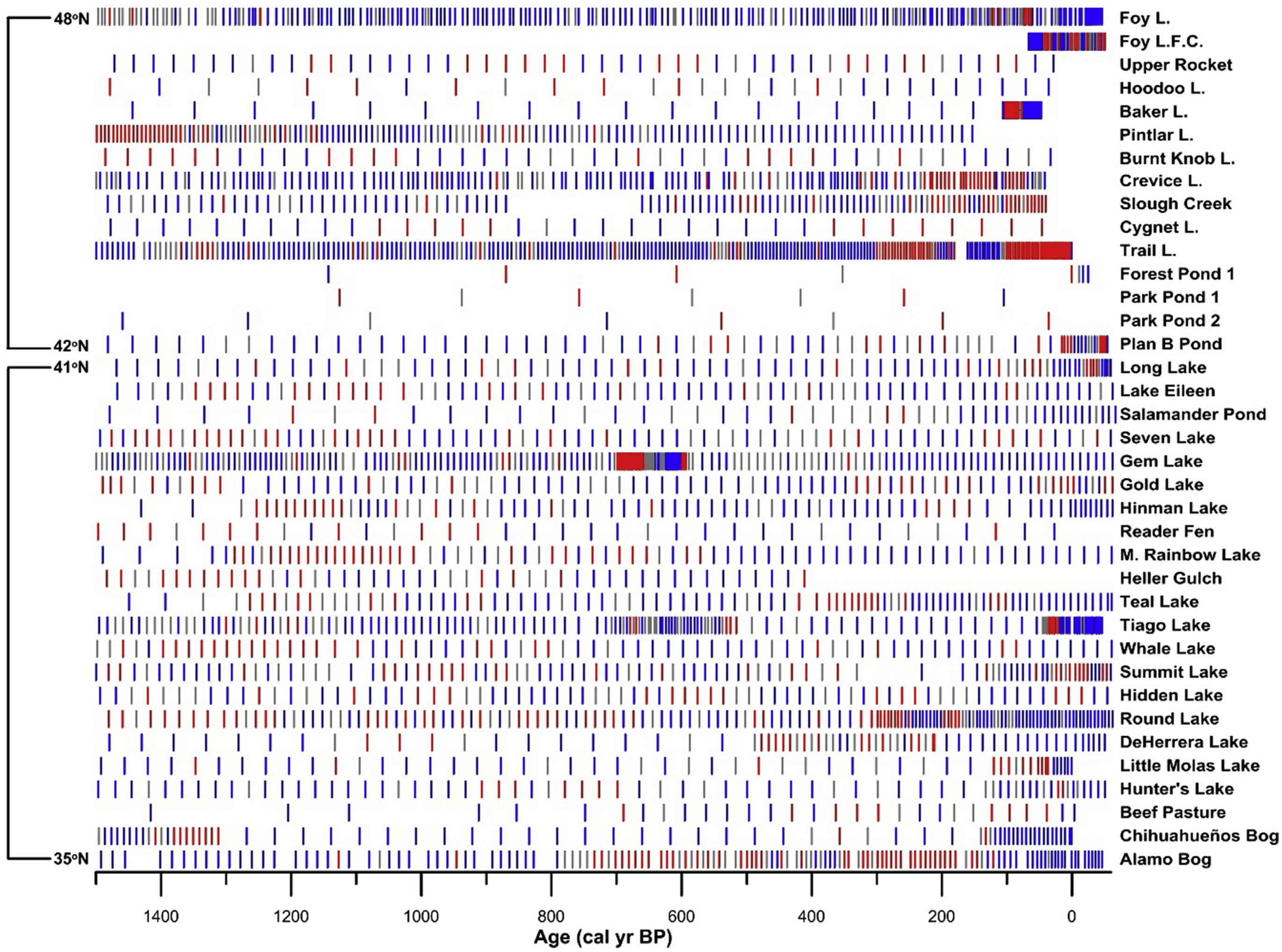

Fig. 3. Hovmöller-type diagram with Z-scores of raw charcoal influxes used in this study from the U.S. Rocky Mountains. The series is organized by region and latitude. Tick marks represent individual charcoal samples showing sampling resolution with a Z-score value shown in color; blue tick marks indicate charcoal influx values < -0.20; gray tick marks indicate charcoal influxes between −0.20 and 0.20; red tick marks indicate charcoal influxes >0.20. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

horizontal distance of 225 km^2, and used a temporal window of 100 years before and after each key time interval. Finally, a tricube distance weighting function was applied to each sample, which considered the spatial distance to the grid center, and temporal distance to the key date (Blarquez and Aleman, 2015).

3.3. Climate data

3.3.1. Reconstructed temperature and precipitation

In order to investigate how previous periods of increased temperatures and summer drought influenced synchronous wildfires in the U.S. Rocky Mountains, this study used a subset of the Mann et al. (2009) hemispheric temperature reconstruction that was aerially averaged for the western U.S. (west of the 100th meridian), as well as the Palmer Drought Severity Index (PDSI) (Palmer, 1965). PDSI was used as a measurement of top soil moisture conditions, which reflects changes in summer precipitation. PDSI grid-points <200 km from any charcoal record were used in this study; NRM is comprised of PDSI grid-points 68, 69, 85, 85, 100 and 101; SRM is comprised of PDSI grid-points 102, 116, 117, 118, 119, 131, and 133 (Fig. 2). Subsequent PDSI reconstruction time series were obtained from the National Oceanic Atmospheric Administration (NOAA.gov; Cook et al., 2004). Each time series from each region was standardized by dividing the average from the standard deviation, and then plotted with a 125-year running average to capture the multidecadal trends, which is the temporal limit of sedimentary charcoal records. Standardized PDSI values range between −0.5 and 0.5. Negative values indicate drought conditions, while positive values indicate wet conditions.

3.3.2. Modern climate analog

The modern climate analog technique is a conceptual model that uses modern extremes (e.g. drought) as analogs of past events (e.g. periods of synchronous wildfire), and is therefore an effective way to identify climate mechanisms associated with past environmental changes (e.g. as seen in reconstructed sedimentary charcoal records) (Edwards et al., 2001; Mock and Brunelle-Daines, 1999; Shinker et al., 2006; Mock and Shinker, 2013; Shinker, 2014). To investigate potential climate processes and mechanisms that may have caused the various spatial patterns of wildfire, we analyzed modern climate analogs from years when wildfires occurred primarily in the NRM region (1988, 2000, 2003, 2007, and 2012), in the SRM region (2000, 2002, 2006, 2012, 2013), and one case year (2012) when large wildfires, synchronous occurred in both regions. These three scenarios are used to explore mechanisms of recent and paleo fire-climate relationships, including typical high-fire conditions in recent decades, as well as potential mechanisms driving high fire activity observed in the past. We examined a variety of surface and atmospheric climate variables from the North American Regional Reanalysis (NARR) dataset (Mesinger et al., 2006) to calculate and map anomalous patterns based on the modern analog years. Three atmospheric variables (e.g. geopotential height at the 500 mbar (mb) level, specific humidity at the 850 mb level, and omega at the 500 mb level) were used in this study. The 500 mb geopotential height was used because it best represents the pressure level at the mid-troposphere. 850 mb specific humidity was used to provide information about moisture availability in the atmosphere (i.e., relative humidity), and 500 mb omega was used to provide information about rising or sinking motions in the atmosphere, which either enhance or suppress precipitation, respectively. The seasonal value (e.g. summer = JJA) of the selected modern analog case years were averaged together (composited) and compared to the long-term mean (1981–2010) to create composite-anomaly values for each season. Composite-anomaly values were then mapped to identify surface and atmospheric conditions that likely support large, synchronous wildfire activity throughout the U.S. Rocky Mountains. Atmospheric variables were mapped at a continental scale to illustrate the large spatial scales at which fire-climate linkages occur.

4. Results

4.1. Northern rocky mountains climate-fire history

Prior-to the MCA in the NRM region, average North American temperature anomalies were consistently positive, while reconstructed PDSI values generally indicate variable summer precipitation (Fig. 4). Wildfire activity in the NRM region was similar to the modern period, according to the RSI values (Fig. 4C). However, RSI values indicate low- and mid-elevations experienced positive wildfire anomalies prior-to 1000 cal yr BP, while high-elevations experienced negative wildfire anomalies.

By ~900 cal yr BP, RSI levels increased to their highest values in high-elevations under warmer- and drier-than-average conditions in the NRM region (Fig. 4). RSI values indicate no apparent increase in wildfire during the MCA at mid-elevations. RSI values indicate a small step-change during the MCA, however, charcoal influx anomalies were still negative.

During cooler-than-average conditions, such as during the Little Ice Age (LIA) between 550 and 250 cal yr, North American temperature anomalies indicate significantly cooler-than-present conditions. Reconstructed PDSI values indicate positive summer precipitation anomalies. Charcoal influxes from the NRM region indicate negative anomalies during the first half of the LIA. However, RSI values indicate a step-change towards positive wildfire anomalies beginning ~300 cal yr BP, driven by an increase in charcoal influx at high-elevations. In comparison, low- and mid-elevation records do not show an increase in wildfire at this time.

During the 20th century, RSI values from mid-elevations record their highest values indicating an increase in charcoal anomalies from the NRM region. RSI values increase at low-elevations as well, while RSI values indicate a dramatic decline in charcoal anomalies at high-elevations ~100 cal yr BP.

4.2. Southern rocky mountains climate-fire history

In the SRM region prior-to 1000 cal yr BP, reconstructed PDSI values indicate generally negative summer precipitation anomalies

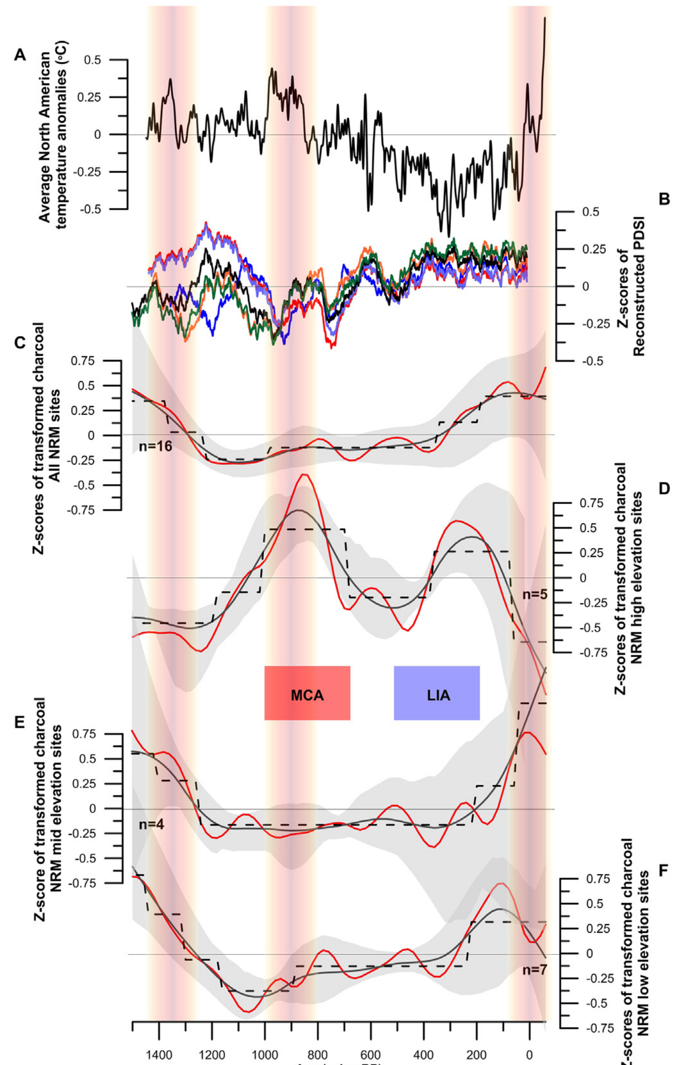

Fig. 4. Northern Rocky Mountains fire-climate linkages over the last 1500 years. A) Reconstructed northern hemisphere average temperature (solid black line) (Mann et al., 2009); B) Reconstructed PDSI smoothed using a 125-yr window (Cook et al., 2004); C) Regional charcoal composite of all charcoal records used in this study from the NRM region; D) Regional charcoal composite of high-elevation charcoal records; E) Regional charcoal composite of mid-elevation charcoal records; F) Regional charcoal composite of low-elevation charcoal records. All charcoal records were smoothed using a lowess curve with 250-year (red line) and 500-year (gray line) moving window widths. The black dashed lines is the regime shift index (Rodionov, 2004). The red shaded boxes indicate three significant periods of fire; 1350 900 cal yr BP, and the 20th century. The red filled box indicates the timing of the Medieval Climate Anomaly (MCA; 1000 to 700 cal yr BP), and the blue filled box indicates the timing of the Little Ice Age (LIA; 550 to 250 cal yr BP) (Mann et al., 2009). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Fig. 5). RSI values indicate positive charcoal anomalies in both mid- and high-elevations centered around 1350 cal yr BP. However, ~1100 cal yr BP, RSI values indicate a step-change to neutral wildfire anomalies.

Roughly 900 cal yr BP, high-elevation charcoal anomalies remained positive until the end of the MCA ~700 cal yr BP when the RSI values indicate a step-change towards negative wildfire anomalies. Mid-elevation charcoal anomalies remained negative during this time.

During the LIA, predominately negative wildfire anomalies prevailed until the modern period throughout the SRM region.

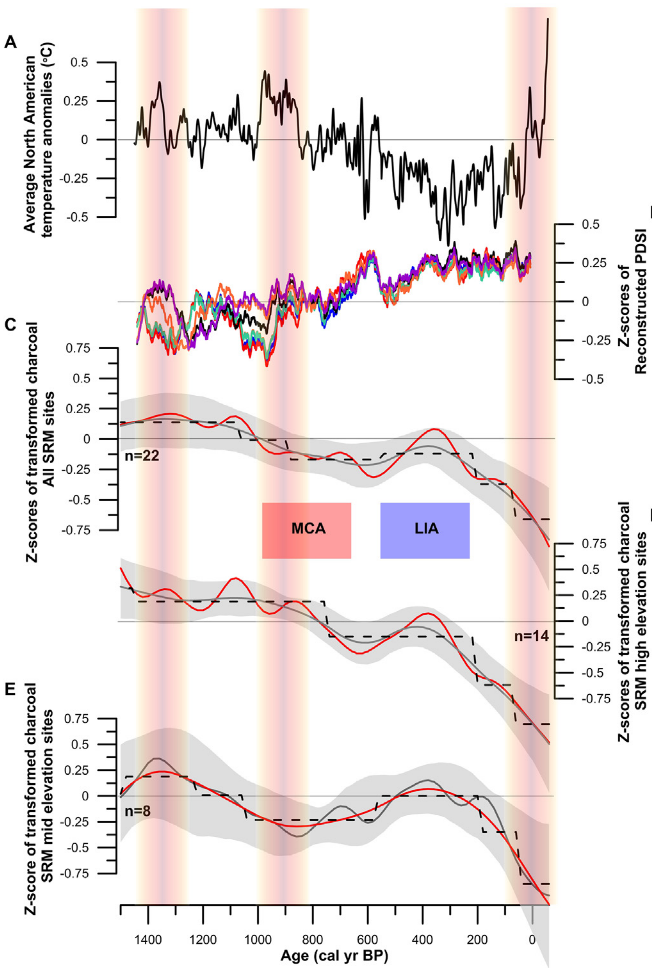

Fig. 5. Southern Rocky Mountains fire-climate linkages over the last 1500 years. A) Reconstructed northern hemisphere average temperature (solid black line) (Mann et al., 2009); B) Reconstructed PDSI smoothed using a 125-yr window (Cook et al., 2004)); C) Regional charcoal composite of all charcoal records used in this study from the SRM region; D) Regional charcoal composite of high-elevation charcoal records; E) Regional charcoal composite of mid-elevation charcoal records. All charcoal records were smoothed using a lowess curve with 250-year (red line) and 500-year (gray line) moving window widths. The black dashed lines is the regime shift index (Rodionov, 2004). The red shaded boxes indicate three significant periods of fire. The red filled box indicates the timing of the Medieval Climate Anomaly (MCA; 1000 to 700 cal yr BP), and the blue filled box indicates the timing of the Little Ice Age (LIA; 550 to 250 cal yr BP) (Mann et al., 2009). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

However, a slight increase in RSI values in mid-elevations indicates neutral wildfire anomalies during the LIA, concurrent with a slight decline in reconstructed PDSI values.

5. Discussion

5.1. Fire-climate linkages among stratified elevation charcoal records

Long-term trends in fire activity over the past 1500 years suggest an overall trend of decreasing wildfires across the western U.S. (Marlon et al., 2012). However, when fire histories for the NRM and SRM regions are partitioned and compared, opposing trends of decreasing and increasing fire in the SRM and NRM, respectively, emerge over the past 1500 years. Further interrogation of the regional fire histories from the region stratified by elevation identified three significant periods of changing wildfire activity; during the modern period (20th century), at ~900 cal yr BP, and at ~1350 cal yr BP.

During the modern period, both mid- and high-elevations in the NRM have generally experienced an increase in wildfire activity, while same elevations in the SRM have experienced a decline in wildfires. The long-term trend in the SRM of decreasing fire corresponds to increasing positive PDSI values (Cook et al., 2004). Typically, the fire season in the SRM begins in late spring/early summer prior-to the onset of the North American Monsoon (NAM), which begins in early July (Baker, 2009). Grissino-Mayer et al. (2004) found that 57% of all fires that occurred prior-to 1880 in the San Juan Mountains of southern Colorado occurred during the late spring/early summer, with only 12% of all fires occurring between mid-June and July (i.e., the height of the NAM season). The authors suggest that in order for wildfires to occur during the NAM season, monsoon rainfall was either diminished, delayed, or failed (Grissino-Mayer et al., 2004), further illustrating the importance of the summer monsoon-related precipitation on wildfire occurrence in the SRM region. However, Anderson (2011) documented a switch from a rain-dominated precipitation regime to a snow-dominated precipitation regime from a site in the SRM region between the MCA and LIA, suggesting the potential link of increasing winter precipitation and decreased fire activity in mid- and high-elevation forests in the SRM region. The increase in wildfires in the NRM has been linked to climatic factors, such as earlier and warmer-than-average spring temperatures, reduced snowpack, and drier summers (Westerling et al., 2006; Morgan et al., 2008; Littell et al., 2009; Westerling et al., 2011; Westerling, 2016).

However, patterns in fire activity during the last two centuries may be linked to Euro-American settlement and activities in mid- and high-elevation conifer forests. These forests typically experience infrequent wildfires, and 20th century fire suppression efforts have likely had minimal impact on mid- and high-elevation conifer forests across the U.S. Rocky Mountains (Romme and Despain, 1989; Johnson et al., 2001; Veblen, 2000; Schoennagel et al., 2004). Rather, many of these forests were heavily logged and grazed in the late 1800s and early 1900s, promoting changes in structure and composition by reducing surface fires (Pyne et al., 1996). In the SRM region, reduced charcoal influx in sediment records were linked to anthropogenic caused changes in forest composition that changed fuel conditions reducing fire in recent times (Anderson et al., 2008).

Around 900 cal yr BP, the spatial pattern of wildfires reveals generally more wildfire activity in the SRM region (Fig. 6). However, the greatest increase in wildfires occurred in the high-elevations forests of the NRM region in response to the driest conditions of the past 1500 years. Similarly, fires increased at high-elevations in the SRM when the driest conditions occurred, which was both prior-to and during the MCA. Modern climate-fire research suggests that areas where snow is a significant portion of annual precipitation area are currently the most sensitive to large wildfires (Westerling, 2016). In the NRM region ~50–80% of its annual precipitation occurs during the winter months (Fig. 1), suggesting the greater importance of winter precipitation, in the form of snowpack, on wildfire activity at high-elevations. During the late 20th century, NRM snowpack has declined to nearly unprecedented magnitudes compared to the last millennium (Pederson et al., 2011). Pederson et al. (2011) suggested a link between reduced snowpack and springtime warming. Because modern climate-fire relationships in the NRM are influenced by warmer temperatures, drier summers, reduced snowpack and earlier and warmer-than-average spring temperatures (Westerling, 2016), it is hypothesized that these same climatic factors contributed to the significant increase in fire at high-elevations in the NRM during the MCA.

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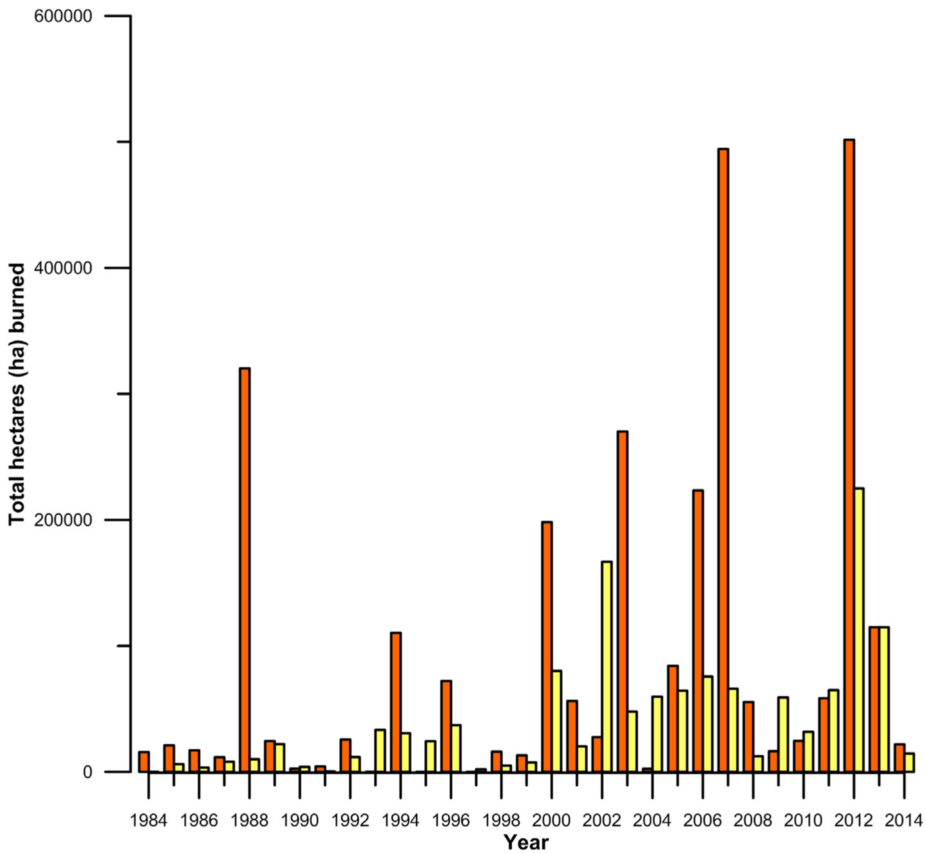

Fig. 6. Histogram showing the total number of hectares burned at low, moderate, and high severity from forested land in the Northern Rocky Mountain region (orange shading) and Southern Rocky Mountains (yellow shading) between 1984 and 2014. Data was downloaded from MTBS.gov. Fires that occurred in Montana, Idaho and Wyoming were summed to create the Northern Rocky Mountain histogram. The Southern Rocky Mountains are comprised of Colorado, Utah, and New Mexico. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

However, modern fire-climate research also suggests that fire occurs throughout the northern and southern Rocky Mountain high-elevation conifer forests under persistent, higher-than-average pressure systems that promote regional drought (Schoennagel et al., 2004; Sibold and Veblan, 2006; Morgan et al., 2008). The importance of persistent regional drought in promoting wildfire activity at high-elevations in both the NRM and SRM was also likely a key factor.

Finally, at ~1350 cal yr BP, synchronous wildfires occurred across most elevations from both regions likely in response to a long-term trend of warmer-than-average temperature and protracted drought conditions (Figs. 4 and 5). With future climate projections suggesting an increase in more intense droughts and increased fire frequency and fire severity (Flannigan et al., 2009; Liu et al., 2016), many forested ecosystems are expected to shift towards novel-disturbance regimes in the western U.S. (e.g. Allen et al., 2011; Westerling et al., 2011). However, while many droughts have plagued the 20th century that resulted in wildfires, droughts in the 20th century were both shorter in duration and less severe than droughts that have occurred in the region in the past (Woodhouse and Overpeck, 1998). Persistent and severe droughts were common prior-to and during the MCA in the U.S. Rocky Mountains. The synchrony in fires at 1350 cal yr BP may represent the expected disturbance response with anthropogenic climate change. Comparing the modern response of fire to the response reconstructed at 1350 cal yr BP suggests that forested ecosystems have not yet experienced a shift to novel-disturbance regimes, but wildfires could potentially synchronize across the entire U.S. Rocky Mountains with continued warming temperatures.

From these three periods of extreme fire activity, we are able to conclude that our results confirm our anticipated response that significant changes in fire activity occurred in response to warmer-than-average temperatures and lower-than-average seasonal moisture in mid-to-high elevation forests.

5.2. Spatial-temporal patterns of wildfire and climate-fire linkages

According to Monitoring Trends in Burn Severity (MTBS) data, the total number of hectares burned within forested ecosystems in the NRM region has increased relative to the SRM region over the past three decades (Fig. 6), which is supported by both sedimentary charcoal records, and recent observations (Westerling et al., 2006; Dennison et al., 2014; Higuera et al., 2015; Westerling, 2016). While the regional summaries from charcoal records capture the temporal trend of increased/decreased fire in the Rocky Mountains, reconstructing spatial patterns of fire though time reveal a more heterogeneous history (Fig. 7). Using a modern climate analog technique of combining years together when large wildfires occurred primarily in the NRM region (Fig. 6) reveals the importance of anomalous high-pressure ridge centered over the northern Great Plains and NRM region (Fig. 8), which influences wildfires by promoting regional droughts (Schoennagel et al., 2004; Sibold and Veblan, 2006; Morgan et al., 2008). However, the lack of atmospheric moisture, demonstrated by anomalously low relative humidity over in the NRM region, in combination with large-scale regions of descending air (Fig. 8) illustrates the spatial extent of dry conditions that likely contributed to increased fires across the NRM region during the 20th century (Fig. 7).

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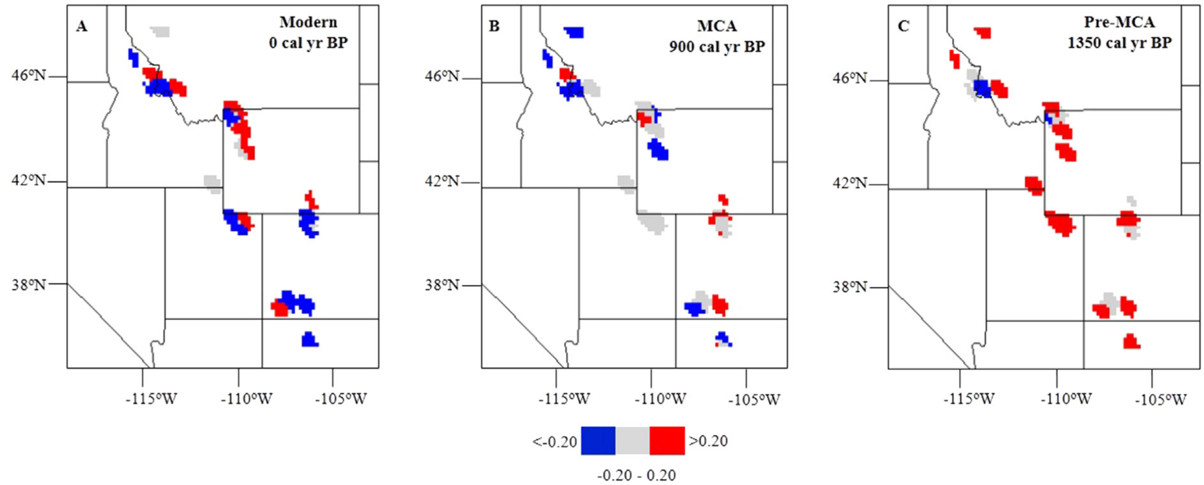

Fig. 7. Regional composite sedimentary charcoal influx records showing positive (red; >0.20), neutral (gray), or negative (blue; <-0.20) anomalies of regional wildfire activity from the NRM and SRM regions during A) the 20th century, B) 900 cal yr BP, and C) 1350 cal yr BP. Each time slice used a base period from 150 to 1500 cal yr BP to avoid the influence of 20th century land cover activities. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Comparing the gridded spatio-temporal paleofire maps (Fig. 7) with modern climate composite anomaly maps (Fig. 8) offers some insight into the spatial extent of key fire-climate mechanisms influencing high fire activity during previous warmer and/or drier paleoclimates (Mann et al., 2009). The five highest area burned years in the SRM region occurred during the summers of 2000, 2002, 2006, 2012, and 2013 (Fig. 6). The climate mechanisms of these recent five anomalous years may provide a proxy for the fire

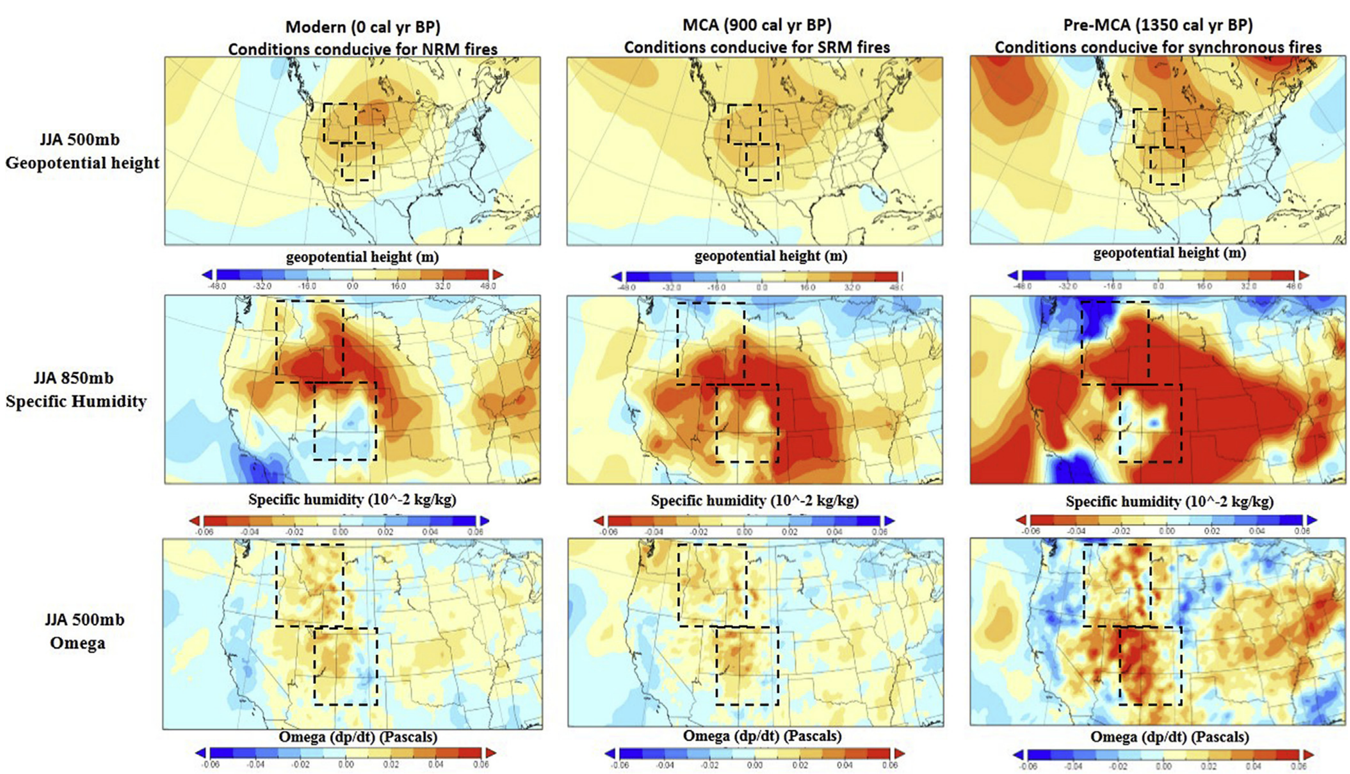

Fig. 8. Composite anomaly maps of the synoptic processes that facilitated to large wildfires during the 20th century (left panel; 0 cal yr BP), the MCA (middle panel; 900 cal yr BP), and pre-MCA (right panel; 1350 cal yr BP). Modern climate analogs used to create composite anomaly maps for the modern period include the summers of 1988, 2000, 2003, 2007, and 2012 when wildfires primarily occurred in the NRM region. Modern climate analogs used for the MCA period include 2000, 2002, 2006, 2012, 2013, when wildfires occurred primarily in the SRM region. The summer of 2012 was used as the climate anomaly for 1350 cal yr BP when conditions were conducive for large wildfires in both regions. From the top down: Composite anomaly map for 500 mb geopotential height during the summer (JJA). Positive values (warm colors) for 500 mb geopotential heights indicate a stronger-than-normal ridge, while negative values (cool colors) indicate a strong-than-normal trough. Composite anomaly map for 850 mb specific humidity during the summer season. Positive values (cool colors) indicate wetter-than-normal conditions in the atmosphere, while negative values (warm colors) indicate dryer-than-normal conditions. Composite anomaly map for 500 mb Omega (vertical velocity) during the summer season (JJA). Positive values (warm colors) for omega indicate enhanced sinking motions (suppress precipitation), while negative values (cool colors) indicate enhanced rising motions (enhanced precipitation). The black dashed boxes denote the NRM (top box) and SRM (bottom box) regions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

conditions experienced ~900 cal yr BP when primarily the SRM region burned compared to the NRM region. These modern climate analogs emphasize the important role of anomalous 500 mb high-pressure ridges centered over the Great Plains and the dry atmospheric conditions needed for synchronous wildfires across the SRM region, demonstrated by the 850 mb specific humidity (Fig. 8).

During the summer of 2012, the total area burned from each region was the highest when compared to the past ~30 years (Fig. 6). The climate mechanisms during the summer of 2012 in particular, provide an opportunity to explore mechanisms required for synchronous wildfires across the region, as experienced ~1350 cal yr BP. Similar to the previous cases, the summer of 2012 can be characterized by anomalously low relative humidity during the summer months across both regions (Fig. 8). However, during the summer of 2012, 500 mb omega demonstrates more anomalous rates of descending air likely in association with a more enhanced high-pressure ridge over central North America, as well in the north Pacific as demonstrated by 500 mb geopotential heights suggesting the influence of more enhanced high-pressure ridges in reducing atmospheric moisture and inhibiting vertical uplift across the U.S. Rocky Mountains. Linkages between fire and climate on large-scales are evident when fires are synchronous across regions, with contingent states of sea surface temperatures and atmospheric pressure in both the Pacific and Atlantic basins synchronizing droughts and wildfires in the western U.S. (Kitzberger et al., 2007). As climate projections for the future suggest an increase in fire frequency and severity in response to warmer temperatures and more severe droughts (Flannigan et al., 2009; Romero-Lankao et al., 2014; Liu et al., 2016), the synoptic processes experienced during the summer of 2012 may represent conditions conducive for synchronous wildfires across the region, as seen ~1350 cal yr BP.

6. Conclusions

The results from our analyses indicate that the recent increase in fire in mid-elevation forests in the NRM is not unique when compared to the reconstructed wildfire anomalies during the past 1500 years (Fig. 4). Rather, our results indicate the sensitivity of high-elevation forests to increased temperatures and decreased seasonal moisture. Specifically, abundant fires occurred ~900 cal yr BP in high-elevation forests in the NRM, while high fire activity occurred at high-elevation forests in the SRM ~1350 cal yr BP. The overall temporal and spatial trends in wildfire activity in the U.S. Rocky Mountains is best captured by combining regionally composited charcoal anomalies with spatially gridded patterns of fire over the past 1500 years.

Modern climate analogs provide a useful technique for encouraging data-model comparisons of sedimentary proxy responses to paleoclimatic patterns (Mock and Brunelle-Daines, 1999). The link between climate mechanisms driving high fire years in recent decades and periods of greater-than-present wildfires over the past 1500 years provides potential mechanisms to explain paleofire reconstructions. By applying a modern climate analog approach, these analogs demonstrate the importance of anomalous low relative humidity (850 mb specific humidity), higher-than-average 500 mb geopotential heights, and anomalous large-scale areas of descending air (500 mb omega), which potentially explains the reconstructed spatial patterns of wildfire during the 20th century, ~900 cal yr BP, and ~1350 cal yr BP. This study suggests Rocky Mountain more frequent and synchronous fire activity could occur across latitudinal and elevational gradients under future warmer climates, particularly if coupled with reduced atmospheric humidity and protracted droughts.

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