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Variability of warm/dry mixed conifer forests in southwestern Colorado, USA: Implications for ecological restoration

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ABSTRACT

There is a need to quantitatively describe forest types and their associated natural fire regimes in the western US to understand their variability and to develop strategies to restore fire dependent landscapes to reduce ecological problems that might ensue from forest structure and fire regime generalizations. We established three study sites in warm/dry mixed conifer across a west–east transect in southwestern Colorado to determine variability in the historical fire regime and fire–climate relationships and to quantify how diverse warm/dry mixed conifer forest composition and structure are along the same west–east transect. At each study site we collected cross-sections from dead fire-scarred trees to reconstruct fire history and established study plots to characterize forest structure. The three warm/dry mixed conifer sites exhibited different fire histories. One site was characterized by numerous smaller fires as well as larger fires that appeared to burn most of the study site with the other two study sites characterized by relatively infrequent, large fire events. There were more unique fire years at each site than synchronous fire years shared by any sites. Current forest stand structure, after extended fire exclusion and past logging across the three sites, also varied with a reverse-*J* distribution indicating strong dominance by small trees for two of the study sites and a truncated age distribution at the other site. Our research illustrates that historical fire regime variability exists within the same vegetation type in a relatively small, ~50 km, geographic locality emphasizing the role that other topographic variables play in determining fire regimes and forest structure. Our findings demonstrate the need to develop site-specific reference conditions and for managers to exercise caution when extrapolating fire regimes and forest structure from one geographic locality to another given a projected warmer climate making conditions more favorable to frequent, large wildfires.

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1. Introduction

Mixed conifer is one of the most complex forest types in the western United States. Mixed conifer forests in the American Southwest (Arizona, New Mexico, and southern Colorado and Utah) cover approximately 1,000,000 ha (Dieterich, 1983) between the generally lower elevation ponderosa pine (*Pinus ponderosa* P. & C. Lawson) and the higher elevation Engelmann spruce (*Picea engelmannii* Parry ex Engelm.) and subalpine fir [*Abies lasiocarpa* (Hook.) Nutt.] forest types. Southwestern mixed conifer forests have been classified in two categories, warm/dry and cool/moist, which denote the ends of a xeric–mesic continuum (Romme et al., 2009). Warm/dry mixed conifer is generally located at the lower elevation of the continuum on predominately southerly aspects and is dominated by fire resistant ponderosa pine (*P. ponderosa*) and Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] but also includes species adapted to mesic conditions such as white fir [*Abies concolor* (Gordon and Glendinning) Hoopes.] and aspen (*Populus tremuloides* Michx.) and sometimes southwestern white pine (*Pinus strobiformis* Engelm.). Surface fires burned with sub- to multi-decadal frequency prior to Euro-American settlement (late 1800s) in warm/dry mixed conifer (Grissino-Mayer et al., 2004a; Fulé et al., 2009). Cool/moist mixed conifer is usually located at the higher elevation of the continuum on predominately northerly aspects and is dominated by mesic-adapted conifers and aspen. Fires in cool/moist mixed conifer forests burned with a sub-decadal to century frequency where surface and crown fire behavior could occur during the same fire event (Margolis and Balmat, 2009; Romme et al., 2009).

Fire suppression along with grazing in the 20th century, which disrupted fine fuel continuity, has increased stand density in warm/dry mixed conifer. Species composition shifted from

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shade-intolerant ponderosa pine to shade-tolerant species such as white fir and Douglas-fir (Mast and Wolf, 2004; Brown and Wu, 2005; Fulé et al., 2009). There has also been increased continuity of vertical and horizontal fuels (Cocke et al., 2005; Margolis and Balmat, 2009). As a result of these changes, a current focus for scientists and land managers is to restore forest stand characteristics that were historically adapted to frequent surface fire but are now at risk of crown fire (Fulé et al., 2003; Heinlein et al., 2005; Falk, 2006). In adjacent pure ponderosa pine forests there is an abundance of research describing the range of variability in stand structure and historical fire regimes prior to Euro-American settlement in the American Southwest (Covington et al., 1997; Fulé et al., 1997; Swetnam and Baisan, 2003; Grissino-Mayer et al., 2004a; Moore et al., 2004; Brown and Wu, 2005). A diverse range of scientifically viable restoration approaches has been proposed to reflect the heterogeneous spatial and temporal forest patterns and fire regimes at local and landscape scales in ponderosa pine in the Intermountain West (Covington et al., 1997; Allen et al., 2002; Iniguez et al., 2008).

Much less information exists about the range of site-specific variability of warm/dry mixed conifer forest composition, structure and fire regimes prior to Euro-American settlement in the American Southwest, particularly in southwest Colorado (Grissino-Mayer et al., 2004a; Korb et al., 2007; Fulé et al., 2009). Given the extensive coverage of warm/dry mixed conifer in this region, these previous studies may not provide an accurate description of variability in warm/dry mixed conifer making additional research valuable. Grissino-Mayer and others (2004a) reconstructed fire regimes in ponderosa pine forests across an elevation gradient in southwest Colorado and found mean fire intervals lengthened with increased elevation with low elevation ponderosa pine sites having 6–10 year mean fire return intervals (MFIs) and higher elevation warm/dry mixed conifer sites having longer MFIs of 18–20 years. Beginning in 2002, we initiated a study within the same region to determine reference conditions of historical fire regime and fire–climate relationships, forest composition, and forest structure for warm/dry mixed conifer at Lower Middle Mountain in southwest Colorado and found mean fire intervals of 24–36 years prior to 1870 (Fulé et al., 2009). We quantified how these variables changed since 1870 and designed and tested three restoration alternatives (thin/burn, burn only, and untreated controls) on four replicated blocks, each approximately 16 ha (Korb et al., 2007; Korb and Fulé, 2008; Fulé et al., 2009). The present study expands upon the Lower Middle Mountain experiment to determine (a) how representative the restoration treatment findings are for the surrounding warm/dry mixed conifer on the San Juan National Forest, and (b) if site-specific information to guide the development of ecological restoration prescription treatments by land managers is required for warm/dry mixed conifer in southwest Colorado.

There is a need to quantitatively describe forest types and their associated natural fire regimes in the western US to understand their variability and to develop strategies to restore fire dependent landscapes to reduce ecological problems that might ensue from forest structure and fire regime generalizations and to evaluate the impacts of recent large wildfires on forest structure (Schoennagel et al., 2004; Beaty and Taylor, 2008). This is especially important because warmer temperatures (ICPP, 2007) have increased fire season length thus amplifying the number of large fires in the western US (Westerling et al., 2006; Littell et al., 2009). To address this need we established a west–east transect of three study sites, including Lower Middle Mountain, at similar latitude (37°N) and elevation range (~2350 to 2750 m) to quantify warm/dry mixed conifer forest composition, structure and fire regime variability. We hypothesized that fire–climate relationships would be similar with climate synchronizing fire occurrence across the three study sites and there would be little variability in forest composition, structure and fire regime among our study sites because of relatively similar latitude and elevation. The main purpose of this paper is to address the following questions: (1) how variable was the historical fire regime and fire–climate relationships in warm/dry mixed conifer across a west-east transect at relatively similar latitude and elevation over ~50 km on the San Juan National Forest? and (2) how diverse is warm/dry mixed conifer forest composition and structure along the same west–east transect?

2. Methods

2.1. Study area

The study area is located in the San Juan Mountains, San Juan National Forest, in southwestern Colorado. Our three study sites, Grassy Mountain, Lower Middle Mountain, and Jackson Mountain represent a west–east transect of warm/dry mixed conifer stands on the San Juan National Forest at similar latitude (37°N) and elevation range (~2350 to 2750 m) covering a distance of ~50 km (Fig. 1). Warm/dry mixed conifer forests occupy 50,525 ha of the San Juan National Forest. Dominant tree species include ponderosa pine, Douglas-fir, white fir and aspen at all three sites. The midstory and understory for all sites were dominated primarily by Douglas-fir and white fir and a variety of shrubs including Gambel oak (*Quercus gambelii*), snowberry (*Symphoricarpus rotundifolius*), and serviceberry (*Amelanchier alnifolia*). Past disturbance history for all sites include sheep and cattle grazing and timber harvesting since the late 1800s with fire suppression as the management policy since the early twentieth century. The Grassy Mountain and Lower Middle Mountain study sites are generally south-facing with 16–20% average slopes. Jackson Mountain is generally east-facing with a 19% slope average. Daily temperatures range from an average maximum of 27.1 °C in July to a minimum of −14.5 °C in January at Grassy Mountain. The greatest amounts of precipitation occur in July and August due to summer thunderstorm activity with precipitation from November to March dominated by snowfall with an average annual snow total of 293 cm (Western Regional Climate Center, Vallecito Dam, 1917–2010, www.wrcc.dri.edu). The Lower Middle and Jackson Mountain study sites have average daily temperatures range from a maximum of 25.7 °C in July to a minimum of −17 °C in January with similar precipitation patterns at Grassy Mountain and an average annual snowfall total of 326 cm (Western Regional Climate Center, Pagosa Springs, 1906–1998, www.wrcc.dri.edu).

2.2. Field methods

This study utilized fire history legacy data collected by the Forest Service at three different mixed conifer sites. For each collection, fire scarred samples were collected from dead wood (logs, stumps, and snags) specimens. No live trees were sampled due to local Forest policy. The lack of live samples was not problematic as dead wood samples were able to provide coverage into the 20th century. The Jackson Mountain fire history was collected in 1997 (Wu, 1999) adjacent to the west end of the forest structure plots. The Jackson Mountain search area was approximately 190 ha. No significant natural barriers exist between the fire history collection area and forest structure plots; therefore, we felt we could reasonably apply the fire history to the forest structure plots established in this study. The Lower Middle Mountain and Grassy Mountain fire history collections were gathered by the Forest Service in 1999 and 2006 respectively, for environmental analyses in association with planned fuels projects. Fire history collection areas and forest structure plots had complete overlap

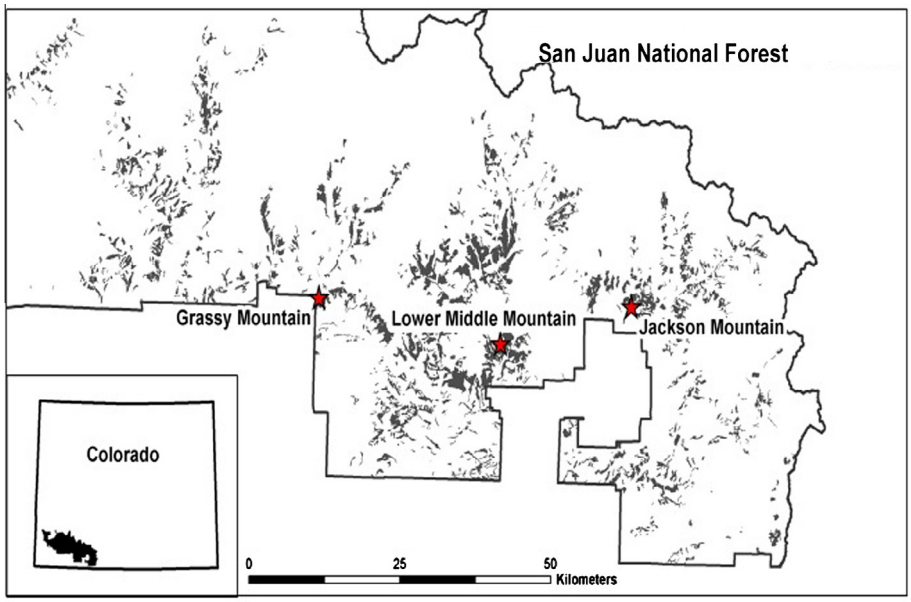

Fig. 1. Study area locations within the San Juan National Forest, southwestern Colorado. Shaded areas represent warm/dry mixed conifer.

at Grassy and Lower Middle Mountain. The fire scar search area at Grassy Mountain was approximately 190 ha and 180 ha at Lower Middle Mountain.

There were 25 forest structure plots per study site that were used to characterize forest structure and vegetation (total $N = 3$ sites $\times$ 25 plots = 75 plots). In 2003 we permanently marked and geo-referenced 240 forest structure plots at Lower Middle Mountain on a 60 m grid; we randomly chose 25 of these plots on 300 m grid to include in this study. In 2006 we permanently marked and geo-referenced 25 forest structure plots on a 300 m systematic grid at the Grassy and Jackson Mountain study sites. We measured overstory trees and saplings taller than breast height (137 cm) in a 400 m^2 (11.28 m radius) circular forest structure plot at Lower Middle Mountain and a variable-radius forest structure plot delineated using a prism with a basal area factor of 2.2 m^2/hectare per tree at Grassy and Jackson Mountain. We double sampled a random selection of forest structure plots to quantify if variation between fixed and variable-radius forest structure plots had an effect on forest structure data; no statistical differences were found. At all study sites, species, condition (living or snag/log classes Thomas et al., 1979), diameter at breast height (dbh), and a preliminary field classification of presettlement or postsettlement origin were recorded for each tree encountered in the forest structure plot. We identified potentially presettlement ponderosa pine trees based on size (>40 cm diameter at "stump height" [dsh], 40 cm above ground level) or yellow bark (White, 1985). Other conifers were also considered as potentially presettlement if dsh > 40 cm; aspen were noted as potentially presettlement if dsh > 20 cm. All potentially presettlement trees were cored, as well as the first five living trees encountered clockwise from north on the forest structure plot.

2.3. Laboratory, statistical, and modeling analysis

2.3.1. Fire history lab methods

Standard dendrochronological methods were used to prepare and visually crossdate all samples against a master chronology developed in the San Juan Mountains (Stokes and Smiley, 1968). Seasonality was assigned to fire years based on the position of the scar within the tree-ring when possible. The position of a scar within an annual tree-ring has been locally correlated to time of year (Grissino-Mayer, 2001). Scars identified in the early (EE) and middle earlywood (ME) correspond with early to mid-summers (mid-June to mid-July). Scars in the late earlywood (LE) and latewood (A) correspond to late summer (mid-July to August). Scars in the dormant (D) position correspond to either the late summer/fall of the ring that precedes it or the spring of the ring that follows it. In this study we assign D scars to the spring of the following annual ring.

2.3.2. Fire history descriptive and test statistics

Fire frequency, severity, and seasonality, were used to characterize the fire regime at each site. We selected 1650–1880 for the designated analysis window. The year 1650 captures the first fire recorded at all sites and 1880 is the locally accepted date of the onset of fire exclusion. We used the program SSIZ (Holmes, 1995; Iniguez et al., 2008) to assess the analysis period dates. SSIZ uses a Monte Carlo approach to calculate estimates of mean numbers of fires and surrounding confidence intervals for randomly selected subsets of fire-scarred tree samples, permitting comparisons among our three sites that differed in sample size. The SSIZ analysis showed that all three sites were statistically indistinguishable and were asymptotic in terms of mean number of fire events per century versus number of sample trees when analyses were calculated based on a minimum of two scarred samples per fire event. Therefore, we used the full data set for calculating fire regime statistics and we set a minimum of samples per fire event. The MFI, Weibull Median Probability Interval (WMPI) and fire interval ranges describe fire frequency at the 10% and 25%-scarred levels. All statistical analyses used fires that scarred a minimum of two samples and met the 10%-scarred filter level. This was done to minimize the inclusion of any false fire scars, it could also remove small fires from the analysis. Percent-scarred levels were used to describe relative fire size within a site (Swetnam and Baisan, 2003). Smaller fires are included in the 10%-scarred level but are filtered out by the 25%-scarred level which represents larger fires.

Past fire severity was challenging to describe. The presence of old, fire-scarred trees and dominance of ponderosa pine and Douglas-fir, the most surface-fire adapted species in our study area, provided evidence of substantial past surface fire. The presence of

other less fire-adapted conifers (white fir and Engelmann spruce) suggested periods or patches of reduced fire frequency and increased stand density along with the development of horizontal and vertical fuel continuity that could support high intensity fire such as crown fire. The presence of aspen is interpreted as evidence of fire which was at least hot enough to stimulate aspen regeneration through suckering, although it is not necessarily correlated with high intensity fire as aspen suckering can also respond to other forest opening opportunities. Age data are important for evaluating past fire severity, but past tree harvesting limited our ability to understand the historic age distribution. In many studies in harvested forests, past forest structure and sometimes past age distributions have been reconstructed through dendrochronological sampling (e.g., Mast et al., 1999), but we did not have sufficient resources to do that in the present study.

To determine whether fire occurrence differed between sites, we ran pair-wise statistical tests to compare fire frequency and fire synchrony. MFIs were compared with Student's *t*-tests. Normality for each fire interval data set was determined and the date transformed prior to running the test (FHX2, Grissino-Mayer, 2001). To determine whether shared fire years were not due to random chance, fire synchrony was tested using a 2×2 contingency analysis (chi-squared test). This analysis tested the null hypothesis ($H_{2\times2}$) that the number of shared fire years between sites is not higher than that expected if fires years were independent occurrences. Rejecting $H_{2\times2}$ suggests that some underlying mechanism synchronized fires between the two sites. To test any relationship between common and unique fire years, a 2×1 contingency analysis was conducted. This analysis tested the null hypothesis ($H_{2\times1}$) that fires are independent occurrences at each site. Rejecting $H_{2\times1}$ indicates that the number of synchronous fires exceeds the number of asynchronous fires whereas not rejecting $H_{2\times1}$ indicates there is no association between fire occurrences between sites.

2.3.3. Fire climate analysis

Short term fire–climate relationships were analyzed with superposed epoch analyses (SEA) (Swetnam, 1993; Grissino-Mayer, 1996) on fire years that met the two scar minimum and 10%-scarred level filter. Fire years were tested against three climate reconstructions: two drought indices and one ENSO (El Niño Southern Oscillation) index. Drought indices included the PDSI (Palmer Drought Severity Index) for the Four Corners (Cook et al., 2004) and an annual precipitation reconstruction from northern New Mexico (PPT, Grissino-Mayer et al., 2004b). The one ENSO index used was the NINO3 sea surface temperature (SST) index (Cook, 2000). El Niño Southern Oscillation has been linked to the wet-dry climate pattern found to precede large fire years in ponderosa pine forests of the Southwest (Swetnam and Baisan, 1996; Grissino-Mayer et al., 2004a; Brown and Wu, 2005). Superposed epoch analysis compares mean climate values of the documented fire events and selected analysis window to bootstrapped confidence intervals to identify important climate patterns and trends that affect fire occurrence. We used an analysis window of 10 yrs: 5 pre-fire years, fire year, four post-fire years.

2.4. Forest structure and composition analysis

We compared forest structural variables including tree density and basal area for individual species among the three study sites with a Kruskal–Wallis test ($P \leqslant 0.05$). Post Hoc tests were conducted with pairwise Kruskal–Wallis two-sample tests following a statistically significant result (Mann–Whitney *U* statistic) and then adjusted alpha levels by the number of pairwise comparisons using a Bonferroni correction (Kuehl, 1994). Nonmetric multidimensional scaling (NMS) was used to examine differences in trees ha^{-1} for all tree species among the three study sites (Clark, 1993). We conducted NMS analyses using PC-ORD software (version 5.10, McCune and Mefford, 2006). We ran the NMS ordination using a Bray-Curtis distance measure, random starting configurations, 50 runs with real data, a maximum of 200 iterations per run and a stability criterion of 0.00001. We compared the stress value of the final solution to 50 random solutions using a Monte Carlo test. Two species, pinon pine (*Pinus edulis* Engelm.) and Rocky Mountain juniper (*Juniperus scopulorum* Sargent) were filtered out because these species did not occur on a 5% minimum of plots (McCune and Grace, 2002). We determined the relationships between tree species and ordination axes using the main matrix Pearson's *r* correlations; tree species with the highest correlation coefficients to have the strongest weight on the axes (McCune and Grace, 2002).

Differences in community forest stand structure, stand density and stand basal area, among the three study sites were determined using a permutational multivariate analysis of variance (PERMANOVA) (Anderson, 2001; McArdle and Anderson, 2001). PERMANOVA uses common ecological distance measures (Bray-Curtis for this study) to examine multivariate data sets and calculates *P*-values using permutations rather than tabled *P*-values that assume normality. We used a one fixed factor design with site as our main effect (PC-ORD software version 5.10, McCune and Mefford, 2006). We analyzed species that were present in a minimum of 5% of the plots as recommended by McCune and Grace (2002). Indicator-species analysis (McCune and Grace, 2002), which uses species richness and associated abundance values of species, was used to identify species that were particularly faithful (i.e., consistent indicators) for a particular study site along our west–east transect in warm, dry mixed conifer. A comparison between the maximum indicator value (0–100) and random trials for occurrence of a given species (1000 Monte Carlo randomizations) provided an approximate *P*-value (McCune and Grace, 2002). Species with $P \leqslant 0.05$ and indicator values (INDVAL) > 25 (INDVAL = relative abundance $\times$ relative frequency; INDVAL ranges from 0 to 100) were accepted as indicator species for a particular study site (Dufrêne and Legendre, 1997).

3. Results

3.1. Fire regime descriptive statistics

3.1.1. Seasonality

We were able to assign seasonality positions to 79% of individual scars found in tree rings. Overall, 63% of individual scars in tree rings were in the DEM (dormant-early-middle) positions and 16% were found in LA (late) ring positions. Each site exhibited the same pattern with a great majority of fires occurring from spring to midsummer and a small minority occurring in late summer to fall.

3.1.2. Fire frequency and severity

MFIs between sites were found to be different. Grassy Mountain burned the most frequently with a sub-decadal MFI of 9 yrs at the 10% -scarred level (Table 1). Jackson and Lower Middle Mountain burned less often. Both had multi-decadal MFIs of 20 and 30 yrs respectively. Student's *t*-test results at the 10%-scarred level showed that Grassy Mountain MFIs were significantly shorter than MFIs at Jackson and Lower Middle Mountain ($p < 0.01$), but MFIs between the latter sites were not statistically different ($p = 0.075$). MFIs changed very little between the 10% and 25%-scarred levels, increasing only 1–4 years at Grassy and Jackson Mountain respectively and remaining unchanged at Lower Middle Mountain and the same pattern of statistical results was found at the 25%-scarred level.

Table 1
Fire history statistics MFI (Mean Fire Interval), SD (Standard Deviation), WMPI (Weibull Median Probability Interval) for three sites in warm/dry mixed conifer, southwestern Colorado for the analysis period 1650–1880. Statistics were calculated using fire dates that met the two scar minimum at the different%-scarred filter levels.

Site	No. of fire dates	No. of intervals	MFI	SD	Median	Range	WMPI
Grassy Mountain							
10% Filter	24	23	9	3.8	9.0	1–17	9
25% Filter	22	21	10	4.4	9.0	4–23	9
Lower Middle Mountain							
10% Filter	8	7	30	11.4	28.0	17–50	29
25% Filter	8	7	30	11.4	28.0	17–50	29
Jackson Mountain							
10% Filter	12	11	20	15.6	13.0	4–61	17
25% Filter	10	9	24	17.3	22.0	4–61	21

The fire history, forest age distribution, and tree species composition found at the study sites revealed a complex pattern of fire regime and forest dynamics. Two sites, Grassy and Lower Middle Mountain, display a moderately long, continuous reverse-*J* age structure while Jackson Mountain has a truncated age structure (Fig. 3). Grassy and Lower Middle Mountain's similarity in age structure pattern is notable given that their MFIs were different. Ponderosa pine dominates the early portion of the age structure at both sites, when fires burned frequently, although less so at Lower Middle Mountain. After the last fire at each site, 1878 at Grassy Mountain and 1861 at Lower Middle Mountain, Douglas-fir and white fir survival increased in association with a lack of fire. Aspen was also present at both sites, but its establishment pattern was not always closely tied to fire occurrence.

Unlike the other two sites, Jackson Mountain's truncated age structure provides some evidence of a relatively severe fire event in the mid-1800s, perhaps during the major fire year of 1847 (Fig. 2). Prior to 1847, Jackson Mountain experienced an unusually long 61 year fire free interval. During that time, survival of Douglas-fir and white fir could have increased causing increased forest density and providing the fuel load and structure for a high severity and likely high intensity fire event. Three large fires 1851, 1861, and 1873, burned after 1847. A notable pulse of aspen establishment, making up more than half of the oldest trees found at the site, appeared after the 1850s (Fig. 2), indicating that one or more of the mid-nineteenth century fires may have been relatively severe. Old trees (pre-1850s) were very rare at Jackson Mountain. The truncated age structure could be related to mortality from severe fire but this cannot be distinguished from past tree cutting. After the last major fire at Jackson Mountain in 1873, tree establishment became dominated by other conifers and ponderosa pine and aspen establishment decreased dramatically.

3.1.3. Fire synchrony and fire climate relationships

In general, there were more unique fire years at each site than synchronous fire years shared by either two or all three sites. Of the 32 fire years documented, 1861 was the only fire year in common across all three sites and 11 other fire years were shared by two of the three sites (Table 2). Grassy Mountain had 14 unique fire years, Jackson Mountain had three, and Lower Middle Mountain had two. $H_{2\times2}$ was rejected in all pairings among all three sites at the 10%-scarred levels ($P < 0.005$), suggesting synchronous fire years are related. Other local and regional studies (Grissino-Mayer et al., 2004a; Brown and Wu, 2005) postulate similar top down controls where regional climate is responsible for synchronizing fire years across the landscape. In contrast, H_{2x1} was not rejected for any of the pairings at the 10%-scarred level indicating that fire years between any two sites are independent events and other factors besides regional climate such as topographic features that prevent fire spread or create unique microclimate are responsible for the independent occurrence of fire years.

Although local site conditions exert influence on fire occurrence at each site, climate plays a strong role in fire occurrence as well. Superposed epoch analysis (SEA) showed drier than average conditions, indices values exceeding 95% confidence limits, for all climate indices during the fire year for all three sites (Fig. 4). SEA also documented a pattern of wetter than average conditions 1–3 years preceding the fire year at Grassy and Jackson Mountain and drier than average conditions 1–2 years preceding the fire year at Lower Middle Mountain. However, index values exceeding the 95% confidence limits in years preceding fire were only found at Grassy Mountain for the PDSI and NINO3 indices.

Unusually long fire-free fire periods predating 1880 were observed in the Lower Middle and Jackson Mountain chronologies (Fig. 2). Lower Middle Mountain's fire-free period occurred from 1685 to 1735 (50 years) and Jackson Mountain's from 1786 to 1847 (61 years). These fire-free periods were identified as significantly long because they fell at or above the upper Weibull probability level (95%) in each data set. The fire-free periods did not line up in this study, but the fire free period at Lower Middle Mountain did match a fire-free period documented by a study at nearby Archuleta Mesa (Brown and Wu, 2005). Because the fire-free periods between Lower Middle and Jackson Mountain did not match up, our findings suggest that local site factors overrode regional climate patterns. The only synchronous fire free period found at all three sites is the current fire-free interval which began with the last fire at each site and extends to the present day. This current fire free period is longer than any historical fire-free interval. The last fire at Grassy Mountain, Lower Middle Mountain, and Jackson Mountain occurred in 1878, 1861, and 1873 respectively. The current fire free period at each site is over 100 years and exceeds the longest pre-1880 fire free periods by 200–300%.

3.2. Forest structure

All three study sites had a true mixture of species consisting of ponderosa pine, a xeric species, and various mesic conifers and aspen. There was a significant difference among the three study sites for tree density based on community data ($F = 5.45$; $P = 0.0002$). All pairwise comparisons were significant; Grassy Mountain had significantly lower stand density than Lower Middle Mountain ($P = 0.0002$) and Jackson Mountain ($P = 0.037$). Jackson Mountain had significantly higher stand density than Lower Middle Mountain ($P = 0.002$). There was no significant difference in tree basal area for community data among the three study sites ($F = 1.34$; $P = 0.23$). Douglas-fir basal area was significantly higher ($P = 0.02$) at Jackson Mountain than the other two study sites with no significant difference in basal area for other individual species (Table 4). White fir comprised the highest proportion of basal area at Grassy (39.3%) and Jackson Mountain (36.3%) and ponderosa pine made-up the largest proportion of basal area at Lower Middle Mountain (36.5%). White fir comprised the main proportion of stand density at Lower Middle (57.9%) and Jackson Mountain (54.1%) and aspen represented the largest proportion of stand density at Grassy (45.3%). White fir tree density was significantly higher at Lower Middle Mountain than Jackson ($P = 0.04$) or Grassy Mountain ($P = 0.003$). In contrast, aspen density was significantly higher at Grassy Mountain than Jackson ($P = 0.004$) or Lower Middle Mountain ($P = 0.01$) (Table 3). Douglas-fir tree density was the highest at Jackson Mountain in comparison to Lower Middle ($P = 0.03$) or Grassy Mountain ($P = 0.001$) (Table 3).

Tree age distribution varied among the three study sites (Fig. 3). Grassy and Lower Middle Mountain had a reverse-*J* distribution indicating strong dominance by small trees and Jackson Mountain had a truncated age distribution (Fig. 3). There was a small pulse of

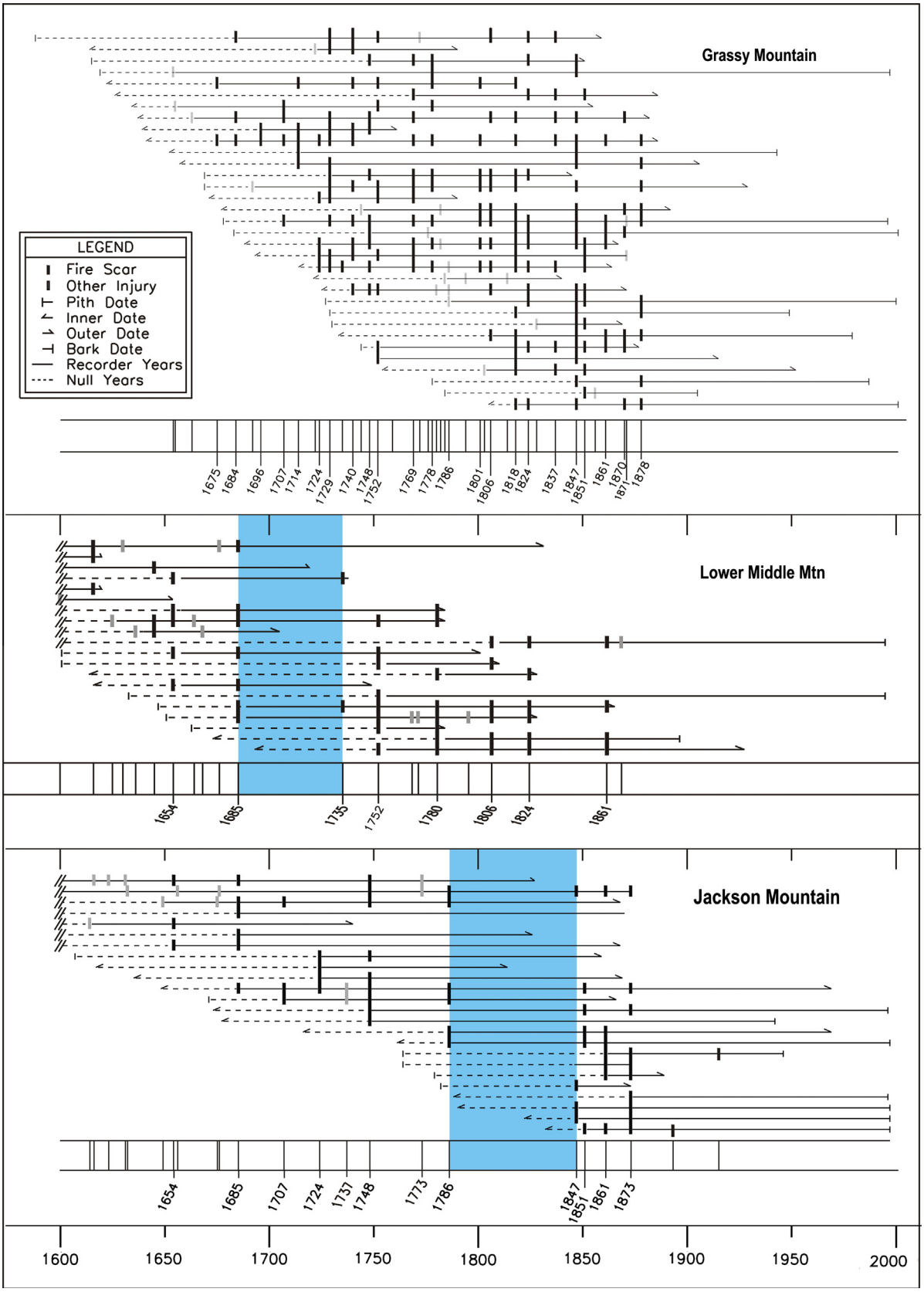

Fig. 2. Fire history plots for each site. Horizontal lines mark time spans of individual trees. Hash marks (//) on the inner (left) side of a sample's time span shows it was truncated for display. Truncated portions were not part of the analysis window. Fire scars are designated by vertical bars. Grey vertical bars denote fires that meet the 10% filter. Black vertical bars denote fires that meet the 10% and 25% filter. The composite fire chronology below each plot displays fires that meet the two scar minimum and 10% filter. Fire years that meet the 25% filter are labeled on the composites. Large, extensive fires can be visually identified in the plots where vertical bars are aligned. The shaded area in the Jackson and Lower Middle Mountain plots highlights an unusually long fire free interval. There was no unusual long interval at Grassy Mountain.

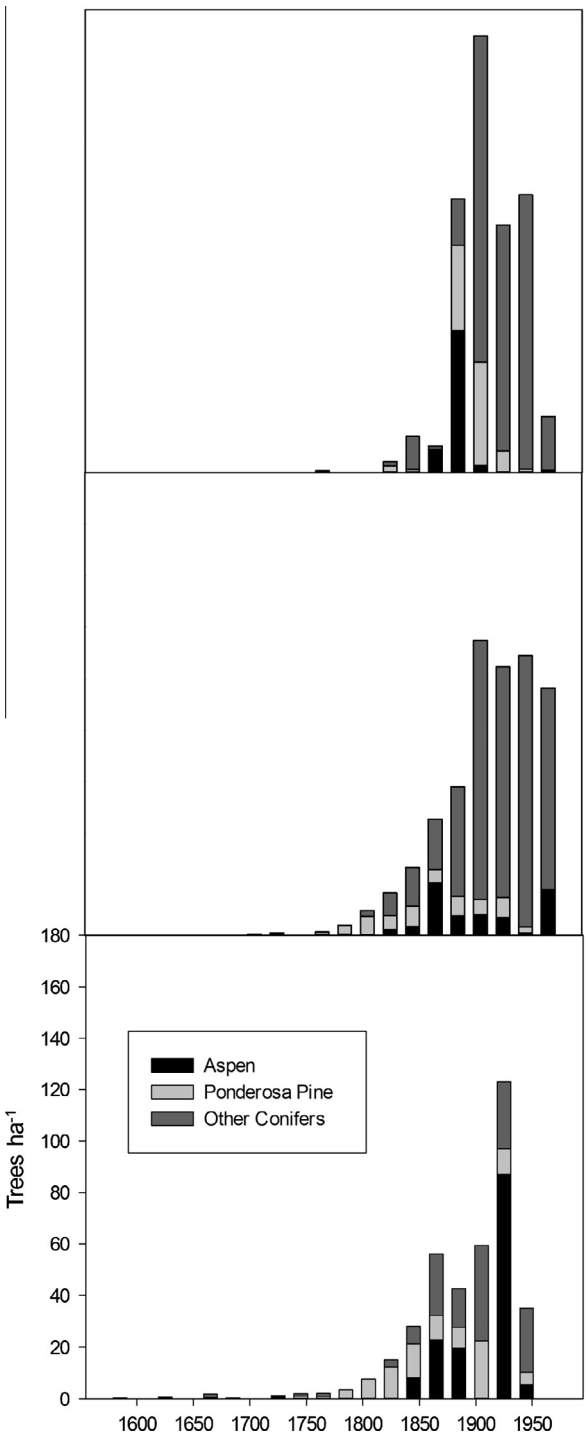

Fig. 3. Age distributions for Grassy Mountain (bottom), Lower Middle Mountain (center), and Jackson Mountain (top). Tree establishment was dominated by ponderosa pine prior to 1870, although aspen and other conifers were all present. Dates shown are tree center dates at coring height (40 cm above ground).

ponderosa pine tree establishment in the early 1900s at Grassy and Jackson Mountain (Fig. 3). Aspen dominated tree establishment at Grassy Mountain after 1870, while white fir dominated tree establishment at Lower Middle Mountain and Douglas-fir dominated tree establishment at Jackson Mountain after 1870 (Fig. 3).

Multivariate comparison of species composition weighted by tree density showed strong separation between Grassy and Lower Middle Mountain with Jackson Mountain more strongly associated with Lower Middle Mountain but overlapping with Grassy Mountain (Fig. 5). Variation along Axis 1 was the result of differences in white fir trees ha^{-1} among study sites and variation along Axis 2 was associated with Douglas-fir basal area/ha variability among study sites (Fig. 5). Indicator species analysis detected species that were particularly consistent indicators for two of our study sites (Table 4). Grassy Mountain had no species that were particularly faithful (Table 4). White fir was the only indicator species for Lower Middle Mountain (IV = 52.9, P = 0.0006) and Douglas-fir was the only indicator species for Jackson Mountain (IV = 35.7, P = 0.033) (Table 4).

Table 2
Fire synchrony for three sites in warm/dry mixed conifer, southwestern Colorado. GMT = Grassy Mountain; LMM = Lower Middle Mountain; JAK = Jackson Mountain. First column lists fire years found at all three sites in bold text. Second column lists fire years shared between GMT and LMM. Third column lists fire years shared between GMT and JAK. Fourth column lists fire years shared between JAK and LMM.

All sites	GMT × LMM	GMT × JAK	JAK × LMM
			1654
			1685
		1707	
		1724	
		1748	
	1752		
		1786	
	1806		
	1824		
		1847	
		1851	
1861	1861	1861	1861

4. Discussion

4.1. Fire regime and fire–climate relationships

4.1.1. Fire regime

The warm/dry mixed conifer fire regime was more variable than that of nearby pure ponderosa pine forests having a dry to moist continuum within warm/dry mixed conifer forests (Grissino-Mayer et al., 2004a). Sub-decadal fire frequency prevailed at Grassy Mountain representing the drier spectrum of the warm/dry mixed conifer fire regime. In contrast, multi-decadal fire frequency, long fire-free periods and possibly locally severe fire prior to 1880 associated with high aspen establishment was observed at Jackson Mountain and Lower Middle Mountain indicative of the moister spectrum of the warm/dry mixed conifer fire regime.

Surface fire was common to all three study sites supporting the classification of all three study sites as warm/dry mixed conifer. Grassy Mountain's MFIs were very similar to pure ponderosa pine in the American Southwest (Grissino-Mayer et al., 2004a; Brown and Wu, 2005), but its moister environment allowed denser stand structure than pure ponderosa pine. Patches of high severity burning could have occurred, particularly after the longer fire-free intervals of 17–23 years (Table 1) due to the increased forest density and fuel structure. In contrast, Jackson and Lower Middle Mountain had longer MFIs and currently denser stand structures than Grassy Mountain. Their fire interval ranges and MFIs are comparable with other warm/dry mixed conifer forests in the region (Santa Fe, New Mexico, Margolis and Balmat, 2009). Other studies in warm/dry mixed conifer reported MFIs much shorter than Lower Middle and Jackson Mountain and more similar to those found at Grassy Mountain (Fulé et al., 2003; Grissino-Mayer et al., 2004a), underscoring the relatively high variability and presence of a dry to moist continuum within warm/dry mixed conifer forests. The majority of fires recorded in our reconstructed chronologies burned moderate to large areas for all three study sites as illustrated by MFIs remaining consistent or with little change

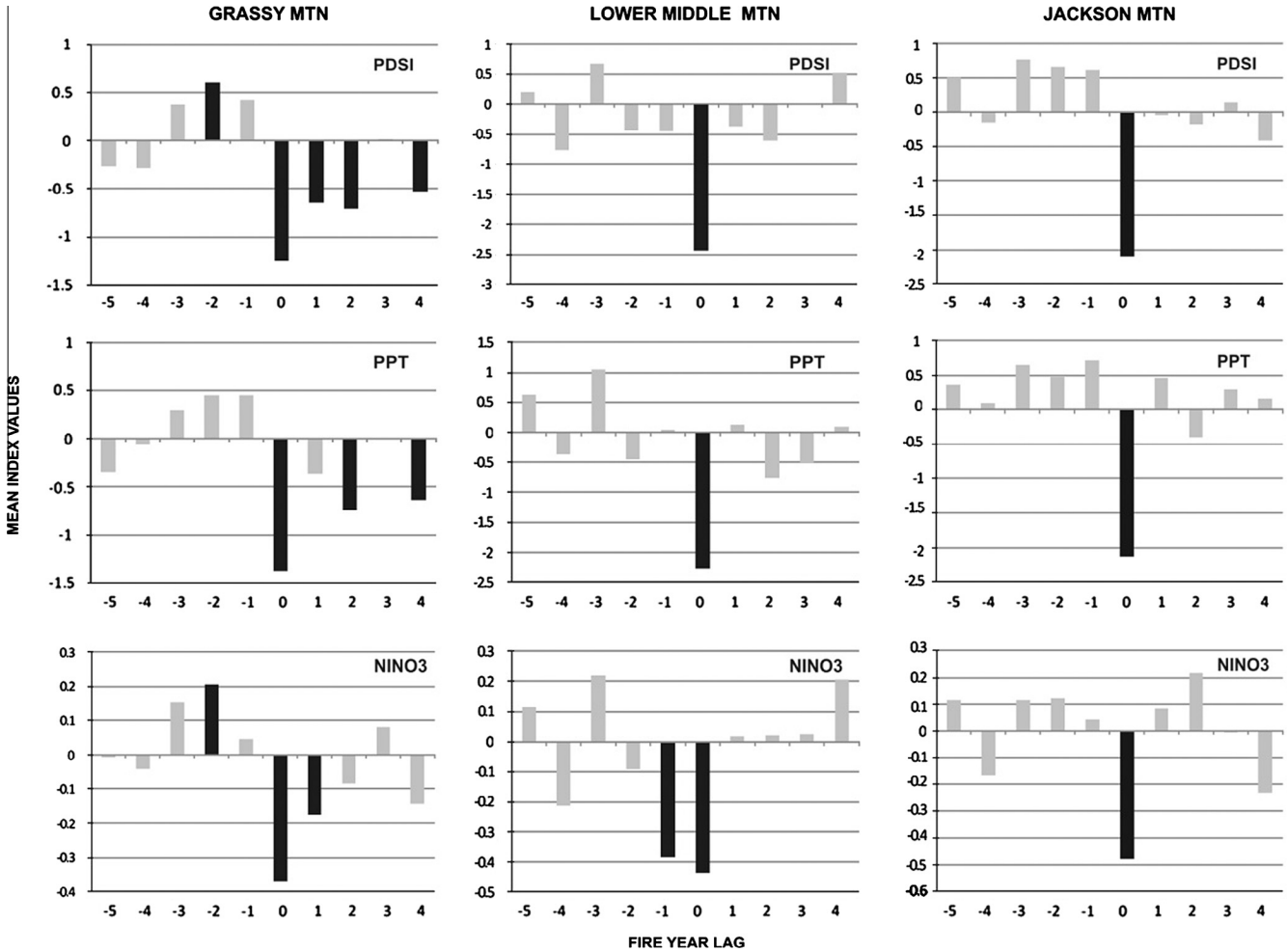

Fig. 4. Superposed epoch analysis (SEA) results for each site. Analysis was performed on fires that met the two scar minimum and 10% filter within the analysis window (1650–1880). Fire years were run against three different climate reconstructions and two drought indices: (1) PDSI for the Four Corners (Cook et al., 2004); (2) annual precipitation reconstruction from northern New Mexico (PPT, Grissino-Mayer et al., 2004a); and, (3) NINO3 sea surface temperature (SST) index (Cook, 2000). Year 0 is the average climate anomaly for the fire year. Negative lag years are the years prior to the fire year. Black bars mark departures that exceed 95% confidence limits at a minimum.

between the 10% and 25%-scarred filter levels. Very small fires did burn at all three study sites, most notably at Grassy Mountain, but these fires were not analyzed because the two scar minimum and%-scarred filters removed them our analysis.

4.1.2. Fire synchrony and fire–climate relationships

Regional climate can synchronize fire years across large areas whereas site-specific factors exert more control over local areas (Brown et al., 2001; Heyerdahl et al., 2001). Fires occurred in years of drier than average conditions for all three study sites. One to three wetter than average years proceeded the fire year at Grassy and Jackson Mountain. In contrast, the fire year was preceded by 1–2 years of drier than average conditions at Lower Middle Mountain (Fig. 4). The pattern at Grassy Mountain is expected because Grassy Mountain's MFIs were similar to pure ponderosa pine fire histories in the region (Swetnam and Baisan, 1996; Grissino-Mayer et al., 2004a; Brown and Wu, 2005) with one to several wet years before a large fire year aiding in creating a continuous fuel bed through increased herbaceous cover. We did not expect to find this same climate pattern at wetter sites that are considered not to be limited by herbaceous fuels. Such forests are often significantly dry in the fire year but are less likely to have an association with significantly wet conditions in prior years (Swetnam and Baisan, 1996).

Table 3
Forest structure for three study sites in warm/dry mixed conifer, southwestern Colorado. Standard errors are shown in parentheses. Differences were determined using Kruskal–Wallis tests followed by pairwise comparisons using a Bonferroni correction. Significant differences among study sites for a particular species are denoted by different letters and highlighted in bold. $P \leqslant 0.05$.

	Basal area (m^2 ha^{-1})	Density (trees ha^{-1})
Grassy Mountain		
Abies concolor	8.4 (1.5) a	**127.3 (34.8) a**
Pinus ponderosa	7.6 (1.6) a	64.4 (21.1) a
Populus tremuloides	4.0 (1.3) a	**171.1 (68.7) a**
Pseudotsuga menziesii	**1.4 (0.7) a**	**15.1 (7.1) a**
Total	21.4 (2.1) a	**378.0 (82.4) a**
Lower Middle Mountain		
Abies concolor	9.6 (0.9) a	**391.9 (30.6) b**
Picea engelmannii	0.1 (0.002)	0.6 (0.1)
Pinus ponderosa	9.8 (1.3) a	55.6 (6.8) a
Populus tremuloides	2.9 (0.6) a	**146.1 (36.3) a**
Pseudotsuga menziesii	**4.6 (0.9) b**	**83.2 (13.9) a**
Total	27.0 (1.6) a	**677.4 (59.7) b**
Jackson Mountain		
Abies concolor	9.4 (1.3) a	**287.9 (64.9) b**
Pinus ponderosa	6.3 (1.5) a	75.4 (20.3) a
Populus tremuloides	3.2 (2.0) a	**54.5 (38.9) b**
Pseudotsuga menziesii	**7.0 (1.6) b**	**114.8 (36.9) b**
Total	25.9 (2.6) a	**532.6 (91.3) c**

Table 4
Indicator species associated with the three study sites in warm/dry mixed conifer, southwestern Colorado. Species with $P \leqslant 0.05$ and indicator values (relative abundance × relative frequency) > 25 were accepted as indicator species for a particular study site.

Study site	Species	Indicator value	*P*
Lower Middle Mountain	*Abies concolor*	52.9	0.0006
Jackson Mountain	*Pseudotsuga menziesii*	35.7	0.033

There were no indicator species for Grassy Mountain.

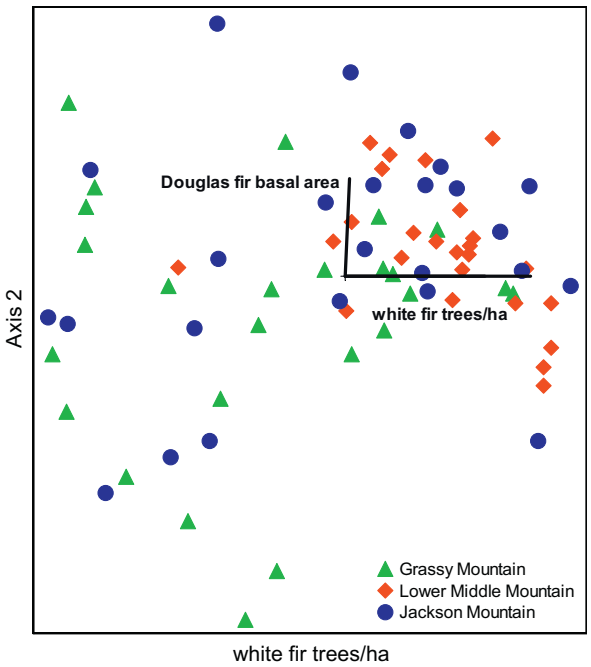

Fig. 5. Non-metric multidimensional scaling ordination of species' tree density for three study sites in warm, dry mixed conifer in the San Juan National Forest, southwestern Colorado. Each symbol represents one plot per study site ($N = 25$/site). The final solution had three dimensions, stress = 14.56 and $P = 0.039$.

The fact that we observed more unique fire years among our study sites than synchronous ones highlights the strong influence local site conditions such as moisture, stand structure, fuel accumulation, topography, and microclimates have on local fire occurrence. Variables linked to topographic differences that influence site moisture conditions would explain some of the differences in fire occurrence among our sites. Southerly aspects receive more solar heating than other aspects making fuels drier. Multiple aspects, fragmented fuel conditions, and complicated topography that harbors moist conditions on northerly aspects and in deep drainages can impede fire spread (Iniguez et al., 2009). Iniguez and others (2008) documented higher fire frequencies and more widespread fires on simpler landscapes lacking deep drainages, cliffs, or other fire spread barriers, which is similar to our Grassy Mountain site. In contrast, complicated landscapes, which are steep and dissected by deep drainages or multiple aspects exhibited longer fire intervals and fewer widespread fires as a whole, which is similar to our Jackson and Lower Middle Mountain sites (Iniguez et al., 2008).

Unusually long fire free periods within the fire chronologies at our three study sites are likely driven by long term fire–climate relationships. Similar fire-free periods have been documented locally and across the region in Arizona and New Mexico (Swetnam and Baisan, 1996; Wu, 1999; Brown and Wu, 2005; Fulé et al., 2009). Explanations for unusually long fire free periods prior to Euro-American settlement (late 1800s) include dampened ENSO amplitude or a cool phase in the Pacific Decadal Oscillation (PDO) that enhances precipitation in the southwestern United States (Grissino-Mayer et al., 2004a; Brown and Wu, 2005). These fire free periods in our study do not line up, illustrating the complexity of understanding long term fire–climate relationships and the need for additional data collection and analysis to understand exactly how climate mechanisms are driving the occurrence of long fire free periods. In contrast, the current fire free interval at each of our study sites that began in the 1870s is much longer than the long fire free periods prior to Euro-American settlement (Fig. 2). The fact that warm/dry mixed conifer forests on the San Juan National Forest are outside their historic range of variability for fire recurrence is linked to evidence that the present forest structure has been pushed outside its historic range as well (Fulé et al., 2009). These forests have had an extended period of time to increase in density and past harvesting preferentially removed fire-resistant pines while fostering regeneration of mesic, shade-tolerant conifers (Fulé et al., 2009). The relatively homogenous and heavy fuel complexes at Jackson and Middle Mountain can support larger high-severity fires under hot and dry conditions. Such conditions are likely to become more common as climate models have predicted arid regions of southwestern North America to shift to warmer, drier conditions in the 21st century (Seager et al., 2007; Seager and Vecchi, 2010).

4.2. Forest structure

There was an inconsistent relationship between tree age distributions and fire scar chronologies at our three study sites where fire scar chronologies represent the occurrence of fire frequency and tree age distributions signify a proxy for the ecological role of fire. For example, tree age distributions were most similar between Grassy and Lower Middle Mountain (Fig. 3) even though these sites had the highest and lowest fire frequencies (Table 1 and Fig. 2). Similarly, fire scar chronologies were more similar at Lower Middle and Jackson Mountain (Table 1 and Fig. 2) but their tree age distributions were distinct with Lower Middle Mountain having numerous old trees and Jackson Mountain having a truncated age distribution with a lack of trees established before the early 1800s (Fig. 3). Without being able to distinguish between the losses of old trees due to locally severe fire, versus harvesting, there is insufficient evidence to describe the relative role of these disturbances.

4.3. Implications for management

What are the implications for ecological restoration? First, we found unexpected diversity in fire regime and forest stand structure illustrating that more site-specific information on topography and other site variables is needed for developing restoration treatment prescriptions and accurate fire behavior models in warm/dry mixed conifer. While this result makes management more complicated, because a uniform prescription would save time and money, it is positive in a biological sense because there is diversity in fire regimes and habitats (Korb et al., 2007). Second, managers cannot infer that the relationship between the pre-settlement forest and the current forest observed at Lower Middle Mountain (Fulé et al., 2009) is similar across all warm/dry mixed conifer forests in the San Juan Mountains. There would be general similarities but details would differ as illustrated along this transect. Finally, the differences we observed imply not just quantitative change in restoration prescriptions (e.g., minor adjustment in prescribed fire intervals) but perhaps a qualitative change (Iniguez et al., 2009) where evidence suggests historical fires of mixed severity at all of our study sites. Restoration actions such as tree thinning and prescribed underburning might be appropriate for sites such

as Grassy Mountain, but allowing spatially variable patches of relatively severe fires to burn at sites such as Lower Middle and Jackson Mountain and perhaps even Grassy Mountain could be ecologically appropriate.

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