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DENDROECOLOGICAL METHODS FOR RECONSTRUCTING HIGH-SEVERITY FIRE IN PINE-OAK FORESTS

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ABSTRACT

Recent high-severity fires in pine-oak forests of the southwestern United States are creating shrubfields that may persist for decades to centuries. Shrubfields embedded in conifer forests that predate documentary records are potential evidence of older high-severity fire patches, and may therefore provide insights into the occurrence and extent of past high-severity fires and vegetation type conversion dynamics. In this paper we test whether dendroecological evidence can be used to reconstruct a high-severity, type-changing fire of known date in a ponderosa pine-dominated (*Pinus ponderosa* var *scopulorum* Engelm.) forest. Dendroecological evidence included (1) Gambel oak (*Quercus gambelii*, Nutt.) regeneration dates, (2) fire scars, (3) death dates, and (4) tree-ring growth changes. We reconstructed the historical fire regime and fire-climate relationship to evaluate whether the recent high-severity fire was driven by climate or fuel build-up related to a fire regime disruption. The dendroecological evidence correctly dated the year (1993) and season (spring) of the documented fire, and synchronous oak re-sprouts provided a means to estimate the minimum high-severity patch size. The historical fire regime at the site (1625–1871) consisted of frequent, low-severity fires occurring in dry years preceded by wet years. Fires stopped in 1871, coincident with increased regional livestock grazing. The 1993 fire occurred under relatively cool and wet conditions, but followed a 122-year fire-free interval (four times the maximum historical interval). Multiple lines of evidence suggest that increased fuel loads from fire exclusion, combined with high winds, were primary drivers of the high-severity fire. The dendroecological approach we outline can be applied to reconstruct high-severity fire across a range of conifer-shrubland ecosystems.

Keywords: high-severity fire, shrubland, *Quercus gambelii*, Gambel oak, tree rings, fire scar, pine-oak, ponderosa pine.

INTRODUCTION

Recent large, high-severity wildfires in the western United States underscore the vulnerabilities of forests to climate change and human land-use (Allen *et al.* 2002; Westerling *et al.* 2006). More than a century of human-caused fire exclusion in the frequent-fire forests of the western U.S. has increased fuel loads and altered forest structure, thereby increasing the probability of high-severity crown fire (Kilgore and Taylor 1979; Covington and Moore 1994; Taylor and Skinner 1998; Allen *et al.* 2002; Hessburg *et al.* 2005; Fulé *et al.* 2009). However, some have challenged this view by proposing that large, high-severity fires are within the natural range of variability in dry conifer forests of the western U.S. (Williams and Baker 2012, but see response by Fulé *et al.* 2014). Nonetheless, high-severity fires are likely to become increasingly common as temperature-driven drought stress is projected to rise in future decades (Williams *et al.* 2013).

One potential consequence of large high-severity fires in the dry conifer forests of the southwestern U.S. is an abrupt post-fire transition from forests to grasslands or shrublands. Historically, species such as Gambel oak (*Quercus gambelii*, Nutt.) commonly existed as a minor sub-canopy component or in the understories of pine-dominated forests and were limited by frequent fires and competition for light (Abella 2008;

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Abella and Fulé 2008). Large patches of pine mortality in recent fires have led to dominance of Gambel oak and other re-sprouting species (*e.g. Robinia neomexicana* A. Gray, *Arctostaphylos* spp., and *Quercus* spp.) (Barton 2002; Savage and Mast 2005; Haire and McGarigal 2008; Collins and Roller 2013; Savage *et al.* 2013).

Little is known about the long-term (multi-decadal to century-scale) ecosystem dynamics of post-fire shrubfields in dry conifer forests of this region. Succession of shrubfields back to pine-dominated forests after high-severity fires may be hampered by multiple contingencies for recruitment of ponderosa pine (*Pinus ponderosa* var *scopulorum* Engelm.) in a xeric post-fire environment (Feddema *et al.* 2013), including the availability of viable seed trees (Puhlick *et al.* 2012). Large high-severity fire patches (100s to 1000s of hectares) represent the most challenging areas for recovery of ponderosa pine because of the generally short-distance dispersal of its heavy, wingless seeds (Larson and Schubert 1970; McDonald 1980). Thus, established ponderosa pine seedlings are rare in high-severity fire patches at distances greater than 250 m from the edge (Haire and McGarigal 2010; Haffey 2014). Furthermore, rapid establishment by re-sprouting shrubs results in a competitive disadvantage for pine seedlings (Shainsky and Radosevich 1986; Oliver 1990), and future disturbances may serve to favor shrubs over pine (Brown 1958; Barton 1999; Savage *et al.* 2013). It is therefore possible that post-fire shrubfields represent alternative metastable states that are more resilient than conifer forests to future disturbance and climate change (Falk 2013).

Given observations of shrubfield persistence for multiple decades following fire (Savage and Mast 2005; Iniguez *et al.* 2009, Savage *et al.* 2013), existing old (pre-1900) patches of Gambel oak or other shrubs could indicate evidence of past high-severity fires in mid-elevation dry conifer forests. There is some evidence from the western U.S. that tree rings can be used to date shrubfield formation following high-severity fire. In southern California, annual rings of chaparral shrubs (*e.g. Adenostoma* spp., *Arctostaphylos* spp., and *Ceanothus* spp.) have been used to indicate stand ages (Keeley 1993; Keeley *et al.* 2008), and synchronous fire scars on isolated stands of bigcone Douglas-fir (*Pseudotsuga macrocarpa* [Vasey] Mayr) were used to reconstruct crown fire history within chaparral shrublands (Lombardo *et al.* 2009). In pine-oak forests on Rincon Peak in southern Arizona, Iniguez *et al.* (2009) used conifer tree-ring evidence of fire (fire scars and death dates) to reconstruct a 60-ha high-severity fire patch dating to 1867, some of which remains an oak shrubfield. In the oak-dominated shrublands of Mesa Verde, Colorado, Floyd *et al.* (2000) used ring counts on oak and other shrubs presumed to have sprouted following fire to estimate decadal-scale fire rotation, and noted multiple high-severity events in the pre-settlement era. In western Colorado, Brown (1958) documented patches of Gambel oak with stems as old as 212 years based on ring counts, but the origins of the patches were not assessed.

Multiple lines of evidence that include shrub regeneration dates have the potential to reconstruct the year, seasonality, and spatial scale of past high-severity fires in this region, as has been demonstrated in upper-elevation mixed conifer-aspen (*Populus tremuloides* Michx.) forests (Margolis *et al.* 2007). Successful employment of these methods at lower elevations depends on overcoming several hurdles, including the ability to accurately crossdate various shrub species (*e.g. Acer* spp., *Robinia* spp., and *Quercus* spp.) to derive post-fire age structures, documenting the temporal distribution of shrub re-sprouting (*i.e.* immediate versus lagged post-fire regeneration), identifying disturbance-related tree-ring growth responses of surviving trees with substantial fire-related crown loss around the high-severity fire perimeter, as well as finding and dating fire-killed conifers within the high-severity patch to confirm tree mortality. It is also important to consider that other factors may explain the presence of large shrubfields, including site characteristics (exposure, steep and rocky terrain, soils), disturbances other than fire (logging, grazing, drought-induced mortality), or some combination of factors. Where evidence exists to support past fire-related shifts from forest to shrublands, determining the timing, scale, and environmental precursors of these events would provide insights into type-change behavior. In addition, assessing stand structure and conifer recruitment in old shrubfields related to high-severity fire would provide data on long-term post-fire successional dynamics, or the potential for type conversion.

The goals of our study are to evaluate whether shrubfields in pine-oak ecosystems can be used to reconstruct high-severity fires and to apply our findings to compare the conditions associated with a recent high-severity fire to historical conditions. We focus on a Gambel oak shrubfield that resulted from a documented (1993) crown fire in a ponderosa pine-dominated forest to answer two research questions: (1) can multiple lines of dendroecological evidence reconstruct the timing (year and season), spatial scale, and historical fire regime of a high-severity fire in pine-oak forests?, and (2) how does the climate and preceding fire-free interval associated with the documented high-severity, type-changing fire compare to the historical (pre-1880) fire-climatology and fire frequency at the site?

METHODS

Study Site

To test our methods, we chose a recent high-severity fire patch on Peggy Mesa in the southwest corner of the Jemez Mountains in north-central New Mexico (35°43′ 41″ N, 106°48′ 5″ W, Figure 1). Mean elevation of the sampling area is 2200 m. The climate is continental and semi-arid. Precipitation is dominated by summer convective storms (rain) associated with the North American Monsoon (Sheppard *et al.* 2002), with highly variable winter precipitation (snow). Annual average precipitation is 496 mm, with 41% of the annual total occurring in July – September (1981–2010; PRISM 2012). Annual average maximum temperature is 16.0°C and annual average minimum temperature is 0.4°C (1981–2010; PRISM 2012). A warm, dry and windy pre-monsoon period occurs annually in the spring and early summer (April – June), which corresponds with the peak annual area burned (Swetnam and Betancourt 1990; Westerling *et al.* 2006). Soils are composed of sandy loam, derived from local sandstone bedrock. Current vegetation within the sampled high-severity fire patch is dominated by Gambel oak. Surrounding (non-lethally-burned) vegetation is dominated by ponderosa pine with tree-form Gambel oak in the sub-canopy and smaller, shrub-form Gambel oak in the understory. Other tree species present at the site include Douglas-fir (*Psuedotsuga menziesii* Mirb. Franco), white fir (*Abies concolor* (Gord. & Glend.) Lindl. Ex Hildebr.), Rocky Mountain juniper (*Juniperus scopulorum* Sarg.), and piñon (*Pinus edulis* Engelm.).

1993 Buchanan Fire

The study site is located within the 4675-ha Buchanan prescribed fire that burned from April 20–23, 1993. In the late afternoon on April 22nd a rapid change in wind direction and high wind speeds drove an independent crown fire that burned with high severity in the pine-oak forest and killed one fire fighter (USDA Forest Service 1993). This extreme fire behavior resulted in multiple high-severity fire patches that regenerated as Gambel oak. From 2013 digital aerial photos (*e.g.* Figure 1), we identified seven patches (totaling 116 ha) dominated by oak shrubs because of clear differences in crown cover, stem height (lack of shadows), foliage color (brown and grey in cool-season imagery), and stand configuration (discontinuous groups) compared to the adjacent, intact, darker evergreen ponderosa pine forest. We focused on the largest discrete high-severity patch (38 ha) within the fire perimeter for this study (Figure 1).

Field Sampling

We adapted the upper elevation high-severity fire reconstruction methods of Margolis *et al.* (2007) to collect four lines of dendroecological evidence for precise dating and assessment of the historical fire regime in the high-severity fire patch. The four lines of evidence included (1) oak regeneration dates, (2) fire scars, (3) death dates, and (4) tree-ring growth changes or injuries (Figure 2). Oak regeneration (re-sprouting) dates were determined from sampling in a random, spatially distributed plot design. In ten circular age-structure plots (0.10 ha) we sampled the two largest-diameter Gambel oak stems at ground level with a chainsaw. Within and around the edge of the shrub patch, we used a targeted sampling approach to collect the additional lines of evidence. The goal of our targeted sampling was to find the longest, most complete

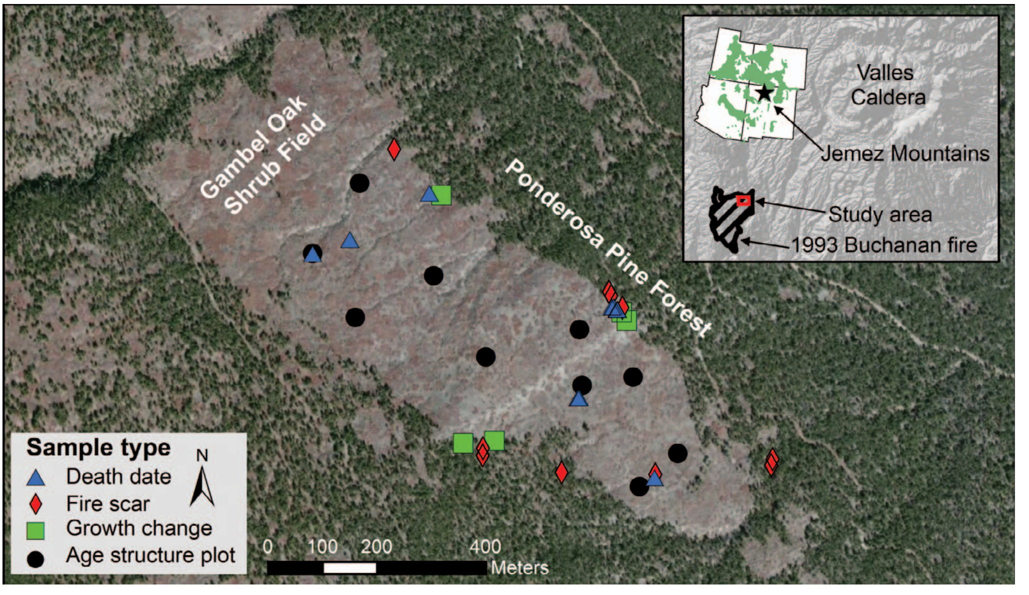

Figure 1. Aerial photo of a high-severity patch in the 1993 Buchanan fire (Jemez Mountains, New Mexico) that abruptly changed from a ponderosa pine-dominated forest to a Gambel oak shrubfield. Symbols indicate multiple lines of tree-ring evidence used to test a method for reconstructing high-severity fire in pine-oak. Inset indicates the location of the study area within the Southwest United States and the range of Gambel oak in green (Little 1971).

tree-ring record of fire that was spatially dispersed within the study site and near the edges of the high-severity burn patch. Targeted fire-scar sampling is an efficient and accurate approach for obtaining a representative fire history (Farris *et al.* 2013). Fire scars were collected to date the recent fire and reconstruct the historical fire regime. Samples were collected with a chainsaw from living trees located on or near the edge of the patch that survived the 1993 fire and from remnant logs and stumps throughout the patch. For death dates, we collected cross-sections from trees that were potentially killed by the 1993 fire (indicated by burned stubs of fine branches or charred bark) and had a clear waney (under bark) surface, beetle galleries, and/or intact bark with no signs of erosion of the outermost sapwood. Living trees located on the edge of the patch that lacked a fire scar, but had obvious fire-related crown damage (*e.g.* Figure 2d), were cored to assess for tree-ring growth changes or anomalies.

As an initial assessment of conifer re-colonization in a shrub patch following high-severity fire, which affects aerial photo interpretation of patch size reconstruction, we recorded the number and species of conifers within each 0.10-ha oak age structure plot. These data were used to calculate overall densities (stems per ha) of post-fire conifer recruitment and maximum distances from the forest edge (measured as the distance between the plot center and the nearest forest edge).

Laboratory Methods

All tree-ring samples were prepared and cross-dated using standard procedures (Speer 2010) to determine annually accurate and precise fire scar dates, tree death dates, tree injury dates, and Gambel oak regeneration (pith) dates. For all fire scars, we recorded the year of scarring and the intra-ring position (seasonality) of the scar (Baisan and Swetnam 1990). We visually assessed cores collected from potentially fire-injured trees for growth changes, multiple missing rings, and increased density of traumatic resin ducts. The timing of identified anomalies was compared with local, climatically-sensitive ponderosa pine tree-ring chronologies from Fenton Lake and Cat Mesa (Swetnam and Lynch 1993) to determine if they were climate-related. If climate variability did not appear to be the major cause of the growth anomaly, we considered the

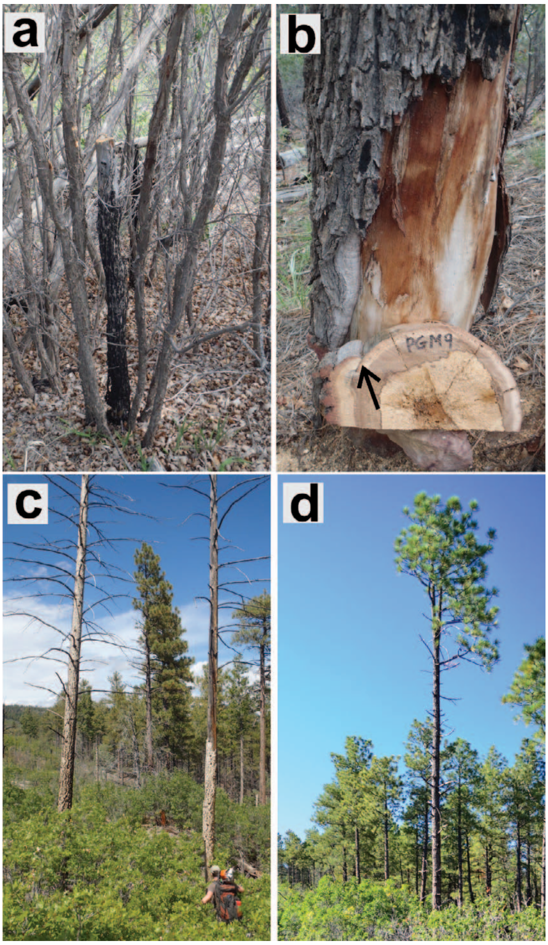

Figure 2. Four lines of dendroecological evidence used to date high-severity fire in pine-oak forests. (a) Gambel oak re-sprouts from near the base of a fire-killed oak stem (the fire-killed stem in this photo was sampled for a death date). The live stems were sampled at ground level to attain a pith date for the year of sprouting. (b) Fire-scarred tree-size oak on the edge of the high severity burn patch. The arrow denotes the fire scar on a cross-section of the tree. (c) Fire-killed conifers inside of the high-severity patch sampled for death dates. (d) Live ponderosa pine on the edge of the high-severity fire patch with substantial fire-caused crown mortality that resulted in tree-ring growth suppression.

synchrony of tree-ring anomalies among trees (and with other lines of fire evidence) to be a response to partial crown mortality from high intensity fire.

Analysis

The four lines of tree-ring evidence were compiled and compared to the known year (1993) and season (April, *i.e.* early growing season) of the Buchanan fire to assess the precision and accuracy of the tree-ring methods. The area of the largest high-severity fire patch was digitized from aerial photos (as described above). Fire-frequency statistics and seasonality of the reconstructed fire regime prior to the 1993 fire were calculated using FHX2 software (Grissino-Mayer 2001). The length of the fire-free interval preceding the 1993 fire was compared to the distribution of historical fire intervals before late 19th Century fire exclusion using the Weibull exceedance interval.

The fire-climatology of the 1993 high-severity fire was quantified using gridded climate data (PRISM 2012) and fire incident reports. Departures of monthly temperature and precipitation for the month and year of the fire (April 1993) and preceding months (October 1992 – March 1993) were compared to average conditions over the full record (1895–2013) and recent decades (1981–2010). Fire-climatology of the historical fire regime was quantified using superposed epoch analysis (SEA; Swetnam 1993). Tree-ring reconstructed inter-annual climate variables used in the SEA include prior cool-season precipitation (prior October through current June) from the Jemez Mountains, New Mexico (Touchan *et al.* 2011) and summer (June through August) Palmer Drought Severity Index (PDSI; Cook and Krusic 2004: gridpoint 133).

RESULTS

We crossdated tree-ring samples from 45 trees of five species to reconstruct the high severity fire (Table 1). The combination of the four lines of evidence (Gambel oak regeneration, fire scars, death dates, and tree-ring growth anomalies) dated the fire correctly to 1993 at the beginning of the growing season (Figure 3). All sampled Gambel oak ramets re-sprouted the year of the fire (pith date of 1993), with no lagged recruitment detected in our sample. Large inner rings on the oak regeneration indicated favorable initial growth (see photo inset on Figure 3). The "bark-ring" death dates for all sampled trees that appeared to be killed by fire were 1992 (complete ring), indicating that the trees died after the end of the 1992 growing season, but before the onset of

Table 1. Number, species, and tree-ring sample type of trees sampled for high-severity fire history reconstruction at Peggy Mesa, New Mexico.

Species[a]	Age Structure	Death Date	Fire Scar	Growth Change	Total Sampled Trees
JUSC		1	2		3
PIED		1			1
PIPO		5	4	5	14
PSME		1	1		2
QUGA	20	3	2		25
All species	20	11	9	5	45

[a]JUSC = *Juniperus scopulorum*. PIED = *Pinus edulis*. PIPO = *P. ponderosa*. PSME = *Pseudotsuga menziesii*. QUGA = *Quercus gambelii*.

growth in the spring of 1993. This is consistent with the timing of the fire in April. The five sampled living ponderosa pine with visible fire-related crown damage (*i.e.* killed branches on their lower boles, and/or on the side facing the high-severity burn patch) had reduced tree-ring growth beginning in 1993 (see photo inset on Figure 3). For example, one tree had four missing rings

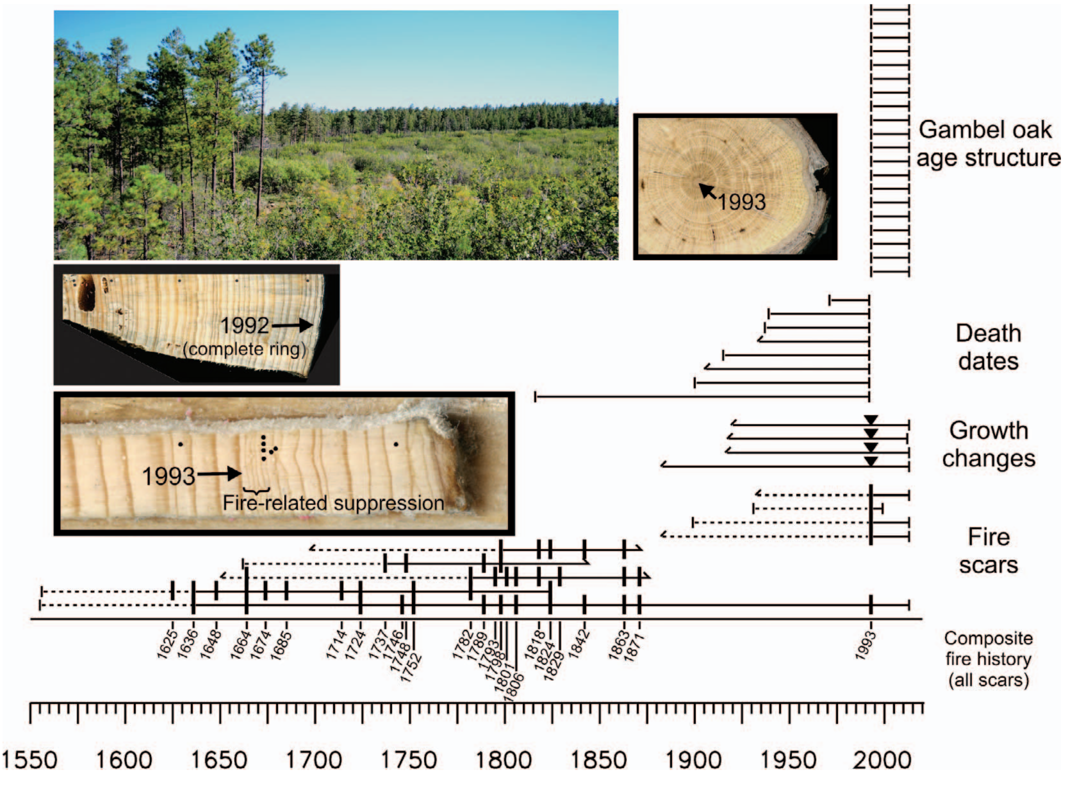

Figure 3. Four lines of tree-ring evidence used to reconstruct a 1993 early growing season (April 22) high-severity fire in pine-oak. The composite fire-scar fire history indicates a historically frequent, low-severity fire regime (1625–1871) followed by an anomalous (122 year) fire-free interval that preceded the 1993 high-severity, type-changing fire. Inset photographs show the Peggy Mesa shrubfield site, a sampled Gambel oak ramet, a fire-killed ponderosa pine, and a tree-ring growth suppression following fire on a surviving ponderosa pine, such as the one left-center in the top image. Each horizontal line represents the timeseries of individual trees, with dotted lines showing non-fire-recording years and solid lines recorder years on fire-scarred trees, vertical lines represent pith or bark rings, arrows represent inner and outer rings, triangles indicate growth changes, and bold vertical lines indicate fire scars.

between 1993 and 1999, which is a period when only one ring (1996) is occasionally absent on trees from local chronologies. Four of the five fire-scarred trees sampled along the perimeter of the high-severity fire patch had a dormant-season scar occurring between the 1992 and 1993 growth rings. The fifth fire-scarred tree, a 450-year-old live ponderosa pine with 13 fire scars, recorded the fire as a 1993 early-earlywood scar.

The historical fire regime within and around the 1993 crown fire patch was characterized by frequent, low-severity fires for over 250 years until fires stopped in 1871 (Figure 3). The mean fire interval across all trees and for all scars during the period 1625–1871 was 10.7 years, with a Weibull median fire interval of 9.5 years. Preceding the 1993 Buchanan fire, there was a 122-year fire-free interval (Figure 3). This interval was over 100 years longer than the upper bounds of the Weibull exceedance interval (19 years) and four times longer than the historical maximum fire interval (30 years). The seasonality of historical fires was predominantly spring and early summer (97% dormant, early-earlywood, and middle-early wood), which was similar to the season of the 1993 fire.

The preceding cool-season climate associated with the 1993 fire was cool (>1 standard deviation below the mean) and wet (>130% of average) compared to recent decades (1981–2010) and long-term (1895–2013) averages. The month of the fire (April 1993) was dry (21% of average precipitation [1981–2010 and 1895–2013]) and strong winds were reported during the high-severity fire behavior (USDA Forest Service 1993). Historical fire occurrence (1625–1871) was associated with below-average cool-season precipitation preceding the fire season and above-average cool-season precipitation three years prior to the fire (Figure 4). A similar fire-climate relationship (dry during the fire year and wet in prior years) was indicated with PDSI (Figure 4).

Mean density of conifer regeneration in the oak shrub patch 20 years following the 1993 high-severity fire was 11 trees ha^{-1}. Conifer seedlings were present in only four of the ten plots. Most (8 of 11) seedlings were ponderosa pine, but Rocky Mountain juniper (n = 2) and Douglas-fir (n = 1) were also present. Maximum distance of a post-fire ponderosa pine seedling to the patch edge was 77 m. Rocky Mountain juniper seedlings were found the farthest (135 m) from the forest edge.

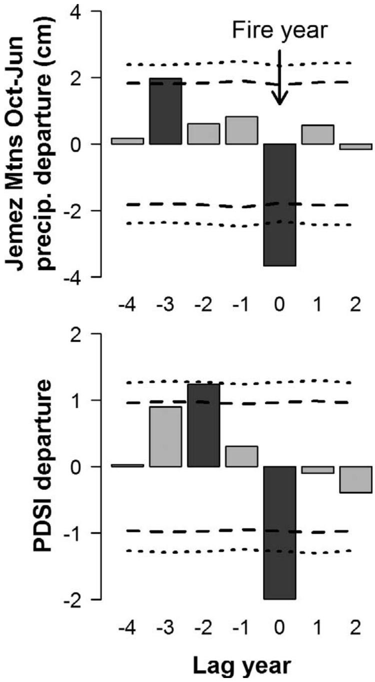

Figure 4. Superposed epoch analysis indicating that historical fire occurrence (1625–1871) on Peggy Mesa, New Mexico, is associated with dry conditions during the fire year, preceded by generally wet conditions (n = 24 fire years). Dashed and dotted lines represent 95% and 99% confidence intervals determined from 1000 iterations of Monte Carlo simulation.

DISCUSSION

Tree-ring Reconstruction Methods

We successfully used multiple lines of dendroecological evidence to reconstruct the year (1993) and season (spring–early growing season) of a high-severity fire in a pine-oak forest in the southwestern U.S., as verified by documentary records. The multi-proxy, dendroecological approach substantially strengthened our ability to determine the timing, scale, and contributing factors of a high-severity, type-change fire at Peggy Mesa. The possibility of a fall 1992 fire (after the growing season) could not have been ruled out using only regeneration dates, death dates, or tree-ring growth suppressions. A fire scar recorded in the earlywood of 1993 was used to date the fire to the spring of 1993. Although not commonly used for dendrochronology, Gambel oak proved to be a robust species for accurate crossdating back to the pith ring. Additionally, in the case of this spring high-severity fire at Peggy Mesa, Gambel oak pith dates are a reliable proxy for the disturbance year, but require further evidence (*e.g.* fire scars, tree death dates) to be confidently connected to a past high-severity fire. Based on the success of this multiple lines of evidence approach, we have confidence in this method to reconstruct high-severity fire in older shrubfields that were potentially type-converted from pine-dominated forests.

One challenge of reconstructing older high-severity fires from oak patches is the possible rarity of remnant fire-killed trees with intact outside surfaces that can provide ‘‘bark-ring’’ tree death dates. The most direct evidence of past high-severity fire is the presence of fire-killed trees. Yet, after only twenty years post-fire at Peggy Mesa, very few fire-killed trees were still standing. Studies of snag dynamics in fire-killed forests in Arizona and Oregon indicate similar low rates of snag retention greater than 20 years post-fire among multiple conifer species, with larger snags generally lasting longer (Everett *et al.* 1999; Passovoy and Fulé 2006; Roccaforte *et al.* 2012). Most of the snags that persisted at Peggy Mesa 20-years post-fire were Douglas-fir and Rocky Mountain juniper, although they were a minor part of the pre-fire stand composition. The boles of these snags were in good condition, with charred bark still attached and many charred fine branches (Figure 2c). Nearly all of the fire-killed ponderosa had fallen by 2013 (20 years post-fire), and substantial portions of the tree boles were too decayed for tree-ring sampling. Many of our samples of fire-killed ponderosa pines, therefore, came from the upper portions of the boles that were leaning against oak clumps and stayed off the ground. Because ponderosa pine makes up a majority of conifers killed in high-severity fires within the pine-oak forest type in the southwestern U.S., a lack of fire-killed, tree death dates might prove to be a challenge in interpreting high-severity fire as the cause of older patches of Gambel oak. Some evidence for tree mortality may be attained by mapping logs or by sampling for near-bark outer-ring dates, where possible, if much of the former forest has fallen or decomposed.

Although loss of remnant logs and snags from the pre-existing forest caused by decomposition limits the discovery and use of the death-date line of evidence within high-severity burn patches, it is notable that this evidence may still be found with extensive searching. For example, Margolis *et al.* (2007) successfully located fire-killed conifers as old as 160 years post-fire in mesic mixed-conifer and aspen stands in the southwestern U.S. Also, in a relatively dry pine-oak forest in southern Arizona, Iniguez *et al.* (2009) found old fire-killed trees in shrub-dominated patches that dated to 1867, thereby dating high-severity burn patches that were essentially converted to shrub patches, and that have now persisted for 147 years. It may be that this line of evidence, *i.e.* remnant, fire-killed snags and logs, is relatively more abundant now than in the past because of fire suppression. The lack of fire for more than a century has likely prevented some old, dead wood within shrub patches from burning up during subsequent fires.

Patch size is perhaps the most important metric of high-severity fire regimes (Agee 1993), and is therefore an important aspect of fire history reconstruction. The synchrony of oak recruitment throughout the fire patch (all 1993 pith dates, Figure 3), provided a means to estimate pre-instrumental high-severity patch size. The low density of conifer recruitment (11 trees ha^{-1}) into this small shrub patch 20 years post-fire suggests that post high-severity fire shrub patches in the region could be delineated from aerial photos for decades, if not longer. Observations of conifer regeneration from the forest edge inward (*e.g.* Haire and McGarigal 2008, 2010), suggest that delineating the original edges of the high-severity patch from aerial imagery will become more difficult over time. Additional errors in patch-size reconstruction from shrubfields could include dense post-fire conifer recruitment (*e.g.* Savage and Mast 2005, Iniguez *et al.* 2009) that may not be as clearly visible as shrubfields on aerial imagery. Height differences between the lethally burned and non-lethally burned vegetation may be used to overcome these challenges. Should older shrubfields re-burn, however, the existing shrubfield patch could be expanded in size (Savage *et al.* 2013), which would inflate estimates of patch size for the older high-severity fire.

Current vs. Historical Fire Regime

The 1993 high-severity fire at Peggy Mesa, which abruptly changed a pine-dominated forest to a shrubfield, occurred at a site where fire historically burned frequently (10-year return interval), with low severity for hundreds of years (Figure 3). The 122-year fire-free interval that preceded the 1993 high-severity fire was anomalous compared to the previous 400 years (Figure 3). Long fire-free intervals have been associated with pre-1900 high-severity, type-conversion fire in the region (Iniguez *et al.* 2009). In this case, a rocky, topographically heterogeneous landscape structure reduced the likelihood of fire spread into an isolated pine-oak forest stand that burned with high severity following a 48-year fire-free interval. In contrast, the end of the frequent fire regime at Peggy Mesa in 1871 is synchronous with the collapse of frequent fire regimes locally (Touchan *et al.* 1996) and at dozens of other dry conifer sites across the region (Swetnam and Baisan 1996). This was clearly initiated by the introduction of large numbers of livestock in the late 1800s that removed the fine fuels that carried surface fires (Allen 2007). The synchronous cessation of surface fire in the late 1800s has been related to increased forest density in piñon-juniper, ponderosa pine, and dry mixed conifer forests throughout the region (Allen *et al.* 2002; Fulé *et al.* 2009; Margolis 2014), and likely resulted in high tree density, high fuel loads, and increased ladder fuels that supported crown fire at Peggy Mesa. All but one of the trees sampled at Peggy Mesa, which were alive in 1993, regenerated after frequent fires stopped in 1871 (Figure 3), suggesting that a high density of young trees fueled the 1993 high-severity fire. The climate associated with the 1993 high-severity fire was mild (wet and cool) compared to the long-term instrumental record and the historical fire-climatology, suggesting that climate was not a primary driver of change in fire severity. Strong winds were reported during the event and likely were a contributing factor (USDA Forest Service 1993). Overall, these findings highlight the important role of human-caused changes in fire regimes and forest structure, combined with fire weather, to produce an ecologically-significant forest-to-shrub transition. This contradicts the conclusions of Williams and Baker (2012), that recent high severity fires in dry conifer forests are not associated with human land use.

CONCLUSIONS

Abrupt post-fire transitions of ponderosa pine-dominated forests to shrubfields are increasingly common following large high-severity fires in the southwestern U.S. With little known about the long-term (decades to centuries) consequences and ecosystem dynamics of these transitions, reconstructing the origins of existing, old (pre-1900) shrubfields is an important area for future research. In this paper, we have validated dendroecological methods that can be applied to test whether shrubfields originated from high-severity fire, with the potential to provide crucial information on high-severity fire in the historic era and post-fire successional trajectories. The chronological and spatial control associated with these methods can then help to decipher endogenous (*e.g.* increased fuel loads) versus exogenous (*e.g.* extreme drought) factors that could have led to type conversion. We emphasize the need to use multiple lines of evidence in these tests. The combined use of different types of tree-ring evidence provides a cross-check and verification of results from individual proxies, thereby increasing overall confidence in the reconstructions. Characterizing post-fire shrubfields with these methods will provide important data for determining if recent post-fire forest-to-shrub transitions are an early seral successional stage (similar to post-disturbance quaking aspen) or whether they are an alternative metastable state that will persist for centuries.

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