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A comparison and integration of tree-ring and alluvial records of fire history at the Missionary Ridge Fire, Durango, Colorado, USA

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Abstract

We used tree-ring and alluvial sediment methods to reconstruct past fire regimes for a mixed conifer forest within a 1 km^2 drainage basin which was severely burned by a wildfire near Durango, Colorado. Post-fire debris flow events incised the valley-filling alluvial sediments in the lower basin, and created exposures of fire-related of deposits of late-Holocene age. Tree-ring and alluvial sediment fire history records were created separately, and then compared and integrated to create a ~ 3000 year record of past fire activity. The tree-ring record showed that from AD 1679 to 1879, there were frequent surface fires, while patches of high-severity fire occurred during widespread fire years. The alluvial record showed that a low- to moderate- and mixed-severity fire regime has likely been dominant over the past ~ 2600 calibrated calendar years before present, as shown by locally episodic deposition of charcoal-rich, fine-grained sediments. Radiocarbon dating suggested that in two stratigraphic sections, there was rapid deposition of several fine-grained sediment layers. One of these episodes occurred during the Medieval Climatic Anomaly (AD 900–1300). A charcoal-rich debris flow deposit in the oldest exposed part of the stratigraphic record dated to ~ 2600 calibrated calendar years before present. This event was potentially equivalent in magnitude to the debris-flow events following the recent wildfire in the study area, and is evidence of a high-severity fire that burned a large proportion of the study basin. The timing of this event coincides with a period of less frequent, yet more severe wildfires in a nearby lake sediment record, and is associated with the end of a Neoglacial period of cooler and wetter temperatures.

Introduction

Wildfires in the western USA have increased in size and severity over the past century, raising concerns among fire ecologists, forest managers, and the public (Allen *et al*., 2002; Covington and Moore, 1994; Running, 2006). Twentieth century land-use changes and climate variability are the two primary explanations for the increase in extensive and severe forest fires over the past 10–15 years (Pierce *et al*., 2004; Westerling *et al*., 2006). Euro-American settlement throughout the late nineteenth century and subsequent fire suppression practices have altered historical fire regimes and increased forest density in some lower-elevation conifer ecosystems across the western US, and thus created the risk for high-severity fires today (Fulé *et al*., 1997, 2009). Fire history research provides a context for comparing recent wildfires with historical fire regimes, and for improving our understanding of the long-term dynamics of fire processes and their drivers. Methods of reconstructing past fires include the use of historical documents, fire scars in tree rings, stand establishment dates and charcoal preserved in alluvial fan, bog and lake sediments (Agee, 1993; Meyer *et al*., 1995; Pierce and Meyer, 2008; Swetnam and Baisan, 2003; Westerling *et al*., 2006; Whitlock and Anderson, 2003). Modern observations and records (e.g. fire atlases, satellite data) provide the most detailed and precise estimates of fire history, but relatively complete and reliable records are limited to the late twentieth and twenty-first centuries, and in most cases, only the past few decades. Tree-ring methods provide data with relatively high spatial and temporal resolution, though they tend to better preserve evidence of low-severity fires, and usually cover the past three to five centuries. Charcoal preserved in alluvial, bog and lake sediments can identify changes in fire regimes over centennial to millennial timescales, and can be used to identify long-term trends in fire and climate relationships. However, these methods have lower temporal resolution when compared with tree-ring and documentary methods, and vary in their potential to record the severity and extent of past fires (Pierce and Meyer, 2008; Swetnam and Anderson, 2008).

Fire history reconstructions using charcoal from sedimentary sources suggest that the relatively short time period encompassed

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by most tree-ring records (~ 500 years or less) is too brief to resolve centennial- or millennial-scale fire regime changes that are climatic in origin, such as effects of the 'Medieval Climatic Anomaly' (MCA, AD 900–1300) or the 'Little Ice Age' (LIA, AD 1300–1850) (Pierce and Meyer, 2008; Whitlock *et al*., 2008). The MCA was a period of increased climatic variability and several extended droughts across the western US (Cook *et al*., 2004; Meko *et al*., 2007; Stine, 1994), while the LIA was a period of inferred cooler and wetter climate throughout the Northern Hemisphere (Armour *et al*., 2002; Cook *et al*., 2004; Grove, 1988; Petersen, 1994). One consequence of the temporal limitation of tree-ring records is that inferences about anthropogenic causes of recent fire regime changes (e.g. livestock grazing or fire suppression) may be complicated by longer-term climatic changes. Recent high-severity 'megafires' may not be unprecedented, and the events and trends of the past two decades may be a largely climate-induced response of ecosystems, similar to prior Holocene episodes of severe fires, as shown by alluvial sediment records in the northern Rockies and southern New Mexico (Frechette and Meyer, 2009; Pierce and Meyer, 2008; Pierce *et al*., 2004).

In order to discuss fire events and fire regimes throughout this paper, we begin with the definitions of fire severity and fire regimes in western ecosystems. At the stand level, low-severity fires char litter and surface fuels, leaving no exposed soil, and induce little heat damage to the underlying soil. Tree mortality is limited to scattered individuals. Moderate-severity fires char litter and portions of the underlying duff, with some heat damage and partial exposure of mineral soil. Moderate-severity fires result in some tree mortality, though limited to individual trees or small groups. High-severity fires completely consume the litter and duff, while exposing and damaging the underlying soil and causing at least 80% tree mortality (DeBano *et al*., 1998). Mixed-severity fire events contain both low- and high-severity fire in adjacent forest patches of approximately 10–20 ha (Fulé *et al*., 2003; Iniguez *et al*., 2009), and therefore, create partial exposure of mineral soil at the scale of tributary watersheds. A fire regime describes the role of fire in an ecosystem, by defining the frequency, severity and seasonality of fire events (Agee, 1993). Questions about the past versus present role of high-severity crown fires are most actively debated in the context of pure ponderosa pine (*Pinus ponderosa*) and mixed conifer forests (pine, Douglas-fir, true firs and other conifer species mixtures) in the western US (Allen *et al*., 2002; Baker *et al*., 2007; Brown *et al*., 2008; Hessburg *et al*., 2005). Frequent, low-severity surface fires were clearly predominant in most pure ponderosa pine landscapes of the southwestern US prior to AD 1900 (Allen *et al*., 2002; Swetnam and Baisan, 1996). 'Mixed' or 'variable' severity fire regimes, including both low-severity surface fire and patches of high-severity crown fire (~ 10 ha), occurred during the pre-1900 era in some ponderosa pine dominant and mixed conifer landscapes in southern New Mexico and Arizona (Iniguez *et al*., 2009; Swetnam *et al*., 2001). Crown fires also played a significant role in ponderosa pine dominant forests in the Colorado Front Range (Brown *et al*., 1999; Ehle and Baker, 2003; Sherriff and Veblen, 2006), while the evidence of past crown fire activity in the Black Hills of South Dakota is currently being debated (Brown, 2006; Brown *et al*., 2008; Shinneman and Baker, 1997).

Millennial-length fire history records are valuable for determining the full range of variability in historical fire regimes, and can help evaluate the relative impacts of climate variability and twentieth-century land-use practices on recent wildfire activity. Alluvial fan sediment records provide fire history information for a specific area, because each sampling site represents the contributing area of a watershed. Fire-related sedimentation events from several sites are then composited to create a regional fire history chronology extending up to several thousand years (Meyer *et al*., 1995; Pierce and Meyer, 2008; Pierce *et al*., 2004). These methods have been used to interpret both low- and high-severity fire regimes in xeric to mesic forests types throughout the Rocky Mountains (Frechette and Meyer, 2009; Jenkins, 2007; Meyer *et al*., 1995; New, 2007; Pierce *et al*., 2004).

In this study, we compared tree-ring and alluvial fan records of fire history for a single low-order drainage basin with predominantly mixed conifer forest located in southwestern Colorado. Most of this drainage was burned by the Missionary Ridge Fire in 2002, and post-fire erosion exposed charcoal-rich sediment layers in alluvial stratigraphy. We used tree-ring records to better interpret fire event information from the alluvial sediments, while also improving our understanding of long-term changes in mixed-severity fire regimes in the Southern Rockies. Alluvial fan fire history records have been documented at several locations in the western US, and thus far, this proxy method has been compared with stand-age reconstructions at one study area in southern New Mexico (Frechette and Meyer, 2009; Meyer *et al*., 1995; Pierce *et al*., 2004). Tree-ring records have previously been compared with fire events reconstructed from charcoal deposition in lakes and bogs (Allen *et al*., 2008; Whitlock *et al*., 2004) in the same study areas. The most challenging aspect of the comparison of tree-ring records and charcoal-based fire history records is the different temporal resolution of the available dating methods. Radiocarbon dating is used to determine the age of charcoal pieces in lake, bog or alluvial fan deposits, which yields calendar age ranges of 200–400 years for each event. In contrast, tree-ring records represent fire events with annual to decadal resolution, and can more precisely determine the location of the fire. In previous comparisons of tree-ring records with charcoal records from lake or bog sediments, charcoal records were unable to capture all of the events observed in the tree-ring record, though general trends in the data were similar. In addition, Frechette and Meyer (2009) used stand-establishment data from the contributing watershed of an alluvial fan to constrain the age of a fire-related sedimentation event to the late 1800s, which was dated with radiocarbon methods (AD 1700–present).

Questions to be addressed in this study include: (1) How does the fire history information derived from sediment deposits within the past 500 years compare with the fire history reconstructed from tree-ring records? (2) What does the combined fire history record suggest about the timing, extent and severity of past fires in the study basin? (3) Is there evidence of stand-replacing fires and post-fire geomorphic responses similar to the 2002 Missionary Ridge Fire event over millennial timescales?

Study area

The study basin is located in southwestern Colorado, where the recent Missionary Ridge Fire offers a comparative event for understanding how fire behavior may have changed over the past several millennia. In June of 2002, the Missionary Ridge Fire burned more than 30 000 ha of the San Juan National Forest (Figure 1), with more than 60% of the area burned at moderate

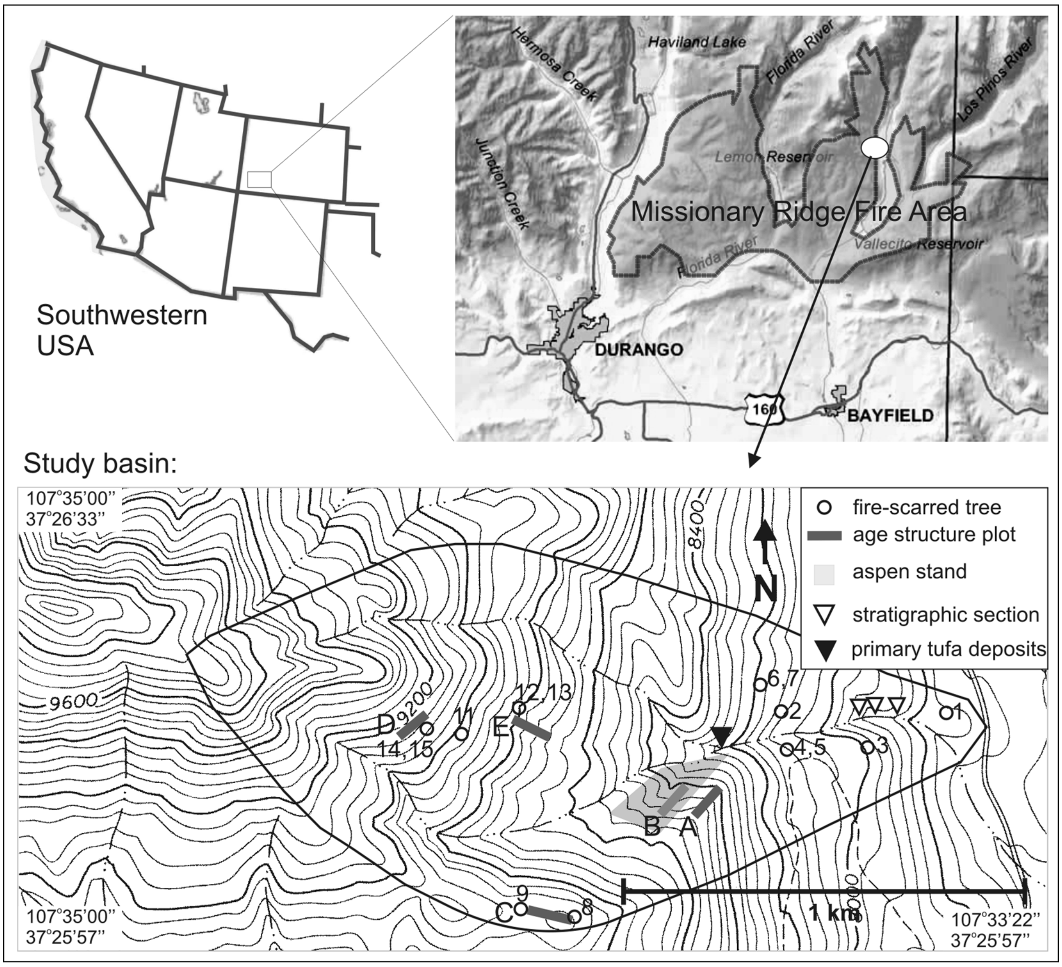

Figure 1. Location of the study basin within Missionary Ridge Fire area in southwestern Colorado. The basin was burned up to 80% by moderate and high-severity fire during the Missionary Ridge Fire in June, 2002. The black outline represents the watershed boundary, and the location of fire-scarred trees (open circles), age-structure plots (gray line), aspen stand (gray polygon), tufa deposit (black triangle) and stratigraphic sections (open triangle) are indicated in the topographic map of the study basin

and high severities (Burned Area Emergency Repsonse (BAER) Report, 2002). The study site is a 1 km^2 drainage basin on the northwest side of the Vallecito Reservoir (Figure 1). The elevation ranges from 2350 m at the drainage outlet to 3000 m at the top of the basin. Precipitation recorded at the Vallecito Reservoir dam (2300 m) over the past 60 years averages 67 cm/year. The basin is underlain by Permian-age limestone and sandstone (Hermosa and Cutler formations) with glacial till deposits up to 2700 m (Gonzales *et al*., 2004), and the soils are primarily cryalfs and udalfs (Jeff Redders, USFS, personal communication, 2006). The forest type is mixed conifer with a species composition of Douglas-fir (*Pseudotsuga menziesii*), white fir (*Abies concolor*), ponderosa pine (*Pinus ponderosa*), Engelman (*Picea engelmannii*) and blue spruce (*Picea pungens*). On northeast-facing slopes, the mixed conifer stands have a greater proportion of Douglas-fir, white fir, and spruce relative to ponderosa pine. On southeast-facing slopes, the stands have more ponderosa pine relative to other species, representing warmer and drier conditions. A pure aspen (*Populus tremuloides*) stand is located in the center of the basin, and scattered aspen individuals and clusters of 2–3 trees grow elsewhere within the mixed conifer stands on the northeastern aspects.

Over 80% of the study basin was burned at moderate and high severities during the Missionary Ridge Fire. In the summer following the fire, debris flow and sediment-laden flood events were generated in response to short-duration, high-intensity convective storms of less than or equal to a two year recurrence interval (Cannon *et al*., 2003, 2008). Throughout the study area, post-fire debris flows and sediment-laden floods were generated from 21 out of 44 basins (with minimum area of 0.5 km^2), which had at least 50% of the contributing area burned at moderate and high severities (Cannon *et al*., 2003; Gartner *et al*., 2005). In the study basin, the post-fire flood and debris flow events deeply incised tributary channels and alluvial fan deposits, thus creating exposures of Holocene alluvium up to several meters below the pre-fire surface. The exposed stratigraphy in the incised channel walls exhibited several fine-grained sediment layers with distinct charcoal lenses, and an initial study following the fire in 2002 dated several fire-related deposits to the middle to late Holocene (Gonzales *et al*., 2004). Since the initial study, taller stratigraphic sections with buried wood became exposed due to further erosion. These exposures (> 4 m) combined with adequate tree-ring material presented an opportunity to compare alluvial and tree-ring records of fire history at the same study site.

Table 1. Age-structure plot information

Plot ID	Size (ha)	Landscape feature	Aspect	Trees/ha	Forest type
A	0.1	Ridge	East	1500	mixed conifer
B	10	Slope (25°)	North	–	pure aspen
C	0.3	Ridge	East	465	mixed conifer
D	0.4	Slope (25°)	East	340	mixed conifer
E	0.4	Slope (10°)	East	875	mixed conifer/aspen

Methods

Tree-ring methods

In order to reconstruct a range of fire severities, we collected a combination of partial and full sections from fire-scarred trees, as well as cores from conifer and aspen trees to determine stand age-structures. In mixed-severity fire regimes, fire scars may be recorded on surviving trees at the edges of high-severity patches, and age structures can be used to infer high-severity fire occurrence and extent (Higuera *et al*., 2005; Huckaby *et al*., 2001; Iniguez *et al*., 2009; Margolis *et al*., 2007). The inner ring dates of the oldest trees in forest patches, particularly if they cluster within a decade of a surface fire date, may be inferred to relate to high-severity fire at that location. This assumption is most clearly justified in the case of aspen trees, which commonly re-sprout prolifically and rapidly from root stock following stand-replacing fires (Margolis *et al*., 2007). We sampled 14 fire-scarred ponderosa pine trees located in three clusters throughout the study basin (Figure 1), where full and partial cross-sections containing the scars were sampled from both living and dead trees (Arno and Sneck, 1977). In addition to fire-scar sampling, we also collected age-structure data from fixed area plots and transects. We sampled conifer age-structure data from four 0.1–0.4 ha plots (Figure 1, Table 1). For all trees in each plot, we recorded the diameter at breast height (DBH), x and y coordinates relative to one corner, species and percentage of green canopy. We cored all trees larger than 25 cm DBH at an average height of 30 cm. Age-structure data were also collected from the aspen stand (~ 10 ha) located in the center of the basin (Figure 1). Two 100 m transects were placed along the contour of the slope, and two trees were sampled at 20 m intervals along each transect. The aspen trees were cored until the pith was obtained at a height of 30 cm.

All fire-scarred sections and age-structure cores were mounted and sanded using progressively finer grades of sandpaper down to 400 grit. The samples were crossdated (annual dates were assigned to individual tree rings) according to standard dendrochronological methods (Stokes and Smiley, 1968). If the age-structure cores did not include the pith, the number of missing rings and the growth rate were estimated with transparencies of concentric circles (Applequist, 1958). We estimated the age at coring height of our samples using data reported in other studies from Colorado and the Southwest (Heinlein *et al*., 2005; Kaufmann *et al*., 2000). Recruitment ages were calculated by adding the number of years estimated to reach the coring height to the pith ages determined by the growth rate and concentric circles. Given the uncertainty of estimating the tree recruitment ages, the data were grouped into 10 year bins for analysis. We plotted all crossdated fire-scar samples in a master fire chronology using a spreadsheet program, and observed the temporal patterns in the surface fire history (Dieterich, 1980). A period of analysis was defined in order to characterize the fire event patterns during a period of adequate sample depth. The period of analysis began with the first fire to scar at least three recording trees. A recording tree is one that has already been scarred by a fire, and is more susceptible to subsequent scarring than unscarred trees (Romme, 1980). The end of the period of analysis was determined by the last widespread fire year at the end of the nineteenth century. The Mean Fire Interval (MFI) was first calculated for all surface fire years, including fires that scarred only one tree, as well as those scarring a minimum of two trees. The number of recording trees and the percentage of trees scarred in a fire year were calculated to identify the fires that were widespread within the site. Researchers have generally used a ‘filter’ or minimum threshhold of 25% of the sampled trees scarred in a fire year in order to determine the widespread fire years for a site (Swetnam and Baisan, 1996; Van Horne and Fulé, 2006). We used a more stringent filter of 50% or more trees scarred to identify the widespread fire years because our fire-scar sample size was relatively small (13 trees), and the samples were dispersed in the study area. The spatial pattern of the surface fires was also estimated by mapping the locations of scarred and recording trees for the widespread fire years on a topographic map of the study area (Brown *et al*., 1999). Examination of these fire years enabled us to make reasonable inferences about patterns of fire extent within the basin. In addition, the age-structure data were plotted by species, and analyzed to interpret tree recruitment patterns from AD 1600 to 1900. Age-structure data for each plot were displayed as histograms of the number of trees recruited per decade, and the recruitment patterns were then compared with the fire-scar data to interpret both fire extent and severity patterns.

Alluvial sediment methods

Three stratigraphic sections were located within a 75 m reach of the incised channel just above the alluvial fan head (Figure 2). Several buried logs were trapped in one of the sections, and these were sampled with a hand saw. Individual deposits were distinguished by changes in sorting, sedimentary structures, texture, color, and often by the presence of charcoal lenses (Figure 2). The deposit characteristics were described and used to infer flow processes ranging from low-energy streamflow to debris flow. Moderately to well-sorted deposits with stratification or imbrication of clasts were inferred to be fluvial or hyperconcentrated-flow deposits (Costa, 1988; Pierson, 2005). Poorly sorted deposits with randomly oriented clasts, supported by a fine-grained matrix were inferred to be debris flow deposits (Costa, 1988). All of the deposits had abundant charcoal and were associated with fire-related disturbance in the contributing basin.

The deposit characteristics of each fire-related sedimentation event were used to infer low- to moderate-severity, mixed- and high-severity fires occurring at the scale of the contributing basin (Pierce *et al*., 2004). Using the geomorphic response following the Missionary Ridge Fire as a guide, charcoal-rich debris flow deposits were inferred to indicate that a large portion of the basin was likely burned by a high-severity fire (Cannon *et al*., 2003). The association of charcoal-rich debris flow deposits with high-severity fire is based on considerable research observing the geomorphic response of hillslopes and low-order drainage

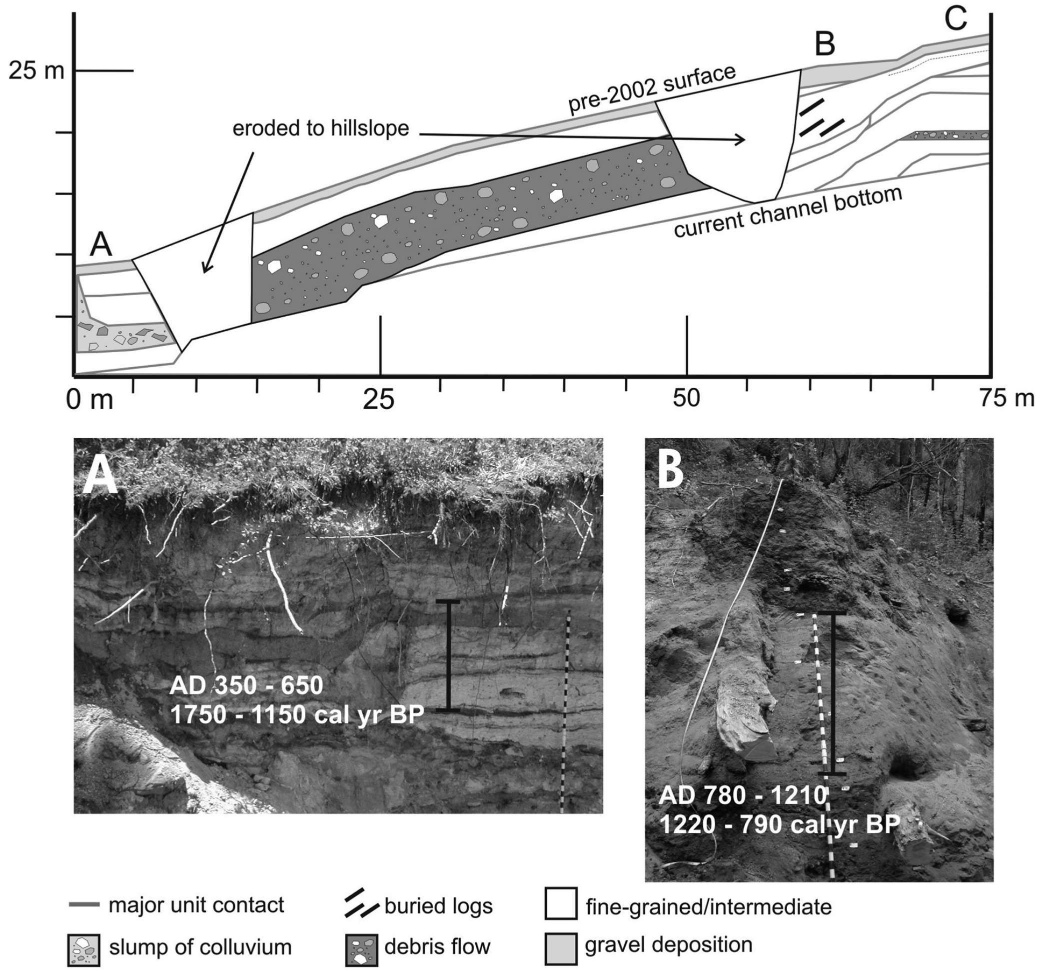

Figure 2. Cross-section view of the exposed channel reach with the labeled stratigraphic sections. The figure is drawn to scale with 2× vertical exaggeration. The deposit types are grouped as fine-grained or intermediate, gravel deposition, and debris flow, while major boundaries are indicated with gray lines. (A) Stratigraphic section A above the slump of colluvium with several fine-grained layers bounded by charcoal lenses. (B) Stratigraphic section B with the buried logs. The period of rapid deposition in each section photo is labeled with a vertical line and the 2-sigma calendar age range

basins to severe wildfires (Meyer *et al*., 1995; Pierce *et al*., 2004). At the plot or hillslope scale, the exposed mineral soil, resulting from canopy, litter and duff consumption, is considered one of the most significant factors associated with increased runoff and erosion (Benavides-Solorio and MacDonald, 2001, 2005; Johansen *et al*., 2001; Robichaud and Waldrop, 1994). On the catchment scale, the percentage of high-severity burn can influence the type of geomorphic response when variables such as basin morphometry and bedrock type are held constant (Cannon and Gartner, 2005; Cannon and Reneau, 2000; Meyer and Wells, 1997). We used previous studies as a guide for interpreting relatively well-sorted streamflow deposits. In these studies, charcoal-rich sheetflood deposits were used to interpret more limited and dilute sediment transport following low-moderate severity fires (Pierce *et al*., 2004). Areas of intact canopy, litter and duff limit runoff and erosion at the hillslope scale, and reduce the likelihood of high-magnitude sedimentation events on the basin scale (Benavides-Solorio and MacDonald 2001, 2005; Cannon and Reneau, 2000). Hyperconcentrated-flow deposits, which have less sorting and imbrication of clasts relative to streamflow deposits, were used to infer mixed-severity fire events at the scale of the study basin (Costa, 1988). Mixed-severity fires likely contained a greater proportion of high-severity burned area, when compared with low-moderate fires, though not as extensive as basin-wide high-severity fires.

The chronology of fire events was determined by radiocarbon dating of charcoal fragments from the deposits (Meyer *et al*., 1995; Pierce *et al*., 2004). Charcoal was separated from the bulk sediment, and examined for annually produced plant material such as twigs and needles. The age of these materials may be closest to the fire event, since they may decompose more rapidly than larger woody debris. When annual material was not available, angular charcoal pieces were used, even though they could be from remnant logs, potentially yielding an age several decades older than the actual fire event. Rounded charcoal pieces were avoided, since they were likely reworked from older deposits. Samples were submitted for radiocarbon dating at the NSF – Arizona Accelerator Mass Spectrometry (AMS) Laboratory. Radiocarbon ages were converted to calendar ages with the CALIB 5.0 program with the INTCAL04 calibration curve (Reimer *et al*., 2004; Stuiver and Reimer, 1993). Calendar ages were reported with their full 2-sigma age range (usually 200–400

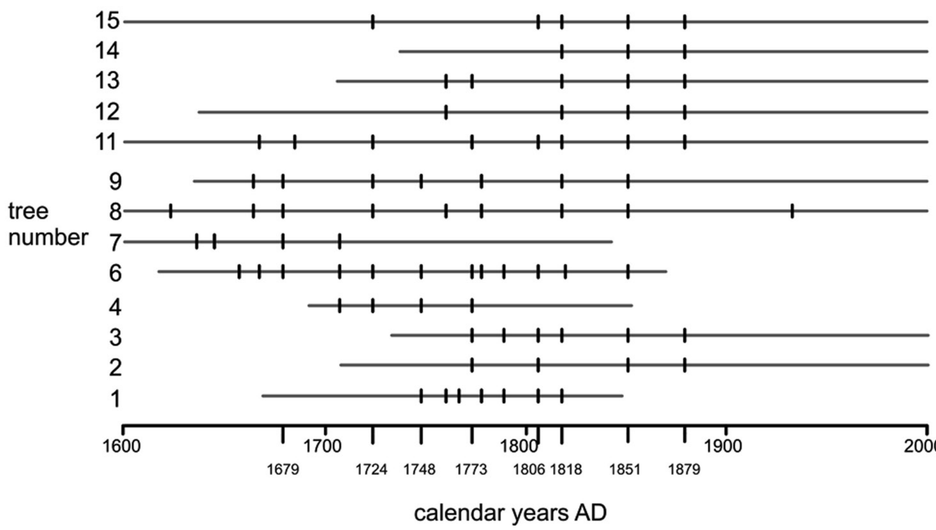

Figure 3. In the master fire chronology, each horizontal line represents one tree, and they are arranged in order of increasing elevation in the basin. Each tick mark represents one fire scar. The widespread fire years, indicated by a minimum of 50% of recording trees scarred, are labeled on the x-axis

years). When necessary to assign a point estimate for a range of calendar ages for a sediment deposit, we used the median of the probability distribution, as provided by the CALIB 5.0 program.

Results

Tree-ring results

We successfully crossdated 13 of 14 fire-scarred samples, and included all fire events in the master fire chronology (Figure 3). From visual inspection of the master fire chronology, the fires appeared to be more frequent and patchy during the late seventeenth and eighteenth centuries, followed by a shift to more synchronous and widespread fires in the nineteenth century (Figure 3). The Mean Fire Interval (MFI) was calculated for the entire period of analysis from AD 1679 to 1879, as well as for subperiods of AD 1679–1789 and AD 1789–1879. The subperiods were defined by the fire date of 1789, and were used to compare the pattern of surface fires between the eighteenth and nineteenth centuries. The year 1789 was chosen because it was the last fire event before the shift in fire frequency apparent in the master fire chronology. The period of analysis ends in 1879, when the last widespread surface fire occurred within the study area. The frequent surface fire regime ended abruptly near the end of the nineteenth century, when Euro-American settlement reached southwestern Colorado (Figure 3; Blair *et al*., 1996; Grissino-Mayer *et al*., 2004; Wu, 1999). With the exception of one scarred tree in 1933, there were no other fires indicated by tree-ring or documentary records during the twentieth century, until the study area was burned in 2002. During this exceptional fire-free interval, fuels likely increased in the understory, creating a dense forest structure conducive to the severe fire behavior experienced during the Missionary Ridge Fire (BAER Report, 2002).

The MFI for all fires during the entire period of analysis was 14.3 years, while the MFI for fires scarring a minimum of two recording trees (equivalent to 25% of the sample) was 18.2 years (Table 2). The MFI for a minimum of two scarred trees for the subperiod from AD 1679 to 1789 was 15.7 years, while the MFI (minimum two trees) for the subperiod from AD 1789 to 1879 was 22.5 years. This suggests that fires were slightly more frequent during the earlier part of the record, though a Wilcoxon rank-sum test comparing the MFI values for the two subperiods showed no significant difference ($Z = 1.24$, $p > 0.1$). The 50% filter of scarred recording trees in a fire year was applied while reviewing the location of the scarred trees (Figure 3, Table 3).

Table 2. Fire-scar statistics for the period of analysis (AD 1679–1879), and the two sub-periods

Period of analysis	No. of intervals (min. two trees)	Range of intervals (min. two trees)	MFI for all scars (standard dev)	MFI for min. two trees
1679–1879	11	5–33	14.3 (9.1)	18.2 (8.8)
1679–1789	7	5–28	12.2 (7.2)	15.7 (8.0)
1789–1879	4	12–33	18.0 (11.9)	22.5 (9.7)

MFI, Mean Fire Interval, calculated for all trees scarred, and a minimum of two trees scarred.

Table 3. Fire year statistics

Fire year	No. recording trees	No. scarred trees	Percentage
1679	5	4	80
1685	5	1	20
1707	6	3	50
1724	7	6	86
1748	8	4	50
1760	10	4	40
1767	10	1	10
1773	12	6	50
1778	12	4	33
1789	12	3	25
1806	12	6	50
1818	13	9	69
1820	13	1	8
1851	11	9	82
1879	9	7	78

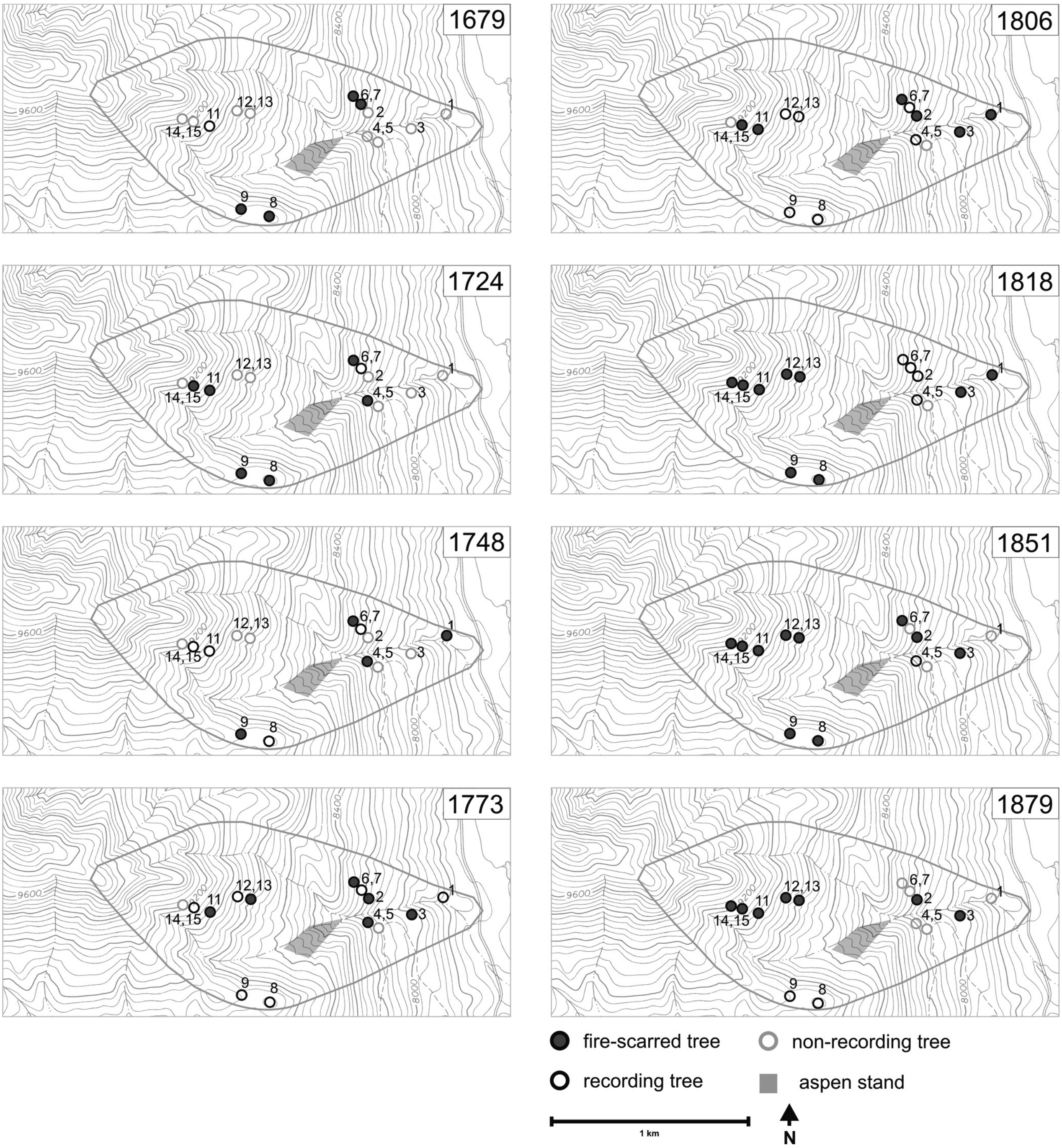

Figure 4. Map of recording and non-recording trees during widespread fire years. Open grey circles represent non-recording trees, while black open circles represent recording trees. A grey-filled circle is a recording tree, which was scarred by fire in a particular fire year

This analysis identified the following widespread fire years: 1679, 1724, 1748, 1773, 1806, 1818, 1851 and 1879. A fire in the year 1707 was also recorded on at least 50% of the sampled trees, but all of these trees were located within ~ 100 m of each other (Figure 1, Figure 3), and therefore, this year was not included with the widespread fire years. The widespread fire years were mapped to infer the spatial pattern and extent of these surface fires (Brown *et al*., 1999). Figure 4 shows the locations of recording and scarred trees, which group into three clusters throughout the basin. This analysis showed that 1724, 1818 and 1851 were the years with the most extensive spread of surface fire, because fire was recorded in all three of the clusters (Figure 4).

The age-structure data were analyzed for the individual plots to identify potential recruitment patterns related to high-severity fire events (Figure 5) (Higuera *et al*., 2005; Huckaby *et al*., 2001). The sampling was not intended to test for a shift in species and tree density associated with fire exclusion during the twentieth century. The lack of twentieth-century recruitment in our data was a result of sampling primarily large and mature trees. On plots C, D and E, the ponderosa pine recruitment was continuous throughout the period of analysis, with one noticeable gap in the early 1700s. The first evidence of Douglas-fir and white fir recruitment on these plots begins in the mid 1700s. During the 1800s, the recruitment changes from being dominated

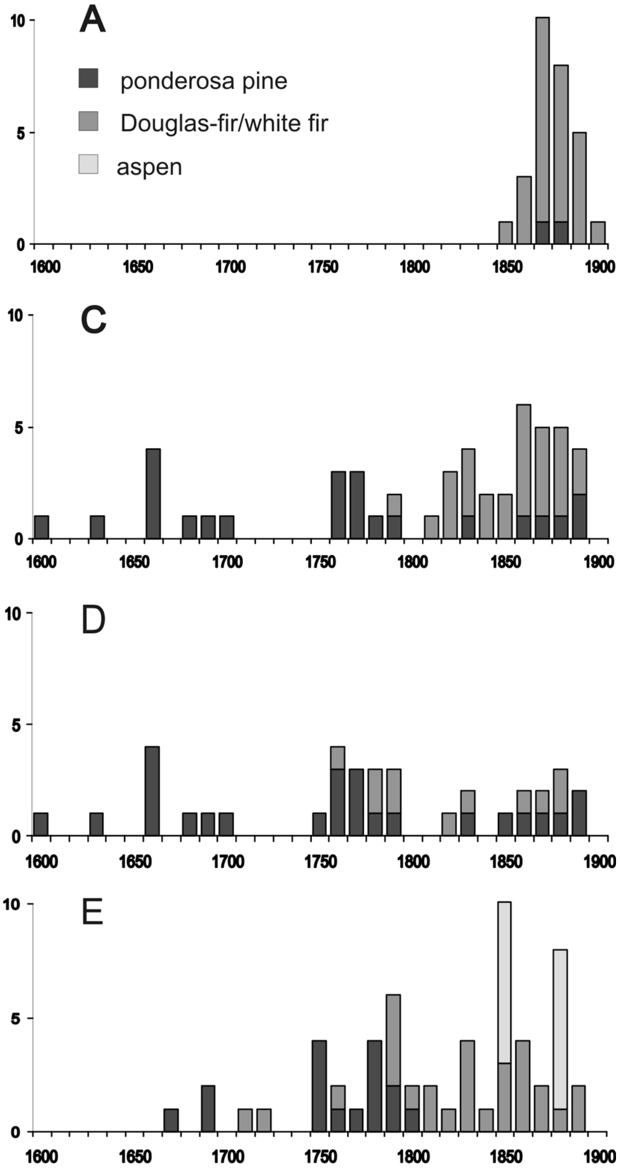

Figure 5. Age-structure data arranged by plot and species. The number of trees per decade is indicated on the y-axis, and the species is indicated by color. Dark gray represents ponderosa pine recruitment, medium gray represents Douglas-fir and white fir recruitment and light gray indicates aspen recruitment

by ponderosapine to mostly Douglas-fir and white fir, which could be associated with the shift to less frequent and more synchronous fires in the nineteenth century.

The pattern of recruitment in plot A suggests a high-severity fire event may have occurred during the mid-1800s in this location. Plot A had a single pulse of recruitment in the mid to late 1800s, and the oldest tree in the plot dates to the 1850 decade. This recruitment could represent regeneration following a high-severity fire during the 1851 fire year, because the lack of older individuals within the plot indicates mortality related to fire or other disturbance (Higuera *et al*., 2005; Huckaby *et al*., 2001). In addition, Plot E exhibits ponderosa pine and Douglas-fir recruitment starting in the late 1600s, and two distinct peaks of aspen regeneration in the nineteenth century. The sampled aspen had pith ages of 1851 and 1879, which suggests regeneration related to high-severity fire. However, the aspen with different ages were located adjacent to one another, and also near to older ponderosa pine and Douglas-fir predating 1851. Since even-aged aspen were not located in a distinct patch within the plot, the interpretation of high-severity fire in the plot is uncertain. However, pith ages from the 10 ha aspen stand located on a north-facing slope in the center of the basin provides strong evidence of high-severity fire (Figure 1). The pith ages of all samples had an age distribution from AD 1879 to 1881, indicating that the stand likely regenerated where a patch of high-severity fire burned during the 1879 fire year, which was noted as a widespread fire year (Figures 3 and 4). There were no burned snags within the stand, which suggests that the slope may have been populated by aspen (rather than conifer) prior to the 1879 fire.

Alluvial stratigraphy results

Deposit characteristics and their relation to burn severity. The majority of the alluvial deposits were fine-grained and well-sorted (Figure 2). The fine-grained deposits ranged in thickness from 10 to 50 cm, and were composed of silt- and sand-sized sediments, with a low proportion of clay (Thien, 1979). Within the thicker deposits, there were gravel lenses of about 10 cm thickness, indicating weak stratification of the deposits. There was weak imbrication of the gravel-sized clasts (0.5–2.0 cm) within the lenses. These fine-grained deposits were likely deposited by streamflow, yet may have had high sediment to water ratios, possibly approaching hyperconcentrated flow conditions (Costa, 1988; Pierson, 2005). Towards the top of each stratigraphic section, the deposits consisted of well-sorted gravel-sized clasts, which also indicated streamflow conditions. The abundance of charcoal in the fine-grained deposits is evidence of past fire activity in the basin. Individual, thin (10–50 cm) deposits of fine-grained sediment are associated with low–moderate fire events, as described in the methods.

Most of the fine-grained deposits had a light yellow color, suggesting that the matrix and clast material was composed of tufa material (Figure 2). The matrix was composed of silt-sized sediments, which effervesced strongly and dissolved when saturated with acid. The larger sand- to gravel-sized clasts in all of the fine-grained deposits exhibited structures from primary tufa deposits (i.e. fragments of root casts). The bedrock in the upper third of the basin was the Pennsylvanian-age Hermosa Group limestone (Gonzales *et al*., 2004), and tufa deposits were found ~100 m upstream of the sampling locations, where they consisted of root casts and thin sheets of calcium carbonate exposed along the channel. The tufa-rich composition of the fine-grained deposits sampled near the mouth of the drainage suggests that they were derived from these tufa deposits by erosion and downtream transport of channel sediments with little incorporation of hillslope material.

A few of the deposits were considered intermediate between the fine-grained and poorly sorted debris flow deposits. They had a matrix with a similar texture as the tufa-rich deposits, yet the matrix had a distinctly darker gray color and there were pebble- to cobble-sized clasts supported by the matrix. The clasts were composed of both tufa fragments, as well as of other lithologies (local bedrock and glacial deposits), and there was no imbrication of the clasts. Based on their color, texture and range of clast sizes, these intermediate deposits indicate a potentially

Table 4. Radiocarbon ages: stratigraphic section A

Sample ID	Depth below surface (m)	Deposit type	Charcoal material	Radiocarbon age	2-sigma calendar age range (BC/AD)
2	4.5	fine-grained	bark	2745 ± 37	976–814 BC
3		colluvium	angular	2941 ± 45	1297–1011 BC
4	2.75	fine-grained	angular	2454 ± 42	756–410 BC
6	2.47	fine-grained	spruce twig	1747 ± 36	AD 183–404
10	1.65	fine-grained	seed coat	1557 ± 36	AD 420–579
10-1	1.65	fine-grained	small branch	1737 ± 38	AD 218–408
11B	1.5	fine-grained	angular	1511 ± 35	AD 434– 633
12	1.23	fine-grained	bark	1591 ± 35	AD 401– 549
13	1.13	intermediate	twig	1489 ± 35	AD 442– 646
14B	0.98	fine-grained	4 seeds	1577 ± 55	AD 354– 604
15	0.85	fine-grained	bark	976 ± 35	AD 996–1155
16A	0.75	fine-grained	angular	642 ± 34	AD 1282–1397
16B	0.75	fine-grained	angular	480 ± 34	AD 1402–1461
17A	0.65	fine-grained	seed	917 ± 39	AD 1028–1207
18A	0.45	fine-grained	angular	907 ± 35	AD 1036–1208
18C	0.45	fine-grained	angular	760 ± 46	AD 1176–1376
19A	0.1	fine-grained	twig	91 ± 34	AD 1682–1936
debris flow along reach		debris flow	angular	2491 ± 42	782–416 BC

Radiocarbon ages are from the NSF-AMS Facility at the University of Arizona. The conversion from radiocarbon years to calendar years was performed with CALIB 5.0, INTCAL04 (Reimer *et al*., 2004; Stuiver and Reimer, 1993). The 2-sigma age range is indicated in the right-hand column.

higher-energy transport process. We classify these deposits as hyperconcentrated flow, because the degree of sorting does not suggest debris flow conditions. The darker color of the matrix may represent fine charcoal disseminated in the matrix. Furthermore, these deposits had macroscopic charcoal, indicating an association with fire-related disturbance, and they likely represent mixed-severity fires events. From the tree-ring results, it is evident that patches of high-severity fire (~ 10 ha) occurred during some of the widespread surface fire years (e.g. 1851, 1879). On the basin scale, these mixed-severity fires may have generated sufficient runoff to transport hilllslope and channel sediment, while the increased runoff may have also mobilized cobble-sized clasts from the channel.

Many of the fine-grained and intermediate deposits were separated by charcoal lenses, which sometimes had weak stratification, and were composed of primarily silt- and sand-sized charcoal fragments (Figure 2). These were likely deposited by streamflow processes, and were not identified as *in situ* burned soil horizons. They also contained angular charcoal pieces between 2 and 5 mm, and there were no distinguishable needles or other organic material indicative of an *in situ* burned soil surface (Meyer *et al*., 1995; Pierce *et al*., 2004). These charcoal lenses usually defined the breaks in texture and color of the fine-grained deposits, and occasionally extended for several meters along the exposure.

There were two debris flow deposits observed in this channel reach (Figure 2). One of the deposits was thin (45 cm) and localized (section C), and had a cohesive fine-grained matrix supporting cobble-sized clasts. The second debris flow deposit was exposed for at least 40 m of the reach. This deposit had a dark brown matrix, which supported a range of poorly sorted cobbles and boulders up to 1 m in diameter. The cobbles and boulders were a mix of lithologies including the local bedrock and granitic boulders derived from the glacial till deposits. In the case of this debris flow deposit, the link to extensive high-severity fire is confidently interpreted. The debris flow deposit contained abundant charcoal in the matrix. Given the association of high-severity fire with debris flow generation following low-recurrence interval, and short-duration convective storms (Cannon and Gartner, 2005; Cannon *et al*., 2008), we infer that an extensive, high-severity fire created the conditions conducive to debris flow generation.

Chronology of deposition. The oldest deposit (2745 ± 37 radioncarbon years) is a tufa-rich, fine-grained deposit at the bottom of stratigraphic section A, which had a median age of 2884 calibrated calendar years before present (cal. yr BP) (Figure 2). The two debris flow deposits (2491 ± 42; 2509 ± 34 radiocarbon years) had similar calibrated calendar ages of 2626 and 2637 cal. yr BP, and likely represent the same depositional event (Table 4). Lying above the oldest deposit (2884 cal. yr BP) in stratigraphic section A, there was a slump of hillslope colluvium. The slump likely occurred following the debris flow event at ~ 2600 cal. yr BP, and is evidence of channel scour at this location. The age of the charcoal contained in the slump was ~ 3100 cal. yr BP, and could reflect charcoal incorporated in the hillslope soil at an earlier time.

Within the combination of all three stratigraphic sections, fine-grained deposition was recorded from ~ 2600 cal. yr BP to present (Figure 6; Tables 4, 5 and 7). Three of the deposits within stratigraphic sections A and B were also classified as intermediate deposits. The results of the radiocarbon dating indicated that deposition was locally episodic, with periods of rapid deposition followed by hiatuses. In Figure 6, all calibrated calendar ages from the fine-grained sediment layers in stratigraphic sections A and B are plotted with depth below the incised surface. Most notably, in stratigraphic section A, a sequence of five thin, tufa-rich, fine-grained deposits and one intermediate deposit all had overlapping ages between AD 350 and 650 (1750–1150 cal. yr BP) (Photo A, Figure 2). In stratigraphic section B, nine radiocarbon ages from a 1.5 m thick deposit containing buried wood ranged from AD 780 to 1210 (1220–790 cal. yr BP). The calendar age range of the buried wood contained in this deposit was statistically similar to the surrounding sediment (Table 6). We attempted to crossdate these buried wood samples, but the growth was complacent, and there were not enough

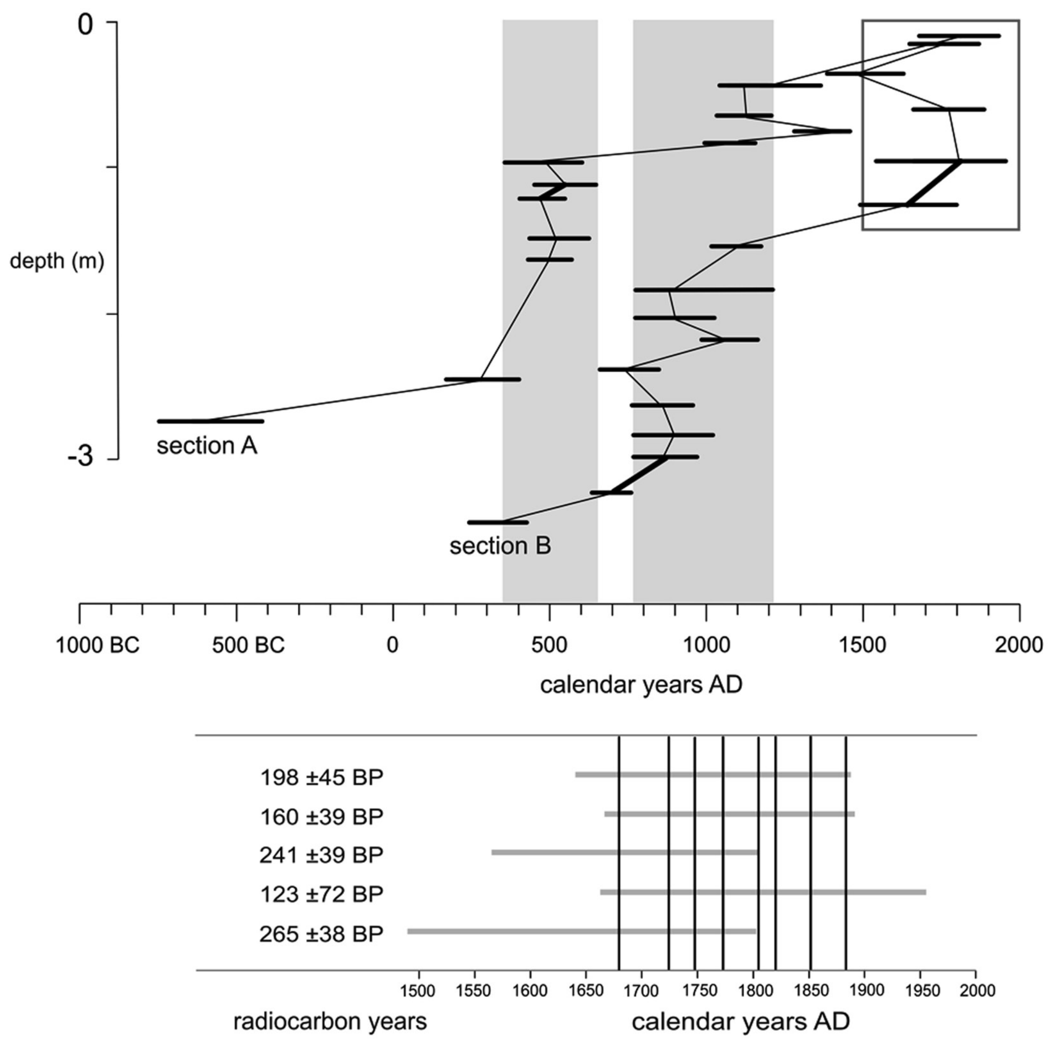

Figure 6. In the upper portion of the figure, the chronology of fine-grained deposition in stratigraphic sections A and B shows the past ~ 2600 calibrated calendar years before present. Each horizontal line is located at the median depth of a sediment layer, and the length represents the 2 sigma range of the calibrated calendar ages. The darker vertical lines represent intermediate deposits, which are composed of a darker matrix color and cobble-sized clasts. The depth of each deposit was measured from the height below the pre-fire surface. The gray bands indicate the period of rapid deposition in each stratigraphic section, and each band corresponds with the range of calendar ages in the photos in Figure 2. The box in the upper right-hand corner of the upper figure outlines the last 500 years of deposition. In the lower portion of the figure, five of the youngest radiocarbon ages from stratigraphic section B (outlined in the box) are listed on the left side. Three of the ages (265 ± 38, 123 ± 72, 241 ± 39) are from the intermediate deposit at the top of section B, which we aimed to connect with the tree-ring record. The top two radiocarbon ages are fine-grained units lying stratigraphically above the intermediate deposit in stratigraphic section B. The horizontal gray lines show the 2-sigma range of the calibrated calendar ages for each radiocarbon age. The vertical black lines represent the widespread fire years determined by the minimum of 50% scarred trees

rings. We interpreted that these two sequences of sediment layers with overlapping radiocarbon ages were rapidly deposited, and possibly represent a single depositional event (Meyer *et al*., 2001). There is evidence of older charcoal ages within stratigraphic section B, though this is likely from reworking of charcoal fragments from deposits upstream.

Discussion

Comparison of tree-ring and alluvial fire history records

The tree-ring record indicated a fire regime of frequent, surface fires during the late seventeenth to nineteenth centuries, while mixed-severity fires occurred during widespread fire years. These findings are similar to fire histories reported for mixed conifer stands elsewhere in the San Juan Mountains (Fulé *et al*., 2009; Grissino-Mayer *et al*., 2004; Wu, 1999). These studies reported a high degree of synchrony among the scarred trees in mixed conifer sites, indicating that widespread fires were common in this ecosystem. The alluvial record was primarily composed of thin, fine-grained deposits with two sequences of rapid deposition of several sediment layers. In stratigraphic section A, one sequence contained five individual fine-grained units and one intermediate deposit (Figure 2). Our preferred interpretation for this sequence is that it represents multiple pulses of sedimentation following a mixed-severity fire. However, this sequence of

Table 5. Radiocarbon ages: stratigraphic section B

Sample ID	Depth below surface (m)	Deposit type	Charcoal material	Radiocarbon age	2-sigma calendar age range (BC/AD)
01A	3.45	fine-grained	angular	1680 ± 35	AD 256–428
01B	3.45	fine-grained	angular	1732 ± 35	AD 234–401
3B	3.25	intermediate	needles	1660 ±180	–44–762 BC/AD
3C	3.25	intermediate	angular	1345 ± 35	AD 635–771
04LB	3	fine-grained	twig	1139 ± 35	AD 780–985
04UA	2.85	fine-grained	twigs	1116 ± 39	AD 783–1016
05A	2.65	fine-grained	angular	1160 ± 35	AD 777–971
06LA	2.4	fine-grained	twig	1279 ± 35	AD 659–857
06UA	2.2	fine-grained	twigs	971 ± 42	AD 992–1160
07LA	2.05	fine-grained	twigs	1082 ± 50	AD 783–1031
07UA	1.85	fine-grained	twigs	1123 ± 39	AD 781–1011
07-B-1	1.85	fine-grained	angular	910 ± 40	AD 1032–1210
08LA	1.55	fine-grained	root	942 ± 40	AD 1019–1184
9	1.25	intermediate	twigs	265 ± 38	AD 1490–1800
10A	0.95	charcoal lense	needle	123 ± 72	AD 1665–1954
10B	0.95	charcoal lense	wood	241 ± 39	AD 1521–1806
11A	0.6	gravel rich	twigs	160 ± 39	AD 1663–1890
12	0.35	gravel rich	needles	460 ± 53	AD 1324–1629
13	0.15	gravel rich	twigs	198 ± 45	AD 1641–1885

Radiocarbon ages are from the NSF-AMS Facility at the University of Arizona. The conversion from radiocarbon years to calendar years was performed with CALIB 5.0, INTCAL04 (Reimer *et al*., 2004; Stuiver and Reimer, 1993). The 2-sigma age range is indicated in the right-hand column.

Table 6. Radiocarbon ages: buried wood from stratigraphic section B

Sample ID	Depth below surface (m)	Material	Radiocarbon age	2-sigma calendar age range (BC/AD)
3	> 6	buried wood	2151 ± 43	360–55 BC
051	4.25	buried wood	1613 ± 45	AD 340–552
2B	3.2	buried wood	1216 ± 34	AD 690–890
01B	2.0	buried wood	889 ± 34	AD 1040–1217
07B	2.0	buried wood	1009 ± 46	AD 899–1157

Radiocarbon ages are from the NSF-AMS Facility at the University of Arizona. The conversion from radiocarbon years to calendar years was performed with CALIB 5.0, INTCAL04 (Reimer *et al*., 2004; Stuiver and Reimer, 1993). The 2-sigma age range is indicated in the right-hand column.

units (one depositional event) is puzzling because most of the material was composed of tufa-rich sediment, which has a source within the channel area in the center of the basin. One potential explanation is that this depositional event is related to a high-magnitude runoff event, which eroded channel sediment and transported fine-grained sediment with charcoal downstream. It is possible that high-intensity or long duration rainfall generated significant runoff from unburned hillslopes, or hillslopes burned at low- to moderate-severity, while sediment yields remained insignificant (Benavides-Solorio and MacDonald, 2001, 2005; Johansen *et al*., 2001; Robichaud and Waldrop, 1994). The increased runoff could have eroded channel sediments and charcoal from one or more surface fires stored upstream and then deposited sediment with charcoal lenses behind obstructions as the channel gradient decreased. This channel has a steep gradient with a step-pool morphology, where boulders and woody debris provide locations for trapping relatively thick packages of sediment (Chin, 1989). In stratigraphic section B, another sequence of five individual fine-grained units with overlapping radiocarbon ages (AD 780–1210 (1220–790 cal. yr BP)) also indicates multiple pulses of sedimentation during a single depositional event. Many of the individual deposits in this sequence contain clasts of tufa, as well as other lithologies in the basin (local bedrock and decomposed granitic boulders from glacial till deposits). This single depositional event (Figures 2, 6) most likely represents a mixed-severity fire event.

The tree-ring record can be used to define the timing and severity of fire-related sedimentation events represented within the past 400 years of the alluvial stratigraphic record. The two records are best compared by the largest or most severe fire event occurring within the past 400 years prior to the Missionary Ridge Fire in 2002. An intermediate deposit was located near the top of stratigraphic section B, and it contained chunks of burned wood (2–3 cm in diameter) encased in a silty matrix (Figures 2, 6, Table 4). As described above, this deposit had a darker matrix color and a greater degree of sorting than the fine-grained units,

Table 7. Radiocarbon ages: stratigraphic section C

Sample ID	Depth below surface (m)	Deposit type	Charcoal material	Radiocarbon age	2-sigma calendar age range (BC/AD)
4a	2.35	fine-grained	detrital angular	2276 ± 43	403–206 BC
5	2.05	debris flow	detrital angular	2509 ± 34	789–521 BC
5b	1.8	burned layer	detrital angular	1876 ± 41	AD 53–238
6	1.75	fine-grained	detrital angular	1730 ± 34	AD 237–399
6b	1.64	Burned layer	detrital angular	1831 ± 42	AD 77–320

Radiocarbon ages are from the NSF-AMS Facility at the University of Arizona. The conversion from radiocarbon years to calendar years was performed with CALIB 5.0, INTCAL04 (Reimer *et al*., 2004; Stuiver and Reimer, 1993). The 2-sigma age range is indicated in the right-hand column.

and this indicates an association with a mixed-severity fire event. Three radiocarbon ages (265 ± 38, 123 ± 72, 241 ± 39) from this deposit have a calibrated calendar age range of approximately AD 1500–1950 (Figure 6). Although the calibrated age range is quite broad during this period (~ 450 years), it is likely that this deposit was generated in response to one of the mixed-severity fire events identified in the tree-ring record (i.e. 1851 or 1879).

The tree-ring record reveals two mixed-severity fire events, which occurred during widespread fire years in the nineteenth century. The nineteenth century is recognized as a period of more widespread and synchronous fire activity throughout the southwestern US (Grissino-Mayer and Swetnam, 2000; Swetnam and Baisan, 2003). The aspen stand, dating to 1879, is located in the center of the basin, and indicates a 10 ha patch of high-severity fire. This was also the year of the Lime Creek Burn, a historically documented stand-replacing fire, which burned extensively in upper elevation mixed conifer and spruce-fir forests approximately 25 km to the west of the study basin (Toney and Anderson, 2006). Given the location of the aspen stand in the center of the study basin, this patch of high-severity fire would have likely generated sufficient runoff to transport hillslope and channel sediment. Therefore, the intermediate deposit (AD 1500–1950) near the top of stratigraphic section B may be associated with the 1879 mixed-severity fire event (Figure 6). The association of conifer recruitment ages with the surface fire history also suggests that a mixed-severity fire occured in 1851. This was one of the most widespread surface fire years in the southwestern US and in the Colorado Front Range (Swetnam and Baisan, 1996; Brown *et al*., 1999). However, the conifer recruitment exhibited by age-structure plot A is located on the southern ridge of the drainage (Figure 1, Figure 4), and fire in that area likely did not initiate the identified sediment deposition in the channel. If runoff were generated from this location, it likely would have been trapped by intact litter and duff on the slopes below the plot and above the channel.

Combined fire history record

The alluvial record can be used to interpret the longer-term fire history record for the site. The nature of the fine-grained deposition following the debris-flow event at ~ 2600 cal. yr BP suggests that a low–moderate and mixed-severity fire regime was dominant during this period. In addition to sediment characteristics, there were no clear erosional surfaces, and little evidence of previously incised channels that might relate to runoff associated with extensive high-severity fires. Although small patches (10–20 ha) of high-severity fire occurred as part of the mixed-severity fire regime, large extensive patches of high-severity fire equivalent to the Missionary Ridge Fire are unlikely to have occurred over the past ~ 2600 cal. yr BP. Given the available sediment in the channel, if a high-severity fire of comparable extent to the Missionary Ridge Fire had occurred, it likely would have initiated a debris flow and scoured the available channel material. We recognize the possibility that a high-severity fire may have occurred over the past ~ 2600 cal. yr BP, and that no geomorphic response followed the event. Furthermore, it is possible that a high-severity fire caused the thicker, depositional events in stratigraphic both sections A and B, yet this type of fire event likely did not exceed (or was of a different nature than) the ~ 2600 cal. yr BP fire event, and 2002 Missionary Ridge Fire. We also suggest that extreme rainfall may have been a factor in producing relatively thick deposits containing several layers of fine-grained sediments with charcoal lenses behind obstructions in the channel. Ultimately, the combination of rainfall conditions and burn severity patterns associated with the episodic deposition in stratigraphic sections A and B is unknown, because no direct analogs for these deposit types were observed following the Missionary Ridge Fire.

The period of rapid deposition at *c*. AD 780–1210 contains several buried logs, which have no evidence of charring, and may reflect a mortality-inducing event (such as drought or beetle outbreaks) to generate the woody material. The timing of this event corresponds with the MCA, a period of increased climatic variability and extended droughts documented in tree-ring reconstructions from the western US (Cook *et al*., 2004; Dean *et al*., 1994; Meko *et al*., 2007; Salzer and Kipfmueller, 2004). This sedimentation event also corresponds with the occurrence of high-severity fires interpreted from debris flow deposits within alluvial fan sites in southern New Mexico (Frechette and Meyer, 2009) and the northern Rockies (Pierce and Meyer, 2008). While the rapid deposition of fine-grained sediments in our study site corresponds temporally with fire-related debris flow deposition elsewhere, the texture of the deposits in our study site is very different, and may not represent the same fire regime changes as suggested by these other studies. Additional evidence of fire regime changes during the MCA in the southern Rockies comes from lake and bog charcoal records, which show increased fire event frequencies (increased number of charcoal peaks) in mixed conifer ecosystems during the late Holocene (~ 1000 cal. yr BP) (Allen *et al*., 2002; Anderson *et al*., 2008).

In our study basin, there was clear evidence of one extensive high-severity fire, resulting in the generation of a substantial debris flow at approximately ~ 2600 cal. yr BP. This debris flow scoured the channel, and possibly caused colluvium to slump from the hillslope into the channel. We infer that this event may have been similar in magnitude to the geomorphic response following the 2002 Missionary Ridge Fire, where up to 80% of the basin was burned by moderate- and high-severity fire. Although data from one basin do not indicate a regional shift in fire regime at this time, the ~ 2600 cal. yr BP debris flow event possibly relates to broader-scale climate and vegetation changes. The debris flow event coincides with the end of a Neoglacial period, characterized by wetter and possibly cooler climate roughly between 3800 and 2500 cal. yr BP Holocene (Armour *et al*., 2002; Enzel *et al*., 1992; Koehler *et al*., 2005). A charcoal record from a nearby (~ 25 km to the west) high-elevation lake surrounded by spruce-fir forests shows less frequent, but more intense fires during the period from 4100 to 2620 cal. yr BP (Toney and Anderson, 2006). Pollen records from two subalpine lakes in western Colorado also indicate that the forests were more dense from 4400 to 2600 cal. yr BP, and there was a shift to less dense vegetation occuring around ~ 2600 cal. yr BP (Fall, 1997; Toney and Anderson, 2006).

Conclusion

The fire behavior interpreted from the combined tree-ring and alluvial record indicates that the Missionary Ridge Fire had more extensive high-severity burn than all fires that have occurred in the studied watershed during the past ~ 2600 cal. yr BP. At approximately that time, an extensive, high-severity fire occurred in the basin, indicated by debris flow deposition, channel scouring and colluvial slumping. Following this, the alluvial record suggests a fire regime of low-moderate and mixed-severity fires, over the past ~ 2600 cal. yr BP. The tree-ring record shows evidence of both low-moderate and mixed-severity fires from AD 1679 to 1879, and the sediment record seems to correspond with this type of fire regime. The tree-ring record also shows that the twentieth century was unusual in lacking surface fire events. We conclude that the fire regime since 1879 has changed markedly, with a striking decrease in fire frequency during the twentieth century. Moreover, the Missionary Ridge Fire was probably the most extensive moderate- and high-severity fire to have occurred in the study basin in at least 400 years, as indicated by the tree-ring record, and perhaps as long as ~ 2600 years, as suggested by the alluvial record. Replication of alluvial sediment studies in other watersheds are needed to confirm the timing and character of sediment deposits observed in our study site, and better understand fire regime changes in the region.

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