**Final Report**

**Proposal Title:** Reconstruction of Fire History Using Tree-Ring and Alluvial Sediment Records in the Western San Juan Mountains, Colorado

**JFSP Project ID:** 11-3-1-27

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**Abstract:**

In the past few decades, wildfires have increased in size and severity in the Southwest and across the western US (Westerling *et al.* 2006; Williams *et al.* 2013). These recent trends in fire behavior represent a drastic change in arid, ponderosa pine and mixed conifer forests when compared with tree-ring records of fire history for the past ~ 400 years (Swetnam and Baisan 1996). Over the past century, forest ecosystems with frequent, low-severity surface fires have transitioned to severe fire behavior, influenced by a combination of land-use impacts and recent climate change (Allen *et al.* 2002). There is a need for improved understanding of fire-climate associations over the Holocene, which can help land managers to justify forest treatments aimed to mitigate fire severity in a future of projected warmer and drier climate conditions.

This study presents a late-Holocene record (~ 3,000 years) of fire history and associates changes in fire regimes with climate variability over annual to multi-decadal time scales. Tree-ring and alluvial-sediment sampling sites were paired in four small, tributary basins located in the western San Juan Mountains of Colorado. In our study sites, tree-ring records show that fire return intervals were longer and fire behavior included small patches of high-severity fire the north-facing slopes. Increased fire barriers and steep topography decreased fire frequency and extent relative to gentle terrain elsewhere in the range, and contributed to a lack of synchrony among fire years throughout the study area. These results support research from the San Juan Mountains, which suggested that historical fire regimes were partially influenced by local-scale topography. This study also suggests that local topography may have an overall greater influence on site-level fire regimes, except during the most extreme drought years in the region.

The alluvial-sediment record shows four peaks in high-severity fire activity over the past 3,000 years ranging between 200 – 400 years in length. The timing of peaks coincided with decadal-length drought episodes and was often preceded by multiple decades of above average winter precipitation. The pattern of multi-decadal scale climate variability was likely partially influenced by the Pacific Decadal Oscillation (Macdonald and Case 2005). Furthermore, the fire-climate associations were not consistent among all peaks suggesting an additional influence of local-scale topographic factors on fire activity. One prominent peak occurred during the Medieval Climate Anomaly (MCA, 900 – 1300 AD), corresponding with increased fire activity in several alluvial-sediment and lake-sediment records from across the western US. At this time, fire regimes across the western US may have been influenced by large-scale trends in temperature and drought (Cook *et al.* 2004; Trouet *et al.* 2013).

Finally, the sampling of alluvial-sediment and tree-ring data allowed for site-level comparisons between recent alluvial deposits and specific fire years interpreted from the tree-ring records. Three comparisons tested the assumptions of fire size and severity interpretations based on the sediment characteristics of individual alluvial deposits. Good correspondence between the fire behavior represented by both proxy records indicated that alluvial-sediment methods have reasonable methods and interpretations of past fire activity. Each of these methods tends to represent different components of the historical fire regime with alluvial-sediments biased towards the infrequent, high-severity events of the record. The combination of different proxy types in the same study sites greatly enhanced the fire history and fire-climate interpretations than using a single proxy method alone.

**Background and purpose:**

There has been an increase in the frequency and size of wildfires across the western US in recent decades (Running 2006). At the scale of the western US, this increase in fire activity has been associated with earlier snowmelt and warmer summer temperatures (Westerling *et al.* 2006). Regional-scale studies have also shown that the total area burned has increased over the past few decades with only slight increases in the proportion of high-severity burned area (Holden *et al.* 2007; Miller *et al.* 2008). In these studies, the total area burned exhibited high interannual variability, which was well-correlated with different metrics of precipitation, streamflow and temperature (Holden *et al.* 2007, 2012; Williams *et al.* 2010). For the Southwest, the increase in total area burned has been linked with extreme winter drought, especially in the past decade (Williams *et al.* 2010, 2013). Furthermore, individual fire size has increased dramatically in recent years, and the most significant change has been the maximum patch size of high-severity burned area (Miller *et al.* 2008; Andrea Thode, *personal communication*). For example, in the recent Las Conchas fire in northern New Mexico, high-severity patches exceeded 1000 ha (10 km2), resulting in very large expanses of complete tree mortality, along with consumption of litter, duff and understory fuels.

In ponderosa pine and mixed-conifer ecosystems of the Southwest, the recent fire behavior indicates a drastic shift in fire severity when compared with historical fire regimes (Swetnam and Baisan 1996). Tree-ring records and documentary sources show that prior to the 20th century, frequent, low-severity surface fires burned in the understory of open forests. At longer intervals, small patches of high-severity fire occasionally burned in the relatively mesic or isolated stands, though rarely exceeding a few hectares (Iniguez *et al.* 2009). Following Euro-American settlement in the region at the end of the 1800's, grazing practices and fire suppression limited surface fires from spreading in lower-elevation conifer forests. As a result, the absence of nearly all fire activity greatly increased stand densities over the past century, leading to increased fire severity today (Fulé *et al.* 1997).

There is a strong association of total area burned with extreme drought conditions in recent years across the Southwest, although the trends in burn severity suggest an additional influence of land-use history. Given the combined impacts of climate and land-use history on recent fire behavior, researchers are concerned with how to prepare for a future with continued extreme fire behavior. Future climate scenarios indicate severe multi-decadal droughts and warmer temperatures for the Southwest over the next century (Seager *et al.* 2007). In response to these projected climate changes, forest restoration treatments (i.e. thinning, prescribed burning) have been proposed (and are underway) to reduce stand densities along the wildland-urban interface (Allen *et al.* 2002). Such treatments require continued justification of their value and necessity, which has prompted additional research into better understanding historical fire regimes. Research questions surrounding this issue include:

*(1) Were fires as large and severe in the past, and how were these fires related to climate?*
*(2) Will the size and severity of future fires continue to grow in the coming decades?*
*(3) Can forest treatments be effective at reducing fire severity in the face of climate change?*

Analysis of historical fire-climate associations can help answer the questions outlined above, if performed over a time period when climate conditions were similar to the predicted climate scenarios. For example, the Medieval Climate Anomaly (MCA, 900 to 1300 AD) was a period with multi-decadal droughts and overall warmer temperatures across the western US (Cook et al. 2004). The current drought has been severe since the turn of the century in the Southwest, however, it is not yet considered longer or more severe than drought episodes of the past two millennia (Routson *et al.* 2011; Williams *et al.* 2013). Therefore, examining fire regimes during the MCA and other severe drought episodes can provide increased knowledge on how fire regimes will respond to similar drought conditions in the future. Ultimately, the potential of future warming and drying in the Southwest indicates the drastic need to apply forest treatments in many locations in order to increase forest resilience.

Fire history research aims to reconstruct fire regimes over a range of temporal and spatial scales. Fire regimes are defined by the frequency, size, severity and seasonality of fire events for an ecosystem. There are four major methods of fire history research, and each method has different strengths and weaknesses. Annual fire history records can be derived from documentary records of the 20th century, along with fire-scar and age-structure data derived from tree-rings. These records have high spatial and temporal precision, and can show interannual variability in fire occurrence, severity and extent. Fire-scarred trees are the best record of past surface fires and have illustrated the dominant role of fire in many forest types, especially low to mid-elevation conifer forests in arid regions (Swetnam and Baisan 2003). Large networks of fire-scarred trees have been used to analyze regional and hemispheric-scale climate influences on fire synchrony among hundreds of sites over the past few centuries (Kitzberger *et al.* 2007; Falk *et al.* 2011).

Over longer time scales, fire histories covering the Holocene (past 10,000 years to present) can be interpreted from charcoal deposited in lakes/bogs/meadows and charcoal contained within alluvial-sediment deposits (Whitlock and Anderson 2003; Pierce and Meyer 2008). Alluvial-sediment methods documents wildfires occurring within the contributing area of small tributary basins. The size and severity of these fire events are interpreted from the characteristics of sediment deposits in an alluvial fan exposure. Data from multiple alluvial fans across a study area are composited to show trends in the fire frequency and severity. On the other hand, charcoal fragments found within a lake-sediment core are counted to show trends in regional fire activity over millennial time scales. These records are valuable for analyzing centennial-scale trends in fire and climate, though fire size and severity is difficult to infer from this method. Overall, both alluvial-sediment and lake-sediment records can be used to analyze the influence of climatic periods such as the Medieval Climate Anomaly or Little Ice Age (~ 1300 to 1850 AD) on historical fire regimes (Marlon *et al.* 2012).

**Study Description and Location:**

*Overview of study:*

The JFSP GRIN award provided partial support for the dissertation of the Co-PI, Erica Bigio. The goal of her dissertation was to collect two methods of fire history in the same study sites, and to use the strengths and weaknesses of each record to better interpret changes in fire regimes over the late Holocene. Alluvial-sediment data were collected from three low-order tributary basins in the western San Juan Mountains (see further description below), and used to develop a chronology of historical fire events covering the past 3,000 years for the region. The alluvial-sediment record was paired with tree-ring material sampled from the hillslopes above many of the sediment exposures. Tree-ring samples included fire-scarred trees to interpret historical fire frequency and extent, along with age-structure data to evaluate historical fire severity. An additional basin with paired sampling of tree-ring and alluvial sediment was collected as part of Erica Bigio's Master's thesis, and selected data from this prior study was incorporated into the analysis associated with the dissertation (Bigio *et al.* 2010).

The pairing of both tree-ring and alluvial sediment methods in the same study sites is a unique approach for fire history research. The coordinated sampling of each proxy type provided the opportunity to test assumptions of each method. Initially, the fire history information derived from each method was independently compared with climate information and used to illustrate fire-climate associations at a range of temporal scales. Following this, the youngest alluvial-sediment data was compared with tree-ring data from the same locations, which served as both an independent check of interpretations and helped to calibrate of ages of fire events derived from the alluvial record (Whitlock *et al.* 2004; Swetnam *et al.* 2009; Farris *et al.* 2010; Bigio *et al.* 2010).

The JFSP GRIN award also supported the exploration of applying a new charcoal analysis method for interpreting fire severity from alluvial-sediment deposits. A charcoal sample has a reflectance value, which can be measured by the amount of light reflected off a sample at a given wavelength (Scott and Damblon 2010). This value is dictated by the cell wall structure, which becomes homogenized as the temperature increases during charcoal formation. Therefore, this reflectance value is proxy for the temperatures during wildfires as understory fuels are burning. This method has been successfully tested with archaeological samples, laboratory samples and a few samples collected from recent wildfires. This project explored whether the reflectance values could determine whether charcoal found in sediment deposits were created under the conditions of low- or high-severity fires.

The Co-PI, Erica Bigio, sampled charcoal following two recent wildfires in the Southwest (the Horseshoe II fire in southern Arizona (2011) and the Las Conchas fire in northern New Mexico (2011) to use as a calibration set. Charcoal was also separated from several alluvial deposits from the study area in the San Juan Mountains. These samples were brought to the laboratory of of Dr. Andrew Scott at the University of London-Royal Holloway, where the Co-PI learned about the methods of charcoal preparation, data collection and analysis of reflectance values. A limited number of charcoal samples were analyzed from alluvial-sediment deposits, which may be used for future research proposals.

*San Juan Mountains, Colorado, USA*

The study area was located in the western San Juan Mountains of southwestern Colorado, just north of the town of Durango, Colorado (Figure 1). The San Juan Mountains are a linear east-west trending mountain range with rugged terrain and steep elevational gradients, contributing to complex patterns of different vegetation types in close proximity. At mid-elevations throughout the range, the forest is composed of ponderosa pine (*Pinus ponderosa*) with Gambel oak (*Quercus gambelii*) understory, extensive shrub fields and two phases (warm/dry and cool-moist) of mixed conifer forests (Blair et al., 1996; Korb and Wu, 2011; Romme et al., 2009). Aspen (*Populus tremuloides*) woodlands and spruce-fir forests occupy the higher elevations, along with alpine meadows at the upper forest border (Blair et al., 1996; Romme et al., 2009).

In the past, there were several episodes of glacial activity, resulting in broad U-shaped valleys trending north to south in the mountain range (Blair and Gillam, 2011). Many small and steep tributary basins are located along the margins of these broad valleys exhibit Holocene-age alluvial fans at their outlet. In the summer of 2002, the Missionary Ridge Fire burned more than 30,000 hectares and burned through ponderosa pine and mixed conifer and spruce-fir forest, resulting in a patchwork of low, moderate and high-severity burned areas (BAER report, 2002). There were extensive patches of high-severity burned area and these patches covered large proportions of the tributary basins along the Animas, Florida and Los Pinos River valleys. The high-severity fire consumed litter and duff on the forest floor and increased runoff led to flood and debris flow activity along these valleys. The increased runoff and erosion left deeply incised stream channels and deep exposures cut into the alluvial-sediment of tributary stream channels and alluvial fans. These events provided the rare opportunity to sample observe and sample older alluvial-sediment deposits, many of which showed evidence of abundant charcoal and older burned soil surfaces.

Alluvial-sediment data was collected from six low-order tributary basins within the Missionary Ridge Fire area (Figure 1). Of these basins, tree-ring data were collected from three basins. The two largest basins: Haflin Creek (420 ha) and Stephen's Creek (1560 ha) were located on the east side of the Animas Valley. The third and smallest basin is named the 'Marina' (70 ha), and is located about 25 km to the east, along the west side of Vallecito Reservoir. Data from a fourth basin from the Master's thesis of the Co-PI was incorporated for the alluvial-sediment data analysis. The largest drainage basins located along the East side of the Animas have strong aspect differences, which influence different vegetation compositions on north and south-facing slopes. The south-facing slopes tended to have open stands of ponderosa pine with Gambel Oak understory. Many stands on the south-facing aspect were exceptionally old, with individuals between 500 – 800 years old, especially along steep, bedrock ridges. The forests on the north-facing slopes were denser and they were composed of even mixes of Douglas-fir, white fir and small proportions of ponderosa pine and limber pine.

**Key findings:**

This dissertation is organized into three manuscripts and each is intended for publication in a peer-reviewed journal. These manuscripts are the majority of deliverables identified in the original proposal, and they are listed in the deliverables table later in this report. The first publication covers the tree-ring data with fire-climate associations of the past 400 calendar years before present. This publication is finished and will be submitted to the journal Forest Ecology and Management in December 2013. The second publication covers the alluvial-sediment record with fire-climate associations of the past 3,000 calendar years before present. This publication needs minor revising and wil be submitted to the International Journal of Wildland Fire in January 2013. The third publication is a comparison of three recent alluvial-sediment deposits with tree-ring data from the contributing area upstream of the deposit. This will be submitted for publication in the spring of 2014, and the journal has yet to be determined.

*Publication 1: The influence of local-scale topography and regional-scale climate drivers on historical fire regimes in the western San Juan Mountains, Colorado.*

The first publication documents annual changes in the frequency, size and severity of wildfires over the past ~ 300 years, using a combination of fire-scar and age-structure data from tree-rings. Several fire-scar trees and age-structure plots were collected from three basins and analyzed for fire frequency and severity within each basin. In the two largest basins, there were clear differences in forest composition, fire frequency and severity by aspect. The south-facing slopes were dominated by open ponderosa pine, and the majority of fire-scarred trees were found on this aspect. The north-facing slopes were composed of denser mixed conifer stands with a large proportion of Douglas-fir and white fir. On the south aspect, fire frequency was significantly higher and there was evidence of continuous recruitment of trees at most age-structure plots. On the north-facing slopes, many of the age-structure plots exhibited even-aged cohorts (i.e., pulsed tree establishment), which is interpreted as evidence of mixed or high-severity fire behavior. At the basin scale, the MFI ranged between 11 - 14 years for all fire years and between 22 - 26 years for more extensive fires (25% scarred, min 2). For the ponderosa pine stands, these values were longer than elsewhere in the San Juan Mountains, and this is partially related to the steep terrain and increased fire barriers in the study sites.

There were 27 unique fire years, when fires ranged between localized to widespread within a single basin, but were not recorded in other basins. There were 15 years, when fires occurred in at least two basins, often burning extensively across each basin. The fire years were more often localized and restricted to a single basin, suggesting that fire frequency and extent were influenced fire barriers and complex topography of the landscape. Fire-climate analysis included an SEA of two different groups of fire years. One group included all unique fire years, where fire only occurred in a single basin. The second group included all years when synchronous fire occurred in two or three basins. Both groups showed that dry PDSI values during the year of the fire, while the second group showed significantly wet PDSI conditions for two years prior to the fire year. We suggest that fire barriers restricted fire to individual basins, except when regional-scale climatic drivers increased fuels across the landscape, which was the minority of fire years.

*Publication 2: Late Holocene fire and climate history in the western San Juan Mountains, Colorado*

The second publication focuses on the development of fire history data using the sedimentary structures of charcoal-rich alluvial deposits found in six tributary basins. We reconstructed 34 fire events by radiocarbon dating of charcoal pieces within sediment deposits. We developed a chronology of fire-related sedimentation for the past 3,000 calendar years before present (BP). Among all basins, there was increased high-severity fire events between 2,700 – 2,400 cal yr BP, 1,500 – 1,300 cal yr BP, 1,100 – 800 cal yr BP and 550 – 350 cal yr BP. Low-severity fire events dominated the record between 2,400 – 2,000 cal yr BP. We compared the episodes of high-severity fire activity with several independently-derived, high-resolution reconstructions of precipitation, PDSI, and temperature covering the past 2,000 years (Cook *et al.* 2004; Meko *et al.* 2007; Routson *et al.* 2011; Williams *et al.* 2013). We specifically looked at periods of wetter or cooler climate conditions, followed by multiple years to decades of extreme drought conditions.

Many of the high-severity peaks were preceded by periods of overall wetter and cooler climatic conditions, which probably led to increased fuel accumulation throughout the basins. The peaks often coincided with one or two multi-decadal droughts, and if not, then several extreme drought years. Ultimately, the best correspondence between high-severity fire activity and multi-decadal climatic shifts was observed during the Medieval Climate Anomaly. Two multi-decadal droughts and one significant pluvial period coincided with the Medieval peak in high-severity fires. This was also the time of best correspondence among several alluvial-sediment records and increased biomass burning across the western US (Marlon *et al.* 2012). The multi-decadal shifts between wet and dry climate over the past 1,200 years were partly influenced by the Pacific Decadal Oscillation (Mantua and Hare 2002; Macdonald and Case 2005).

*Publication 3: A comparison of tree-ring and alluvial-sediment fire history interpretations, testing the link between proxy methods with a debris flow probability model.*

The third publication compares specific fire events identified within the past 400 years in both the alluvial-sediment deposits and tree-ring data. This analysis aimed to test the assumptions and fire-event interpretations derived from each method alone. In the case of alluvial-sediment methods, the interpretation of fire size and severity relies on modern observations of geomorphic responses following wildfires in small tributary basins. However, the interpretation of extensive, low-severity fires from the paleorecord is based primarily on hillslope and plot-scale studies of runoff and sediment yields. Therefore, an important question for interpreting alluvial-sediment records is whether debris flows may possibly be the result of an extreme rainfall on extensive low-severity fire, and what the likelihood of such a scenario is. As part of this analysis, we used an existing empirical debris flow probability model to evaluate whether it is possible to generate debris flows from wildfires with a low proportion of high-severity fire following relatively extreme rainfall conditions (i.e. greater intensity for a 1 hour storm). Finally, we compared alluvial-sediment data with tree-ring data in three drainage basins to provide an independent check of fire size and severity interpretations based on each method. We used the debris flow probability model to confirm of the correspondence between the tree-ring and alluvial-sediment record.

We found that increasing rainfall intensities had less impact on debris flow probability than increasing proportions of high-severity burned area in a contributing basin. We found good correspondence between the type of fire-related sediment deposit (i.e. debris flow vs. streamflow deposit) and the extent of mixed and high-severity fire estimated from the tree-ring record. The correspondence of each type of deposit with fire extent from the tree-ring record was well-supported by the debris flow probability model. The case of least correspondence was related to the location of high-severity burned area within the basin. The results show that the interpretations of fire severity and extent from the alluvial-sediment record are reasonable, and we feel confident to with our existing interpretations of the longer-term alluvial-sediment record. The comparison also showed that the alluvial-sediment record does not represent the total number and frequency of low-severity fires occurring over the past 400 years. We suggest that the longer-term alluvial-sediment record should be interpreted for shifts in fire severity over the late Holocene.

*Additional findings: Charcoal-reflectance values of alluvial-sediment deposits:*

We measured charcoal reflectance value on seven samples at the lab of Dr. Andrew Scott at the University of London Royal Holloway. The seven samples were from a range of sediment deposits, which represented low and high-severity fire events. Typically, each sample was composed of many charcoal fragments and up to 50 measurements were taken per sample. The average of the measurements provided a single reflectance value for the sample, although the range of measurements had considerable deviation from the mean. We compared our reflectance values with a mean wildfire value derived from a limited set of samples from the Hayman Fire. The high-severity deposit in our study had similar mean values to that of the Hayman wildfire sample, as did a modern charcoal sample from a high-severity portion of the Missionary Ridge Fire. The mean from two low-severity samples were lower than that of the Hayman fire sample. These preliminary results suggest that charcoal reflectance values are significantly different between charcoal created under conditions of low-severity or high-severity fire effects. Further confirmation of this is required using a calibration data set. Our preliminary results also suggest that interpretations of fire-severity based on sediment characteristics are reasonable.

## Management Implications:

*Historical fire frequency varied with topography and fire barriers:*

Knowledge of historical fire frequencies may be used to justify mechanical thinning and prescribed fire treatments aimed to reduce stand densities ponderosa pine and mixed-conifer stands throughout the San Juan Mountains (Korb *et al.* 2012). The majority of the management implications were interpreted from the tree-ring reconstructions of fire regimes in our study sites (with review of other prior work in the range). Our work suggested that longer fire return intervals may be appropriate for ponderosa pine-oak stands located in dissected topography with many fire barriers compared with stands located in gentle terrain. Fire return intervals were generally longer for the ponderosa pine stands located on the south-facing slopes of Steven's Creek and Haflin Creek, where dissected topography prevented fire spread and lengthened fire return intervals. If restoration treatments were applied to portions of the landscape with steep, dissected topography, then longer fire return intervals (i.e., 15 – 25 years) for prescribed fire may be used. However, the pre-settlement stand densities for ponderosa pine in our study sites were similar to other ponderosa pine stands elsewhere in the range (Brown and Wu 2005).

*Fire severity varied with aspect:*

Our work also suggested that warm-dry mixed conifer stands may experience mixed and high-severity fire on north-facing aspects at the hillslope scale. These patches were likely between 10 – 50 ha and were more common on steep hillslopes in dissected terrain when compared warm-dry mixed conifer stand elsewhere in the range (Korb and Wu, 2011). Even on the north-facing aspects, the mixed- and high-severity fire events likely alternated with low-severity fire at different temporal scales. High-severity fire tended to occur following long fire-free intervals at the hillslope scale and coincided with extreme drought years. Extreme drought years influenced fire to spread across fire barriers, where fuels had accumulated during prior fire-free intervals.

*Topographic influences were more common than regional-scale climatic influences:*

There was significant variability in the timing of fire years and length of fire return intervals throughout the range, and this likely relates to a stronger influence of topography on historical fire regimes relative to climatic influences. The majority of fire years were limited to a single study basin and many fire years were out of sync with other fire years throughout the range. Fire years did become synchronized in response to prior wet climate conditions and extreme drought during during the fire year. This fire-climate association is typical of other sites elsewhere in the southwest, where the regional-scale influence of the ENSO cycle synchronized fire activity across many study sites. However, this was not the majority of fire years for our study area, suggesting the more important influence of local-scale topography such as fire barriers which prevent fire spread. Overall, our findings highlight the variability in fire regimes across the San Juan Mountains and support the use for site-specific fire history information for deciding restoration treatments (Korb *et al.* 2012, 2013).

*Late Holocene fire regimes and the context of the Missionary Ridge Fire:*

The alluvial-sediment record illustrated four peaks in high-severity fire activity over the past 3,000 years. These peaks were composed of different numbers of low and high-severity fire events interpreted at the drainage basin scale and then composited together. We interpreted that peaks composed of fire events from multiple watersheds represented more extensive fires. There were two peaks in high-severity fire, when fire events were synchronous across at least three watersheds in the same century, and this was used as an indicator of more extensive fires across study area. These peaks occurred around 900 cal yr BP (early-mid 12$^{th}$ century) and 500 cal yr BP (16$^{th}$ century). The other high-severity peaks were documented in only two basins and often represented relatively small areas of high-severity within each basin.

The more recent peak high-severity fire activity was recorded in five watersheds (16$^{th}$ century) and approached the extent of fire during the Missionary Ridge Fire. However, we are not confidant that the size of high-severity patches were equivalent to those observed following the recent Missionary Ridge Fire. Many of the sampling locations were located in the upper watershed, where the interpretation of fire size was limited to the contributing area above the sampling location. Therefore, the overall fire size and the proportion of high-severity fire burned area were smaller than the Missionary Ridge Fire for many of the contributing basins. In contrast, the Missionary Ridge Fire burned across the entire landscape with at least 80% high-severity fire in entire contributing area of six sampled watersheds. Not only did the Missionary Ridge burn at high-severity on mesic, north facing slopes, but also consumed forest stands with very old living trees (500 - 800 years old).

**Relationship to other recent findings and ongoing work:**

*Fire history research in San Juan Mountains*

There have been several fire history studies conducted over the past several years using either tree-ring or lake-sediment methods. The tree-ring studies have been collected from ponderosa pine to upper-elevation mesic mixed conifer forests (Grissino-Mayer *et al.* 2004; Brown and Wu 2005; Fulé *et al.* 2009; Korb *et al.* 2013). These studies show that frequent surface fire was dominant in ponderosa pine and xeric mixed conifer sites with an increase in fire return intervals with elevation. Our study sites were located in the center of the range with more steep and dissected terrain compared to sites elsewhere in the range. Recent work by Korb and others (2013) focused on the variability in mixed conifer stands at three locations throughout the range. Their study found that fire frequency and the timing of fire free intervals varied greatly among mixed conifer stands with similar composition. The findings are in agreement with our study, which associated similar results to complex topography and fire barriers.

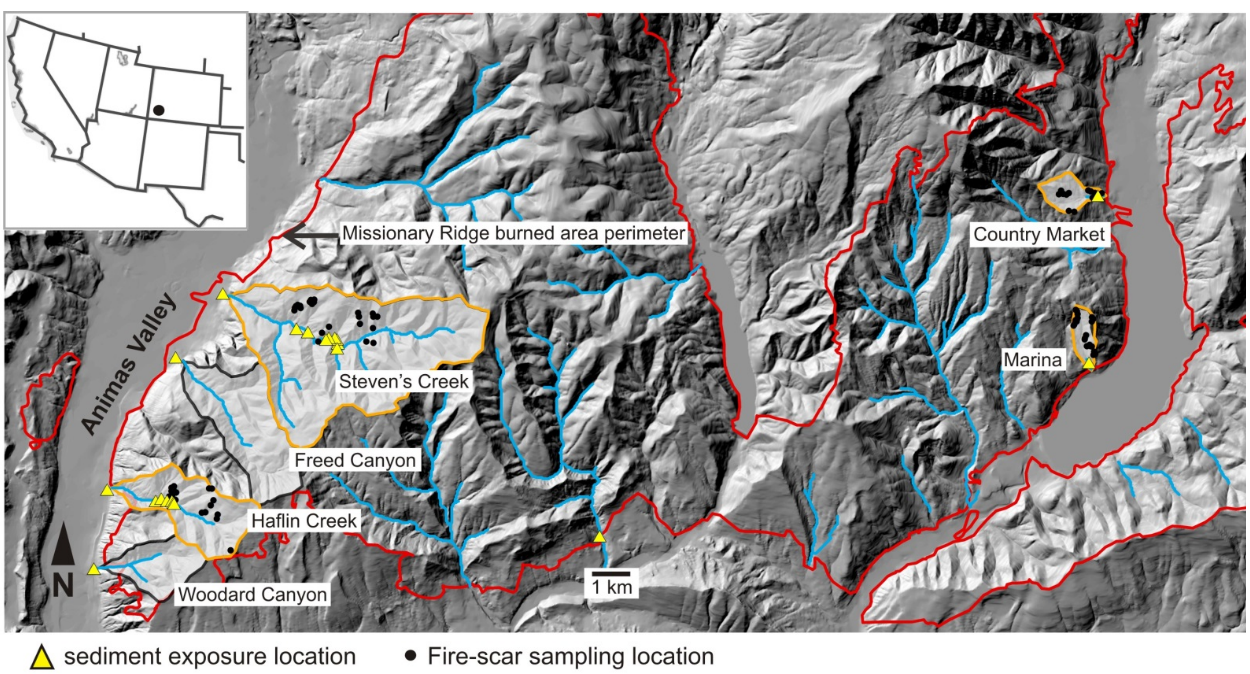
Our study was the first study using alluvial-sediment methods in the San Juan Mountains, and it complemented the existing collection of lake-sediment studies. There have been several lake-sediment studies from relatively mesic mixed conifer sites and higher elevation spruce-fir sites from across the San Juan Mountains (Toney and Anderson 2006; Anderson *et al.* 2008). Our study shows a significant peak in fire activity between 2,700 and 2,000 cal yr BP. This corresponds well with other lake-sediment studies, which showed a maximum in fire frequency generally between 2,000 – 1,000 cal yr BP. The maximum in fire frequency was associated with a transition to more open forests 2,600 – 2,000 cal yr BP, which coincided with the end of a Neoglacial period of cooler climates. Our work was also compared with recent alluvial-sediment records from the western US, where fire activity was best correlated during the Medieval Climate Anomaly.

**Future work needed:**

The historical fire regime analysis could be incorporated into management plans of the San Juan National Forest. We plan to discuss results with forest service employees, whom we have communicated with over the years. Future work on fire regimes could focus on higher elevation areas, which to our knowledge, have had almost no tree-ring based fire history work. The charcoal reflectance values seem promising, although future work is needed for calibration of the method with modern wildfire charcoal samples. We plan to use data derived from this project for writing proposal on both of these future work topics.

Please look for forthcoming publications on the research in this report:
www.ltrr.arizona.edu/~tswetnam

**Figure 1:**



**Deliverables table:**

Deliverables identified in proposal:

| Deliverable Type | Description | Status |
|---|---|---|
| Publication in refereed journal | Tree-ring fire history paper | Manuscript complete,<br>It will be submitted to Forest Ecology and Management in December 2013. |
| Publication in refereed journal | Alluvial sediment fire history paper, including charcoal analysis | Manuscript complete,<br>It will be submitted to IJWF in January 2014. |
| Publication in refereed journal | Combined synthesis of tree-ring and sediment fire history paper, including fire and climate associations for past ~ 3,000 years | Manuscript in prep,<br>It will be submitted for publication next spring, journal yet to be determined. |
| Conference presentation | Presentation at 5th International Fire Ecology and Management Congress in Portland, OR (Dec 2012) | Complete |

Additional deliverables completed and in progress:

| Deliverable Type | Description | Status |
|---|---|---|
| Outreach presentation | Summary of research presented at Fort Lewis College in Durango, Colorado – attended by Geology and Biology undergraduate students and members of the community | April 2013 |
| Teaching materials prepared | Fire-scar samples were prepared for Professor Cythia Dott (FLC, Biology Department) for teaching about tree-rings and fire history in an undergraduate Ecology course. | Completed October 2013 |
| Report to Forest Service | We plan to write a report for the San Juan National Forest. It will include the Management Implications described above. | In progress |

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