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Late Holocene Relationships Among Fire, Climate, and Vegetation in Rangeland Ecosystems of Southwestern Idaho

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Abstract
Rangelands are characterized by more arid climates than forested regions; therefore, establishing fire histories using traditional methods (e.g. fire-scars from trees or charcoal in lake sediments) is problematic. This study uses radiocarbon dating of charcoal preserved in alluvial fans and stream deposits to reconstruct a record of fire and geomorphic response in rangelands of southwestern Idaho. Samples indicate three primary periods of fire-related activity: 4400 – 4000, 2000 – 1400, and 650-400 cal yr BP. Charcoal macrofossil identification and comparison with other regional climate and fire records indicate this area has likely switched between a „fuel-limited' system (fires limited by lack of fuels), and a „moisture-limited' system (fires limited by too much moisture) with changes in Holocene climate. Over the past ~2000 yr, samples from this rangeland site indicate most fires occurred during wetter times than the record average. During overall wetter periods, (e.g. LIA; 600-100 cal yr BP) tree density may have increased, and fires occurred during intervals of relative drought. During times of prolonged drought (e.g. MCA 1025-650 cal yr BP) fire was recorded during a wetter interval. After ~600 cal yr BP, fire activity is similar to the record of low intensity fires in a nearby ponderosa pine-dominated drainage, and sagebrush is common in charcoal samples. Inferred shifts in the forest-rangeland ecotone are consistent with those reported elsewhere in the Great Basin. A comparison of OSL and ^{14}C ages shows good correspondence between charcoal ages and the charcoal containing sediments, indicating fire-related sedimentation occurs soon after fire.

Key words: fire history, rangelands, Holocene, sedimentary charcoal, geomorphology, Idaho, fuel-limited, moisture-limited

Introduction

Climate is a primary control on the occurrence and severity of wildfire. On annual to decadal timescales, climate controls the continuity and condition of fuels (e.g. Heyerdahl *et al.*, 2002; Westerling *et al.*, 2006; Kitzberger *et al.*, 2007; Morgan *et al.*, 2008), while on centennial to multi-millennial timescales, climate controls vegetation type, extent, and subsequent fire regime (Meyer *et al*, 1992; Millspaugh *et al*., 2000; Grissino-Mayer and Swetnam, 2000; Whitlock *et al*., 2003; Pierce *et al*, 2004). While many studies have examined fire histories in forested ecosystems, few have studied long-term (10^2-10^3 yr) fire histories in rangelands. Rangelands comprise ~ 80% of the western United States and are used for livestock grazing, recreation, and provide critical habitat for many species within a diverse ecosystem. Between 2005 and 2007, greater than 10,400 km^2 of rangeland burned in Idaho, Oregon, Utah, Nevada, and Montana (www.nifc.gov, 2008). Given ecological concern for such species as the sage grouse, a sagebrush obligate (Wambolt *et al*., 2001; Baker, 2006), range managers must now balance the needs of multiple users with vegetation changes and habitat restoration (Chambers and Pellant, 2008).

Determining whether a given ecosystem is „fuel limited' (where fire is limited by lack of available fuel) or „moisture limited' (where fire is limited by too much moisture) is difficult in ecotonal regions such as rangelands, where both Holocene climate change and changes in land-use have influenced fuel density, fuel quality and fuel type. Assessing how fire frequency and relationships among climate, fire and vegetation in rangeland ecosystems have changed in historic times requires a longer term (thousand-year) record of fire activity. While fire histories in forested ecosystems can be determined using dendrochronologic methods (stand ages and fire scars), and charcoal from lake sediments have been used to reconstruct fire history in a variety of ecosystems (e.g. Whitlock *et al.,* 2003; Millspaugh *et al*., 2000; Camill *et al*., 2003), both trees and lakes are rare in the arid to semi-arid rangelands of the American West.

In addition to fire scars, lake cores, and ecologically-based fire reconstructions, charcoal fragments preserved in stream sediments and alluvial fans provide a longer term (thousand year) record of fire and geomorphic response to fire (e.g. Meyer *et al*., 1995; Pierce *et al*., 2004; Frechette and Meyer, 2009). These alluvial deposits record both the timing of fire (from radiocarbon dating of charcoal fragments) and the geomorphic response to fire. This study uses charcoal records in alluvial sediments to describe a record of geomorphic response to fire and relationships among fire, drought, and vegetation in a rangeland watershed of southwestern Idaho over the past ~6000 years. Specifically this study examines whether peaks in fire activity correspond with intervals of drought or wet intervals in order to assess whether this rangeland ecoyststem is fuel-limited or moisture-limited with respect to fire, and how both climate and late Holocene vegetation change influence fire activity.

Study Area

The Wood Creek study area is located south-east of Boise, Idaho, in the northern end of the Danskin Mountains (Figure 1). The ~ 26 km^2 study area lies entirely within the Cretaceous Idaho batholith granite. Extensive hydrothermal alteration and subsequent weathering of the granite produced a thick, grussy mantle in the study area (Clayton 1974), making this region a sensitive recorder of erosional events (Meyer *et al*., 2001; Pierce *et al*., 2004). Elevations range from 1073 m to 1621 m, and the area receives between 37 and 57 cm of annual precipitation. The region is dominated by Pacific-derived moisture, and most precipitation falls as rain or snow during the winter months, with typically dry summers (Meyer *et al*., 2001).

Analysis of remotely sensed data (ETM+ data, collected on 2 June 2000) indicates shrub and grass communities cover 93% of the study area (Figure 1). More xeric communities on southerly aspects in the study area are dominated by big sagebrush (*Artemisia tridentata*) and bitterbrush (*Purshia tridentata*) with an understory of cheatgrass (*Bromus tectorum*) and native bunchgrasses. Northerly aspects are dominated by mesic communities that include serviceberry (*Amelanchier alnifolia*), Rocky Mountain maple (*Acer glabrum*), several species of currant (*Ribes sp.*), big sagebrush, aspen (*Populus tremuloides*), and isolated stands of ponderosa pine (*Pinus ponderosa*) and Douglas fir (*Pseudotsuga menziesii*). Riparian corridors are dominated by willow (*Salix sp.*) and cottonwood at lower elevations (*Populus sp.*).

Fire Regimes in Rangeland Ecosystems and Regional Changes in Holocene Climate

Semi-arid and arid ecosystems are typically fuel-limited communities with respect to fire. While fire return intervals vary considerably (Figure 2), sagebrush rangelands are generally fuel-limited and most forests are moisture-limited with respect to fire. Ponderosa pine is near the center and experiences fire return intervals that range over nearly two orders of magnitude (e.g. Sherriff and Veblen, 2007; Fulé et al., 2003; Fulé et al., 1997). Fires generally occur in wet years or following a period of wet years, and fire return intervals depend on the time required to develop a continuous fuel load (Miller and Tausch, 2001). More mesic forested communities have moisture-limited fire regimes, where fuels are generally too wet to carry a fire, and large fires may occur during periods of drought (e.g. Romme, 1982; Meyer *et al*., 1995; Kipfmueller and Baker, 2000; Hallet et al, 2003; Schoennagel *et al*., 2004; and Margolis *et al*., 2007). Other communities, including some ponderosa pine and Douglas fir forests may exhibit both fuel-limited and moisture-limited fire behavior (e.g. Brown and Sieg, 1999; Pierce *et al*., 2004; Schoennagel *et al*., 2004)..

Diaries from the early settlers on the Oregon Trail describe the Idaho Snake River Plain as a “sea of sagebrush” (Yensen, 1982). With increased traffic along the emigrant trails, surrounding areas soon became overgrazed (Yensen, 1982) and significantly altered by the introduction of cheatgrass. Cheatgrass first appeared in the western U.S. in the 1890’s, quickly spread throughout rangelands in the Great Basin, and is now present within all of the continuous U.S. and most of Canada (http://plants.usda.gov). By the 1940’s, cheatgrass was the dominant species on over six million acres of the Snake River Plain of southwestern Idaho, and present throughout at least another 10-15 million acres (Stewart and Hull, 1949). Cheatgrass, like other fire-adapted annuals, invades and thrives in recently burned areas (e.g. Conrad *et al*., 1966; Billings, 1994; Crawford *et al*., 2001), and increased dry fuel loads in cheatgrass-dominated areas increases fire frequency (e.g. Stewart and Hull, 1949; Miller and Tausch, 2001; Brooks *et al*., 2004; Knick *et al*., 2005). The resulting shorter fire return intervals may not allow enough time for recovery of sagebrush ecosystems (Brooks *et al*., 2004; Miller and Tausch, 2001; Stewart and Hull, 1949).

Other land use changes, however, may have promoted longer fire return intervals in rangelands. In some areas of the Great Basin, juniper woodlands likely have expanded onto formerly grass and sagebrush-dominated rangelands (Burkhardt and Tisdale, 1976; Miller and Wigand, 1994; Miller and Tausch, 2001; Baker and Shinneman, 2004; Morris *et al*., 2009). Although reductions in fire frequency are a commonly cited cause of encroachment (Burkhardt and Tisdale, 1976; Miller and Wigand, 1994; Miller and Tausch, 2001), juniper expansion in the western U.S. has also been attributed to natural post-glacial migration (e.g. Lyford *et al*., 2003), wetter than average climate with mild winters during the late 1800's and early 1900's, as well as reduced fuel loads due to grazing (Miller and Wigand, 1994; Miller and Tausch, 2001). A review of fire history records in piñon-juniper woodlands by Baker and Shinneman (2004) concludes that fire regimes are in these ecosystems poorly understood, and a lack of sufficient reliable data precludes accurate reconstructions of fire return intervals or fire severity.

Fire scars from stands of ponderosa pine adjacent to rangelands have been used to approximate rangeland fire return intervals (Miller *et al*., 2001; Miller and Tausch, 2001; Miller and Rose, 1999); however, the reliability of such estimates has been called into question (Baker, 2006). Miller and Tausch (2001) report fire return intervals for sagebrush ecosystems of ten to twenty years, yet sagebrush has been shown to take over thirty years to recover to prior stand heights and densities after fire (Wambolt *et al*., 2001). Baker (2006) argues that fire return intervals are commonly twice the duration of the recovery time, as documented in southwestern piñon-juniper woodlands and in lodgepole pine and spruce-fir forests; therefore fire return intervals should be at least 60 years in sage-dominated ecosystems.

Fire scars from ponderosa pine forests along the forest-prairie ecotone in the Black Hills of South Dakota indicate that fire return intervals ranged from ten to thirteen years, which is about half of the fire return interval reported for interior locations within the forest (Brown and Sieg, 1999). Miller and others (2001) used ecotonal stands of ponderosa pine to estimate fire return intervals of approximately ten to twenty years in mountain big sagebrush communities throughout the Great Basin. All of these studies indicate a near absence of fire since the late 1800's and woodland expansion and thickening. In the Colorado Front Range, however, fire-scar studies indicate large stand-replacing fires in higher elevation ponderosa pine forests even during the relatively cooler interval of the 1800's, and widespread fires were recorded in 1786 and 1859 (Veblen *et al*., 2000). Widespread fires also burned in ponderosa forests of the Black Hills in 1863 (Brown and Sieg, 1999).

Pollen, carbonate, and charcoal records from Kettle Lake in the grasslands of North Dakota indicate that during the late Holocene, grass abundance and fire activity increased during moist periods and decreased during dry periods (Clark *et al.,* 2002; Brown *et al*., 2005), suggesting a fuel-limited system. Fire return intervals in these grasslands are ~160 years, but are not regularly spaced in time (Brown *et al*., 2005). Records of fire activity and vegetation type over the past 5,500 years from a permanent spring in central Nevada also indicate a generally fuel limited system: dry periods were characterized by a shift to salt desert scrub vegetation and low fire activity while wet intervals were characterized by vegetation shifts to Wyoming big sagebrush and increased fire activity (Mensing *et al*., 2006). Fire activity reached a peak of approximately one fire per century between 5,500 and 4,700 cal yr BP (Mensing *et al*., 2006).

Fire records reconstructed from alluvial fan sediments in ponderosa pine and Douglas fir forests in the South Fork Payette study area ~100 km to the northeast of the Wood Creek study area indicate climate-driven shifts between fuel-limited and moisture-limited fire regimes over millennial time periods (Meyer and Pierce, 2003; Pierce *et al*., 2004; Pierce and Meyer, 2008). Large fire-related sedimentation events and inferred severe fires were widespread throughout a range of ecosystems in the study area and occurred during intervals of major drought, including the Medieval Climatic Anomaly (MCA) ~1025 – 670 cal yr BP (Stine, 1994; Esper *et al*., 2002; Stine, 1998; Crowley, 2000; Bradley *et al*., 2003; Cook *et al*., 2004). In the western US, the MCA included severe and widespread multidecadal droughts (Stine, 1998; Woodhouse and Overpeck, 1998; Cook *et al*., 2004), with increased fire activity across diverse northwestern conifer forests (Meyer *et al*., 1995; Rollins *et al*., 2001). The MCA also included some unusually wet decades in the Western US (e.g. Adams, 2003), which could also increase fire activity by first increasing fuel loads during wet intervals, then drying fuels during droughts.

Frequent, small fire-related sedimentation events were recorded during wetter periods in the South Fork Payette area, including the Little Ice Age (LIA) ~600 – 100 cal yr BP. Cooler conditions during the LIA have been well documented in the western US (Carrara, 1989; Luckman, 2000) and throughout the northern hemisphere (Grove, 1988; Pollack *et al*., 1998; Esper *et al*., 2002).

Methods

We identified fire-related deposits, characterized stratigraphic characteristics and sampled charcoal macrofossils from alluvial fans and terraces. Accelerator mass spectrometry (AMS) ^{14}C dates from these charcoal samples provide a chronology of fires while types of deposits (e.g. debris flow, sheetfloods or flood) are used to infer the origin of the sedimentation event (e.g. alluvial fan or main channel flood), and the magnitude of the geomorphic response to fire (Table 1). Sand samples dated using Optically Stimulated Luminescence (OSL) techniques are used to establish the timing of recent incision on Wood Creek and confirm ages of charcoal correspond with ages of associated deposits. Radiocarbon ages were calibrated into conventional calendar years (cal yr BP) using the CALIB 5.0.1 program (Stuiver and Reimer, 1993) and the intcal04.14c calibration data set (Reimer *et al*., 2004). Throughout this paper, radiocarbon ages are given with standard one sigma age ranges from the calibrated age probability distribution. For OSL dating, sand samples were collected in metal tubes and dated using the OSL Single Aliquot Regenerative dose protocol (Murray and Wintle, 2000, 2003; Wintle and Murray, 2006).
We identified vegetation types by comparing charcoal macrofossils with modern examples and with photographs and anatomical descriptions (Table 2) from the Crow Canyon Archeological Center (Adams and Murray, 2004). Identification of charcoal macrofossils yields some information on what vegetation types were present at the time of the fire. While this is in no means a large enough sample to determine the composition of the vegetation communities present, it does indicate that some types were present. The lack of charcoal from a certain species does not preclude its presence; however, woody species that are more common on the landscape are also generally more likely to be represented in charcoal samples. Fine charcoal from burned non-woody species (e.g. grasses) are less likely to be preserved in the alluvial record, and small samples that are present are difficult to identify.

We compare our fire record to three independent reconstructions of climate. Cook *et al*., (2004) used tree ring records to reconstruct the Palmer Drought Severity Index (PDSI), a widely-used measure of moisture deficits over the past 2000 years. This reconstruction is available on a 2.5-degree gridpoint system throughout the United States and Canada. Because the Wood Creek study area is located near the center of four of these gridpoints, we created a composite using the inverse-distance weighted average of the four surrounding gridpoints (56, 57, 69, and 70). Two other reconstructions we used were drought area index (DAI, Cook *et al*., 1997, 1998, 2004), which measures the number of gridpoints that exceed a threshold level of drought from PDSI reconstructions, and July temperatures from tree ring records in the Salmon River region (Biondi *et al*., 1999, 2006).

To assess relationships between climate and fire, we calculated the mean and standard deviation of the PDSI reconstruction for each climate period, for each sample, and for the whole record (Table 1). Only samples that have their complete radiocarbon probability distribution within the period of the PDSI reconstruction were used. We used the probability distribution of the calibrated radiocarbon dates to create a weighted average using the following formula:

$$\sum_i^n pI \qquad (1)$$

where p is the annual probability taken from the calibrated radiocarbon age, I is the reconstructed PDSI value for the corresponding year, and i and n describe the range of years included in the calibrated radiocarbon age. This weighted average is then compared to the mean PDSI for the sample to determine if climate conditions at the time of the fire were likely wetter or drier than the mean (Table 1). Fuel-limited conditions are inferred when the time of the fire is wetter than the mean value; moisture-limited conditions are inferred the time of the fire is drier than the mean (see Nelson, 2009 for details on reconstructions).

Results

We dated 25 radiocarbon samples from eight locations (five terrace sites and three alluvial fans) within the Wood Creek study area (Figure 3). Nearly half of the samples came from debris flow deposits and nearly one-third came from slackwater or floodplain deposits. Dated samples cluster into three periods of increased fire-related activity (Figure 3). The earliest of these periods, between 4400 and 4000 cal yr BP, is recorded in flood deposits along Wood Creek. Charcoal macrofossils identified from this period include deciduous and coniferous species. The second period of activity, between 2000 and 1400 cal yr BP, is recorded by a series of debris flow and sheetflooding events in tributaries and along Blacks Creek. Charcoal recovered during this period is dominantly conifer. The most recent period of increased activity, from 650 – 300 cal yr BP, is recorded by debris flow activity in both tributaries and along the main channel followed by floodplain sedimentation. Charcoal macrofossils identified from this period include sagebrush, conifer, and deciduous species.

Records of fire in the Wood Creek drainage are compared with a drought reconstruction from tree-ring records (Cook *et al*., 2004; Figure 4). A 200-year moving average of the PDSI reconstruction for grid points adjacent to the study area (Cook *et al*., 2004) is used to delineate wet and dry climate intervals as compared to the mean PDSI for the entire ~2000 year drought reconstruction (mean PDSI of -0.24). PDSI values during the probability distribution for the calibrated radiocarbon samples are compared with the mean PDSI value for the period of record (last 2000 years). A comparison of the unweighted sample average PDSI with the mean PDSI indicates that more fires burned when climate was wetter (nine of 14 samples) than when climate was drier (four of 14 samples). One sample had an unweighted average that was equal to the reconstruction's mean. The comparison between weighted PDSI sample averages and unweighted sample averages shows similar results; eight of the 14 samples indicate conditions were likely wetter than average at the time of the fire and six samples indicate that conditions were likely drier.

In addition to the widely recognized Little Ice Age (LIA, 600 – 100 cal yr BP) and Medieval Climatic Anomaly (MCA, 1025 – 670 cal yr BP), this study also identifies the driest of the four periods in the PDSI reconstruction as the "Early Dry Period" (EDP, 1950 – 1700 cal yr BP; -0.87 mean PDSI) and the wettest of the four periods as the "Early Wet Period" (EWP, 1700 – 1100 cal yr BP; 0.06 mean PDSI; Figure 4). The EDP and the MCA (-0.67 mean PDSI) were the two periods that were drier than the reconstruction's mean and the EWP and the LIA (-0.17 mean PDSI) were both wetter than the reconstruction's mean (see Nelson, 2009 for additional details).

Charcoal Macrofossil Identification

Macrofossil identification yields a fairly even distribution between sagebrush (21%), deciduous species (21%, most likely willow or aspen), and conifer species (25%). One-third of the samples were not identifiable, most often because charcoal specimens were too small to preserve ring structures. Sagebrush and deciduous charcoal were most commonly associated with floodplain and debris flow deposits, while conifer samples came largely from debris flow and channel deposits. The earliest identifiable occurrence of sagebrush within the study area is at ~2234 cal yr BP. Sagebrush is rare until the MCA but is the most abundant charcoal type during the LIA. While the lack of sagebrush macrofossils prior to ~2234 cal yr BP and variations in abundance could certainly be due to a small sample size and/or lack of macrofossil preservation, sagebrush appears to have increased in abundance over the last 1400 years. Of note, a debris flow in the upper Blacks Creek basin (Figure 1) during the „Early Wet Period' burned ponderosa pine during a multi-decadal drought between 1,516 and 1,408 cal yr BP. Ponderosa pine is not found in the Blacks Creek drainage now, and ponderosa pine was not present in any older charcoal samples from Blacks Creek.

Recent fires and sedimentation events in Wood Creek

A small fire during July of 2007 burned north-facing slopes in the Wood Creek drainage from just above the Bender Creek Trailhead to the confluence with Bender Creek and areas to the south in the Bender Creek, Flat Creek, and Jack Creek drainages (Figure 1). While the winter following the fire was wetter than average, peak flows on the nearest gaged rivers to the study site indicate 2007-2008 was not an unusually wet year (United States Geological Survey, 2009). Peak flows on the Middle Fork Boise River and on the South Fork Boise River at Featherville had recurrence intervals of 5.4 and 2.4 years, respectively.

Within one year of the 2007 fire, numerous sheetflood deposits were noted at the mouths of burned sub-basins in the Bender Creek drainage, as well as flood deposits on the Bender Creek floodplain. Sheetflood deposits contain abundant, coarse charcoal (especially on upper surfaces of deposits), and were especially prominent in north-facing basins. Criteria for burn severity classification (Lewis *et al*., 2006; Robichaud *et al*., 2000) indicate south aspect slopes were burned at low severity. Burn severity on north aspect slopes ranged from low to high, with high burn severity areas concentrated in conifer stands. More severely burnt, steep hillslopes produced dry ravel immediately following the fire, and while observations indicate that severely burned basins generally produced greater incision, gully formation, and sheetflooding, most burned basins showed some geomorphic response. Most fan surfaces were only slightly incised (~5– 20 cm), and no incision was observed along the axial stream itself.

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OSL and Radiocarbon dating of recent incision on Wood Creek

OSL dating of sand samples in fire-related deposits or deposits stratigraphically above or below fire-related deposits 1) confirms the timing of sedimentation events corresponds with the timing of fires, 2) provides a cross-check on the accuracy of both dating methods, and 3) establishes the timing of recent stream incision within the Wood Creek watershed. OSL dating of fine sands in a floodplain deposit (Site ST4) produced an age of 2,090 ± 270 yr (sample USU-157; Table 1) which lies stratigraphically above a radiocarbon sample with an age of ~2,158 – 2,329 cal yr BP (sample ST4-5; Table 1). The ages of these two samples are within the range of sample error, although the slightly older age for the underlying radiocarbon-dated sample is also consistent with its lower stratigraphic position. Similarly, an OSL age of 6,100 ± 710 yr from sands from a floodplain unit (USU-160) is overlain by a 10 cm thick debris flow and then another floodplain deposit containing charcoal dated to ~ 6,500-6,630 cal yr BP (Sample ST8-4). These OSL and ^{14}C ages are within the range of error for the samples and indicate relatively rapid accumulation of sediment at this site.

Radiocarbon and OSL dating of main channel sediments over a ~3500 meter reach of Wood Creek shows between ~1-6 m of channel incision, with incision increasing downstream (Figure 5). Dates on charcoal within floodplain deposits and the overlying debris flow at sites ST2 and ST3 and an OSL age from the top of site ST2 provide maximum ages for this incision. Charcoal within the uppermost floodplain at ST3 dates to 525-498 cal yr BP, and the overlying and capping debris flow (site ST2), dates to either 308 – 282 cal yr BP or 169 – 153 cal yr BP, though most probably the former. The OSL age for a sandy deposit overlying the ~280-300 cal yr BP debris flow at the top of a 2.5 m terrace at ST2 is 90 ± 1480 years (USU-158) using a minimum age model and peak fitting. The wide error is the result of partial bleaching, which may indicate that these sands were deposited very rapidly. Since incision along Wood Creek must have occurred after deposition of these units (after ~100-200 years ago) this indicates episodic incision rates as high as ~6 m/100 yr in the lower section of this reach (Figure 5).

Discussion

Records of fire-related sedimentation events from the Wood Creek study area suggest fire in this rangeland ecosystem has been limited by both fuel continuity and high moisture at different times over the last several thousand years. In general, during multi-decadal to centennial-scale intervals of drought (e.g. the MCA and the EDP), grass and forb density likely decreased and the lower treeline elevation likely increased, resulting in a fuel-limited system (Figure 4). During these intervals of overall drought, peaks in fire activity in this rangeland ecosystem correspond with wetter intervals (e.g. ~850 and ~1900 cal yr BP; Figure 4). Conversely, during wetter intervals (e.g. the LIA and the EWP), grass, forb and sagebrush growth was likely enhanced, treeline probably moved down in elevation, and fires burned during episodes of drought (e.g. ~500 cal yr BP; Figure 4).

Fire Records and Regional Climate Reconstructions

A comparison between regional Holocene climate reconstructions and records of fire-related sedimentation in Wood Creek allows a more detailed examination of the role of climate in rangeland fire activity (Figure 4). The reconstructions used in this study include Palmer Drought Severity Index (Cook *et al*., 2004), Drought Area Index (Cook *et al*., 1998), and July temperature (Biondi *et al*., 2006). We also compared our record of fire-related activity in Wood Creek with regional records of fire and geomorphic response reconstructed from alluvial deposits from the South Fork Payette River, Idaho, (Pierce *et al.,* 2004) and from Yellowstone National Park (Meyer *et al.,* 1995; Figure 3). We selected these sites for comparison because 1) all three studies use very similar methods to reconstruct fire records and 2) all records are from the intermountain Pacific-northwest, so climate forcing mechanisms should be comparable. Records from the moister, higher elevation (~2500 m), predominantly lodgepole pine (*Pinus contorta*) forests of Yellowstone National Park, ~ 450 km to the northeast of the Wood Creek study area, provides a regional example of a „moisture-limited' system. The Yellowstone study indicates that severe, stand-replacing fires occur during periods of intense drought such as during the MCA and the late 1980's (Meyer *et al*., 1995). Fire records from ponderosa pine and Douglas fir forests in the South Fork Payette study area ~100 km to the northeast demonstrate both frequent sheetflood deposits and thin debris flows and inferred lower-severity surface fires during the overall moister conditions of the LIA („fuel limited'), and widespread severe fires during times of prolonged drought such as the MCA reflecting „moisture limited' conditions (Pierce *et al.,* 2004). The Payette study demonstrates that while frequent low intensity fires are the dominant fire regime in this ponderosa pine-dominated ecosystem, large stand-replacing fires also occur during intervals of prolonged drought.

Fire and climate: ~4500-1400 cal yr BP

The peak in fire activity in Wood Creek ~4400-4000 cal yr BP is curious when placed within the broader context of fire and climate in the western U.S. In both the Payette and Yellowstone systems, ~4400-4000 cal yr BP represents a minima in fire activity; this is also is a minima in fire-related sedimentation in the Sacramento Mountains of New Mexico (Frechette and Meyer, 2009) and southwestern Colorado (Toney and Anderson, 2006). Records from New Mexico (Buck and Monger, 1999), Colorado (Toney and Anderson, 2006), and northern Wyoming (Lyford *et al*., 2003) indicate generally wet conditions; if moister climates during this time were regional, increased fire activity in Wood Creek suggests a fuel limited system during this time. Geomorphic response to fire in the Wood Creek appears limited to main channel flooding events that resulted in floodplain aggradation, and identified charcoal macrofossils represented primarily deciduous species.

Generally, fires during the second period of increased fire-related activity in Wood Creek (2000 – 1400 cal yr BP) correlate with the record of large events in the Payette and fires in Yellowstone. Events occurring at ~1460 cal yr BP, ~1640 cal yr BP, and ~1880 cal yr BP are synchronous with large fire events in the Payette ponderosa forests to the north. The peak in fire activity during the EDP (~1800-1900 cal yr BP) occurred during a time that, while still drier than average, was wetter than the overall period. Macrofossils indicate all three of these events burned conifers within the Wood Creek study area; the fire ~1461 cal yr BP burned ponderosa pine in the upper Blacks Creek watershed, a basin that does not currently have any conifers. In eastern Oregon, pollen and packrat midden records from juniper woodlands record an upward shift in the lower treeline sometime between 1900 and 1000 cal yr BP and inferred drier conditions (Miller and Wigand 1994). Pollen records from Mission Cross Bog in northern Nevada record several centennial-scale droughts during this period, and an upward shift in the lower treeline (Mensing *et al*., 2008).

Fire and climate: Medieval Climatic Anomaly and the Little Ice Age

Unlike the Payette and the Yellowstone record, the Wood Creek study area does not show a major peak in fire activity during the MCA. The overall climate in the Western US during this time was characterized by both multidecadal drought and by wet intervals (e.g. Adams, 2003; Stine, 1998; Pierce and Meyer, 2008), and the one fire that did burn during the MCA (~1025 – 670 cal yr BP) in Wood Creek is centered on a wet interval between two major multi-decadal droughts, suggesting a fuel-limited system (Figure 4).

On the other hand, the peak in fire activity during the LIA ~550-300 cal yr BP occurred during an interval of relative drought during an otherwise wet interval (Figure 4). This peak also corresponds well with the peak in „small events' in the South Fork Payette River area and with a minimum in fire activity in Yellowstone. This suggests a moisture-limited fire regime for both the Payette ponderosa and the Wood Creek rangeland systems, when fires burned during relatively dry periods during an otherwise wetter time. In the cooler and wetter lodgepole pine-dominated forests of Yellowstone, generally wetter conditions during the LIA limited fires altogether. Other studies indicate frequent surface fires were typical of the forest – prairie ecotone (Brown and Sieg, 1999) and the forest – sagebrush ecotone (Miller and Tausch, 2001) during the Little Ice Age.

The record of July temperature from east-central Idaho (Biondi et al., 2006; Figure 4) and the record of drought from gridpoints adjacent to the study area (Cook et al., 2004) does not show a clear relationship between drought and high July temperatures over the last ~800 years. While ~700-600 cal yr BP is both cool (Biondi et al., 2006) and relatively moist (Cook et al., 2004), low(high) temperatures and wet(dry) conditions do not correspond at other times in the LIA (600-300 cal yr BP). Likewise, while fire activity is low ~700-600 cal yr BP in Yellowstone and the Payette, and is relatively low in Wood Creek, the Wood Creek fire record does not show a clear connection with temperature during the LIA. This could reflect a lack of causal relationship between July temperature and drought, regional climate differences between east-central Idaho and southwestern Idaho, or difficulties in comparing records of different lengths and resolutions.

Recent fires and geomorphic response

Sediment erosion and deposition following a fire in the summer of 2007 provides a modern analog for past events, and indicates geomorphic response to fire is likely not limited by sediment supply or the frequency or magnitude of precipitation events in this area. Peak flows on the nearest gaged rivers to the study site indicate 2007-2008 was not an unusually wet year, with recurrence intervals of 5.4 and 2.4 years (United States Geological Survey, 2009). Other studies also show that in recently burned areas, large debris flows and sediment-laden floods can be generated by precipitation events with return frequencies of 1 or 2 years (Cannon *et al*., 2001), either in the form of brief, high-intensity convective storms or lower-intensity frontal storms (Cannon, 2001). Several factors may act to increase the effectiveness of such storms, including soil-water repellency (Pierson *et al*., 2001), clogging of soil surfaces with ash, and reductions in surface roughness (Lavee, *et al*., 1995; Pierson *et al*., 2001; Pierson *et al*., 2002). Since abundant sediment is available for transport within the study area, and since storms capable generating geomorphic responses to fire are more common than fires, fires (not storms) are likely the limiting factor in the generation of fire-related sedimentation events. Debris flow and sheetflood deposits which lack in charcoal are not related to fire are found in stratigraphic sequences in the study area; this also suggests storm events are not limiting the depositional record within this area.

Summary and Conclusions

The Wood Creek study area provides a record of fires and geomorphic response that can be used to better understand late Holocene relationships among fire, climate and vegetation change in rangeland ecosystems. Close correspondence between OSL ages of deposits and ^{14}C ages of charcoal indicate that ages of fire-related deposits agrees with ages of fires reconstructed from charcoal fragments. This supports modern observations that indicate storms of sufficient magnitude to produce fire-related sedimentation occur soon after fires, and that charcoal preserved in alluvial records is of similar age to the containing deposits. Fire records, combined with charcoal macrofossil identification and independent reconstructions of drought in the Wood Creek study area, indicate the forest-rangeland ecotone boundary has likely changed with changes in Holocene climate. During moister times where lower treeline elevation moved down and vegetation density increased, fires likely occurred during times of drought (moisture limited). During drier times when treeline moved up in elevation and vegetation density decreased, fires likely burned during wetter intervals (fuel limited). This study shows evidence of both fuel limited and moisture limited fire regimes, although fuel-limited conditions appear to have been more common during the last 2,000 years. Perhaps this forest – rangeland ecotone is best described as “fire-prone” though with a slight tendency toward fuel-limited behavior. While identification of charcoal macrofossils in this study provides a snapshot of the presence (although not absence) of vegetation over the late Holocene, further study is needed to establish relationships among climate change, vegetation, and fire response.

The results of this study have important implications for fire regimes within the context of future climate change. Climate-driven shifts in both fire regimes and lower-elevation treeline are evident in this study area over the past several thousand years. Generally cooler temperatures during the LIA contrast with instrumental records showing temperature increases between ~0.5-1.0 °C since the late 1800’s (Jones *et al*., 1999; Jones and Lister, 2002; Briffa and Osborn, 2002), and summer temperatures in the western U.S. are projected to increase with anthropogenically-induced future climate change (IPCC, 2007). Preliminary data indicates very little overlap between modern temperature and precipitation distributions in the Wood Creek area and the temperature and precipitation requirements for ponderosa pine and Douglas fir (Thompson et al., 1999). In other words, the conifers that germinated during the Little Ice Age at lower elevations in southwestern Idaho may not grow back following disturbance. In low elevation forests that have burned in the last several decades in the region, observed seedling recruitment is negligible. In a warmer and drier future, low elevation forests and rangelands will likely respond non-linearly to fire, resulting in both abrupt changes in ecosystem boundaries, and shifts between fuel-limited and moisture-limited fire regimes. Further study of past records of fire and vegetation change is needed to establish relationships among vegetation, fire and climate in this dynamic setting, and to place future change within a longer-term context.

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