Long-Term Fire History from Alluvial Fan Sediments: The Role of Drought and Climate Variability, and Implications for Management of Rocky Mountain Forests

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Brief summary: Alluvial fan deposits preserve millennial-length records of fire. We used these records to examine changes in fire over the last 2,000 years in Yellowstone National Park mixed-conifer forests and drier central Idaho ponderosa pine forests. Severe fires occur in both areas during past intervals of drought and increased climate variability.
Abstract. Alluvial fan deposits are widespread and preserve millennial-length records of fire. We used these records to examine changes in fire regimes over the last 2,000 years in Yellowstone National Park mixed-conifer forests and drier central Idaho ponderosa pine forests. In Idaho, frequent small fire-related erosional events occurred within the Little Ice Age ~1450-1800 AD, when greater effective moisture likely promoted grass growth and low-severity fires. This regime is consistent with tree-ring records showing generally wetter conditions and frequent fires before European settlement. At higher elevations in Yellowstone, cool conditions limited overall fire activity. Conversely, both Idaho and Yellowstone experienced a peak in fire-related debris flows ~950-1150 AD. During this generally warmer time, severe multidecadal droughts were interspersed with unusually wet intervals that likely increased forest densities, producing stand-replacing fires. Thus, severe fires are clearly within the natural range of variability in Idaho ponderosa pine forests over longer timescales. Historical records indicate that large burn areas in Idaho correspond with drought intervals within the past 100 yr, and that burn area has increased markedly since ~1985. Recent stand-replacing fires in ponderosa pine forests are likely related to both changes in management and increasing temperatures and drought severity during the 20th century.

Additional keywords: Ponderosa pine, Yellowstone, Idaho, debris flows

Introduction

The 20th century increase in global temperature (e.g. Jones and Moberg, 2003; Brohan, et al., 2006) has been accompanied by a decrease in precipitation over the western United States (Karl and Knight, 1998) and recent (~1999-2005) severe drought (Cook et al., 2006; www.drought.unl.edu). Drought conditions correspond with an increase in the size and severity of large fires, and studies demonstrate that 20th century fire occurrence in the in the western U.S. is strongly linked to changes in climate (Westerling et al., 2006). For example, in 2002 record precipitation deficits in the western U.S.
led to fires that burned over 2.8 million hectares, including the largest fires of the past century in Colorado, Oregon and Arizona (www.nifc.gov, NASA, 2004). In 2006, wildland fires in the western states of Washington, Idaho, Montana, Alaska and Utah burned over 1 million hectares, or 30% of the total wildland fire acres burned across the entire U.S (www.nifc.gov). The economic costs associated with droughts and fires are significant: droughts are the most costly natural disasters in the U.S. (Cook et al., 2006), and fire-fighting expenditures by federal land-management agencies now regularly exceed $1 billion dollars per year (Whitlock, 2004).

In order to understand how forests may respond to fire in a potentially warmer and drier future, it becomes increasingly important to examine longer records of fire and the relationships between fire and drought on different timescales. Analysis of trends in the regional Palmer Drought Severity Index (PDSI) and percent land area in the western U.S.A. experiencing drought indicate that the duration of the current drought is unusual when compared with conditions over the past century (Cook et al., 2004). When compared with drought reconstructions between ~900-1250 AD, however, 20th century droughts are not extreme (Cook et al., 2004). This indicates that over centuries to millennia, the western U.S.A. experiences more severe droughts—and likely more severe fires—than have been typical over the instrumental period of record. Proxy records used in fire reconstructions include charcoal records from lake sediments, fire-scar records from trees, stand-age reconstructions, and alluvial fan records of fire-related sedimentation. These records indicate fires correspond with drought conditions over decadal (e.g. Swetnam and Betancourt, 1990; Kipfmueller and Swetnam, 2000), centennial (e.g. Meyer et al., 1995; Pierce et al., 2004), and millennial time-scales (e.g. Thompson et al., 1993; Whitlock et al., 2003).

To assess the effects of climate change on fire regimes in northern ponderosa pine and mixed conifer forests, we have described and interpreted fire-induced deposits preserved in alluvial fans in the South Fork Payette River area of central Idaho and Yellowstone National Park over the last 2000 years, and compared these records with regional drought reconstructions (Cook et al., 2004). This study provides 1) a summary of historic (last ~100 yr) fires and drought in the Boise National Forest of central Idaho, 2) an examination of alluvial fan records of fire over the last 2000 years in central Idaho and
Yellowstone National Park within the context of millennial-scale reconstructions of drought, and 3) a comparison between records of fire recorded in alluvial fan sediments and other proxy records of fire.

**Study area**

The South Fork Payette study area is located in the mountainous terrain north of the Snake River Plain in south-central Idaho (Fig. 1). Annual precipitation, which falls mostly as snow derived from Pacific moisture, varies from about 1000 mm at high elevation sites to about 600 mm in the lowest valleys. Variations in climate and vegetation within the Idaho study area are determined largely by elevation and aspect. On south-facing slopes in the lower basin (below ~900 m), shrubs, grasses, forbs, and sparse ponderosa pines characterize hillslope vegetation. At elevations between 900-1400 m, open ponderosa pine forests cover south-facing slopes and mixed pine and Douglas-fir (*Pseudotsuga menziesii*) forests are found on north-facing and more mesic sites. Higher elevations above about 2200 m are typified by ponderosa pine and Douglas-fir forests on south-facing slopes, and spruce (*Picea engelmannii*), Douglas-fir and pine forests on north-facing slopes.

Northeastern Yellowstone National Park is located ~400 km to the east of the Idaho study area on the borders between Idaho, Montana and Wyoming (Fig. 1). The northern Yellowstone National Park study area lies at a higher elevation (>2000 m) and is covered by dense mesic conifer forests dominated by lodgepole pine (*Pinus contorta*). Douglas-fir and Engelmann spruce (*Picea engelmannii*) are also common, with a transition to subalpine fir (*Abies lasiocarpa*) and whitebark pine (*Pinus albicaulis*) at higher elevations (ca. 2750-3050 m). Within the focus of this study in northeastern Yellowstone, annual precipitation varies from 360 mm at lower elevations (2000 m; Lamar Ranger Station) to as much as 1300 mm at 3050 m along the eastern park boundary (Dirks and Martner, 1982). While Yellowstone also receives most precipitation as winter snow, summer convective storms provide a source of intense, but localized, moisture.

**Background**
Tree-ring records of fire in ponderosa pine forests, climate change, and management

Since ~1900, documented increases in tree density and changes in forest structure in some western USA ponderosa forests (Cooper, 1960; Covington and Moore, 1994; Arno et al., 1995; Swetnam and Baisan, 1996; Fule et al., 1997) have been accompanied by a shift from frequent surface fires during the pre-settlement era to large stand-replacing fires during recent decades (e.g. Westerling et al., 2006). This shift has often been attributed to 20th century fire suppression, grazing, and other land uses that limit surface fires and promote increased stand densities and ladder fuels (Steele et al., 1986; Baisan and Swetnam, 1990; Covington and Moore, 1994; Brown and Sieg 1996; Fulé et al. 1997; Covington, 2000). Management in ponderosa forests has sought to re-establish or mimic the high-frequency, low-severity fire regime and low tree densities that are believed to be characteristic of the pre-settlement era (White House, 2002; U.S. Department of Agriculture, 2002). The pre-settlement ‘reference period’ for fire regimes in ponderosa pine forests, however, is mostly from tree-ring records developed during the last 500 years, a time characterized by cooler climates than today. Cooler conditions during the “Little Ice Age” (LIA) ~1400-1900 AD 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). Generally cooler temperatures during the pre-European settlement era 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; Jones and Moberg, 2003; Brohan et al., 2006).

Most of the studies that demonstrate a pattern of frequent non-lethal fires in ponderosa forests during the pre-settlement era are from the American Southwest. Fire-scar studies from ponderosa-dominated forests in other regions often do not support this model of frequent, low-severity fires, even during the relatively cooler and wetter conditions of the Little Ice Age (see review in Baker et al., 2006). For example, fire-scar records demonstrate a history of mixed-severity fires in pure ponderosa pine and mixed ponderosa-Douglas fir forests in the Rocky Mountains of Colorado (Brown et al., 1999; Huckaby et al., 2001; Ehle and Baker, 2003; Romme et al., 2003). Similarly, tree-ring data from ponderosa pine-Douglas-fir forests in Montana (Barrett, 1988; Arno et al., 1995) and ponderosa forests of the Black Hills
of South Dakota (Shinneman and Baker, 1997) indicate pre-settlement fire regimes characterized by a mix of frequent low-severity and infrequent high-severity fires.

*Tree-ring records of fire in Idaho and Yellowstone*

With the exception of Steele et al. (1986), few detailed fire history studies exist for mid-elevation ponderosa pine-Douglas fir forests of central Idaho. Existing fire-scar reconstructions of fire history in ponderosa pine-Douglas-fir forests in Boise National Forest indicate that between 1700-1895 AD, mean fire return intervals ranged from 10 years at drier sites to 22 years at moister sites (Steele et al., 1986). In the 1900’s, fire return intervals lengthened considerably; 3 of 7 sites do not show any record of fire between 1900-1983, while the other 4 sites only record 1 or 2 fires during this interval (Steele et al., 1986). Fires were severe during the 1900’s, however, with extensive (>160 km² and 90 km²) burns in the Boise National Forest during the 1931 drought.

The Selway-Bitterroot Wilderness Area, ~300 km to the northeast of the South Fork Payette study area, includes a range of forest types from low-elevation ponderosa pine forests to high-elevation mixed conifer forests. Fire-scar records extending back to 1709 AD from the Selway-Bitterroot (Kipfmueller and Swetnam, 2000) were compared with fire years from historical fire atlas data and tree-ring reconstructions of PDSI (Cook et al., 1999). Results of superposed epoch analysis (used to establish associations between surface fire and antecedent climate conditions) show that drier than average conditions during the summer of the fire were significantly (p < 0.001) related to the largest fire years (Kipfmueller and Swetnam, 2000). A significant (p < 0.05) relationship was also found between wet conditions four years prior to the year of a fire event in the Selway-Bitterroot forests (Kipfmueller and Swetnam, 2000), and likely reflects the influence of antecedent moisture on the growth of young trees and other fine fuels.

In Yellowstone National Park, dense, high-elevation lodgepole pine-dominated forests burn primarily in large, severe fires with recurrence intervals of ~200 to >350 years (Meyer et al., 1992; Barrett, 1994; Meyer et al., 1995), and 150-350 year-old even-aged forest stands are common in high-
elevation forests (Romme, 1982; Romme and Despain, 1989). Fire-scar records and stand ages from Yellowstone mixed conifer forests show large burn areas in the early to mid-1700’s and mid-1800’s (Romme and Despain, 1989; Barrett, 1994).

Records of fire preserved in alluvial fans compared with tree-ring and lake charcoal records of fire

Alluvial-fan records add to data from other charcoal-based proxy records of fire that provide evidence of relationships between fire, vegetation, and climate over centennial to millennial timescales (Fig. 2). Alluvial fan records provide a longer fire record than tree-rings, are more ubiquitous in mountain environments than lakes, and record stand-replacing fires. The typical time-scale of alluvial fan records is intermediate between lake records and tree-ring records, thereby allowing documentation of fire response to multi-decadal to millennial-scale climate change.

Pollen and charcoal records from lake sediments can be used to reconstruct relationships among fire, climate, vegetation and geomorphic response on millennial to multi-millennial timescales. On multi-millennial timescales, fire frequency inferred from lake charcoal records in the northwestern US increased during warmer, drier intervals coincident with the mid-Holocene solar insolation maximum ~10-6 ka (Long et al., 1998; Millspaugh et al., 2000; Long and Whitlock, 2002; Brunelle and Whitlock, 2003; Whitlock, 2003). Increased fire frequency is inferred to be associated with decreased fire severity, based on contemporary associations that show an inverse relationship between fire severity and fire frequency in forested ecosystems (McKenzie et al., 2000; McKenzie et al., 2004).

Fire-scar proxy records preserved in tree-rings provide annual to seasonal resolution of fires, and can be used in conjunction with records of climate preserved in tree-rings to resolve relationships between fire, temperature, and precipitation over annual to centennial timescales. These records can also be used to reconstruct fire return intervals, burn areas, and fire seasonality, which provides valuable information to managers and scientists who seek to understand fire regimes and how fire regimes change among different regions and forest types. Fire scars do not, however, record stand-replacing fire. Stand-age reconstructions can be used in conjunction with fire-scar records or can be used independently to establish
the time of the last stand-replacing disturbance (including fire) within a forest. These records, however, are limited by the ages of stands or fire-scarred trees, which is typically <500 years in ponderosa pine forests.

Alluvial fan records of fire do record stand-replacing fires (indeed, severe widespread fires are a major cause of datable sedimentation events), and alluvial fan records of fire extend back >10,000 years. Although alluvial-fan deposition is discontinuous in both space and time, the episodic nature of deposition on alluvial fans can be offset by compiling the records from individual stratigraphic sections, yielding a detailed history for the region (e.g. Meyer et al., 1995; Pierce et al., 2004). The method of reconstructing an area-wide composite chronology using partial records from many different alluvial fans is analogous to fire history reconstructions that use area-wide composites of fire-scar records from tree rings (e.g., Swetnam and Betancourt, 1990; Brown et al., 1999). Alluvial fan stratigraphy is complex and variable, and analysis of fire related deposits requires intensive field study and interpretation of stratigraphic relationships.

**Historic records of drought and fire in central Idaho**

Across the west, the mid-1980’s are marked by a distinct increase in large (>400 ha) wildfires corresponding with higher summer temperatures and inferred earlier snowmelt (Westerling et al., 2006). Historic (1908-2006) records of fires in the ponderosa pine and Douglas-fir-dominated Boise National Forest mirror regional trends (Fig. 3). Annual area burned (km²) in historic fires in the Boise National Forest was calculated from spatial coverages of burn areas (spatial data courtesy of the Boise National Forest). Burn area data were compared with monthly PDSI values and with mean summer (June, July, August) temperature for Idaho Climate Division Four (http://lwf.ncdc.noaa.gov). Between 1908 and 2006, historic burn area data from the Boise National Forest show that fires burned at least 4097 km², although the total burn area is likely higher since small fires in remote areas were less likely to be recorded during the early part of the 20th century. Palmer Drought Severity Index (PDSI) values for central Idaho show that drought severity has significantly (p < 0.01) increased over the period of
instrumental record (1895-2006). Mean summer temperature (June-August) has also increased by ~0.3 °C. In Yellowstone, PDSI values show a very significant (p < 0.001) increase in drought conditions since instrumental records began in 1895, accompanied by an increase in summer (June-August) temperatures of over 2°C (p < 0.01) between 1985 and 2002.

The majority of the fires in the Boise National Forest burned during two intervals of severe drought: 1015 km² (25% of the total burned area) between 1926-1935, and 2363 km² (58% of the total burned area) from 1985 to 2006, including a few severe fires totaling >800 km² in 1994. Interestingly, the large fire year of 1926 does not correspond with anomalously low regional PDSI values. This discrepancy could be due to a number of factors, including a difference between regional PDSI and local soil moisture values, antecedent moisture, fuel conditions, or high winds that could have contributed to large burn areas during this year.

The earlier part of the ~1936-1984 interval of limited fire activity corresponds with moister conditions (~1940-1965) and a decrease in summer temperatures (~1942-1958). The dramatic decrease in burn area ~1950-1985, however, likely reflects at least in part the influence of fire suppression. Only 228 km² burned between 1950-1984 (6% of the total burned area; 35% of the total time interval). These decades are marked by increased effectiveness in fire suppression due to increases in road access in forested areas, the use of aircraft and motorized equipment in fire-fighting efforts, and increased monetary support for fire-fighting efforts.

**Records of fire preserved in alluvial fan sediments**

To investigate changes in fire activity over millennial-timescales, we identified individual fire-related sedimentation events in alluvial fans in central Idaho (Pierce et al., 2004) and Yellowstone (Meyer et al., 1995), described deposit characteristics in the field, and radiocarbon dated charcoal fragments to create composite chronologies for the two study areas. In central Idaho, we radiocarbon-dated 91 charcoal samples from 35 alluvial fan sections associated with 34 different tributary basins ranging in size
from 0.01-6 km². In northern Yellowstone National Park, 50 charcoal samples from 34 fan sections were dated (Meyer et al., 1995).

Fires dramatically increase rates of erosion on recently burned slopes. Evidence of fires and fire-related erosion and deposition is recorded in alluvial fans as fire-related deposits and buried burned soil surfaces (‘burn surfaces’). The thickness and character of fire-related deposits provide information about the severity of the associated burn. Deposit characteristics (sedimentary structures, sorting, clast size and content, proportions of sand, silt, and clay in the fine [< 2 mm] fraction of the deposit, and color) were described in the field and used to characterize deposits within a fan section. Boundaries between deposits were determined by the presence of burn surfaces, erosional surfaces, and variations in deposit characteristics (Fig. 2).

Abundant angular charcoal fragments and (or) dark mottles of charcoal or charred material in deposits are characteristic of fire-related deposits. Burn surfaces within fan sediments are also indicative of past fire activity, and are characterized by discrete, laterally extensive layers of charred organic material of the litter layer (e.g., conifer needles, twigs, and grasses) approximately 0.5->2 cm thick (Fig. 2). In severe burns, the litter layer is almost completely ashed. Since these severely burned ashy surfaces are not usually preserved, presence of an underlying burn surface is not required for recognition of fire-related units. In many cases, burn surfaces are directly overlain by a fire-related deposit. An undisturbed and continuous surface implies rapid burial by postfire sediments prior to bioturbation and (or) erosion. If the overlying deposit contains coarse, abundant charcoal fragments, this further indicates that the depositional event is likely a response to the fire represented by the underlying burned surface.

**Dating methods**

Individual charcoal fragments were ¹⁴C-dated by accelerator mass spectrometry (AMS) at the NSF Arizona AMS Facility. To avoid dating samples of inner heartwood and bark from older trees that have ‘inbuilt’ ages significantly older than the fires that burned them (Gavin, 2001), small twigs, cone fragments, needles, and seeds were selected for dating where available. These materials are also less
likely to survive multiple cycles of erosion and deposition. Individual charcoal fragments were selected for dating to avoid mixing of charcoal ages. Rootlets were removed manually, and acid and base washes were used to remove soluble carbonate and organic contaminants. Identification of charcoal macrofossils helped determine the type of vegetation burned. Macrofossil identification is especially important because it helps establish whether major vegetation changes (and associated changes in fire regimes) have occurred over the dated interval. ‘Inverted’ dates (those with dates significantly older than underlying dates in a sequence) can be caused by bioturbation, deep burning of roots, reworking of older charcoal from existing soils or deposits, or large inbuilt ages. Analysis of radiocarbon dates within their stratigraphic context and careful selection of samples limits error from these sources. For multiple ages obtained within the same deposit, the youngest age was assumed to have the least inbuilt age and to be the most accurate. After removal of inverted and multiple ages (Pierce et al., 2004), probability distributions for 97 radiocarbon ages (\(^{14}\text{C yr BP}\)) were calculated using their associated one sigma analytical uncertainty and calibrated to calendar years before present using the program CALIB 4.3 (Stuiver and Reimer, 1993). Individual probability distributions from the calibrated ages of radiocarbon samples were summed to produce an overall probability spectrum for fire-related sedimentation events over the Holocene for the Idaho study area. Materials in deposits known to be less than \(~200\) yr BP were not collected for dating in order to avoid the large analytical error, thus ambiguous age, associated with these samples.

Classification of large and small fire-related events

In central Idaho, large fire-related events were differentiated from small events based on stratigraphic characteristics (Pierce et al., 2004). Burn severity is reflected in the volume and to some extent the transport processes of postfire alluvial-fan deposits. Severely burned basins tend to produce thick debris-flow and sheetflood deposits (Cannon et al., 2003; Meyer et al., 2001; Meyer and Pierce, 2003) that can be preserved in alluvial fans. We define ‘large fire-related events’ as events represented by debris-flow units with abundant coarse angular charcoal that are generally coarser grained than other units.
in a stratigraphic section and comprise at least 20% of the thickness of the section (Pierce et al., 2004). These deposits are often underlain by burn surfaces and most likely represent high-severity burns. Divergence and thinning of debris flows tend to occur down the length of alluvial fans, and distal fan units are usually thinner than proximal ones (Blair and McPherson 1994; Meyer and Wells, 1997; Meyer, 1993). Because even large debris flows often produce thin deposits locally, the relative thickness of deposits at any fan position provides a usable measure of relative event size. We therefore define ‘large events’ as having a large thickness relative to the rest of the stratigraphic section. Deposits that are clearly fire-related (contain abundant coarse charcoal), but that do not fit the criteria stated above are classified as small fire-related events. In the Idaho study area, these are commonly pebble and finer sheetflood deposits of cm-scale thickness that likely issued from low- to moderate-severity burns. Most alluvial fan sites at middle to low elevations in the study area are characterized by a mix of large and small event deposits.

**Records of drought and fire in central Idaho and Yellowstone over the last 2000 years**

In Yellowstone National Park mixed-conifer forests and in central Idaho ponderosa pine forests, charcoal fragments and fire-related deposits in alluvial fan sediments record changes in fire regimes and geomorphic response over the last 8,000 years (Meyer et al., 1995; Pierce et al., 2004). In order to compare our results with other regional studies of drought (Cook et al., 2004), and because the majority of our dates (54 of 97) fall within the last few millennia, this paper focuses on fire-related sedimentation over the last ~2000 years.

In Idaho, the highest frequency of fire-related erosional events occurred as small events during cool episodes such as the Little Ice Age (~1400-1900 AD), when greater effective moisture likely promoted grass growth and low-severity fires (Fig. 4a). The peak in frequent, low-severity fires in Idaho ~1400-1700 AD corresponds with tree-ring records of frequent fires in ponderosa forests during the pre-European settlement era in central Idaho (Steele et al., 1986) and in ponderosa forests throughout the western US. At the same time, fire-related sedimentation was minimal in the high-elevation mixed
conifer sites of Yellowstone – evidence that a cooler, effectively wetter climate prevented most fires from spreading in this moister environment. A similar lull in fire-related sedimentation is centered ca. 400-600 AD.

The Little Ice Age interval characterized by frequent fires in Idaho and limited fire activity in Yellowstone corresponds with records of wetter-than-normal conditions throughout much of the western U.S. (Cook et al., 2004). Between ~1500-1850 AD, tree-ring reconstructions indicate the percent drought area in the west dropped below the long-term (~1200 yr) average, and regional Drought Area Index (DAI) for the western USA is lower during this interval (Cook et al., 2004). Local PDSI reconstructions from tree-ring records for central Idaho and northern Yellowstone (http://www.ncdc.noaa.gov; reconstructions centered on 115.0°W 45.0°N and 110.0°W 45.0°N, respectively) show a lower range of variability in drought conditions ~1400-1900 than the prior interval ~200-1300 AD, and records from both regions exhibit a series of 8-10 decadal to multi-decadal wet episodes (PDSI > 0; Fig. 4a) during the Little Ice Age.

Conversely, both Idaho and Yellowstone fan records show a peak in fire-related debris flows between ~950-1150 AD corresponding with “Medieval Climatic Anomaly” (MCA) drought conditions ~900-1300 AD. Drought indices for the western US indicate that 1140-1175 AD is the most extreme period of multidecadal drought in the last 1200 years (Fig. 5; Cook et al., 2004). In Idaho, despite the fact that large fire-induced debris flows account for only a small proportion of the total number of fire-related events, 24-27% of the total dated fan thickness was emplaced by only 9 major debris flows between ~950-1150 AD. During this time, apparently stand-replacing fires occurred throughout the study area, including low-elevation rangeland sites, mid-elevation ponderosa pine-dominated sites, and high elevation mixed conifer forests (Pierce et al., 2004). Evidence of large debris flows ~950-1150 AD corresponds with recent fire-related debris flows in Idaho study area that have produced significant (~43,000 Mg/km²) amounts of sediment (Meyer et al., 2001).

Prior to the onset of regional drought conditions during medieval times, PDSI reconstructions indicate several dry intervals between ~600-750 AD. PDSI records from the Yellowstone show four
decadal to multi-decadal intervals of drought between ~600-750 AD; drought reconstructions from central Idaho show intervals of drought ~600-630, and two drought intervals between ~700-750 AD (Fig. 4b). These intervals of drought correspond with peaks in large fire-related debris flows in Yellowstone and Idaho ~650-775 AD (Fig. 4b). While sample depth during this interval is low and regional DAI has not been extended back prior to 824 AD, regional PDSI reconstructions indicate drier than average conditions for Wyoming, Colorado, and the American Southwest during the interval between 600-750 AD (Fig. 5).

Multidecadal climate variability and fire

The peak in fire-related sedimentation in Idaho and Yellowstone ~900-1250 AD corresponds with PDSI reconstructions of multidecadal drought conditions in central Idaho and northern Yellowstone 900-950 AD, 1000-1020 AD, 1120-1170 AD, and 1220-1270 AD (Fig. 4b). Interestingly, this interval also contains prolonged wet episodes ~1080-1120 AD and ~1175-1220 AD. Vegetation growth during these wet intervals likely provided fuel for large fires during the subsequent drought (1230-1280 AD). The pronounced alternations between wet and dry intervals during the MCA highlight the fact that climate during this interval may have been quite variable (Fig. 5). Lake-level reconstructions from the Great Basin (Adams, 2003), western regional tree-ring records of drought area (Cook et al., 2004), records of drought in now-submerged tree stumps in the Sierra Nevada (Stine, 1994), lake salinity changes in South Dakota (Laird et al., 1998), and intervals of dune stability and soil formation vs. dune mobility in Wyoming (Mayer and Mahan, 2003) all indicate that the Medieval Climatic Anomaly was characterized by both droughts and wet intervals of multidecadal length. Prior to the MCA, relatively wetter conditions in the northern Rocky Mountain region ~540-560 AD may have enhanced fire activity during subsequent dry intervals ~600-675 AD (Fig. 5). Both during the MCA and ~540-675 AD, prolonged wet intervals could enhance tree germination and understory growth of young trees, brush, and grasses at moisture-limited sites, creating denser stands and abundant ladder fuels for fires during subsequent droughts.

Regional DAI shows lower variability during the Little Ice Age (DAI values range between ~25-35 %) than during the Medieval Climatic Anomaly (DAI ranges between ~25-50%). Peaks in ‘small-
event’ fire activity in Idaho during the Little Ice Age, however, appear to correspond with intervals of relative drought within this overall cooler and effectively moister time (Fig. 4b). For example, the ~1600 cal yr BP peak in fire-related sedimentation in Idaho may partly reflect the well-documented “late 16th century megadrought” (Woodhouse and Overpeck, 1998; Cook et al., 2003). Other drought episodes in the western US during the LIA, including the 1660-1675 AD “17th century pueblo drought”, and 1865-1875 AD “mid-19th century megadrought” (Woodhouse and Overpeck, 1998; Cook et al., 2003) are associated with peaks small fire-related events in Idaho between 1400 and 1850 AD. Widespread fire in the mid-1800’s follows a wet interval from ~1825 to 1840 (Cook et al., 2003) that may have promoted seedling generation and understory growth. Fire-scar records and stand ages from Yellowstone mixed conifer forests also show large burn areas in the mid 1700’s and mid 1800’s (Romme and Despain, 1989; Barrett, 1994).

High climate variability on annual timescales (alternating wet and dry intervals) has been shown to promote surface fires (e.g. Swetnam and Betancourt, 1990, Swetnam and Betancourt, 1998, Kipfmueller and Swetnam, 2000). The growth of grasses and fine fuels is enhanced by several wet years, followed by drying of fuels and ensuing fires during a subsequent drought year. Wet and dry intervals on multidecadal timescales may enhance fire activity through an analogous mechanism. Long intervals of wetter-than-average conditions could suppress surface fires and significantly increase stand densities, in addition to increasing fine fuel production in moisture-limited forests. Multi-decadal drought could then act to desiccate both understory fuels and the forest canopy, including increased ladder fuels that developed during the preceding moist decades. Severe and prolonged droughts result in large canopy fires even in forests normally too wet to burn, as in the higher elevations of Yellowstone, synchronizing severe fires across disparate forests of the western United States (as in 2002). In this way, prolonged wet-dry intervals could enhance fire activity in both fuel-limited forests and in forests where normal high moisture levels usually preclude stand-replacing fire. This hypothesis is supported by evidence of severe, likely stand-replacing fire in Yellowstone, and at a range of elevations and forest types in Idaho during past wet-dry intervals ~950-1250 AD.
Conclusions and Implications for Management

Over both the last century and the last two thousand years, drought is a primary driver of fire activity in central Idaho and Yellowstone. These results support other studies that conclude that climate is a major control over fire occurrence during both the pre-settlement era (e.g. Whitlock et al., 2003; Swetnam and Betancourt, 1990) and in recent decades, when climate, not land management, is likely the predominant factor in our study areas and over much of the northern Rocky Mountain region (e.g. Balling et al., 1992; Westerling et al., 2006). Historic fire records from the ponderosa pine-dominated Boise National Forest show that large burn areas correspond with past intervals of drought. PDSI and temperature records from central Idaho indicate that the 1985-2006 fires and fires during the ‘dust bowl’ era drought of the 1930’s correspond with intervals of drought and high summer temperatures. Over 3375 km² or >80% of the total burn area occurred during these two intervals of drought, and over 50% of the area burned after 1985. This pattern mirrors national trends; across the west, the mid-1980s are marked by a distinct increase in large (>400 ha) wildfires corresponding with higher summer temperatures and inferred earlier snowmelt (Westerling et al., 2006). In addition, since 1970, 60% of the increase in large wildfires has occurred in mid-elevation (1680-2590 m) forests of the Northern Rockies where fire suppression has had little effect (Westerling et al., 2006). Therefore, while fire suppression and other land use changes in the Boise National Forest may have played a role in reducing fire activity in the 1950’s-1970’s, recent drought is likely the primary driver of recent stand-replacing fires.

In Idaho ponderosa forests, the highest frequency of fire-related erosional events occurred as small events during inferred multi-centennial cool episodes, in particular during the “Little Ice Age” ~1400-1900 AD. Large fire-related debris flows are not unprecedented, however, and widespread, likely severe fires occurred during past intervals of multidecadal drought ~900-1300 AD. These fires burned throughout a range of forest types including Idaho ponderosa forests, lower elevation rangeland sites, and high elevation mixed conifer and lodgepole pine-dominated sites in Idaho and in Yellowstone. These results indicate that large stand-replacing fires were part of the natural range of variability in fire regimes
in ponderosa pine forests during past intervals of drought. Fire-related sediments and burn surfaces provide records of fire and geomorphic response over millennial timescales. In addition, soil erosion and sediment loading of streams following severe crown fires is of major concern in forest ecology, fisheries, and overall land management. Alluvial fan records provide a way of assessing whether recent post-fire erosion is unusual or unprecedented over longer time periods.

In addition to drought, high multidecadal climate variability may promote widespread fires. A strongly variable climate during Medieval time ~900-1300 AD is associated with large fire-related debris flows throughout a range of forest types in central Idaho and Yellowstone. Other proxy records from the western U.S. provide evidence of an at times extremely dry, but also highly variable Medieval climate (e.g. Stine, 1994; Laird et al., 1998; Adams, 2003; Cook et al., 2004). More recently, generally wet conditions ~1960-1980 AD may have contributed to large burn areas during droughts in the 1980’s to present. Multidecadal wet intervals likely increase stand densities and ladder fuels. If followed by prolonged severe drought, desiccation of the forest canopy may result in large canopy fires, even in typically low-density ponderosa pine stands, as well as in high-elevation forests normally too wet to burn. We propose that through these processes, high-amplitude multidecadal wet-dry cycles enhance canopy fire activity in a range of forest types.

Evidence for geomorphically effective stand-replacing fires in Idaho ponderosa forests supports other studies that demonstrate a diverse pre-settlement fire regime in ponderosa pine-dominated forests in the Colorado Front Range, Montana, and the Black Hills of South Dakota, one that includes high-severity fires (e.g. Brown et al., 1999; Huckaby et al., 2001 Ehle and Baker, 2003; Romme et al., 2003; Barrett, 1988; Arno et al., 1995; Shinneman and Baker, 1997; Baker et al., in press). Recent research demonstrates that a model of low-severity fire alone is not suitable as a basis for restoration efforts in all ponderosa-dominated forests (e.g. Baker et al., in press). In addition, reference conditions for ponderosa forests that are defined based on fire regimes during the cooler, effectively wetter conditions of the Little Ice Age cannot apply to warmer climates of the present and probable future. Attempts to ‘restore’ a forest to either (1) a fire regime that is less diverse than those of the past, or (2) fire regimes characteristic of a
climate that no longer exists, may therefore be both costly and ineffective. Given that our results support a natural regime of mixed-severity fire in ponderosa-dominated forests in Idaho, a fire model that only includes frequent, low-severity fire is not applicable to this region. With predicted future warming, a high probability of severe fires in ponderosa forests will likely persist. Management should therefore consider how to maintain ecosystem resiliency within the context of a warmer and more fiery future.

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References


Fig. 1. Location of Idaho and Yellowstone National Park study areas with state boundaries in white and elevations coded as green (low) to light gray (high) shades. The majority of the Idaho study area is dominated by ponderosa pine forests, although south and southwest facing-slopes at elevations below 1300 m and elevations below 1000 m are predominantly rangeland, and elevations over 2130 m are dominated by higher elevation mixed-conifer forests. Most of the glaciated Yellowstone study area lies at over 2000 m elevation and is covered by dense conifer forests dominated by lodgepole pine.
Fig. 2. Example of an alluvial fan site in Idaho showing the continuity of burned buried soil surfaces (thin dark bands), the radiocarbon ages and analytical error of charcoal from these surfaces, and overlying charcoal-rich debris-flow deposits. The burn surfaces and overlying deposits can also be seen in smaller trenches oriented parallel to the main axis of the fan, ~15 meters above, and ~10 meters below this trench. Close-up shows stratigraphy, the continuity of units, and lack of bioturbation within the burn surfaces.
Fig. 3. Burn areas and records of drought over the last century in the ~10,570 km² Boise National Forest. (a) Burn area associated with 20th century fires within the South Fork Payette study area. The year of the fire is shown in year AD, where colors grade from yellow (early 20th century) to red (1991-2000). Note the generally larger burn area for fires in recent times (1980’s through present) and fires in the 1930’s era drought. (b) Approximate area burned annually in the Boise National Forest between 1908-2006 (Data courtesy of the Boise National Forest). Intervals of major fires occurred 1926-1935, and after 1985. (c) Monthly Palmer Drought Severity Index (PDSI) for Idaho division 4 (south-central to north-central Idaho) 1895-2006
Negative PDSI values (note inverted scale) represent below average soil moisture conditions and there is a significant (p<0.01) decrease in PDSI over the period of record. Trendline shows the yearly moving average PDSI value.
**Fig. 4.** Comparison of Drought Area Index (DAI) for the western USA (top), PDSI reconstruction for central Idaho and the Yellowstone area (middle) and fire related sedimentation events in Yellowstone and Idaho (bottom). DAI and PDSI data are from Cook et al. (2004) and are available online at http://www.ncdc.noaa.gov/paleo/newpdsi.html. A 50-year running mean has been applied to the DAI data to highlight multidecadal trends. PDSI reconstructions (note inverted scale) are from tree-ring records for central Idaho (gridpoint 69, 115.0°W 45.0°N) and the Yellowstone area on the northwestern border of Wyoming (gridpoint 100, 110.0°W 45.0°N). The number of tree-ring records in Idaho and Yellowstone used for the PDSI reconstructions varies from 1-9 (Yellowstone) and 2-9 (Idaho) where sample depth increases with decreasing age. Plots show the 20 year low-pass filter of the PDSI data. (a) Probability distributions of individual radiocarbon ages on fire-related sedimentation events based on their analytical uncertainty, calibrated into calibrated year BP (Stuiver and Reimer, 1993), where the ‘zero’ year is AD 1950. Individual probabilities are summed to show the overall spectrum of relative probability for the last 2000 years of fire-related sedimentation in the Idaho area (Pierce et al., 2004; blue and black lines) and in Yellowstone (Meyer et al., 1995; gray-filled curves). In order to reduce the influence of short-period variations in atmospheric radiocarbon (peaks unrelated to fire-related sedimentation peaks), calibrated probability distributions were smoothed using a 100-year running mean. Idaho ‘small events’ (blue line) are thin deposits likely related to low- or moderate-severity burns. ‘Small events’ dominate the record of all fire-related events (black line). Maxima in the record of Idaho small events corresponds with minima in fire-related sedimentation in Yellowstone, most notably during the ‘Little Ice Age’ (LIA) ~1400-1900 AD. The lower probability of events in recent times (last ~300 years) results from the selection of fewer near-surface deposits for dating because of bioturbation and large uncertainties in
radiocarbon calibration during this time. Blue vertical shading shows intervals of relative
drought from DAI and PDSI data and corresponding peaks in fire related sedimentation in Idaho
~1430-1490, 1550-1585, 1630-1660, and 1770-1800 AD.

(b) Red line shows Idaho ‘large events’ (major debris flows) likely related to severe fires. Large
fire-related events in Idaho ponderosa forests coincide with fire-related debris flow events from
severe fires in Yellowstone lodgepole-dominated forests (orange shading). Peaks in fire activity
in both areas correspond with multidecadal drought shown in the DAI and PDSI records (Cook
et al., 2004), and the prominent peak in large-event probability corresponds with regional
drought during the ‘Medieval Climatic Anomaly’ ~900-1300 AD. Red shaded bars show
intervals characterized by drought and large fire-related debris flows in both areas.
Fig. 5. Examples of the spatial distribution of relatively wet intervals and subsequent dry intervals inferred from tree-ring reconstructions of PDSI (Cook et al., 2004). Maps were created online (http://www.ncdc.noaa.gov/cgi-bin/paleo/pd04plot.pl) using summer (June-August) PDSI values across North America for specified years, where warmer colors indicate more pronounced drought conditions. Two wet-dry intervals are shown: the pre-Medieval wet interval (540-560 AD) and subsequent drought (600-675 AD) in Idaho and the Northern Rockies, and the medieval wet interval (1070-1090 AD) and subsequent drought (1130-1160 AD). The ~1140-1160 drought is one of the most severe intervals of multidecadal drought in the last millennia (Cook et al., 2004). In both intervals (600-675 AD and 1130-1160 AD), drought corresponds with peaks in fire-related debris flows in Yellowstone and Idaho. Exact comparison is difficult, however, given the error in radiocarbon dating (± 30 years) and potential inbuilt age in charcoal samples.