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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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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 2000 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 probably 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 between ~950 and 1150 AD. During this generally warmer time, severe multidecadal droughts were interspersed with unusually wet intervals that probably 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 years 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: debris flows, Idaho, ponderosa pine, Yellowstone.

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*. 2007; www.drought.unl.edu, accessed 4 January 2008). Drought conditions correspond with an increase in the size and severity of large fires, and studies demonstrate that 20th-century fire occurrence in the western USA is strongly linked to changes in climate (Westerling *et al*. 2006). For example, in 2002 record precipitation deficits in the western USA 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, accessed 4 January 2008; 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 US (www.nifc.gov). The economic costs associated with droughts and fires are significant: droughts are the most costly natural disasters in the USA (Cook *et al*. 2007), and firefighting expenditures by federal land-management agencies now regularly exceed US$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 percentage land area in the western USA experiencing drought indicates 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 USA 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 timescales (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

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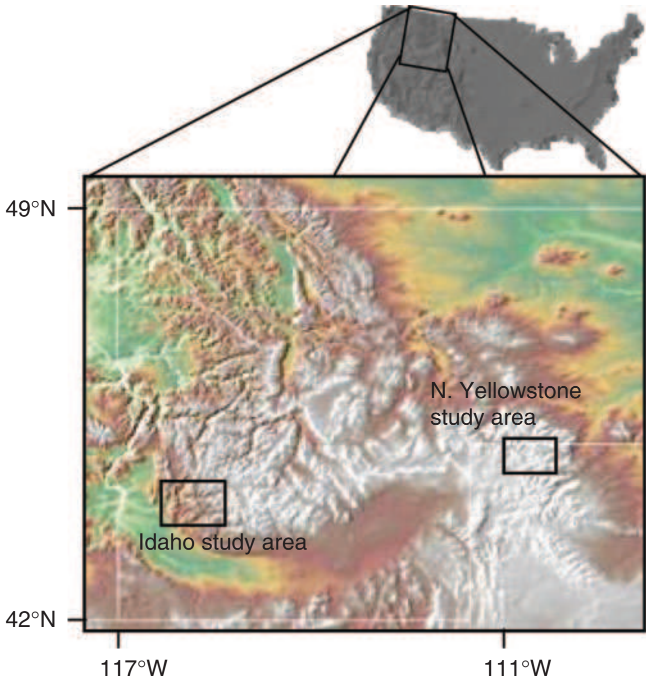

Fig. 1. Locations of Idaho and Yellowstone study areas. The majority of the Idaho study area is dominated by ponderosa pine forests, although south- and south-west-facing slopes at elevations below 1300 m, and elevations below 1000 m are predominantly rangeland and elevations over 2130 m are dominated 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.

compared these records with regional drought reconstructions (Cook *et al*. 2004). The present study provides (1) a summary of historic (last ∼100 years) 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 ∼1000 mm at high elevation sites to ∼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 characterise hillslope vegetation. At elevations between 900 and 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 ∼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.

North-eastern 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 (∼2750–3050 m). Within the focus of the present study in north-eastern 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). Although Yellowstone also receives most precipitation as winter snow, summer convective storms provide a source of intense, but localised, 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; Fulé *et al*. 1997) have been accompanied by a shift from frequent surface fires during the presettlement 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). Recent 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 presettlement era (White House 2002; US Department of Agriculture 2002). The presettlement 'reference period' for fire regimes in ponderosa pine forests, however, is mostly from tree-ring records developed during the last 500 years, a time characterised by cooler climates than today. Cooler conditions during the 'Little Ice Age' (LIA) ∼1400–1900 AD have been well documented in western North America (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 and 1.0°C since the late 1800s (Jones *et al*. 1999; Briffa and Osborn 2002; Jones and Lister 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 presettlement era are from the American South-west. 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 LIA (see review in Baker *et al*. 2007). 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

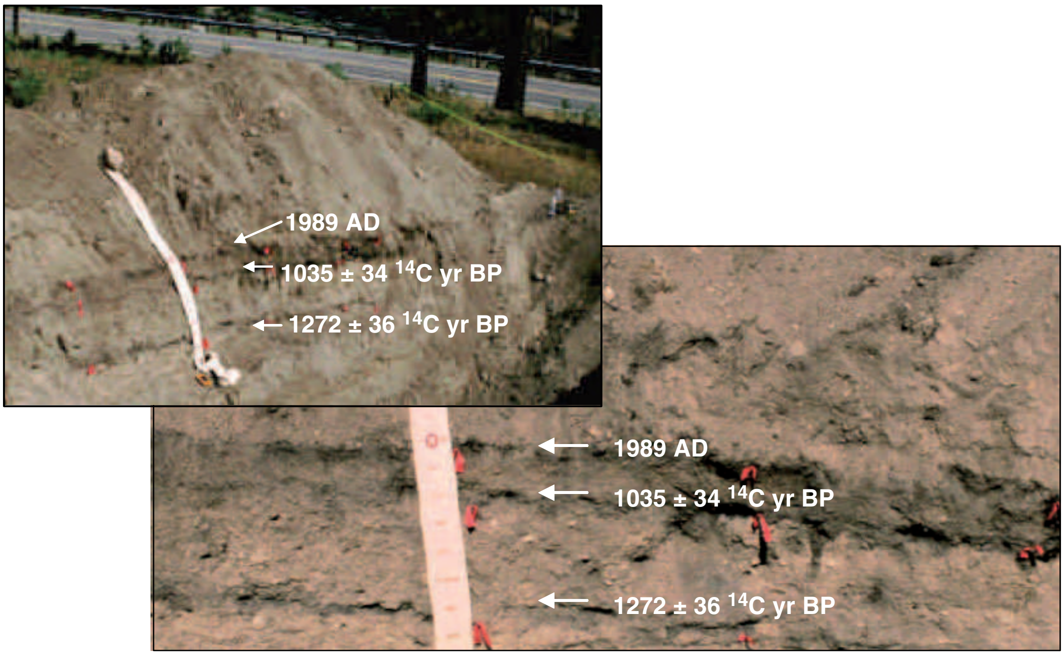

Fig. 2. Example of an alluvial fan site in Idaho showing the continuity of burned buried soil surfaces, the radiocarbon ages and analytical error of the burned soil surfaces, and overlying charcoal-rich debris-flow deposits. The burn surfaces and overlying deposits can also be seen in smaller trenches oriented parallel to the main axis of the fan, ~15 m north of this exposure, and ~10 m south of this exposure. Close-up shows stratigraphy, the continuity of units and lack of bioturbation within the burn surfaces. The continuous massive debris-flow deposits lack erosional features and variations within deposits indicative of multiple pulses of deposition.

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 presettlement fire regimes characterised 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 and 1895, mean fire return intervals ranged from 10 years at drier sites to 22 years at moister sites (Steele *et al*. 1986). In the 1900s, fire return intervals lengthened considerably; three of seven sites do not show any record of fire between 1900 and 1983 AD, whereas the other four sites only record one or two fires during this interval (Steele *et al*. 1986). Fires were severe during the 1900s, however, with extensive (>160 and 90 km^2) burns in the Boise National Forest during the 1931 AD drought.

The Selway-Bitterroot Wilderness Area, ~300 km to the north-east 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 4 years before 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, 1995; Barrett 1994), 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-1700s and mid-1800s (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 timescale of alluvial fan records is intermediate between lake records and tree-ring records, thereby allowing documentation of fire response to multidecadal- 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 multimillennial timescales. On multimillennial timescales, fire frequency inferred from lake charcoal records in the north-western US increased during warmer, drier intervals within the Pleistocene-early Holocene solar insolation maximum ~8000–14 000 years ago (Long *et al*. 1998; Millspaugh *et al*. 2000; Long and Whitlock 2002; Brunelle and 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, 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 provide 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 age 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 (Fig. 2). Prior studies in the north-western USA indicate alluvial fan records of fire extend back >10 000 years (Meyer *et al*. 1995) and >8000 years (Pierce *et al*. 2004). 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-1980s were 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 (km^2) in historic fires in the Boise National Forest was calculated from spatial coverages of burn areas compiled by the Boise National Forest based on aerial extents of mapped historic fires. 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, accessed 4 January 2008). Between 1908 and 2006, historic burn area data from the Boise National Forest show that fires burned at least 4097 km^2, although the total burn area is likely higher because small fires in remote areas were less likely to be recorded during the early part of the 20th century. 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 km^2 (25% of the total burned area) between 1926 and 1935, and 2363 km^2 (58% of the total burned area) from 1985 to 2006, including a few severe fires totalling >800 km^2 in 1994. Interestingly, the large fire year of 1926 does not correspond with anomalously low regional PDSI values. This discrepancy could be due to several 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 ~1936–84 interval of limited fire activity corresponds with moister conditions (~1940–65) and a decrease in summer temperatures (~1942–58). The dramatic decrease in burn area between ~1950 and 1985, however, likely reflects at least in part the influence of fire suppression. Only 228 km^2 burned between 1950 and 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 motorised equipment in firefighting efforts, and increased monetary support for firefighting 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 to 6 km^2. 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 colour) were described in the field and used to characterise deposits within a fan section. Boundaries between deposits were

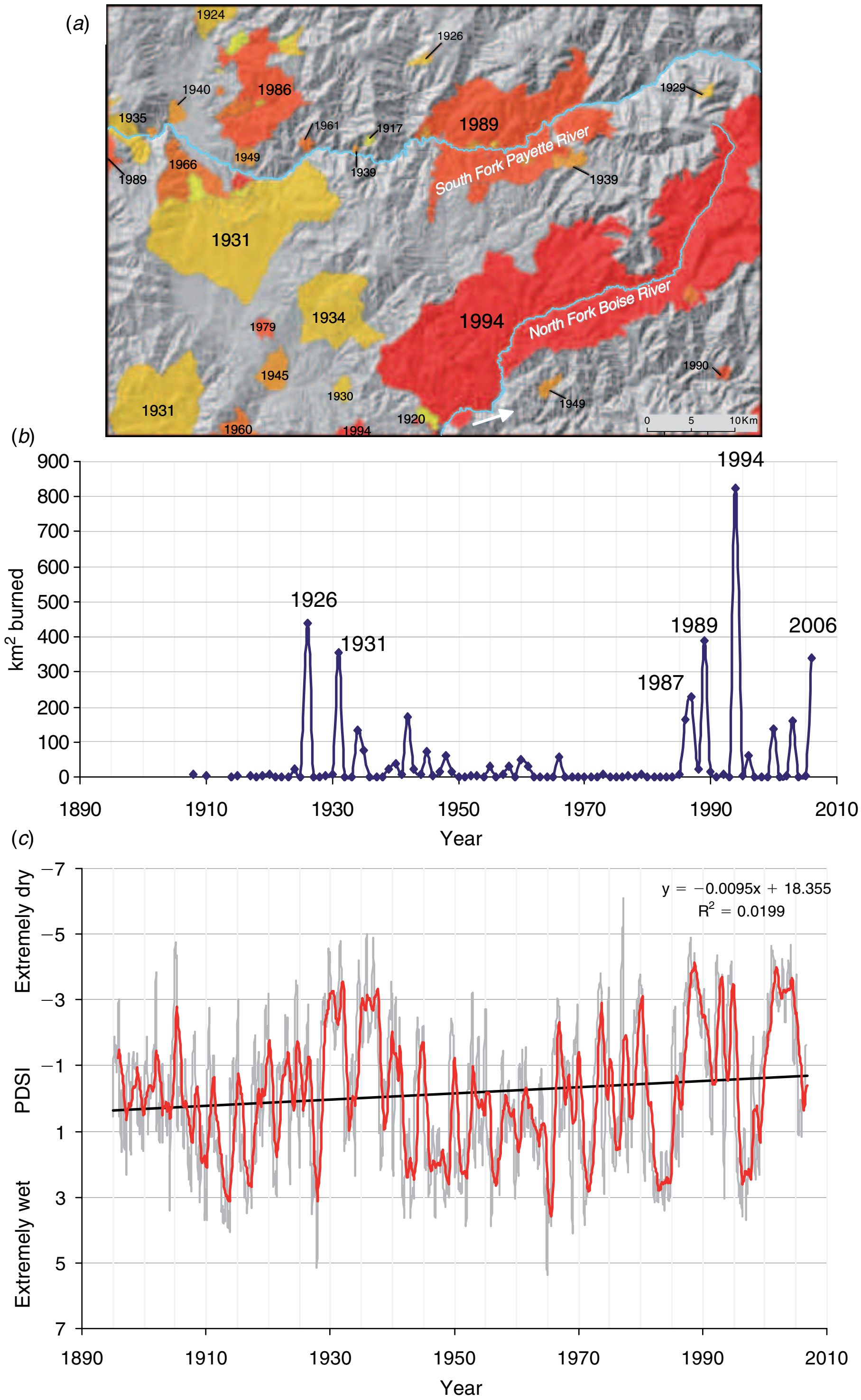

Fig. 3. (*a*) Burn area associated with 20th century fires within and near the South Fork Payette study area, located within the Boise National Forest (data courtesy of the Boise National Forest). The year of the fire is shown in year AD where colours grade from yellow (early 20th century) to red (1991–2000). Note the generally larger burn area for fires in recent times (1980s through present) and fires in the 1930s-era drought. (*b*) Approximate area burned annually in the ~10 570 km^2 Boise National Forest between 1908 and 2006 (data courtesy of the Boise National Forest). Intervals of major fires occurred 1926–35, and after 1985. (*c*) Monthly Palmer Drought Severity Index (PDSI) for Idaho division 4 (south-central to north-central Idaho) 1895–2006 (http://cdo.ncdc.noaa.gov/, accessed 4 January 2008). Negative PDSI values represent below-average soil moisture conditions and there is a significant ($P < 0.01$) decrease in PDSI over the period of record. The dark line shows the 12-month moving average PDSI value.

determined by the presence of burn surfaces, erosional surfaces, and variations in deposit characteristics (Fig. 2).

Abundant angular charcoal fragments and 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 characterised by discrete, laterally extensive layers of charred organic material of the litter layer (e.g. conifer needles, twigs, and grasses) ~0.5 to >2 cm thick (Fig. 2). In severe burns, the litter layer is almost completely ashed. As 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 post-fire sediments before bioturbation and 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 ^{14}C-dated by accelerator mass spectrometry (AMS) at the National Science Foundation (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, 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}C years before present (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 years 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 post-fire alluvial-fan deposits. Severely burned basins tend to produce thick debris-flow and sheetflood deposits (Meyer *et al*. 2001; Cannon *et al*. 2003; Meyer and Pierce 2003) that can be preserved in alluvial fans. We defined 'large fire-related events' as events represented by debris-flow units with abundant coarse angular charcoal that were generally coarser grained than other units in a stratigraphic section and comprised 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 (Fig. 4). 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). 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 defined 'large events' as having a large thickness relative to the rest of the stratigraphic section. Deposits that were clearly fire-related (containing abundant coarse charcoal), but that did not fit the criteria stated above were classified as 'small fire-related events' (Fig. 4). 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 characterised 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 8000 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, the present paper focusses 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 LIA (~1400–1900 AD), when greater effective moisture likely promoted grass growth and low-severity fires (Fig. 5*a*). Idaho small events (Fig. 5*a*, blue line) are thin deposits likely related to low- or moderate-severity burns. Small events dominate the record of all fire-related events (Fig. 5*a*, black line). 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. 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 centred ~400–600 AD. Blue vertical

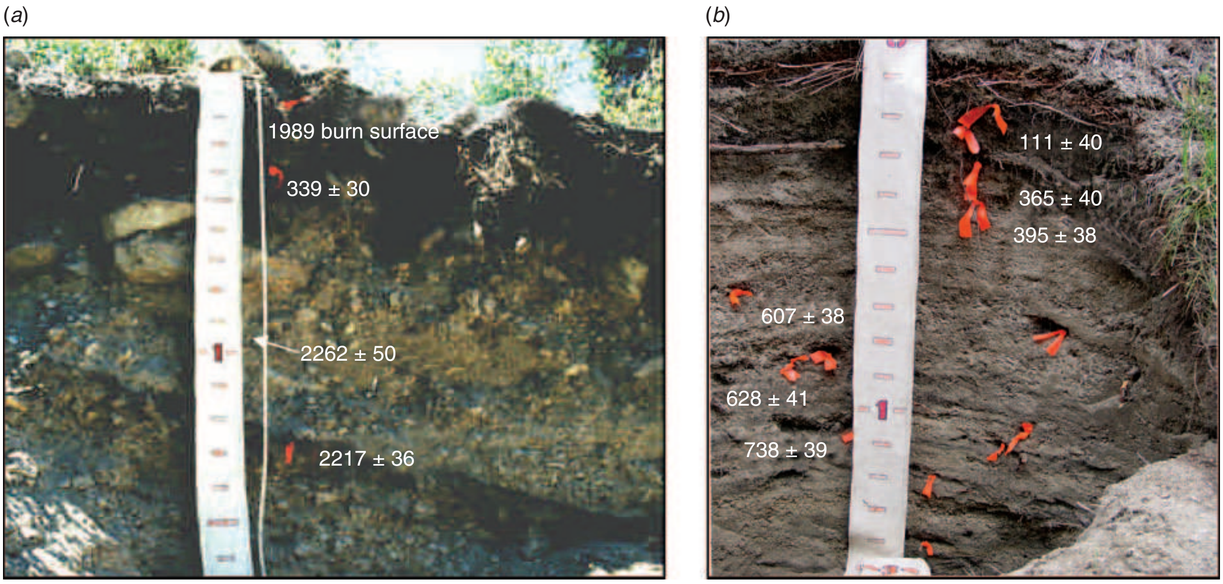

Fig. 4. Examples of small and large fire-related deposits in alluvial fan sections in the South Fork Payette study area. (*a*) Example of a series of 'small events'. This photo shows a series of charcoal-rich sheetflood deposits and burned buried surfaces. Flagging shows charcoal sample locations, and associated radiocarbon ages and error in radiocarbon years before present. Note scale of photo (exposure is ~1.5 m from surface). (*b*) Example of a 'large event'. This photo shows an ~90-cm thick fire-related debris flow (2262 ± 50 ^{14}C years before present (BP)) overlying a distinct burned buried soil (2217 ± 36 ^{14}C years BP). The deposit and soil surface are continuous, and the debris flow comprises ~40% of the total deposit thickness. The lack of bioturbation of the burned buried soil surface and the statistically indistinguishable ages of the soil and the deposit suggest the fire that burned the soil was the same fire that produced the overlying debris flow.

shading shows intervals of relative drought from DAI and PDSI data and corresponding peaks in fire-related sedimentation in Idaho ~1430–90, 1550–85, 1630–60, and 1770–1800 AD.

The LIA interval characterised by frequent fires in Idaho and limited fire activity in Yellowstone corresponds with records of wetter-than-normal conditions throughout much of the western USA (Cook *et al*. 2004). Between ~1500 and 1850 AD, tree-ring reconstructions indicate the percentage drought area in the western USA dropped below the long-term (~1200 year) 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, accessed 4 January 2008; reconstructions centred 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 AD than the prior interval ~200–1300 AD, and records from both regions exhibit a series of eight to 10 decadal to multidecadal wet episodes (PDSI > 0; Fig. 5*a*) during the LIA. Within this generally wetter interval, peaks in fire-related sedimentation still occur during periods of relative drought. Blue vertical shading (Fig. 5*a*) shows intervals of relative drought from DAI and PDSI data and corresponding peaks in fire-related sedimentation in Idaho ~1430–90, 1550–85, 1630–60, and 1770–1800 AD.

Conversely, both Idaho and Yellowstone fan records show a peak in fire-related debris flows between ~950 and 1150 AD corresponding with 'Medieval Climatic Anomaly' (MCA) drought conditions between ~900 and 1300 AD. Drought indices for the western US indicate that 1140–75 AD was the most extreme period of multidecadal drought in the last 1200 years (Fig. 6; 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 nine major debris flows between ~950 and 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). Interpretation that large debris flows stemmed from severe fires ~950–1150 AD is supported by recent debris flows from severe burns in the Idaho study area that yielded massive (~43 000 Mg km^{-2}) 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 and 750 AD. PDSI records from Yellowstone show four decadal to multidecadal intervals of drought between ~600 and 750 AD; drought reconstructions from central Idaho show intervals of drought between ~600 and 630 AD, and two drought intervals between ~700 and 750 AD (Fig. 5*b*). These intervals of drought correspond with peaks in large fire-related debris flows in Yellowstone and Idaho between ~650 and 775 AD (Fig. 5*b*). Although sample depth during this interval is low and regional DAI has not been extended back before 824 AD, regional PDSI reconstructions indicate drier than average conditions for Wyoming, Colorado, and the American South-west during the interval between 600 and 750 AD (Fig. 6).

Multidecadal climate variability and fire

The peak in fire-related sedimentation in Idaho and Yellowstone between ~900 and 1250 AD corresponds with PDSI

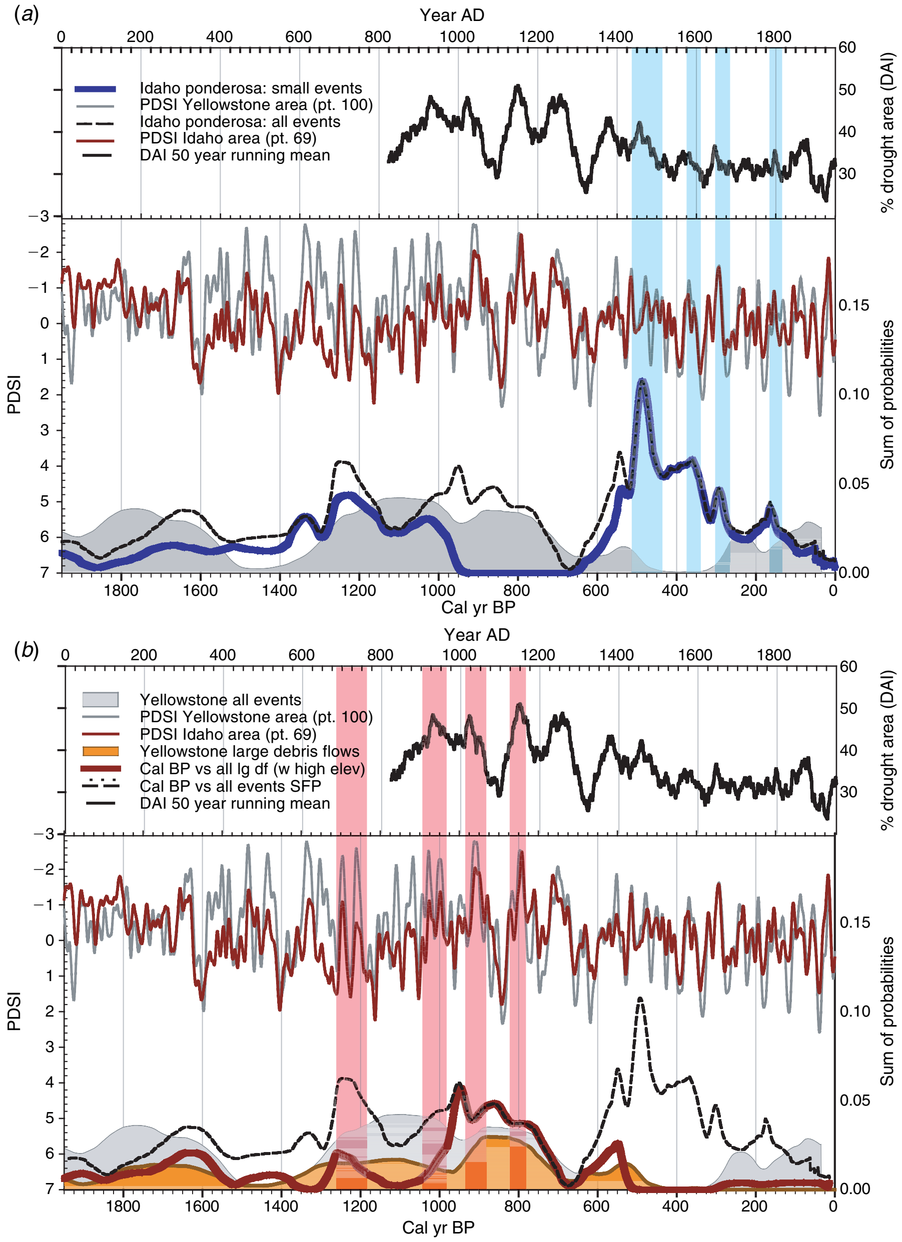

Fig. 5. Both (*a*) and (*b*) show a comparison of Drought Area Index (DAI) for the western USA (top), Palmer Drought Severity Index (PDSI) reconstruction for central Idaho and the Yellowstone area (middle) and fire-related sedimentation events in Yellowstone and Idaho (bottom). DAI and PDSI data are from Cook *et al*. (2004) and are available online at http://www.ncdc.noaa.gov/paleo/pdsidata.html (accessed 4 January 2008). A 50-year running mean has been applied to the DAI data to highlight multidecadal trends. PDSI reconstructions are from tree-ring records for central Idaho (gridpoint 69, 115.0°W 45.0°N) and the Yellowstone area on the north-western 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 one to nine (Yellowstone) and two to nine (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 before present (BP) (Stuiver and Reimer 1993), where the 'zero' year is 1950. Individual probabilities are summed to show the overall spectrum of relative probability for the last 2000 years of fire-related sedimentation (bottom curves). Probability distributions from Idaho (Pierce *et al*. 2004) show 'small events' (solid blue line) and all events (dashed black line). Probability distributions from Yellowstone (Meyer *et al*. 1995) for all fire-related events are shown by the grey-filled curve. 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. (*b*) Red (solid) line shows Idaho 'large events' (major debris flows) likely related to severe fires, and the dashed black line shows the record of all Idaho events. Large fire-related events in Idaho ponderosa forests are correlated with fires in Yellowstone lodgepole-dominated forests, where large debris flow events in Yellowstone are shown with orange (dark) shading and all Yellowstone events are shown with grey (light) shading (Meyer *et al*. 1995). 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 characterised by drought and large fire-related debris flows in both areas.

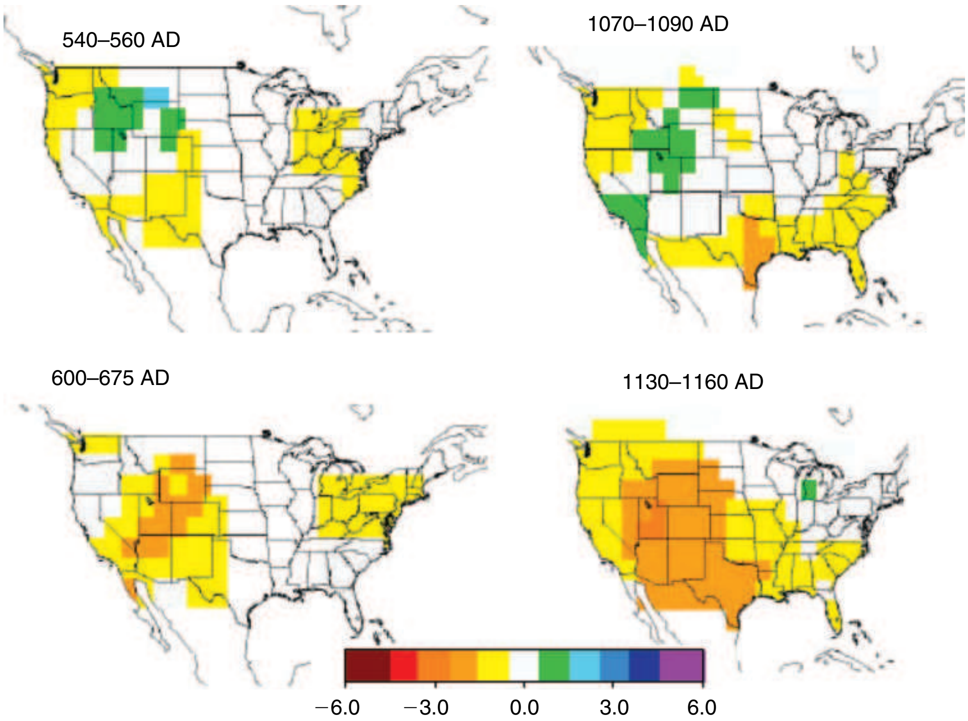

Fig. 6. Examples of the spatial distribution of relatively wet intervals and subsequent dry intervals inferred from tree-ring reconstructions of Palmer Drought Severity Index (PDSI) (Cook *et al*. 2004). Maps were created online (http://www.ncdc.noaa.gov/cgi-bin/paleo/pd04plot.pl, accessed 4 January 2008) using summer (June–August) PDSI values across North America for specified years, where warmer colours indicate more pronounced drought conditions. Two wet–dry intervals are shown: the premedieval wet interval (540–560 AD) and subsequent drought (600–675 AD) in Idaho and the Northern Rockies, and the medieval wet interval (1070–90 AD) and subsequent drought (1130–60 AD). The ∼1140–60 AD drought is one of the most severe intervals of multidecadal drought in the last millennia (Cook *et al*. 2004). In both intervals (600–675 and 1130–60 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.

reconstructions of multidecadal drought conditions in central Idaho and northern Yellowstone 900–950, 1000–20, 1120–70, and 1220–70 AD (Fig. 5*b*). Interestingly, this interval also contains prolonged wet episodes between ∼1080–1120 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. 6). 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 Mono Lake, California (Stine 1994), lake salinity changes in South Dakota (Laird *et al*. 1998), and intervals of dune stability and soil formation *v.* dune mobility in Wyoming (Mayer and Mahan 2004) all indicate that the MCA was characterised by both droughts and wet intervals of multidecadal length. Prior to the MCA, relatively wetter conditions in the northern Rocky Mountain region between ∼540 and 560 AD may have enhanced fire activity during subsequent dry intervals ∼600–675 AD (Fig. 6). Both during the MCA and between ∼540 and 675 AD, prolonged wet intervals could enhance tree germination and understorey 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 LIA (DAI values range between ∼25 and 35%) than during the MCA (DAI ranges between ∼25 and 50%). Peaks in small-event fire activity in Idaho during the LIA, however, appear to correspond with intervals of relative drought within this overall cooler and effectively moister time (Fig. 5*a*). For example, the ∼1600 AD peak in fire-related sedimentation in Idaho may partly reflect the well-documented 'late 16th century megadrought' (Woodhouse and Overpeck 1998; Cook *et al*. 2004). Other drought episodes in the western US during the LIA, including the 1660–75 AD '17th century pueblo drought' (Woodhouse and Overpeck 1998; Cook *et al*. 2004) are associated with peaks in small fire-related events in Idaho between 1400 and 1850 AD. Widespread fire in the mid-1800s followed a wet interval from ∼1825 to 1840 AD (Cook *et al*. 2004) that may have promoted seedling generation and understorey growth. Fire-scar records and stand ages from Yellowstone mixed-conifer forests also show large burn areas in the mid-1700s and mid-1800s (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, 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. Multidecadal drought could then act to desiccate both understorey 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, synchronising 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 between ~950 and 1250 AD.

Conclusions and implications for management

Over both the last century and the last 2000 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 presettlement era (e.g. Swetnam and Betancourt 1990; Whitlock *et al*. 2003) 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 1930s correspond with intervals of drought and high summer temperatures. Over 3375 km^2 or >80% of the total burn area occurred during these two intervals of drought, and over 50% of the area burned after 1985 AD. 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, whereas fire suppression and other land-use changes in the Boise National Forest may have played a role in reducing fire activity in the 1950s–1970s, 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 multicentennial cool episodes, in particular during the LIA between ~1400 and 1900 AD. Large fire-related debris flows are not unprecedented, however, and widespread, likely severe fires occurred during past intervals of multidecadal drought between ~900 and 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 times (between ~900 and 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 USA 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 between ~1960 and 1980 may have contributed to large burn areas during droughts in the 1980s 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 presettlement 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. Barrett 1988; Arno *et al*. 1995; Shinneman and Baker 1997; Brown *et al*. 1999; Huckaby *et al*. 2001; Ehle and Baker 2003; Romme *et al*. 2003; Baker *et al*. 2007). 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*. 2007). In addition, reference conditions for ponderosa forests that are defined based on fire regimes during the cooler, effectively wetter conditions of the LIA 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

Adams K (2003) Age and paleoclimatic significance of late Holocene lakes in the Carson Sink, NV, USA. *Quaternary Research* **60**, 294–305. doi:10.1016/J.YQRES.2003.07.006

Arno SF, Scott JH, Hartwell MG (1995) Age-class structure of old growth ponderosa pine/Douglas fir stands and its relationship to fire history. US Forest Service Research Paper INT-RP-481. (Ogden, UT)

Baisan CH, Swetnam TW (1990) Fire history on a desert mountain-range – Rincon Mountain Wilderness, Arizona, USA. *Canadian Journal of Forest Research* **20**, 1559–1569. doi:10.1139/X90-208

Baker WL, Veblen TT, Sherriff RL (2007) Fire, fuels and restoration of ponderosa pine–Douglas fir forests in the Rocky Mountains. *Journal of Biogeography* **34**, 251–269. doi:10.1111/J.1365-2699.2006.01592.X

Balling RC, Meyer GA, Wells SG (1992) Climate change in Yellowstone National Park: is the drought-related risk of wildfires increasing? *Climatic Change* **22**, 35–45. doi:10.1007/BF00143342

Barrett SW (1988) Fire suppression's effects on forest succession within a central Idaho wilderness. *Western Journal of Applied Forestry* **3**, 76–80.

Barrett SW (1994) Fire regimes database for coniferous forests in the inland Northwest. USDA Forest Service contract report INT-92676-RJVA. (Missoula, MT)

Blair TC, McPherson JG (1994) Alluvial fans and their natural distinction from rivers based on morphology, hydraulic processes, sedimentary processes, and facies assemblages. *Journal of Sedimentary Research* **64**, 459–489.

Briffa KR, Osborn TJ (2002) Paleoclimate – blowing hot and cold. *Science* **295**, 2227–2228. doi:10.1126/SCIENCE.1069486

Brohan P, Kennedy JJ, Haris I, Tett SFB, Jones PD (2006) Uncertainty estimates in regional and global observed temperature changes: a new dataset from 1850. *Journal of Geophysical Research* **111**, D12106. doi:10.1029/2005JD006548

Brown PM, Sieg CH (1996) Fire history in interior ponderosa pine forests of the Black Hills, South Dakota, USA. *International Journal of Wildland Fire* **6**, 97–105. doi:10.1071/WF9960097

Brown PM, Kaufmann MR, Shepperd WD (1999) Long-term, landscape patterns of past fire events in a montane ponderosa pine forest of central Colorado. *Landscape Ecology* **14**, 513–532. doi:10.1023/A:1008137005355

Brunelle A, Whitlock C (2003) Post-glacial fire, vegetation, and climate history in the Clearwater Range, Northern Idaho, USA. *Quaternary Research* **60**, 307–318. doi:10.1016/J.YQRES.2003.07.009

Cannon SH, Gartner JE, Parrett C, Parise M (2003) Wildfire-related debris-flow generation through episodic progressive sediment-bulking processes, western USA. In 'Debris-flow hazards mitigation: mechanics, prediction, and assessment'. (Eds D Rickenmann, C Chen-lung) pp. 71–82. (Milllpress: Rotterdam)

Carrara PE (1989) Late Quaternary glacial and vegetative history of the Glacier National Park region, Montana. *U.S. Geological Survey Bulletin* **1902**, 1–64.

Cook ER, Meko DM, Stahle DW, Cleaveland MK (1999) Drought reconstructions for the continental United States. *Journal of Climate* **12**, 1145–1162. doi:10.1175/1520-0442(1999)012<1145:DRFTCU>2.0.CO;2

Cook ER, Woodhouse C, Eakin CM, Meko DM, Stahle DW (2004) Long-term aridity changes in the western United States. *Science* **306**, 1015–1018. doi:10.1126/SCIENCE.1102586

Cook ER, Seager R, Cane MA, Stahle DW (2007) North American drought: reconstructions, causes, and consequences. *Earth-Science Reviews* **81**, 93–134.

Cooper CF (1960) Changes in vegetation, structure, and growth of south-western pine forest since white settlement. *Ecological Monographs* **30**, 129–164. doi:10.2307/1948549

Covington WW (2000) Helping western forests heal – the prognosis is poor for US forest ecosystems. *Nature* **408**, 135–136. doi:10.1038/35041641

Covington WW, Moore MM (1994) South-western ponderosa forest structure: changes since Euro-American settlement. *Journal of Forestry* **92**, 39–47.

Dirks RA, Martner BE (1982) The climate of Yellowstone and Grand Teton National Parks. US National Park Service, Occasional Paper 6. (Washington, DC)

Ehle DS, Baker WL (2003) Disturbance and stand dynamics in Ponderosa pine forests in Rocky Mountain National Park, USA. *Ecological Monographs* **73**, 543–566. doi:10.1890/03-4014

Esper J, Cook ER, Schweingruber FH (2002) Low-frequency signals in long tree-ring chronologies for reconstructing past temperature variability. *Science* **295**, 2250–2253. doi:10.1126/SCIENCE.1066208

Fulé PZ, Covington WW, Moore MM (1997) Determining reference conditions for ecosystem management of south-western ponderosa pine forests. *Ecological Applications* **7**, 895–908. doi:10.1890/1051-0761(1997)007[0895:DRCFEM]2.0.CO;2

Gavin DG (2001) Estimation of inbuilt age in radiocarbon ages of soil charcoal for fire history studies. *Radiocarbon* **43**, 27–44.

Grove JM (1988) 'The Little Ice Age.' (Methuen: New York)

Huckaby LS, Kaufmann MR, Stoker JM, Fornwalt PJ (2001) Landscape patterns of montane forest age structure relative to fire history at Cheesman Lake in the Colorado Front Range. In 'Ponderosa Pine Ecosystems Restoration and Conservation: Steps toward Stewardship. Proceedings RMRS-P-22'. (Eds RK Vance, CB Edminster, WW Covington, JA Blake) pp. 19–27. (US Department of Agriculture: Ogden, UT)

Jones PD, Lister DH (2002) The daily temperature record for St Petersburg (1743–1996). *Climatic Change* **53**, 253–267. doi:10.1023/A:1014918808741

Jones PD, Moberg A (2003) Hemispheric and large-scale surface air temperature variations: an extensive revision and an update to 2001. *Journal of Climate* **16**, 206–223. doi:10.1175/1520-0442(2003)016<0206:HALSSA>2.0.CO;2

Jones PD, New M, Parker DE, Martin S, Rigor IG (1999) Surface air temperature and its changes over the past 150 years. *Reviews of Geophysics* **37**, 173–199. doi:10.1029/1999RG900002

Karl TR, Knight RW (1998) Secular trend of precipitation amount, frequency, and intensity in the United States. *Bulletin of the American Meteorological Society* **79**, 231–242. doi:10.1175/1520-0477(1998)079<0231:STOPAF>2.0.CO;2

Kipfmueller KF, Swetnam TW (2000) Fire–climate interactions in the Selway-Bitterroot Wilderness Area. In 'Proceedings RMRS-P-15-Vol-5: Wilderness Science in a Time of Change'. (Eds DN Cole, SF McCool, WT Borrie, J O'Loughlin) pp. 270–275. (USDA Forest Service: Ogden, UT)

Laird KR, Fritz SC, Maasch KA, Cumming BF (1998) A diatom-based reconstruction of drought intensity, duration, and frequency from Moon Lake, North Dakota: a sub-decadal record of the last 2300 years. *Journal of Paleolimnology* **19**, 161–179. doi:10.1023/A:1007929006001

Long CJ, Whitlock C (2002) Fire and vegetation history from the coastal rain forest of the western Oregon coast range. *Quaternary Research* **58**, 215–225. doi:10.1006/QRES.2002.2378

Long CJ, Whitlock C, Bartlein PJ, Millspaugh SH (1998) A 9000-year fire history from the Oregon Coast Range, based on a high-resolution charcoal study. *Canadian Journal of Forest Research* **28**, 774–787. doi:10.1139/CJFR-28-5-774

Luckman BH (2000) The Little Ice Age in the Canadian Rockies. *Geomorphology* **32**, 357–394. doi:10.1016/S0169-555X(99)00104-X

Mayer JH, Mahan SA (2004) Late Quaternary stratigraphy and geochronology of the western Killpecker Dunes, Wyoming, USA. *Quaternary Research* **61**, 72–84. doi:10.1016/J.YQRES.2003.10.003

McKenzie D, Peterson DL, Agee JK (2000) Fire frequency in the interior Columbia River Basin: building regional models from fire history data. *Ecological Applications* **10**, 1497–1516. doi:10.1890/1051-0761(2000)010[1497:FFITIC]2.0.CO;2

McKenzie D, Gedalof Z, Peterson DL, Mote P (2004) Climatic change, wildfire, and conservation. *Conservation Biology* **18**, 890–902. doi:10.1111/J.1523-1739.2004.00492.X

Meyer GA, Pierce JL (2003) Climatic controls on fire-induced sediment pulses in Yellowstone National Park and Central Idaho: a long-term perspective. *Forest Ecology and Management* **178**, 89–104. doi:10.1016/S0378-1127(03)00055-0

Meyer GA, Wells SG (1997) Fire-related sedimentation events on alluvial fans, Yellowstone National Park, USA. *Journal of Sedimentary Research* **A67**, 776–791.

Meyer GA, Wells SG, Balling RC, Jull AJT (1992) Response of alluvial systems to fire and climate change in Yellowstone National Park. *Nature* **357**, 147–150. doi:10.1038/357147A0

Meyer GA, Wells SG, Jull AJT (1995) Fire and alluvial chronology in Yellowstone National Park: climatic and intrinsic controls on Holocene geomorphic processes. *Geological Society of America Bulletin* **107**, 1211–1230. doi:10.1130/0016-7606(1995)107<1211:FAACIY>2.3.CO;2

Meyer GA, Pierce JL, Wood SH, Jull AJT (2001) Fires, storms, and erosional events in the Idaho batholith. *Hydrological Processes* **15**, 3025–3038. doi:10.1002/HYP.389

Millspaugh SH, Whitlock C, Bartlein PJ (2000) Variations in fire frequency and climate over the past 17 000 yr in central Yellowstone National Park. *Geology* **28**, 211–214. doi:10.1130/0091-7613(2000)28<211:VIFFAC>2.0.CO;2

NASA (2004) Looking at Earth, drought signals severe fire season in the US. Available at http://www1.nasa.gov/vision/earth/lookingatearth/Western_Drought.html [Verified 4 January 2008]

Pierce JL, Meyer GA, Jull AJT (2004) Fire-induced erosion and millennial-scale climate change in northern ponderosa pine forests. *Nature* **432**, 87–90. doi:10.1038/NATURE03058

Pollack HN, Huang S, Shen P (1998) Climate change record in subsurface temperatures: a global perspective. *Science* **282**, 279–281. doi:10.1126/SCIENCE.282.5387.279

Romme WH (1982) Fire and landscape diversity in subalpine forests of Yellowstone National Park. *Ecological Monographs* **52**, 199–221. doi:10.2307/1942611

Romme WH, Despain DG (1989) The Yellowstone fires. *Scientific American* **261**, 37–46.

Romme WH, Veblen TT, Kaufmann MR, Sherriff R, Regan CM (2003), Ecological effects of the Hayman fire. In 'Hayman fire case study. US Forest Service, General Technical Report RMRS-GTR-114'. (Ed. RT Graham) pp. 181–195. (US Forest Service: Fort Collins, CO)

Shinneman DJ, Baker WL (1997) Non-equilibrium dynamics between catastrophic disturbances and old-growth forests in ponderosa pine landscapes of the Black Hills. *Conservation Biology* **11**, 1276–1288. doi:10.1046/J.1523-1739.1997.96198.X

Steele R, Arno SF, Geier-Hayes K (1986) Wildfire patterns change in central Idaho's ponderosa pine–Douglas-fir forest. *Western Journal of Applied Forestry* **1**, 16–18.

Stine S (1994) Extreme and persistent drought in California and Patagonia during medieval time. *Nature* **369**, 546–549. doi:10.1038/369546A0

Stuiver M, Reimer PJ (1993) Extended ^{14}C data base and revised CALIB 3.0 ^{14}C age calibration program. *Radiocarbon* **35**, 215–230.

Swetnam TW, Baisan CH (1996) Historical fire regime patterns in the south-western United States since AD 1700. USDA Forest Service, General Technical Report RM-GTR-286. In 'Proceedings of the Second La Mesa Fire Symposium'. (Ed. CD Allen) pp. 11–32. (USDA Forest Service: Los Alamos, NM)

Swetnam TW, Betancourt JL (1990) Fire–Southern Oscillation relations in the south-western United States. *Science* **249**, 1017–1020. doi:10.1126/SCIENCE.249.4972.1017

Swetnam TW, Betancourt JL (1998) Mesoscale disturbance and ecological response to decadal climatic variability in the American South-west. *Journal of Climate* **11**, 3128–3147. doi:10.1175/1520-0442(1998)011<3128:MDAERT>2.0.CO;2

Thompson RS, Whitlock C, Bartlein PJ, Harrison SP, Spaulding WG (1993) Climatic changes in the western United States since 18 000 yr BP. In 'Global Climates since the Last Glacial Maximum'. (Eds HE Wright Jr, JE Kutzbach, T Webb III, WF Ruddiman, FA Street-Perrott) pp. 468–513. (University of Minnesota Press: Minneapolis, MN)

US Department of Agriculture (2002) A collaborative approach for reducing wildland fire risks to communities and the environment: 10-year comprehensive strategy. Available at http://www.forestsandrangelands.gov/plan/documents/11-23-en.pdf [Verified 4 January 2008]

Westerling AL, Hidalgo HG, Cayan DR, Swetnam TW (2006) Warming and earlier spring increase Western US forest wildfire activity. *Science* **313**, 940–943. doi:10.1126/SCIENCE.1128834

White House (2002) Healthy forests: an initiative for wildfire prevention and stronger communities. Whitehouse, Washington, DC. Available at http://www.whitehouse.gov/infocus/healthyforests/Healthy_Forests_v2.pdf [Verified 4 January 2008]

Whitlock C (2004) Forests, fires and climate. *Nature* **432**, 28–29. doi:10.1038/432028A

Whitlock C, Shafer SL, Marlon J (2003) The role of climate and vegetation change in shaping past and future fire regimes in the northwestern US and the implications for ecosystem management. *Forest Ecology and Management* **178**, 5–21. doi:10.1016/S0378-1127(03)00051-3

Woodhouse CA, Overpeck JT (1998) 2000 years of drought variability in the central United States. *American Meteorological Society* **79**, 2693–2714. doi:10.1175/1520-0477(1998)079<2693:YODVIT>2.0.CO;2

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