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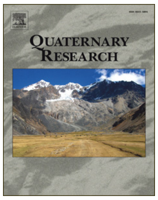

Holocene fire occurrence and alluvial responses at the leading edge of pinyon–juniper migration in the Northern Great Basin, USA

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A B S T R A C T

Fire and vegetation records at the City of Rocks National Reserve (CIRO), south-central Idaho, display the interaction of changing climate, fire and vegetation along the migrating front of single-leaf pinyon (*Pinus monophylla*) and Utah juniper (*Juniperus osteosperma*). Radiocarbon dating of alluvial charcoal reconstructed local fire occurrence and geomorphic response, and fossil woodrat (*Neotoma*) middens revealed pinyon and juniper arrivals. Fire peaks occurred ~10,700–9500, 7200–6700, 2400–2000, 850–700, and 550–400 cal yr BP, whereas ~9500–7200, 6700–4700 and ~1500–1000 cal yr BP are fire-free. Wetter climates and denser vegetation fueled episodic fires and debris flows during the early and late Holocene, whereas drier climates and reduced vegetation caused frequent sheetflooding during the mid-Holocene. Increased fires during the wetter and more variable late Holocene suggest variable climate and adequate fuels augment fires at CIRO. Utah juniper and single-leaf pinyon colonized CIRO by 3800 and 2800 cal yr BP, respectively, though pinyon did not expand broadly until ~700 cal yr BP. Increased fire-related deposition coincided with regional droughts and pinyon infilling ~850–700 and 550–400 cal yr BP. Early and late Holocene vegetation change probably played a major role in accelerated fire activity, which may be sustained into the future due to pinyon–juniper densification and cheatgrass invasion.

Introduction

In western North America, ongoing and future climate and land-use change could trigger widespread and possibly abrupt shifts in dominant vegetation, wildfire regimes, and post-fire erosion. These shifts will in turn impact fire and flood risks, conservation efforts, forest products, water resources, and other ecological goods and services. Our ability to anticipate and adapt to these changes will depend on how well we understand the effects of climatic change on vegetation, fire, and geomorphic response, and how these factors interact at different spatial and temporal scales (Allen, 2007).

Fire regimes are characterized by fuel consumption and fire spread patterns, fire size, and the distribution, frequency, intensity and severity of fire (Keeley et al., 2009). Climate ultimately governs vegetation and fire regimes, and vegetation-driven changes in fuel availability and continuity are primarily responsible for extent and severity of wildfires. Over annual to decadal time scales, climate variability controls the availability and moisture content of vegetation as fuel, and affects the frequency and regional synchroneity of wildfires (Heyerdahl et al., 2002; Westerling et al., 2006; Littell et al., 2009). Over decadal to millennial time scales, climate modulates the composition and structure of plant populations, and the nature of the fire regime, including patterns of fire frequency, intensity, and spread (Grissino-Mayer and Swetnam, 2000; Mensing et al., 2006). Through strong positive feedbacks, changing fire regimes can also impact vegetation and fuels. Despite the primary control of climate on both fire regimes and vegetation, the causal links, temporal sequencing, and lags among climatic change, vegetation, and fire are complex.

An important objective for multiproxy paleoecological studies is to sort out what circumstances determine the order and lags of reconstructed changes in vegetation and fire both locally and regionally (Clark et al., 1996; Veblen et al., 2003; Unbanhowar, 2004). More simply, which comes first, the change in vegetation or the shift in fire regime? Directional changes in fire regimes coeval with changing vegetation across the region would implicate a greater role for vegetation change (composition and structure). Synchronies in shifting fire regimes across different vegetation types, some stable and others not, would suggest a more direct influence of climate on fire regimes.

A related issue is how climate and vegetation interact to modify the mechanisms and magnitude of fire-related erosion and sedimentation. Unfortunately, few studies have the appropriate temporal and spatial resolution to relate changes in vegetation, fire, and geomorphic response throughout the Holocene. Wildfires are known to trigger and accelerate hillslope erosion (e.g., Cannon et al., 2001a,b, Meyer et al., 2001; Cannon et al., 2010) and the type of geomorphic response (e.g., sheetfloods vs. debris flows) can be related to fire severity

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(Meyer et al., 2001; Pierce et al., 2004). Although post-fire geomorphic responses ultimately hinge on the occurrence, duration and intensity of rainfall in the window of time between fire and recovery of vegetation (Cannon et al., 2001a,b), the nature of fire-related erosion is controlled by several factors that include basin topography (Cannon et al., 2001a, b, 2010), vegetation type and structure (e.g., Wilcox et al., 2011), and fire size and severity (Meyer et al., 2001; Pierce et al., 2004; Cannon et al., 2010).

We use a novel approach of combining alluvial records of fire-related sedimentation with adjacent fossil woodrat (*Neotoma*) midden records of vegetation change in south-central Idaho. The City of Rocks National Reserve (CIRO) and adjacent Castle Rocks State Park encompass a maze of deeply weathered and towering granite outcrops separated by alluvial valleys. The numerous rock crevices and shelters preserve fossil woodrat middens and a record of plant migration, while the entrenched streams and arroyos expose fire-related deposits and charcoal in the alluvial stratigraphic sequences. The midden record is the focus of a separate paper (Betancourt, unpub. data), and the paleo-vegetation record is summarized here for comparison with the charcoal and alluvial stratigraphy.

CIRO is located along the late-Holocene migration front of Utah juniper [*Juniperus osteosperma* (Torr.) Little] and single-leaf pinyon (*Pinus monophylla* Torr. & Frém.). Holocene shifts in temperature and precipitation/snowpack, and their annual phasing (seasonal timing), likely drove the northward migration of these two dominant conifers and associated changes in fire regime. The fortuitous preservation of fire and vegetation paleorecords within the same and adjacent drainage basins allows long-term analysis of fire, vegetation, and geomorphic change at CIRO.

Study area

CIRO is located on the southern slope of the Albion range on the Utah–Idaho border (Fig. 1). The study area spans an elevational range of 1600–2700 m. Mean annual precipitation is 280 mm, where most precipitation falls between April and June (Western Regional Climate Center).

Geologically, CIRO is comprised of the Almo granitic pluton (29 Ma) which intruded into the Elba quartzite (1.6 Ga) and Green Creek Complex (2.5 Ga) of metasediments and granitic basement rock (Miller et al., 2008). Granite spires provide world-famous climbing opportunities, although most of CIRO is characterized by gentle to moderate slopes, with a mean slope of 15.6°. Mechanical and chemical weathering and erosion of Almo granite have blanketed CIRO in erodible granite grus (Pogue and Katz, 2008). Active arroyo cutting and fluvial incision reveal fire-related deposits in six headwater basins that drain into the Raft River, a tributary of the Snake River, Idaho (Table 1; Fig. 2). Livestock grazing and dry farming began at CIRO in 1888 (Morris, 2006), and this sparsely populated region is still primarily a ranching and agricultural community.

CIRO is a floristically diverse woodland–steppe ecotone, with over 450 documented plant species (John, 1995). Lower elevations (<1800 m) are dominated by big sagebrush (*Artemisia tridentata* Nutt.), antelope bitterbrush [*Purshia tridentata* (Pursh) DC] and an understory of native and non-native bunch grasses. Single-leaf pinyon dominates middle elevations (1600–2000 m) with Utah juniper and Rocky Mountain juniper (*Juniperus scopulorum* Sarg.). Patches of curl-leaf mountain mahogany (*Cercocarpus ledifolious* Nutt.) and aspen (*Populus tremuloides* Michx.) occupy middle to upper elevations (>1800 m). Limber pine (*Pinus flexilis* James) dominates the higher elevations (>2000 m). The reserve is dissected by riparian habitat that includes Rocky Mountain maple (*Acer glabrum* Torr.), box elder (*Acer negundo* L.), redosier dogwood (*Cornus sericea* L.) and narrow leaf cottonwood (*Populus angustifolia* James) (City Of Rocks National Reserve Vegetation Map).

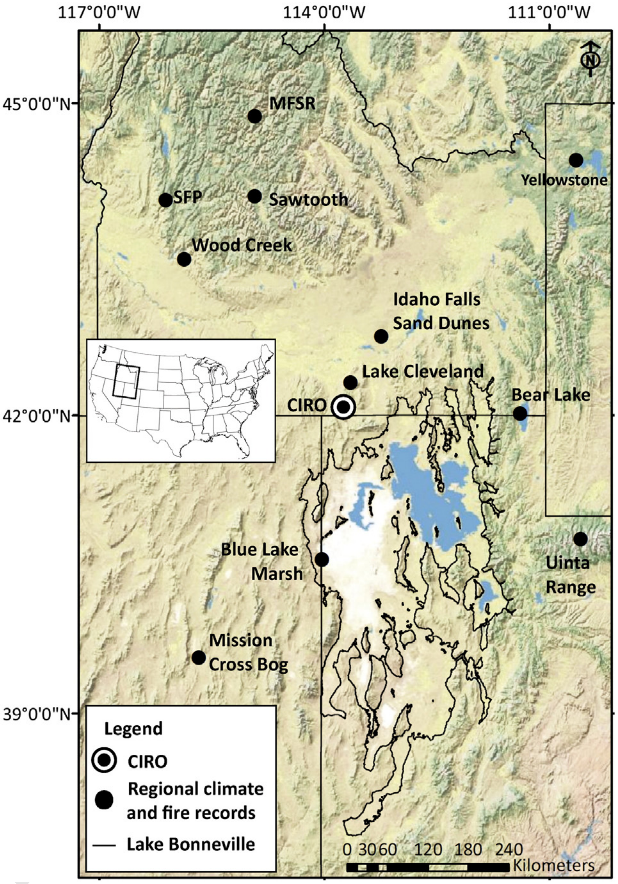

Figure 1. Map showing location of CIRO relative to sites of reconstructed paleoclimate and fire used for comparison in this study. Paleoclimate record sites include: the Bonneville Basin, UT (Murchison, 1989; Patrickson et al., 2010), Blue Lake Marsh, UT (Louderback and Rhode, 2009), Bear Lake, ID (Doner, 2009; Moser and Kimball, 2009), Uinta Range, UT (Gray et al., 2004; Corbett and Munroe, 2010), Lake Cleveland in the Albion Range, ID (Davis et al., 1986), Idaho Falls Sand Dunes, Snake River Plain, ID (Rittenour and Pearce, 2011) and Mission Cross Bog, NV (Mensing et al., 2008). Reconstructed fire history sites include Yellowstone, WY (Meyer et al., 1995), Wood Creek, ID (Nelson and Pierce, 2010), the South Fork of the Payette River, ID (SFP; Pierce et al., 2004), the Middle Fork of the Salmon River, ID (MFSR; Riley, 2012), and the Sawtooth Range, ID (Svenson, 2010). The Lake Bonneville outline shows the approximate extent of the Bonneville highstand (20,000–16,000 yr BP; Automated Georeference Center, 2001).

Methods

We identified incised streams, incised alluvial fans and arroyos using aerial photography in CIRO and nearby Castle Rocks State

Table 1
Summary of CIRO basin characteristics, number of alluvial charcoal and midden sampling sites and number of fire radiocarbon ages per basin.

Basin name	Basin area (km^2)	Lithology	# of alluvial stratigraphy sites	# of midden sites	# of ^{14}C (fire) ages
Almo Creek	57.9	Quartzite to west, gneiss to east	2	0	3
Stines Creek	6.9	Quartzite to west, gneiss to south	1	0	1
Graham Creek	14	Quartzite to west, granite to east, gneiss to south	1	0	1
Circle Creek	17.4	All granite except gneiss fin to east	10	18	25
Heath Canyon	13.9	Granite to north, quartzite to south	1	0	7
Emigrant Canyon	13.3	Quartzite	0	2	0

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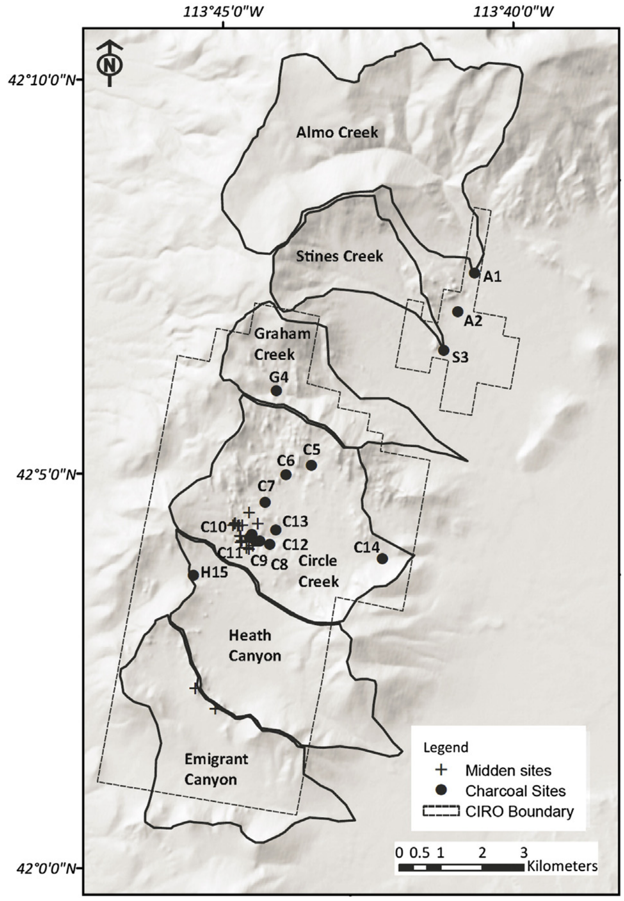

Figure 2. Map showing the CIRO study area, Castle Rocks State Park boundary (north) and the CIRO park boundary (south), six delineated drainage basins, charcoal sampling sites, and midden sampling sites. Subbasins within Circle Creek (C5–C14) are not shown, but include North Fork of Circle Creek, Center Circle Creek, South Fork of Circle Creek, as well as numerous unnamed small basins. The main fork of Circle Creek is established near site C14.

Park, which are both managed by the National Park Service office in Almo, Idaho. In the field, targeted exposures were cleaned with a shovel and thoroughly examined for alluvial charcoal. Exposures containing charcoal were sampled for radiocarbon dating and macrofossil analysis.

To create a spatially representative dataset of fire events, we dated charcoal samples from many of the small drainages throughout the study area. In exposures containing multiple fire-related deposits, we dated charcoal fragments from multiple distinct units. At exposures containing a few charcoal-rich deposits, we dated the uppermost unit (>25 cm depth to avoid surface material that may have experienced bioturbation) and the lowermost unit, so that we could reconstruct a time frame of fire and deposition at the site. The number of charcoal samples collected varied depending on fragment size and abundance.

We used deposit characteristics (e.g., clast sorting, size, orientation, and matrix textures) to infer depositional processes (e.g., sheetflood, debris flow, overbank flood, channel flood), and identified soil properties according to Birkeland et al. (1991; Table 2). Charcoal-rich deposits are termed "fire-related" and post-fire geomorphic response is inferred from deposit characteristics (e.g., sheetfloods vs. debris flows). Variations in depositional process may in turn reflect variations in fire-severity and size. Prior studies of fire events preserved in alluvial records (Meyer et al., 1995; Pierce et al., 2004), combined with modern studies of post-fire erosional response (e.g., Cannon et al., 2001a), show that severely burned basins are more likely to produce large debris flows than similar basins with low burn severity, even during 1–2 year storm events. Conversely, basins burned in patchy or lower severity fires produce erosional events with lower proportions of sediment, such as sheetfloods or floods (e.g., Pierce et al., 2004). While other factors such as storm severity can also control the type of erosional response following fire, for a given basin, variations in the types of fire-related deposit can be used to infer possible changes in fire severity and extent within a given basin.

We prioritized annually-produced wood (i.e. twigs, leaves, seeds) for radiocarbon dating to decrease "inbuilt age," which is the difference between the age of wood formation and date of fire (Gavin, 2001). We selected angular wood fragments over rounded ones, according to Folk (1965), to avoid dating re-worked charcoal (e.g., Meyer et al., 1995). Charcoal macrofossils (defined as >1 mg) were dated with Accelerator Mass Spectrometry (AMS) ^{14}C. AMS ^{14}C dates were calibrated into calendar years before 1950 AD. (cal yr BP) using the CALIB 6.0.1 program (Stuiver and Reimer, 1993) and results are presented as the median of the 1σ and 2σ age distributions (Table 3). Individually calibrated fire ages were summed and presented as a cumulative probability distribution.

Given the resolution of radiocarbon dating and inbuilt age of the charcoal, it is not possible to determine if charcoal samples with overlapping 1σ and 2σ ages were produced from the same fire.

Table 2
Summary of deposit characteristics at CIRO.

Depositional process	Deposit characteristics	Sorting	Texture	Clast size range	Maximum clast size	Deposit thickness
Sheetflood deposit	Clast-supported, form alternating fine/coarse grained couplets	Moderately-well sorted	Fine unit: loam, sandy-loam, silty-loam, coarse unit: sand, loamy-sand, sandy-loam	Fine unit: <20% coarser than 2 mm, coarse unit: 20–50% coarser than 2 mm	Fine unit: 3 mm, Coarse unit: 10 mm	Individual couplets vary between 0.25 and 6 cm
Debris flow deposit	Matrix-supported, randomly oriented clasts floating in a fine-grained matrix, form cohesive vertical and sometimes overhanging faces in stratigraphic profile	Poorly-sorted	Matrix: loam, silty-loam, sometimes silty-clay-loam	30% coarser than 2 mm	1–20 cm, rarely exceed 20 cm	Vary in depth but can reach 100+ cm
Overbank deposit	Thick, fine-grained units	Well-sorted	Loam, silty-loam, silty-clay-loam	5–40% coarser than 2 mm	Finer than 10 mm	Vary in depth but can reach 75 cm
Channel flood deposit	Clast-supported, imbrication	Poorly to moderately-well sorted	Sand	5–50% coarser than 2 mm	30 cm	Vary in depth but can reach 75 cm

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Table 3
Data table summarizing 1) site and sample identification, 2) uncalibrated ages and associated errors, 3) calibrated ages including 1σ and 2σ error ranges, 4) median calibrated age, 5) associated depositional processes abbreviated as SF = sheetflood deposit, DF = debris flow deposit, OB = overbank deposit, CF = channel flood deposit and BS = buried soil, 6) location in stratigraphic profile, 7) wood type, 8) charcoal species abbreviated as J = juniper, SB = sagebrush and P = pine with relative percentages of each vegetation type shown in parentheses and ordered respectively, 9) and charcoal abundance within the deposit.

Site ID	Lab ID	Sample ID	^{14}C age BP	Analytical error ±	Calibrated age (cal yr BP)	Error (1σ)	Error (2σ)	Deposit type	Depth (cm)	Charcoal type	Burned vegetation-type (%) (J) (SB) (P)	Charcoal abundance
Drainage Basin: Almo Creek												
A1	80536	KWCA02-2-3A	485	20	520	512–527	506–535	SF	130	Twig	(17) (67) (17)	Abundant
	AA88400	KWCA02-5	2428	39	2470	2370–2514	2362–2582	SF	185	Wood	(40) (40) (20)	Present
A2	80537	AHCA06B-3	900	20	810	767–839	756–886	SF	135	Wood	(0) (100) (0)	Scarce
Drainage Basin: Stines Creek												
S3	80538	AHCA04	10,875	35	12,740	12,656–12,803	12,626–12,887	BS/DF	105	Wood	Not identified	Scarce
Drainage Basin: Graham Creek												
G4	AA88389	KWCR06-3	1655	37	1560	1521–1609	1418–1468	DF	90	Twig	(50) (7) (43)	Abundant
Drainage Basin: Circle Creek, location: North Fork of Circle Creek												
C5	AA88388	SPCR03-1	180	35	180	132–208	103–300	DF	50	Wood	(38) (25) (38)	Present
C6	AA88390	NCCR01-1	415	35	490	485–495	480–500	SF	80	Twig	(40) (50) (10)	Present
	AA88391	NCCR01-4	356	35	400	377–428	314–498	DF	135	Wood	(28) (40) (32)	Abundant
	AA88397	NCCR04-5B	846	42	760	708–790	681–802	SF	160	Twig	(0) (89) (11)	Present
Drainage Basin: Circle Creek, location: Middle Fork of Circle Creek												
C7	AA88398	KWCR15-1	913	36	830	781–880	750–917	OB	95	Wood	(15) (69) (15)	Abundant
Drainage Basin: Circle Creek, location: South Fork of Circle Creek												
C8	AA88396	TRCR02-2B	786	36	710	682–724	671–752	DF	75	Wood	(40) (60) (0)	Present
	80,524	TRCR02-4A	3990	20	4490	4483–4512	4418–4450	SF	160	Branch	(35) (35) (41)	Present
	80525	TRCR05A-1	8605	25	9550	9535–9567	9519–9588	DF	175	Wood	not identified	Scarce
	80526	TRCR05C-4	9155	25	10,290	10,250–10,319	10,240–10,319	SF	250	Wood	(67) (11) (22)	Abundant
	80527	TRCR05B-5	9390	25	10,620	10,572–10,657	10,549–10,702	SF	300	Wood	(100) (0) (0)	Scarce
C9	AA88384	KRCR01-1A	308	35	390	358–430	298–469	SF	25	Needle	(47) (27) (27)	Abundant
	AA88385	KRCR01-7B	425	35	490	468–516	430–531	SF	150	Pod	(7) (57) (36)	Abundant
C10	AA88387	KWCR04-1	3393	41	3640	3607–3687	3554–3725	SF	50	Twig	(50) (50)	Scarce
	AA88392	KWCR11-1	9469	56	10,720	10,598–10,783	10,553–10,869	OB	230	Wood	(100) (0) (0)	Present
C11	80534	KWCR03-2-1A	2250	20	2290	2288–2327	2182–2331	DF	75	Wood	(33) (0) (67)	Abundant
	80535	KWCR03-2-2	2050	20	2020	1988–2019	1972–2033	CF	140	Wood	not identified	Abundant
C12	80518	TRCRO4-1C	375	20	450	334–349	325–363	SF	60	Seed	(32) (32) (37)	Abundant
	80519	TRCRO4-2B	660	20	610	567–584	562–594	SF	115	Branch	(33) (67) (0)	Abundant
	80520	TRCR04-3B	770	20	690	676–699	674–727	DF	145	Seed	(23) (46) (31)	Abundant
	80521	TRCR04-5	5995	20	6830	6792–6866	6761–6897	DF	250	Wood	(0) (33) (67)	Present
	80522	TRCR04-6A	6090	20	6950	6928–6980	6894–7007	DF	335	Wood	(8) (46) (46)	Abundant
	80523	TRCR04-7B	6280	60	7210	7154–7290	7012–7330	SF	380	Wood	(0) (45) (55)	Abundant
C13	80539	AHCR19-3	175	20	184	150–189	268–282	DF	75	Twig	(40) (40) (20)	Abundant
Drainage Basin: Circle Creek, location: Main Fork of Circle Creek												
C14	80528	CCCR01-2-1	4135	20	4680	4602–4684	4580–4801	SF	83	Wood	(0) (100) (0)	Scarce
	AA88386	CCCR01-2B	5864	45	6680	6632–6733	6549–6782	SF	180	Wood	(0) (43) (57)	Present
	80529	CCCR02-4	6165	20	7080	7017–7128	6989–7167	SF	230	Wood	(0) (72) (28)	Abundant
Drainage Basin: Heath Canyon												
H15	AA88394	KWCR17-1	189	34	180	147–191	136–225	SF	30	Twig	(25) (0) (75)	Abundant
	80531	KWCR18-2-2B	2230	20	2240	2185–2243	2169–2318	BS/DF	290	Wood	(0) (67) (33)	Abundant
	80532	KWCR18-2-3B	5905	20	6720	6714–6743	6670–6756	DF	350	Pod	(33) (0) (67)	Abundant
	80533	KWCR18-2-3C	6230	25	7170	7137–7214	7041–7227	DF	420	Wood	(92) (0) (8)	Abundant
	AA88393	KWCR12-4B	8862	59	9970	9882–10,148	9728–10,148	DF	500	Wood	(92) (0) (8)	Abundant
	AA88395	KWCR18-3	10,034	56	11,540	11,395–11,643	11,278–11,770	DF	560	Twig	(71) (12) (18)	Abundant

Separate sites containing charcoal with similar ages that were geographically distinct (i.e., found in separate tributaries) were assumed to represent periods of multi-basin fires, and large probability peaks were used to denote large, widespread fire events. Small and/or lower severity fires are inferred from fire-related sheetflood deposits, whereas large and/or higher severity fires are inferred from fire-related debris flow deposits (Meyer et al., 2001; Pierce et al., 2004).

We applied a stratigraphically-based model to correct the fire record for “taphonomic bias”, which is the over-representation of younger macrofossils relative to older macrofossils due to destructive weathering and erosional processes observed in archeological and geologic records. Surovell et al. (2009) based this empirical model on terrestrial records of volcanic ash deposition where frequency distributions appear to diminish over time and on ice sheet records of volcanic deposition that are presumably not subjected to destructive terrestrial processes because they do not exhibit characteristics of a fading record. The correction is as follows:

$$n_t = 5.73 \times 10^6 (t + 2176.4)^{-1.39}$$

where n_t is the number of radiocarbon dates surviving from time t.

Surovell et al. (2009) recommend application of the taphonomic bias correction for samples older than 750 cal yr BP because younger samples are least likely to experience decomposition. We suggest that the fading fire record at CIRO, however, is primarily a function of depth of incision, where fire-related deposits deeper than natural exposures are not exposed and therefore not sampled. All but one exposure with ages <5000 cal yr BP (96%) were sampled from 0–200 cm depth,

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while 77% of samples with ages >5000 cal yr BP are exposed between 200 and 600 cm. One debris flow deposit containing sparse charcoal was dated 12,700 cal yr BP. Several fire-related deposits older than 9000 cal yr BP, however, contain abundant charcoal, suggesting that charcoal decomposition is not as important as stratigraphic exposure, or that charcoal preservation varies on a site-by-site basis (Table 3). Based on these age–depth relationships, taphonomic bias likely plays a secondary role in the CIRO record. Accordingly, the Surovell et al. (2009) correction was applied only to ages >5000 cal yr BP, when ages are under-represented due to lack of exposure.

We binned the radiocarbon-dated and stratigraphically-inferred ages of deposits (based on location within the profile, upper and lower age constraints, and depositional characteristics) into 500-year bins to identify Holocene trends in fire-related sedimentation, and separated debris flow deposits, sheetflood deposits and overbank deposits to examine changes in depositional process over time. We identified and classified charcoal macrofossils (10–200 mg) using a 20× power microscope as "pine", "juniper" or "sagebrush" based on wood characteristics (see Weppner, 2012) by comparison with magnified images and descriptions of burned wood (Adams and Murray, 2011). Based on first appearance in the woodrat midden record, we assumed that pine charcoal prior to 2800 cal yr BP belongs to limber pine, and after that date to either limber pine or single-leaf pinyon. We assumed that juniper charcoal before 3800 cal yr BP was Rocky Mountain juniper, whereas charcoal since then was Utah juniper or Rocky Mountain juniper.

Thirty fossil woodrat middens were collected, dated and analyzed, spanning the last 45,000 yr, using well-established methods detailed in Betancourt et al. (1990). Here we focus primarily on the occurrences of Utah juniper and single-leaf pinyon plant macrofossils, and the inferred colonization and expansion history of these two trees. In addition, we infer periods of high ecosystem productivity during the Holocene (i.e., times when woodrat populations flourished and midden construction increased) from relative abundances of radiocarbon ages in middens from CIRO, Oneida Narrows in southeastern Idaho and the Lost River Range in south-central Idaho (Webb and Betancourt, 1990; Smith and Betancourt, 2003). Midden ages were not corrected for taphonomic bias because middens are typically preserved in rock shelters and therefore less susceptible to erosion and weathering processes.

Results

The midden record indicates that Rocky Mountain juniper, limber pine and sagebrush have occupied CIRO since ~45,000 cal yr BP. Utah juniper colonized CIRO ~3800 cal yr BP and single-leaf pinyon ~2800 cal yr BP (Fig. 5a). Single-leaf pinyon is abundant in middens from ~2800–2400 cal yr BP, but absent in ones dated ~2400–700 cal yr BP. This suggests that either slow expansion or colonization occurred as two events, with the first event as a failed invasion and the second event successfully establishing single-leaf pinyon as the dominant species after 700 cal yr BP. (Fig. 5b). Summed probability distributions of midden radiocarbon ages from CIRO, Oneida Narrows, and the Lost River Range record a peak between 5000 and 1500 cal yr BP. No midden ages are recorded between ~1500 and 1100 cal yr BP, but increase again 700–300 cal yr BP (Fig. 5c; Smith and Betancourt, 2003).

Alluvial charcoal radiocarbon ages show five episodes of enhanced fire activity during the Holocene (Fig. 5d). The first episode (~10,700–9500 cal yr BP) records five fires in Circle Creek and Heath Canyon over a ~1000 year period, the second fire episode ~7200–6700 cal yr BP records seven fires in Circle Creek and Heath Canyon during a ~500 year timeframe, and the third fire period (~2400–2000 cal yr BP) records five fires in Circle Creek, Heath Canyon and Almo Creek during a ~400 year period. The two most recent fire episodes are the most geographically widespread (fires burned in all basins except Graham Creek) and occurred 850–700 and 550–400 cal yr BP recording 15 fires during ~450 yr. No fires were recorded between 9500–7200 and 6700–4700 cal yr BP (see Weppner, 2012 for more details).

Two stratigraphic profiles (C6 and C11) produced stratigraphically-inverted radiocarbon ages from distinct deposits with clear boundaries. Because 1σ and 2σ age errors do not overlap (Table 3), we infer that older macrofossils were transported from an earlier fire. Although these ages cannot date depositional process, they do represent timing of past fires because all ages are from charcoal fragments.

Charcoal identification, where possible, showed mostly juniper (79%; cf. *J. scopulorum*) between 11,500 and 9900 cal yr BP, while pine (cf. *P. flexilis*) and sagebrush account for 14% and 7%, respectively. Between 7200 and 6700 cal yr BP, macrofossils consist of 20% juniper (cf. *J. scopulorum*), 40% sagebrush and 40% pine (cf. *P. flexilis*). At 4700–1500 yr BP, which includes the period during first colonization of *J. osteosperma* and *P. monophylla*, was split roughly three ways among juniper (cf. *J. scopulorum*/*J. osteosperma*), sagebrush, and pine (*P. flexilis*/*P. monophylla*). Between 850–700 and 550–400 cal yr BP, however, the majority of the charcoal samples were sagebrush (Fig. 5e).

Deeply-incised arroyos that contain abundant fire-related deposits are common in granitic and gneissic basins at CIRO (Table 1). However, fire-related deposits are limited in deep arroyos formed in quartzite basins (Table 1). This suggests that hillslopes formed in more resistant quartzite are less susceptible to fire-related erosional events. For example in 2000, a mixed-severity crown fire burned ~8.5 km^2 in quartzite terrain of southern CIRO (Monitoring Trends in Burn Severity, 2011). Local residents observed increased fire-related surface erosion during a storm event a few days following this fire (Morris, 2006), which probably was due to surface rilling (Skakesby and Doerr, 2006). There was no field evidence, however for large-scale, post-fire erosion, such as sheetflood or debris flow deposition. The quartzite terrain, now characterized by standing dead pinyon and juniper, has since been invaded by cheatgrass. By contrast, field observations in granitic and gneissic basins indicate active arroyo cutting and regular sheetflood transport of sediments from upstream channels and arroyos. During a two-week storm totaling 2 cm of precipitation (July–August 2010; Western Regional Climate Center), 30 cm of material was eroded from the base of arroyo C12, fresh incision occurred at arroyos C8 and H15, and sheetfloods were deposited elsewhere. Debris flows, however, are rare in the modern record because no large fires have burned in granitic basins. In the paleorecord, sheetflood deposits comprise 57% of total measured alluvial thickness, whereas debris flow deposits and overbank deposits make up 37% and 6% of alluvial thickness, respectively (Fig. 5f).

Between 6500 and 2500 cal yr BP, only 4% of alluvial thickness was deposited, and debris flow deposition was minimal (Fig. 5f). Four thin (<10 cm), muddy debris flow deposits containing fine-grained clasts were identified during this time. These deposits are notably different from the thick (>40 cm) debris flow deposits containing coarser clasts, four of which were deposited before 9500 cal yr BP, and fourteen were deposited after 2400 cal yr BP. (Figs. 3 and 5f). Stratigraphic age gaps were observed at C12 between ~700 and 7000 cal yr BP, which is separated by 100 cm of undated charcoal-poor sheetfloods, and at H15 between 2200 and 6800 cal yr BP (Fig. 3). Neither site, however, shows stratigraphic evidence of erosion (e.g., cut-and-fill or unconformable contacts between deposits), and dated units are laterally continuous within exposures.

Although modern soils at CIRO are poorly developed, with absent to weakly developed B-horizons (USDA et al., 2011), we observed four well-developed Holocene soils (Weppner, 2012). At site S3, A and Bt horizons developed on a 12,700 cal yr BP debris flow deposit that was subsequently buried by sheetfloods and capped by an undated debris flow deposit that also exhibits extensive soil development. At H15, A and Bt horizons are developed on a ~2230 cal yr BP debris flow deposit buried under <300 cal yr BP sheetflood deposits. Another soil containing a Bt horizon was developed on a 2290 cal yr BP fire-related debris flow deposit exposed in streambank site C10/C11.

Q7

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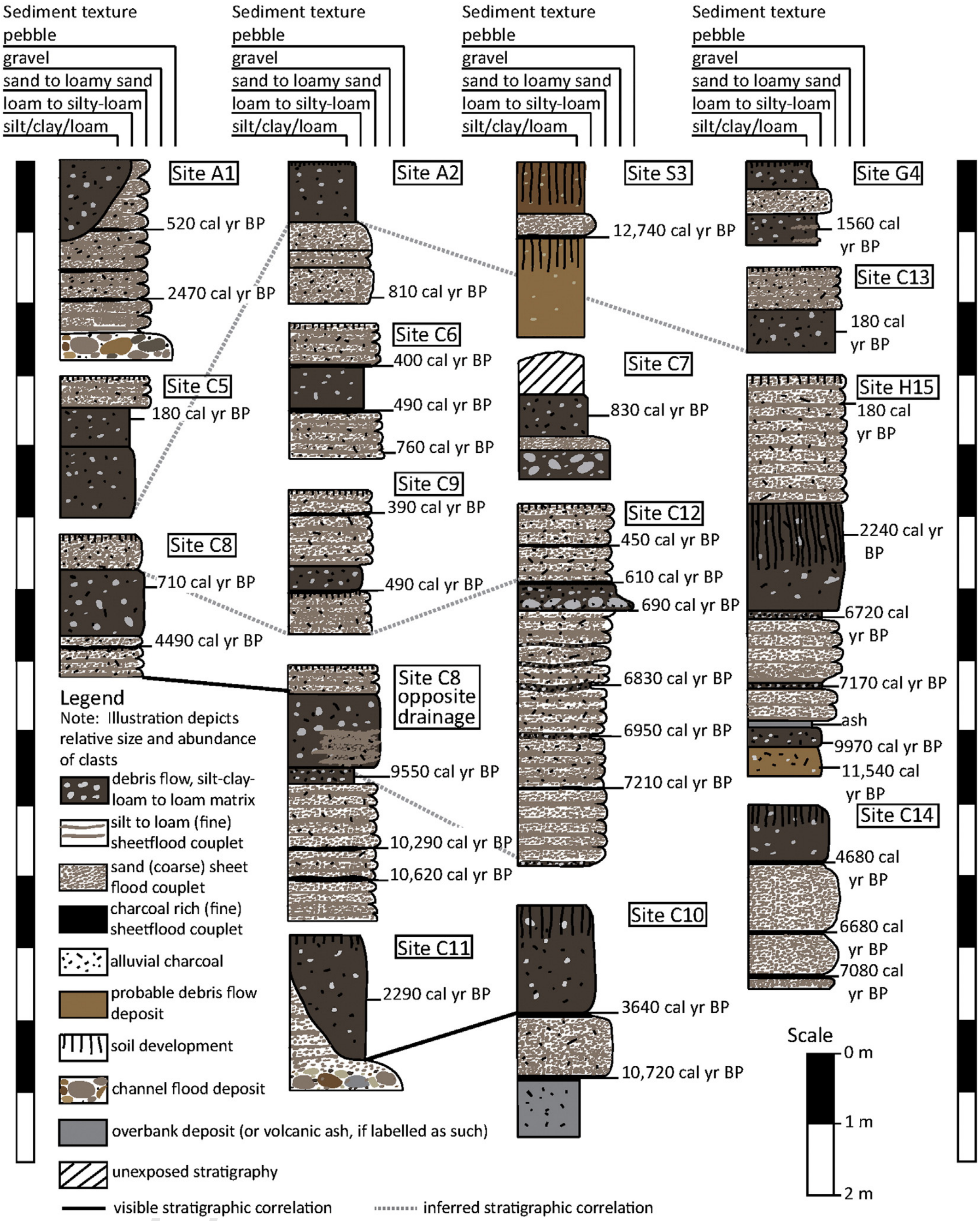

Figure 3. Summary illustration of the stratigraphic characteristics of each charcoal sampling site. Stratigraphic correlations between sites are shown by solid black lines for visible stratigraphic correlations and by dotted gray lines for inferred stratigraphic correlations. A black/white vertical scale is provided on each side of the figure.

Discussion

Holocene fire and vegetation at CIRO

The CIRO alluvial charcoal record shows both discrete peaks in fire activity and intervals of no fire-related sedimentation over the last 13,000 yr. Examination of the fire record within the context of vegetation change from local and regional woodrat midden series indicates that some peaks in fire activity correspond temporally with vegetation shifts. Independent regional records of Holocene climate change suggest that climate drives shifts in vegetation, fire regime and fire-related deposition. Below we discuss these trends within four characteristic time periods of the Holocene (Fig. 6).

Early Holocene (13,000–9500 cal yr BP)

Beginning ~11,500 cal yr BP at CIRO, post-glacial climate warmed abruptly (Davis et al., 1986; Murchison, 1989; Madsen et al., 2001; Doner, 2009; Louderback and Rhode, 2009) and frequent fires produced charcoal mostly identified as juniper, which we assumed to be Rocky Mountain juniper (Figs. 5a, 6). Regionally, lake charcoal records indicate that fire frequency increased throughout a wide range of ecosystems in response to the drying and dying of Pleistocene vegetation (e.g., Millspaugh et al., 2000; Power et al., 2008a,b; Marlon et al., 2009; Whitlock et al, 2012). Regional vegetation reconstructions Q8 from pollen and midden records indicate increases in southern or lower elevation plants 11,500–9500 cal yr BP (Fig. 6; Jackson et al.,

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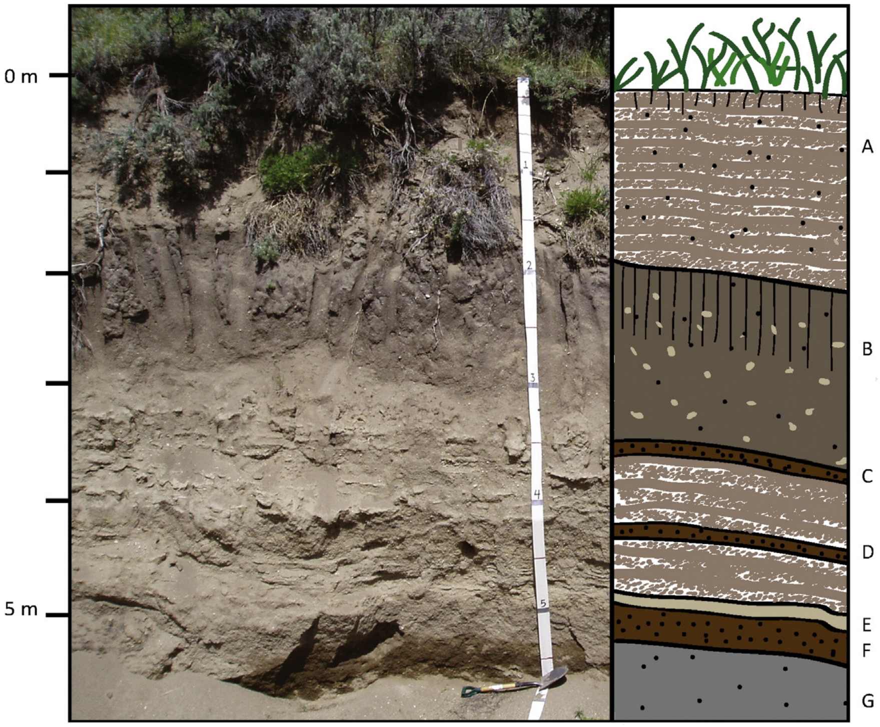

Figure 4. Arroyo site H15. Unit A consists of charcoal-rich sheetflood deposits that are younger than 300 cal yr BP. Unit B is a buried soil developed on a 2240 cal yr BP charcoal-rich debris flow deposit that forms abrupt upper and lower boundaries. Units C and D are both thin, muddy charcoal-rich debris flow deposits dated 6720 and 7170 cal yr BP, respectively. Both units overlie thick packages of undated, charcoal-poor sheetflood deposits which we infer to have been deposited during the drier middle Holocene on sparsely vegetated hillslopes. Unit E is a tephra unit that was not dated because it was contaminated by significant mixing. Unit F is a 9970 cal yr BP charcoal-rich debris flow deposit. Unit G is a thick 11,540 cal yr BP charcoal-rich debris flow deposit.

2005; Doner, 2009; Louderback and Rhode., 2009). During the same time, CIRO experienced a reduction in the dominance of limber pine and extirpation of mixed-conifer and subalpine elements. Seven fires were recorded at CIRO before 9500 cal yr BP. Given the poor preservation of charcoal and the lack of exposure of early Holocene stratigraphy, the actual number of fire-related sedimentation events probably was much higher (Surovell et al., 2009), indicating an interval of widespread and severe fires at CIRO.

Early to Middle Holocene (9500–6500 cal yr BP)

No fires were recorded at CIRO between 9500 and 7200 cal yr BP (Fig. 5c) when regional climate was characteristically wetter and cooler, as indicated by lake records from Bear Lake, Idaho and the Uinta Range, Utah (Fig. 6; Moser and Kimball, 2009; Corbett and Munroe, 2010) and by a 8300 cal yr BP Lake Bonneville highstand, possibly 60 m higher Q9 than the Gilbert shoreline (Fig. 6; Oviatt, 1997; Patrickson et al., 2010). The highstand and other regional climate correspond to the “8.2 ka cool interval”, a widely-recognized Heinrich event (e.g., Alley et al., 1997) that increased local snowpacks (Dean et al., 2002).

Climate began to warm 8200–4000 cal yr BP (Louderback and Rhode, 2009) when regional midden records indicate decreased ecosystem productivity (Fig. 5b; Smith and Betancourt, 2003), Lake Bonneville was periodically low (Murchison, 1989), and pinyon–juniper (PJ) woodlands in the Great Basin inhabited elevations 500 m higher than today (Miller and Tausch, 2001). Records from Lake Bonneville and Bear Lake, however, suggest briefly wetter, cooler conditions beginning 7500 cal yr BP (Fig. 6; Murchison, 1989; Doner, 2009; Louderback and Rhode, 2009) that may have increased fuels for frequent fires between 7200 and 6700 cal yr BP at CIRO. Post-Mazama (~7700 cal yr BP; Zdanowicz et al., 1999) increases in lake sediment charcoal 20 km north at higher elevation Lake Cleveland (Davis et al., 1986) corroborate the CIRO record, suggesting large and widespread fires (Fig. 6). Alluvial charcoal records from lodgepole forests in Yellowstone, south-central Idaho sagebrush steppe, central Idaho lodgepole-dominated forests, and central Idaho ponderosa forests also show increased fire activity between 7500 and 6200 cal yr BP (Fig. 7; Meyer et al., 1995; Meyer and Q10 Pierce, 2003; Pierce et al., 2004; Nelson and Pierce, 2010; Riley, 2012) during extended warmer, drier climate in the Rockies (Shuman et al., 2009).

Middle Holocene fires at CIRO may mark structural changes in vegetation; sampled charcoal macrofossils switched from mostly Rocky Mountain juniper to 20% Rocky Mountain juniper, 40% sagebrush and 40% limber pine (Table 3; Fig. 5a). The geomorphic response also shifted from episodic debris flows to frequent fire-related and charcoal-poor sheetflooding events. Charcoal-poor sheetflooding suggests increased hillslope erosion on sparsely vegetated (fuel-limited) hillslopes (Pierce et al., 2004). In central Idaho, analogous post-fire sheetflooding was recorded in the South Fork Payette and Middle Fork Salmon River drainages during the 7500–6200 cal yr BP fires (Pierce et al., 2004; Riley, 2012). Unlike CIRO, the Payette and Salmon watersheds are characterized by steep, granitic hillslopes prone to post-wildfire debris flows. However during this fire-prone period, debris flow activity was limited and frequent sheetflood deposition occurred at the base of what are now debris flow-prone, north-facing, and forested slopes (Meyer et al., 2001; Pierce et al., 2004; Riley, 2012).

Middle to Late Holocene (6500–2500 cal yr BP)

No fires were recorded at CIRO between 6700 and 4700 cal yr BP during regional, prolonged drought (Fig. 6; Murchison, 1989; Louderback and Rhode, 2009; Shuman et al., 2009; Corbett and Munroe, 2010; Whitlock et al., 2012), when upper treeline in the Albion Mountains reached maximum elevations at 4500 cal yr BP (Davis et al., 1986). At CIRO, low vegetation densities following previous fires, sustained by persistent drought, inhibited fuel accumulation on hillslopes. Similar fire-free periods are registered in other alluvial charcoal records, suggesting that low fuel supplies were regionally persistent (Fig. 7; Pierce et al., 2004; Nelson and Pierce,

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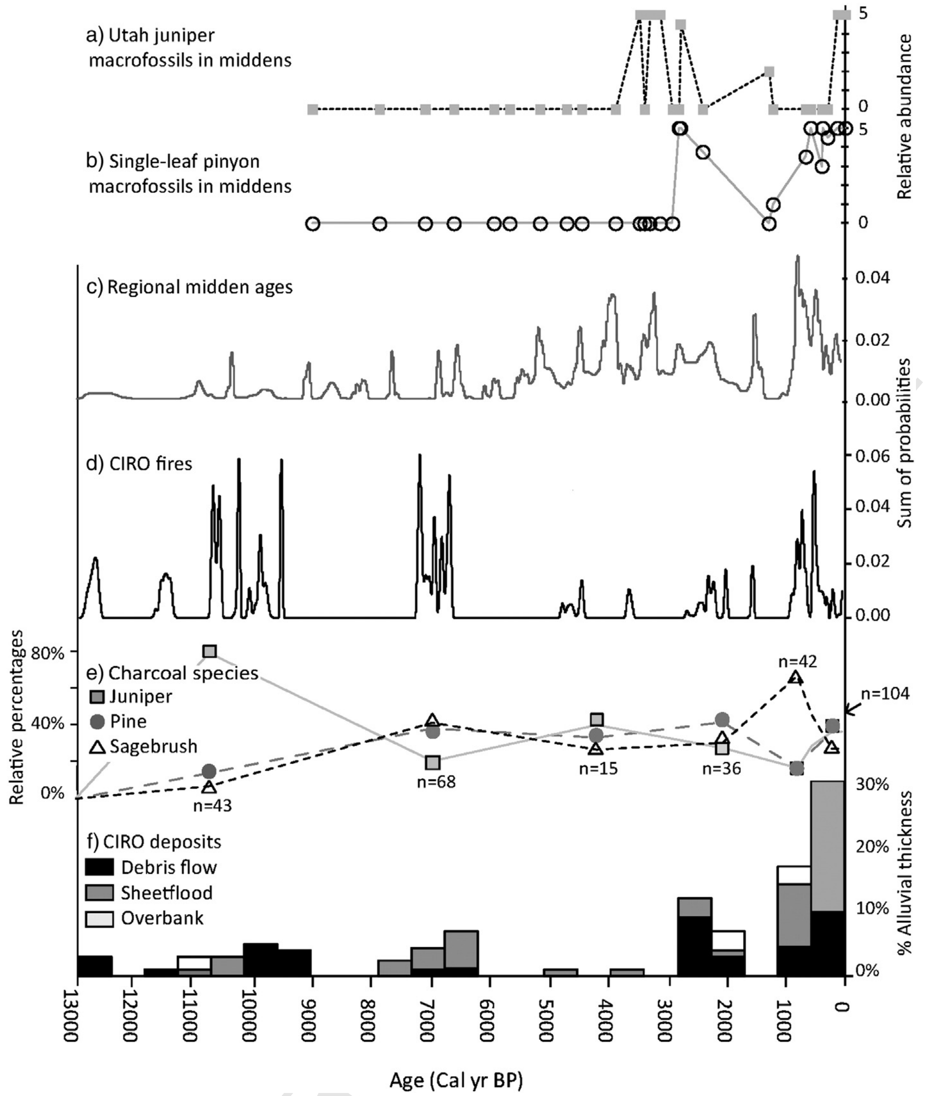

Figure 5. Summary of results from fire, vegetation and depositional processes data plotted versus time. Relative abundance of a) Utah juniper and b) single-leaf pinyon plant macrofossils in CIRO woodrat middens; c) calibrated radiocarbon ages for middens in southern Idaho as an indicator of ecosystem productivity, d) calibrated radiocarbon ages for alluvial charcoal with >5000 cal yr BP ages corrected according to Surovell et al., 2009, e) relative percent of charcoal species, plotted as discrete points and binned per mean age of fire interval (dashed lines simply connect points), and f) stratigraphic record of percent alluvial thickness per depositional process.

2010; Svenson, 2010). In northeastern Yellowstone, however, fire activity increased beginning ~6500 cal yr BP in a moist, densely vegetated ecosystem where past fires have been correlated with severe drought (Fig. 7; Meyer et al., 1995).

Fires at CIRO were infrequent between 4700 and 3600 cal yr BP when regional midden records suggest a return to cooler, wetter climate ~4500–2000 cal yr BP (Fig. 5b; Smith and Betancourt, 2003). Lake Bonneville shorelines elevated (Murchison, 1989), upper treeline descended in the Albion Mountains (Davis et al., 1986) and other regional paleoclimate records suggest cooler, wetter climate (Fig. 6; Madsen et al., 2001; Mensing et al., 2008; Louderback and Rhode, 2009). During this time, Utah juniper migrated to CIRO 3800 cal yr BP, followed by single-leaf pinyon 2800 cal yr BP (Fig. 5c).

Westerling et al. (2011) predicts that as climate warms, fire rotation times will progressively decrease until there is insufficient time for forest regeneration between fire events. Eventually, fire strips the landscape of available fuels. This paradigm may be reflected in the CIRO record when frequent fires during the interval 7200–6700 cal yr BP were followed by no recorded fires until 4700 cal yr BP, potentially due to exhaustion of fuels accumulated during the earlier wetter interval. Prior to the ~7200–6700 cal yr BP fires, limber pine, Rocky Mountain juniper and sagebrush occupied CIRO. Although single-leaf pinyon had not yet arrived, estimates for post-fire regeneration of PJ woodlands are 150–200 yr (Goodrich and Barber, 1999), while post-fire sagebrush recovery takes 35–100 yr (Baker, 2006) and >500 yr are estimated for regeneration of limber pine forests (Rebertus et al., 1991). During the 7200–6700 cal yr BP fires, CIRO burned a minimum of seven times. Although this frequency applies to the entire study area (not individual basins), synchronous fire activity at nearby Lake Cleveland (Davis et al., 1986) suggests widespread fires. This high fire frequency may have exceeded the time interval needed for the regeneration of limber pine and Rocky Mountain juniper, and persistent warm and dry conditions after ~6700 cal yr BP likely continued to reduced vegetation densities and suppress fire.

Late Holocene (2500 cal yr BP-present)

Recent Holocene fires at CIRO burned when ecosystem productivity was high (e.g., denser forest and continuous fuels; Smith and Betancourt, 2003; Fig. 5b) and correspond to regional droughts that were preceded by above average moisture (Fig. 8). Frequent fires

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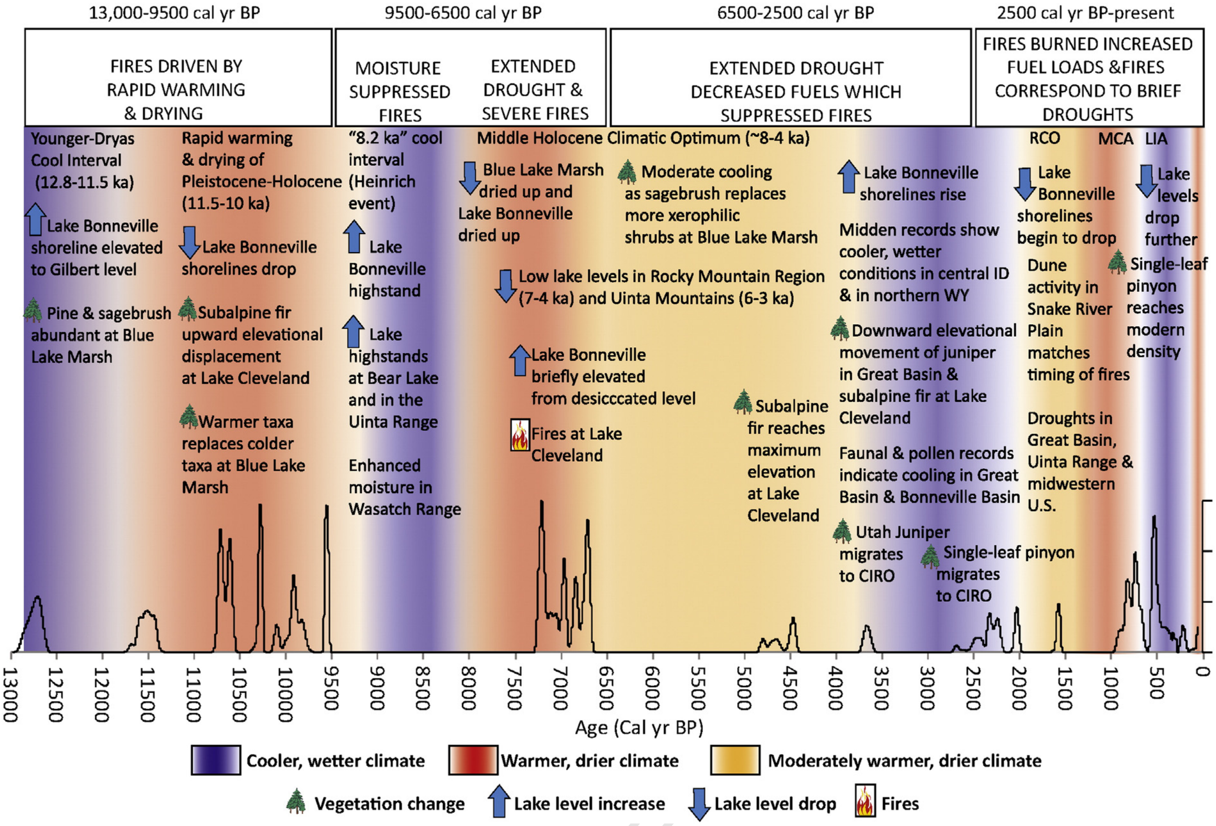

Figure 6. Summary of regional and global climate conditions compared with the CIRO fire record. The top of the figure references time periods discussed in the text and general fire trends from the CIRO charcoal record. The upper text of the climate summary shows widely recognized climatic variations within the Holocene (e.g., Lamb, 1972; Berger, 1978; Q2 Alley et al., 1997; Bianchi and McCave, 1999; Grove, 2001; Dean et al., 2002; Kaufman et al., 2004). RCO refers to the Roman Climate Optimum, MCA refers to the Medieval Climatic Q3 Anomaly and LIA refers to the Little Ice Age. Regional and local climate events are also shown (Davis et al., 1986; Murchison, 1989; Oviatt, 1997; Madsen et al., 2001; Dean et al., 2002; Smith and Betancourt, 2003; Gray et al., 2004; Jackson et al., 2005; Doner, 2009; Louderback and Rhode, 2009; Moser and Kimball, 2009; Shuman et al., 2009; Corbett and Munroe, 2010; Patrickson et al., 2010; Rittenour and Pearce, 2011).

burned during PJ expansion, indicating that fuel availability was likely no longer limiting fire at CIRO.

Fires that burned at CIRO between 2400 and 2000 cal yr BP correspond to ~2 ka drought (inferred from dune activation in the Snake River Plain, ID, Rittenour and Pearce, 2011), and to multidecadal droughts (2500 and 2200 cal yr BP) at Mission Cross Bog, NV (Fig. 8; Mensing et al., 2008). Comparison of CIRO fires after 1600 cal yr BP with reconstructed PDSI (Cook et al., 2004) indicates that all recorded fires were preceded by wetter than average conditions but ignition occurred during drought. These reconstructed PDSI droughts are corroborated by multiple climate records (Fig. 8; Gray et al., 2004; Stahle et al., 2007; Rittenour and Pearce, 2011). No fires were recorded between 1500 and 1000 cal yr BP, when PDSI reconstruction indicates warmer but less variable climate (Fig. 8; Cook et al., 2004).

After its arrival, single-leaf pinyon expanded slowly and did not establish dominance across CIRO until 700 cal yr BP. Macrofossil evidence (Fig. 5a) suggests fires ~850–700 and 550–400 cal yr BP burned mostly in stands of sagebrush; reduction in sage cover could have facilitated single-leaf pinyon infilling in rocky areas and encroachment on adja-
Q12 cent sagebrush stands that occupy deeper soils (Chambers, 2001).

Increased forest densities during the Little Ice Age (LIA) likely supplied fuel for the greatest recorded fire peak at CIRO 550–400 cal yr BP, a fire peak that is also recorded in multiple regional alluvial charcoal records across a range of ecosystems in Idaho including the sagebrush steppe of Wood Creek (Nelson and Pierce, 2010), the ponderosa and Douglas fir dominated South Fork of the Payette (Pierce et al., 2004), the lodgepole pine to rangeland ecosystems of the Middle Fork of the Salmon River (Riley, 2012), and the lodgepole and mixed conifer forests of the Sawtooths (Fig. 7; Svenson, 2010). While the timing of this fire peak is similar, these separate ecosystems likely burned differently; for example, in the South Fork Payette, frequent, low-severity fires typical of ponderosa pine and Douglas fir forests were prevalent, although some of these fires were likely stand-replacing (Fig. 7; Pierce et al., 2004). At CIRO, a new fire regime likely took hold, and high-severity fires typical of PJ woodlands (Baker and Shinneman, 2004; Romme et al., 2009) and sagebrush steppe (Kauffman and Sapsis, 1989) produced multiple, fire-related debris flow and sheetflood deposits that account for approximately 50% of the total measured alluvial thickness (Fig. 5f).

Holocene shifts in fire-related geomorphic response

The nature of Holocene alluvial deposits may reveal shifts in past hillslope vegetation densities and the nature and severity of wildfires. Unlike lake charcoal records, alluvial charcoal records are not continuous; however, the episodic nature of alluvial deposition provides insight into both fire activity and landscape response. For example, modern and paleorecords of fire-related deposition have shown that sheetfloods are characteristically deposited following low-severity fires or following storms/fires on drier or south-facing slopes, whereas post-fire debris flows often follow high-severity fires burning forested slopes (Cannon et al., 2001a,b; Meyer et al., 2001; Pierce et al., 2004). Cannon et al. (2010) identified a 16.7° slope threshold for debris flow formation. Mean slopes at CIRO are ~15.6° indicating past fires may not have generated debris flows on most hillslopes. Yet, our record shows that episodic fire-related debris flows were deposited during the early and late Holocene, but were rare between 7000

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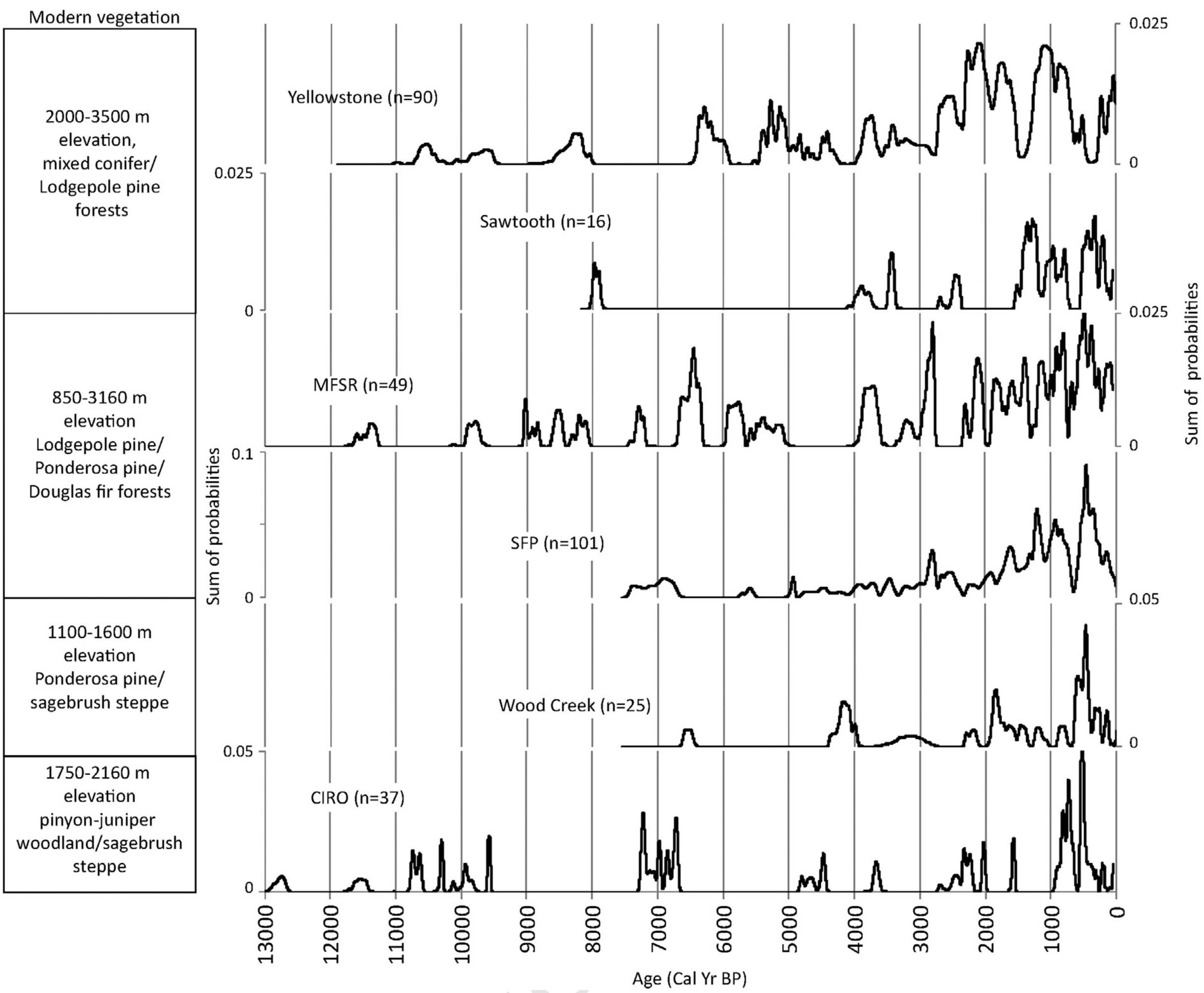

Figure 7. Regional alluvial charcoal records (moving top to bottom) from Yellowstone National Park, WY (Meyer et al., 1995), the Sawtooth Mountains, Idaho (Svenson, 2010), Middle Fork of the Salmon River, ID (MFSR; Riley, 2012),Wood Creek, ID (Nelson and Pierce, 2010), the South Fork of the Payette River, ID (SFP; Pierce et al., 2004) and the CIRO record. The general modern ecosystem characteristics (elevation and forest-type) are shown along the left side of the figure and correspond to the alluvial charcoal data shown on the right side. The sum of probability axes vary between records and sample population sizes are given for each record. As demonstrated in the text, the Surovell et al. (2009) correction should be applied to each study area based on individual study area characteristics, therefore the CIRO data and the other included alluvial charcoal data have not been corrected for taphonomic bias in this figure.

and 2500 cal yr BP when sheetfloods comprise the majority of deposits (Fig. 5d).

At CIRO, the notable absence of fire-related debris flow deposition between 7000 and 2500 cal yr BP during warmer, drier climate (Fig. 4D) suggests several scenarios that are not mutually exclusive: 1) a discontinuous fuel source restricted fire size and severity; 2) frequent sheetflooding limited colluvial storage and soil development of in situ-weathered silt and clay-sized particles; and 3) the drier climate of the mid-Holocene restricted storm events needed to ignite fires and produce debris flows (Fig. 9). Unless the combined conditions of severe fire, adequate silt and clay-rich colluvium, and storms are met, our records indicate that debris flows are not common at CIRO.

The July insolation maximum (Berger, 1978) was manifested by regionally warmer, drier climate between ~8 and 4 ka that likely reduced hillslope vegetation density (Murchison, 1989; Louderback and Rhode, 2009; Shuman et al., 2009; Corbett and Munroe, 2010). Enhanced erosion rates have been attributed to drought-induced reductions in vegetation (Allen and Breshears, 1998). At CIRO, charcoal-poor sheetfloods constrained by deposits dated 6700–3600 cal yr BP indicate that while enhanced sheetflood deposition occurred during droughty climate (Fig. 5d), this hillslope erosion was not triggered by fire. Despite dry conditions during this time, fire activity at CIRO was limited.

Between 8000 and 4000 cal yr BP, sagebrush, Rocky Mountain juniper and limber pine occupied CIRO (Fig. 5a). These trees and shrubs do not typically sustain low-severity fires during drier climate when ground fuels are discontinuous (Baker and Shinneman, 2004; Mensing et al., 2006; Romme et al., 2009). Fuel suppression by drought and/or lack of ignition during convective storms may explain no-fire (and low-fire) intervals during the bulk of this time frame. Mid-Holocene fires (that produced thin, muddy debris flows and sheetfloods) were ignited during drought following brief periods of increased moisture, when accumulated fine fuels increased fuel connectivity for fire spread on an otherwise sparsely-vegetated landscape. Nevertheless, low colluvial supply, diminished by frequent sheetflood deposition (10,600–7200 cal yr BP), may have inhibited development of larger debris flows. This combination of evidence (prolonged dry climate, thin deposits, and limited fire-related deposition) 6700–4700 cal yr BP suggests that the landscape had limited fuel, and low sediment supply on hillslopes.

After 2400 cal yr BP, Utah juniper and single-leaf pinyon expanded during wetter, cooler climate, fire activity increased and erosion shifted back to episodic debris flow deposition. This erosional shift may be entirely attributable to denser vegetation that changed fire regimes from low-severity to high-severity fires. Evidence of soil development ~12,700, 2300 and 2200 cal yr BP also indicates more densely vegetated

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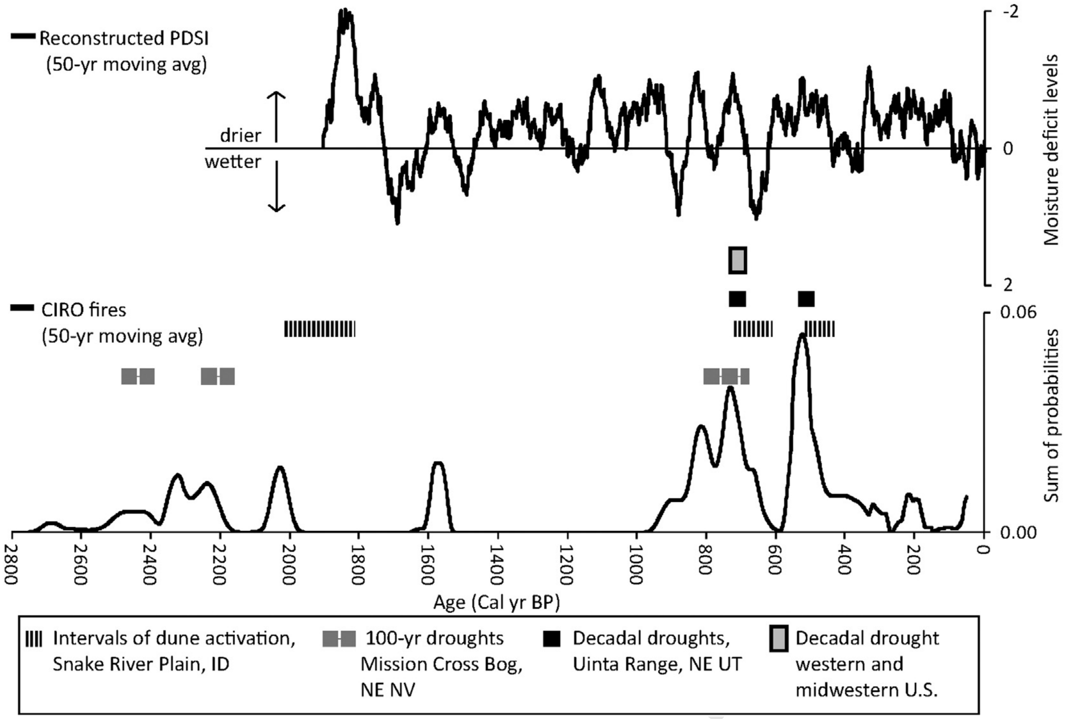

Figure 8. A 2800-yr comparison of the CIRO fire record (bottom black line) to Palmer Drought Severity Index reconstructed from tree rings (upper black line; Cook et al., 2004), and to records of drought from the Snake River Plain, ID (Rittenour and Pearce, 2011), Mission Cross Bog, NV (Mensing et al., 2008), Uinta Range, UT (Gray et al., 2004) and the Midwestern U.S. (Stahle et al., 2007). To highlight longer term trends, fire and PDSI data were smoothed using a 50 year moving average in Microsoft Excel (50-yr moving avg).

and stabilized hillslopes. Stable well-developed soils would increase silt and clay content through loess-trapping and pedogenic processes, which also would increase the thickness of colluvium. Thick, well-developed soils, combined with ash production from fires, would provide both the mobile regolith and the fine-textural component necessary for debris flow development.

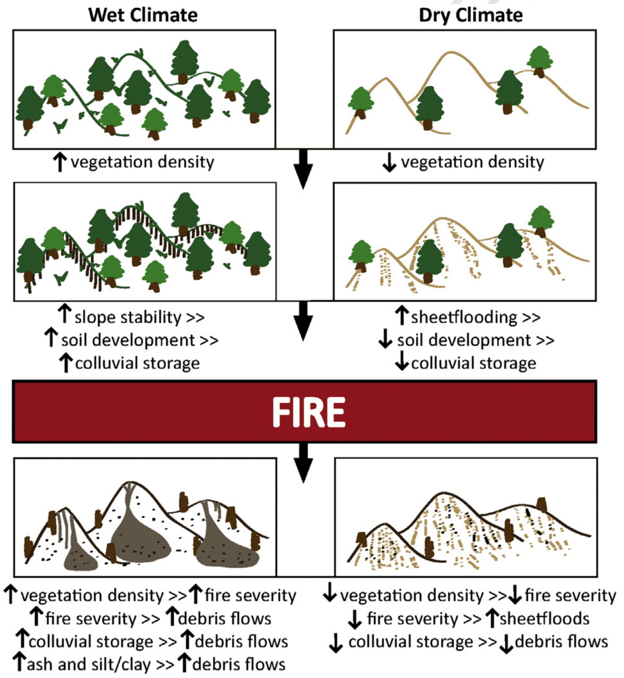

Figure 9. Conceptual model of feedbacks among wet climate vs. dry climate, vegetation, fire, and fire-related erosional response from burned hillslopes.

Broad-scale linkages among climate, vegetation and fire

Over the last few centuries in most areas in western North America, years of widespread burning in the observational or tree-ring record are associated with winter/spring drought, advanced timing of snowmelt and greenup, and hot summers (Westerling et al., 2003, 2006; Heyerdahl et al., 2008; Littell et al., 2009; Falk et al., 2010; Trouet et al., 2010; Gedalof, 2011). Q13 Well-resolved proxies for temperature, precipitation and associated fire occurrence are too spotty in the region to evaluate fire–climate relationships through the entire Holocene.

Controls on fire–climate relationships, such as precession-driven changes in insolation and the seasonal timing of moisture delivery, have not been constant over the Holocene (e.g., Berger, 1978), and changes in the seasonality of precipitation and summer convective storms could broadly influence fire activity throughout the western U.S. (e.g., Minckley et al., 2012; Brunelle et al., 2013). More importantly perhaps, precessional changes likely produced gradual shifts in the annual phasing of regional temperatures. This may have affected the dominant controls of seasonal climate on wildland fire during the Holocene, including the severity of winter/spring drought, the timing of spring, and the intensity of summer heat loads. For example, the shift from cooler to warmer winters into the late Holocene could have advanced the onset of spring snowmelt and vegetative growth, exhausting soil moisture and flammability earlier in the dry summer. Finally, hydroclimatic areas with coherent, long-term variations in temperature or precipitation, and thus decadal-scale or longer patterns in fire synchrony, likely shifted with ocean temperatures over the Holocene (Kitzberger et al., 2007). Q14

CIRO (~42°N) lies in the transition zone (40–42°N) of a north–south dipole in regional precipitation (Dettinger et al., 1998; Brown and Comrie, 2004; Wise, 2010; Pederson et al., 2011). Q15 During the 20th century, both the width and location of this transition shifted, though the transition is most stable in the northern Great Basin, where CIRO is located (see Shinker, 2010). The location of CIRO near this dipole complicates comparison of the climatic controls on fire

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in this ecosystem with other studies investigating the climate drivers of fire in the western U.S.

In the introduction, it was suggested that multiproxy (climate, vegetation, fire, and alluvial) records like the one at CIRO, in comparison with other similar records across the region, could be used to sort out the chronological order and causal links between climate, vegetation, fire and erosional processes. Both the CIRO study and regional paleorecords lack the necessary specificity and resolution to fully account for the order and causality of multiple events and processes throughout the Holocene, but they do permit a few generalizations.

Throughout the Holocene, synchronous periods of fire activity throughout a range of diverse ecosystems in the northern Rockies indicate that widespread climate change, not specific vegetation migrations, drives fire activity. Other asynchronous fires periods suggest that local vegetation change (e.g., migrations or changes in fuel conditions) and/or regional climate variability also drives fires. For example, the prominent peak in fire activity in the CIRO record ~10,700–9500 cal yr BP is consistent with a pronounced peak in fire throughout many ecosystems (e.g., Power et al., 2008a,b; Marlon et al., 2009; Whitlock et al., 2012) in response to broadscale dieoffs of Pleistocene vegetation, consumption of the dead biomass by large and roughly synchronized fires, and accelerated erosion and sedimentation associated with broadscale biomass burning. The profound changes in both composition and structure of vegetation have been mostly directional and associated with regional warming, the decline of Pleistocene vegetation, and post-glacial reorganization (including plant migrations from both the south and lower elevations).

While many lake charcoal records show a general decrease in fire activity following the Pleistocene–Holocene transition (e.g., Power et al., 2008a,b; Marlon et al., 2009; Whitlock et al., 2012), alluvial charcoal records from CIRO and throughout the Northern Rocky Mountain region (e.g., Meyer et al., 1995; Pierce et al., 2004; Nelson and Pierce, 2010) are characterized by multi-century episodes of elevated fire occurrence punctuating multi-millennial intervals with little or no fire-related sedimentation. While most lake charcoal records do show this general decrease in fire activity following the Pleistocene–Holocene transition, both alluvial and lake records record a notable peak in fire activity during the mid-Holocene (~7500–5000 cal yr BP). For example, elevated charcoal levels were recorded ~7500–6500 cal yr BP at both CIRO and at higher elevation Lake Cleveland, ~20 km north of CIRO (Davis et al., 1986). This mid-Holocene peak is recorded in other alluvial charcoal records in central Idaho (Pierce et al., 2004; Riley, 2012), and in lake charcoal records throughout the Northern Rocky Mountains (e.g., Power et al., 2011), likely in response to regional drought conditions (Fig. 6; Murchison, 1989; Louderback and Rhode, 2009; Shuman et al., 2009; Corbett and Munroe, 2010; Whitlock et al., 2012).

Asynchronous peaks in fire activity among different vegetation types during the late Holocene likely indicate that local vegetation and climate changes also play an important role in driving regional pulses in fire and fire-related sedimentation. At CIRO, however, we cannot precisely order, and therefore relate, the late Holocene colonization and expansion by PJ woodland with peaks in the alluvial charcoal record 2400–2000, 850–700, and 550–400 cal yr BP. At CIRO, and elsewhere along the northern peripheries of PJ woodlands, fire and other ecological disturbances associated with regional multi-decadal droughts during the Medieval Climate Anomaly could have enhanced colonization and expansion of Utah juniper and single-leaf pinyon. The densification of pinyon–juniper (PJ) woodland at CIRO over the last millennium likely and uniquely increased the likelihood of local crown fires. In the future, the combination of dense PJ woodland and cheatgrass invasion at CIRO could, in fact, produce a sustained shift in fire and fire-related erosion and sedimentation.

Management implications

Consistent with historical observations of PJ expansion in the western U.S. (Romme et al., 2009), repeat photography documents PJ density increases and downslope infilling at CIRO during the last ~150 yr (Morris, 2006). Our study documents accelerated PJ infilling at CIRO beginning 700 cal yr BP, long before Euro-American settlement of CIRO commenced in 1888 AD. This long-term PJ expansion at CIRO relates largely to climate-driven expansion and/or natural post-glacial vegetation colonization, and falls within the natural range and variability of this system. However, PJ expansion is often attributed to land use practices that include fire exclusion and livestock grazing, which may be enhancing modern tree densities (e.g., Shinneman and Baker, 2009; Powell et al., 2013).

At CIRO, fire has been a natural component of PJ woodlands since colonization, and fires were most frequent after PJ populations expanded 700 years ago. High-severity fires in dense PJ stands shifted erosional processes from sheetflooding to more catastrophic debris flows. Modern stand densities suggest increased risk of severe fires. For example, during the summer of 2001, a 71-km^2 mixed-severity fire that burned into the southern portion of CIRO was indeed stand-replacing and lightning caused, indicating that given adequate ignition, the CIRO PJ woodlands are ripe to burn. Along with fire damage, fire-related debris flows would likely extend beyond burned areas, threatening park structures and infrastructure.

Conclusions

Climatically-modulated changes in vegetation, fire regimes and geomorphic processes during the last 13,000 yr are inferred from alluvial charcoal and woodrat midden records from CIRO. These records reveal fuel and drought controlled fire peaks in the early and late Holocene, and low fire activity in the dry fuel-limited mid-Holocene. In addition, alternations between debris flows and sheetfloods exposed in alluvial stratigraphic records reveal variations in erosional response to intense stand-replacing fires burning dense vegetation vs. less severe fires burning lower fuel-loads.

Fires (10,700–9500 cal yr BP) that produced thick debris flow deposits containing abundant Rocky Mountain juniper macrofossils correspond to warming climate of the Pleistocene–Holocene transition. Dense late-glacial juniper forests supplied fuel and colluvium for episodic debris flow deposition following large, high severity fires. Regional climate records indicate an overall cooler/wetter climate 12,700–8000 cal yr BP, particularly when compared with middle and late Holocene climates. This suggests that 10,700–9500 cal yr BP fires burned dense fuels that were ignited during episodic drought.

During the warmer, drier climate of the mid-Holocene (~8000–4000 cal yr BP), fire activity was generally low, with the notable exception of the interval between 7200 and 6700 cal yr BP. Thick packages of fire-related sheetfloods from this interval contain macrofossils of limber pine, Rocky Mountain juniper and sagebrush. Other regional records show a peak in fire activity ~7.5–6 ka, possibly due to increased fuel loads and/or increased ignitions during a wetter interval in the otherwise dry and stable mid-Holocene.

According to Great Salt Lake and other paleorecords, arrivals of Utah juniper (~3800 cal yr BP) and single-leaf pinyon (~2800 cal yr BP) was associated with cooler, wetter conditions during the late Holocene. Note, however, that in the Wyoming Basins, late Holocene Utah juniper migration was associated instead with drought in the central Plains (Lyford et al., 2003). It is unclear whether this signifies regional differences between the northern Great Basin and the Great Plains, or more likely the northward expansion of Utah juniper (and pinyon) is being driven by synchronous warming across both regions.

Nevertheless, following PJ migration, clusters of debris flow-producing fires were recorded at 2400–2000, 850–700, and 550–400 cal yr BP that burned during annual to decadal droughts preceded by annual to decadal intervals of above average moisture (Cook et al., 2004). This suggests that variable climate shifted both vegetation and fire regime, where high severity fires in dense PJ were no longer limited by fuel availability but rather by likelihood of ignition. PJ expansion

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stabilized hillslopes and provided ample colluvial supply for post-fire debris flow deposition. Although the gently-sloping, granitic terrain at CIRO is not conducive to debris flow development, episodic fire-related debris flows deposited during the early and late Holocene suggest that fire has pushed erosional responses past geomorphic thresholds.

Fires recorded ~550–400 cal yr BP at CIRO and in multiple regional alluvial charcoal records (Pierce et al., 2004; Nelson and Pierce, 2010; Svenson, 2010; Riley, 2012) implies significant regional climate forcings. During the LIA, large fires that produced debris flows burned when cooler, wetter conditions were punctuated by severe droughts (Cook et al., 2004). Although these fires burned at roughly the same time under similar climate conditions, the nature of these fires varied according to ecosystem and pre-fire fuel conditions.

At the beginning of this paper, we raised the question of which comes first, the shift in fire and erosion regime or the change in vegetation? Our record indicates since PJ colonization of CIRO, high-severity wildfires have burned dense fuel loads that accumulated and subsequently dried during periods of variable climate. In the last ~150 yr, PJ woodlands have increased in density and expanded into neighboring vegetation communities at CIRO (Morris, 2006) and throughout the western U.S. (Romme et al., 2009). High tree densities and near-continuous cheatgrass cover through the woodland and adjacent open lands have increased the risk of crown fires and fire-related debris flows at CIRO. This elevated fire risk will be exacerbated by earlier and warmer growing seasons, and an increased potential for climate extremes in both precipitation and temperatures caused by amplified levels of atmospheric greenhouse gases (e.g., Groisman et al., 2005; Duffy and Tebaldi, 2012).

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