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Review

Fire and restoration of piñon–juniper woodlands in the western United States: a review

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Abstract

Piñons and junipers, that dominate many semi-arid landscapes in the western United States, have invaded some sagebrush and grassland areas and possibly increased in density since EuroAmerican settlement. Exclusion of fire by livestock grazing and intentional suppression is thought to have been a cause of these changes. National assessments suggest that many woodlands have missed one or more low-severity surface fires and are thus in poor condition, requiring restoration. We undertook a systematic review of seven questions about fire history, fire severity, and the role of fire in these woodlands to evaluate the scientific basis for the national assessment. First, unless piñons and junipers record fire by means of fire scars, it will be difficult to reconstruct fire history. Evidence suggests that most species of piñons and junipers can record fire by means of scars, but scars may be uncommon or absent in some cases and common in others. This variability in scarring has competing explanations that are poorly substantiated. Second, evidence exists for at least three modes of low-severity surface fires in these woodlands: (1) spreading surface fires, (2) patchy surface fires of small extent, and (3) an absence or near absence of surface fires. Methodological problems limit our ability to assess how common each mode is, but spreading, low-severity surface fires were likely not common. Third, there are no reliable estimates of mean fire intervals for low-severity surface fires in these woodlands because of methodological problems. Fourth, fires can kill small trees in true savannas and grasslands, helping to maintain a low tree density, but in most piñon–juniper woodlands low-severity surface fires do not consistently lower tree density and may become high-severity fires. Fifth, nearly all observed fires since EuroAmerican settlement in these woodlands were high-severity fires. In only two studies is there sufficient information to allow a conclusion about whether high-severity fires have or have not increased since settlement, and in these cases the authors conclude they have not. Sixth, the fire rotation for high-severity fires is estimated in only two studies, 400 years in one case, 480 years in the other. Finally, fires may in some cases burn with mixed severity. In conclusion, national fire plans and assessments of the condition and health of piñon–juniper woodlands in the western United States are based on premature and likely incorrect conclusions about the natural fire regime in piñon–juniper woodlands. Local research is essential, at the present time, if effective, scientifically based restoration prescriptions are to be derived.

Keywords: Piñon–juniper; Woodland; Fire history; Restoration; Ecosystem health; Western US

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1. Introduction

> "The shaggy bark of the juniper made fire brands to Satan's liking. Flaming strips of this bark, often 2 feet or more in length, were hurled ahead to wrap themselves around other trees which caught fire with a roar and gave off ropelike strips of bark to repeat the process" (Hester, 1952, p. 27, describing a 1950 high-severity fire in piñon–juniper)

Woodland conifers in the genera *Pinus* (piñons) and *Juniperus* (junipers) dominate millions of hectares in the western United States (Mitchell and Roberts, 1999). Trees in piñon–juniper woodlands are, in places, increasing in density and expanding into adjoining sagebrush shrublands and grasslands, which is often considered degradation. Causes are thought to be fire exclusion, livestock grazing, climatic fluctuations, and other factors (West and Young, 2000). Yet, it is difficult to determine which factor is most important or how each factor has contributed to change. Fire, the subject of this review, is thought by some to have been frequent enough, before exclusion, to have maintained low-density piñon–juniper savannas and woodlands in some areas and to have prevented tree invasion into sagebrush and grasslands (Gottfried et al., 1995; West, 1999; Brown et al., 2001). However, in other areas, evidence of low-severity surface fire is lacking, and the natural fire regime was dominated by high-severity fires (Floyd et al., 2000). Low-severity surface fires are those that burn primarily in surface fuels, leaving a high percentage of overstory trees alive. High-severity surface fires that kill most overstory trees and high-severity crown fires are lumped here as "high-severity fires" as they cannot be separated in the pre-EuroAmerican record. A "mixed-severity fire" is one that burns partly as a low-severity surface fire and partly as a high-severity fire.

There is interest in restoring piñon–juniper woodlands, sagebrush, and grasslands, that are considered degraded, often by simply removing or reducing piñons and junipers (e.g., Brockway et al., 2002). This is controversial because most past tree removals aimed to increase forage for livestock, but often failed to provide lasting benefit and had adverse effects on wildlife (Lanner, 1977; Despain, 1987). Thinning also may be inappropriate where the fire regime lacked low-severity surface fires (Romme et al., 2003). Yet, new proposals for tree removal have been made or are being considered (e.g., Pieper et al., 2002), including thinning trees (Bledsoe and Fowler, 1992; Jacobs and Gatewood, 1999; Brockway et al., 2002). Proposals for restoration of piñon–juniper ecosystems often omit a consideration of the role of fire (e.g., Brockway et al., 2002), perhaps because fire in these woodlands is poorly understood (Gottfried et al., 1995; Paysen et al., 2000; Miller and Tausch, 2001). In addition, national-level policy for fire management and woodland restoration is being guided by coarse-level classification of piñon–juniper fire regimes, yet these fire-regime classifications do not agree (Frost, 1998; Brown, 2000; Hardy et al., 2000). It was unclear to us at the outset whether the disagreement is a matter of interpretation or of fundamental uncertainty in the state of present knowledge.

We undertook a systematic review to address these and other unresolved questions about fire history and fire effects on trees relevant to restoration of piñon–juniper woodlands and savannas in the 11 western states (Fig. 1). In a systematic review, before gathering and analyzing studies, criteria are specified for: (1) searching for studies, (2) including a study, (3) assessing the quality of evidence, (4) extracting evidence, and (5) comparing evidence (Englund et al., 1999; Gates, 2002). Systematic reviews have become essential in scientific fields, such as medical research, where economic or health stakes are high and studies offer inconsistent or contradictory results (Egger et al., 2001). Many conservation or restoration questions also have high stakes and may benefit from systematic review (e.g., Bender et al., 1998; Hartley and Hunter, 1998). A systematic review may become a statistically rigorous "meta-analysis" if data can be analyzed as "effect sizes" (Gates, 2002), but this is not possible with the questions we address. However, non-statistical systematic approaches can still improve narrative reviews by reducing reviewer bias.

2. Methods

We identified questions about fire history, fire severity, and fire effects on trees in piñon–juniper woodlands (Table 1). Questions 1–3 ask primarily about low-severity surface fires. Question 4 asks about the effects of fires on tree populations. Questions 5–7 ask about mixed- and high-severity fires.

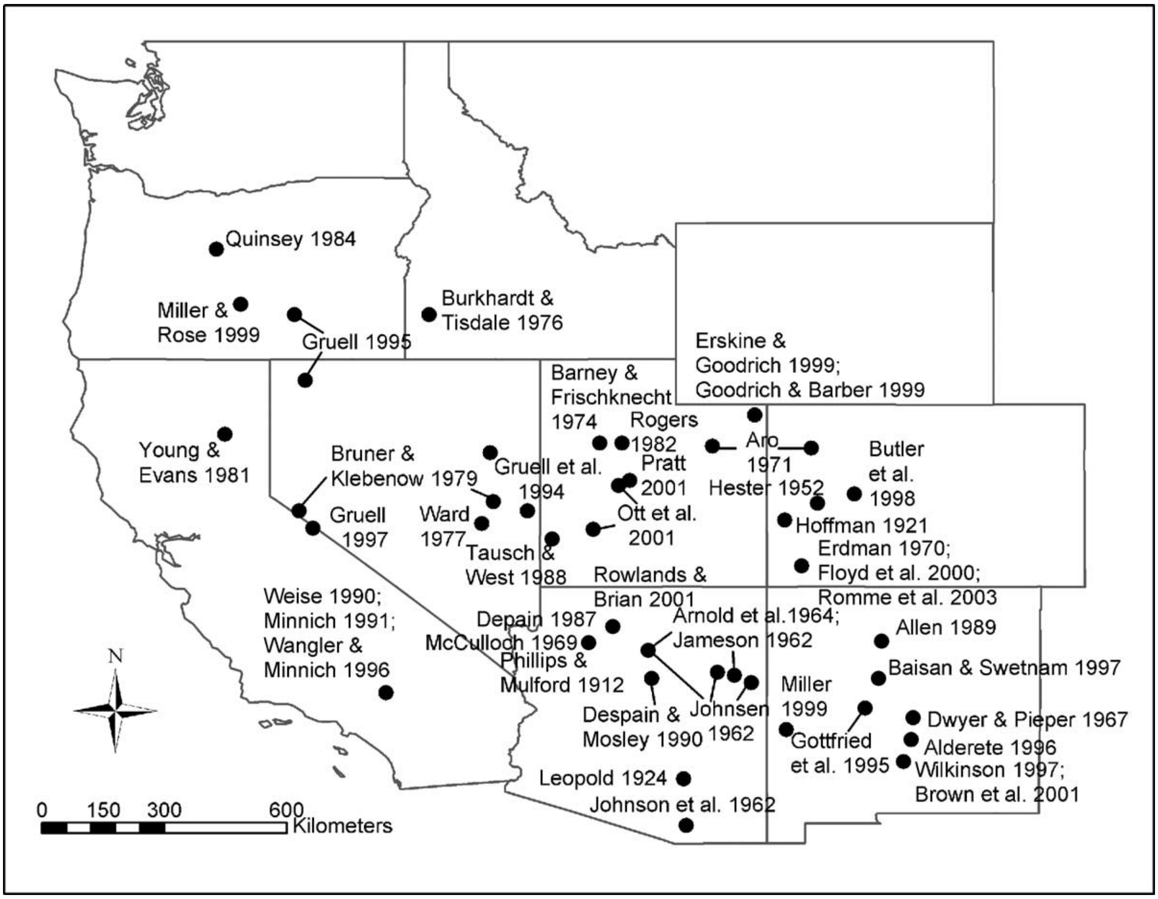

Fig. 1. Sites for each study included in the review. Two studies are not mapped. Martin (1978) sampled in an unknown part of eastern Oregon. Koniak (1985) sampled throughout Nevada.

Potential studies to include in the review were located using established methods (Gates, 2002). We searched online databases (Academic Search Premier, AGRICOLA, Biological Abstracts, BioOne, Ingenta, OCLC First Search, and the Tall Timbers Fire Ecology Database) and major academic libraries with online access ($n = 16$) in the 11 western states using the keywords: piñon, juniper, fire, and combinations and variations of these words (e.g., Latin names, wildfire). We also searched the web using Google and these same keywords. Scientific journals known to cover fire in western landscapes were searched manually, including Journal of Range Management and Journal of Forestry. We also searched bibliographies in narrative reviews (Wright et al., 1979; Young, 1983; Agee, 1993; Gottfried et al., 1995; Gruell, 1999; Paysen et al., 2000; Miller and Tausch, 2001) and in all located studies as they were found. Key gray literature was searched manually, including conference proceedings and bibliographies on piñon–juniper woodlands and fire history (e.g., Aldon and Springfield, 1973; Zarn, 1977).

Potential studies were then screened for inclusion using quality criteria developed to evaluate the evidence in each study relative to the questions (Table 1). These criteria are derived in part from Baker and Ehle (2001), but also a preliminary scan of the literature. To be included, a study must contain at least one piece of primary evidence of at least ‘‘low’’ quality relevant to at least one question (Table 1). Using weak inclusion criteria, such as these, and not looking at results while applying criteria, help avoid selection bias (Englund

Table 1
Questions addressed and criteria for rating the quality (high, medium, low) of evidence presented in studies

(1) Do piñons and junipers accurately record fires by means of fire scars?	
High	Area searched for fire scars was measured or is well described, and number or percentage of trees or area with and without fire scars
Medium	Qualitative assessment of trees or area with and without fire scars, or some, but not all of the above (high) criteria are met
Low	Fire scars or their absence are reported, but not scar abundance
(2) Did spreading low-severity surface fires occur in piñon–juniper woodlands?	
High	Historical observations of spreading surface fires, or cross-dated, coincident, past fire dates combined with age-structure data that together indicate fire spread on the surface
Medium	Cross-dated, coincident, past fire dates without age-structure data that indicate fire spread on the surface, but with other evidence of spread
Low	Coincident past fire dates from fire scars, but without cross-dating or without age structure or without some other evidence of spread on the surface, or general interpretations of fire regimes or general historical summaries without reports of actual observations
(3) What is the MFI for low-severity surface fires in piñon–juniper woodlands?	
High	Evidence that fires were spreading surface fires (see question 2), and random sampling sites within a defined area, and objective, unbiased selection of sampling trees, and $\geq$10 sampling trees per site and at least 1 site, and cross-dating used to date fire years
Medium	Evidence that fires were spreading surface fires (see question 2), and two or more, but not all of the other above (high) criteria are met
Low	Evidence that fires were spreading surface fires (see question 2), and none or only one of the other above (high) criteria are met
(4) Did spreading low-severity surface fires maintain a savanna woodland structure or maintain low tree density in woodlands or limit tree invasion into sagebrush?	
High	Evidence is from either prescribed fires or wildfires, and quantitative evidence of rates of mortality or survival of trees
Medium	Evidence is from either prescribed fires or wildfires, and qualitative evidence of rates of mortality or survival of trees
Low	Qualitative summaries of evidence of mortality or survival of trees, or any evidence of success or failure in executing prescribed fires
(5) Did high-severity fires occur in piñon–juniper woodlands?	
High	Modern reconstructions (tree rings) or historical observations of high-severity fires prior to EuroAmerican settlement, and evidence that most trees were killed (e.g., age structure suggesting even-aged stands), and evidence that fire was the agent (e.g., charred, standing wood, cross-dated fire scar that is congruent with the age structure)
Medium	Modern reconstructions or historical observations of high-severity fires prior to EuroAmerican settlement, but without evidence that most trees were killed or without evidence that fire was the agent (e.g., age structure suggesting even-aged stands, but no fire scars)
Low	Qualitative summaries of evidence of occurrence or absence of past high-severity fires
(6) What is the fire rotation for high-severity fires in piñon–juniper woodlands?	
High	Rotation derived from an estimate of actual area burned, and rotation derived from >1000 ha of data and >50 years of observations
Medium	Rotation derived from age structure of extant stands, or rotation derived from an estimate of actual area burned, but from <1000 ha of data or <50 years of observations
Low	Rotation derived from rates of succession
(7) Did mixed-severity fires occur in piñon–juniper woodlands?	
High	High-quality evidence (see questions 2 and 5) that individual fires were spreading low-severity surface fires in some areas and high-severity fires in other areas
Medium	Medium-quality evidence, as above
Low	Low-quality evidence, as above

et al., 1999). Of 70 potential studies, 46 met these criteria and 24 did not for a variety of reasons (Table 2).

Data were extracted by reading the source material at least twice, explicitly searching for terms, phrases, and material related to each question. This material was marked in each article and placed in tables (e.g., Table 3). Qualitative information (e.g., interpretations) not suitable for tables was extracted as direct

Table 2
Potential studies that were excluded (evidence quality = 0) from tabulations, and the reason for exclusion

Author(s)	Reason(s)
Agee (1993)	Review, no primary evidence
Barber and Josephson (1987)	No evidence about fire severity
Blackburn and Bruner (1975)	Review, no primary evidence
Brown (2000)	Review, no primary evidence
Bunting (1987)	Review, no primary evidence
Chappell (1997)	Could not obtain
Evans (1988)	Review, no primary evidence
Everett and Clary (1985)	Review, no primary evidence
Everett and Ward (1984)	No evidence about trees or fire severity
Gruell (1996)	Review, no primary evidence
Gruell (1999)	Review, no primary evidence
Jameson (1966)	No primary evidence
Johnson and Smathers (1976)	No evidence specific to piñon–juniper
Miller and Tausch (2001)	Review, no primary evidence
Moir (1982)	Outside the study area
Paysen et al. (2000)	Review, no primary evidence
Pieper and Wittie (1990)	Review, no primary evidence
Segura and Snook (1992)	Outside the study area
Swetnam (1983)	No data on piñon–juniper woodlands
West (1999)	Review, no primary evidence
Wink and Wright (1973)	Outside the study area
Wittie and McDaniel (1990)	Herbicide treatment before fire
Wright et al. (1979)	Review, no primary evidence
Young (1983)	Review, no primary evidence

quotes, which were stored in a file, and used to supplement and interpret information in the tables. Marked articles and extracted quotes were then given to the second author, who checked for missing, unmarked material, and checked that marked material was interpreted and transferred correctly to tables. While previous reviews were excluded from the tables, we also extracted relevant quotes from reviews, stored these quotes in a file, and later compared them to our findings.

3. Results and discussion

3.1. Do piñons and junipers accurately record fires by means of fire scars?

Fire history cannot be precisely reconstructed and dated for the time before historical records begin unless fire scars left on surviving trees can be dated. Ideally, fire-scar evidence within and on the perimeters of fires would provide accurate fire dates and spatial information for both low- and high-severity fires. Thus, the first question asks whether these fires leave scars that can be dated on piñons and junipers.

Nineteen studies provide primary evidence about this general question (Table 3). Three of the five studies with high-quality evidence found no scarred trees, but the other two found large numbers ($n > 25$) of scarred trees. The two studies with medium-quality evidence, that report counts, collectively found 34 scarred piñons and junipers while the other five studies with medium-quality evidence reported scars to be common. Qualitative assessments by authors of the 19 studies mirror this quantitative range, with some authors reporting few or no fire scars (Allen, 1989; Wilkinson, 1997; Floyd et al., 2000; Brown et al., 2001; Romme et al., 2003), while others report scars to be common (Leopold, 1924; Miller, 1999) or at least not uncommon (Quinsey, 1984; Goodrich and Barber, 1999). Scars are common on junipers in savannas or former savannas (Leopold, 1924; Johnsen, 1962; Miller, 1999), which are grassy parks and foothills with widely spaced trees, mostly in the southwest (McPherson, 1997). Thus, it appears that piñons and junipers do provide fire scars, at least under certain conditions.

However, given the great variability in the abundance and presence of fire-scarred trees found in these studies (Table 3), it would be premature to conclude that piñons and junipers consistently and accurately record fires. The variability in the number of fire-scarred trees needs to be explained, but there are presently no primary data, only interpretations or hypotheses that explain this variability. These generally fall within two main categories, centered around how accurately fire is recorded by scars: (1) fire-scar records sometimes are inaccurate, and the varying abundance of scars reflects variation in how well fire is recorded by scars, not variation in the abundance of fire, and (2) the varying abundance of scars reflects a corresponding varying abundance of low-severity surface fires.

First, we addressed the interpretation that the scar record can be inaccurate. A prevailing explanation is that low-severity surface fires were common, but piñons and junipers failed to record them consistently,

Table 3
Data relevant to question 1 from studies included in the review. Quality criteria and the question are in Table 1

Author(s)	State	Elevation (m)	Quality	Number of scarred trees[a]							Where scars were found and not found							Type of setting[b]			
				JUDE	JUMO	JUOC	JUOS	PIED	PIMO	PIPO, PIJE	On burn edges	In old woodlands	In fire-limited sites	In savannas	Not in young woodlands	Scars hard to find	Scars not found	Savanna	Lower ecotone	Closed woodland	Upper ecotone
Allen (1989)	N NM	2016–2048	Low		P			P		9						X					X
Arnold et al. (1964)	N AZ	–	Low				0	>1			X									X	
Baisan and Swetnam (1997)	C NM	2225–2380	Low							21[c]											X
Burkhardt and Tisdale (1976)	SW ID	1580–2073	Medium			C						X			X				X	X	
Despain and Mosley (1990)	N AZ	2050	High				0	0		1							X				X
Floyd et al. (2000), Romme et al. (2003)	SW CO	2060–2485	High				0	0		0							X			X	X
Goodrich and Barber (1999)	NE UT	–	Medium					C			X									X	
Gottfried et al. (1995)	C NM	1900–2100	Medium					C												X	
Gruell (1995)	SE OR NW NV	–	Low			P						X	X							X	
Gruell (1997)	E CA	1920–2347	Low						14	8		X	X		X	X				X	
Gruell et al. (1994)	E NV	2036–2377	Medium				3		23			X	X		X	X				X	
Johnsen (1962)	N AZ	1430–1980	Low		P							X		X				X			
Leopold (1924)	S AZ	–	Medium	C								X		X				X			
Miller (1999)	SW NM	1750–2983	Medium	C								X		X				X			
Miller and Rose (1999)	E OR	1450–1875	Low			P				10					X				X		
Rowlands and Brian (2001)	N AZ	1769–1867	High				0	0									X			X	
Tausch and West (1988)	SW UT	2000	High				25	2												X	
Wilkinson (1997), Brown et al. (2001)	S NM	2400–2440	Medium					7		1										X	X
Young and Evans (1981)	N CA	1350–1430	High			28[d]						X			X					X	

[a] Species abbreviations are: JUDE, *Juniperus deppeana*; JUMO, *Juniperus monosperma*; JUOC, *Juniperus occidentalis*; JUOS, *Juniperus osteosperma*; PIED, *Pinus edulis*; PIMO, *Pinus monophylla*; PIPO, *Pinus ponderosa*; PIJE, *Pinus jeffreyi*. "P" in a column indicates that information pertains to that species, but scars were not sought or the number of scars was not reported. "C" indicates that the author reported scars to be common. "0" indicates that scars were sought but not found. "X" indicates qualitative observations were made.

[b] Savannas are characterized by a low density of junipers in a continuous grassland matrix. Lower ecotone is the boundary with sagebrush or grasslands. Closed woodlands lack the continuous grassland matrix of savannas and often have tree crowns that are close together. Upper ecotone is the boundary with the ponderosa pine zone or Jeffrey pine zone, or with mixed conifers.

[c] Baisan and Swetnam (1997) do not identify whether scars were removed from PIPO or piñons and junipers, but PIPO is more likely.

[d] Young and Evans also mention that 1% of big sagebrush communities contained additional fire scars.

because these trees do not scar well (Agee, 1993; Gottfried et al., 1995). Scarring could certainly be underestimated, because a scar may have been formed without the bark being charred (Quinsey, 1984). However, studies reviewed above indicate that piñons and junipers can scar quite well and scars can be common (Table 3). Moreover, past studies suggest that all species can record fire scars (Table 3). Piñons do not appear to be poorer recorders of fire, although this was suggested earlier (Gottfried et al., 1995).

A related argument is that the scar record is not accurate because piñons and junipers commonly were killed outright by surface fires or, if they were scarred, then they suffered high mortality due to fungal infections (Gottfried et al., 1995; Wilkinson, 1997; Miller and Rose, 1999; West, 1999; Paysen et al., 2000; Brown et al., 2001). However, if piñons and junipers were commonly killed by fire, then this represents high-severity fire, not low-severity surface fire, which by definition has many survivors. This argument thus seems to support the alternative idea that the absence or rarity of fire scars accurately indicates that low-severity surface fire is rare and high-severity fire is common.

Another related argument is that if piñons and junipers do not scar well, scarred trees may be concentrated in: (1) older woodlands where trees have a higher chance of surviving a low-severity surface fire, and (2) sites where fire was of lower intensity (e.g., fuel-limited, rocky sites) (Gruell et al., 1994; Gruell, 1995, 1996, 1997). Nine of 19 studies do report that scarred trees are limited to, or most common in older woodlands or are absent from, or uncommon in younger woodlands (Table 3). However, the alternative explanation is that, if surviving trees with scars are only found on these sites, then low-severity surface fire may be common only in fuel-limited sites or old woodlands. Young woodlands and woodlands with more continuous grassy or shrubby understories, using the same reasoning, should be naturally subject to high-severity fires. This argument, too, seems to support the alternative perspective that the absence or rarity of fire scars accurately indicates that low-severity surface fire is rare and high-severity fire is common.

Second, we assessed the alternative interpretation that the relative abundance of fire scars does accurately reflect the abundance of surface fires. Scars may clearly be uncommon because low-severity surface fire is uncommon or absent (Floyd et al., 2000; Romme et al., 2003). To support this conclusion for their study area in southwestern Colorado, Floyd et al. (2000) and Romme et al. (2003) report that nearby ponderosa pines, known to be good recorders of low-severity surface fire, also lack fire scars. Gruell (1997) reports that Jeffrey pines (also thought to be good recorders) may have multiple scars, while nearby piñons have few scars. He, too, seems to interpret a lower scar abundance as indicating less fire, as he suggests that lower fuel levels in the piñon stand may mean a lower fire frequency relative to the adjoining Jeffrey pine stand. If this argument, that few scars means little low-severity surface fire, is correct, then younger woodlands may often lack scars because low-severity surface fire is uncommon in these young woodlands-fires, if they start, are soon high severity. Scars in older woodlands, then, would reflect an increasing tendency for trees to be able to survive fire as they age. However, Floyd et al. (2000) found no scars in older woodlands either, suggesting low-severity surface fires to be absent from both young and old woodlands.

Question 1, in conclusion, does not have simple, clear answers. The hypothesis that low-severity surface fires occur without leaving fire scars cannot presently be excluded, even though this hypothesis has little evidence at the present time. For example, there are no studies that show that low-severity surface fires actually occurred without leaving fire-scar evidence. The literature does seem instead to be more consistent with the idea that the abundance of fire scars reflects the abundance of low-severity surface fires where scars are rare, low-severity surface fires were likely rare and high-severity fire was likely common. However, without modern calibration and more systematic analysis of scarring, these competing explanations of the accuracy of fire evidence cannot be fully resolved. Modern calibration means measuring and analyzing how fire-scar evidence is left by modern fires as a way to develop valid methods for reconstructing the abundance and pattern of past fires (Baker and Ehle, 2001).

3.2. Did spreading low-severity surface fires occur in piñon–juniper woodlands?

The answer to this question should be simple, but is not, because of few observations of recent fires and general methodological problems in dating and reconstructing the spatial extent of past low-severity surface fires (Baker and Ehle, 2001). Published observations of recent low-severity surface fires in piñon–juniper woodlands are few—we found only three, but only one was a natural ignition. The South Canyon fire, in western Colorado, that led to the death of 14 firefighters, began as a naturally ignited surface fire that backed down a hill from a ridge-top ignition point, reaching about 50 ha on the surface before becoming a high-severity fire (Butler et al., 1998). Two accidental ignitions burned as low-severity surface fires in savanna areas in the southwest (Johnson et al., 1962; Dwyer and Pieper, 1967).

Early historical observations of low-severity surface fires inside piñon–juniper woodlands, or summaries that suggest observations were made, lack detail, and so are rated ''low quality'' (Table 4). Phillips and Mulford (1912, p. 9), describing a piñon–juniper area near the Grand Canyon in Arizona, wrote only that: ''Surface fires are the most common, but crown fires sometimes occur.'' Hoffman (1921, p. 538), describing piñon–juniper woodlands on the northwest edge of the Uncompahgre Plateau in western Colorado, wrote: ''Crown fires have occurred that have totally destroyed many acres of trees and countless ground fires have run in past years that destroyed reproduction and injured the larger trees, allowing fungous diseases to get a hold and spread with great rapidity,'' but provides no other information. This statement is puzzling to us, as in the Summer of 2003, we specifically sought evidence of low-severity surface fires in the form of fire scars at 60 random sites scattered across the Uncompahgre Plateau, including the area Hoffman describes. A preliminary analysis suggests that fire scars or the injuries that Hoffman describes are rare or absent, even where trees several hundred years old are still present.

Reconstructions of pre-EuroAmerican fires in piñon–juniper woodlands are hampered by two problems. First, the minimum evidence needed to firmly establish that a low-severity surface fire burned through a piñon–juniper woodland (or other forest) is substantial: a reliable date (i.e., cross-dated fire scars) for the fire at two separate points combined with age data or other evidence that the fire did not kill most overstory trees between the two points (Ehle and Baker, in press). The second problem is that getting reliable fire dates from piñons and junipers is difficult—we could find no studies that report much success. Without cross-dating, a procedure whereby tree-ring growth fluctuations are matched with a reliable master chronology, it is impossible to be certain of fire dates and thus to establish that a particular fire burned across an area of woodland (Kipfmueller and Swetnam, 2001).

Cross-dated fires are presently limited to sites with nearby ponderosa pine trees, whose scars can usually be cross-dated. This occurs only in the upper ecotone, where piñon–juniper woodlands meet ponderosa pine (Allen, 1989; Baisan and Swetnam, 1997; Wilkinson, 1997) or in the lower ecotone where young or scattered older junipers in sagebrush communities are sometimes found along with stringers or clusters of ponderosa pine (Miller and Rose, 1999). The bulk of the piñon–juniper zone, away from these ecotones, presently lacks cross-dated fire information.

Two studies with cross-dated fires in the upper ecotone (Table 4) lack age structure or other evidence that intervening trees pre-date (and thus survived) the spreading fire, but make inferences that fires spread on the surface. Allen (1989) argues that low-severity surface fires likely spread through piñon–juniper woodlands he studied, since nearby ponderosa pine areas with coincident (and cross-dated) fires spatially bracketed these woodlands, and there are no topographic barriers. Allen (1989) found 13 fires between 1725 and 1883 A.D. that spatially bracket the piñon–juniper woodland. Many of these likely were spreading low-severity surface fires, although without age structure evidence to the contrary, a particular fire could have been high-severity or mixed-severity in the piñon–juniper area. Baisan and Swetnam (1997) have evidence of five or more cross-dated fires that spread among sampling sites a few kilometers apart, but no intervening age-structure data were collected. A third study with cross-dated fires in the upper ecotone (Despain and Mosley, 1990) we think has evidence of mixed-severity fire, not surface fire (see Section 3.7).

In the lower ecotone, the only study with both cross-dated fires and age-structure data offers compelling evidence that fires periodically spread through parts of sagebrush communities across about a 15 km area. These fires likely killed young junipers, except for a few surviving trees on rocky sites (Miller and Rose,

Table 4
Data relevant to questions 2 and 3. MFI values are reported values for pre-EuroAmerican settlement only and are rounded to the nearest integer (e.g., 11.2 is reported as 11). Quality criteria and the questions are in Table 1

Author(s)	State	Elevation (m)	Quality for surface fires	Fire-history reconstructions[a]				Observations			Type of setting				Quality for MFI	MFI (years)	MFI type
				Cross-dated fires	Age structure	No. of scarred trees	No. of spreading surface fires	No. of spreading surface fires	General interpretation	Historical summary	Savanna	Lower ecotone	Closed woodland	Upper ecotone			
Allen (1989)	N NM	2016–2048	Medium	Y	N	9	13[b]							X	Low	16	CR[c]
Baisan and Swetnam (1997)	N NM	2225–2380	Medium	Y	N	21	M							X	Low	6–11	C
Burkhardt and Tisdale (1976)	SW ID	1580–2073	Low	N[d]	N	M	S	U				X	X		Low	13–32[e]	C
Butler et al. (1998)	W CO	1830–2070	High					1					X			–	–
Despain and Mosley (1990)	N AZ	2050	Low	Y	Est	0	U							X		–	–
Floyd et al. (2000), Romme et al. (2003)	SW CO	2060–2485	High	N	Est	0	0	0					X	X		–	–
Gruell (1997)	E CA	1920–2347	Low	N	N	22	S				X		X	X	L	8	C
Gruell et al. (1994)	E NV	2036–2377	Low	N	Y	26							X		Low		
North-facing																20	C
South- and west-facing																≥50–100	C
Hoffman (1921)	W CO	–	Low							X						–	–
Leopold (1924)	S AZ	–	Low	N	N	M	U				X				Low	10	I[f]
Miller and Rose (1999)	E OR	1450–1875	High	Y	Y	10	7					X			Low	12–27	C
Minnich (1991)	S CA	–	Low						X				X			–	–
Phillips and Mulford (1912)	N AZ	–	Low							X						–	–
Rowlands and Brian (2001)	N AZ	1769–1867	High	N	N	0	0						X			–	–
Wangler and Minnich (1996)	S CA	1300–2700	Medium					0					X			–	–
Wilkinson (1997), Brown et al. (2001)	S NM	2400–2440	Low	N	N	8	U						X	X		28	I
Young and Evans (1981)	N CA	1350–1430	Low	N	Y	28	U						X				

[a] Abbreviations are: Y, yes; N, no; M, many; S, some; U, unknown; Est, estimated from diameter data.

[b] Calculated from data in Allen (1989, Table 4.3).

[c] MFI types are: I, individual-tree; C, full composite; CR, restricted composite of fires that scar ≥25% of recorder trees.

[d] Burkhardt and Tisdale refer to "cross-dating" but do not mention a master chronology or present dates of individual fires to single years. We interpret their dating to be a process of comparing dates among trees, but not a formal cross-dating procedure using a master chronology.

[e] Calculated from data in Burkhardt and Tisdale (1976, Table 1).

[f] Leopold cites "a decade" based on an estimate from a single large juniper and functional arguments about the rate of recovery from fire.

1999). It appears to us that these fires were effectively high-severity fires, since they apparently killed a high percentage of junipers, leaving survivors only in rocky areas. Low-severity surface fires imply high rates of survival of overstory trees throughout the burn area.

In true savannas (see definition in Section 3.1), where fire scars are often found, it is remarkable that no studies provide reliable fire dates or compelling direct evidence of low-severity surface fire spread prior to EuroAmerican settlement. Instead, most studies conjecture that if fire scars are abundant, then fires were frequent and these frequent fires were low-severity spreading surface fires. This conjecture, for example, underlies Aldo Leopold's early suggestion (1924) that since fire scars were observed to be common in the southern Arizona foothills, these fires likely were frequent spreading fires that kept the brush down. Newspaper accounts suggest that large fires did burn in these juniper–oak communities between 1859 and 1890 A.D. (Bahre, 1985), but it is not clear that these were low-severity surface fires, as destruction of trees is mentioned. Moreover, Johnsen (1962, p. 204) wrote that: "The presence of fire scars on these older trees is questionable evidence of grass fires since grass fires seldom are hot enough to damage the larger junipers and many of these scars could be from lightning striking the individual trees, a common occurrence even now." This is not a trivial concern—Baker and Ehle (2001) found that about 50% of fires reported in fire-history studies of ponderosa pine forests were documented by scars on only 1–2 trees, suggesting many fires could be small and potentially insignificant. We suspect that spreading low-severity surface fires did occur in savannas even though direct evidence of spread is presently lacking.

In closed woodlands, there is also no direct evidence of spreading low-severity surface fires from cross-dated fires, but the same conjecture that fires did spread is made nonetheless in studies by Burkhardt and Tisdale (1976), Young and Evans (1981), Gruell et al. (1994), Gruell (1997), Wilkinson (1997), and Brown et al. (2001) that lack cross-dating of piñons and junipers. Evidence from available dates for fires in these studies does not support this conjecture. For example, Gruell et al. (1994, Table 2) shows that 25 fire years were found, but only three (that might actually be spreading fires) are documented by more than one scarred tree. However, in the absence of successful cross-dating, it is impossible to tell whether more of these fire years would line up, suggesting spreading fires, or if these fire scars may simply represent isolated, small fires that did not spread substantially.

Would naturally patchy fuels in piñon–juniper woodlands, due to rockiness and low productivity, lead to patchy low-severity surface fires that spread, but seldom or never over large areas? This idea is consistent with evidence from one study area with cross-dated fire scars (Baisan and Swetnam, 1997; Wilkinson, 1997), observations of modern fires in another (Burkhardt and Tisdale, 1976), and inferences from a study without cross-dated fires in another (Gruell et al., 1994). Gottfried et al. (1995) report that even in rocky areas of the Los Pinos Mountains in central New Mexico, fire scars suggest that occasional large, spreading fires occurred, but it is unclear whether this conclusion is based on cross-dated fire scars.

Evidence that spreading low-severity surface fires did *not* occur in some areas comes from studies that searched systematically for fire scars but did not find them. Two studies with high-quality evidence (Floyd et al., 2000; Rowlands and Brian, 2001) searched known areas and found little or no fire evidence at all (e.g., fire scars, charred wood), suggesting that low-severity surface fires had not occurred. Aerial photographic analysis of burn patches also has been used to argue that low-severity surface fires were uncommon (Wangler and Minnich, 1996), but no evidence is presented that surface fires could be detected, if they had occurred, using aerial photographs. A functional argument has also been made, that low-severity surface fires would have been uncommon in piñon–juniper woodlands because the dominant piñons would fare poorly with frequent low-severity surface fires (Minnich, 1991). However, this argument does not rely upon direct evidence that low-severity surface fires were absent. Studies with moderately reliable evidence, reviewed above, suggest that some low-severity surface fires did burn through some piñon–juniper woodlands, at least in the upper ecotone.

In summary, in piñon–juniper woodlands of the 11 western states, at least three modes of surface-fire occurrence and behavior are supported by moderately or highly reliable evidence: (1) spreading low-severity surface fires, only documented in some upper ecotones with ponderosa pine (Allen, 1989) or in lower ecotones with sagebrush (Miller and Rose, 1999), although these latter fires were likely high-severity, (2) patchy low-severity surface fires of generally small extent (Baisan and Swetnam, 1997; Wilkinson, 1997), and (3) an absence or near absence of spreading low-severity surface fires (Floyd et al., 2000; Romme et al., 2003). It is not presently known how much of the piñon–juniper woodland in the 11 western states was dominated by each mode. However, reliable evidence of spreading low-severity surface fires is presently lacking for most of the piñon–juniper zone in the West, suggesting low-severity surface fires were likely not a common type of fire in these woodlands.

3.3. What is the mean fire interval (MFI) for low-severity surface fires in piñon–juniper woodlands?

Even where low-severity surface fires are documented, in the upper ecotone, no reliable estimates of MFI are available for these fires (Table 4, Question 3). Available evidence is rated low quality because evidence that fires were low-severity surface fires is lacking (Section 3.2), cross-dating was not or could not be used, a statistically valid sample was not collected, or sample size is small. These are problems for studies of low-severity surface fires in general (Baker and Ehle, 2001).

No MFI estimate is rated moderately or highly reliable, but different types of MFI estimate (Table 4) also should not be directly compared (Baker and Ehle, 2001). Composite estimates come from pooling of all fires recorded on trees in an area before calculating intervals, implying that each fire burned the whole stand. Individual-tree estimates come from averaging among intervals on single trees, which assumes that fires did not burn more than the tree recording the fire. This likely underestimates the amount of fire. However, composite estimates likely overestimate the amount of fire, so some authors counteract this by restricting composite estimates to fires that scar a certain percentage of trees (e.g., >25%) in a sampling area. Unrestricted composite estimates (Table 4) range from 8 years (Gruell, 1997) to 50–100 years (Gruell et al., 1994), while one restricted composite estimate is 16 years (Allen, 1989), and the individual-tree estimate of Wilkinson (1997) and Brown et al. (2001) is 28 years. The actual MFI might lie between these estimates, if sampling biases are not considered. However, researchers bias MFI estimates by purposely seeking trees that contain multiple fire scars, which likely overestimate the amount of fire (Baker and Ehle, 2001). MFI estimates for ecotonal areas, that have been studied, cannot presently be corrected for this and other sampling problems. Cross-dated, low-severity surface-fire data and reliable MFI estimates are thus not available for any of the piñon–juniper zone in the West.

3.4. Did spreading low-severity surface fires maintain a savanna woodland structure or maintain low tree density in woodlands or limit tree invasion into sagebrush and grasslands?

Juniper savannas (usually lacking piñons), are characterized by a low density of trees in a continuous grassland matrix, and cover about 10 million ha of land, mostly in the southwestern United States and northern Mexico (McPherson, 1997). While arid soils and climate may play a role in savanna development, fire is widely thought to be a key factor in maintaining savannas (McPherson, 1997).

It seems logical that fires did spread in juniper savannas, but data to support this idea are surprisingly meager. Only two studies report observations of the effects of low-severity surface fires (accidental, not natural ignitions) in savannas (Johnson et al., 1962; Dwyer and Pieper, 1967), and another study reports observations from two prescribed fires and a wildfire in grasslands invaded by a low density of junipers (Jameson, 1962; Arnold et al., 1964). Prescribed fires may have different effects than do natural fires, as prescribed fires often are ignited when weather conditions are mild. Nonetheless, these fires killed a high percentage of small trees in savannas and grasslands invaded by small trees (Table 5). Some authors (Miller and Rose, 1999; Miller and Tausch, 2001) conjecture that a fire every 45–90 years would be sufficient to maintain a low-density woodland structure, based on the time it takes for a tree to reach a height (e.g., >3 m) where survival is high (Table 5). As explained in Section 3.2, however, there are no reliable data on low-severity surface fire frequency in juniper savannas, and thus no direct evidence for a conclusion that fire frequency was high in juniper savannas or has changed since EuroAmerican settlement.

Table 5
Data relevant to question 4. Quality criteria and the question are in Table 1[a]

Author(s)	State	Elevation (m)	Quality	No. of prescribed fires	No. of wildfires	Trees/hectare		Percent mortality and other observations
						Before	After	
Grassland with low pj								
Arnold et al. (1964), Jameson (1962)	N AZ	1800	High	2	1	ca. 150		
January and March (prescribed), June (wildfire)								70–100% of trees <1.2 m tall
January and March (prescribed), June (wildfire)								30–40% of trees 1–5–1.8 m tall
March (prescribed), June (wildfire)								60–90% of trees >2.1 m tall
Dwyer and Pieper (1967)	S NM	1830–1980	High		1	–	–	
Juniperus monosperma (69.8% of stand)								100% of trees <1.2 m tall
Juniperus monosperma (69.8% of stand)								24.2% of all trees
Pinus edulis (30.2% of stand)								13.5% of all trees
Johnson et al. (1962)	S AZ	1525	High		1			
Juniperus deppeana								32% of 1–3 in. diameter trees
Juniperus deppeana								23% of 4–6 in. diameter trees
Juniperus deppeana								22% of 7–9 in. diameter trees
Juniperus deppeana								28% of all trees
Juniperus monosperma								79% of 1–3 in. diameter trees
Juniperus monosperma								73% of 4–6 in. diameter trees
Juniperus monosperma								77% of 7–9 in. diameter trees
Juniperus monosperma								76% of all trees
Sagebrush with low pj								
Ward (1977)	E NV	–	High	1		215	0	
Grassland with moderate pj								
Alderete (1996)	S NM	1940	High	1				
Pinus edulis						67	1	
Juniperus deppeana and *Juniperus monosperma*						2427	2340	
Sagebrush with moderate pj								
Bruner and Klebenow (1979)	C NV	–	Low	30		–	–	12 of 20 burns successful
Burkhardt and Tisdale (1976)	E OR	1400–2100	Low		U			Most trees <50 years killed
Martin (1978)	E OR	–		U		–	–	
Juniperus occidentalis backing fire (moderate conditions)			High					Most trees >1.8 m survived
Juniperus occidentalis backing fire (higher temperature and winds)			High					Most trees >4.0 m survived
Juniperus occidentalis head fire (modest conditions)			High					All trees <1.5 m killed; 73% survival for trees >6.3 m
Juniperus occidentalis head fire (extreme conditions)			High					All trees <4.5 m killed; 37% survival for trees >4.8 m
Juniperus occidentalis wildfires			Low		U			<30% survival in most fires

Quinsey (1984)	E OR	–	High					
Xeric burns		730–866		2	1			All trees killed
Mesic burns		1085–1207		2				5 of 6 young trees killed on one, 5 of 20 killed on the other
Ward (1977)	E NV	–	High	4		680	0	All trees killed
Closed pj woodland								
Alderete (1996)	S NM	1940	High	1				
Pinus edulis						460	227	Notes poor fire spread
Juniperus deppeana and *Juniperus monosperma*						1080	833	Notes poor fire spread
Arnold et al. (1964)	N AZ	–	Low		16	–	–	100% except unburned islands
Aro (1971)	CO, UT	–	Low	1	2	–	–	High
Bruner and Klebenow (1979)	C NV	–	Low	10		–	–	All burns unsuccessful
Despain (1987)	NW AZ	–	Low	9		–	–	ca. 22,000 acres burned
Erskine and Goodrich (1999)	NE UT	–	Low	7				Near 100% on ca. 3000 acres burned
Goodrich and Barber (1999)	NE UT	–	Low		3	–	–	Nearly all trees killed
Tausch and West (1988)	SW UT	2000	High		1	–	–	38% of juniper and 0.6% of piñon survived
Weise (1990)	S CA	1463, 2133	High		2	–	–	10 and 36% survival

[a] In this table, ‘‘low pj’’ means low-density piñon–juniper, ‘‘moderate pj’’ means moderate-density mature piñon–juniper or high-density young piñon–juniper.

Moderately dense woodlands with a grassy understory are not true savannas, as savannas have a low density of trees in a matrix of grass (McPherson, 1997). Moderately dense mature piñons and junipers with a grassy understory have been burned in prescribed surface fires in one case (Table 5). Most piñons were killed, while junipers were hardly reduced, possibly due in part to moist burning conditions (Alderete, 1996). This study does not suggest that tree density will be maintained at a low level by periodic low-severity surface fires in these grassy woodlands. As in savannas, there is no direct evidence of the frequency of past surface fires in these woodlands with grassy understories (Section 3.2).

Low- or moderate-density piñon–juniper woodlands with a sagebrush or shrubby understory are also not true savannas (McPherson, 1997), and fires in these woodlands have quite variable effects (Table 5), probably because of variable fuel loads and burning conditions. For instance, some prescribed fires were difficult to start, and fires may be limited to moderate to severe weather conditions (Bruner and Klebenow, 1979). Some successfully ignited fires killed trees of all sizes (Ward, 1977), particularly on xeric sites (Quinsey, 1984). On more mesic sites (Quinsey, 1984) and under modest burning conditions (Martin, 1978), larger trees may survive (Table 5). Even under extreme conditions, large trees may survive in some cases (Martin, 1978). In sagebrush with a low density of trees, complete mortality of trees in one case (Ward, 1977) is consistent with evidence that periodic fires that burn sagebrush stands in the ecotone with piñon–juniper woodlands can kill invading trees (Miller and Rose, 1999). Absence of fire between 1655 and 1750 A.D., however, did not lead to tree invasion into big sagebrush in one study area, suggesting that fire is not the sole limitation on tree invasion (Young and Evans, 1981). Natural fires in these woodlands, if they behaved as demonstrated in these prescribed fires, would not have maintained low tree density or increased mean tree size, as is expected in true savannas. These fires, instead, likely failed to spread in some cases and caused partial or complete mortality of trees in other cases (Table 5).

In the densest, closed woodlands (where tree canopies nearly touch), many authors have remarked about the difficulty of intentionally igniting fires, except under extreme burning conditions (Aro, 1971; Bruner and Klebenow, 1979; Despain, 1987). When prescribed ignitions have been successful, all or nearly all trees were killed, and some of these fires burned thousands of hectares (Table 5). Wildfires that burned in closed woodlands often also led to complete tree mortality.

Together these studies suggest that fire certainly can kill young trees, particularly in grassy areas, but when understories include shrubs or when trees are denser, fire behavior and tree mortality are more variable. High-severity fires can certainly limit woodland extent, but evidence indicates that low-severity fires, outside true savannas, do not consistently thin these woodlands.

3.5. *Did high-severity fires occur in piñon–juniper woodlands?*

Since EuroAmerican settlement, 126 observed or reconstructed wildfires in piñon–juniper woodlands have been reported in the literature for the 11 western states (Tables 5 and 6). Of these, 2 were low-severity surface fires (Dwyer and Pieper, 1967; Johnson et al., 1962, Table 5), 3 were possibly mixed severity (Section 3.7), and 121 were high severity (Table 6). Most likely, 6 of the post-settlement high-severity fires occurred before woodlands were significantly modified by land uses (i.e., 1865–1885 A.D.; Arnold et al., 1964; Wangler and Minnich, 1996), and thus also represent natural fires. Many high-severity fires kill all trees, but unburned islands are sometimes left on rocky outcrops and ridges, on topographic breaks, and in otherwise rough terrain (Arnold et al., 1964; Despain, 1987; Wangler and Minnich, 1996; Goodrich and Barber, 1999; Miller and Rose, 1999).

Prior to EuroAmerican settlement, ≥16 fires are documented to have had a high-severity component (Table 6). Four of these 16 were possibly mixed severity (see Section 3.7) and 12 or more were likely entirely high severity. There is no accurate count of the number of low-severity surface fires prior to EuroAmerican settlement in these woodlands for comparison (see Section 3.2). High-severity fires in the pre-EuroAmerican period are documented from five areas: Mesa Verde National Park in southwestern Colorado, the San Bernardino Mountains in southern California, the Stansbury Mountains in northwestern Utah, the Sheeprock Mountains in central Utah, and the Sacramento Mountains in southern New Mexico (Table 6).

Table 6
Data relevant to questions 5–7[a]. Quality criteria and the questions are in Table 1

Author(s)	State	Elevation (m)	Quality	Reconstructed	Observed	Pre-EuroAmerican	Post-EuroAmerican	High severity	Unburned islands	Mixed severity	Quality (rotation)	Fire rotation (years)
Arnold et al. (1964)	N AZ	1800	High	16			16	X	Yes	No	–	–
Aro (1971)	NW CO NE UT	–	High		2		2	X	–	–	–	–
Barney and Frischknecht (1974)	C UT	1775–2375	High	28		≤5	≥23	X	No	No	–	–
Butler et al. (1998)	C CO	1775–2100	High		1		1	X	–	–	–	–
Despain and Mosley (1990)	N AZ	1890–2075	High	4		3	1		–	X	–	–
Erdman (1970)	SW CO	2060–2485	High	1	2	1	2	X	No	No	–	–
Floyd et al. (2000), Romme et al. (2003)	SW CO	2060–2485	High	2	6	2	6	X	No	No	High	ca. 400
Goodrich and Barber (1999)	NE UT	–	High	1	2		3	X	Yes	–	–	–
Gruell (1997)	E CA	1920–2347	High	1			1	X	–	–	–	–
Hester (1952)	W CO	–	High		1		1	X	–	–	–	–
Hoffman (1921)	W CO	–	Low		U		U	X	–	–	–	–
Koniak (1985)	NV, CA	1665–2230	High		21		21	X	No	No	–	–
McCulloch (1969)	N AZ	1950–2133	High		1		1	X	No	No	–	–
Minnich (1991)	S CA	–	Low	U		U	U	X	–	–	Low	"Centuries"
Ott et al. (2001)	W UT	1620–1980	High		4		4	X	No	No	–	–
Phillips and Mulford (1912)	C AZ	–	Low	U		U	U	X	–	–	–	–
Pratt (2001)	C UT	1875–1950	High		1		1	X	Yes	No	–	–
Quinsey (1984)	E OR	730–866	High		1		1	X	No	No	–	–
Rogers (1982)	NW UT	1743	High		1	1		X	Yes	No	–	–
Tausch and West (1988)	SW UT	2000	High	1		1				X	–	–
Wangler and Minnich (1996)	S CA	1300–2700	High		38	2	36	X	Yes	No	High	480
Weise (1990)	S CA	1463, 2133	High		2		2			X	–	–
Wilkinson (1997), Brown et al. (2001)	S NM	2400–2420	Medium	1		1		X	–	–	–	–

[a] U, unknown, and – means that no information was provided. The column labeled "Observed" means only that someone, not necessarily the author, observed the fire or recorded its occurrence. Prescribed fires are excluded from this analysis as are high-severity fires that kill invading piñons and junipers in sagebrush communities (Miller and Rose, 1999).

Documentation includes early photographs and age- or size-structure analysis. It can be argued that fires that burned through sagebrush communities in the ecotone with juniper in the Pacific Northwest were effectively high-severity fires, since few trees apparently survived except in rocky areas where fire did not carry (Miller and Rose, 1999). Early post-settlement high-severity fires are also documented in northern Arizona (Arnold et al., 1964).

There are significant methodological problems in documenting the occurrence or absence of pre-EuroAmerican high-severity fires in piñon–juniper woodlands. Cross-dating is problematic for these fires, just as for low-severity surface fires. Trees may not re-invade high-severity burns for several decades, but the lag can vary (Miller and Tausch, 2001). Tree-ring dating may thus be inconclusive even if a cross-dated fire scar is available, as it is difficult to convincingly associate an episode of tree establishment with a fire-scar date decades earlier. A close agreement of a fire-scar date and dates of tree mortality or subsequent tree origins has been the prime signal for high-severity fires in fire-history reconstructions in other ecosystems (Ehle and Baker, in press). Without this agreement, agents other than fire (e.g., insects, drought) cannot be excluded as the cause of an episode of mortality or tree regeneration. Dating the approximate year of death of charred, standing trees (Despain and Mosley, 1990) might be possible for high-severity fires in the last century or two. In piñon–juniper woodlands, early photographs, in some cases, may provide strong evidence that high-severity fires did or did not occur, but do not provide estimates of fire rotation, and images are limited to the late 1800s and early 1900s after photography became common.

Have high-severity fires increased in these woodlands since EuroAmerican settlement, possibly because fires, that formerly would have been low-severity surface fires, now burn as high-severity fires? Available data reveal that high-severity fires have been common and almost no low-severity surface fires have occurred in piñon–juniper woodlands since EuroAmerican settlement (Table 6). But, without information about pre-EuroAmerican fires, this information tells us nothing about whether high-severity fires have or have not increased. High-severity fires are, in fact, documented prior to EuroAmerican settlement in at least five areas scattered around the West (Table 6). Only in the San Bernardino Mountains of southern California and Mesa Verde National Park, Colorado, where there is evidence of high-severity fires prior to EuroAmerican settlement and analysis of high-severity fires after settlement, is there a basis for determining whether high-severity fires have or have not increased. In these two areas, the authors conclude that high-severity fires have not increased. In most of the 11 western states, there is no basis for concluding that high-severity fires have or have not increased in piñon–juniper woodlands since EuroAmerican settlement, since there are no data on the abundance of high-severity fires prior to EuroAmerican settlement.

3.6. *What is the fire rotation for high-severity fires in piñon–juniper woodlands?*

The fire rotation, which is defined as the time required to burn over an area, equal to that of a particular landscape, one time (Baker and Ehle, 2001), has been determined for only two locations in piñon–juniper woodlands, where it is estimated to be about 400 years in one case and 480 years in the other (Table 6). In both cases, the rotation is derived from observations of area burned by high-severity fires since EuroAmerican settlement, but the argument is made that fire suppression has not affected these rates, so that the estimate is essentially an estimate of the natural fire rotation.

3.7. *Did mixed-severity fires occur in piñon–juniper woodlands?*

No authors report mixed-severity fires in piñon–juniper woodlands—it is entirely our interpretation of reported data. Mixed-severity fires are characterized by patches of high severity, evidenced by overstory mortality, contiguous with areas of low-severity surface fire with high overstory survival. Several fires studied by Despain and Mosley (1990) in northern Arizona, a small fire studied by Tausch and West (1988) in southwestern Utah, and two fires studied by Weise (1990) in southern California might have been mixed in severity. However, an alternative explanation of the pattern of patchy overstory mortality is spotting from high-severity fire without spread on the surface among the patches. Since no one has reported observing modern mixed-severity fire in piñon–juniper woodlands, we simply suggest the possibility of this type of fire, which has been documented in other ecosystems.

3.8. Conclusions

Fire history and the effects of fire in piñon–juniper woodlands remain poorly known and understood, as suggested by previous reviewers and authors (Gottfried et al., 1995; West, 1999; Miller and Tausch, 2001). We have more explicitly identified areas of disagreement and uncertainty. For low-severity surface fires, there is substantial uncertainty about the reliability and representativeness of the available fire-scar evidence. Limited success in cross-dating fire scars on piñons and junipers means that most of the piñon–juniper zone in the West lacks reliable evidence of the occurrence and frequency of low-severity surface fires.

There is some reliable evidence that low-severity surface fires may have occurred in the upper ecotone. Yet, while low-severity surface fire regimes remain plausible for other areas, there are almost no direct fire data supporting the notion of frequent low-severity surface fires maintaining savannas or most woodlands. No reliable data suggest that low-severity surface fires occurred or would have consistently lowered the density of trees in moderate-density woodlands with a sagebrush or grassy understory. The closed woodland zone in much of the West, moreover, has virtually no evidence for spreading low-severity surface fires.

In fact, at least on a regional basis, some woodlands did not experience low-severity surface fires, but, rather, were naturally subject to long-rotation high-severity fires. Thus, arguments that piñon–juniper woodlands have become more dense due to fire suppression in these areas seem unlikely. Consequently, fire suppression is not clearly a cause of modern high-severity fires; in some places these high-severity fires are natural, and in much of the rest of the West their occurrence prior to EuroAmerican settlement is unknown. Fires, that are effectively high-severity fires, since they may kill stands consisting primarily of small trees, are well-documented in one case to have been able to prevent tree invasion into sagebrush and grasslands prior to EuroAmerican settlement. However, absence of these fires in another pre-EuroAmerican case did not lead to tree invasion. Thus, the role of fire as a general mechanism maintaining the ecotone and the role of fire suppression in encouraging tree invasions remain poorly supported and uncertain. Variability in the abundance of fire scars and in reports of pre-EuroAmerican high-severity fires and low-severity surface fires suggest that regional and even possibly within-site variation in fire regimes could be substantial. But more specific knowledge of fire regimes is lacking or uncertain for most of the piñon–juniper woodland area in the West.

In spite of these uncertainties, the fire regime of piñon–juniper woodlands has been classified by researchers and used by land managers to assess woodland condition and ecosystem health. These classifications and assessments are not supported by the scientific literature we reviewed. In creating maps of fire regimes, Frost (1998) uses Leopold (1924), apparently as the sole source, to place piñon–juniper woodlands into a "13–25 years" fire- frequency class, even though our review suggests there are many other sources that do not support this classification. Brown (2000) maps piñon–juniper as "Mixed-severity fires 0–34 years." Our review shows that reliable evidence of individual fires of mixed severity is lacking, and fires of higher severity are likely much less frequent than 0–34 years (Section 3.6).

Hardy et al. (2000) is the basis for rating piñon–juniper woodland condition across the West relative to the effects of fire suppression. Hardy et al., based on the expertise of local fire managers, classify the piñon–juniper fire regime as "0–35 yr frequency, low severity," a classification not supported by the scientific evidence we review here. Since these authors place piñon–juniper woodlands mostly within a low-severity, frequent-fire class, these woodlands are considered to have missed two or three fires in the last century. However, our review suggests that, while uncertain, low-severity surface fire was most likely not a common type of fire in piñon–juniper woodlands in the western United States. In some parts of the West, the natural fire regime of piñon–juniper woodlands was clearly dominated by high-severity fires. The condition assessment or Hardy et al. (2000) is thus definitely erroneous for these areas of woodland, likely is in error for much of the rest of the West, and is at best premature given the uncertainty our review identifies. At the present time, our review suggests there is insufficient scientific basis for a national program that rates woodland condition and then applies uniform fire and structural restoration treatments in piñon–juniper woodlands across the West.

If restoration of fire in piñon–juniper woodlands is to be based on sound science, significant methodological hurdles (i.e., modern calibration, cross-dating) must first be addressed and resolved. Only then can fire scientists focus on systematic collection and analysis of the key evidence that can distinguish and quantify the types of fires that occurred in the past. If a network of such studies were available, then a science-based national restoration program could probably be effectively created.

Until this is possible, we suggest a more cautious, research-based local restoration strategy. Localized or site-specific scientific studies are always needed before restoration prescriptions are formulated (Romme et al., 2003), but this is particularly true now, given the uncertain state of the science. We suggest that before undertaking restoration treatments on a particular site, managers or scientists date some of the largest trees on the site. If these trees pre-date EuroAmerican settlement, removing or thinning them is inappropriate if restoration is the goal. Trees that pre-date EuroAmerican settlement represent woodland structure before the impacts of our land uses, and thus need to be preserved during restoration as is true in other ecosystems (e.g., Friederici, 2003). Moreover, old-growth piñon–juniper woodlands have many ecological values that have been under-appreciated (Waichler et al., 2001).

If larger trees on a site post-date EuroAmerican settlement, the stand could represent either (1) piñon–juniper invasion into vegetation that was not previously woodland or (2) natural re-establishment of piñon–juniper following a fire in a former woodland. Natural re-establishment of trees after fire can be quite slow in these woodlands, requiring decades, so that post-fire stands may superficially appear to represent tree invasion. However, post-fire stands can often be identified by the presence of some standing or down charred wood from the fire. Burned woodlands with slowly re-establishing trees do not warrant treatment if the goal is restoration. Invading post-settlement stands and post-settlement trees inside old stands require further research to determine whether restoration is needed, and, if so, what needs to be done. Invasion may be natural (e.g., climatic fluctuations) or human-caused (fire suppression, livestock grazing, increased carbon dioxide). Unless the specific natural or human causes can be distinguished for a site, restoration is likely to be ineffective or possibly mis-directed. The first step in effective restoration is to identify and then modify the cause of degradation (Hobbs and Norton, 1996). If our land uses are found to be responsible for tree invasions or density increases, and if restoration is to have lasting value, it is essential to change the land uses that led to the need for restoration.

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