THE ROLE OF FIRE IN JUNIPER AND PINYON WOODLANDS: A DESCRIPTIVE ANALYSIS

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ABSTRACT

Among the most pronounced vegetation changes in the past 130 years has been the increase in both distribution and density of juniper (*Juniperus* spp.) and pinyon (*Pinus* spp.) across the Intermountain West. Juniper and pinyon species between the Canadian and Mexican borders occupy over 30 million ha throughout this region. Prior to European settlement, woodland species were primarily confined to rocky ridges or surfaces where sparse vegetation limited fire. Woodlands now occupy more productive sites with deeper well-drained soils. Woodland species began their unprecedented and ongoing rates of increase during the late 1800s. Replacement of sagebrush shrub steppe, riparian, and aspen (*Populus* spp.) communities by pinyon and juniper species is largely attributed to the reduced occurrence of fire. An important sagebrush type that has been impacted by recent woodland expansion is mountain big sagebrush (*Artemisia tridentata* var. *vaseyana*). Prior to settlement, mean fire return intervals for a large portion of this cover type were 12–25 years. At present, fire return intervals in this cover type have increased to >100 years. As trees gain dominance and shrubs and herbaceous vegetation decline, fuel structure changes, which contributes to significant increases in the length of mean fire return intervals. Fire-safe communities successionally replace fire-dependent communities. However, in the central and southern portions of the Intermountain West, particularly where pinyon is dominant, dense tree-canopied woodlands are now becoming susceptible to intense crown fires. The intensity of these fires can lead to dominance by exotics, further altering the successional dynamics of the site. During the past, juniper and pinyon woodlands have been treated to control the expansion. However, wildlife and environmental concerns, and different perceptions of the intrinsic values of these environments have recently limited treatment of woodlands, including the use of prescribed fire. During the early to middle stages of development when woodlands contain understories of native shrubs and herbs, they can successfully be treated by various methods, particularly fire. However, once communities become tree-dominated woodlands, treatment becomes difficult and expensive.

keywords: fire history, Intermountain West, invasion, *Juniperus occidentalis, Juniperus osteosperma,* pinyon pine, *Pinus edulis, Pinus monophylla,* succession, Utah juniper, western juniper.

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INTRODUCTION

Among the most pronounced vegetation changes during the past 130 years in the Intermountain West has been the increase in juniper and pinyon woodlands. Post-settlement expansion of these woodlands is considered unprecedented when compared to prehistoric expansions during the Holocene (Miller and Wigand 1994). At present, juniper and pinyon species occupy >30 million ha in the American West between the borders of Canada and Mexico (West 1999). Prior to settlement, these woodlands are estimated to have occupied <3 million ha (Gedney et al. 1999, Miller et al. 1999). Woodland expansion began during the late 1800s throughout most of this region (Cottam and Stewart 1940, Burkhardt and Tisdale 1976, Tausch et al. 1981, Miller and Rose 1995, 1999). Causes of woodland expansion are frequently attributed to the reduced role of fire, introduction of domestic livestock grazing, shifts in climate, and increases in atmospheric CO_2 (Miller and Rose 1999).

Although pinyon and juniper woodlands are estimated to have increased 10-fold during the past 130 years, they currently occupy far less land than they are capable of under current climatic conditions (West and Van Pelt 1986, Betancourt 1987, Miller et al. 2000). In addition, many of these woodlands are in a transitional state where tree densities and cover are continuing to increase, causing declines in understory biomass, cover, and diversity. Woodland expansion into shrub steppe plant communities has resulted in a dramatic increase in length of fire return intervals in the big sagebrush cover type (West 1984, Miller et al. 1999). However, in some areas the rapid expansion and thickening of post-settlement woodlands are creating conditions that produce high-intensity crown fires. These high-intensity fires are capable of causing shifts from woodlands to introduced annual communities (Tausch 1999*a, b*).

Altered disturbance regimes and climate change have resulted in major changes in plant community composition. Since the 1860s, many bunchgrass and

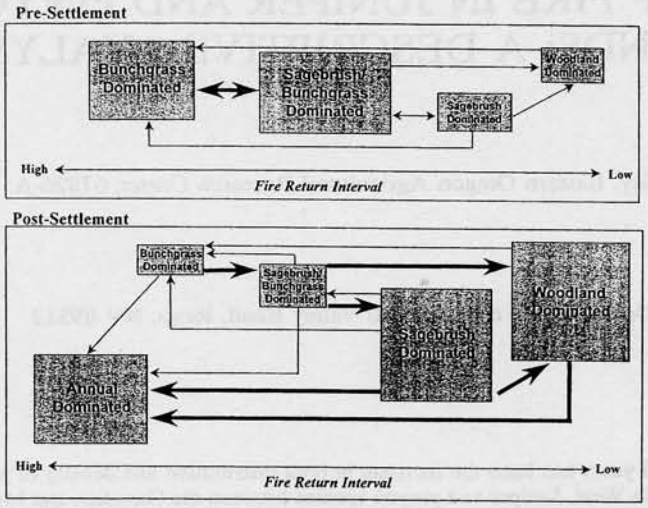

Fig. 1. Pre- and post-settlement shrubland and woodland succession. Size of the boxes represents the dominance of the communities in the Intermountain West. Heavy arrows indicate primary pathways of plant community succession.

sagebrush–bunchgrass communities, which dominated the Intermountain West, have shifted to pinyon and juniper woodland or introduced annual-dominated communities (West 1984, Miller et al. 1994; Figure 1). Concerns related to these changes in community composition are increased soil erosion (Wilcox and Breshears 1994), changes in soil fertility, losses in forage production, changes in wildlife habitat, and alteration of pre-settlement plant communities. In the past, woodlands have been sprayed, burned, cut, and chained with little challenge from various interest groups. However, wildlife concerns, the removal of pre-settlement woodlands, and various environmental issues have challenged and reduced treatment of juniper and pinyon woodlands throughout the Intermountain West. Addressing these concerns requires more study of the ecology, structure, and long-term dynamics of these ecosystems.

This paper summarizes evidence supporting (1) the timing and extent of woodland expansion, (2) changes in mean fire return intervals (MFRI) in shrub steppe and woodland communities since Eurasian settlement, and (3) the role of fire in limiting woodland expansion prior to Eurasian settlement. We focus on juniper and pinyon woodlands occupying the Great Basin, the Colorado Plateau, and regions of eastern Oregon and southern Idaho. Woodland succession and thresholds crossed during pinyon and juniper encroachment into shrub steppe communities are also discussed.

WOODLANDS OF THE GREAT BASIN AND COLORADO PLATEAU

Distribution

The pinyon and juniper woodlands in the Great Basin and Colorado Plateau occupy over 18 million ha (Table 1). Juniper and pinyon species in these 2 regions are predominately Utah juniper (*Juniperus osteosperma*), western juniper (*J. occidentalis* ssp. *occidentalis*), Sierra juniper (*J. occidentalis* ssp. *australis*), single-needle pinyon pine (*Pinus monophylla*), and two-needle pinyon (*P. edulis*). These woodlands occupy a range of environments that vary in climate, soils, and elevation. Woodlands can be found on sites from a few hundred meters above sea level to elevations over 2,800 m. They occur in climates with predominately winter and spring precipitation to regions receiving winter and summer precipitation. Juniper is more widespread than pinyon, usually dominating lower elevations (West et al. 1978). Precipitation varies between 30 and 45 cm per year across a majority of the pinyon and juniper type. However, stands can occupy precipitation zones up to 55 cm per year

Table 1. Estimated area occupied by western (JUOC) and Utah (JUOS) junipers, and single- (PIMO) and two-needle (PIED) pinyon pines in the Intermountain West.

State	Species	Estimated area (ha)	Reference
Arizona	JUOS–Pinyon	4,713,360	Springfield 1976
California	JUOC	519,838	Bolsinger 1989
	JUOC savanna	322,672	Bolsinger 1989
	JUOS–JUCA	440,891	Bolsinger 1989
Colorado	JUOS–PIED[a]	2,404,000	Estimated from Powell et al. 1994
Idaho	JUOC	242,915	Estimate, no reference
	JUOS	55,466	Tueller et al. 1979
New Mexico	JUOS–PIED	1,247,773	Springfield 1976
Nevada	JUOS–PIMO	2,897,154	O'Brien and Woudenberg 1999
	JUOS	681,606	O'Brien and Woudenberg 1999
	JUOC	40,486	Estimate, no reference
Oregon	JUOC	906,478	Gedney et al. 1999
	JUOC savanna	1,140,891	Gedney et al. 1999
Utah	JUOS–PIED	3,144,254	O'Brien and Woudenberg 1999
	JUOS	60,081	O'Brien and Woudenberg 1999
Wyoming	JUOS–PIED	82,186	Powell et al. 1994
Total		18,900,051[b]	

[a] Estimate from Powell et al. 1994, who reported the total area of pinyon–juniper woodlands in Colorado, including the widespread Rocky Mountain (*Juniperus scopulorum*) and eastern redcedar (*Juniperus virginiana*).
[b] Areas or species in the Intermountain region not included are *Juniperus californica* in southern California, *Juniperus* sp. south of the Mogollon Rim in Arizona, *J. monosperma* in New Mexico, and *J. scopulorum*.

(Springfield 1976). The woodland belt, frequently associated with *Artemisia,* typically lies between the submontane shrub or coniferous forest and the desert shrub (Woodbury 1947).

Pinyon and juniper woodlands have been rapidly expanding into big sagebrush (*Artemisia tridentata*), low sagebrush (*A. arbuscula*), black sagebrush (*A. nova*), bitterbrush (*Purshia tridentata*), curlleaf mountain-mahogany (*Cercocarpus ledifolius*), aspen (*Populus tremuloides*), and riparian cover types (Tausch et al. 1981, Miller et al. 2000, Wall et al. 2001). Pre-settlement fire regimes within and across these cover types were historically dynamic both temporally and spatially. Fire regimes are characterized by season, fire return interval, size, spatial complexity, intensity, and fire severity. Fire regimes are influenced by topography, ignition sources, climate, composition of plant communities on the landscape, fuel structure, fuel composition, fuel moisture content, and fuel continuity. All of these factors vary greatly across the Great Basin and Colorado Plateau. For example, fine fuel loads range between 1,100 and 2,750 kg/ha in the mountain big sagebrush, 440 and 775 kg/ha in Wyoming big sagebrush (*Artemisia tridentata* ssp. *wyomingensis*), 370 and 1,000 kg/ha in low sagebrush, and 440 and 620 kg/ha in black sagebrush cover types (Passey et al. 1982, Shiflet 1994). Fine fuel production also varies from year to year with timing and amounts of moisture input. Fuel characteristics will also change temporally as trees gain dominance and understories decline.

Western Juniper

The northwestern portion of the pinyon and juniper region is represented by western juniper. This subspecies occupies 3.2 million ha across eastern Oregon, northeastern California, southwestern Idaho, northwestern Nevada, and a few outlying stands in southern Washington (Table 1). Western juniper is usually the only conifer species occupying a site except where juniper woodlands adjoin ponderosa pine (*Pinus ponderosa)* forests. Precipitation across the majority of the western juniper cover type varies between 30 and 45 cm per year, most of which falls during the winter and spring. However, western juniper can grow in areas receiving as little as 20 cm/yr or exceeding 50 cm/yr of precipitation. Sierra juniper extends along the upper elevation slopes of the Sierra Nevada Mountain range south of Susanville, California, and east and south from the Anchorite Hills (south of Walker Lake in Nevada near the California border) to the Panamit and San Bernardino Mountains. Small pockets of Sierra juniper (Charlet 1996), and hybrids of Sierra and Utah juniper (Terry et al. 2000) also grow in several mountain ranges in central Nevada. Sierra juniper is usually found growing as widely scattered trees with other conifers at elevations between 1,260 and 2,775 m.

Utah Juniper and Pinyon Pine

Utah juniper, the most extensive and abundant juniper species occupying the Intermountain region, is typically associated with both the single-needle and two-needle pinyon (Table 1). In Utah and Nevada, approximately 80% of the woodlands are a mixture of juniper and pinyon with the rest juniper only (O'Brien and Woudenberg 1999). The distribution of precipitation across the range of Utah juniper changes from winter–spring in the northwestern Great Basin to winter–summer in the Colorado Plateau. As the amount of summer precipitation increases, single-needle pinyon is replaced by two-needle pinyon and the dominance of juniper in mixed species stands generally increases (West et al. 1978). Fewer shrubs and increased composition of warm season plants are associated with pinyon and juniper woodlands moving south and east across the Great Basin into the Colorado Plateau (West 1984).

WOODLAND EXPANSION

Prehistoric Woodland Dynamics: Climate and Fire

Distribution and density of pinyon and juniper woodlands changed significantly across the Intermountain West during the transition from the Pleistocene to Holocene periods, and during the Holocene period. Woodland dynamics are largely attributed to long-term shifts in temperature, amounts and distribution of precipitation, and the extent and return intervals of fire (Davis 1982, Thompson and Hattori 1983, Mehringer 1987, Van Devender et al. 1987, Wigand et al. 1995).The prehistoric abundance and distribution of plant species are determined from both plant macrofossils and from fossil pollen recovered from a variety of sources. Studies of fluvial geomorphology (Miller et al. 2001) and studies from ice cores (Tausch et al. 1993) provide collaborative evidence supporting the plant record. Evidence of past climatic patterns and fire regimes, which influenced prehistoric woodland distribution and abundance, provides important clues to understanding the current dynamics and distribution of pinyon and juniper woodlands (Betancourt 1987).

Early Holocene

During the early Holocene (10,000 to 8,000 years before present [BP]), pinyon and juniper began moving upward in elevation and northward in the Great Basin and Colorado Plateau as the climate warmed (Wells 1983, 1987, Betancourt 1987, Thompson 1990). As pinyon and juniper migrated, they often replaced subalpine woodlands that had been present through most of the previous 100,000 years of glaciation. Between 10,000 and 8,000 years BP, two-needle pinyon moved north from what are now the Sonoran and Chihuahuan deserts onto the Colorado Plateau (Betancourt 1987). Utah juniper moved north and east from the Grand Canyon during the same period. Juniper also moved into higher elevation areas of the central and northern Great Basin between 9,000 and 8,000 years BP from its scattered low-elevation refugia of the Pleistocene period (Wigand et al. 1995). Pinyon remained a minor component of Great Basin woodlands during this period (Spaulding 1985, Thompson 1990).

Mid-Holocene

The mid-Holocene (8,000 to 4,000 years BP) was a relatively warm and dry period. Woodlands in the Great Basin occupied sites 500 m higher in elevation than stands during the 20th century (Jennings and Elliott-Fisk 1993, Wigand et al. 1995). Drought-tolerant salt-desert plant species increased substantially in abundance at the lower elevations during this period. Western juniper migrated north and east into northeastern California and southeastern Oregon (Wigand 1987, Mehringer and Wigand 1990). Two-needle pinyon reached its northern-most limits during the mid-Holocene. Ponderosa pine and Gambel oak (*Quercus gambelii*) expanded beyond their current distribution (Betancourt 1987).

Following the mid-Holocene warm period, woodlands continued to fluctuate in abundance and distribution in response to climate and fire (Grayson 1993, Millar 1996, 1997, Tausch 1999*a, b*). Between 5,000 and 4,000 years BP, precipitation increased while temperatures remained warm (Davis 1982, Mehringer 1986, Wigand 1987). Western juniper first appeared in the northerly latitudes of the Great Basin about 4,500 years BP (Wigand 1987), and pinyon and juniper woodlands rapidly increased in range and abundance throughout the Great Basin and Colorado Plateau (Miller and Wigand 1994). However, increases in grass abundance and fire occurrence during this period limited the distribution and development of fully closed stands. Woodlands during this period were relatively open (Miller and Wigand 1994).

Neoglacial

The Neoglacial period (2,500 years BP) that followed the mid-Holocene was characterized by much cooler and wetter conditions (Davis 1982, Wigand 1987, Wigand et al. 1995). Western juniper reached most of its current range by about 3,000 years BP, and pinyon reached most of its current range in the Nevada and Utah sections of the Great Basin by the end of the Neoglacial period (Nowak et al. 1994*a, b,* Wigand et al. 1995). Expansion in woodland area and density also occurred in the southern Great Basin (Wigand et al. 1995). During the Neoglacial period, distribution of woodlands at the intermediate elevations are believed to have been as extensive as present (Davis 1981, Wigand 1987).

Late Holocene

The late Holocene (2,500 to 140 years BP) was a period of changing climatic patterns. Severe drought and major fires immediately followed the Neoglacial (Davis 1981, Wigand 1987, Chambers et al. 1998, Miller et al. 2001), resulting in rapid regional declines in juniper and perennial grasses and expansion of sagebrush at upper elevations and salt-desert shrub vegetation at lower elevations (Wigand et al. 1995). The presence of charcoal layers in pollen cores and sediments indicates that frequent large fires in combination with climate impacted pinyon and juniper abundance and distribution (Wigand et al. 1995, Miller et al. 2001). In the central Great Basin, extensive hill slope erosion accompanied by deposition on alluvial fans and in drainage channels occurred during the first two-thirds of this drought period (Miller et al. 2001). The edaphic and hydrologic results of these events still have a major influence on present-day plant community composition and distribution (Chambers et al. 1998).

Between 1,500 and 1,100 years BP, a period known as the Medieval Climate Anomaly, increases in summer precipitation and grass cover occurred. As moisture conditions improved, woodlands once again began increasing in abundance with both northward and downward re-expansion, particularly for pinyon (Wigand et al. 1995). A drying period, lasting 200 years (900 to 700 years BP) again reduced woodland abundance, although not distribution (Wigand et al. 1995).

The Little Ice Age (700 to 150 years BP) was the wettest and coolest period during the last half of the Holocene. Upper tree lines in the Sierra receded to elevations lower than occurred during the Neoglacial (Woolfenden 1996). Increased cover of herbaceous plant species during this period (Wigand et al. 1995) likely supported higher fire frequencies (Gruell 1999, Miller and Rose 1999), which limited woodland distribution and abundance (Wigand 1987, Miller and Wigand 1994). During the late 1500s, a severe drought possibly accompanied by large fires is thought to have caused extensive mortality of pinyon and juniper woodlands across the American Southwest (Swetnam and Betancourt 1998).

Since the end of the Little Ice Age there has been a general warming trend (Ghil and Vautgard 1991, Woolfenden 1996). Climate conditions during the 20th century were similar to the period immediately following the Neoglacial period. However, a large increase in fire occurrence accompanied post-Neoglacial climate changes (Wigand et al. 1995, Miller et al. 2001) in contrast to region-wide declines in fire events over the last 130 years. The magnitude and rate of woodland expansion during the past 130 years exceeds anything that has occurred for a similar length of time during the last 5,000 years of the paleo-record (Miller and Wigand 1994, Tausch 1999*a*).

Post-settlement Expansion

Historic expansions of pinyon and juniper woodlands are well documented (Cottam and Stewart 1940, Burkhardt and Tisdale 1976, Tausch et al. 1981, Tausch and West 1988, 1995, Miller and Rose 1995, 1999, Gedney et al. 1999, O'Brien and Woudenberg 1999, Tausch and Nowak 1999). Old surveys (Table 2), photographs (Rogers 1982, Creque et al. 1999, Gruell 1999, Soulé and Knapp 1999), and tree-ring chronologies (Table 3) provide evidence documenting the post-settlement expansion. In comparing 2 U.S. Forest Service surveys conducted during 1938 and 1988 across eastern Oregon, Gedney et al. (1999) reported a 600% increase in density and area during this

Table 2. Woodland expansion and/or increase in tree density between a defined period based on early surveys or tree growth rings where chronology was not presented for western (JUOC) and Utah (JUOS) junipers and single–needle pinyon (PIMO).

Species	Increase	Period	Evidence	Location	Reference
JUOC	600% area and density	1938–1988	Survey	E Oregon	Gedney et al. 1999
JUOC	94% density	1900–1995	Tree rings	SE Oregon and NW Nevada	Gruell 1999
JUOC	73% density	1890–1989	Tree rings	NE California	Bolsinger 1989
JUOS	600% area and density	1864–1940	Survey	Utah	Cottam and Stewart 1940
JUOS	Area	>1869	Survey	Utah	Christensen and Johnson 1964
JUOS	Area	1871–1988	Survey	Utah	Sparks et al. 1990
JUOS–PIMO	28% area	1940–1994	Survey	W Nevada	Tausch and Nowak (unpublished)
PIMO–JUOS	80% density	1860–1970	Tree rings	SW Utah	Tausch and West 1988, 1995
PIMO–JUOS	60% area	1900	Survey	westcentral Nevada	Toiyable National Forest (Bridgeport District), 1999

50-year period. Cottam and Stewart (1940) also reported a 600% increase in area and density of Utah juniper in southwest Utah between 1864 and 1940.

Other evidence supporting the post-settlement expansion of pinyon and juniper is the low proportion of pre-settlement trees (established prior to the 1860s) to trees establishing during the past 130 years. Although both pinyon and juniper are relatively long lived, Miller et al. (1999) estimated ≤10% of woodlands today are composed of trees establishing prior to 1860.

Tree-ring Chronologies

Tree-ring chronologies (Table 3) provide some of the strongest evidence supporting the recent expansion of pinyon and juniper woodlands. These chronologies describe both the age composition and dynamics of woodlands across the Great Basin and Colorado Plateau. Western and Utah junipers can easily attain ages exceeding 1,000 years and pinyon can exceed 600 years (Tausch et al. 1981, Waichler et al. 2001). However, >90% of today's woodlands are composed of trees establishing after 1860 (Miller et al. 1999). Large increases in pinyon and juniper establishment generally began between 1860 and 1880, peaked during the early 1900s, and are continuing to increase in area and density across the Intermountain Region. Miller et al. (2000) concluded the majority of the 2 million ha of western juniper in Oregon is still in transition from shrub steppe to juniper woodland. Knapp and Soulé (1998) reported continued rapid increases in tree cover between 1972 and 1995 on sites in central Oregon. In Utah and Nevada, 45 to 50% of the woodlands are in early to mid-successional stages and an additional 30 to 35%, although relatively dense, are not yet fully occupied (O'Brien and Woudenberg 1999). Woodland dynamics in the southern Great Basin and Colorado Plateau have not been as unidirectional as the Great Basin. Major disturbance events, such as severe droughts in the Southwest (Betancourt et al. 1993) and recent crown fires in dense pinyon–juniper in the southern Great Basin (Tausch 1999*b,* West 1999), have opened up many woodland areas that often shift to annual grasslands.

Harvesting did occur during the 1860s in major mining areas of Nevada and Utah (Young and Budy 1979), and earlier by Native Americans in the southwest (Betancourt and Van Devender 1981). However, harvesting was minimal across the majority of the range now occupied by western and Utah juniper and the associated pinyon species. The presence of old stumps and logs, which can persist for hundreds of years in this semi-arid climate, are indicators as to whether woodlands were present prior to the 1860s. Miller and Rose (1995, 1999) found little evidence of old stumps and logs in western juniper woodlands associated with mountain big sagebrush in the High Desert and Klamath Ecological Provinces. In Arizona, Despain and Mosley (1990) concluded pinyon and juniper had significantly increased based on the scarcity of decaying old wood in the woodlands.

FACTORS INFLUENCING HISTORIC WOODLAND EXPANSION

Factors most frequently attributed to the increase in both density and area of pinyon and juniper are climate, the introduction of livestock, post-industrial increases in atmospheric CO_2, and the reduced role of fire.

Climate

From 1850 to 1916, winters became milder and precipitation was greater than the current long-term average across much of the Great Basin (Antevs 1938, Wahl and Lawson 1970, LaMarche 1974, Graumlich 1987). This wet period coincides with the initiation and peak period of woodland establishment (Table 3). Wet, mild conditions promote vigorous growth in juniper (Fritts and Xiangdig 1986, Holmes et al. 1986).

Livestock

Introduction of livestock during the 1860s and the large buildup of animals from the 1870s through the early 1900s coincides with the initial expansion of pinyon and juniper woodlands throughout the Great Basin and Colorado Plateau (Table 3). Domestic grazing likely influenced pinyon and juniper woodland expansion through the reduction of fine fuel loads, which significantly altered the fire regime (Campbell 1954, Ellison 1960, Burkhardt and Tisdale 1976, Miller and Rose 1999), the increase in shrub density and cover, providing a greater number of optimal sites for tree establishment (Miller and Rose 1995), and through the

Table 3. Initiation of western (JUOC) and Utah (JUOS) junipers and single–needle (PIMO) and two–needle (PIED) pinyon pines expansion and peak establishment, based on tree-ring data. Sample size = number of trees sampled.

Cover type	Species	Initiation years	Peak years	Sample size	Location	Reference
Sagebrush	JUOS and PIMO	1850–1860s	1870–1920	>1,000	Nevada and W Utah	Tausch et al. 1981
	PIMO and PIED	1860s	1860–1945	3/plot	Nevada and Utah	O'Brien and Woudenberg 1999
Mountain big sagebrush	JUOC	1860s	1880–1920	<1,000	E Oregon	Gedney et al. 1999
	JUOC	1890s	1902–1936	228	Silver Lake, Oregon	Adams 1975
	JUOC	1870s	1910–1940		Owyhee Mountain, Idaho	Burkhardt and Tisdale 1976
	JUOC	1880s		>1,000	Prineville, Oregon	Eddleman 1987
	JUOC	1880s		>1,000	Steens Mountain, Oregon	Miller and Rose 1995
	JUOC	1870s			Hart Mountain, Oregon	Gruel 1999
	JUOC	1870s	1905–1925	>1,000	Paisley, Oregon	Miller and Rose 1999
	JUOS–PIMO	1870s			W Nevada	Gruell 1999
	JUOS–PIMO	1880s			E Nevada	Gruell 1999
Wyoming big sagebrush	PIMO and JUOS	1830–1840	1910–1920	>1,000	SW Utah	Tausch and West 1988
Wyoming and low sagebrush	JUOC	1880s	1890–1910	>100	NW California	Young and Evans 1981
Low sagebrush	JUOC	1870s		500	Paisley, Oregon	Miller and Rose 1995
Black sagebrush	JUOS	1860s			E Nevada	Blackburn and Tueller 1970
Aspen	JUOC	1890s	1910–1920	1,000	SE Oregon, NE California, NW Nevada	Wall et al. 2001

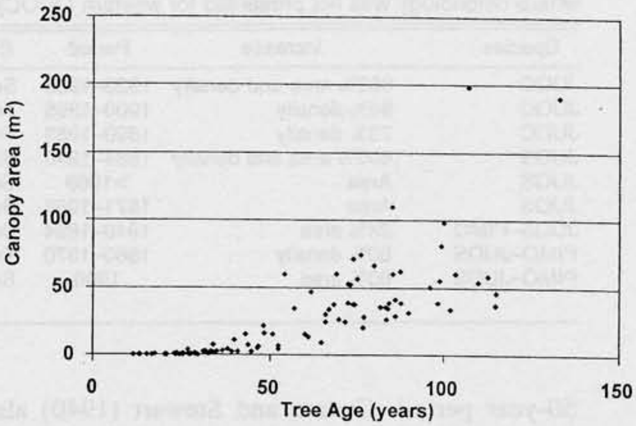

Fig. 2. Western juniper canopy area and age for individual trees (R.F. Miller, unpublished data).

reduction of competition from herbaceous species (Cottam and Stewart 1940, Madany and West 1983, Burwell 1998, 1999). Miller and Rose (1999) reported the role of fire in southcentral Oregon was significantly reduced after 1870, shortly after the introduction of large numbers of livestock during the late 1860s, and 46 years before organized fire suppression. These findings are similar to results from ponderosa pine forests in the Pacific Northwest (Heyerdahl et al. 2001) and Southwest (Savage and Swetnam 1990, Swetnam and Betancourt 1998), where fire events declined between 1874 and 1900. Additional evidence further supporting the link between livestock and fire was reported in the Chuskas area of Arizona where fire declined after 1829, shortly after the buildup of Navajo sheep herds (Savage and Swetnam 1990).

Atmospheric CO_2

Rising levels of atmospheric CO_2 have also been cited as causing the increase in woody species throughout the West (Johnson et al. 1990, Knapp and Soulé 1996). Increases in atmospheric CO_2 levels do not coincide with the initial increase or peak periods of pinyon and juniper establishment (Table 3). However, the influence of rising atmospheric CO_2 levels on tree growth (Knapp et al. 2001) or the competitive relationships between trees and understory species during the second half of the 20th century are not well understood. The initial post-settlement increase and peak establishment of pinyon and juniper occurred during the late 1800s and early 1900s. Peak canopy expansion, however, occurred during the second half of the 20th century. Tree canopies usually develop slowly during the first 45 to 50 years before rapidly expanding (Barney and Frischknecht 1974). This occurs with both juniper (Figure 2) and pinyon (Figure 3; Tausch and West 1988). Elevated CO_2 levels may be accelerating canopy expansion of pinyon and juniper woodlands.

Fire

Fire is considered to be the most important factor in maintaining shrub steppe communities and open

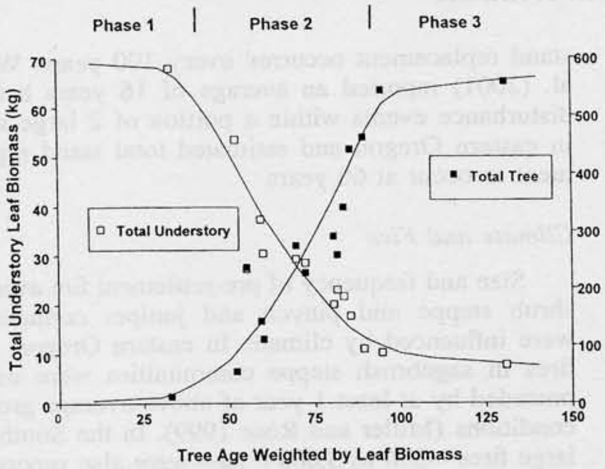

Fig. 3. Comparison of both the total tree leaf biomass (closed boxes) and total understory leaf biomass (open boxes) over time as indexed by the range in the leaf biomass weighted average age of pinyon for 14 plots in southwestern Utah (Tausch and West 1995). *X*-axis = sum of (average tree age/plot × leaf biomass) across all plots/total leaf area of the stand.

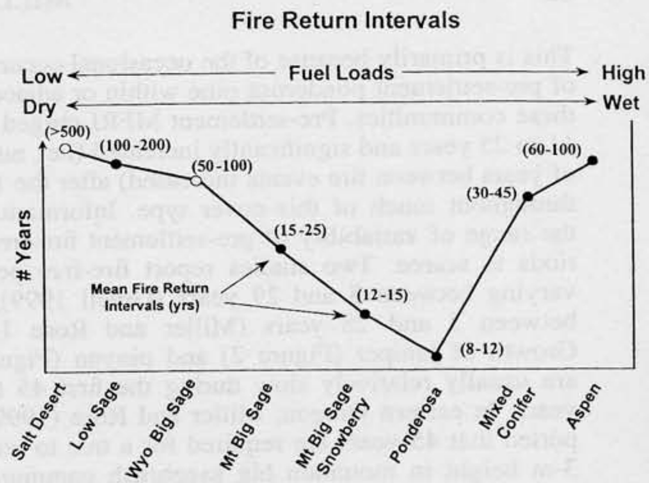

Fig. 4. Estimated (open circles) and documented (closed circles) fire mean return intervals for major vegetation cover types in the Great Basin.

pinyon and juniper savannas prior to Eurasian settlement (West 1999). Limited data exist describing fire histories across shrub steppe communities and woodlands in the Great Basin. In the southwestern U.S., there is little information available on fire regimes in pinyon and juniper woodlands (Swetnam and Baisan 1995). Unlike ponderosa pine, pinyon pine and juniper seldom scar repeatedly (Gruell 1999, West 1999); thus, it is difficult to develop fire histories for pinyon and juniper woodlands. In addition, sites occupied by old-growth juniper, or pinyon, are not representative of more productive deeper soil sites, which support expanding post-settlement woodlands. Old-growth trees are commonly found on relatively fire-safe sites characterized by rocky surfaces with limited fine fuel loads (Burkhardt and Tisdale 1976, Young and Evans 1981, Holmes et al. 1986, Miller and Rose 1995, 1999, West et al. 1998, Burwell 1998, 1999). Evidence indicating that woodland expansion was limited by frequent fire events prior to settlement includes (1) sites supporting old-growth trees are usually considered fire safe because of rocky surfaces, shallow soils, and limited accumulations of fine fuels; (2) the majority of young stands have expanded into more productive communities with fine fuel loads sufficient to carry fire; and (3) the time sequence of woodland expansion and increased fire return intervals are synchronous.

Fire Histories

Fire histories in mesic shrub steppe communities can be developed from fire scars collected from ponderosa pine growing in or adjacent to mountain big sagebrush communities. Cross-dating burned pinyon or juniper stumps and logs, and developing stand age structure can also be used to research fire history.

The most extensive fire history information in semi-arid shrub steppe plant communities has been developed for the mountain big sagebrush–Idaho fescue (*Festuca idahoensis*) association (Table 4; Figure 4).

Table 4. Pre–settlement mean fire return intervals (MFRI = average number of years between fire events) in sagebrush and aspen cover types associated with sagebrush. Change indicates the decade when the average number of years between fire events increased.

Cover type	MFRI (yr)	Change	Location	Reference
Open pinyon–juniper woodland	25	1880s	N Arizona	Despain and Mosley 1990
Mountain big sagebrush	20–25	1890s	NW Wyoming	Houston 1973
	20		NW California	Martin and Johnson 1973
	11	1910	SW Idaho	Burkhardt and Tisdale 1976
	15–20		New Mexico	Gottfried et al. 1995
	12–15	1870s	southcentral Oregon	Miller and Rose 1999
	13	late 1800s	E Oregon	Gruell 1999
	15–20	1860s	E Nevada	Gruell et al. 1994
Wyoming big sagebrush	130	1870s	SW Utah	Tausch and West 1988
	8–10		W Nevada	Gruell 1999
Low sagebrush		1860	NW California	Young and Evans 1981
	138	1870	southcentral Oregon	Miller and Rose 1999
Aspen	100[a]	1870s	SW Colorado	Romme et al. 1996
	60[a]	1870s	E Oregon, NE California, NW Nevada	Wall et al. 2001
Pinyon–juniper	400		SW Colorado	Floyd et al. 2000

[a] Stand replacement interval based on aspen age structure; disturbance may not be fire.

This is primarily because of the occasional occurrence of pre-settlement ponderosa pine within or adjacent to these communities. Pre-settlement MFRI ranged from 11 to 25 years and significantly increased (i.e., number of years between fire events increased) after the 1860s throughout much of this cover type. Information on the range of variability of pre-settlement fire-free periods is scarce. Two studies report fire-free periods varying between 8 and 29 years (Gruell 1999), and between 3 and 28 years (Miller and Rose 1999). Growth of juniper (Figure 2) and pinyon (Figure 3) are usually relatively slow during the first 45 to 50 years. In eastern Oregon, Miller and Rose (1999) reported that 45 years are required for a tree to reach a 3-m height in mountain big sagebrush communities. Juniper trees <3 m tall are easily killed by fire (Jameson 1962, Dwyer and Pieper 1967, Bunting 1984). Pre-settlement fire return intervals for the mountain big sagebrush–Idaho fescue association (Table 4) were sufficient to inhibit western juniper encroachment into mountain big sagebrush communities.

Limited data exist on MFRI for the more arid Wyoming big sagebrush cover type. The lack of ponderosa pine and limited amount of old stumps and logs make it difficult to reconstruct a fire history for this cover type. Two studies report fire-free periods of 8 and 130 years (Table 4). Estimated pre-settlement MFRI for this cover type ranged between 50 and 100 years (Wright and Bailey 1982).

Mean fire return intervals reported for the low sagebrush–Sandberg bluegrass (*Poa secunda*) cover type (Table 4) were considerably longer than neighboring mountain big sagebrush communities (Miller and Rose 1999). Fire-free periods varied from 90 (Young and Evans 1981) to 138 years (Miller and Rose 1999) for this cover type. Tree growth rates are relatively slow: the average age of a tree 3 m tall ranges from 75 to 90 years. A MFRI of 100 years should be adequate to create a low-density stand of widely scattered trees in low sagebrush–Sandberg bluegrass cover types.

Juniper has also been invading aspen (*Populus tremuloides*) stands in the northwestern Great Basin (Miller and Rose 1995, Wall et al. 2001) and on the eastern Sierra Nevada front (R.J. Tausch, personal observation). In approximately 100 aspen stands measured across southeastern Oregon, northeastern California, and northwestern Nevada below 2,100 m in elevation, Wall et al. (2001) reported that 12% of the aspen stands were completely replaced by western juniper. Western juniper was the dominant tree species in 23% of the stands and common to codominant in 42%. Western juniper began invading aspen stands during the 1890s, with peak establishment occurring between 1900 and 1940. No western juniper tree measured across these aspen stands was >140 years old. Fire has been reported to play an important role in the maintenance of healthy aspen stands (Bartos and Mueggler 1981, Jones and DeByle 1985, DeByle et al. 1989). Romme et al. (1996) reported fire had burned within a 77-km^2 aspen stand during nearly every decade between 1760 and 1870. They estimated total stand replacement occurred every 100 years. Wall et al. (2001) reported an average of 16 years between disturbance events within a portion of 2 large stands in eastern Oregon and estimated total stand replacement to occur at 60 years.

Climate and Fire

Size and frequency of pre-settlement fire events in shrub steppe and pinyon and juniper communities were influenced by climate. In eastern Oregon, large fires in sagebrush steppe communities were usually preceded by at least 1 year of above-average growing conditions (Miller and Rose 1999). In the Southwest, large fires—200 to 3,000+ ha—were also reported to occur most frequently during a near-average precipitation year proceeded by 2 wet years (Baisan and Swetnam 1990, 1997). In these semi-arid ecosystems, fuels are often not continuous and limiting in abundance. A series of wet years allows fuels to accumulate and become more contiguous.

Wetter than average conditions during the late 1800s and early 1900s would have allowed fine fuels to accumulate, increasing the probability of large fires occurring during this period. However, extremely heavy livestock grazing during this time period reduced fine fuel accumulations and thus significantly reduced the potential for fire (Burkhardt and Tisdale 1969, Miller and Rose 1999). In addition to the reduced threat of fire, climatic conditions during this time period were ideal for juniper and pinyon establishment and growth (Fritts and Xiangdig 1986).

Climate also influences size and frequency of fire where perennial native herbaceous understories have been replaced by exotic annuals such as cheatgrass (*Bromus tectorum*). Growing conditions that favor cheatgrass can influence the size of area burned (Knapp 1995).

Fire Storms in the Woodlands

With the post-settlement reduction in fire frequency, a long-term change in woodland vegetation structure began throughout the Great Basin and the Colorado Plateau (Miller and Rose 1995, 1999, Gruell 1999, Tausch 1999*a, b,* Miller et al. 2000). As trees begin to dominate a site, suppression of understory species reduces the susceptibility of the site to fire. However, recently pinyon and juniper are becoming more susceptible to crown fires as woodlands approach the late stages of development and canopies become dense, particularly in areas dominated by pinyon pine. As tree crowns increase in size, the continuity of the crown fuels increases across the landscape (Tausch 1999*a, b*). In Texas, woodlands with tree canopy cover exceeding 35% were capable of supporting a crown fire (Bryant et al. 1983). In many areas, pinyon canopy cover now exceeds 50%, and in some areas 80%. These dense woodlands can easily support crown fires during drought conditions and sufficient wind velocities. Recent woodland surveys of part of the East Walker River watershed in eastern California and Nevada indicate closed stand woodlands currently represent about 33% of the total woodland area. Surveys also indicate that the area of closed stand conditions will likely double during the next 40 to 50 years (U.S. Department of Agriculture, Forest Service, Humboldt-Toyiabe National Forest, Bridgeport Ranger District internal report, 1999). Similar increases will probably occur in the majority of woodlands associated with pinyon throughout the Great Basin. The prospect of continued canopy closure, and thus the potential for increasing fire size and intensity in pinyon–juniper woodlands, needs further study and verification.

During the 1999 and 2000 fire seasons, nearly 1.2 million ha burned in the Nevada and Utah sections of the Great Basin. Major parts of these fires were in pinyon–juniper woodlands. In at least 2 instances, large portions of the woodlands on an entire mountain range were lost (R.J. Tausch, personal observation). Flame lengths in excess of 120 m have been reported for closed woodland stands under high wind conditions by fire suppression personnel (R. Wilson, University of Nevada Extension, personal communication). On 1 fire in Utah, closed stand woodlands burned so hot that Gambel oak clones were killed and unable to sprout following the fire (S. Monsen, U.S. Forest Service, personal communication).

Contrasting the Great Basin and Colorado Plateau

It is difficult to compare the age structure, stand dynamics, and fire histories of pinyon and juniper woodlands in the Great Basin and Colorado Plateau due to limited fire history studies and chronologies of pinyon and juniper in the American Southwest. The ratio of pre- and post-settlement pinyon and juniper trees is not well documented for the Colorado Plateau. Woodlands in the American Southwest appear to be more susceptible to large die-offs during severe droughts (Betancourt et al. 1993). Severe drought conditions during the late 1500s may explain the scarcity of pinyon >400 years old in central New Mexico. High tree mortality also occurred in the Southwest during the drought of the early 1950s. Extensive mortality of western juniper and Utah Juniper in the central and northern Great Basin has not been observed. Seasonality of fire is also different between the 2 regions. The majority of pre-settlement fires in the Southwest occurred during late spring through mid-summer (Baisan and Swetnam 1990) compared to late summer and fall in the more northerly regions of the Great Basin (Miller and Rose 1999).

WOODLAND SUCCESSION

Stand Development

Prior to settlement, MFRI were adequate to inhibit the encroachment of pinyon and juniper into more productive shrub steppe communities occupying deeper soils. However, as the number of years between fire events increased, pinyon and juniper readily invaded these communities where they are both well adapted and competitive. The period of time required for the complete transition of shrub steppe to closed pinyon and juniper woodland is variable and dependent on both rate of tree establishment and site potential. In eastern Oregon, post-settlement western juniper stands were in various stages of woodland succession ranging from open to closed, even though initial invasions began during the 1860s for all of the stands (Miller and Rose 1999). The minimum time required to reach woodland closure is 60 to 90 years (Barney and Frischknecht 1974, Miller and Rose 1995, Tausch and West 1995, Miller et al. 1999) with the potential for rapid canopy closure to occur within 45 to 50 years after establishment (Figures 2 and 3). Woodland dominance at the landscape level also influences the rate of encroachment and closure on adjacent open areas (Milne et al. 1996). When woodlands dominate approximately 60% of the landscape, remaining open plant communities are replaced more rapidly.

Establishment of pinyon or juniper may be greatly limited following a fire event where the shrub layer has been removed. Erdman (1970) reported pinyon and juniper did not establish on an old burn until 100 years after fire. In Nevada, Everett and Ward (1984) noted the absence of pinyon in the early stages of succession following fire. Several authors have reported the importance of shrubs facilitating the establishment of trees (Everett and Ward 1984, Eddleman 1987, Miller and Rose 1995, Chambers 2001), which could explain the lag period of tree establishment following a fire event or the slower rate of succession for some stands. Shrubs provide safe sites for juniper and pinyon establishment and enhance growth rates of young trees compared with locations in the shrub canopy interspace.

During woodland development, plant species diversity, richness, composition, production, and fuel characteristics change. In many pinyon and juniper woodlands, the understory is often sparse (West et al. 1978, 1998). Species diversity and seed reserves often decrease with the progression of woodland succession (Erdman 1970, Koniak and Everett 1982). In Utah, Huber et al. (1999) reported that 20% canopy cover of pinyon and juniper was the threshold where plant diversity and species richness rapidly declined. However, Miller et al. (2000) concluded the influence of western juniper tree canopies on herbaceous species diversity and richness varied depending on the site. They found no significant reduction in herbaceous species richness or diversity on deep, well-drained soils. Herbaceous species did, however, decline in cover, diversity, and richness where restrictive soil layers were present within 45 cm of the soil surface (Bates et al. 2000, Miller et al. 2000).

In contrast to the herbaceous layer, shrubs have been reported to decline across all soil types in big sagebrush communities as juniper increases (Cottam and Stewart 1940, Barney and Frischknecht 1974, Adams 1975, West 1984, Tress and Klopatek 1987, Tausch and West 1988, 1995, Miller et al. 2000). During woodland succession the decline in mountain big sagebrush canopy is not proportional to the increase in juniper canopy (Figure 5). As the woodland canopy

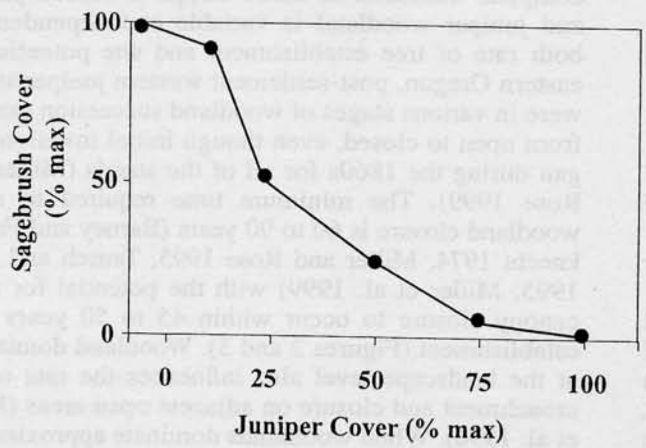

Fig. 5. The relationship between mountain big sagebrush and juniper cover (derived from Tausch and West 1995 and Miller et al. 2000).

approaches 50% of maximum potential for the site, big sagebrush cover and biomass decline to approximately 20–25% of maximum potential (Tausch and West 1995, Miller et al. 2000). Structural complexity declines as shrub canopies and densities decrease. Loss of shrubs greatly affects fuel loads in the understory and wildlife habitat.

Woodland Response Following Fire

Post-burn initial floristics is largely dependent on the pre-burn plant composition and fire tolerance of these species. Plant composition prior to the burn is usually affected by the successional stage of the woodland (West and Van Pelt 1986) as is the percent of trees surviving a fire event. Erdman (1970) concluded plant succession following fire in pinyon and juniper woodlands in the Southwest was relatively predictable and the stages following fire were similar to those reported by Barney and Frischknecht (1974) for juniper woodland in westcentral Utah (Figure 6). Barney and Frischknecht (1974) reported the annual grass–forb stage might be by-passed with the perennial grass–forb stage directly following fire events depending on preburn composition. Opportunities for annuals to become established following a fire decrease as the initial response of the perennial herb component increases (Pickett 1976). Although herbaceous species present prior to the fire event often reappear immediately following a burn, this may be difficult to predict because of the difficulty of determining a response from seed pools (Everett and Ward 1984). Site factors such as slope and aspect can also influence plant response following fire (Koniak 1983).

THE ROLE OF EXOTICS IN WOODLANDS

The invasive grass, cheatgrass (*Bromus tectorum*) has become widespread throughout lower elevation woodlands in the Great Basin. Cheatgrass already had a broad distribution throughout the region by the late 1800s (Stewart and Hull 1949). By the 1920s, this species represented an important forage resource in Nevada (Young and Evans 1989). During the 1930s, the increases in fire frequency that followed cheatgrass range expansion became apparent in southern Idaho (Stewart and Hull 1949).

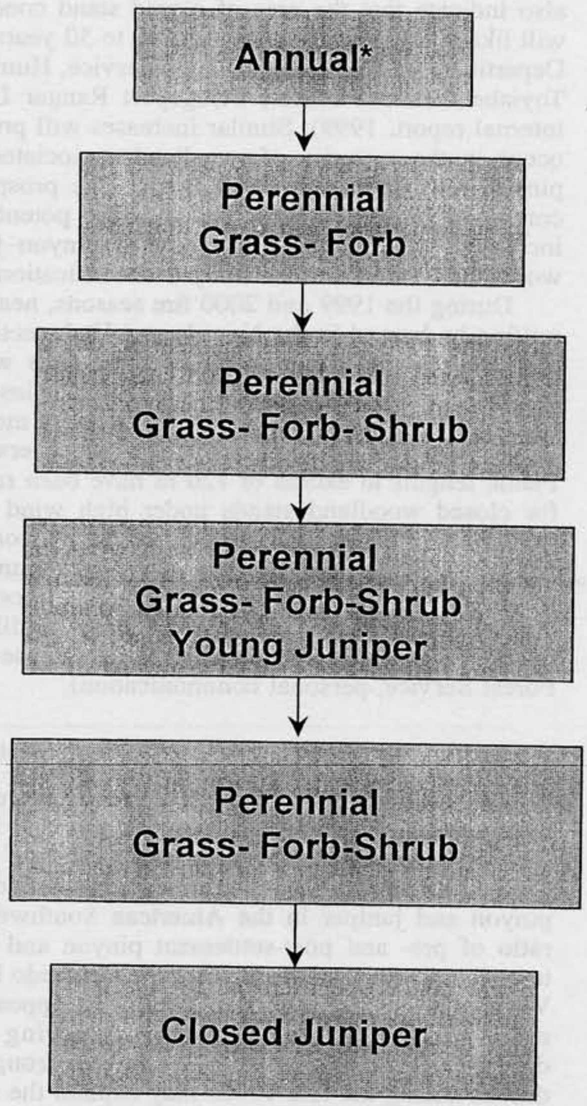

Fig. 6. Successional stages following fire in juniper woodland (from Erdman 1970, Barney and Frischknecht 1974). Depending on condition and stage of woodland development, the annual stage may be skipped, and perennial greases and forbs dominate the site immediately following the fire event.

As exotic annuals increase, a dramatic increase in fire size and frequency has been documented (Young and Evans 1973, Whisenant 1990, Swetnam et al. 1999, Tausch 1999*b*). Once established, cheatgrass responds rapidly to woodland fires and shifts the seasonality of fire to the more active growing period of native perennials (Whisenant 1990). Repeated fires can simplify vegetation into a homogeneous landscape dominated by exotic annuals (Young and Evans 1973, Young 1991). Following fire, soil, water, and available nutrients generally increase, at least for short periods of time (Blank et al. 1994). Increases in nutrients, especially nitrogen, enhance growth of cheatgrass

(McLendon and Redente 1991, Young et al. 1999), and can be a predictor of community invasibility (Burke and Grime 1996).

The cooler and more mesic woodlands appear to be less susceptible to invasion and complete dominance by introduced annuals. However, a better understanding of environmental and ecological factors that influence woodland susceptibility to invasive species is needed. Many new exotic weeds are spreading into woodlands with as yet unknown consequences. If woodland areas can be returned to fire regimes more similar to those that occurred during the Little Ice Age it may help to prevent a widespread weed invasion of these ecosystems (Swetnam and Betancourt 1998, Swetnam et al. 1999).

MANAGEMENT CONSIDERATIONS

Pinyon and juniper woodlands have large ecological amplitudes occupying a variety of parent materials, soils, topographic positions, and climates. These woodlands can occupy and dominate many different plant cover types. Adding to the spatial complexity of these woodlands across the Intermountain Region are temporal dynamics. Many pinyon and juniper woodlands are in various stages of succession from early to late development. The stage of woodland development affects fuel loads, wildlife habitat, management options, cost of conversion, and response to treatment. When developing a woodland management plan, managers should take the following into consideration:

(1) Heterogeneity of management area (e.g., landforms, parent materials, soils, topography, plant cover types, etc.).
(2) Role of pre-settlement fire.
(3) Consideration and maintenance of old growth trees and woodlands.
(4) The degree of change in plant community structure and composition since the late 1800s.
(5) Changes in disturbance regimes (e.g., grazing, fire suppression) that have contributed to shifts in plant composition and structure.
(6) The current stage of woodland succession across the management unit.
(7) Abundance and continuity of fuel loads.
(8) Understory composition, including the presence of exotic species.
(9) Fire tolerance of native understory species.

The goals and objectives for managing pinyon and juniper woodlands should also be well defined and account for landscape variability across the woodland management area. The most frequent reasons for treating woodlands are fuel load reductions to reduce the size and severity of future fires, restoring pre-settlement plant communities and disturbance processes (e.g., fire), increasing landscape heterogeneity, increasing ground cover for watershed protection, enhancing wildlife habitat, and increasing forage production.

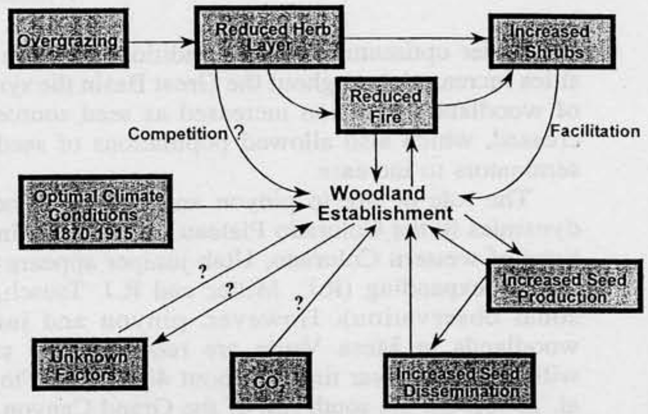

Fig. 7. Conceptual model illustrating factors influencing woodland expansion since the late 1800s.

CONCLUSIONS

Limited studies have documented fire histories in shrub steppe communities across the Intermountain West. However, parallel studies in ponderosa pine communities support the model that fire was the major controlling factor preventing the encroachment of pinyon and juniper into pre-settlement shrub steppe communities. Evidence that supports the role of pre-settlement fire as an important disturbance process limiting the expansion of pinyon and juniper woodlands includes: (1) plant macrofossil, pollen, and ash sediment data; (2) sites supporting old-growth pinyon and juniper are usually relatively fire safe because of limited fine fuel accumulations; (3) the majority of post-settlement stands have expanded into more productive communities with fine fuel loads sufficient to carry fire; (4) fire return intervals between 11 and 25 years have been reported for relatively productive sagebrush communities; and (5) the time sequence of woodland expansion and increased MRFI are synchronous.

The conceptual model in Figure 7 illustrates the factors resulting in the post-settlement establishment and expansion of pinyon and juniper woodlands in the Great Basin. Prior to settlement, MFRI were short enough to inhibit the encroachment of pinyon and juniper into the deeper soil sagebrush cover types. Periodic fires in these cover types limited the numbers of safe sites for tree establishment by reducing shrub cover and killed tree seedlings and saplings. The period of wet, mild conditions between the late 1800s and early 1900s enhanced tree establishment. During the past, wet conditions increased the potential for more frequent and extensive fires, inhibiting woodland encroachment. Livestock played an indirect role through the removal of fine fuels and increasing safe sites (shrub cover) for tree establishment. We hypothesize that in the absence of livestock, fire events would have increased rather than decreased during the early period of post-settlement woodland expansion (1870 to 1916). Above average fine fuel accumulations would have occurred during this period due to the wetter than average conditions. However, fuel removal by livestock grazing during this wet period significantly reduced the threat of fire, thus allowing trees to establish under optimum growing conditions. As tree densities increased throughout the Great Basin the synergy of woodland expansion increased as seed sources increased, which also allowed populations of seed disseminators to increase.

The role of fire in pinyon and juniper woodland dynamics in the Colorado Plateau is less clear. In portions of western Colorado, Utah juniper appears to be rapidly expanding (R.L. Miller and R.J. Tausch, personal observation). However, pinyon and juniper woodlands in Mesa Verde are relatively old stands with a fire turnover time of about 400 years (Floyd et al. 2000). On the south rim of the Grand Canyon, pinyon and juniper woodlands—although not as old as those at Mesa Verde—appear to have established prior to Eurasian settlement (R.L. Miller and R.J. Tausch, personal observation). However, it appears that tree densities have significantly increased during the past 100 to 200 years on both sites. In northern Arizona, Despain and Mosley (1990) reported tree densities increased significantly during the past 200 years in pinyon and juniper woodlands containing trees older than 300 years.

Additional studies documenting long-term fire histories in shrub steppe and pinyon and juniper communities, and woodland age chronologies in the Intermountain West will help us put present-day plant communities into historical context with communities of the past. These data are important in measuring the degree of plant community change, in determining the ecological significance of fire and plant community dynamics, and in helping us to reintroduce fire as a management tool to restore and maintain plant communities in the Great Basin and Colorado Plateau.

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