J. Range Manage.
52:550–559 November 1999

Fire history and western juniper encroachment in sagebrush steppe

RICHARD F. MILLER AND JEFFREY A. ROSE

Authors are Professor of Rangeland Resources and research associate at the Eastern Oregon Agricultural Research Center, Oregon State University Burns, Ore. 97720.

Abstract

The recent expansion of juniper into sagebrush steppe communities throughout the semiarid Intermountain West is most frequently attributed to the reduced role of fire, introduction and overstocking of domestic livestock in the late 1800s, and mild and wet climate conditions around the turn of the century. This hypothesis has, however, limited quantitative support. There are few studies of fire history in the sagebrush steppe and none that examine the chronosequence of changes in mean fire intervals, introduction of livestock, and coincident climatic conditions with the initiation of postsettlement juniper expansion. This study was undertaken to test the hypothesis that the postsettlement expansion of juniper was synchronous with the introduction of domestic livestock, reduction in fire frequency, and optimal climate conditions for plant growth. We documented the fire history and western juniper (*Juniperus occidentalis* Hook.) woodland chronology for a sagebrush steppe in a 5,000 ha watershed in south central Oregon. Regional tree ring data were used as proxy data for presettlement climatic conditions. Western juniper age distribution was determined by coring trees across the study area. Fire history was constructed from several small clusters of presettlement ponderosa pine (*Pinus ponderosa* Laws.) scattered across the study area. Samples were crossdated to determine fire occurrence to the calendar year. Mean fire intervals were computed for each cluster based on cumulative fire history of each tree sampled within the cluster. Fire events in low sagebrush (*Artemisia arbuscula* Nutt.) were documented by determining death dates of fire-killed western juniper trees. Records dating the introduction and buildup of livestock during the late 1800s and dates of initial fire suppression were summarized. Western juniper expansion began between 1875 and 1885, with peak expansion rates occurring between 1905 and 1925. The fire record spans 1601 to 1996. Before 1897, mean fire intervals within individual clusters ranged from 12 to 15 years with years between fires varying between 3 to 28. Nearly one third of the fires in the basin were large and usually proceeded by one year of above-average tree ring growth. Two fire events were recorded in the sparsely vegetated low sagebrush site, 1717 and 1855. The last large fire occurred in the study area in 1870 and the last small fire in 1897. The time sequence of wet climatic conditions between 1870 and 1915, introduction of livestock, and the reduced role of fire support the hypothesis that these factors contributed to the postsettlement expansion of western juniper.

Key Words: woodland, succession, *Juniperus occidentalis*, *Artemisia*

Resumen

La reciente expansión del "Juniper" hacia las comunidades esteparias de "Sagebrush" de la región semiárida intermontñosa del oeste, frecuentemente se atribuye a varios factores: 1) la reducción del fuego, 2) la introducción y uso de cargas animal altas de ganado doméstico a fines del siglo pasado y 3) las condiciones climáticas templadas y húmedas que ocurrieron a inicios del presente siglo. Sin embargo, esta hipótesis tiene un soporte cuantitativo limitado. Hay pocos estudios del historial del fuego en las estepas de "Sagebrush" y ninguno que examine las cronosecuencia de los cambios en términos de intervalos del fuego, introducción del ganado y las condiciones climáticas coincidentes con el inicio de la expansión del "Juniper" después de la colonización. Este estudio se llevó a cabo para probar la hipótesis de que la expansión del "Juniper" después de la colonización fue sincrónica con la introducción del ganado doméstico, una reducción en la frecuencia del fuego y condiciones climáticas óptimas para el crecimiento de la planta. Documentamos la fire historia y cronología de un bosque de "Western juniper" (*Juniperus occidentalis* Hook.) en una estepa de "Sagebrush" dentro de una cuenca hidrológica de 5,000 ha en la parte sur-central de Oregon. Se utilizaron datos de anillos de arboles regionales como datos equivalentes para las condiciones climáticas post-colonización. La distribución de la edad del "Western juniper" se determinó mediante el muestreo de árboles a lo largo del área de estudio. La historia del fuego se construyó a partir de pequeños grupos de "Poderosa pine" (*Pinus ponderosa* Laws.) originarios de antes de la colonización y distribuidos en el área de estudio. Las muestras se sometieron a una comparación cruzada de fechas para determinar la ocurrencia del fuego en base a calendarios anuales. La media de

This research was supported by the Eastern Oregon Agricultural Research Center (EOARC), Oregon State University, and the Fremont National Forest, Paisley Ranger District. EOARC is operated jointly by the Oregon State Agricultural Research Center and USDA-ARS. The authors wish to thank Jim Agee, Chris Baisan, Gregg Riegel, Tony Svejcar and the 3 anonymous reviewers for their constructive comments. We also wish to thank the International Tree Ring Laboratory at the University of Arizona for their technical expertise.

Oregon State Agricultural Experiment Station Technical Paper Number 11458.

Manuscript accepted 24 Jan. 1999,

tiempo entre fuegos de 3 a 28 años. Casi un tercio de los fuegos del fondo de la cuenca fueron grandes y usualmente precedidos por un año con tasas de crecimiento de los anillos arriba del promedio. Se registraron dos eventos de fuego en un sitio de "Sagebrush" con vegetación escasa, en 1717 y 1855. El último gran fuego que ocurrió en el área de estudio fue en 1870 y el útimo fuego pequeño se registró en 1897. La secuencia de tiempo de condiciones climáticas húmedas entre 1870 y 1915, la introducción del ganado y la reducción de la función del fuego soportan la hipótesis de que estos factores contribuyeron a la expansión del "Western juniper" después de la colonización.

Expansion of western juniper (*Juniperus occidentalis* Hook.) into sagebrush steppe communities in the interior Northwest U.S. coincides with Euro-American settlement (Burkhardt and Tisdale 1976, Young and Evans 1981, Miller and Rose 1995). In the American southwest and southern Great Basin, pinyon-juniper woodlands have also expanded during this period (Blackburn and Tueller 1970, Tausch and West 1988). The historic expansion of juniper parallels the increase of woody plant abundance in grasslands in Southwestern United States (Archer et al. 1988, Archer 1989), Africa (Kelly and Walker 1976), Australia (Harrington et al. 1984), and South America (Smeins 1983). The current expansion of juniper woodlands in the Intermountain West is believed to be unparalleled in the past 6,000 years (Miller and Wigand 1994). Pre-settlement expansions occurred during cool wet periods whereas the current expansion is occurring during a warmer drier period. Recent expansion has also occurred during increasing atmospheric CO_2 levels (Knapp and Soule 1996). Miller and Wigand (1994) concluded that current tree densities are considerably greater than past Holocene expansions based on juniper pollen abundance.

The recent expansion of western juniper began during the late 1800s (Young and Evans 1981, Eddleman 1987, Miller and Rose 1995). Postsettlement juniper woodland expansion in the West has been most frequently attributed to the introduction and overstocking of livestock, the reduced role of fire, and optimal climatic conditions during the late 1800s (Tausch et al. 1981, West 1984, Miller and Wigand 1994). However, few studies have been conducted that directly support this idea. Only a handful of studies have documented mean fire intervals in the sagebrush steppe biome, and few if any have evaluated the chronosequence of the introduction of livestock, the reduced role of fire, and climatic conditions with the initiation of postsettlement woodland expansion. More recently, researchers have attributed the increase of woody plants to the rise in atmospheric CO_2 (Johnson et al. 1990, Knapp and Soule 1996).

Relict juniper woodlands are primarily confined to rocky surfaces or ridges and pumice sands with sparse vegetation (West 1984, Miller and Rose 1995, Miller et al. 1999b). However, current expansion has occurred on the more productive sagebrush sites with deep well drained soils. Fire is believed to have been important in shaping these sagebrush steppe communities in the Intermountain West before Eurasian settlement (Wright and Bailey 1982, Miller et al. 1994). In the semiarid region of the Intermountain Northwest, presettlement mean fire intervals between 15 to 25 years have been reported for the mountain big sagebrush steppe (Houston 1973, Burkhardt and Tisdale 1976, Martin and Johnson 1979). The decline in fire has been attributed to the reduction in fine fuels due to heavy livestock grazing in the late 1800s, reduced anthropogenic set fires during the 19th century (Burkhardt and Tisdale 1976, Miller et al. 1994), and suppression of wildfire beginning in 1910-1930 (Agee 1993).

Optimal climatic conditions during the late 1800s and early 1900s may have also interacted with the reduced role of fire and overgrazing by domestic herbivores to accelerate the rate of western juniper expansion into shrub steppe communities. During this period, winters became more mild and precipitation increased above the current long-term average (Antevs 1938, Graumlich 1987), conditions which promote vigorous growth in western juniper (Fritts and Xiangdig 1986, Holmes et al. 1986).

This study was designed to: (1) document the chronology of western juniper age distribution; (2) document pre- and postsettlement mean fire intervals in a mountain big sagebrush steppe community; and (3) determine the proportion of large to small fires, and evaluate their relationship to growing conditions in years preceding and concurrent with fire events. We hypothesize that postsettlement western juniper expansion was synchronous with the introduction and overstocking of domestic livestock, changes in mean fire intervals, and optimal climate conditions for plant growth.

Methods

Site Description

The study area is located within the Fremont National Forest in the upper Chewaucan River basin, 8 km south of Paisley, Oregon (Fig. 1). The study unit encompasses 5,000 ha, which lies above alluvial bottomlands along the Chewaucan River and below the ponderosa pine forest community. Elevation ranged between 1,450 and 1,875 m. Topography is typified by highly dissected benchlands and toeslopes ranging from gentle to moderately steep. Aspect is predominately west to northwest. Soils range from deep to moderately deep residual soils weathered from breccias and tuffs to shallow clayey residual soils (Wenzel 1979). Climate is cool and semi-arid, characteristic of the northern Great Basin. The long term average precipitation is approximately 400 mm (Taylor 1993) and is received primarily as snow in November to January and as rain March through June. Vegetation is characterized by 2 predominant plant communities. On moderate to moderately deep soils mountain big sagebrush with Idaho fescue (*Festuca idahoensis* Elmer) dominates. The low sagebrush (*Artemisia arbuscula* Nutt.)–sandberg bluegrass (*Poa sandbergii* Vasey) community occupies the stoney shallow heavy clay soils on the benchlands. Associated with these plant communities are western juniper trees in varying levels of density.

Livestock were introduced in the late 1860s in the Chewaucan River Basin (Oliphant 1968). By November of 1873, approximately 4,000 cattle were reported in the lower river basin with several thousand sheep moving in the following year. During the next 5 years, livestock numbers increased rapidly and peaked at the end of the 19th century. Since 1915, sheep have declined on the Fremont

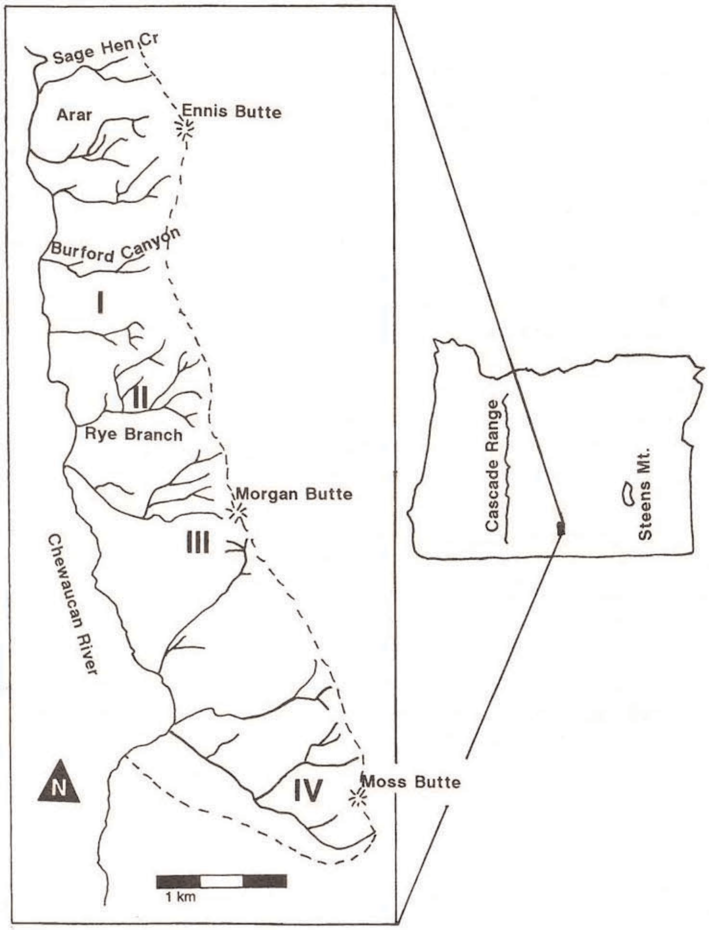

Fig. 1. Map of the upper Chewaucan River basin. The four fire scar collection sites, I– IV. The Ennis Butte low sagebrush site (Arar), is also located on the map.

National Forest from nearly 400,000 AUM's (animal unit months) to less than 1,000, while cattle numbers have declined from 95,000 AUM's to 60,000 AUM's (Fremont National Forest, Paisley, Oregon, file records). The US Forest Service office in Paisley, the agency responsible for resource management on the study area, was established in 1908 which marks the beginning of fire suppression in the study area. However, prior to the late 1940s, fire suppression efforts were minimal in the sagebrush steppe due to limited access and low timber value.

Plot selection

A 1:24,000 US Geological Survey map of the study area was over-laid with a 0.4 km acetate grid. Two hundred and fifty points were systematically selected from the grid to evenly cover the study area for a rapid survey. Each of the 250 points marked on the map was visited and the plant community (dominant shrub and perennial grass), percent slope, aspect, elevation, and presence or absence of presettlement western juniper, old stumps, and logs were recorded. Each site was categorized into 1 of 4 woodland transition stages; early, mid, late, and closed (Miller et al. 1999a). Criteria used to define the 4 stages were tree cover, height, leader growth on sapling and full size trees, and live and dead shrub canopy cover. Juniper canopy cover for the different woodland transitional stages in the mountain big sagebrush community are; early ≤5%, mid 6–20% (both characterized by active terminal and lateral leader growth for all age classes of trees), late 21–35%, and closed >35% (both stages having reduced to no lateral juniper leader growth). A total of 32 plots were selected for intensive measurement through a stratified random sample across the sagebrush communities and woodland transitional stages representative of the study area. Eight plots were selected in the early low sagebrush steppe, the only woodland stage present in this community on the study area, and 8 in each of the early, mid, and closed woodland transition stages in the mountain big sagebrush—Idaho fescue steppe community (late stage accounted for <2% of the study area and was heavily disturbed by recent tree cutting).

Tree Measurements

Western juniper density, height, and canopy cover were measured in each of the 32 study sites in a circular plot with a radius of 20 m in the mountain big sagebrush and 30 m in the low sagebrush steppe communities. All western juniper trees were counted and separated into 4 classes; juvenile <30 cm, sapling 30 cm to 3 m, mature >3 m, and presettlement. Presettlement trees were identified by their growth form characterized by rounded spreading canopies, large basal branches often nearly touching the ground, large irregular tapering trunks, deeply furrowed and fibrous bark, strip bark, and the presence of a bright-green arboreal fruticose lichen (*Letharia* sp.) (Burkhardt and Tisdale 1976, Miller et al. 1999b). Both tree and shrub canopy cover were estimated and recorded into 1 of 6 cover classes (percent cover: <1, 1–5, 6–10, 10–20, 21–35, >35). All trees were cored or cross sectioned within each plot. Western juniper trees > 10 cm in diameter were cored at 30 cm above the stem base and cross sections were collected at ground level from trees ≤10 cm in diameter. In addition, 15 western juniper trees approximately 30 cm tall were cut at the base in the open woodland stands in both sagebrush steppe communities to determine the number of years to core height. The number of standing dead trees, stumps, and downed logs were also recorded for each plot. We also cored 15 presettlement trees located outside of the intensive plots. We attempted to select the oldest trees in the study area based on morphology.

Differences in western juniper age structure between late and earlier stages of woodland development were determined using the Kolmogorov-Smirnov nonparametric test to compare age class distributions, and the Kruskal-Wallis test to compare average age between stands (Zar 1984). Analysis of variance and the Waller-Duncan Bayes LSD at the 95% probability level were used to evaluate differences in sapling (trees <3 m in height) and large tree densities, and tree and shrub canopy cover between stands (Petersen 1985).

Fire History

A limited number of small clusters of presettlement ponderosa pine trees are scattered across the study area. Examining fire history using western juniper is difficult because the thin-thinned barked tree is susceptible to fires, particularly within the first 50 years of growth. Thus the high rate of mortality leaves little record of past fire events. In addition, presettlement trees typically occur on relatively fire safe sites. Fortunately, the more fire-tolerant ponderosa pine sometimes co-occurs with western juniper, and fire history can be inferred from this species. We made a general search of the study area for fire scarred trees. Four clusters contained fire scarred ponderosa pine trees. Fire history was documented by collecting partial cross sections (Arno and Sneck 1977) from 3 scarred trees within clusters, I, III, and IV, and 1 cross section from cluster II (Fig. 1). In clusters I and IV, trees with the maximum number of fire scars visible on the surface were selected for sampling. In clusters II and III only 1 and 3 scarred trees occupied these sites, respectively. Cross sections were removed from the area of the tree with the greatest numbers of fire scars visible on the surface. Cross section surfaces were re-cut with a band saw and sanded with progressively finer grits from 60 to 400. Samples were crossdated to assign accurate dates to each fire occurrence. Two increment cores from a minimum of 5 presettlement ponderosa pine trees were collected from each cluster to develop a master chronology for crossdating. A total of 91 fire scars between 1457 and 1996 were measured. Of the 91 scars, 12 were difficult to determine the exact year of the burn, 9 occurring before 1700. These scars were adjusted to a fire scar date with a tree in the same cluster if a scar occurred within 2 years. If no scars occurred within 2 years or sample size was limited to 1 tree, date of fire occurrence was based on the number of rings from the nearest crossdated fire. The fire return interval was based on a composite from the 3 trees sampled in clusters I, III, and IV. Sampling in clusters provides a more complete record of fire occurrence (Kilgore and Taylor 1979). Individual trees in a cluster may not record each fire event. Estimates of relative fire size were based on the coincidence of fire dates among the different clusters. Large fires were defined as a fire event recorded in three or more clusters in the same year. Seasonality of fires was estimated from the relative position of the fire scar within the annual ring (Dieterich and Swetnam 1984, Baisan and Swetnam 1990).

We also attempted to determine the occurrence of fire events in the fuel limited low sagebrush—sandberg bluegrass steppe community. Twelve datable cross-sections of 12 burned western juniper stumps and logs were collected in a general search across the Ennis Butte basin (Fig. 1). We assumed that synchronous fire dates on 3 or more tree samples distributed across the area indicated a fire that burned across the low sage community rather than a single tree fire. Selection criteria used for burned samples were: (1) wood must contain > 100 growth rings, (2) the sample contained a portion of uncharred outside wood, and (3) have a surface unexposed to weathering (wood surface faced downward but not in contact with the ground). Burned samples were crossdated to determine the date of the outermost ring on the uncharred portion of the sample. Since the outside living portion of the tree (sapwood) remains uncharred and dead wood chars during a fire event we assumed the tree was living at the time of fire.

The FHX2 software package for analysis of fire history from tree rings (Grissino-Mayer 1995) was used to evaluate mean fire history data (mean fire intervals, maximum hazard function, etc.). The distribution of fire interval data were determined with the Kolmogorov-Smirnov test for goodness-of-fit and the two-parameter Weibull distribution. Mean fire intervals were computed for each site based on cumulative fire history of each tree sampled within a cluster. The earliest fire scar dated was 1457, however, presettlement mean fire intervals were computed for each cluster when sample size was > 2. Presettlement fire intervals were calculated for events prior to 1871. Superposed epoch analysis was used to evaluate the relationship of growing conditions in years preceding, concurrent, and following fire events (Grissino-Mayer 1995). This analysis determines the degree that tree ring growth departed from the mean in years prior to, during, and following fire events. Tree ring data collected in the region from western juniper (Holmes et al. 1986) were used as proxy data to evaluate presettlement growing conditions. Although tree ring indices (standardized ring-width chronology) do not directly reflect climatic conditions, they do indicate environmental conditions for tree growth and fine fuel accumulations (Fritts 1976). Western juniper growth readily responds to moist conditions (Fritts and Xiangdig 1986), and ring width has been used to indicate long term climatic conditions (Holmes et al. 1986). Western juniper rings in southeastern Oregon also correlate well with moisture conditions throughout this region (Chris Baisan, International Tree Ring Laboratory, University of Arizona, Tucson, personal communication). Due to the difficulty in assigning exact years of fire occurrence before 1700 and limited sampling depth, we compared tree ring growth conditions with fire events after 1700.

Results

Juniper Expansion

Western juniper began increasing between 1875 and 1885 in both low and mountain big sagebrush communities across the Chewaucan River Basin (Fig. 2). Tree establishment increased rapidly during the following decades. Mean age of trees across the study area was 68 years. Presettlement trees (> 130 years) accounted for less than 1% of the total population. Only 3 presettlement trees were recorded in the mountain big sagebrush plots. Large woody material decays slowly in this semiarid area. In this study and in an old growth western juniper woodland approximately 80 km to the northeast (Miller unpublished data), dates of death of cross-dated logs and charred stumps found throughout the site ranged from 130 to 280 years. The absence of stumps, snags, and charcoal provides good evidence that there were no western juniper present in the presettlement mountain big sagebrush

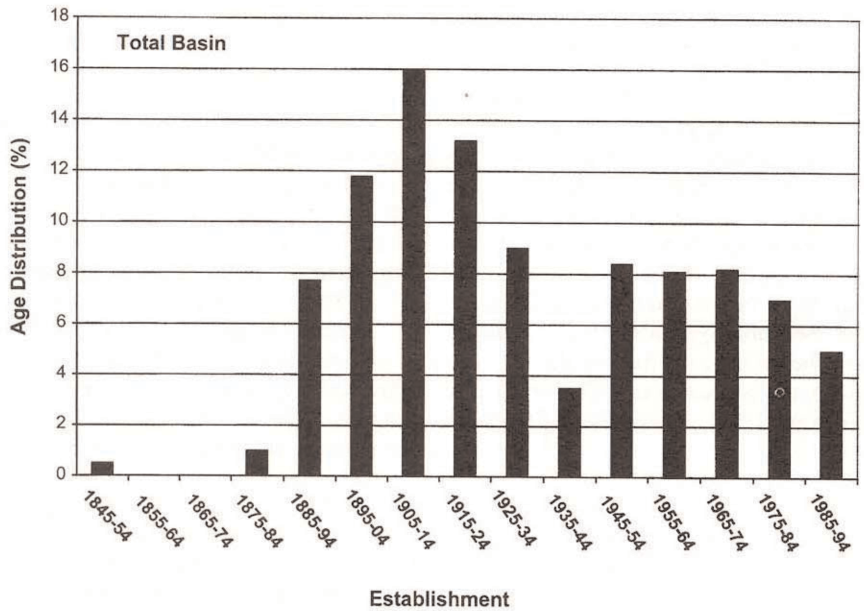

Fig. 2. Age structure of western juniper trees by decade across the 32 plots (n=510) within the Chewaucan River basin.

steppe community. In the low sagebrush steppe community, approximately 1.5 % of the western juniper trees measured were older than 130 years old. In addition, old stumps, logs, and charcoal were frequently observed across this community. Presettlement trees cored off the plots were all located on rocky shallow soil sites. Nine trees were 255+ years old (rot occurred in the 1730s) and six trees ranged in age between 352 and 876 years.

Two distinct patterns of western juniper woodland development occurred across the study area. On the mountain big sagebrush steppe community, woodlands were characterized by stands in early to mid-transition with < 10% tree canopy cover, and closed canopy exceeding 35% tree canopy cover. Since both early- and mid-transition stages were not significantly different in age structure, tree density and percent shrub cover they are grouped into open woodlands for the remaining of the discussion. Based on the 250 rapid survey points, closed stands accounted for 12% of the land area. Open woodlands accounted for 42% and 46% of the land area for mountain big sagebrush and low sagebrush, respectively. In the low sagebrush steppe community, western juniper stand structure was open with < 5% canopy cover.

Expansion of western juniper in open and closed woodlands began during the period between 1875 to 1885 (Fig. 3). However, woodland development occurred at different rates (Table 1). Saplings were common in open stands, but absent in closed stands. Age class distributions were also significantly different (P=0.05) between the closed stands in the mountain big sagebrush steppe and the open mountain big sagebrush and low sagebrush steppe communities. Mean age of closed stands was also significantly older (P=0.05) than the open western juniper stands (Table 1). Frequency of age distribution across decades in closed stands, based on the Kolomogorov-Smirnov nonparametric test, was significantly different between 1875 and 1995. Shrub cover was still a dominant component in the open stands. In the closed stands the skeletons of dead shrubs characterized the understory.

Western juniper establishment in closed stands peaked between 1885 to 1915, with 78% of the trees establishing during this period (Fig. 3). Establishment began to decline after 1915, with no measurable recruitment after 1945. Mean stand density of closed stands was 456 ha^{-1} and tree canopy cover exceeded 35%. Western juniper establishment in open woodlands has occurred more gradually, continuing throughout the 20th century in both mountain big sagebrush and low sagebrush steppe communities. Frequency of tree age distribution across decades in open stands was not significantly different when compared to a frequency of even establishment (P=0.05) from 1875 through 1995.

Fire History

Age of fire scarred ponderosa pine trees sampled ranged between 275 to 590 years. The fire record we analyzed spans the period from 1601 to 1996 and includes 33 fires in the study area (Fig. 4). All scars occurred near or at the termination of tree ring width development indicating late summer and fall fires. Season of fire events was evenly proportioned during late summer and fall. The Weibull function best fit the distribution of fire events occurring across the study area. Before 1871, a fire event occurred somewhere in the study area on an average of every 7.7 years. The number of years between 2 fire events occurring somewhere in the study area varied between 1 and 19. The maximum hazard function was 45 years (100% probability that a fire would occur somewhere inside the study area in less than a 45

Table 1. Stand characteristics of open and closed stands in mountain big sagebrush and low sagebrush communities. Saplings are western juniper trees between 0.3 and 3m tall. Frequency of age distribution of juniper establishment is computed for decades from 1885 through 1995.

	Mountain big sagebrush		Low sagebrush
	open	closed	open
Mean tree age (years)	62.6±14.1[a1]	86±7.8[b]	63±19.8[a]
Median tree age (years)	65	85	65
Tree age range (years)	2–106	8–146	2–176
Saplings Ha^{-1}	16[a]	0[b]	5[c]
Trees Ha^{-1}	114[a]	456[b]	51[c]
Mean tree cover (%)	5[a]	40[b]	3.5[a]
Mean shrub cover (%)	26	0.8	16
Frequency of age distribution	ns	s	ns

[1]Within rows, means with the same lower case letter are not significant at the P=0.05.

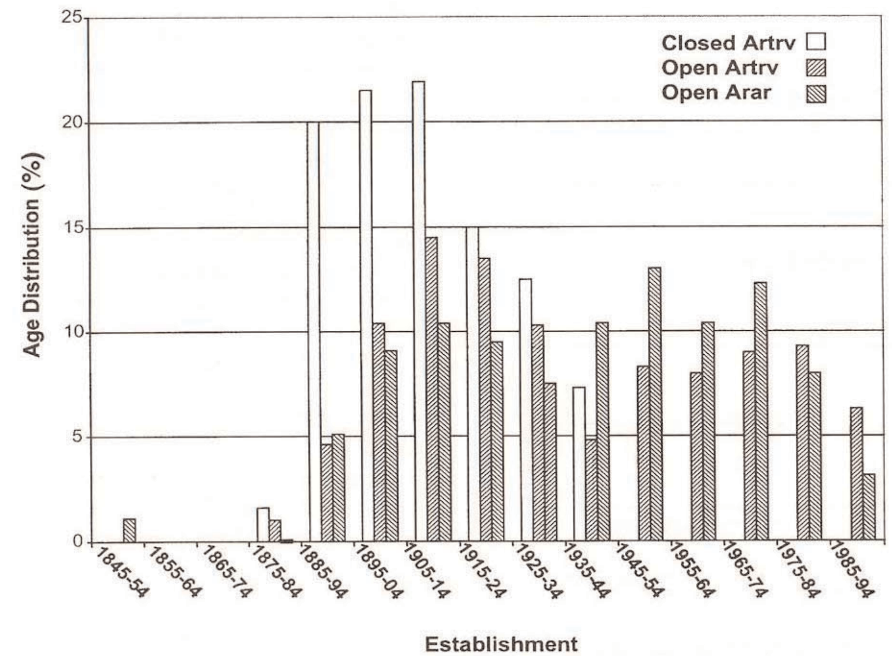

Fig. 3. Age structure of western juniper trees by decade for open low sagebrush (ARAR) (n=88), and open and closed mountain big sagebrush (ARTRV) (n=422).

Table 2. Presettlement mean fire interval computed for the fire period in each cluster where sample size is > 2 (except for site II, n=1). The minimum and maximum number of years between 2 fire events within a cluster are presented as the fire interval range. The mean fire interval and range for the study area indicates a fire occurred somewhere in the study area at a minimum mean fire interval of 7.7 years with years between fires varying between 1 and 19.

Site and	Fire Interval	
Fire Period	Mean	Range
I	(years)	
1783–1870	12	3–23
II		
1654–1870	27	12–54
III		
1693–1870	12	4–28
IV		
1601–1870	15	6–28
Study Area		
1654–1870	7.7	1–19

year period). Mean fire intervals at individual ponderosa pine clusters ranged from 12 to 15 years (Table 2). The range of years between fire occurrences within pine clusters was 3 to 28. Nearly 30% of the fire events between 1693 and 1900 occurred across 3 or more clusters, indicating relatively extensive fires across the study area (Fig. 4). The last large fire occurred in 1870. Approximately 60% of the fire occurrences burned only 1 site. The 5 fire events occurring between 1871 and 1897 were small. None of the 10 fire scarred trees sampled were further marked by fire during the following 99 years. Maximum hazard function for this period has increased to 1,000 years.

Burned wood samples collected in the Ennis Butte basin suggested 2 fire events, 1717 (n=3) and 1855 (n=7), occurred across the low sagebrush steppe community. Both fires were apparently large, burning across all 4 pine clusters (Fig. 4). Both fire events were preceded by 2 to several years of above average growth.

Superposed epoch analysis indicated that wet conditions generally preceded large fire events (Fig. 5). Small fires did not correlate with tree ring growth. The majority of large fires occurred during near average years.

Discussion

Woodland Establishment

Postsettlement expansion of western juniper in the Chewaucan River basin began during 1875-1885. The increase in western juniper coincided with the rapid increase in domestic livestock, reduction in fire frequency, and increased tree ring width. Woodland expansion, however, preceded fire suppression by 25 to 30 years and active suppression in the shrub steppe by 60 years. Expansions in other portions of its range have been reported to begin between the 1870s and 1890s (Young and Evans 1981, Eddleman 1987, Miller and Rose 1995). Establishment rates rapidly accelerated after 1885 peaking between 1905 and 1915. The Kolmogorov-Smirnov test identified 2 distinct patterns of western juniper establishment in the mountain big sagebrush steppe community (Fig. 3). First, tree establishment in what are now closed woodlands, occurred primarily between 1885 and 1925. These stands were characterized by no tree recruitment after 1945, suppressed understory tree growth, large overstory trees containing dead basal limbs, little to no lateral leader growth, and terminal leader growth limited to branches near the top of canopy dominant trees. The majority of shrubs in these stands were dead, similar to findings reported for dense Utah juniper (*Juniperus osteosperma* (Torr.) Little) woodlands (Barney and Frischknect 1974). The chronology of tree establishment in closed stands was similar to the chronology of establishment reported for western juniper stands in northeastern California (Young and Evans 1981) and southwestern Idaho (Burkhardt and Tisdale 1969). In Nevada and Utah, peak expansion of pinyon-juniper woodlands also occurred between 1870 and 1920 (Tausch et al. 1981). The second pattern of tree establishment, which is characterized by the open western juniper stands has occurred at a slower but more steady rate since the 1870s. Multiple tree age classes, the presence of a shrub steppe understory, and terminal and lateral leader growth on all age classes of trees characterize these stands. This establishment pattern is similar to woodland development reported on Steens Mountain in southeastern Oregon (Miller and Rose 1995).

Several researchers have attributed the increase of woody plants in the West to the rise in atmospheric CO_2 (Johnson et al. 1990, Knapp and Soule 1996). However, CO_2 levels were barely above pre-industrial levels late in the 1800s during the initiation of juniper woodland expansion in the West (Young and Evans 1981, Eddleman 1987, Miller and Rose

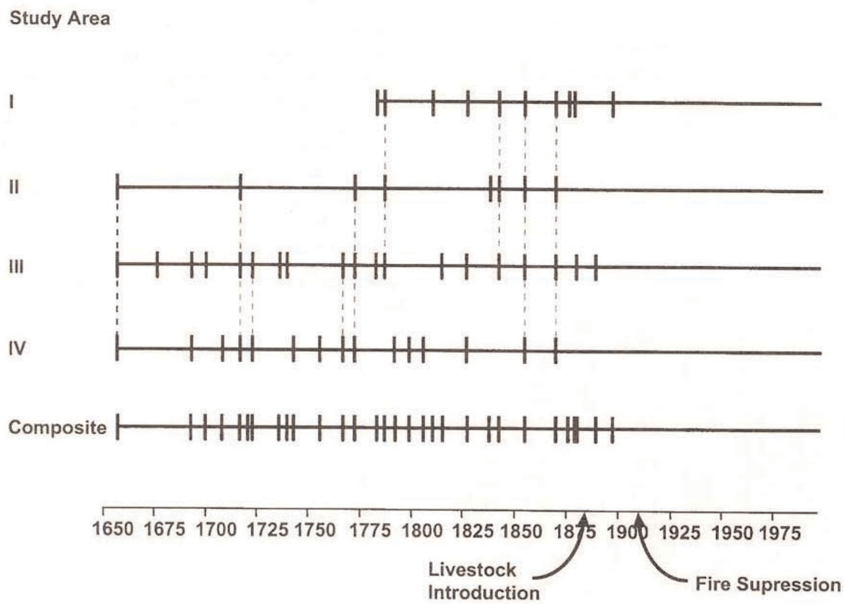

Fig. 4. Master fire chronology for the mountain big sagebrush steppe community in the upper Chewaucan River basin. Fire history extends from 1601 to 1996. Each horizontal line represents a sample composite for each collection site with the bottom line being a composite for all fire scar samples across the 4 sites. Each vertical line designates a fire occurrence. Dashed lines connect collection sites where fires occurred across 2 or more sites in the same year.

1995.). In addition, the peak in woodland expansion during the early part of this century, in this and other studies (Young and Evans 1981, Tausch et al. 1981), and the relatively even establishment of other juniper stands throughout this century do not correlate with the continued rise in atmospheric CO_2.

Tree densities in the study area have been increasing in the low sagebrush steppe community since the 1870s. This has also occurred on Steens Mountain (Miller and Rose 1995) and northeastern California (Young and Evans 1981). In northeastern California, 83% of the trees had established after 1900 on several low sagebrush sites. However, due to slower tree recruitment and growth rates, tree densities were less than in the mountain big sagebrush steppe community. Young and Evans (1981) also found low recruitment rates of western juniper in low sagebrush communities in California.

Climate

Climate has been implicated in the literature as enhancing the postsettlement expansion of western juniper during the late 1800s and early 1900s (Miller and Wigand 1994). Following the end of the Little Ice Age in the mid-1800s, winters became more mild and precipitation increased above the current long term average until 1916 in southeastern Oregon, northeastern California, and northern Nevada (Antevs 1938, Graumlich 1987). Regional tree ring chronologies in southeastern Oregon indicate 5 consecutive years of above average growth from 1875 to 1879 (Holmes et al. 1986). Tree ring widths exceeded average growth (mean tree ring indices derived from 1700 to 1996) in 70% of the years between 1875 and 1915. This wet period coincides with peak juniper establishment across the study area. In pinyon-juniper woodlands the greatest rate of increase in establishment occurred between 1870 and 1920 (Tausch et al. 1981), a milder and wetter period than average (Wahl and Lawson 1970, LaMarche 1974).

Livestock

Expansion of western juniper in the Chewaucan River basin also coincided with the introduction of domestic livestock. Grazing may have enhanced the expansion of western juniper in several ways including: (1) the reduction of fine fuels (Campbell 1954, Ellison 1960, Burkhardt and Tisdale 1976), (2) alteration of plant community structure (Miller et al. 1994), and (3) reduction of competition from herbaceous species (Cottam and Stewart 1940, Madany and West 1983). The last large burn in 1870 occurred during the first few years of the livestock era when animal numbers were relatively low and prior to active fire suppression efforts. Only 5 small fire events occurred in the study area following the introduction of livestock. Plant community structural changes may also have accelerated tree establishment. Sagebrush cover, which generally increases under heavy grazing and reduced fire occurrence (Miller et al. 1994), provides safe sites for tree establishment and enhances sapling growth rates (Burkhardt and Tisdale 1976, Eddleman 1987, Miller and Rose 1995).

Fire

In the mountain big sagebrush steppe community, mean fire intervals, prior to 1871, ranged from 12 to 15 years similar to those estimated for mountain big sagebrush communities in other regions of the West (Houston 1973, Burkhardt and Tisdale 1976, Martin and Johnson 1979). The number of years between fires within the 3 tree clusters ranged between 3 and 28 years prior to settlement with a 100% probability of a fire occurring within 45 years. In the mountain big sagebrush steppe community a minimum of 45 years is required for a tree to reach a 3 m height. Western juniper trees < 3 m tall are easily killed by fire (Bunting 1984). In southwestern Idaho, Burkhardt and Tisdale (1976) reported that fire return intervals of 40 to 50 years would be adequate to inhibit western juniper encroachment into shrub steppe communities. The frequency of presettlement fire return intervals in the Chewaucan Basin was sufficient to limit the establishment of western juniper. Postsettlement expansion coincided with the declining role of fire.

The presence of presettlement western juniper trees on low sagebrush communities is usually attributed to the lack of fine fuels and thus low probability of fire (Burkhardt and Tisdale 1969, Vasek and Thorne 1977, Miller and Rose 1995). Old trees are usually sparsely distributed across these communities (Holmes et al. 1986). The low density of presettlement trees may be attributed to a combination of limited tree seedling establishment due to the heavy clay

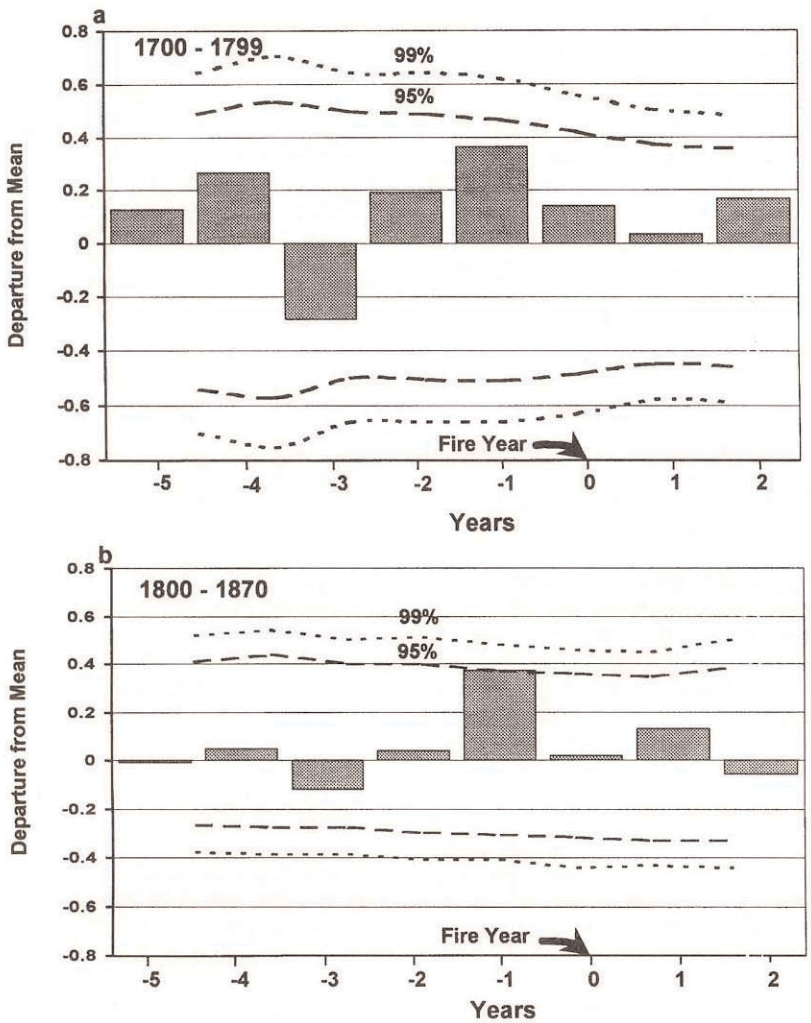

Fig. 5. Plots of superposed epoch analysis comparing tree ring indices (from Holmes et al. 1986) departures from the long-term average for large fire events between (a) 1700 to 1799 and (b) 1800 to 1870. Dashed lines are 95 and 99% confidence limits.

soils, slow growth rates, and occasional fire events. However, tree densities have significantly increased in this community since 1875 in the Chewaucan River basin (this study), northeastern California (Young and Evans 1981), and Steens Mountain in southeastern Oregon (Miller and Rose 1995).

Mean fire intervals were considerably longer in the low sagebrush communities than in neighboring mountain big sagebrush communities due to lower productivity and fuel accumulations. Prior to the fires in 1717 and 1855, tree ring growth in southeast Oregon ranged above the long-term average in 1715 and 1716, and 1851 to 1854 (Holmes et al. 1986). Greater than average accumulations of fine fuel were probably present allowing fire to burn across the typically fuel limited low sagebrush community. Mean fire intervals of around 100 years were probably adequate to create a stand of widely scattered western juniper in low sagebrush plant communities. The average age of 3 m tall trees ranged between 75 and 96 years. In northeastern California, Young and Evans (1981) reported up to 90 years between fire occurrences on low sagebrush communities.

In our study, climate seemed to control large fires, but did not correlate with small fire events. Large fires were usually preceded by at least 1 year of above average tree ring growth. In the Intermountain West, Knapp (1995) reported the size of area burned in the 1980s increased when climate conditions favored growth of annual and perennial grasses during the summer prior to the fire event. In the Southwest, large fires, 200 to 3000+ ha, were a common occurrence (Baisan and Swetnam 1990, Swetnam and Dieterich 1985). These large fires generally occurred in a near average year that had been preceded by 2 wet years (Baisan and Swetnam 1990, 1997). The greater number of small fires in this study may be related to limited and spatially heterogeneous fuel accumulations due to a relatively high mean fire interval for these semi-arid communities. Other researchers have found a relationship between fire frequency and fire size (Swetnam 1993).

The fire frequency in the study area began to decline after 1870, following the introduction of livestock. Wet conditions throughout southeastern Oregon during this period (Antevs 1938, Graumlich 1987), although enhancing juniper establishment, should have perpetuated large fires due to above average accumulations of fuel. However, during the late 1800s accumulation of fine fuels was limited by livestock. In northeastern California, there was no evidence of fire after settlement in a western juniper woodland (Young and Evans 1981). In a pinyon-juniper woodland in eastern Nevada, the frequency of fire declined after 1860 (Gruell et al. 1994). In ponderosa pine forests in the Southwest, fire declined between 1874 and 1898 (Savage and Swetnam 1990). The exception was in Chuskas, Arizona where fire declined after 1829, which coincided with the buildup of Navajo sheep herds. The decline in mean fire intervals and increase in western juniper establishment preceded effective fire suppression efforts by 60 years.

The declining role of fire in shrub steppe communities and the increase in density and expansion of western juniper has ecological parallels in ponderosa pine communities of the Southwest. The conversion of pine savannas and open forest to dense forests has been attributed to the reduced role of fire and favorable climatic conditions for tree establishment (Swetnam and Dieterich 1984, Savage and Swetnam 1990, Savage 1991). The decline in fires in the Southwest also coincides with the introduction of livestock (Savage and Swetnam 1990, Savage 1991), 45 years before fire suppression (Madany and West 1983).

Conclusions

Western juniper chronology in the Chewaucan River basin clearly showed major structural change across sagebrush steppe communities since 1875. The most rapid period of establishment in mountain big sagebrush steppe occurred between 1885 and 1925, a period of wetter than average conditions, few fires, and intensive livestock grazing. The initiation of woodland expansion and pattern of establishment do not support the hypothesis that rising levels of CO_2 is a primary factor driving 20th century juniper woodland succession in the northern portion of the Great Basin. Prior to 1880, fire probably played a major role in limiting western juniper encroachment into these sagebrush communities. Mean fire intervals of less than 15 years were adequate to inhibit western juniper encroachment and probably limit sagebrush cover allowing the herbaceous layer to dominate the landscape. The co-occurrence of wet climatic conditions, introduction of livestock, and the reduced role of fire support the hypothesis that all these factors contributed to the postsettlement expansion of juniper in the West.

Literature Cited

Agee, J.K. 1993. Fire ecology of Pacific Northwest forests. Island Press, Washington, D.C.

Antevs, E. 1938. Rainfall and tree growth in the Great Basin. Carnegie Institution of Washington, Publ. 469, Amer. Geogr. Soc., Spec.Publ. 21. New York, N.Y..

Archer, S. 1989. Have southern Texas savannas been converted to woodlands in recent history? Amer. Natur. 134:545-561.

Archer, S., C. Scifres, and C.R. Bassham. 1988. Autogenic succession in a subtropical savanna: conversion of grassland to thorn woodland. Ecol. Monogr. 58:111–127.

Arno, S.F. and K.M. Sneck. 1977. A method of determining fire history in coniferous forests in the mountain West. USDA For. Serv. Gen. Tech. Rep. INT-42. Washington, D.C.

Baisan, C.H. and T.W. Swetnam. 1990. Fire history on a desert mountain range: Rincon Mountain Wilderness, Arizona, USA. Can. J. For. Res. 20:1559-1569.

Baisan, C.H. and T.W. Swetnam. 1997. Interactions of fire regimes and land use in the Central Rio Grande Valley. USDA For. Ser. Res. Pap., RM-RP-330.

Barney, M.A. and N.C. Frischknecht. 1974. Vegetation changes following fire in the pinyon-juniper type of west-central Utah. J. Range Manage. 27:91–96.

Blackburn, W.H. and P.T. Tueller. 1970. Pinyon and juniper invasion in black sagebrush communities in east-central Nevada. Ecol. 51:841–848.

Bunting, S. 1984. Prescribed burning of live standing western juniper and post-burning succession, p. 69–73. *In:* T.E. Bedell (comp.), Oregon State Univ. Ext. Ser. Proc. Western juniper short course. Oct., 15–16, Bend, Ore.

Burkhardt, J.W. and E.W. Tisdale. 1969. Nature and successional status of western juniper vegetation in Idaho. J. Range Manage. 22:264–270.

Burkhardt, J.W. and E.W. Tisdale.. 1976. Causes of juniper invasion in southwestern Idaho. Ecol. 57:472–484.

Campbell, R.S. 1954. Fire in relation to forest grazing. Unasylva 8:154–158.

Cottam, W.P. and G. Stewart. 1940. Plant succession as a result of grazing and of meadow desiccation by erosion since settlement in 1892. J. For. 38:613–626.

Dieterich, J.H. and T.W. Swetnam. 1984. Dendrochronology of a fire-scarred ponderosa pine. For. Sci. 30:238–247.

Eddleman, L.E. 1987. Establishment of western juniper in central Oregon, p. 255–259 *In:* R. L. Everett (ed.) Proc. Pinyon juniper conference. USDA, For. Ser., Gen. Tech. Rep. INT 215. Washington, D.C.

Ellison, L. 1960. Influence of grazing on plant succession of rangelands. Bot. Rev. 26:1–78.

Fritts, H.C. 1976. Tree rings and climate. Academic Press, London, United Kingdom.

Fritts, H.C. and W. Xiangdig. 1986. A comparison between response-function analysis and other regression techniques. Tree-ring Bull. 46:31–46.

Graumlich, L.J. 1987. Precipitation variation in the Pacific Northwest (1675–1975) as reconstructed from tree rings. Ann. Assoc. Amer. Geogr. 77:19–29.

Grissino-Mayer, H.D. 1995. User's Manual FHX2: Software for the analysis of fire history from tree rings. Lab. of Tree-Ring Res., Univ. of Arizona, Tucson, Ariz.

Gruell, G.E., L.E. Eddleman, and R. Jaindl. 1994. Fire history of the pinyon-juniper woodlands of Great Basin National Park. USDA–Nat. Park Ser., Pacific Northwest Reg.. Gen. Tech. Rep. NPS/PNEOSU/NRTR-94/01. Seattle, Wash.

Harrington, G.N., A.D. Wilson, and M.D. Young (eds.). 1984. Management of Australia's rangelands. Comm. Sci. Indust. Res. Org., Melbourne, Australia.

Holmes, R.L., R.K. Adams, and H.C. Fritts. 1986. Tree-ring chronologies of western North America: California, eastern Oregon, and Northern Great Basin. Lab. Tree-Ring Res., Univ. of Arizona, Chron. Ser. VI.

Houston, D.B. 1973. Wildfires in northern Yellowstone National Park. Ecology 54:1109–1117.

Johnson, H.B., H.S. Mayeux Jr., and H.W. Polley. 1990. Increasing CO_2 and plant interactions: effects on natural vegetation. Vegetatio 104–105:157–170.

Kelly, R.D. and B.H. Walker. 1976. The effects of different forms of land use on the ecology of a semi-arid region of southeastern Rhodesia. J. Ecol. 64:553–576.

Kilgore, B.M. and D. Taylor. 1979. Fire history of a sequoia-mixed conifer forest. Ecol. 60:129–142.

Knapp, P.A. 1995. Intermountain West lightning-caused fires: climatic predictors of area burned. J. Range Manage. 48:85–91.

Knapp, P.A. and P.T. Soule. 1996. Vegetation change and the role of atmospheric CO_2 enrichment on a relict site in central Oregon: 1960–1994. Ann. Assoc. Amer. Geogr. 86:387–411.

LaMarche, V.C., Jr. 1974. Paleoclimatic inferences from long tree-ring records. Sci 183:1043–1048.

Madany, M.H. and N.E. West. 1983. Livestock grazing-fire regime interactions within montane forests of Zion National Park, Utah. Ecol. 64:661–667.

Martin, R.E. and A.H. Johnson. 1979. Fire management of Lava Beds National Monument, p 1209–1217. *In:* R. E. Linn (ed.) Proc. First Conf. Sci. Res. Nat. Parks. USDI Nat. Parks Ser. Trans. Proc. Ser. No. 5.

Miller, R.F. and J.A. Rose. 1995. Historic expansion of *Juniperus occidentalis* (western juniper) in southeastern Oregon. Great Basin Nat. 55:37–45.

Miller, R.F. and P.E. Wigand. 1994. Holocene changes in semiarid pinyon-juniper woodlands. BioScience 44:465–474.

Miller, R.F., J.A. Rose, and T.S. Svejcar. 1999a. Conversion of sagebrush steppe to juniper woodland. pp. 385–390 *In:* Monsen, S.B., S. Richards, R.J. Tausch, R.F. Miller, C. Goodrich, (comp.); Proc.–Ecology and Management of Pinyon-Juniper Communities Within the Interior West. USDA For. Ser., RMRS-P-9

Miller, R.F., T.J. Svejcar, and N.E. West. 1994. Implications of livestock grazing in the Intermountain sagebrush region: plant composition, p. 101–146. *In:* M. Vavra, W. A. Laycock, and R. D. Pieper, (eds.), Ecological Implications of Livestock Herbivory in the West. Soc. Range Manage., Denver, Colo.

Miller, R.F., R. Tausch, and W. Waichler. 1999b. Old-growth juniper and pinyon woodlands. pp. 375–384 *In:* Monsen, S.B., S. Richards, R.J. Tausch, R.F. Miller, C. Goodrich, (comp.); Proc.—Ecology and

Management of Pinyon-Juniper Communities Within the Interior West. USDA For. Ser., RMRS-P9.
Oliphant, J.O. 1968. On the cattle ranges of the Oregon country. University of Washington Press, Seattle, Wash.
Petersen, R.G. 1985. Design and analysis of experiments. Marcel Dekker, Inc. New York. N.Y.
Savage, M. 1991. Structural dynamics of a southwestern pine forest under chronic human influence. Ann. Assoc. Amer. Geogr. 8:271–289.
Savage, M. and T. W. Swetnam. 1990. Early 19th-century fire decline following sheep pasturing in a Navajo ponderosa pine forest. Ecol. 71:2374–2378.
Smeins, F.E. 1983. Origin of the brush problem – a geographical and ecological perspective of contemporary distributions, p. 5–6. *In:* Brush Manage. Symp. Texas Tech Press, Lubbock, Tex.
Swetnam, T.W. 1993. Fire history and climate change in giant sequoia groves. Sci. 262:885–889.
Swetnam, T.W. and J.H. Dieterich. 1985. Fire history of ponderosa pine forest in the Gila Wilderness, New Mexico, p. 390–397. *In:* J.E. Lotan, B.M. Kilgore, W.M. Fisher, and R.W. Mutch (tech. coord.) Proc. Workshop on Wilderness Fire. USDA For. Ser. Gen. Tech. Rep. INT-182.
Tausch, R.J., and N.E. West. 1988. Differential establishment of pinyon and juniper following fire. Amer. Midl. Natur. 119:174–184.
Tausch, R.J., N.E. West, and A.A. Nabi. 1981. Tree age and dominance patterns in Great Basin pinyon-juniper woodlands. J. Range Manage. 34:259–264.
Taylor, G.H. 1993. Normal annual precipitation; state of Oregon. Oregon Climate Service, Oregon State Univ., Corvallis, Ore.
Vasek, F.C. and R.F. Thorne. 1977. Transmontane coniferous vegetation, p. 797–832. *In:* Barbour, M.G. and J. Major (eds.). Terrestrial Vegetation of California. Calif. Native Plant So. Spec. Publ. No. 9.
Wahl, E.W. and T.L. Lawson. 1970. The climate of the mid-nineteenth century United States compared to the current normals. Monthly Weather Rev. 98:259–265.
Wenzel, D.L. 1979. Soil resource inventory Fremont National Forest; Pacific Northwest Region. USDA For. Serv.
West, N.E. 1984. Successional patterns and productivity potentials of pinyon-juniper ecosystems, p.1301–1332. *In:* Developing Strategies for Rangeland Management. Nat. Res. Council/National Acad. of Sci. Westview Press, Boulder, Colo.
Wright, H.A. and A.W. Bailey. 1982. Fire ecology. John Wiley and Sons. New York N.Y..
Young, J.A. and R.A. Evans. 1981. Demography and fire history of a western juniper stand. J. Range Manage. 34:501–506.
Zar, J.H. 1984. Biostatistical analysis. Prentice-Hall International, Inc. London, United Kingdom.