Fire regimes of juniper communities in the Columbia and northern Great basins 2019

Figure 1—A western juniper woodland burning in the 2017 Buck Butte Fire near Klamath Falls. Oregon Department of Forestry image by Bryson Williams.

Citation: Murphy, Shannon K.; Fryer, Janet L. 2019. Fire regimes of juniper communities in the Columbia and northern Great basins. In: Fire Effects Information System, [Online]. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory (Producer). Available: https://www.fs.fed.us/database/feis/fire_regimes/Columbia_GB_juniper/all.html

ABSTRACT

This synthesis summarizes information available in the scientific literature on historical patterns and contemporary changes in fuels and fire regimes in juniper communities of the Columbia and northern Great basins. Limited evidence suggests that many presettlement juniper woodlands and savannas had open stand structures, and they typically occurred in claypan soils or shallow soils on rocky sites. Few fire history studies have been conducted in these regions, and sample sizes were small and methodologies challenging, so historical fire regimes are poorly understood. Information was lacking for fire regimes of Utah and Rocky Mountain juniper communities in the regions covered in this synthesis; thus, fire regime information comes from western juniper communities.

Presettlement fires were ignited by lightning and American Indians. Patchy surface and crown fires occurred in presettlement western juniper woodlands and savannas. Fire frequencies and patterns likely varied among juniper communities, depending on soils and vegetation growing in and around them. Fire history data were insufficient to characterize typical fire intervals, but limited data suggest fire frequencies varied in pure western juniper woodlands and savannas. Estimates of fire intervals ranged from 10 to >150 years, but are thought to be >50 years, which is the approximate age that junipers survive low-severity fire. Fires were likely to have occurred during years that followed at least 1 year of above-average precipitation, when fine fuels accumulated. LANDFIRE modeled a mean fire interval of around 100 years. Fires were likely more frequent in western juniper woodlands with ponderosa pine than without ponderosa pine. Many fires in juniper woodlands were probably small due to dissected terrain and sparse fuels, but large fires also occurred.

Since the late 1800s, juniper communities have expanded their range (expansion) and increased in density (infill) in many areas of the Columbia and northern Great basins, primarily into big sagebrush steppe. Juniper expansion and infill is attributed to a combination of interrelated factors including fire exclusion, climate variability, and overgrazing by livestock. In many locations, expansion has resulted in type conversions from big sagebrush steppes to woodland transitional communities characterized by young junipers with shrub understories. As succession proceeds, juniper canopies close and shrubs in the understories die out. Some of these communities are outside the historical range of variability. In late succession, these communities are susceptible to crown fires during severe fire weather. Nonnative annual grasses have increased surface fuel loads and continuity in juniper and adjacent shrub and grassland steppe communities. This has resulted in shorter fire intervals and larger fires in juniper-sagebrush ecosystems than what likely occurred historically.

Table of Contents

INTRODUCTION

This Fire Regime Synthesis provides information on western juniper, Utah juniper, and Rocky Mountain juniper communities in the Columbia and northern Great basins (fig. 2). It brings together information from two sources: the scientific literature as of 2019, and the Biophysical Settings (BpS) models and associated Fire Regime Data Products developed by LANDFIRE, which are based on literature, local data, and expert estimates. This synthesis summarizes what was known about historical and contemporary fire regimes in juniper communities of the Columbia and northern Great basins as of 2019, and identifies areas lacking fire history data. It cites primary literature and several literature reviews [2, 8, 22, 102].

Nomenclature: When junipers are referred to at the genus level (e.g., “junipers” or “juniper woodlands”), the information pertains to all three juniper species discussed in this synthesis. Common names are used throughout. See table A1 for a complete list of common and scientific names of species mentioned in this synthesis and links to FEIS Species Reviews.

The term “savanna” has been used to refer to both western juniper-bunchgrass [32] and western juniper-low sagebrush communities [102, 133]. Where the plant community is not specified, “savanna” refers to both types. “Steppe” may refer to either shrub or bunchgrass steppes [32]; where the plant community is not specified, “steppe” refers to both types. “Woodland transitional community” refers to communities in which western juniper is successionally replacing what had been a big sagebrush community.

Except when historical time frames are specifically provided in this synthesis, “presettlement” refers to the time period prior to European-American settlement in these basins, which began around the early 1870s [102]. “Postsettlement” refers to the time after that.

Juniper Biophysical Settings in the Columbia and northern Great basins

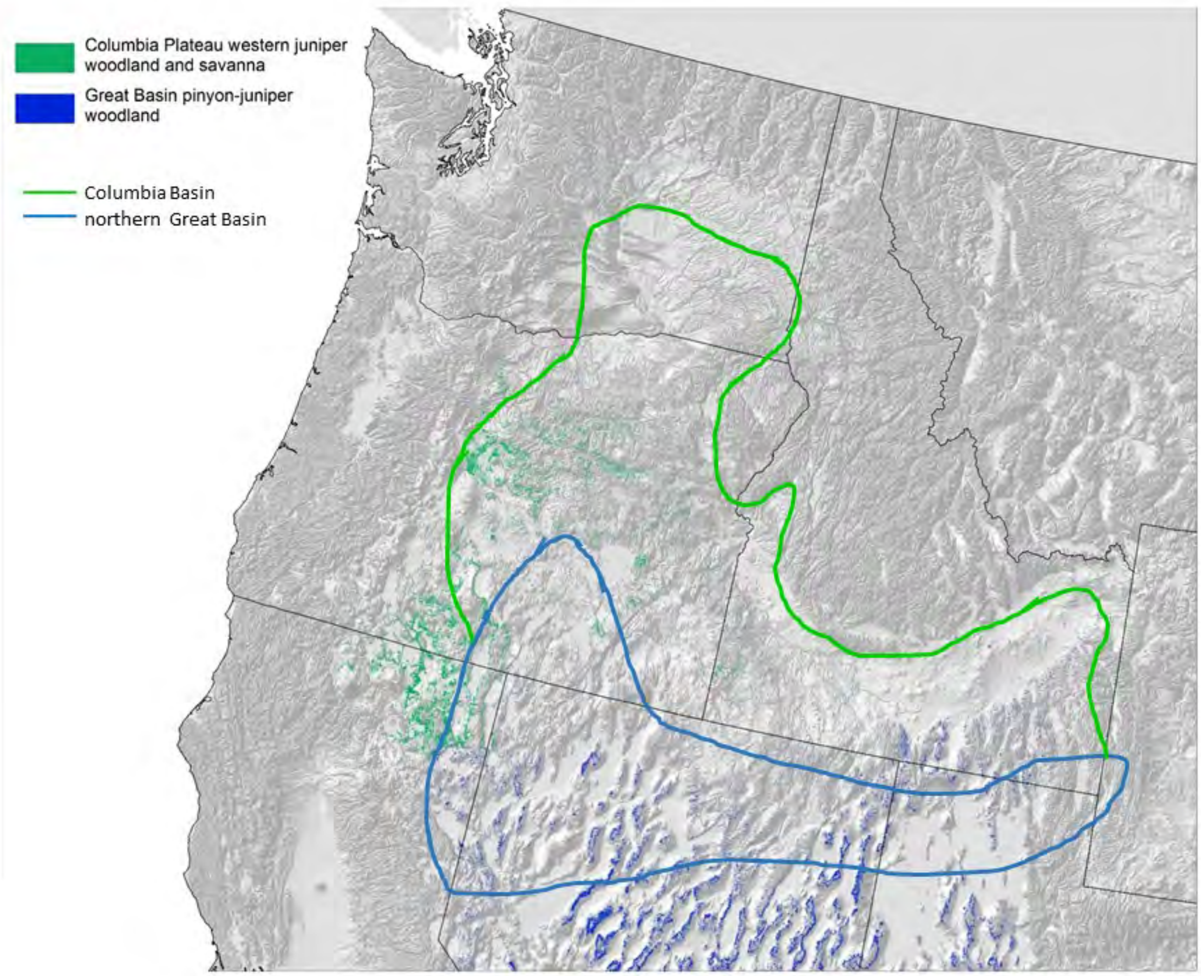

Figure 2—Distribution of juniper communities in the Columbia and northern Great basins based on the LANDFIRE Biophysical Settings (BpS) data layer [84]. LANDFIRE did not map BpSs 0911150, 1710170, and 1811150 because they are uncommon in these regions. Click on the map for a larger image.

The following FEIS Fire Regime Syntheses and Reports provide information on communities that are adjacent to and overlap with juniper communities in the Columbia Basin and/or Great Basin:

- Mountain big sagebrush

- Wyoming big sagebrush and basin big sagebrush
- Mixed dwarf sagebrush
- Mountain-mahogany
- East Cascades ponderosa pine and montane mixed-conifer
- Quaking aspen communities of the Sierra Nevada and southern Cascades
- Great Basin quaking aspen

SITE CHARACTERISTICS AND DISTRIBUTION

COLUMBIA BASIN

Climate in the Columbia Basin is semiarid and primarily continental. The region has hot, dry summers, cool to cold winters, low mean annual relative humidity, low mean annual precipitation, and high winds [34, 156]. Moist marine air from the west and dry, cold air from the north help moderate temperatures in summer and bring cold temperatures in winter [41]. Mean temperatures on the Columbia Plateau range from 31 °F (0 °C) in January and 65 °F (18 °C) in July [156]. Mean annual precipitation in the western juniper zone of central Oregon ranges from 7.8 to 12.2 inches (198-310 mm), falling about equally as rain and snow [34, 43]. On the Walla Walla Plateau of north-central Oregon, western juniper communities occur in areas that receive <12 inches (305 mm) annual precipitation [145].

Juniper zones have relatively narrow elevational belts and variable topography. Across the Columbia Basin, elevations for individual juniper zones range from <650 feet (200 m) for western juniper woodlands along the Columbia River in Washington [121] to >5,000 feet (1,500 m) for western juniper woodlands in central Washington [121, 155] and 4,790-6,200 feet (1,460-1,880 m) for Utah juniper/red-osier dogwood riparian communities in south-central Idaho [55]. Juniper woodlands occur in canyons and on flats, foothills, mesas, and playas [54, 62, 65, 89, 121, 128], on all aspects and slope positions [34, 54, 62, 65, 89, 121, 128]. At low elevations, western juniper is most common on north slopes [43].

Soils of juniper woodlands are typically shallow [13, 23, 24, 34, 176]. Historically, juniper woodlands and isolated, old-growth (i.e., presettlement) stands were usually restricted to rocky outcrops adjacent to shrub and perennial bunchgrass steppes, or to coniferous woodlands and forests, all of which usually have deeper soils [60, 65, 121]. On Steens Mountain in southeastern Oregon, Miller and Rose [107] reported that western juniper grew “only occasionally” on deep, well-drained soils. Western juniper does not grow on thin scablands of the Columbia Plateau [54, 164], although it grows on adjacent, more developed soils [60].

Soils supporting western juniper communities in the Columbia Basin are most often derived from igneous parent materials [32, 34, 145]. Western juniper communities also occur on soils derived from sedimentary [54, 118] and metamorphic [54] parent materials and on alluvial and colluvial fans [27]. Rocky Mountain juniper communities occur on calcareous soils in the Wallowa Mountains [27, 39].

Soils of juniper communities are generally medium-textured with abundant coarse fragments [32], but soil textures vary from fine to coarse [34, 54, 65]. Juniper savannas with bunchgrass understories often have fine-textured soils [127]. In southeastern Washington, western juniper-antelope bitterbrush-big sagebrush/cheatgrass savannas occur on stable dunes widely separated by unstable dunes [32].

NORTHERN GREAT BASIN

For the Great Basin, this synthesis covers the area north of the Humboldt River-Interstate 80 corridor. Climate of the northern Great Basin is semiarid [119], with hot, dry summers and cool to cold, moist winters [39, 43]. Mean annual precipitation in western juniper communities ranges from 7.8 to 12.2 inches (200-312 mm) [43]. In northern Nevada, annual precipitation averages 7.1 to 13.5 inches (180-340 mm) in Utah juniper communities [13, 14, 15, 17]. Precipitation generally increases west to east [43, 119]. Monsoons deliver summer rains [119], especially in the northeastern portion of the basin [39].

The elevational climate gradient in the northern Great Basin is steep [99, 119]. Frosts and drought during the growing season generally restrict junipers to relatively narrow elevational belts [121]. Elevations in juniper zones generally range from about 5,200 to 6,900 feet (1,600-2,100 m) [13, 14, 15, 17, 107], although NatureServe [121] reports a range of 4,900 to 9,200 feet (1,500-2,800 m). On Steens Mountain, western juniper/mountain big sagebrush/Idaho fescue communities extend from 4,757 to 6,890 feet (1,450-2,100 m) [107].

The Great Basin has mostly north-south oriented mountain ranges separated by alluvial basins [119]. Juniper communities generally occur on dry slopes, rimrocks, mesas, plateaus, and ridges [121] and in high basins. For example, Utah juniper dominates cold lower slopes and high basins in northern Nevada [128]. Utah juniper communities occupy all aspects [13, 14, 17, 128], with north- and east-facing aspects most common at low elevations and south- and west-facing aspects most common at high elevations [13]. In northern Nevada, they occur on all aspects on 10% to 60% slopes [14, 15, 17]. In the southern Ruby Mountains, Utah juniper stands generally occupy south- and west-facing slopes, while singleleaf pinyon stands occupy east-facing slopes [86].

Soils in the juniper zone of the northern Great Basin are usually shallow, rocky [17, 39, 128], and often skeletal [17, 39]. They include a variety of parent materials [17, 39, 60, 121, 172], with all soil textures represented [13, 14, 17, 39, 128, 172]. Rocky Mountain juniper woodlands occur on calcareous soils in the northeastern and east-central Great Basin [14, 39]. Western juniper stands sometimes occur on geothermically acidified soils, particularly in the western Great Basin [128]. Soil moisture regime is xeric to aridic [172].

PLANT COMMUNITIES

Juniper communities are classified into pinyon-juniper formations in the broad sense (e.g. [48, 80]). However, pinyons usually do not codominate with junipers in the regions covered in this synthesis [39, 89, 90], although they codominate with junipers on some woodlands in central [17] and northern [86, 90, 172] Nevada and along the rim of the Bonneville Basin in northern Utah [172].
Miller et al. [102] separate old-growth western juniper communities into three categories based on stand structure:

- Small stands isolated on rocky outcrops and ridges. Understories are typically sparse.
- Woodlands with tree canopies of typically <20%, but occasionally >35%. Shrubs (usually big sagebrush) and bunchgrasses dominate the understory.
- Savannas with tree canopies of <10%. They are described as "savanna-like" with sagebrush (usually low sagebrush), perennial grasses, and forbs; savannas probably account for the largest land area of old growth.

They use a fourth category to describe postsettlement big sagebrush steppe communities succeeding to western juniper woodlands [102]:

- Woodland transitional; these are western juniper-big sagebrush communities in successional stages ranging from open stands of juniper with shrub and herb understories (early succession) to nearly closed canopies with sparse understories (late succession); herein, referred to as woodland transitional communities.

The most extensive area of old-growth woodland occurs in northeastern California and northwestern Nevada (northwestern High Desert Province) and in central Oregon (Mazama Province). Cover of western juniper varies widely in these regions, from 10% to 60% [102].

Three juniper woodland series occur in the regions covered in this synthesis: western juniper, Utah juniper, and Rocky Mountain juniper. Western juniper series occur in the western portion of the Columbia Basin [121], the northwestern rim of the Great Basin in northeastern California and northwestern Nevada [92, 121] and the northern rim of the Great Basin in southern Idaho [23]. Utah juniper series dominate the juniper zone in most of northwestern Nevada [17, 128]. Utah juniper and Rocky Mountain juniper series overlap in north-central and northeastern Nevada and southern Idaho, although Utah juniper series are more prevalent [89, 95]. Rocky Mountain series occur mostly in the northeastern Great Basin, usually in mesic or riparian zones [39, 125].

A summary of modeled fire regime information for the Biophysical Settings (BpSs) covered in this synthesis and links to BpS descriptions are provided in table A2. Ranges of the BpSs covered in this synthesis are shown in figure 2.

Juniper woodlands and savannas typically have low plant species diversity [39, 62]. Woodlands usually have widely spaced junipers and very sparse shrub and herbaceous layers. Juniper-bunchgrass savannas generally occur at lower elevations (<5,000 feet (1,500 m)) on more xeric sites, and they have more open canopies than juniper woodlands [121, 128]. Historical accounts from the 1800s reported sparse, scattered western junipers growing among perennial bunchgrasses throughout central and southeastern Oregon [107, 116].

Generally for juniper communities, canopy cover of >40% is considered closed [155]. With cover that high, mature junipers generally outcompete understory vegetation for light, soil moisture, nutrients [35], and root space [155, 170]. Shrub and groundlayer vegetation is typically sparse in juniper communities with either closed canopies [34, 86, 92, 107, 155, 170] or dry soils with low water-holding capacity [92]. However, Idaho fescue may persist under closed juniper canopies [155]. On Steens Mountain in southwestern Oregon, atypical canopy cover of nearly 100% is reported for western juniper on sites where it has successionally replaced quaking aspen [107].

COLUMBIA BASIN

Western juniper series occur throughout the Columbia Basin [34, 92, 121]. Western juniper is usually the only tree present [24, 34, 92, 121] except where western juniper woodlands finger into quaking aspen stands [107] or adjoin higher-elevation ponderosa pine communities [42, 102].

The largest contiguous areas of western juniper occur in a band from central Oregon northeasterly to west-central Idaho [156]. Western juniper series are most common in central Oregon [34, 43, 92, 121], especially around the Deschutes, Crooked, and John Day rivers [43]. Western juniper communities are more scattered and discrete elsewhere [156].

Shrub and bunchgrass steppe vegetation comprise the understory of western juniper woodlands and savannas of Oregon and southern Idaho. At low elevations, western juniper communities often form a mosaic with and grade into big sagebrush [121, 155], low sagebrush [52, 176], and/or Palouse (bunchgrass) prairie [65, 121, 155] steppes. On the western edge of the Columbia Basin, western juniper woodlands grade into ponderosa pine or ponderosa pine-lodgepole pine communities [34, 92, 121, 155]. Dominant shrubs in western juniper woodlands include antelope bitterbrush, curlleaf mountain-mahogany, low sagebrush, mountain and Wyoming big sagebrush, scabland sagebrush, and yellow rabbitbrush [34, 54, 121]. The shrub layer may be lacking on xeric sites [128]. Graminoids dominate the ground layer; these include native bluebunch wheatgrass, Idaho fescue, Sandberg bluegrass, squirreltail, and threadleaf sedge [34, 121]; and nonnative cheatgrass and crested wheatgrass [34, 62, 121].

Utah juniper communities are occasional in riparian zones of the Columbia Basin [64, 120]. In south-central Idaho, sandbar willow and common chokecherry are associated species in Utah juniper/redosier dogwood riparian communities, with 30% to 50% canopy cover of Utah juniper [55].

NORTHERN GREAT BASIN

Juniper woodlands in this region occur from the east slope of the southern Cascade Range east to northwestern Utah. Western juniper [128] or Utah juniper [39, 121] dominate these woodlands; oneseed juniper is sparse [70] and does not dominate in this region [40, 69, 155]. Western juniper woodlands occur on the northwestern edge of the northern Great Basin [92, 121, 155]. Utah juniper dominates most of the juniper zone in the northern Great Basin [121]; generally, in areas north of the Humboldt River [39]. Western and Utah juniper series generally occur above lower-elevation shrub steppe series [13, 14, 17, 155].

Throughout most of the northern Great Basin, junipers are the only trees occupying upper hillslopes [24, 121]. Juniper zones occur above arid shrub steppe zones. Occasionally, there is a perennial bunchgrass zone below [102]. Where there are higher-elevation mountain ranges, other conifers dominate zones above the juniper zone [99, 119]. Ponderosa pine, Jeffrey pine, and/or Sierra juniper occur above and finger into the western juniper zone on the western edge of the northern Great Basin [60, 92, 121]. Rocky Mountain Douglas-fir and/or quaking aspen occur above the Utah juniper zone in the Independence and Jarbidge ranges of Nevada [90, 125]. Singleleaf pinyon codominates with Utah juniper on some sites north-central Nevada [17] and in the Ruby Mountains of Nevada [90].

The shrub and groundlayer understories are typically sparse in the juniper zone. Dominant shrubs include black sagebrush, curlleaf mountain-mahogany, littleleaf mountain-mahogany, and mountain big sagebrush [14, 121, 128]. Dominant grasses include native basin wildrye , bluebunch wheatgrass, Idaho fescue, Indian ricegrass, prairie Junegrass, needle and thread, Sandberg bluegrass, squirreltail, [14, 121, 128], and/or nonnative cheatgrass [14] and crested wheatgrass [47].

Utah and Rocky Mountain junipers cooccur and may codominate woodlands in north-central Nevada [89], southern Idaho [95], and northwestern Utah [125]. Along their common border in the northeastern Great Basin, Rocky Mountain juniper typically occupies the upper slopes of the juniper zone [39]. Utah juniper dominates most woodlands in the northern Ruby Mountains, but Rocky Mountain juniper occasionally dominates sparse stands in mesic canyons [86].

Rocky Mountain juniper communities occupy low foothill zones just above sagebrush zones [39, 89]. In mountainous zones, they occur just below or intermixed with mountain shrubland, Rocky Mountain Douglas-fir, and quaking aspen communities [89, 162]. Mountain-mahogany and big sagebrush commonly dominate the shrub layer; basin wildrye, bluebunch wheatgrass, needle and thread, and/or cheatgrass dominate the ground layer [162].

Rocky Mountain juniper is less drought-tolerant than Utah juniper, so it is often restricted to riparian zones, ravines, and sheltered canyons [55, 64, 89, 162]. It dominates some riparian zones and adjacent upland communities of the northern Great Basin [39, 125]. A Rocky Mountain juniper/redosier dogwood community occurs on a tributary of the Little Lost River in east-central Idaho [64], and Rocky Mountain juniper/mesic forb communities occur in riparian canyons along the Bruneau and Jarbidge rivers in southwestern Idaho [120].

HISTORICAL STAND STRUCTURE AND FUELS

HISTORICAL STAND STRUCTURE

Stand structures of presettlement juniper communities are not well known. They are inferred from chronosequence studies (e.g., [105, 114]) and stand structures of contemporary old-growth woodlands, which are thought to be similar to stand structures of presettlement juniper communities [133, 158]. Presettlement woodlands (i.e., many junipers >150 years old) are typically associated with shallow, rocky, or claypan soils, steep slopes, ridges, and rimrocks [13, 17, 23, 24, 34, 39, 102, 128, 176]. Age classes from seedling to senescent are represented [23, 24, 68, 176], with some junipers >1,000 years old [121]. Western juniper stands are diverse in structure and composition, varying from open savannas to nearly closed-canopy woodlands, although canopy cover in most stands is usually open [17, 54, 65] (<20%) [102]. For example, Miller et al. [102] report that western juniper-low sagebrush savannas of Oregon typically have tree and shrub cover of <20%, but tree cover is usually <5% on claypan sites. Surveys conducted the Oregon in the 1960s found variable canopy closure of western juniper woodlands. In the pumice zone of central Oregon, surveys found mean foliage cover of western juniper on loamy soils ranged from about 12% in a western juniper/big sagebrush/Idaho fescue woodland to about 77% in a western juniper/Idaho fescue woodland, with western juniper the only tree in both communities [34]. Surveys conducted in 1969 in Utah juniper woodlands across northern Nevada showed a trend of low Utah juniper cover and much bare ground (table 1). Utah juniper was the only tree in all plant communities surveyed [13, 14].

In Lava Beds National Monument, northeastern California, western juniper cover in a western juniper/curlleaf mountain-mahogany-mountain big sagebrush-antelope bitterbrush/western needlegrass woodland ranged from 1% to 7.7% in three early-succession stands and 20.4% to 20.6% in two late-succession stands. Standing dead trees >12 inches diameter (30 cm), including charred snags, ranged from 2.1 to 21.8 snags/acre (5.1- 54/ha) in early-successional stands and 8.1 to 10.1 snags/acre (20-25/ha) in late-successional stands. Shrub cover ranged from 18% to 34% in early- and 8.5% to 14% in late-successional stands; herbaceous cover was <5% in all successional stages. Bare ground ranged from 33% to 65% in early- and 54% to 67% in late-successional stands [114].

Table 1a—Stand structure of Utah juniper communities in northern Nevada. Plots for shrubs and herbs were 20 x 20 inches (50 x 50 cm) [13] or 30 x 30 inches (75 x 75 cm) [14].					
Variable	------Plant community------				
	Utah juniper/big sagebrush/Sand-berg bluegrass, northwestern NV [13]	Utah juniper/low sagebrush/Sand-berg bluegrass, northwestern NV [13]	Utah juniper/black sagebrush/cheat-grass, near Elko, NV [14]	Utah juniper/rubber rabbitbrush/western wheatgrass, near Elko, NV [14]	Utah juniper/rubber rabbitbrush-cheatgrass, near Elko, NV [14]
Juniper density	85 stems/acre (210/ha)	70 stems/acre (170/ha)	35 stems/acre (86/ha)	10 stems/acre (25/ha)	26 stems/acre (64/ha)
Juniper canopy cover	11.4%	3.0%	4.4%	3.5%	11.4%
Shrub cover	5%	15.7%	~17%	~6.4%	~13.2
Groundlayer cover					
herbaceous	25.5%	24.9%	not provided	not provided	2.6% for cheatgrass; forb cover not provided
lichen	not measured	not measured	28.0%	not measured	not measured
litter	42.5%	23.5%	44.0%	40.0%	58.6%
bare ground	33.0%	34.0%	12.5%	59.0%	38.6%
pavement	13.5%	29.5%	13%	1.0%	1.9%
rock	11.0%	13.0%	2.5%	0.0%	0.9%

Succession

Juniper is a late-successional or "climax" cover type in the Columbia and northern Great basins [92], and fire sets succession back to earlier stages [56, 108, 169]. Surface fire usually kills young junipers [22, 91], although large trees often survive. Based on chronological studies, it takes at least 45 to 50 years [24, 108], or tree height of about 10 feet (3 m) [8, 24], for junipers to grow large enough to survive surface fires [24, 51, 52, 108, 113, 176]. On unproductive sites, it may take >90 years [20, 24, 106, 108]. Water, gravity, and birds disperse juniper seeds into new areas and fresh burns [86]. After stand-replacement fire, an herbaceous-dominated community first develops or—on sites with sprouting shrubs such as curlleaf mountain-mahogany and rabbitbrushes—a shrub/herb-dominated community. Junipers establish slowly, usually beneath shrub canopies [43, 86]. Where junipers occur with pinyons, junipers usually establish first [86].

Succession from a shrub steppe to a woodland transitional community is a slow process. The minimum time for a western juniper overstory to begin suppressing the shrub understory is 30 to 50 years [20, 102]. It typically takes from 45 to 90 years for western juniper to approach stand closure on cool, moist sites and 100 to 170 years on warm, dry sites [66, 102, 161]. For example, near Prineville, Oregon—where juniper expansion is extensive—postsettlement western junipers with a maximum age of about 100 years dominate former mountain big sagebrush communities [161]. Similar successional patterns are noted for Utah juniper [10, 111, 154], although those studies took place outside regions discussed in this synthesis. The successional progression from shrub steppe to woodland transitional community has been assigned to three or four phases (fig. 4):

- Phase I: Juniper is present but shrubs and herbs are dominant.
- Phase II: Juniper codominates with shrubs and herbs.
- Phase III: Juniper dominates and native shrubs and herbs are reduced, although cheatgrass is often present [88, 102, 109, 134].

By phase III, shrub cover is typically <1% on dry sites with sagebrush and ≤5% on mesic sites with less drought-tolerant shrubs such as wax currant and mountain snowberry [109]. A closed canopy-stage is sometimes included:

- Phase IV: Juniper dominates, shrubs are few (<10% cover) or dead, and cover of native herbs is scarce [109, 117]. Cheatgrass may dominate groundlayer vegetation.

Figure 3—Successional phases from shrub steppe to woodland transitional community.

Phase I. A big sagebrush community in Deschutes County, Oregon. Cover is mostly mountain big sagebrush with scattered western juniper seedlings and saplings. Forest Service, U.S. Department of Agriculture image by Janet Fryer.

Phase II. A mountain big sagebrush-western juniper woodland transitional community near Lakeview, Oregon. Cover is about an even mix of sagebrush and juniper. Bureau of Land Management, U.S. Department of the Interior image by Todd Forbes.

Phase III. A western juniper-mountain big sagebrush woodland on Steens Mt., Oregon. Sagebrush cover is in decline. Agricultural Research Service, U.S. Department of Agriculture image.

Phase IV. A western juniper/cheatgrass-bluebunch wheatgrass woodland in Wheeler County, Oregon. The juniper canopy is closed, and sagebrush remains only in skeletal form. Forest Service image by Janet Fryer.

A model to estimate the time needed for mountain big sagebrush communities to transition from initial western juniper establishment to late-seral woodland along elevational and aspect gradients is shown in figure 4 [67, 104].

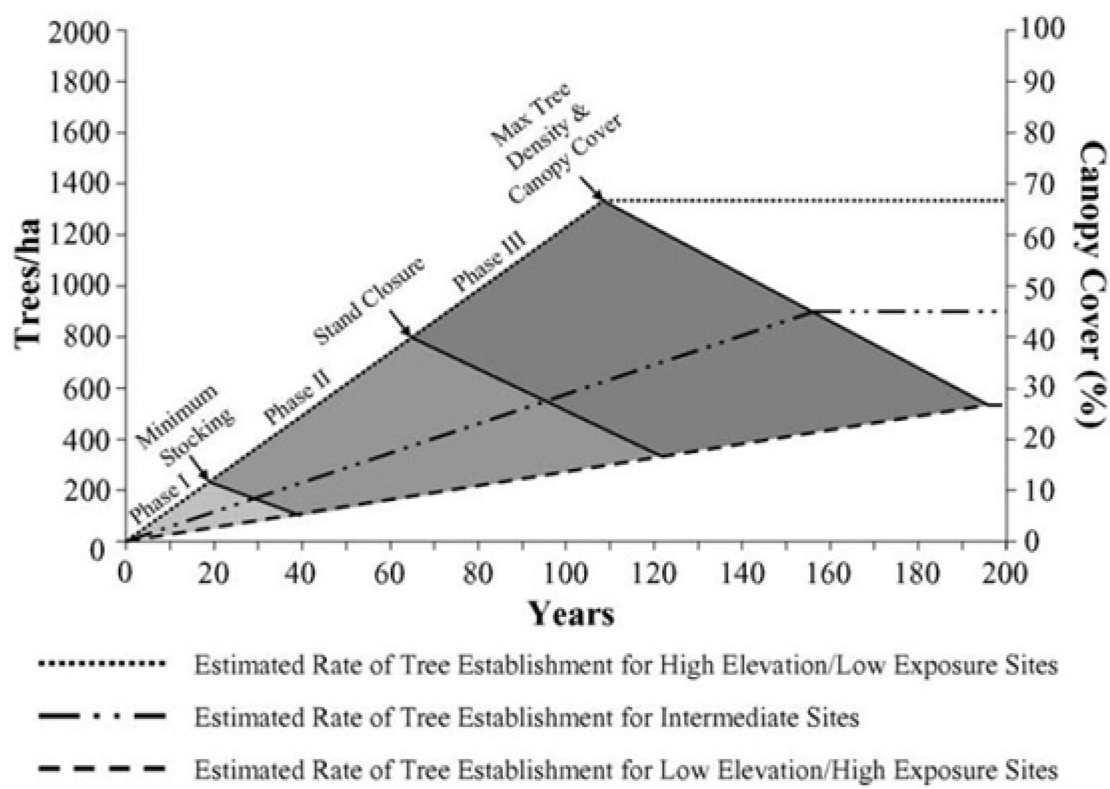

Figure 4—Hypothesized times from initial western juniper establishment (early phase I) to development of late-successional woodland (phase III), and estimated maximum density and canopy cover of western juniper for stands developing on mountain big sagebrush sites with varying elevation and insolation exposure (i.e., a gradient of relatively cool/moist to warm/dry sites) [67, 104].

Extent of juniper communities has been dynamic over long time periods. Juniper woodlands have expanded and contracted throughout the Holocene, due largely to changing climate and fire patterns (e.g., [36, 102, 112, 159]). Juniper may replace sagebrush and other shrubs as the overstory dominant when intervals between fires are long enough for juniper seedlings to establish and mature [106].

Many sources document expansion of western juniper into big sagebrush and bunchgrass steppes, and increasing density (infill) of existing woodlands [96, 98, 99, 102, 107, 116, 127, 143, 154]. These include old photographs [96, 143], old surveys [102], personal observations [107, 116], age-structure analyses [102, 154], tree-ring chronologies [102, 111, 146], and increased juniper pollen counts in lake sediment cores [98, 99, 102]. Western junipers have also expanded into in fire-excluded ponderosa pine communities on the Modoc Plateau [105] and the Deschutes and Fremont national forests [164]. Conversion of mountain big sagebrush steppes to woodland transitional communities is mostly occurring on relatively deep, fine-textured soils [102, 127]. Comparisons of extent of juniper woodlands from the early 1930s to the mid-1950s with that of the late 1990s found large increases in the western juniper cover type in the Upper Klamath, Columbia Plateau, Owyhee upland, Blue Mountain, Snake headwater, and northern Great Basin regions ($P < 0.2$). Proportional area of the western juniper cover type nearly doubled on the Columbia Plateau, from 5.9% to 10.9%. In the northern Great Basin, proportional area of the western juniper cover type increased from 15.3% to 22.2% [56]. In northeastern California, succession from Wyoming big sagebrush steppes to transitional western juniper-Wyoming big sagebrush communities apparently started in the late 1800s [105, 176]. On Juniper Hill in Lassen County, California, the oldest western juniper growing in Wyoming big sagebrush steppe established around 1855, and 84% of junipers established between 1890 and 1920 [176]. In Wyoming big sagebrush communities, conifer expansion is most common on relatively warm, moist sites [67, 104, 106].

The synchronous combination of reduced fire frequency [21, 23, 24, 52, 71, 102, 108, 110, 130] and optimal climate for conifer establishment at the turn of the 20th century [18, 29, 106, 122, 138, 139] are considered primary causes of juniper expansion into shrub and bunchgrass steppes. Contributing and coincident causes included livestock overgrazing, tree harvest, and cessation of aboriginal burning practices. See Contemporary Changes in Stand Structure for further discussion on these topics.

HISTORICAL FUELS

Information on historical fuels in juniper ecosystems was lacking as of 2019. However, information was available on fuels in contemporary old-growth juniper woodlands, which can provide insights into historical fuels. Soil moisture gradients across juniper communities likely resulted in differences in fuel continuity in presettlement juniper woodlands [51, 52, 114, 133]. Increasing moisture availability, leading to more abundant and continuous fine fuels, contributes to more frequent fires [131]. One or more years with above-average precipitation promotes fine fuel production in juniper-sagebrush ecosystems [108].

Discontinuous fuels limit fire spread into old-growth juniper stands on shallow, rocky (fire-resistant) sites [2, 24, 102, 174, 176]. Productive sites with big sagebrush historically had heavier fuel loads and likely burned more frequently and at higher intensities than less productive sites with low sagebrush [51, 52, 68]. Juniper snags and downed logs are long-lived [114], so "very old" (>500 years) western juniper stands usually have standing and downed dead trees that can persist for several hundred years due to slow decomposition [102]. Historically, fine fuels (bunchgrasses) carried the surface fires that burned adjacent steppes [52]. Fires often extinguished when they reached juniper communities on rocky outcrops [127, 171] because surface fuels were sparse [133]. On the Owyhee Plateau, for example, old-growth western junipers are commonly found on relatively fire-safe sites (i.e., rocky surfaces, shallow soils, limited soil moisture) with low productivity and limited fine fuels [24, 61, 102, 107, 108, 163, 176]. On the Hart Mountain National Antelope Refuge, Oregon, Gruell [52] reported that fuels were "light and discontinuous" in western juniper-low sagebrush savannas with shallow soils. However, fires burned onto old-growth, rocky sites occasionally, as evidenced by charred wood fragments and charcoal in soil, fire-charred snags, and fire-scarred live junipers [24, 176]. Bunchgrasses likely carried these surface fires [24]. Western juniper communities with fairly continuous, bunchgrass understories probably burned over a wider range of weather conditions than western juniper communities with shrub understories and fewer bunchgrasses [2].

Density of surface fuels likely varied historically among sites and interannually within sites, so not all sites had discontinuous surface fuels in all years [108]. A pioneer account of the lake region of southern Oregon and northeastern California reported that "the mountains supported a scattered growth of cedars [western junipers] and are commonly clothed with luxuriant bunchgrasses" (Russell 1884, cited in [51]).

Harvesting for fuelwood and other products reduced juniper fuels during the settlement period [85, 154, 176]. In in the late 1800s and early 1900s, junipers were harvested heavily for the charcoal industry, particularly near mines [85]. Junipers were sometimes cut to ground level [85, 154]. Physical evidence (e.g., stumps) of the historical density and extent of juniper woodlands has often been removed from these heavily harvested areas [154].

Understory fuels are sparse in woodland transitional communities in late succession. Surface fuels are limited when canopy cover reaches around 40% or more. Consequently, surface fires generally do not carry, but crown fires can occur with severe fire weather (strong winds, high air temperature, and low relative humidity and fuel moisture) [155].

HISTORICAL FIRE REGIMES

OVERVIEW

Historically, fire helped shape plant community composition, stand structure, and successional patterns in juniper-sagebrush ecosystems [52, 105, 111, 175]; however physical evidence of past fires is scant in many juniper communities. Junipers younger than about 50 years typically do not survive fire [59, 108] and historically, old-growth juniper stands on rocky, refugia sites rarely burned [108]. Although some old-growth junipers in woodlands and savannas have survived surface fires with scarring (e.g., [24, 105, 176]), little evidence of fire may remain after crown fires (e.g., [51, 52]).

Fire frequencies and patterns among juniper woodlands probably varied, depending on soils and vegetation growing around and within the woodlands. Heterogeneity of soil moisture, depth, and texture affects continuity and abundance of fine fuels at fine spatial scales [105, 131], with continuity of fine fuels increasing with increasing soil moisture and depth [131]. Patchy fire likely created a mosaic of burned and unburned areas in historical juniper landscapes [52], with fire frequency and pattern varying across the landscape by soil types and associated fuel loads [51, 52, 114, 133].

Fire history studies of juniper woodlands and savannas in the Columbia and northern Great basins are few; only seven were available as of 2019 (table A3). Sample sizes were small (<50 fire-scarred trees) for four of these studies. Therefore, most information in the sections that follow is inferred from limited data from fire scars and chronosequence studies, and sometimes from fire histories in adjacent sagebrush communities rather than in juniper communities. All fire history studies discussed in this synthesis were conducted in communities with western juniper. No fire history studies were found for communities with Utah or Rocky Mountain juniper in the regions covered in this synthesis. Four of seven studies were conducted in western juniper/big sagebrush woodland transitional communities, not juniper woodlands or savannas. Because they reflect changes from historical fire regimes, details of studies in woodland transitional communities are discussed in Contemporary Changes in Fire Regimes.

Researchers on most (13 of 19) study sites used for the 7 studies used fire scars on ponderosa pines as proxies to infer fire history of western juniper communities (see table A3). While such studies provide insights into fire histories of sagebrush communities, they do not provide direct evidence of fire histories of juniper woodlands and savannas. Ponderosa pine and western juniper cooccur and their communities overlap on the western and northern edges of the Great Basin, but fire histories of the two communities may be quite different due to heterogeneity of soil textures and depths, microtopography, and plant community composition [105, 131]. For example, Miller and Heyerdahl [105] suggest that even though ponderosa pine and western juniper woodlands grow adjacently in Lava Beds National Monument, the ponderosa pine/Idaho fescue association historically contained abundant and continuous fine fuels that carried frequent surface fires. Most likely, fires rarely spread into the adjacent western juniper/western needlegrass association due to sparse fine fuels on the shallow, coarse soils [105]. The distributions of ponderosa pine and junipers do not overlap in interior areas of the Columbia and northern Great basins, so studies using ponderosa pine proxies likely do not represent fire histories of pure western juniper communities (see Limitations of Information).

Historically, fires were more likely to burn into juniper communities from big sagebrush than from low sagebrush communities. Mountain big sagebrush and low sagebrush communities grow in close proximity to juniper communities in many areas of the Columbia and northern Great basins. Mountain big sagebrush communities are generally more productive, with more mesic, deeper soils and greater fuel accumulations [108]. Therefore, fires were probably considerably more frequent in mountain big sagebrush communities than in low sagebrush communities [51, 52, 108].

FIRE IGNITION AND SEASON

Fire Ignition

Lightning and American Indians were the historical ignition sources for juniper and adjacent steppe communities [49, 51, 93, 112, 131, 142, 143]. Schroeder and Buck [140] estimated that lightning ignites 11 to 40 fires per million acres (4-16 fires per million ha)/year in the Great Basin. Lightning started 67% of fires in Lava Beds National Monument in north-central California (time period: 1936-1979), accounting for 1.8 lightning fires/year, or 1 fire for every 26,000 acres (10,500 ha)/year [93].

American Indians apparently burned juniper and adjacent plant communities for many reasons, including to promote plants used for food, tools, and shelter; drive game; improve forage for game; reduce woody plants to facilitate hunting and travel; and signal other tribal members or repel attacks [93, 112, 116, 142, 143]. Information on American Indian-set fires is mostly anecdotal and based on journals from early European-American travelers in the Columbia and Great basins [51, 143]. Shinn [142] concluded that nomadic Paiute of eastern Oregon likely used fire abundantly. Early descriptions of American Indian burning in southeastern Oregon and northern Nevada were recorded in Hudson Bay Company journals from 1826 to 1832, and are summarized by Gruell [51]. While experts conclude that American Indian-set fires were prevalent throughout the Intermountain region, historical extent and frequency of those fires are unknown, and it is unlikely that fire was used universally with equal regularity among tribes and across regions [142, 143].

Fire Season

Fire season in the Columbia and Great basins runs from early summer through fall [74, 114]. Fires historically burned most often in mid- to late summer, after herbaceous species had cured [22]. In the Intermountain region of California, Idaho, Oregon, and Utah, large contemporary fires mostly occur in July and August, with small fires more widely distributed throughout the fire season. Large fires are most common in the peak fire season. Contemporary fire data from sagebrush and bunchgrass steppes and ponderosa pine savannas showed that >82% of large fires (>4,962 acres (2,008 ha)) occurred in July and August (time period: 1980-1995). Less than 1% occurred before June, and <6% occurred after August. Although 71% of small fires (<0.2 acre (0.08 ha)) occurred in July and August, 7% occurred before June, and 15% occurred after August. The timing of median-sized fires (99.3-297.5 acres (40.2-120.4 ha)) depended on location, with median-sized fires igniting earliest in the southern part of the Intermountain region and becoming more common later in summer in the northern part [74].

The fire season in the Great Basin normally begins in June and lasts through September [114, 140], or into October in dry years [140]. At Lava Beds National Monument, severe fire weather and dry lightning storms occur in July, August, and September [93, 105]. About 45% of lightning-ignited fires occur in July, about 25% in May and June, and about 30% in August and September [93]. In western juniper/mountain big sagebrush woodland transitional communities of northeastern California and central, southern, and southeastern Oregon, most fire scars on ponderosa pines were located at or near latewood, indicating late summer or fall fires [108, 113].

FIRE TYPE AND FREQUENCY

Type

Observations in contemporary juniper woodlands and savannas and limited fire history studies suggest that fires of all types historically occurred in juniper communities, including surface fires; patchy, mosaic fires comprised of surface and crown fires [57, 114, 126]; and stand-replacement crown fires [73, 104, 111, 150] that occur during extreme fire weather (high winds, low relative humidity, and low fuel moisture). LANDFIRE [84] models also predict fires of all types for historical juniper communities (table 2).

Table 2—Modeled fire intervals and severities in juniper communities [84].

Fire interval[a] (years)	Fire severity[b] (% of fires)			Number of Biophysical Settings (BpSs) in each fire regime group				
	Replacement	Mixed	Low (surface)	I	II	III	IV	V
97-185	22-32	36-65	5-38			15		

[a]Average historical fire interval derived from LANDFIRE [84] succession modeling (labeled "MFRI" in LANDFIRE).
[b]Percentage of fires in 3 fire severity classes, derived from LANDFIRE succession modeling. Replacement-severity fires cause >75% kill or top-kill of the upper canopy layer; mixed-severity fires cause 26%-75%; low-severity fires cause <26% [11].

Burkhardt and Tisdale [24] noted that on rocky ridgetops of the Owyhee Plateau, southwestern Idaho, contemporary fires in western juniper woodlands are "spotty", mosaic surface fires "of low intensity, usually resulting in minor injury to some of the large junipers and no damage to others". In Lava Beds National Monument, an 1856 fire burned three western juniper/mountain big sagebrush/western needlegrass stands; one stand had a mosaic, surface-and-crown fire and the other two had stand-replacement fires [105, 114].

Frequency

Fires were historically spatially and temporally complex in juniper communities, with a wide range of fire frequencies depending on many factors [105, 134]. Coarse-scale estimates of fire intervals for these plant communities vary from decades to centuries [8, 46, 105], which may not account for the fine-scale variation that determines fire intervals at local scales relevant for resource managers [105]. Variations in soils and moisture availability that affect plant productivity and fuel accumulation typically dictate fire frequency and burn patterns in western juniper communities [21].

Methodology Challenges: Using fire-scarred junipers to determine historical fire frequencies is problematic. To date, cross-dated fire studies in pure juniper communities are few (3 of 7) [105, 108, 113] because junipers often lack fire scars and when they do have scars, sample sizes may be small due to scarcity of appropriate sites and junipers with fire scars that cross-date [8, 114]. Fire scars on junipers can be difficult to distinguish from mechanical injuries [24], and fires enlarging or obliterating previous juniper scars may result in underestimates of fire occurrence, especially the farther back in time fire reconstructions are attempted [24, 176]. On some sites, lack of scars is attributed to surface fires of such low severity that they did not scar the junipers; on others, to stand-replacement fire that left no living junipers [8]. Western juniper forms annual rings "more reliably" than Utah or Rocky Mountain juniper [105]. Fire-scarred junipers were common on western junipers on the Owyhee Plateau, southwestern Idaho [24], but scarce on Utah junipers in northeastern Nevada [53].

For some conifer-dominated communities, intervals for stand-replacement fires are readily determined by cohort age of the dominant conifer, which establishes in early postfire years (e.g., [123]). However, juniper establishment following stand-replacement fire is incremental over decades, with seedlings establishing on burns from nearby seed sources and/or onsite parent trees that fire missed [24, 118].

Because postfire establishment is incremental, intervals between stand-replacement fires are not easily determined using juniper age [8]. However, juniper ages can help estimate time-since-fire on burns.

Overview of Fire History Studies: Historical mean fire intervals (MFIs) of fires in juniper/big sagebrush woodlands are not well known but thought to be mostly >50 years [6, 102, 106, 109, 111]. Some experts suggested that fires occurring every few decades in old-growth western juniper/mountain big sagebrush stands were likely small, low-intensity surface fires that scarred few trees [21, 24].

Estimates for historical fire intervals western juniper-low sagebrush savannas generally range from around 100 years [83, 176] to ≥150 years [102, 105, 114], although a study on Juniper Hill in northeastern California found some western juniper-low sagebrush savannas burned at widely varying frequencies (~10-100 years between fires) [176], suggesting at least occasional low-severity fire.

Estimates for historical fire intervals in mountain big sagebrush steppes succeeding to western juniper/mountain big sagebrush woodland transitional communities generally range from 15 to 25 years (e.g., [93, 113]). Burkhart and Tisdale [24] stated that 30- to 40-year fire intervals are sufficient to keep western juniper from establishing in sagebrush steppes. Historically, short fire intervals in adjacent sagebrush and/or bunchgrass steppes apparently restricted most western junipers to rocky sites with sparser fuels and longer fire intervals [1, 2, 21, 24, 52, 68, 102]. Researchers estimate that historically, fire intervals of ~50 years in productive mountain big sagebrush communities likely excluded most western juniper establishment [108]. Whereas, historical fire-free intervals of >90 years allowed for persistence of widely scattered western junipers in less productive, fuel-limited low sagebrush communities [108, 176].

Results of fire history studies in western juniper woodlands, savannas, and woodland transitional communities are summarized in table A3. Details of studies in woodlands and savannas are discussed below by region.

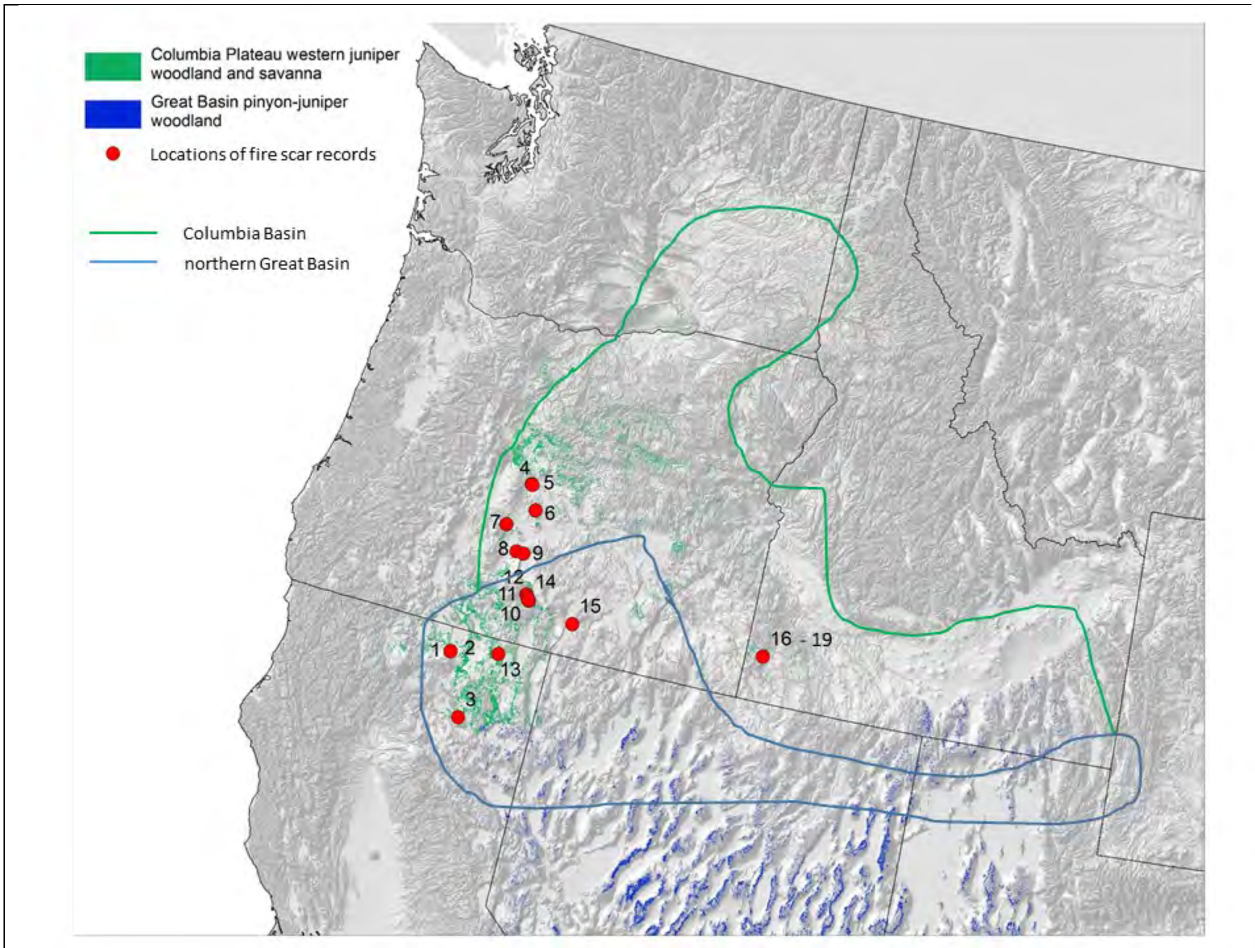

Figure 5—Locations of fire scar records for studies conducted in juniper communities of the Columbia and northern Great basins. See table A3 and discussions that follow for study details. Some site locations are approximate, based on study descriptions. Click on the map for a larger image.

Columbia Basin

Reviews report fire intervals of 7 to >100 years for western juniper series across the Inland Northwest [2, 3, 57] , including western juniper series in the Blue Mountains [3]. These estimates combine western juniper communities with big sagebrush and low sagebrush understories. As of 2019, only one fire history study [24] was conducted in western juniper woodlands of this region, and it combined data from old-growth western juniper woodlands and western juniper/mountain big sagebrush woodland transitional communities. Burkhardt and Tisdale [24] reported fire intervals of 10 to 60 years on four ~640-acre (260-ha) sites on the Owyhee Plateau (time period: 1650-1920), using scars from western junipers that mostly occurred in old-growth woodlands. Periodic fires apparently burned some of the 500,000-acre (200,000 ha) plateau nearly every year. Evidence of fire (i.e., charcoal in soil, charred wood, and logs) was found in every old-growth stand examined. Some western junipers in woodlands bore fire scars, providing evidence of low- to moderate-severity surface fires [24].

Northern Great Basin

As of 2019, four fire history studies covering three areas had been conducted in this region [93, 105, 114, 176]. Studies in Lava Beds National Monument [93, 105, 114] suggest western juniper communities in northeastern California historically experienced both short and long intervals between fires (<10 years to centuries), with short intervals where western juniper occurred with ponderosa pine. Martin and

Johnson [93] estimated an historical range of 7 to 17 years for western juniper-ponderosa pine woodlands at the southern end of the monument (n = 8 sites), although the presettlement time frame these fire interval estimates represented was not provided. Based on evidence from age class distribution, stand structure, and charred wood, Miller et al. [105, 114] speculated that presettlement (before 1870) fires were stand-replacing and occurred at long intervals (~150 years) in western juniper/mountain big sagebrush/western needlegrass stands. Since fire usually kills young (<50 years) western junipers, they surmised that presence of old trees (>140 years) indicated long periods without fire. They found western junipers >250 years old on study plots and western junipers 300 to 500 years old on nearby rock outcrops [105, 114]; intervals long enough for closed-canopy woodlands to develop [105]. Based on tree ages and the scarcity of trees that established before 1750, they concluded that two stand-replacement fires burned in the old growth, one in the early 1700s and one in 1956. The 1956 fire killed large western junipers, suggesting a relatively long fire-free interval prior to the fire and consistent with a fire in the early 1700s. The authors suggested that limited continuity and abundance of fine fuels contributed to long fire-free intervals in the old-growth stands [114].

A study on Juniper Hill found widely varying fire frequencies (~10-100 years) for a western juniper-low sagebrush savanna [176].

FIRE SEVERITY AND INTENSITY

Historical fire severities are not well known for juniper communities. Miller et al. [104] noted that "very few studies in the Great Basin Region have addressed fire severity or collected fire behavior data" (see Limitations of Information). Fire severity was likely variable in presettlement juniper woodlands and savannas. As evidenced by fire scars, communities on shallow, rocky or other unproductive soils probably burned at mostly low severity, when generally sparse fuels were abundant enough to carry surface fire [24]. In woodlands with deeper soils and more continuous surface fuels, fires were probably of low and moderate severity in most years, but closed-canopy woodlands likely experienced crown fires during severe fire weather [104]. For isolated, old-growth stands, Miller et al. [102] stated that "fire events were typically limited to one or several trees", and "stand replacement and mixed-severity fire events were infrequent (more than 150 years)". LANDFIRE [84] models predict fires of all severities in juniper woodlands and savannas (table 1).

Based on evidence from stand structure and age class distribution, Miller et al. [114] reported presettlement (before 1870) western juniper communities at Lava Beds National Monument historically experienced mixed-severity and crown fires. Presence of old trees, tree infill, and charred wood near Valentine Cave suggested a mixed-severity fire occurred at that site. Absence of old growth but abundant large, charred western juniper stumps suggest that an 1856 fire burned at high severity at two nearby sites [114].

No studies to date provided measurements of fire intensity in juniper woodlands or savannas. Historically, fires were probably most intense in woodlands with shrubby understories that provided ladder fuels [131] and more intense in fall than in spring [137]. Fires on fuel-limited, rocky sites were probably spotty and of low intensity [2, 24, 63] except during severe fire weather [63]. Agee [1] noted that total fuel load—and therefore fire intensity—increases the longer juniper communities are fire-free. This is, providing fuel layers shift from surface fuels consisting of fine bunchgrasses with horizontal fuel continuity to ladder fuels of young juniper with coarser leaves, thicker stems, and greater vertical fuel continuity [1].

FIRE PATTERN AND SIZE

Studies of historical fire patterns and sizes in juniper woodlands and savannas were lacking as of 2019. Heterogeneity of plant communities and fuels across the landscape likely resulted in mosaic fires. Many fires likely extinguished when they reached fire-safe, rocky areas dominated by old-growth western juniper, but large fires also occurred in some areas.

Pattern

A model [134] and data from Lava Beds National Monument [114] suggest that juniper woodlands burn in mosaics of surface and crown fire, with unburned patches due to discontinuous surface fuels. Burkhart and Tisdale [24] noted that fires were "spotty" in old-growth western juniper woodlands on the Owyhee Plateau. Roth et al. [134] simulated the interactions of successional stages with occurrence and spread of surface fire in western juniper/mountain big sagebrush woodland transitional communities on the Owyhee Plateau. In their model, landscapes in successional phase III burned in patchy mosaics with "limited surface fire spread" under moderate fire weather (e.g., 27 °C air temperature, 4.5 m/s wind speed, and 10% moisture for 10-hour fuels). At the landscape level, fire occurrence and spread increased as total number of patches increased, and patch density increased with successional advancement toward phase III ($P < 0.1$ for all associations) [134].

Size

No quantitative estimates of historical fire sizes in juniper woodlands or savannas were found in the literature reviewed for this synthesis. Limited evidence suggests that most fires in juniper communities were relatively small, but large or widespread fires occurred in some years [108]. Bunting [21] concluded that in many areas of the Great Basin, fires in juniper woodlands were not extensive in presettlement times. The topography of juniper-dominated areas is often dissected [23, 24, 176] and/or mixed with other plant communities, limiting fire spread [105, 114]. For example, old-growth juniper stands are often confined to relatively fire-safe, rocky outcrops [23, 24, 176], and sparsely-vegetated low sagebrush or stiff sagebrush communities often grow adjacent to western juniper communities in the Great Basin. Those often fuel-limited sagebrush communities do not readily carry fire except under severe fire weather [21], thus limiting fire spread into juniper communities [21, 114, 127, 161]. However, fire can spread where grasses provide continuous surface fuels. Agee [2] noted that although the extent of fires in presettlement western juniper communities is not well known, fire "had the potential to cover wide areas" if surface fuels were relatively continuous. On Juniper Hill, there were 3 decades with fires that scarred more than two widely separated trees in western juniper-low sagebrush savannas (1640-1650, 1750-1760, 1830- 1840). This "probably represents" one large fire/decade [176].

Studies in mountain big sagebrush woodland transitional communities suggest that in south-central Oregon, most fires were large in the presettlement period (before 1870), but small during the settlement period (1871-1899). Miller et al. [108, 113] used ponderosa pine fire scars as proxies to determine fire histories of four western juniper/mountain big sagebrush woodland transition sites (<2.5 acre (1 ha) each) in the upper Chewaucan Basin. Three of 11 presettlement fires occurred on three sites, and 6 fires occurred on at least two sites (time frame: 1780-1869), suggesting large fires [113]. Large fires were defined as those recorded in 3 or more ponderosa pine clusters in the same year within the 12,000-acre (5,000-ha) study area. The authors concluded that one-third of presettlement fires were "extensive" [108]. However, they found evidence of only four small fires during the settlement period [113].

Historically, large fires in western juniper-big sagebrush ecosystems may have occurred the year after 1 or more years of above-average precipitation that promoted fine fuel production. In the Upper Chewaucan River basin, most large fires in sagebrush communities occurred in years with near-average precipitation that had been preceded by at least 1 year of above-average precipitation. For example, two large fires that burned across mountain big sagebrush and low sagebrush communities in 1717 and 1855 were preceded by 1 or more years of above-average growth of ponderosa pine. The authors concluded that wet climatic conditions in the basin led to increased fine fuel accumulation and consequently, large fires [108].

CONTEMPORARY CHANGES IN STAND STRUCTURE AND FUELS

CONTEMPORARY CHANGES IN STAND STRUCTURE

Stand structure of contemporary juniper communities is highly variable. Old-growth or climax (i.e., many trees >150 years old) juniper woodlands are generally very open, with trees sometimes exceeding 1,000 years. Young or seral woodlands (i.e., many trees <100 years old) may be more closed, and trees tend to have pointed rather than rounded growth forms. NatureServe [121] reports that old, open stands and young, denser stands of western juniper were about equally distributed in Columbia Basin in the 2000s. Young juniper stands usually occupy slopes and valley bottoms below old-growth woodlands [23]. Young stands are often uneven-aged and associated with relatively deep soils that once supported big sagebrush steppes and hence, have substantial shrub understories that can become ladder fuels [23, 176]. On the Owyhee Plateau, old-growth western juniper/big sagebrush-antelope bitterbrush woodlands on rocky, shallow soils had <1% shrub cover, while western juniper/big sagebrush-antelope bitterbrush woodland transitional communities had up to 20% shrub cover [23].

Relative densities of juniper communities can vary even on adjacent sites, due in part to differences in soil and other site characteristics, fire history, successional stage, and plant community composition. Densities of western juniper in young stands are often substantial. On the Owyhee Plateau, densities of young, transitional western juniper stands (trees 33-88 years old) were almost twice that of old stands (trees 185-365 years old). Density averaged 172 adult trees/acre (425/ha) in western juniper/mountain big sagebrush/Idaho fescue woodland transitional stands, but only 96 adult trees/acre (237/ha) in old-growth stands [23]. In two adjacent juniper-dominated communities in northeastern California, density of western juniper varied substantially by plant community and understory dominant. In a western juniper/Wyoming big sagebrush woodland transitional community, density averaged 60 trees/acre (150/ha). In contrast, in a less productive western juniper-low sagebrush savanna, density was only 96 trees/acre (237/ha). Western junipers on the low sagebrush sites were older than those on the big sagebrush sites, with some trees >300 years old. Eighty-three percent of the western junipers growing with low sagebrush had established by 1900, with most establishing before 1800. Only 35% of western junipers growing with Wyoming big sagebrush had established by 1900, with 84% establishing between 1890 and 1920 [176].

Juniper Expansion

Stand structure of juniper woodlands and savannas on unproductive soils has likely not changed much from historical times. However, juniper expansion into and successional advancement of steppe communities, particularly big sagebrush steppe, is drastically changing stand structure and community composition on some sites. In presettlement times, junipers generally did not grow in big sagebrush steppes with deep soils; soils that now support expanding, juniper/big sagebrush woodland transitional communities [24, 61, 107, 108, 163, 176]. However, western juniper grew at low densities in some low sagebrush steppes and western juniper-low sagebrush savannas in presettlement times [107]. Miller et al. [102] described western juniper's pace of expansion since the 1870s as that of "unprecedented rates compared to any other time period during the Holocene". Many existing stands have become denser than they were historically (infill) [63, 102, 121], particularly in the Columbia Basin [102, 121]. Juniper expansion and infill have been attributed to a combination of causes [102, 108, 154].

Comparisons between historical and contemporary photographs show substantial infill of juniper woodlands and expansion into steppes over the last century [51, 142, 143]. Repeat photographs comparing images taken at Hart Mountain National Antelope Refuge, Oregon, and Sheldon National

Wildlife Refuge, Nevada, in 1897 and in the 1930s to those taken in 1994 show cover of western juniper has greatly increased [51]. Photos taken in east-central Oregon between 1880 and 1930s and in 1976 also show substantial increases in cover of western juniper [142, 143].

In Lava Beds National Monument, U.S. Army photographs taken in 1872, and stand reconstructions of the area using snags and stumps, document open ponderosa pine woodlands with some western juniper. Vegetation mapped in 1974 over the same areas show many ponderosa pine woodland stands have converted to western juniper/curlleaf mountain-mahogany-antelope bitterbrush woodland transitional stands. Where remnant ponderosa pine stands still exist, they often have dense understories of shrubs and heavy fuel loadings [93].

Among western, Utah, and Rocky Mountain juniper, western juniper in particular has expanded into other community types [50, 94, 102, 106, 121, 141]. Its expansion has been documented throughout much of northeastern California [92, 114, 176]; northern Nevada [128]; central, southern, and eastern Oregon [67, 142]; and southwestern Idaho [23, 67]. Most trees in areas of expansion are <100 years old (e.g., [23, 107, 112, 116, 130, 176]). Often, expansion spreads continuously downslope from old-growth juniper stands on ridges and rimrocks [23]. Most juniper expansion has been into productive mountain big sagebrush communities with relatively deep soils, although western juniper is also expanding into adjacent Wyoming and basin big sagebrush; low sagebrush; scabland sagebrush; and curlleaf mountain-mahogany shrub steppes [102]; bunchgrass steppes [56, 57, 102, 108, 169]; ponderosa pine [57, 102] and Jeffrey pine [104] woodlands and forests; and quaking aspen stands [107, 149].

Rates of juniper infill and expansion vary, depending on site, and generally began in the late 1800s [23, 51, 68, 107] and early 1900s [51, 52, 105]. Peak establishment of western juniper in southern and central Oregon and in northeastern California occurred from about 1890 to 1930 [108, 116]. A study near Prineville, Oregon, found no evidence of western juniper occupation prior to 1880 in what was historically mountain big sagebrush/Sandberg bluegrass steppe. By 1980, western juniper density averaged 412 trees/acre (1,018/ha) on those sites. At that density, the steppe had converted to western juniper forest [35]. As of 1978, 84% of western junipers in a western juniper/Wyoming big sagebrush woodland transitional community on Juniper Hill had established between 1890 and 1920 [176]. In Nevada, peak establishment of Utah juniper occurred from the late 1800s to the 1930s [154]; times and rates of expansion of Utah juniper elsewhere are poorly documented.

Miller and Rose [108] described two distinct patterns of western juniper expansion into big sagebrush communities in south-central Oregon; patterns that have been observed in other locations. The first pattern occurs in former mountain big sagebrush steppes that are now closed woodlands (phase IV), where expansion occurred relatively rapidly between 1885 and 1925. These closed woodlands have had no tree recruitment since 1945 and have large overstory trees, no subcanopies, and suppressed understories [108]. This chronology is similar to those reported for western juniper stands encroaching Wyoming big sagebrush steppes in northeastern California [176] and mountain big sagebrush steppes in southwestern Idaho [23]. The second pattern occurs in open western juniper stands where trees have established gradually but steadily in mountain big sagebrush steppes since the 1870s. These stands have multiple tree age classes, subcanopies, and shrub understories [108]. This pattern is similar to the woodland development reported on Steens Mountain in southeastern Oregon [107]. The authors did not speculate on possible causes for these different patterns.

Juniper tree densities have been increasing in low sagebrush communities since the 1870s in south-central Oregon [108]. However, western juniper infill within and expansion into low sagebrush on shallow, unproductive soils [23, 52], has mostly been slow and limited [23]. In Lassen County, California, western juniper density increased more slowly in western juniper-low sagebrush savanna (mean = 11 trees/acre (28/ha) since 1990) than in western juniper/Wyoming big sagebrush steppe (mean = 61 trees/acre (150/ha) since 1990), resulting in an average of 28 trees/acre in low sagebrush compared to 150 trees/acre in Wyoming big sagebrush as of 1978 [176]. On Juniper Hill, most western junipers in low sagebrush stands established before 1800, although there was a "resurgence in establishment" from 1850 to 1900 [176]. Based on woody debris remnants (snags, stumps, and charcoal) and tree age reconstructions in south-central Oregon, Miller et al. [102, 108] determined that western juniper was historically present in low numbers in a low sagebrush-Sandberg bluegrass savanna on shallow, stony claypan soils but not in a nearby mountain big sagebrush/Idaho fescue steppe on moderately deep to deep soils (time frame: 1601-1870). Since large woody material decays slowly in the semiarid environment, they concluded that the absence of woody debris provides evidence that western juniper did not grow in the presettlement mountain big sagebrush community. However, woody debris was frequently observed in the low sagebrush community. Across 2,500 acres (1,000 ha), only three western junipers were of presettlement age (>130 years) in mountain big sagebrush plots (n = 24 plots, 1,257 m^2) compared to nine western junipers >255 years old and six trees >350 years old in low sagebrush plots (n = 8 plots, 2,827 m^2) [102, 108].

Causes of Expansion

Juniper expansion and infill have been attributed to a combination of coincident factors including fire exclusion [21, 23, 24, 102, 108, 130] and cessation of burning by American Indians [107, 111]; climate variability [23, 102, 152, 174] including warm, relatively wet climate in the late 1800s that fostered juniper growth and seed production [24, 81, 102, 108, 166] and climate-related, contemporary increases in atmospheric carbon dioxide that can accelerate juniper growth [102]; and livestock overgrazing [23, 24, 102, 108, 121, 130]. The relative importance of these factors likely varies among locations [36, 133]. Young and Evans [176] concluded that "there is no simple, single factor that causes wholesale shifts in dominance of rangeland plant communities". Miller et al. [102] concluded that the "combination of reduced fire occurrences and optimal climatic conditions for conifer establishment at the turn of the century were probably the two dominant factors that initiated post-settlement western juniper expansion".

- Fire exclusion
- Climate variability
- Overgrazing

Fire exclusion

Fire intervals of <45 to 50 years likely historically limited western juniper expansion into steppe vegetation [24, 108]. The probability that western juniper establishes and matures in steppes greatly increases as fire intervals exceed 70 years [102]. Juniper expansion and infill increased substantially in many areas after fire exclusion was implemented [50, 51, 71, 110]. Because the timing of juniper expansion into surrounding sagebrush steppe communities coincides with European-American settlement and subsequent fire exclusion, researchers suggest fire exclusion was a primary factor causing substantial increases in juniper in the early 1900s [24, 102, 176]. Burkhardt and Tisdale [24] concluded that fire exclusion contributed directly and prominently to western juniper expansion into mountain big sagebrush steppes on the Owyhee Plateau. Without fire, juniper was no longer restricted to fuel-limited sites. They noted a considerable decline in fires since 1910, coinciding with substantial western juniper expansion [24]. At Lava Beds National Monument, Miller and Heyderdahl [114] concluded that "in the absence of fire, most plant associations [of mountain big sagebrush and curlleaf mountain-mahogany] will eventually be dominated by western juniper and hence will be outside their range of historical variation in vegetation composition and structure". Based on rate postfire succession, they concluded that that western juniper likely did not occur in mountain big sagebrush associations before the early 1900s [114].

Miller et al. [102] provide three lines of evidence that expansion of juniper woodlands was limited by frequent fires in shrub and grassland steppes before European-American settlement:

(1) sites supporting old-growth junipers are usually fuel-limited (i.e., fires in persistent, old-growth stands were likely to be rare),
(2) most young western juniper stands occupy productive sites where fine fuel loads can carry fire, and
(3) the time sequence of woodland expansion is synchronous with the decline in fire frequency.

However, fire exclusion alone does not account for juniper expansion. Miller and Rose [108] found that juniper woodland expansion in southeastern Oregon preceded the implementation of fire exclusion by at least 25 years and effective fire suppression by 60 years. Due to limited access and low timber value [108], widespread fire suppression was limited in sagebrush steppes and juniper woodlands until the late 1940s [108, 112, 113, 116, 130].

The settlement period also coincided with decline of burning by American Indians [102, 107]. By the late 1700s, American Indian populations throughout the Intermountain West had been reduced by about 80% [36, 116]. By the mid- to late 1800s, American Indians had been relocated to reservations, and their influence on the landscape was severely diminished [51, 53, 59, 107]. Some have suggested that the decrease in American Indian ignitions was largely responsible for reduced fire frequencies in sagebrush steppes, contributing to subsequent juniper expansion and infill in some areas [53, 59].

In part, juniper expansion may be due to recovery from aboriginal harvesting that occurred before European settlement. In arid regions where other sources of wood are scarce, American Indians might have reduced juniper populations by harvesting for fuelwood, especially at low elevations. Under this scenario, contemporary juniper populations are recovering from earlier American Indian use [127, 136].

Climate variability

Juniper zones tend to expand when climate is warm and moist. Juniper-sagebrush ecosystems experienced two periods of warmer-than-average temperatures in the 20th and 21st centuries. In southeastern Idaho, Miller and Rose [107] reported steady increases in density of western juniper stands from the 1880s to the late 1950s and "geometric" increases in stand densities from 1960 to the early 1990s. Winters were warmer and precipitation higher from 1850 to 1916 than long-term means [5, 82, 102, 165], and this likely promoted establishment and growth of junipers [102, 108, 147]. Limited information suggests juniper woodland expansion began in the Great Basin between 1850 and 1870, prior to European-American settlement in many areas (Mehringer 2005, personal communication cited in [102]), suggesting that a warm, wet climate initiated juniper expansion before fire suppression and livestock grazing began. Juniper expansion in the late 20th century occurred during a period that was also warmer, but mostly drier, than average [107].

Elevated levels of atmospheric carbon dioxide during the last half of the 20th century may be contributing to faster rates of juniper growth and consequently, faster rates of regeneration, expansion, and infill in some areas [75, 76, 102, 146, 147]. Annual sapwood growth in western juniper (i.e., bole growth) has been substantially greater since the 1950s compared to prior years, when atmospheric carbon dioxide concentrations were lower. Elevated carbon dioxide levels may have a drought-ameliorating effect by increasing water-use efficiency of junipers [77, 78].

Long-term changes in juniper abundance and distribution are attributed to interactive effects of climate change and fire frequency [102]; however, paleoecological studies of juniper communities in the Columbia and Great basins are sparse. Limited studies show an upward shift of juniper zones during periods of dry climate, and downward shifts during periods of wet climate [99, 100, 112, 168]. Severe drought and widespread fires during the late Holocene (2,500-1,500 BP) coincided with declines of western juniper in the Great Basin [102]. In eastern Oregon, pollen and woodrat midden records show an upward elevational shift in the western juniper treeline sometime between 1,900 and 1,000 BP [112], when there were several centennial-scale droughts. Pollen records from northern and central Nevada show similar shifts in Utah juniper treelines during that period [100]. A pollen study in southern Nevada found the lowest elevational limits of junipers were approximately 2,300 feet (700 m) around 13,000 BP, when the climate was relatively warm and wet. The present lowest range of Utah Juniper is around 5,600 feet (1,700 m) [97]. Woodrat midden and pollen studies in southeastern Utah document successional replacement of blue spruce-Rocky Mountain Douglas-fir-limber pine forests with Utah juniper woodlands in the mid-Holocene (~7,200-3,400 BP), when climate was warmer and drier than previously [12].

Data from an unpublished (as of 2019) paleoecological study near Bend, Oregon, suggest that climate changes other than warming and increased moisture may lead to juniper expansion. On Horse Ridge, western juniper showed an abrupt increase in establishment around 1550 CE. Based on tree-ring reconstructions, this period of establishment was not associated with either climate warming or increases in winter precipitation in the area, although Heyerdahl [58] suggested this establishment may be linked to deep snowpack that protected western juniper seedlings from frost. The researchers found "no evidence of fire" around 1550 CE [58].

Overgrazing

Junipers commonly establish and spread in overgrazed steppe vegetation [92]. Their expansion is associated with heavy livestock grazing and a corresponding decrease in bunchgrasses [121, 171] in the late 1800s [107, 112, 116]. In the Columbia Basin, western juniper expansion into steppes often occurs on alluvial soils with a history of livestock grazing and/or fire exclusion [121].

Declines in fire occurrence in the Columbia (e.g., fig. 6) and northern Great basins in the late 1800s were coincident with livestock introductions [49, 50, 102, 108, 110, 113, 124]. Some researchers considered the removal of fine fuels by grazing during the wet and mild climate period of the late 1800s and early 1900s instrumental in initiating juniper expansion [112, 116]. Without the removal of fine fuels, the concurrent wet climatic period would likely have perpetuated large fires due to increased fuel accumulations [108]. Livestock were introduced in south-central Oregon by the late 1860s, with stocking levels peaking at the end of the century [102, 110, 113, 124]. There were ~4,000 cattle in the lower Chewaucan River Basin of south-central Oregon in 1873, with several thousand domestic sheep added in 1874 [108]. Grazing began in 1869 on the Owyhee Plateau of southwestern Idaho, and the area was heavily stocked within 20 years [23, 24]. Livestock were introduced in the Great Basin in the 1860s at extremely high stocking densities [50, 51]. Often, steppes and woodlands were grazed season-long by large herds [1, 3].

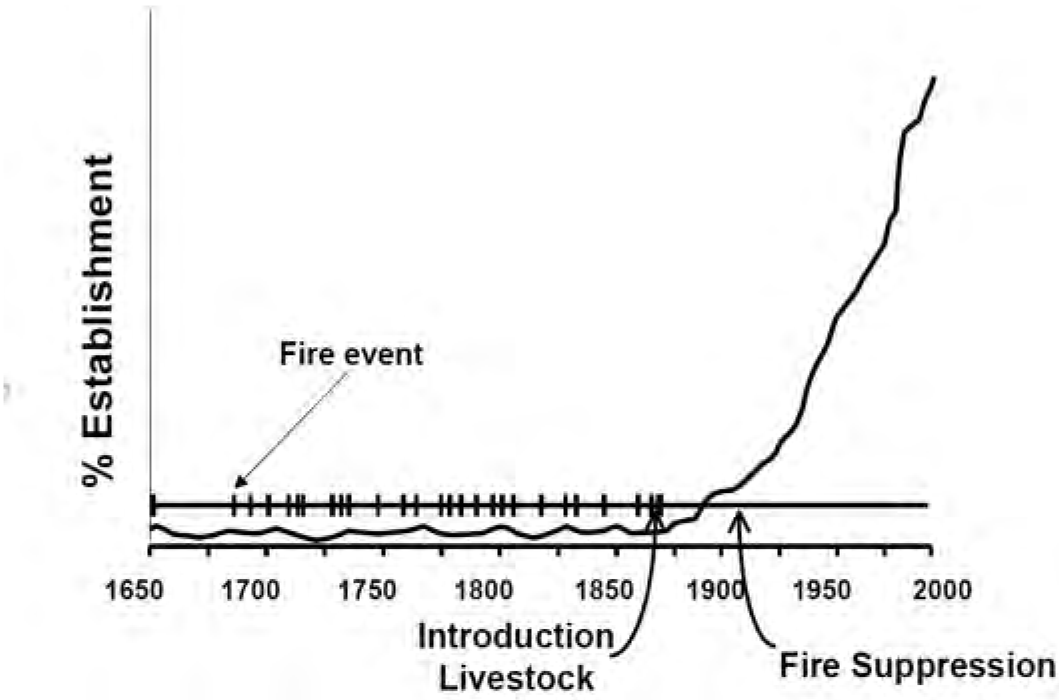

Figure 6—Time frame of western juniper establishment in the Chewaucan River basin [113].

Mature western junipers increased seed production during this period and sagebrush—a juniper nurse plant—increased in cover on overgrazed sites; consequently, expansion and infill occurred [16, 24, 102, 108, 154]. Increased soil disturbance and subsequent erosion due to overgrazing likely also contributed to establishment and spread of western juniper [33, 130].

While livestock grazing indirectly contributed to juniper expansion, livestock probably did not contribute to it directly. Juniper foliage and cones are unpalatable to livestock, so they are poor seed dispersers [24]. Experts contend that livestock browsing can be dismissed as a cause for increasing rates of juniper seed dispersal because native wildlife have been eating juniper cones and dispersing the seeds for millennia [24, 130].

Western juniper continues to expand its density and range within the two basins [76, 102, 107, 108, 166], even where livestock are excluded [147]. On the Crooked River National Grassland, central Oregon, western juniper expanded into basin big sagebrush/Sandberg bluegrass stands on both grazed and ungrazed plots. However, density of western juniper was lower on ungrazed plots (73 trees/acre (180/ha)) than on plots with a 100-year history of domestic sheep and cattle grazing (138 trees/acre (340/ha)). Trees on ungrazed plots ranged from 61 to >233 years old, and seedlings and saplings were lacking. Trees on grazed plots were all <60 years old, and most had established within the previous 35 years (1946-1981) [130].

CONTEMPORARY CHANGES IN FUELS

The amount of understory shrub and herbaceous surface fuel determines whether surface fire carries in seral juniper woodlands [130]. Livestock grazing has reduced fine fuels on some sites [24, 121]. Fewer surface fuels make it difficult for some seral juniper woodlands to burn [154, 155]. The shrub layer may carry fire in woodland transitional communities, especially in early succession when junipers are widely spaced [133]. In woodland transitional communities, fuel loads are shifting from shrubby and herbaceous surface fuels to canopy fuels. Sagebrush is an important ladder fuel in midsuccession (early phase III) [131]. By late succession (late phase III and phase IV), fuel loads have shifted from surface fuels to juniper canopies [23, 130]. Young and Evans [176] stated that because "western juniper communities have purged their understories of almost all herbaceous and shrub vegetation, the western juniper communities growing on big sagebrush sites are virtually fireproof, except under the most severe burning conditions". Miller et al. [102] suggest that as succession advances, herbaceous cover and biomass decrease most rapidly on xeric sites and sites with shallow soils.

Density of western [51, 102] and Utah juniper [51] has increased greatly since presettlement times (see Contemporary Changes in Stand Structure). As junipers begin to dominate a site, cover and biomass of shrub and herbaceous fuels generally decrease [88, 102, 108, 134], and the potential for passive and active crown fires increases [133]. Late-successional woodlands (phases III-IV, ≥35% canopy cover) are particularly susceptible to crown fire during severe fire weather [154, 155]. Fire type and frequency have probably not changed as much in juniper woodlands and isolated, old-growth stands on shallow, rocky sites; however, when nonnative annuals invade these communities, they are subject to more frequent surface fires than what occurred historically [51, 52].

LANDFIRE [83] models and photo series [148, 157] can help assess fuels in juniper communities.

Nonnative Invasive Annuals

Nonnative annuals are replacing native herbaceous species on many sites in the Columbia and northern Great basins. Annual grasses threaten juniper-sagebrush ecosystems because they alter fuel characteristics in invaded communities and have the potential to lengthen the fire season and increase the frequency, size, spread rate, and duration of wildfires [4, 9, 30, 74, 87, 106, 126]. Consequently, most sagebrush species cannot regenerate, a grass/fire cycle establishes, and the shrub and bunchgrass layers convert to annuals [9, 19, 31, 79, 152]. Cheatgrass [9, 74, 104, 126, 132, 135, 144] and medusahead [44, 74, 135, 151, 176] are of greatest concern in juniper-sagebrush ecosystems. Nonnative annual mustards may also provide fine fuels [160], and their litter may facilitate cheatgrass establishment [37, 38]. Tall tumblemustard in particular often occurs with cheatgrass; it is one of the most widespread invasive forbs in the Great Basin [129, 177]. Cheatgrass fires tend to burn fast and cover large areas, with a fire season from 1 to 3 months longer than that of plant communities with bunchgrass surface fuels [126, 132].

In general, warm, dry sites are more vulnerable to cheatgrass establishment and spread than cooler, moister sites [26, 28, 103, 106, 152, 173], and south-facing slopes and shallow soils are more vulnerable than north-facing slopes and deep, loamy soils [88, 152]. For example, on the Toiyabe Range of central Nevada, singleleaf pinyon-Utah juniper stands on warm, xeric slopes had higher cover of cheatgrass than stands on cooler slopes [28]. On the east slope of the Sierra Nevada, sites dominated by Jeffrey pine and western juniper stands are apparently more resistant to invasion by cheatgrass than warmer, lower-elevation sites [104].

CONTEMPORARY CHANGES IN FIRE REGIMES

Presettlement fires in big sagebrush and low sagebrush communities were frequent enough to keep western juniper establishment at low levels (e.g., [24, 51, 52, 68]). Compared to presettlement times, fires became less frequent on many juniper-big sagebrush sites in the Columbia and Great basins in the 20th and 21st centuries due to a combination of fire exclusion and other factors, facilitating juniper expansion. Most decreases in fire frequency are in woodland transitional communities [24, 51, 52, 108, 113, 115, 176].

For example, fire occurrence apparently decreased substantially after 1900 on western juniper/mountain big sagebrush sites (<2.5 acre (1 ha)) in northeastern California and central and southeastern Oregon. No fires were recorded at 6 of 10 sites since the late 1800s, and only 1 to 3 fires since 1900 on 4 other sites. In contrast, 108 fires were recorded prior to 1870. Sample sizes were small in this study [113] (2-5 ponderosa pines sampled per site, see table A3), so some fires may have been undetected. In the Chewaucan River basin, presettlement (before 1871) MFI averaged 7.7 years for the 12,000-acre (5,000-ha) study area. In mountain big sagebrush steppe, fire scars on clustered ponderosa pines showed presettlement MFIs ranging from 12 to 15 years. From 1650 to 1870, seven fires were assumed to be large or "extensive" fires from 1650 to 1870 because they each scarred three to four ponderosa pine clusters, presumably during the same fire. This suggests a 1537 years for large fires [68]. No fires had occurred in the study area since 1897 [108].

Gruell [51, 52] concluded that fires were historically frequent enough to prevent western juniper establishment and spread into mountain big sagebrush steppes on the Hart Mountain National Antelope Refuge. Evidence of historical presence of conifers—including snags, stumps, and charred wood—was almost completely lacking within extant mountain big sagebrush stands, and all western junipers in the mountain big sagebrush community established after 1900 [51]. Gruell surmised that such residual woody material would be present if conifers had been historically important in the mountain big sagebrush stands. He noted that fire intensity has shifted from low to high in infilled juniper communities in the region, and that areas of juniper expansion are more susceptible to widespread fires than they were historically. He concluded that decades of successful fire exclusion and overgrazing—which resulted in large increases in woody fuels—and subsequent increases in fine fuels after reductions in livestock grazing and invasion of nonnative annuals, have increased the potential for large wildfires in the region [51, 52].

Under contemporary climate conditions, both junipers and nonnative annuals have the potential to expand into and dominate even larger areas of juniper-sagebrush ecosystems than they do currently [152, 174], and future climate changes may exacerbate this trend on some sites [29, 45, 106, 122, 138, 141]. Climate change models for the juniper-sagebrush biome predict increasing temperatures, increasing atmospheric carbon dioxide, more frequent episodes of severe weather (droughts and storms), decreasing snowpack, and variable changes in precipitation [25, 106]. Projected effects of climate changes on juniper-sagebrush ecosystems are varied. Many projections predict widespread vegetation shifts by the end of the century, with some locations becoming less suitable for juniper and others becoming more so [18, 29, 106, 122, 138, 139]. Under some climate change projections (warmer temperatures and more precipitation), the juniper zone is expected to expand and the sagebrush zone retract as junipers continue to move downslope into sagebrush communities (e.g., [29, 45, 122, 138, 141]).

Restoration

Junipers are important components of juniper-sagebrush ecosystems. These native trees provide structural diversity and important wildlife habitat. Restoration of juniper-sagebrush ecosystems has focused on reducing extent of juniper zones and returning junipers to densities that allow recovery of understory shrubs and bunchgrasses [101, 102, 113]. Expansion of juniper into shrub and bunchgrass steppes has detrimental effects to ecosystem function. It can redistribute soil organic matter, deplete nutrients, reduce stream flows and forage production, and alter wildlife habitat. Accelerated erosion and loss of nutrients occur when shrub and bunchgrass layers decline with advancing succession towards juniper dominance. Increases in juniper density can deplete soil water, decreasing the length of the growing season by as much as 4 to 6 weeks [102].

Restoration in juniper-encroached communities has focused primarily on reducing juniper density and extent with mechanical (e.g., chaining, bulldozing), prescribed fire, and/or herbicide treatments [112]. These treatments are controversial and may have complex hydrological and ecological effects [112]. Miller et al. [102] caution that effects of western juniper encroachment have not been studied at watershed levels; only anecdotal evidence exists for streams, springs, and meadows drying up with increases in western juniper. Populations of nonnative herbaceous species, particularly cheatgrass and medusahead, may increase after mechanical treatments and/or fire. Posttreatment responses of nonnative invasive species is site-specific and depends on what species were present before treatment. Intense or frequent disturbances may result in a type conversion to annual grassland [102]. See the Species Review on western juniper and the following field guides for further information on restoration of juniper-sagebrush ecosystems:

- Piñon and juniper field guide: Asking the right questions to select appropriate management actions (2009) [153]
- Western juniper field guide: Asking the right questions to select appropriate management actions (2007) [101]

LIMITATIONS OF INFORMATION

Figure 7—Utah juniper burning in a small, patchy 2013 wildfire in a Utah juniper/Wyoming big sagebrush/Sandberg bluegrass association near Malta, Idaho. Image by L. K. Derrick, used with permission of Project Noah.

Most fire history studies in juniper communities of the Columbia and northern Great basins have been conducted in western juniper communities. Fire history studies of Utah juniper and Rocky Mountain juniper communities were lacking for these regions.

For fire history studies of western juniper, most (13 of 19 study sites) were conducted near ponderosa pine ecotones or in big sagebrush-western juniper-ponderosa pine woodland transitional communities [51, 93, 108, 113, 115] (see fig. 5 and table A3), and they used fire scars on ponderosa pine as proxies for estimating historical fire frequencies in western juniper woodlands [51, 52, 93, 108, 113, 115]. Such studies provide insights into historical fire regimes of western juniper and big sagebrush communities near ponderosa pine. However, ponderosa pine does not grow in interior portions of the Columbia and northern Great basins, where most of the juniper-sagebrush biome occurs in those regions. Therefore, fire history studies conducted near ponderosa pine ecotones likely do not reflect fire histories of juniper communities in interior locations. Fire studies conducted in western juniper-low sagebrush savannas were few (2 of 19 study sites, 1 of which combined results from a mountain big sagebrush site), even though these savannas occupy the largest land cover of the western juniper types in the Columbia Basin [102].

There are other limitations of using fire scars recorded in ponderosa pine to interpret historical fire frequencies in juniper communities. It is uncertain how often fires in ponderosa pine communities spread across ecotones into juniper and sagebrush communities [7, 159, 167]. Studies using ponderosa pine scars as proxies may imply that fire was historically more frequent in juniper communities than it actually was [167]. Even when ponderosa pine is present in western juniper communities, it is often unevenly and sparsely distributed, making sample sizes small [51, 52, 105, 108, 113, 114, 115]. At Lava Beds National Monument, Miller et al. [105, 114] found fire intervals were longer (>150 years) in pure western juniper stands than fire intervals in stands where western juniper occurred with ponderosa pine. Their findings support LANDFIRE models, which predict long fire intervals (mean = 97 years) for western juniper woodlands [83].

Determining fire severity is difficult in juniper-sagebrush ecosystems [104]. Assessing fire severity in woodland transitional communities is particularly problematic when severity is measured as percent mortality of the canopy (e.g., [11]). In these communities, the canopy is transitioning from sagebrush to junipers. Since junipers are more fire-resistant than sagebrush, fire severity may be classified differently depending on whether fire effects to the juniper canopy or sagebrush canopy are assessed. Keeley [72] suggested fire severity is better measured as the consumption of organic matter and color of the ash than as effects to the canopy. Miller et al. [104] stated that “Keeley’s definition is a more useful measure of fire severity on rangelands” than defining fire severity by percent mortality of the canopy.

APPENDICES

Table A1—Common and scientific names of plant species mentioned in this synthesis. Links go to FEIS Species Reviews.

Common name	Scientific name
Trees	
blue spruce	*Picea pungens*
chokecherry	*Prunus virginiana*
Jeffrey pine	*Pinus jeffreyi*
junipers	*Juniperus* spp.
limber pine	*Pinus flexilis*
lodgepole pine	*Pinus contorta*
Rocky Mountain lodgepole pine	*Pinus contorta* var. *latifolia*
Sierra lodgepole pine	*Pinus contorta* var. *murrayana*
oneseed juniper	*Juniperus monosperma*
pinyons	*Pinus* spp. (*Strobus*, subsection *Cembroides*)
ponderosa pine	*Pinus ponderosa*
Pacific ponderosa pine	*Pinus ponderosa* var. *benthamiana*
Columbia ponderosa pine	*Pinus ponderosa* var. *ponderosa*

quaking aspen	*Populus tremuloides*
Rocky Mountain Douglas-fir	*Pseudotsuga menziesii* var. *glauca*
Rocky Mountain juniper	*Juniperus scopulorum*
Sierra juniper	*Juniperus grandis*
singleleaf pinyon	*Pinus monophylla*
Utah juniper	*Juniperus osteosperma*
western juniper	*Juniperus occidentalis*
Shrubs	
antelope bitterbrush	*Purshia tridentata*
big sagebrush mountain big sagebrush Wyoming big sagebrush	*Artemisia tridentata* *Artemisia tridentata* subsp. *vaseyana* *Artemisia tridentata* subsp. *wyomingensis*
black sagebrush	*Artemisia nova*
curlleaf mountain-mahogany	*Cercocarpus ledifolius*
littleleaf mountain-mahogany	*Cercocarpus intricatus*
low sagebrush	*Artemisia arbuscula*
mountain snowberry	*Symphoricarpos oreophilus*
rabbitbrushes	*Chrysothamnus* and *Ericameria* spp.
redosier dogwood	*Cornus sericea*
sagebrush	*Artemisia* spp.
sandbar willow	*Salix exigua*
scabland sagebrush	*Artemisia rigida*
wax currant	*Ribes cereum*
yellow rabbitbrush	*Chrysothamnus viscidiflorus*
Graminoids	
basin wildrye	*Leymus cinereus*
bluebunch wheatgrass	*Pseudoroegneria spicata*
cheatgrass*	*Bromus tectorum*
crested wheatgrass*	*Agropyron cristatum*
Idaho fescue	*Festuca idahoensis*
Indian ricegrass	*Achnatherum hymenoides*
prairie Junegrass	*Koeleria macrantha*
medusahead*	*Taeniatherum caput-medusae*
needle and thread	*Hesperostipa comata*
Sandberg bluegrass	*Poa secunda*
squirreltail	*Elymus elymoides*
threadleaf sedge	*Carex filifolia*
Forbs	
mustards	Brassicaceae
tall tumblemustard*	*Sisymbrium altissimum*
*Nonnative herb.	

Table A2. BpSs covered by this Fire Regime Synthesis

Data are derived from LANDFIRE succession modeling. Fire regime groups I-V describe a pattern of fire frequency and severity for historical fire regimes. Fire interval refers to average historical fire interval in years. Percent of fires is listed by severity class: Replacement-severity fires cause >75% kill or top-kill of the upper canopy layer; mixed-severity fires cause 26%-75%; and low-severity fires cause <26%. Terms are defined in the FEIS Glossary (http://www.fs.fed.us/database/feis/glossary2.html).

Region	Biophysical Setting name	BpS code	BpS URL	Fire regime group	Fire interval (yr)	% of fires replacement severity	% of fires mixed severity	% of fires low severity
California	Columbia Plateau western juniper woodland and savanna	0610170	http://www.fs.fed.us/database/feis/pdfs/BpS/0610170.pdf	III	97	26	36	38
California	Great Basin pinyon-juniper woodland	0610190	http://www.fs.fed.us/database/feis/pdfs/BpS/0610190.pdf	III	166	32	45	23
Pacific Northwest	Columbia Plateau western juniper woodland and savanna	0710170	http://www.fs.fed.us/database/feis/pdfs/BpS/0710170.pdf	III	97	26	36	38
Pacific Northwest	Great Basin pinyon-juniper woodland	0710190	http://www.fs.fed.us/database/feis/pdfs/BpS/0710190.pdf	III	166	32	45	23
Great Basin	Columbia Plateau western juniper woodland and savanna	0910170	http://www.fs.fed.us/database/feis/pdfs/BpS/0910170.pdf	III	97	26	36	38
Great Basin	Great Basin pinyon-juniper woodland	0910190	http://www.fs.fed.us/database/feis/pdfs/BpS/0910190.pdf	III	166	32	45	23
Great Basin	Inter-Mountain Basins juniper savanna	0911150	https://www.fs.fed.us/database/feis/pdfs/BpS/0911150.pdf	III	185	22	44	33
Great Basin	Columbia Plateau western juniper woodland and savanna	1210170	http://www.fs.fed.us/database/feis/pdfs/BpS/1210170.pdf	III	97	26	36	38

Great Basin	Great Basin pinyon-juniper woodland	1210190	http://www.fs.fed.us/database/feis/pdfs/BpS/1210190.pdf	III	166	32	45	23
Great Basin	Colorado Plateau pinyon-juniper woodland	1710160	http://www.fs.fed.us/database/feis/pdfs/BpS/1710160.pdf	III	128	29	65	5
Great Basin	Columbia Plateau western juniper woodland and savanna	1710170	http://www.fs.fed.us/database/feis/pdfs/BpS/1710170.pdf	III	97	26	36	38
Great Basin	Great Basin pinyon-juniper woodland	1710190	http://www.fs.fed.us/database/feis/pdfs/BpS/1710190.pdf	III	166	32	45	23
Great Basin	Columbia Plateau western juniper woodland and savanna	1810170	http://www.fs.fed.us/database/feis/pdfs/BpS/1810170.pdf	III	97	26	36	38
Great Basin	Great Basin pinyon-juniper woodland	1810190	http://www.fs.fed.us/database/feis/pdfs/BpS/1810190.pdf	III	166	32	45	23
Great Basin	Inter-Mountain Basins juniper savanna	1811150	http://www.fs.fed.us/database/feis/pdfs/BpS/1811150.pdf	III	185	22	44	33

Table A3. Summary of fire history studies of western juniper communities in the Columbia and northern Great basins.

Fire frequency intervals and information from fire history studies in western juniper communities of the Columbia and northern Great basins. Some study site locations are approximate in figure 5. See table A2 for further information about associated BpSs and figure 5 for a map of study site locations.

Location (map number from fig. 5)	Basin	Plant community[a] (BpS series)	Elevation, aspect	Study details	Fire scar species	Historical period studied	MFI[b] (years)	Interval range (years)	MFI from LANDFIRE (2008) models (years)	Contemporary findings	Citation(s)
Studies in juniper woodlands or savannas:											
Lava Beds National Monument, Siskiyou/Modoc counties, California (1)	Great Basin	ponderosa pine-western juniper/mt. big sagebrush/ cheatgrass woodland (710190)	3,940-5,000 ft. (1,200-1,525 m)	fire scars from 66 snags (presumably ponderosa)	ponderosa pine	before 1973	7.3-17.0; point fire interval	not determined	97	ponderosa woodland converting to denser juniper-shrubland	[93]
Lava Beds National Monument, Siskiyou/Modoc counties, California (2)	Great Basin	western juniper/mt. big sagebrush/western needlegrass woodland (710190)	4,400-5,200 ft. (1,340-1,585 m)	19 charred snags were aged	western juniper; cross-dated	before 1870	≥150	not determined	97	mt. big sagebrush sites converting to woodland transitional communities dominated by junipers	[105, 114]
Juniper Hill, Lassen County, California (app. location WNW of Eagle Lake) (3)	Great Basin	western juniper-low sagebrush/ cheatgrass savanna (710190)	4,430-4,690 ft. (1,350-1,430 m)	fire scars sampled from 28 juniper over 620 acres (250 ha) of woodland; fire-scar intervals reported by decade	western juniper	1640-1860	not calculated	10-100	97	expansion is slow; only 17% of western junipers established after 1900	[176]
Fremont National Forest, upper Chewaucan River basin, 8 km south of Paisley, south-central Oregon (14)	Great Basin	low sagebrush/Sandberg bluegrass (710170)	4,760-6,150 ft., mostly W/NW (1,450-1,875 m)	fire scars from 12 cross-sections of burned juniper stumps and logs	western juniper, cross-dated	2 fires: 1717 (*n*=3), 1855 (*n*=7)	>100 (estimate)	not determined	97	no fires since 1897	[108, 115]

Studies in woodland transitional communities:											
sites across northeastern California and central and southeastern Oregon (4-13)	Columbia Basin	mt. big sagebrush/Idaho fescue (710170, 710190, 910170)	5,180 ft. (1,580 m)	Pine Mt. site 1: 10 fires from scars on 4 ponderosas	ponderosa pine, cross-dated	1740-1870	13	7-23	97	1 fire 1900-2001	[113]
	Columbia Basin		5,300 ft. (1,615 m)	Pine Mt. site 2: 17 fires from scars on 5 ponderosas		1626-1870	15	4-32		2 fires 1900-2001	
	Columbia Basin		5,380 ft. (1,640 m)	Moohoo'oo Mt. site: 10 fires from scars on 4 ponderosas		1820-1870	12	7-25		3 fires 1900-2001	
	Columbia Basin		4,630 ft. (1,410 m)	Cinder Butte site: 7 fires from scars on 2 ponderosas		1750-1870	17	not deter-mined		no fires 1900-2001	
	Columbia Basin		5,330 ft. (1,625 m)	Dead Indian site: 7 fires from scars on 4 ponderosas		1830-1870	6.2	3-10		2 fires 1900-2001	
	Columbia Basin		5,450 ft. (1,660 m)	Picture Rock Pass site: 8 fires from scars on 2 ponderosas		1751-1870	16.0	5-32		no fires 1900-2001	
	Great Basin		3,400 ft. (1,645 m)	Chewaucan Lower site: 6 fires from scars on 3 ponderosas		1780-1870	17	12-26		no fires 1900-2001	
	Great Basin		5,580 ft. (1,700 m)	Chewaucan Middle site: 19 fires from scars on 3 ponderosas		1650-1870	12	3-28		no fires 1900-2001	
	Great Basin		6,200 ft. (1,890 m)	Chewaucan Upper site: 20 fires from scars on 4 ponderosas		1600-1870	14	3-25		no fires 1900-2001	

	Great Basin		5,000 ft. (1,525 m)	Devil's Garden site: 4 fires from scars on 3 ponderosas		1800-1870	17	11-25		no fires 1900-2001	
Fremont National Forest, upper Chewaucan River basin, 8 km south of Paisley, south-central Oregon (14)	Great Basin	mt. big sagebrush/Idaho fescue (710170)	4,760-6,150 ft., mostly W/NW (1,450-1,875 m)	sampled 10 trees total, from 4 small clusters of ponderosa on <2.5 acres (1 ha), over a 12,000-acre (5,000-ha) watershed; 91 fire scars from 33 fires recorded	ponderosa pine, cross-dated	1601-1870	12-15 years	3-28	97	no fires since 1897	[108, 113, 115]
Hart Mountain National Antelope Refuge, Oregon (15)	Great Basin	mt. big or low sagebrush/ bluebunch wheatgrass-Idaho fescue (910190)	5,860-7,060 ft. (1,786-2,152 m), based locations of sampled ponderosa and aspen	sampled in shrub steppe communities; juniper in <4% of area; fire history reconstructed from a single, 2-tree cluster of ponderosa over 30 acres (12 ha); 9 fires recorded	ponderosa pine	1760-1861	13	3-32	97	Aged 43 junipers; of those associated with mt. big sagebrush, 94% were of post-1900 origin & averaged 82 years old (range: 59-110 years). Junipers with low sagebrush were older (x=143 years) and varied more in age (ranged 63-289 years).	[51, 52]

Owyhee Plateau, southwestern Idaho (16-19)	Columbia Basin	mosaic of mt. big sagebrush/ bluebunch wheatgrass-Idaho fescue and old-growth western juniper (1810190)	5,184-6,801 ft. (1,580-2,073 m)	**For full study:** Sampled in 4 areas of about 640 acres (260 ha) each within mosaic of seral & old-growth stands. Fire scars sampled from cross-sections of 50 fire-scarred junipers primarily found in old-growth stands.	western juniper				97	only 2 fires recorded since 1910 on all sites	[24]
				Indian Meadows site:		1690-1920	28	10-60			
				Mud Flat site:		1710-1920	29	10-60			
				Combination Ridge site:		1650-1930	23	10-50			
				Juniper Mt. site:		1700-1910	13	10-30			

[a]Plant community type was not always explicit in the literature and was inferred from site information (e.g., elevation, aspect, geography).

[b]MFI = Mean fire interval. Values are composite mean fire intervals unless otherwise noted.

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