Fire regimes of mountain big sagebrush communities

Figure 1—Prescribed fire on a mountain big sagebrush site in the Clear Lake Hills, Modoc County, California. Photo by Kenneth Fulgham; used with permission.

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ABSTRACT

This synthesis summarizes information available in the scientific literature on historical patterns and contemporary changes in fuels and fire regimes in mountain big sagebrush communities. This literature suggests that presettlement fires in the sagebrush biome were both lightning- and human-caused. Peak fire season occurred between April and October and varied geographically. Wildfires were high-severity, stand-replacement fires. Fire frequency estimates range from decades to centuries, depending on the applicable scale, methods used, and metrics calculated. Fire frequency was influenced by site characteristics. Because mountain big sagebrush communities occur over a productivity gradient driven by soil moisture and temperature regimes, fire regimes likely varied across the gradient, with more frequent fire on more productive sites that supported more continuous fine fuels. Sites dominated by mountain big sagebrush burned more frequently than sites dominated by Wyoming big sagebrush, because the former tend to be more productive. Mountain big sagebrush communities adjacent to fire-prone forest types (e.g., ponderosa pine) may have had more frequent fires than those adjacent to less fire-prone types (e.g., pinyon-juniper) and those far from forests and woodlands. Most fires were likely small (less than ~1,200 acres (500 ha)), and large fires (>24,000 acres (10,000 ha)) were infrequent. Historically, large fires in big sagebrush were most likely after one or more relatively wet years or seasons that favored growth of associated grasses, allowing fine fuels to accumulate and become more continuous.

Since European-American settlement, fuel and fire regime characteristics in many big sagebrush communities have shifted outside the range of historical variation. Settlement generally began in the mid-1800s and caused changes in ignition patterns and fuel characteristics, although the timing and magnitude of these changes varied among locations. Since then, fuels and fire regimes in many sagebrush ecosystems have changed due to a combination of interrelated factors, including land development for agriculture and energy, urbanization and infrastructure development, proliferation of nonnative invasive plants, woodland expansion, overgrazing by livestock, fire exclusion, and climate changes. Since 1980, the number of fires each year and total annual area burned have increased in the sagebrush biome. However, in most mountain big sagebrush communities, available data suggest that fire frequency has either not changed or has been reduced, with the exception of an area in the Colorado Plateaus ecoregion where fire frequency may have increased due to frequent prescribed burning.

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INTRODUCTION

This Fire Regime Synthesis brings together information from two sources: the scientific literature as of 2018, and the Biophysical Settings models and associated Fire Regime Data Products developed by LANDFIRE. This synthesis focuses on communities where mountain big sagebrush was historically a late-seral dominant, and it:

- provides information on historical fire regimes and contemporary changes in fuels and fire regimes,
- identifies areas lacking fire history data,
- supplements information provided by FEIS Species Reviews, and
- assists LANDFIRE with data revisions.

Common names are used throughout this Fire Regime Synthesis. For a complete list of common and scientific names of plant species discussed in this synthesis and links to FEIS Species Reviews, see table A1.

Six subspecies of big sagebrush grow in the western United States: the three major subspecies—mountain big sagebrush, basin big sagebrush, and Wyoming big sagebrush—and three subspecies with limited distributions—Mojave big sagebrush, xeric big sagebrush, and snowfield big sagebrush [37,40,83,110,127,149,150]. In this synthesis, "big sagebrush" refers to the big sagebrush species complex. In many cases, particularly regarding historical and prehistorical mountain big sagebrush fire regimes, clear distinctions among sagebrush taxa are lacking. Although mountain big sagebrush biology and ecology differ from that of the other big sagebrush subspecies and from other sagebrush taxa [207,321], Kitchen and McArthur [158] suggested that inferences made about the fire ecology of the sagebrush group as a whole will largely hold true for all big sagebrush subspecies. The following reviews of fire regimes in big sagebrush ecosystems are cited throughout this synthesis: [92,158,159,165,211,217,220,223,286,296,319].

The following FEIS publications cover fire regimes of sagebrush communities other than mountain big sagebrush:

- Wyoming big sagebrush and basin big sagebrush communities
- Mixed dwarf sagebrush communities

For information regarding the biology and ecology of mountain big sagebrush, how fire affects it, and how mountain big sagebrush communities respond to fire, see the FEIS Species Review about mountain big sagebrush.

In this synthesis, the "historical" or "presettlement" period refers to the period during the Little Ice Age, about 1300 to 1850, after which substantial European-American settlement and development began in most locations in the sagebrush biome [211]. The Little Ice Age was the wettest and coolest period during the most recent part of the Holocene [211], but there is no evidence that climate changes during the Little Ice Age resulted in species extinctions or substantial changes in the ecological relationships of plants [120]. Hann et al. [120] concluded that prior to European-American settlement, broad-scale biophysical relationships in the Great Basin had been relatively stable for about 2,000 years, with sagebrush, graminoids, junipers, and pinyons dominating the landscape. However, the relative abundance and distribution of sagebrush, graminoids, junipers, and pinyons have fluctuated over the past 2,000 years due to variability in climate and wildfire [198,211,233,335]. Since the end of the Little Ice Age, the global climate has been warming, with important implications for sagebrush ecosystems (see Climate Change). Kitchen and McArthur [158] cautioned that "judgments made when comparing presettlement big sagebrush conditions corresponding to the end of the Little Ice Age with contemporary environmental conditions should be tempered by the context of the corresponding change in climate".

PLANT COMMUNITIES, SITE CHARACTERISTICS, AND DISTRIBUTION

- **PLANT COMMUNITIES AND SITE CHARACTERISTICS**
  - **Climate**
- **DISTRIBUTION**
  - **Sagebrush Distribution**
  - **Conifer Distribution**

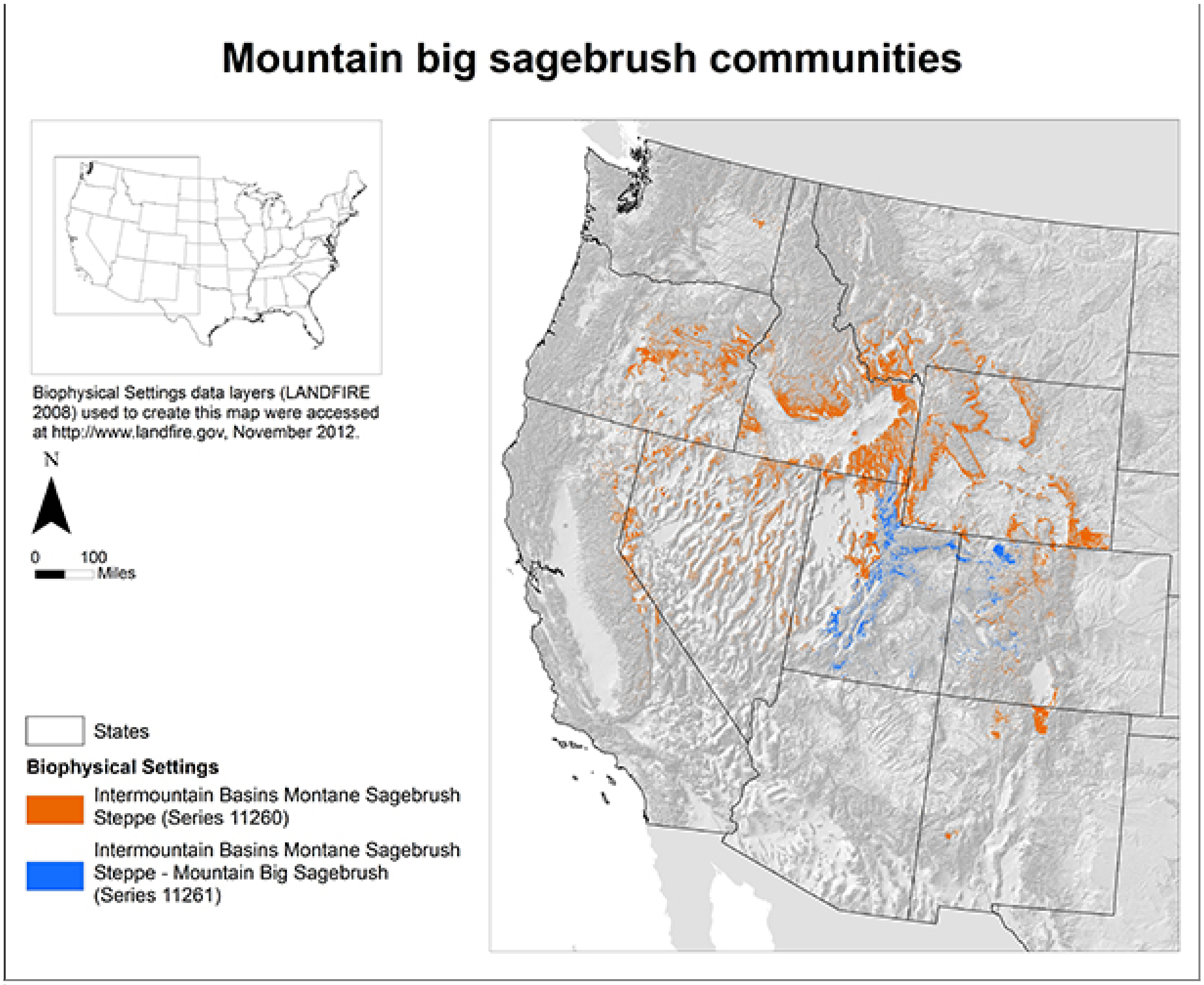

Figure 2—Historical land cover distribution of mountain big sagebrush communities based on the LANDFIRE Biophysical Settings data layer [182]. Click on the map for a larger image.

PLANT COMMUNITIES AND SITE CHARACTERISTICS

The focus of this synthesis is communities or ecosystems historically dominated by mountain big sagebrush. Researchers identify three primary big sagebrush ecosystems: Intermountain Basins montane sagebrush steppe, Intermountain Basins big sagebrush steppe, and Intermountain Basins big sagebrush shrubland. The first is primarily dominated by mountain big sagebrush, while the latter are primarily dominated by Wyoming big sagebrush and/or basin big sagebrush [24,231,242,272]. Mountain big sagebrush and Wyoming big sagebrush ecosystems occur along a gradient of soil moisture and temperature regimes, which are driven by a combination of soil characteristics, climate, elevation, and topography. Resilience to disturbances and resistance to nonnative plant invasions also change along this gradient, generally increasing with increasing soil moisture availability and decreasing with increasing soil temperature [73,208] (figure 3). Mountain big sagebrush steppe ecosystems occur on the wettest, coolest sites [209,226,321] and correspond to LANDFIRE's Intermountain Basins Montane Sagebrush Steppe Biophysical Settings series 11260 and 11261 [171].

In mountain big sagebrush communities other shrubs, such as antelope bitterbrush, may codominate. Other common or codominant shrubs include mountain silver sagebrush, snowfield big sagebrush, xeric big sagebrush, threetip sagebrush, stiff sagebrush, low sagebrush, rubber rabbitbrush, yellow rabbitbrush, mountain snowberry, wild crab apple, Woods' rose, wax currant, snowbrush ceanothus, and Saskatoon serviceberry [231]. Mountain big sagebrush stands typically have an abundant perennial herbaceous layer (>25% cover, in many cases >50% cover). However, conditions can range from an open steppe with abundant perennial grasses and low shrub cover (i.e., sagebrush-grasslands) to a closed shrubland with low grass cover (i.e., sagebrush shrublands) [231], depending on site characteristics and successional status [326,330] (see Kinds of Fuels). On relatively productive sites—often characterized by deeper soils with greater water-holding capacity—common grasses include bearded wheatgrass, melicgrass, slender wheatgrass, western needlegrass, and Columbia needlegrass. On less-productive, drier sites the principal grasses are Idaho fescue, bluebunch wheatgrass, blue grama, and Thurber needlegrass [107,209]. Other associated graminoids include Thurber fescue, bottlebrush squirreltail, tufted hairgrass, Parry's oatgrass, western wheatgrass, California brome, slender wheatgrass, prairie Junegrass, Fendler bluegrass, Sandberg bluegrass, and sedges [231]. Common forb genera include agoseris, Indian paintbrush, cinquefoil, fleabane, phlox, milkvetch, avens, lupine, balsamroot, hawksbeard, desertparsley, yarrow, and buckwheat [209,231]. Historically, mountain big sagebrush communities were generally treeless [351], or had only scattered trees (i.e., very low density with <10% canopy cover) intermixed from adjacent forests and woodlands [172,218]. Contemporary mountain big sagebrush communities with >10% tree canopy cover [172] and those dominated by nonnative annual grasses [173] are considered uncharacteristic of historical conditions.

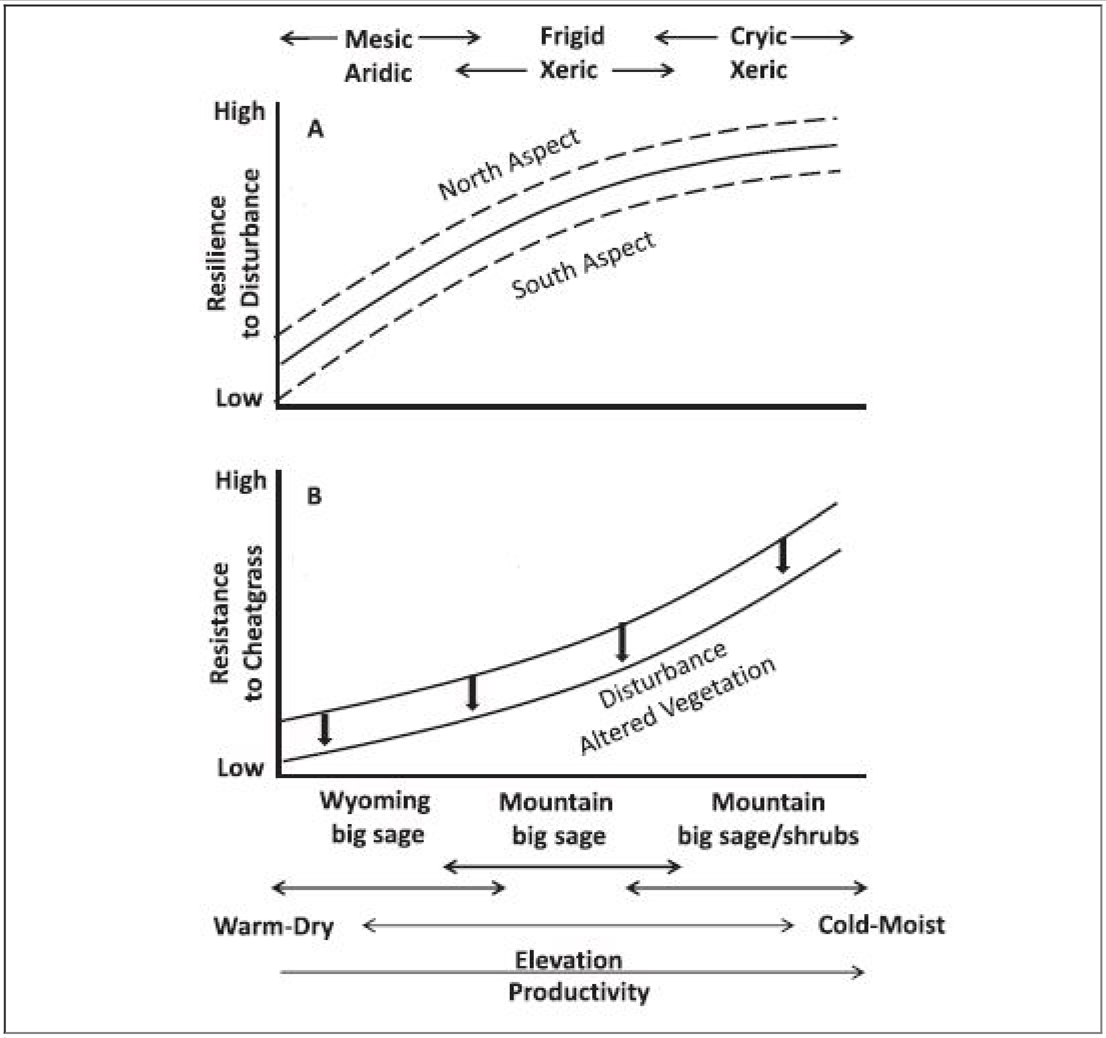

Figure 3—A conceptual model of A) resilience to disturbance and B) resistance to cheatgrass invasion as they relate to soil temperature and moisture regimes, elevation, and productivity gradients in the Great Basin. Predominant sagebrush types that occur along this continuum include Wyoming big sagebrush on warm, dry (mesic/aridic) sites; mountain big sagebrush on cool, moist (frigid/xeric) sites; and mixed mountain shrublands with mountain big sagebrush and sprouting shrubs on cold, moist (cryic/xeric) sites. As environmental gradients move from left to right, resilience, resistance, and biomass (i.e., fuels) increase ([73,208], adapted from [71,72]).

Mountain big sagebrush communities occur on upland sites from foothills to montane and subalpine zones [231]. Although there is considerable elevational overlap between the three big sagebrush ecosystems, mountain big sagebrush communities tend to be at the highest elevations. They also tend to be the most species rich and have greater plant biomass. They cover approximately 3% of the land area in the 11 western-most states [71,162,211,231,242,272].

Table A2 lists the LANDFIRE Biophysical Settings covered in this synthesis, provides links to their descriptions, and summarizes data generated by LANDFIRE models [171].

Big sagebrush ecosystems dominated by Wyoming big sagebrush and/or basin big sagebrush also have an understory of perennial bunchgrasses, but occur on warmer, drier sites and occupy about 12% of the land area in the 11 western-most states [242]. Fire regimes of these ecosystems are covered in the FEIS publication on Wyoming big sagebrush and basin big sagebrush communities.

Climate

Except in areas where mountains receive substantial orographic-induced precipitation, the climate of the Intermountain West—the region of the western United States where mountain big sagebrush communities occur (see Distribution, below)—is semiarid (9.8-19.7 inches (250-500 mm) mean annual precipitation) north of 41 °N latitude, and becomes increasingly arid (<9.8 inches (250 mm) mean annual precipitation) farther south. Seasonality of precipitation varies along a geographic gradient, with the importance of winter and spring Pacific frontal storms decreasing and summer convectional storms increasing from north to south and from west to east [157,162,327]. Temperature extremes in the Intermountain West range substantially, from a January low of -40 °F (-40 °C) to a July high of 113 °F (45 °C) [162]. Wildfires typically start during dry lightning storms in dry, hot summers but can also occur in wet years [220].

DISTRIBUTION

Mountain big sagebrush communities occur in the Intermountain West, the region bounded by the Sierra Nevada and Cascade Range to the west and the front ranges of the Rocky Mountains to the east [254]. Figure 2 shows the distribution of mountain big sagebrush Biophysical Settings as mapped by LANDFIRE [182]. Provencher et al. [252] recommended that managers compare local data with LANDFIRE products to ensure that the accuracy of the products is sufficient for their application. For example, these researchers noted only "moderately successful" agreement between LANDFIRE Biophysical Settings data layers and local data from the Wassuck Range, Nevada [252].

While the historical distribution and relative abundance of sagebrush is debated (see Sagebrush Distribution), it is certain that the land area historically occupied by sagebrush communities has been reduced and altered by the cumulative and interacting effects of livestock grazing and associated land management, agriculture, urban and industrial land uses, proliferation of nonnative invasive plants, woodland expansion, altered fire regimes, climate changes, and other factors [43,52,78,120,164,211,216,222,227,321]; however, few studies have compared historical and contemporary distributions of mountain big sagebrush communities quantitatively (but see [120]). Miller et al. [211] estimated that only 55% of the area delineated on Kuchler's maps as potentially dominated by sagebrush was occupied by sagebrush in 2011. Nearly all sagebrush communities have been grazed, and there are no refugia to use as reference conditions because contemporary communities lack American Indian influences, lack the numbers and some kinds of native animals that were present historically, are affected by nonnative plant invasions, and in many areas have experienced longer fire-free intervals than were historically common [330] (see Contemporary Changes in Fuels and Fire Regimes).

Sagebrush Distribution

Disagreement about the historical distribution and relative abundance of big sagebrush communities occurs throughout the published literature [118,158,199,320]. One school of thought maintains that grassland steppes were not abundant in presettlement landscapes and that the contemporary distribution of big sagebrush steppes is similar to the presettlement distribution, with the exception of lands converted to other uses. While this view acknowledges changes in big sagebrush dominance in response to livestock grazing, altered fire regimes, and other disturbances, it disputes the idea that contemporary big sagebrush stands are the result of widespread succession of grasslands to shrublands due to fire exclusion [158,199]. Advocates of this view (e.g., [60,130,146,203,293,300,321]) generally consider big sagebrush densities to be within the historical range of variation [60,203] and attribute perceived increases in sagebrush distribution since European-American settlement to recovery from past disturbances [69,86,292,335], such as "promiscuous" burning by early European-American settlers [86] (see Ignitions by European-American Settlers). Another school of thought maintains that grassland steppes were abundant during presettlement times and that excessive livestock grazing and the suppression of wildfires have resulted in less fire on the landscape and greater densities of big sagebrush, not only in big sagebrush steppes, but also in grassland steppes. Advocates of this view (e.g., [13,75,79,138,280]), generally consider big sagebrush to be an indicator of grassland degradation [158,199].

The disagreement about the historical distribution and relative abundance of big sagebrush communities is likely to continue because reliable historical information is lacking or inconsistent and because of the likelihood that neither model applies across the entire range of big sagebrush [158,199]. Historical accounts and repeat photographs have been interpreted to support both schools of thought [158,321]. Inconsistencies among historical accounts may be attributed to high variability among vegetation descriptions, which did not differentiate among big sagebrush subspecies and grouped together ecological types that varied in soil moisture and temperature regimes and time-since-last disturbance [118,193]. Repeat photographs from southwestern Montana (1870s–1980s) [13] and central Utah (1870s–2000s) [151] provide evidence and arguments in support of sagebrush spread into grasslands, whereas repeat photographs from Wyoming, northern Utah, and southeastern Idaho—taken first in the 1870s, and again >100 years later (1974–1985)—suggest that grasslands and shrublands in the region had changed little in spite of a wide range of disturbances [146]. Reconstructions derived from General Land Office survey records suggest that 84% of four study areas in sagebrush communities in Idaho, Nevada, Oregon, and Wyoming were historically dominated by large, contiguous areas of "normal or dense" sagebrush cover [60].

Conifer Distribution

Historically, the distribution of juniper and pinyon-juniper communities was dynamic, expanding and contracting throughout the Holocene, largely due to variability in climate and fire patterns [92,205,219,296,342]. Junipers and pinyons probably established in mountain big sagebrush communities adjacent to woodlands during periods of moist climatic conditions or infrequent fires, and were reduced during dry periods or periods with more frequent fires or insect outbreaks [268]. During the Little Ice Age and prior to European-American settlement, the vegetation of the Great Basin was thought to have been a mosaic of juniper or pinyon-juniper woodlands and savannas within a matrix of sagebrush steppes and shrublands; woodlands were relatively open and confined to fire-protected sites [158,217,286].

Since the late 1800s and early 1900s, density of junipers and pinyons has increased in many sagebrush and woodland communities [205,208,218,268], while it has not changed or has declined in others [268]. For example, Kitchen and Weisberg [159] noted that conifer establishment in mountain big sagebrush communities was "minimal" on many sites in Utah and adjacent Nevada, even after apparently long periods without fire. The greatest proportion of juniper and pinyon expansion has occurred on cool to warm, relatively moist sagebrush sites, including mountain big sagebrush sites [144,208,211]. The combined effects of climate and fire frequency continue to be driving forces of conifer density on contemporary landscapes, along with other interacting factors including livestock grazing and carbon dioxide fertilization. The relative importance of each factor likely varies among locations [92,268] (see Woodland Expansion).

HISTORICAL FUELS AND FIRE REGIMES

SUMMARY

Presettlement fires in the sagebrush biome were both lightning- and human-caused [15,113,116,277,301,333,337]. Peak fire season occurred between April and October and varied geographically [188]. Wildfires were high-severity, stand-replacement fires [19]. Fire frequency was influenced by site characteristics, and estimates of frequency ranged from decades to centuries, depending on the applicable scale, methods used, and metrics calculated. Because mountain big sagebrush communities occur over a productivity gradient driven by soil moisture and temperature regimes, fire regimes likely changed across the gradient, with more frequent fire on more productive sites that supported more continuous fine fuels [73,208]. Sites dominated by mountain big sagebrush burned more frequently than sites dominated by Wyoming big sagebrush because the former tend to produce more fine fuels [153,308]. Mountain big sagebrush communities adjacent to fire-prone forest types (e.g., ponderosa pine) may have had more frequent fires [153] than those adjacent to less fire-prone types (e.g., pinyon-juniper) and those

far from woodlands and forests. Most fires were likely small (less than ~1,200 acres (500 ha)), and large fires (>24,700 acres (10,000 ha)) were infrequent [59,60]. Large fires were most likely after one or more cool, wet years that allowed fine fuels to accumulate and become more continuous [19,217,220,222]. Mountain big sagebrush hybridizes with other sagebrush taxa (reviews by [195,318]), and sites occupied by parent taxa and their hybrids may be distinct from one another (e.g., [102,194,204,312]), but no studies examined fire history of hybrid communities. Only one study examined the postfire recovery rate of a community with what appeared to be a sprouting hybrid of mountain big sagebrush, and this study reported relatively fast postfire recovery [2].

HISTORICAL FUELS

Kinds of Fuels

Prior to European-American settlement, equal proportions of sagebrush and grasses were thought to be typical of big sagebrush steppe communities, in general, although the proportion of each growth form likely varied depending on successional stage and site characteristics, with sites ranging from grasslands with scattered sagebrush, to sagebrush shrublands dominated by sagebrush [209,231,296,326,328,330,332]. Typically, annual herbaceous plants dominate immediately after fire. Perennial grasses, forbs, and sprouting shrub species, if present, then increase and dominate for up to 20 years. Mountain big sagebrush may establish early in postfire succession from seeds in the soil seed bank and from seeds dispersed from surviving plants in unburned patches and edges [113,209,228,292,359] (see Fire adaptations). Because mountain big sagebrush must establish from seeds and has slower growth rates than grasses, forbs, and sprouting shrubs, it dominates the postfire plant community much later in succession [39,113]. Our review and analysis of mountain big sagebrush postfire recovery suggests that cover of mountain big sagebrush usually increases steadily over time and reaches about 28% in about 26 to 30 years, on average, although this varies substantially among sites and ecoregions (see Postfire recovery for details). As mountain big sagebrush cover increases during succession, cover of grasses, forbs, and other shrub species declines [8,39,113,210,229,236,329].

Prior to European-American settlement, conifers were thought to be sparse or absent in most mountain big sagebrush communities [218,351] (see Conifer Distribution). However, woodlands can expand into mountain big sagebrush communities on many sites when the interval between fires becomes long enough for trees to establish and mature [211] (see Postfire recovery). On these sites, conifers overtop and shade the understory, causing mountain big sagebrush and herbaceous plant cover to decrease as succession proceeds, such that cover of understory plants in late-successional woodlands is typically low (e.g., [25,167,205,211,218,260,285,316,342,346,347,357]). The transition from midseral to late-seral woodlands causes a shift from shrub and herbaceous fuels to a predominance of tree canopy fuels, which influences fire behavior and severity [91,208,217,268,346,357] (see Woodland Expansion).

Amount and Continuity of Fuels

Quantitative data about presettlement fuel characteristics are lacking for sagebrush communities [193], but contemporary mountain big sagebrush stands often have enough fuel to carry fire [43,193]. In a review, Miller and Eddleman [209] reported that total annual herbaceous biomass produced in contemporary mountain big sagebrush stands ranged from 625 to 2,454 pounds/acre (700-2,750 kg/ha) and in Wyoming big sagebrush stands ranged from 393 to 691 pounds/acre (440-775 kg/ha). Goodrich et al. [107,108,109,111] reported total annual herbaceous production in contemporary mountain big sagebrush communities ranging from 373 to 2,100 pounds/acre (418-2,354 kg/ha). The low end of the range (373 pounds/acre) was from near Dubois, Idaho, where sites were likely near the ecotone with Wyoming big sagebrush [107]. It is unclear how similar contemporary annual herbaceous biomass production is to presettlement production [296]. The predominance of Mollisols in many mountain big sagebrush communities shows long-term (hundreds to thousands of years) dominance of grasses on those sites [107], and suggests that surface fuels in these communities were historically characterized by a relatively dense herbaceous layer. Evidence of a history of frequent (mean fire interval ranged from 6-17 years) and often extensive (33%-50% of fires occurred on more than one site) surface fires from 10 mountain big sagebrush-Idaho fescue sites in California and Oregon suggests that the shrub layer was open and fine fuels were abundant and contiguous [220]. A review of data on annual production capability of sagebrush-perennial grass communities concluded that Great Basin sagebrush-perennial grass communities likely had greater annual herbaceous production than contemporary communities because of the cooler and wetter climate during the Little Ice Age [193]. See Contemporary Plant Communities and Fuels for information on how fuels may have changed since presettlement times due to woodland expansion, establishment and spread of nonnative invasive plants, changes in herbivory, and climate change.

Productivity (i.e., biomass), and thus fuel loading and often fuel continuity, generally increase along an environmental gradient from warm, dry (mesic/aridic) sites to cold, relatively moist (cryic/xeric) sites (figure 3). Thus, the potential for fire ignition and spread also increases along the environmental gradient, such that mountain big sagebrush communities on cool, moist (frigid/xeric) sites burn more frequently than Wyoming big sagebrush, black sagebrush, or low sagebrush communities on warmer, drier sites [208]. On the Hart Mountain National Wildlife Refuge, Oregon, and Sheldon National Wildlife Refuge, Nevada, mountain big sagebrush sites burned more frequently than low sagebrush sites, apparently because mountain big sagebrush sites were more productive and fuels more continuous [117]. Similarly, historical fire frequency estimates from four plant associations in Lava Beds National Monument, California, varied with differences in fine fuel abundance and continuity driven by soil characteristics (i.e., depth and texture). Historical fire interval estimates were shortest (composite median interval = 8 years, maximum interval = 37 years from 1750–1904) in the ponderosa pine/Idaho fescue plant association, where mountain big sagebrush was a transitory component and fine fuels were likely abundant and continuous as indicated by deep, loamy soils with mollic horizons. Similar evidence of relatively abundant fine fuel loads and close proximity to ponderosa pine/Idaho fescue plant associations, along with absence of large western junipers, suggested fire intervals <25 years in the mountain big sagebrush/Idaho fescue-bluebunch wheatgrass plant association; and evidence of low fine fuel loads (shallow soils with weak or absent mollic horizons) along with large western juniper snags suggested fire intervals >80 years in the mountain big sagebrush-bluebunch wheatgrass-Thurber needlegrass plant association. Fire interval estimates were longest ("centuries") in the western juniper-mountain big sagebrush-western needlegrass plant association, where shallow, coarse soils and absence of mollic horizons suggested limited fine fuel production historically, and presence of old western junipers indicated long fire-free periods [210].

Mountain big sagebrush communities often occur within a mosaic of forests, woodlands, shrublands, and grasslands [101,158,191,230,294], and varied historical evidence suggests that fires occasionally spread across these community types [159,220] as long as fuels were relatively continuous [47,220]. Fire-scar chronologies in Utah and eastern Nevada suggested that ecotones between woodland or forest and mountain big sagebrush communities were relatively porous and allowed considerable cross-boundary fire spread [159]. Miller et al. [220] stated that contiguous fuels and similar age structure of ponderosa pine and western juniper trees within woodlands and adjacent mountain big sagebrush communities suggest that fires do not stop at the ecotone [220]. In contrast, communities with sparse and less continuous fine fuels may slow fire spread and act as fuel breaks [47] (see Large Fire Frequency).

HISTORICAL FIRE REGIMES

Figure 4—A sagebrush community adjacent to Seedskadee National Wildlife Refuge, Wyoming. Image courtesy of the U.S. Fish and Wildlife Service.

Introduction

Fire was one of many natural disturbances that affected mountain big sagebrush communities historically. Other important large-scale disturbances in mountain big sagebrush communities included herbivory (e.g., by small mammals, insects, and wild ungulates), freeze-kill, snow mold, and drought [96,249]. Fire or other disturbance is not necessary to maintain mountain big sagebrush dominance in these communities [132,189,309], particularly those far from conifers. In a model of succession in mountain big sagebrush communities in southeastern Oregon that included the effects of fire, insects, voles, freeze-kill, snow mold, and drought, but did not include succession to conifers, Evers [96] concluded that fire had less influence than all other disturbance types, except drought, because other disturbances were more frequent and took fewer years to affect the study area. However, fire is important for killing establishing conifers and maintaining shrub and perennial grass dominance in many cool, relatively moist mountain big sagebrush communities that occur near woodlands and forests [64,126,209,217] (see Woodland Expansion).

Presettlement fire regimes in mountain big sagebrush communities are difficult to characterize over large areas because they were spatially and temporally complex due to local variation in site characteristics (e.g., topography, soils, vegetation, and fuel structure, composition, moisture content, and continuity), grazing and other disturbance history, climate and weather, and lightning and American Indian ignition rates [19,210,217,230,338]. In addition, records of fire history in mountain big sagebrush communities are lacking, and commonly used fire history methods, such as fire-scar analyses, are not possible because mountain big sagebrush plants are killed by fire and hence, do not form fire scars [264]. Instead, inferences suggested by fire adaptations and postfire recovery rates of mountain big sagebrush and associated conifers (where present), and proxy information—including charcoal fragments in soils, wetlands and lakes; fire evidence from adjacent or intermixed conifers; and historical land-survey records—are supplemented with information on contemporary fires to estimate historical fire regime components [19,154,158].

Mountain big sagebrush steppe Biophysical Settings mapped by LANDFIRE [182] occur within 21 ecoregions mapped by Omernik and Griffith [240]. Table 1 summarizes data generated by LANDFIRE models for these Biophysical Settings and shows a range of values for fire frequency and severity.

Table 1—Modeled fire intervals and severities in mountain big sagebrush steppe Biophysical Settings (BpS). Map zone numbers in bold represent BpSs with conifers included in successional models. Click on the maps for larger images.

Map zones	BpS series	Geographic distribution[a]	Fire interval[b]	Fire severity[c] (% of fires)			Fire regime	Citation(s)
				Replacement	Mixed	Low		

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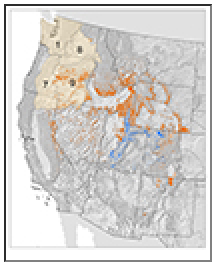
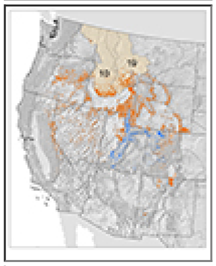
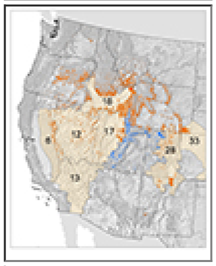
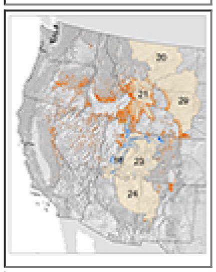
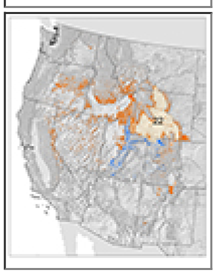
<tr><td>1,7,8,9</td><td>11260</td><td></td><td>20</td><td>100</td><td>0</td><td>0</td><td>II</td><td>[172]</td></tr>
<tr><td>10,19</td><td>11260</td><td></td><td>26</td><td>26</td><td>74[d]</td><td>0</td><td>I</td><td>[177]</td></tr>
<tr><td>6,12,13, 17,18,28, 33</td><td>11260</td><td></td><td>49</td><td>100</td><td>0</td><td>0</td><td>IV</td><td>[173,179,180]</td></tr>
<tr><td>20,21,29</td><td>11260</td><td rowspan="2"></td><td rowspan="2">50</td><td rowspan="2">100</td><td rowspan="2">0</td><td rowspan="2">0</td><td rowspan="2">IV</td><td>[174,178]</td></tr>
<tr><td>16,23,24</td><td>11261</td><td>[175]</td></tr>
<tr><td>22</td><td>11260</td><td></td><td>80</td><td>100</td><td>0</td><td>0</td><td>IV</td><td>[176]</td></tr>
<tr><td colspan="9">[a]Numbered, tan polygons show the area covered by the map zone(s) in each row, dark orange shows the Intermountain Basins Montane Sagebrush Steppe BpSs (series 11260), and blue shows the Intermountain Basins Montane Sagebrush Steppe - mountain big sagebrush BpSs (series 11261).
[b]Mean historical fire interval.
[c]Percentage of fires in each of three fire severity classes. 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% [26,181].
[d]This may be an inaccurate characterization of fire severity and fire regime group for these BpSs. See Historical Fire Type, Severity, and Intensity for more information.</td></tr>
</table>

The close association between mountain big sagebrush and woodland cover types in some areas [172] (see Plant Communities and Site Characteristics) suggests that sometimes these communities may be best considered as different phases of a single system, and that sagebrush communities prone to conifer expansion be considered separately from those that are not prone to such expansion [158,251,288]. LANDFIRE Biophysical Settings models differentiate inconsistently between mountain big sagebrush sites with and without the potential to succeed to conifers. Models for Biophysical Settings in California, the Great Basin, the Northern Great Plains, and the Southwest (map zones 6, 12, 13, 16, 17, 18, 23, 28, and 33) include conifers such as Douglas-fir, subalpine fir, whitebark pine, limber pine, pinyon, and juniper in models when stands are adjacent to conifer communities [173,175,179,180]. Most model descriptions for Biophysical Settings in the Pacific Northwest (map zones 1, 7, 8, and 9) [172] and the Northern Rocky Mountains (map zones 10, 19, 20, and 21) [174,176,177,178] mention the potential for succession to conifers—specifically western juniper, Rocky Mountain juniper, ponderosa pine, and Douglas-fir [172,174,177,178]—but none include conifers in models regardless of adjacency.

The following sections provide discussions and documentation of historical fire regime characteristics in mountain big sagebrush communities.

Historical Fire Ignition

Presettlement fires in the sagebrush biome were lightning- and human-caused [15,113,116,277,301,333,337], and sagebrush communities were generally not ignition-limited [162,193,233]. However, as of this writing (2018) little information was available on historical fire ignitions specific to mountain big sagebrush communities.

American Indian Ignitions

In the sagebrush biome, American Indians both started fires and benefitted from lightning-ignited wildfires. The frequency and purpose of intentional burning varied across the region [7]. Fires were used to improve forage for game, drive game animals, increase production of edible plants and seeds, maintain desirable plant communities, improve visibility, clear campsites, control pests, communicate over distances, and to defend against or attack intruders (e.g., [9,27,113,116,118,119,193,224,264,266,277,281,337]). Some intentionally set fires in sagebrush steppes were relatively large, and multiple fires were often set at once [193].

It is difficult to generalize the effects of American Indian burning on sagebrush ecosystems because the importance of human-caused fires likely varied "from place to place and culture to culture" [7], and historical records regarding American Indian burning practices are lacking for many tribes in the arid and semiarid regions of the western United States [337]. Early accounts suggest that American Indian-set fires were rare in the "drier, sagebrush valleys" [116] and were perhaps more common at higher elevations, where grass fuels were abundant [193,277]. Many authors noted potential bias by European-Americans in recording American Indian-set fires, depending on the observer, vegetation type, and season, which makes reliability questionable and interpretation of these early accounts difficult (e.g., [15,113,116,301]). Oral histories from American Indians would be more reliable, but are too few to draw conclusions regarding fire use in sagebrush communities, and none specifically address mountain big sagebrush communities [15]. Anecdotal and ethnographic accounts describing the use of fire by American Indians within the sagebrush biome are reviewed by many authors [116,118,193,277,337], including several chapters (e.g., [15,113,301,333]) in Fire, Native Peoples, and the Natural Landscape (edited by Vale [302]).

American Indian burning may have reduced fire-free intervals in some areas [12,113,119], such as in the Middle Rockies [28,152], and the seasonality, severity, and size of human-caused fires may have been different from those of lightning-caused fires [12,152,193]. Based on contemporary rates and causes of ignitions, Griffin [113] proposed four hypotheses about American Indian impacts on historical fire regimes in the Great Basin:

1. Anthropogenic ignitions were less important than lightning ignitions across most of the region, and few human-ignited fires occurred outside of sagebrush, pinyon-juniper, and montane forest communities.
2. Human-caused fires were most frequent in the northern Great Basin, particularly in areas with high population densities, including transportation corridors and areas near water.
3. American Indian burning practices made year-to-year ignition frequencies more constant than they would have otherwise been.
4. American Indian burning resulted in more fires in fall, winter, and spring than would have otherwise occurred [113].

However, whether American Indian ignitions were less important than lightning ignitions in the western United States is debated, with some authors suggesting that most historical fires were lightning-caused [113,220], and others suggesting that most were human-caused [152,193,281]. In some places, lightning was insufficient to explain the frequency of fires recorded by fire scars, and ignitions by American Indians have been suggested to explain the difference [15,152]. Authors described the effects of American Indian ignitions as ranging from limited and highly localized (e.g., [15,301,328,329]) to substantial and widespread (e.g., [116,152,193,256,277]). Based on accounts in journals and other historical documents of 145 fires that occurred from 1776 to 1900 in the western United States, Gruell [116] concluded that 41% of fires observed were ignited by American Indians and located primarily at lower and middle elevations, 7% were attributed to other "non-Indian" causes, and no mention of ignition source was made for the remaining 52%. A recent analysis of American Indian fire use in sagebrush-perennial grass communities concluded that the presettlement Great Basin landscape was a "patchwork of areas altered by aboriginal people and areas shaped primarily by biophysical properties" [193]. American Indian impacts in the sagebrush region were likely concentrated near grasslands, low-elevation forests, and in or near settlement areas (e.g., riparian areas and major river valleys) [27,113,119]. However, even remote areas were probably touched by American Indian-set fires, at least on occasion, as fires spread from other areas [116].

Lightning-caused Ignitions
In the Intermountain West, lightning frequency does not generally limit fire frequency [30,162,233]; rather, fire probabilities are associated with fuel loadings, fuel moisture levels, and lightning arc duration [162]. In steppe communities throughout the Intermountain West, the frequency of lightning ignitions varies substantially and is influenced by geography (i.e., climate and weather patterns), topography, and fuel characteristics. Lightning strike density does not appear to be correlated with ignition frequency at regional scales [162], but it likely influences ignition frequency at local scales (e.g., [220]). Between 1980 and 1994, ignition frequency in grass-dominated communities of the Intermountain West (native and nonnative grasslands, sagebrush steppes, and conifer savannas) was highest in the western third of the region and in areas with the largest elevational differences (indicative of sites with varied topography) and the most summer precipitation (associated with greater fuel production). In contrast, lightning strike density was greatest in the southeastern part of the region, decreasing steadily toward the northwest, and was not well correlated with ignition frequency. Ignition frequency was greatest in mountainous areas, including the eastern foothills of the Oregon Cascade Range and the Sierra Nevada, and the foothills of the Carson Range in Nevada and California. High ignition frequency also occurred near the Stansbury Mountains in Utah, along the Snake River Plain of Idaho, and in the Ruby Mountains of Nevada. Low ignition frequency was particularly pronounced in the Lahontan Basin in Oregon and Nevada and the Bonneville Basin in Utah [162]. At smaller spatial scales, ignition frequency may be more strongly influenced by lightning strike density, which varies with topographic position. For example, a study in California and Oregon found that among seven mountain big sagebrush/Idaho fescue sites studied, the site with the most frequent fire (as determined from fire scars on adjacent and intermixed ponderosa pine trees) occurred on a long ridge above a high-elevation tableland—a location that made it highly susceptible to lightning strikes [220].

Ignition frequency may be higher in forests than sagebrush communities [19,98,200]. Based on the number of lightning strikes per fire start from 1986 to 1990 in sagebrush (n = 144), Rocky Mountain Douglas-fir (n = 42), and ponderosa pine (n = 24) communities in Idaho reported by Meisner et al. [200], Baker [19] concluded that ignition frequency was 3 to 6 times lower in sagebrush than in forests.

Historical Fire Season
Peak fire season for contemporary wildfires occurs from April to October, depending on the region, but most wildfires occur in July and August throughout the western United States. Fire occurrence peaks earliest in the Southwest and progressively later to the north and west [30,188,331]. A study of 410,000 reports of fires that occurred from 1980 to 2001 on lands managed by four of the five federal land management agencies in the western United States found that 94% of lightning- and human-caused fires occurred, and 98% of the area burned, between May and October. The fire season in Arizona and New Mexico began as early as May and June. In northern Idaho and western Montana, the fire season was more concentrated toward the later part of summer, with roughly 50% of fire starts occurring in August. In many parts of California the fire season peaked in August and September. The greatest number of reported wildfires occurred in July and August in central Arizona, the Sierra Nevada, the Cascade Range, and the Rocky Mountains [331].

Limited information from fire scars on adjacent and intermixed ponderosa pine trees suggests that fires in mountain big sagebrush communities were most common in summer and fall. In the Upper Chewaucan River basin near Paisley, Oregon, fire scars on 91 ponderosa pine trees indicated that all presettlement fires occurred in late summer and fall [214]. Across seven sites in California and Oregon, fire scars dated from 1600 to 1830 on ponderosa pine trees within and adjacent to mountain big sagebrush/Idaho fescue communities indicated that most presettlement fires occurred from midsummer to late fall, particularly in late summer, when dry lightning storms are most common in the region. Only one spring fire occurred in the fire-scar record across the seven sites. However, spring fires probably burned at relatively low intensities, which may have caused less scarring of trees resulting in an underestimate of spring fires [220].

Small and large fires in the Intermountain region of California, Idaho, Oregon, and Utah mostly occur in July and August, although small fires are more widely distributed throughout the fire season. An analysis of fire data from grasslands, sagebrush steppe, and savanna communities from 1980 to 1995 indicated that >82% of large fires (>4,962 acres (2,008 ha)) occurred in July and August. 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 fires igniting earliest in the southern part of the region and becoming more common later in the summer in the northern part of the region [163].

American Indian-set fires may have extended the fire season in mountain big sagebrush communities. A review of the role of American Indian burning in land management concluded that in North America in general, most intentional American Indian-set fires were set in spring or late fall, when burning conditions were less severe [155].

Historical Fire Frequency

Summary

Historical fire frequency is difficult to estimate in big sagebrush communities because direct evidence of presettlement fires is rare. Fire frequency estimates for big sagebrush communities are based on various sources of information, including fire adaptations and postfire recovery patterns of big sagebrush and conifers; analyses of charcoal fragments in soils or lake and wetland sediments; evidence of fire from adjacent or intermixed conifers; historical land-survey records; and contemporary lightning ignition rates [19,154,158]. Each of these methods has strengths and limitations, and each provides information at particular spatial and temporal scales, all of which must be considered when applying study results to management questions.

Mountain big sagebrush communities occur over a productivity gradient driven by soil moisture and temperature regimes, and historical fire regimes likely varied across this gradient, with more frequent fire on more productive sites that supported more continuous fine fuels [73,208]. However, because mountain big sagebrush is easily killed by fire [8,42,43,62,76,196,237,244,292] and its postfire recovery depends on seedlings establishing and reaching reproductive maturity [212,359], large fires and fires frequent or severe enough to deplete on- and off-site seed sources and prevent establishing plants from reaching maturity are likely to make mountain big sagebrush vulnerable to local extinction and favor grassland steppe over sagebrush steppe [61,159,210,220,336]. Evidence suggests that large fires were infrequent [19,59,60], and that large or widespread fires most likely occurred when fine fuels were abundant and continuous, such as after one or more relatively wet years or seasons (e.g., [118,188,214]).

Postfire recovery time (i.e., the length of time necessary for mountain big sagebrush canopy cover to return to prefire or unburned values) is sometimes used to estimate fire frequency in mountain big sagebrush communities. This is based on the premise that these communities did not burn, on average, more frequently than the time required for mountain big sagebrush to recover, but they did burn frequently enough to prevent succession to woodland [19,158,341]. Previously, we analyzed mountain big sagebrush postfire recovery data from 306 burned sites examined in 20 studies in eight ecoregions (table A3). We found that few sites recovered within 25 years after fire, and most sites began reaching full recovery in about 26 to 30 years (figure 5). However, variability was high: one site reached full recovery in 8 years, while another site had not recovered after 67 years. This broad range in postfire recovery rates suggests that a similarly broad range in fire frequencies would be compatible with mountain big sagebrush persistence and dominance within a landscape [159]. However, seedling establishment during the first few postfire years strongly influences postfire recovery time [42,196,305,356,358], and it depends on a number of factors and can be highly variable among sites and years [320,356], emphasizing the importance of site-specific information for fire management plans and decisions [60,208,268].

Fourteen studies used proxy information to estimate historical fire frequency in mountain big sagebrush communities. Frequency estimates ranged from decades to centuries, depending on the applicable scale, methods used, and metrics calculated. However, some studies showed a similar geographic pattern: fire was most frequent in the western portion of mountain big sagebrush steppe's distribution in California and Oregon and least frequent in the central and eastern portions in Idaho, Montana, Wyoming, Colorado, Utah, and Nevada. Three studies present information on fire activity derived from charcoal analyses. These were located in the Idaho Batholith and Middle Rockies ecoregions and suggest that fire activity in those landscapes was episodic and tended to peak during centuries and decades with higher than average precipitation [137,140,233] (table A4). Eight studies estimated fire frequency from fire scars on ponderosa pine, Rocky Mountain Douglas-fir, and other trees adjacent to and intermixed with mountain big sagebrush communities. These studies reported mean fire intervals ranging from 6 to 61 years, and estimates varied among associated woodland types, site types, and ecoregions [13,48,117,126,135,159,214,220] (table A5). Mean fire intervals reported in these studies were shortest (6-17 years) for sites in the Eastern Cascades Slopes and Foothills and the western portion of the Northern Basin and Range ecoregions, where mountain big sagebrush communities were adjacent to and intermixed with ponderosa pine communities, and longer in the Central Basin and Range (25 years), Colorado Plateaus (61 years), Middle Rockies (17-45 years), and Wasatch and Uinta Mountains (40 years) ecoregions, where mountain big sagebrush communities were adjacent to and intermixed with ponderosa pine, Douglas-fir, lodgepole pine, and other woodland or forest communities. Three studies presented estimates of historical fire rotations in mountain big sagebrush communities in eight ecoregions using vegetation reconstructions based on Government Land Office survey records from the late 1800s and early 1900s. These studies suggest that fire rotations were shortest in the Eastern Cascades Slopes and Foothills and western portion of the Northern Basin and Range (48-77 years) and longest in the Wyoming Basin (588-2,139 years) ecoregions [11,59,60] (table A6).

Fire history data for mountain big sagebrush communities were somewhat limited geographically. Data were available from 10 of the 21 ecoregions in which mountain big sagebrush communities occur, but most were from the Central Basin and Range, Colorado Plateaus, Eastern Cascades Slopes and Foothills, Middle Rockies, Northern Basin and Range, and Wasatch and Uinta Mountains ecoregions. Only LANDFIRE models provide information on fire frequency in mountain big sagebrush communities in all 21 ecoregions. These models estimate mean fire intervals for mountain big sagebrush Biophysical Settings that range from 20 years in parts of the Columbia Plateau, Blue Mountains, Eastern Cascades Slopes and Foothills, and Northern Basin and Range to 80 years in the Wyoming Basin [171] (table 1). Fire history studies from underrepresented areas would benefit fire management as would information on potential fine-scale variation in fire frequency due to soil moisture and temperature regimes, which are important drivers of spatial variation in historical fire regimes in sagebrush steppe communities [210].

Introduction

Historical fire frequency in sagebrush communities is difficult to estimate because plants in these communities do not record fire scars, and stands originating from fire cannot be dated without fire records, which are incomplete [264]. In addition, reference conditions are lacking in contemporary mountain big sagebrush stands due to overgrazing and other disturbances related to European-American settlement [330] (see Distribution). Thus, fire frequency estimates in these communities are based on inferences suggested by mountain big sagebrush's [19,62,158,238,323,338,341] and associated conifer species' [13,66,126,210,264] fire adaptations and postfire recovery rates, and by using proxy information obtained at varying spatial and temporal scales, including:

- macroscopic charcoal fragments from soils or sediments, which are used to identify episodes of high fire activity in sagebrush landscapes during past centuries and millennia [137,140,233];
- fire-scar records from conifers intermixed with or adjacent to mountain big sagebrush communities, which provide approximate return intervals for low-severity (on overstory trees), surface fires at stand and landscape scales over the past several hundred years (e.g., [13,48,117,126,135,160,214,220]);
- historical land-survey records conducted during the late 1800s and early 1900s are used to estimate composition and structure of historical plant communities, which are used to infer fire rotations over large areas [11,59,60];
- stand age-class structure and fire evidence in woodlands with small, intermixed patches and understories dominated by mountain big sagebrush, which are used to estimate fire rotations for stand-replacement fires [19]; and
- contemporary fire frequency relationships within and among forest, woodland, and sagebrush communities, which are used to estimate conversion factors for estimating fire rotations in large patches of mountain big sagebrush [17,19].

Each method has strengths and limitations, and the resulting frequency metrics are not directly comparable to one another because they are calculated using measurements from different kinds of fires (e.g., low-severity, surface fires and high-severity, stand-replacing fires) and different plant communities (e.g., mountain big sagebrush, ponderosa pine, Douglas-fir, and western juniper communities), and apply to different spatial and temporal scales [154].

Because methods and studies included differ, previous literature reviews and analyses of published studies on fire history in mountain big sagebrush communities draw different conclusions about historical fire frequency [19,80,158,165,217,332]. For example, a 2007 review of published studies that used postfire recovery times of big sagebrush and associated conifers to estimate historical fire frequency in big sagebrush communities suggested that historical mean fire intervals in mountain big sagebrush communities and some productive Wyoming big sagebrush and basin big sagebrush communities ranged from 40 to 80 years [158]. A 2001 review of postfire recovery rates and fire history data from fire-scarred trees in and adjacent to mountain big sagebrush communities estimated that fire frequency ranged from 11 to 25 years on mesic mountain big sagebrush sites, and were longer on drier, less productive sites that graded into Wyoming big sagebrush sites [217].

Fire Adaptations and Postfire Recovery

Fire adaptations

Mountain big sagebrush plants are easily killed by fire; they do not sprout [8,42,43,62,76,196,237,244,292]. Thus, mountain big sagebrush cover and density are reduced by fire [212], and postfire establishment is dependent on on-site or nearby off-site seed sources [167,209,228,292,358,359]. Fire can create favorable conditions for mountain big sagebrush germination and seedling establishment by releasing nutrients and reducing cover of vegetation, which increases available growing space and the amount of sunlight reaching the soil surface (e.g., [44,45,46,88,131,208,235,258,259]). Seeds may germinate from short-lived soil seed banks [228,336,358,359] if they survive the fire and are not buried too deeply. Viable mountain big sagebrush seeds must be within 0.6 inch (15 mm) of the soil surface to germinate [141,354], where they are vulnerable to lethal temperatures during fire. Mountain big sagebrush seed production is highly variable, and depends on site and plant characteristics (e.g., size, age, and genetics) [170], but surviving plants in unburned patches and burn edges may produce abundant seeds [32,87,124,317,324,356]. Most mountain big sagebrush seeds fall within 10 feet (3 m) of parent plants [104,124,292,304,322,354], so postfire recovery on large burns may be slow.

Postfire seedling establishment and time to reproductive maturity are primary drivers determining the rate of mountain big sagebrush recovery [212,359]. Seed production, viability, and germination rates do not appear to be limiting factors in mountain big sagebrush establishment after fire [122,236,238,358]; however, seedling establishment during the first few postfire years can be highly variable [320,356]. Mountain big sagebrush postfire recovery is most rapid when seedling establishment is high during the first four postfire growing seasons [42,196,305,356,358]. Once mountain big sagebrush plants reach reproductive maturity (anywhere from 2 [32,239] to >13 years old (e.g., [132,148])), they contribute to postfire recovery. Recovery is inhibited when fire recurs before postfire seedling cohorts reach maturity. Thus, fire intervals that are frequent enough to kill plants before they reach maturity and large, severe fires that deplete on- and off-site mountain big sagebrush seed sources may make mountain big sagebrush vulnerable to local extinction [61,336] and favor grassland steppe over sagebrush steppe [159,210,220]. See the Species Review about mountain big sagebrush for details and documentation of the fire ecology of this species.

Several authors describe mountain big sagebrush as being poorly adapted to frequent fire, based on its inability to survive burning, lack of sprouting ability, and slow postfire recovery [19,323]; while others have suggested that mountain big sagebrush is well adapted to fire, based on its ability to establish quickly from seeds, grow rapidly, reach reproductive maturity at a young age, and recover to prefire abundance soon after fire [62,238]. Baker [19] stated that the regeneration characteristics of mountain big sagebrush and that of many other sagebrush taxa are "consistent with evidence of long fire rotations and mean fire intervals". Similarly, Welch and Criddle [323] stated that mountain big sagebrush's regeneration characteristics "do not support the idea that mountain big sagebrush evolved in an environment of frequent fires (i.e., with fire intervals of <20 to 30 years)", and they suggest that historical fire intervals were likely more than 50 years. Conversely, Bunting [62] referred to mountain big sagebrush as being "well adapted to becoming established following fire" because mountain big sagebrush seeds "establish readily" after fire, and mountain big sagebrush occurs on "very productive sites" and may "return to preburn condition within 15 to 20 years". Thus, different conclusions about mountain big sagebrush's postfire recovery time—which is driven by a number of interacting factors, and is therefore highly variable (see below)—appear to influence perceptions of its adaptations to fire. It is unlikely that historical fire frequency in mountain big sagebrush communities can be resolved by considering mountain big sagebrush's adaptations to fire alone [158].

Postfire recovery

Postfire recovery time (i.e., the length of time necessary for mountain big sagebrush canopy cover to return to prefire or unburned values) is sometimes used to estimate fire frequency in mountain big sagebrush communities based on the premise that mountain big sagebrush communities burned, on average, less frequently than the time required for them to recover [19,341], but more frequently than the time required for them to succeed to woodland [158]. Baker [19] reviewed 11 postfire recovery studies with cover and density data from >56 mountain big sagebrush sites in the Middle Rockies and Snake River Plain. He found that 16 sites showed nearly full recovery 25 to 30 years after fire; he classified these as "fast track" sites. The remaining sites were not yet recovered up to 35 years after fire. Baker estimated that those >40 sites would require 75 or more years to reach full recovery; he classified these as "slow track" sites. Based on these observations and his suggestion that a conservative estimate for "fire rotation and (point) mean fire interval for sagebrush (is) at least twice the recovery period", he suggested a fire rotation or point mean fire interval of at least 50 to 70 years for fast track sites and at least 150 to 200 years for slow track sites [19].

However, two studies of mountain big sagebrush in Utah and adjacent Nevada that used many of the same study areas suggest that the relationship between fire frequency and postfire recovery described by Baker is oversimplified. These studies provide an opportunity to compare postfire recovery time estimated from a chronosequence of paired burned and unburned sites [235] to point mean fire intervals calculated using fire scars dated from 1340 to 1999 on intermixed and adjacent conifers [159]. Mean postfire recovery time was estimated at 37 years (95% CI: 24-84 years) ([235], table A3), and point mean fire intervals were highly variable, ranging from 12 to 109 years on individual trees ([159], table A5). These point mean fire intervals are about 0.32 to 2.95 times the mean postfire recovery time, supporting Baker's [19] suggestion—that point mean fire intervals are at least twice the mean recovery time—at some locations but not at others. Locations where point mean fire intervals were shorter than postfire recovery times may have been dominated by grasses, rather than sagebrush, historically (see below).

The FEIS Species Review about mountain big sagebrush includes a review and analysis of mountain big sagebrush postfire recovery data from 306 burned sites in eight ecoregions examined in 20 studies. Most available data (86%) came from burns ≤25 years old, and few of those sites (9%) had fully recovered. When site-level data were averaged within 5-year bins, sites tended toward full recovery at 28% canopy cover 26 to 30 years after fire; however, not all burns >25 years were fully recovered (figure 5). Postfire recovery times varied within and among ecoregions (figure A1). Sites in the Wyoming Basin appeared to be the slowest to recover (figure A1c), which is consistent with relatively long fire rotations reported by Bukowski and Baker [60] (table A6) and long mean fire intervals modeled by LANDFIRE for the Wyoming Basin [176] (table 1), if assuming a direct relationship between postfire recovery and fire frequency [19,341]. However, unburned cover values at sites in the south-central Wyoming Basin were high, ranging from 42% to 71% with a mean of 56%, which resulted in low postfire recovery values (burned cover divided by unburned cover), even though mountain big sagebrush cover on most burned sites (67%) exceeded 20%, 17 to 25 years after fire. Although "understory fine fuels were on the light side and patchy" due to many years of summer-long grazing on these sites, accounts from early settlers in this area suggest that fine fuels were historically abundant in some mountain big sagebrush areas, as they "were able to put up hay". Relatively fast recovery [19,341] and abundant fine fuels [73,208], therefore, might suggest a history of frequent fire in the area (see Historical Fuels: Amount and Continuity of Fuels). However, fire may still have been infrequent in this ecoregion because of low lightning strike density [314].

Frequent fires favor grassland steppe over sagebrush steppe [159,210,220]. If mountain big sagebrush stands require at least 26 to 30 years, on average, to reach unburned canopy cover of about 28%, sites with very frequent fire (<20-year return intervals) (e.g., [48,117,210,220,221]) would have likely been sagebrush-grassland mosaics where fires were patchy [159,264], and grasslands (e.g., LANDFIRE's Northern Rocky Mountain lower montane-foothill-valley grassland Biophysical Setting (series 11390) [174]) with scattered mountain big sagebrush (<10% shrub cover) and rare trees [16,159,210,220] where fires were relatively uniform. Kitchen and Weisburg [159] concluded that certain criteria would need to be satisfied for very frequent fires to be compatible with mountain big sagebrush presence: 1) fires must have been patchy, leaving unburned seed sources to facilitate reestablishment within burn interiors; 2) residual seed banks survived fires; and/or 3) mountain big sagebrush was an ephemeral component, establishing only during relatively long fire-free intervals [159].

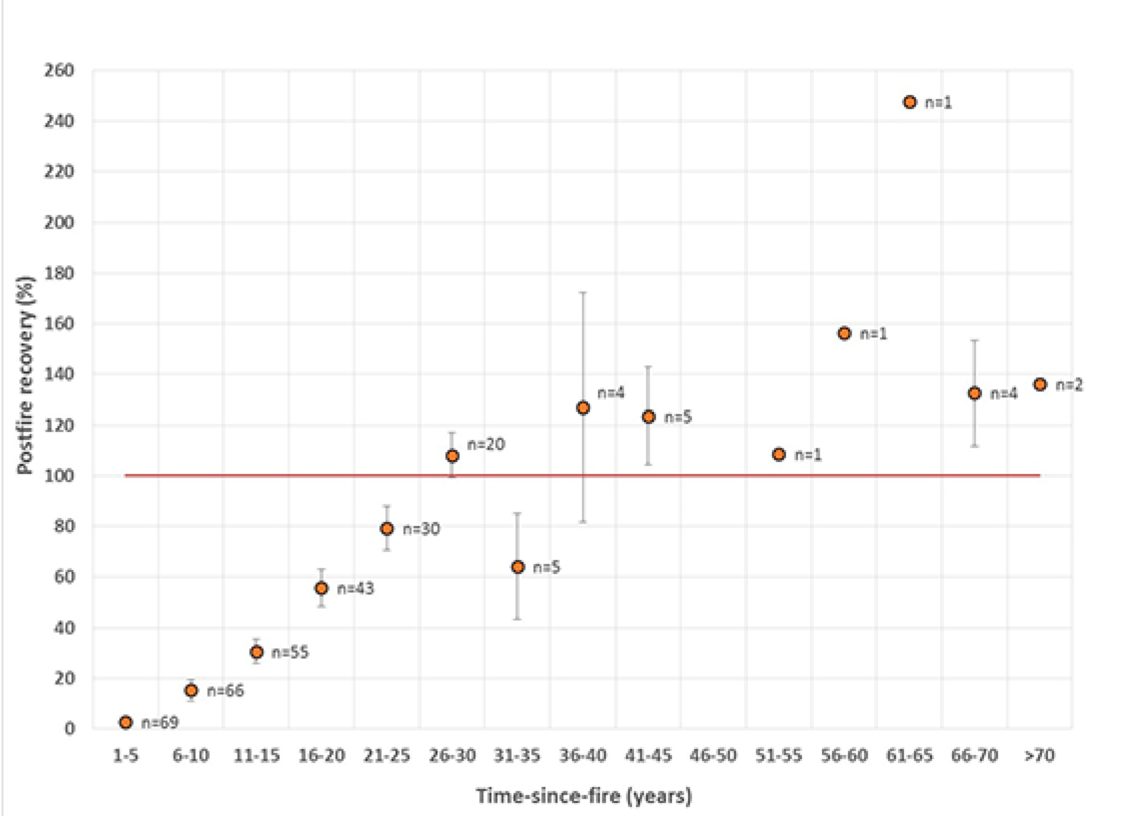


Figure 5—Points show the mean ratio of burned to unburned (or prefire) canopy cover (i.e., "postfire recovery") of mountain big sagebrush within 5-year, time-since-fire bins; error bars are standard errors. The red line indicates recovery to unburned (or prefire) canopy cover.

While conifer establishment in mountain big sagebrush communities may be "minimal" on many sites even after apparently long periods without fire [159], conifers can establish and dominate in mountain big sagebrush communities along woodland-sagebrush ecotones when the interval between fires becomes long enough [159,211] (see Woodland Expansion). The period of time required for mountain big sagebrush steppe sites to succeed to woodland varies among sites. For example, in southeastern Oregon and southwestern Idaho, development of western juniper woodlands in mountain big sagebrush and low sagebrush communities from the time of initial tree establishment to dominance ranged from 80 years on cool, relatively moist sites to >120 years on warm, dry sites [144]. On mountain big sagebrush/Idaho fescue sites in Oregon and California, nearly 80% of western juniper trees established within a 30-year period when few fires were evident in the fire-scar record, and western juniper reached dominance in as few as 60 to 70 years [214,215]. Based on these and other data, researchers developed a conceptual model to estimate the time necessary for mountain big sagebrush communities along elevational and aspect gradients to transition from initial western juniper establishment to late-seral woodland (figure 6). Establishment and spread of other conifers into mountain big sagebrush communities is not well studied.

Fire frequency in mountain big sagebrush communities is sometimes inferred by the presence of conifers, based on the susceptibility of young conifers to fire-caused mortality [13,66,126,210,264]. For example, because western juniper trees <50 years old are easily killed by fire, several authors inferred that mean fire intervals of <50 years would inhibit woodland expansion into sagebrush communities [66,264]. Fire frequencies of 35 to 40 years in Montana apparently excluded Rocky Mountain Douglas-firs from adjacent grasslands and mountain big sagebrush communities, confining them to rock outcrops, talus slopes, or other sites with sparse fuels [13,126]. In mountain big sagebrush/Idaho fescue-bluebunch wheatgrass communities at Lava Beds National Monument, the lack of old live or dead western juniper trees suggested a history of fires frequent enough (<25 years between fires) to limit their establishment and persistence. In a mountain big sagebrush/bluebunch wheatgrass-Thurber needlegrass community at the same site, presence of scattered western juniper snags suggested a history of less frequent fire (>80 years between fires) [210].

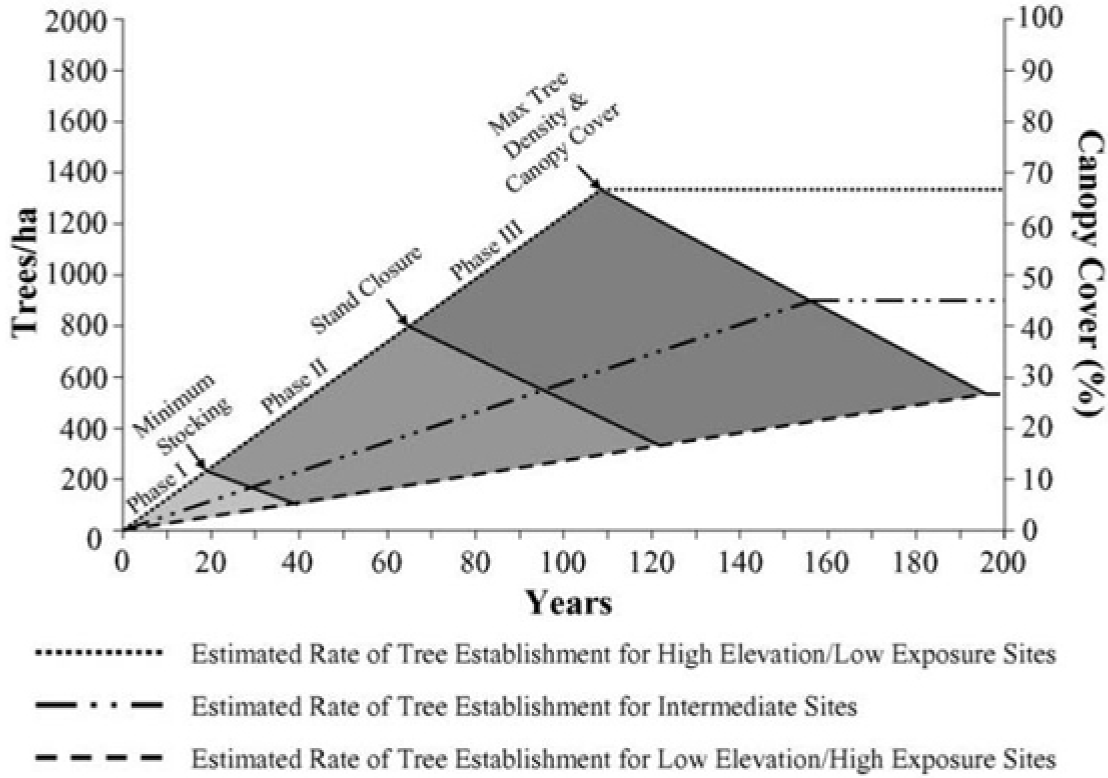


Figure 6—Hypothesized time periods from initial western juniper establishment (early Phase I) to development of late-successional woodland (Phase III), and estimated maximum density and canopy cover of western juniper for stands developing on mountain big sagebrush sites with varying elevation and insolation exposure (i.e., a gradient of relatively cool/moist to warm/dry sites) [144,208].

Charcoal Analyses

Analyses of charcoal fragments from soils [233] or lake and wetland sediments [202] can be used to reconstruct fire history within treeless landscapes. The spatial resolution of these fire histories may be similar to that of fire histories derived from fire-scar analysis (i.e., the site of the soil sample or the watershed of the lake or wetland); however, the temporal resolution depends on sedimentation rates as well as the continuity or number of samples analyzed, and can range from years to centuries [169]. Individual fires cannot usually be resolved from charcoal analyses, but peaks in charcoal abundance or accumulation rates indicate fire "events" or "episodes"—when one or more fires occurred within the time period spanned by the peak—and can be related to changes in fire activity at the site or landscape level [233]. Nelson and Pierce [233] caution that fire frequency estimates obtained from charcoal in sediments and those obtained using fire-scar records should be compared cautiously because of the different temporal resolutions. Additionally, analysis of charcoal peaks is biased toward detection of high-severity crown fires, because low-severity surface fires contribute primarily to background charcoal levels and may not leave distinct peaks [334], while fire scars record low- to moderate-severity surface fires.

Only a few studies of charcoal fragments in soils and sediments had been conducted to examine fire history in sagebrush landscapes to date (2018) (e.g., [137,140,202,233]). Of these, two studies in the Middle Rockies ecoregion [137,140] and one in the Idaho Batholith ecoregion [233] provide fire history information, which pertains to five sites where mountain big sagebrush communities occur in the surrounding area (figure 7). These studies are summarized in table A4. The time period covered by these fire histories varies, ranging from about 550 years (Swan Lake) [140] to about 14,000 years (Blacktail Pond) [137], although vegetation reconstructions based on analyses of pollen [137,140] or plant macrofossils [233] suggest that sagebrush was a common to dominant component of the vegetation during at least the past 550 to 2,000 years at all sites [137,140,233]. Records of fire activity during that period varied among sites, but showed some similar relationships with climate.

Comparisons of peaks in charcoal abundance with climate records suggest that fires occurred in mountain big sagebrush communities during periods that were wetter than average, implying that these are fuel-limited systems where fine-fuel biomass increases during relatively wet periods and is then ignited during relatively dry years [140,233]. For example, charcoal records from Hendrick Pond, Wyoming, indicated that several fire episodes occurred during century-long wet periods centered around AD 550, 790, 1100, 1300, and 1800 [140]. In a southwestern Idaho rangeland, a comparison of fire activity (based on radiocarbon dating of charcoal in soil) to climate reconstructions (based on tree-ring records) over the last 2,000 years showed that fire episodes were more common during centuries that were wetter than average, and that fire activity peaked during drier than average decades within those centuries. For example, fire episodes were frequent during the relatively cool and wet Little Ice Age (AD 1350–1850) and most frequent around AD 1450—a period with several drier than average decades. In contrast, fire episodes were infrequent during the relatively dry Medieval Climatic Anomaly (AD 925–1280), with the exception of a wetter interval centered around AD 1100, when some fire activity was evident [233]. The positive relationship between fire occurrence and relatively wet periods has also been described in landscapes dominated by Wyoming big sagebrush and basin big sagebrush in central Nevada [202].

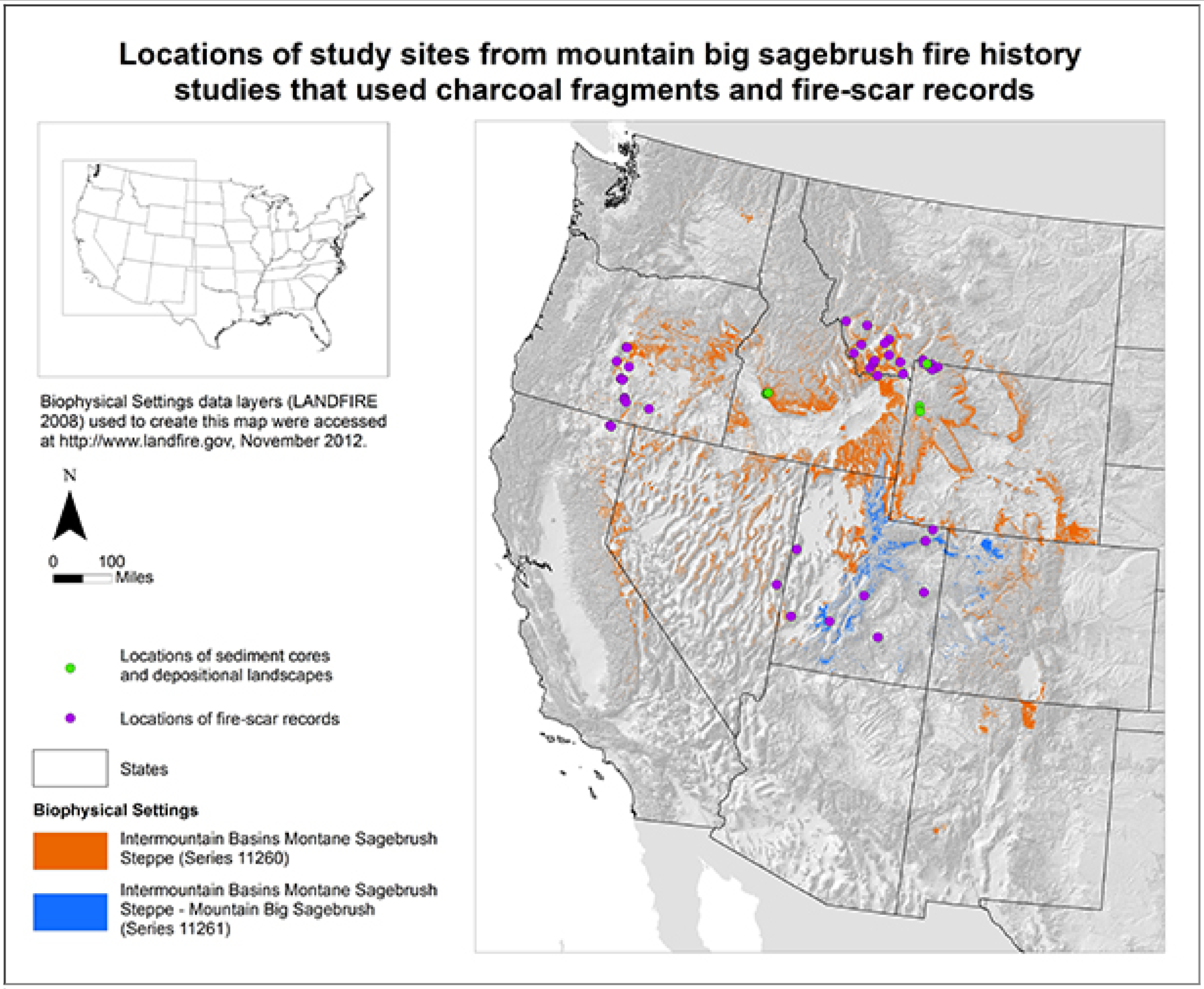


Figure 7—Locations of study sites with fire histories developed from charcoal analyses (green dots) or from fire scars on associated conifers (purple dots) in mountain big sagebrush steppe sites. Historical land cover distribution of mountain big sagebrush steppe is based on the LANDFIRE Biophysical Settings data layer [182]. Click on the map for a larger image.

Fire-scar Records

Fire interval estimates for big sagebrush communities derived from fire-scar records on recording trees intermixed with or adjacent to big sagebrush communities are widely cited in the literature; however, limitations of this approach have led to criticisms from several authors. For example, uncertainty regarding the frequency at which fires spread across ecotones between woodlands or forests and mountain big sagebrush communities makes the applicability and interpretation of fire-scar records for mountain big sagebrush communities uncertain (e.g., [16,296,323]). While observations in Utah, Nevada [159], Oregon, and California [220] suggest that presettlement fires commonly spread across these ecotones (see Historical Fuels: Amount and Continuity of Fuels), adjacent forest and woodland types vary across the range of mountain big sagebrush sites, and each has different historical fuel and fire regime characteristics. Therefore, results from individual studies may not be applicable to other locations. For example, estimates of fire frequency in mountain big sagebrush communities using fire-scar records on adjacent and intermixed ponderosa pines and Rocky Mountain Douglas-firs suggest relatively short fire intervals [13,48,66,117,126,135,214,220], and proximity to these fire-prone forest types may have led to more frequent fires in these mountain big sagebrush landscapes [153] than in those adjacent to less fire-prone types (e.g., pinyon-juniper) and those far from woodlands and forests. In addition, suitable proxy trees are absent from many big sagebrush sites and, where they are present, are often scarce and disproportionately distributed, so sample sizes are often small [158]. In some cases, associated trees may be located on "fire safe" sites such as rocky ridges with sparse fine fuels that are not representative of sagebrush sites [202,214].

Fire-scar records from conifers intermixed with or adjacent to mountain big sagebrush communities were available from 25 sites in six ecoregions (figure 7) and published in eight studies (see table A5 for study details). Among these sites, mean fire interval estimates were shortest for sites in the Eastern Cascades Slopes and Foothills and the western part of the Northern Basin and Range ecoregions, where ponderosa pine was the most common proxy species. In these ecoregions, composite mean fire intervals calculated from fire-scarred ponderosa pine trees intermixed with mountain big sagebrush steppe ranged from 6 to 24 years [48,117,214,220]. Mean fire interval estimates were generally longer (17-45 years) on sites in the Middle Rockies, where Rocky Mountain Douglas-fir was the most common proxy species [13,126,135]. A study examining fire-scarred ponderosa pine and other conifers intermixed with mountain big sagebrush communities in the Central Basin and Range, Colorado Plateaus, and Wasatch and Uinta Mountains ecoregions reported presettlement fire intervals (calculated as the mean number of years between fires from the first recorded fire to 1850) of 30.9 years for sites in which proxy trees were located within mountain big sagebrush communities (embedded chronologies), 41.2 years for sites in which proxy trees were located within 33 feet (10 m) of the forest-steppe ecotone (ecotonal chronologies), and 52.4 years for sites in which proxy trees were located on opposite sides of mountain big sagebrush communities and recorded fire during the same years (two-sided chronologies). Overall, mean fire intervals tended to be shorter for sites in the Central Basin and Range (24.8 years) than the Colorado Plateaus (61.3 years) or Wasatch and Uinta Mountains (39.9 years) ecoregions [160].

Critique of studies using fire scars on associated trees to estimate fire frequency in mountain big sagebrush communities is widespread in the published literature, with most suggesting that the fire intervals presented by some authors (e.g., [13,135,214]) are too short to allow for full mountain big sagebrush recovery, and that methods and related assumptions used in these studies led to overestimates of fire frequency [16,323]. For example, Houston [135] calculated presettlement (1485–1890) point mean fire intervals for mountain big sagebrush steppe in the Northern Yellowstone Winter Range of 32 to 70 years from 34 trees on seven sites. He also calculated presettlement composite mean fire intervals of 17 to 41 years by cross-dating fire scars on 2 or 3 trees from Rocky Mountain Douglas-fir forest-sagebrush steppe ecotones in each of six stands on four of the same sites. Based on these data and the assumption that fire frequency had been reduced by both fire suppression efforts and cessation of burning by American Indians since the park was established in 1872, Houston proposed 20 to 25 years as the "best estimate of the true fire frequency" after excluding the shortest and longest composite intervals from his dataset [135]. Many authors (e.g., [123,158,323,342]) suggested that fire intervals of 20 to 25 years were incompatible with big sagebrush dominance, and that his assumptions were dubious. Mean fire intervals suggested by Kitchen and McArthur [158] (40-80 years) were more similar to Houston's [135] pre-1890 point mean fire intervals (32-70 years) than his estimate of 20 to 25 years. Other researchers stated that horsebrush and rabbitbrush would dominate many sagebrush-grass communities in northern Idaho with fires that frequent [123,342]. Welch and Criddle [323] suggested that Houston was "overoptimistic" about how soon fire suppression became effective in Yellowstone National Park, and that it may not have been effective until the 1950s.

Miller and Rose [214] also estimated very short mean fire intervals for mountain big sagebrush communities in south-central Oregon based on fire-scarred ponderosa pines in four small clusters of trees scattered within a mountain big sagebrush-grassland matrix. Pre-1900 composite mean fire intervals were 12 to 15 years in three of the four clusters (n = 3 fire-scarred trees/cluster); the fourth cluster had only one fire-scarred tree, with a mean point fire interval of 27 years. Of the 25 fires identified, seven were "large" fires (i.e., they scarred trees in at least three clusters) [214]. Kitchen and McArthur [158] estimated an approximate return interval of 38 years for these seven large fires and concluded that this frequency estimate was likely "more realistic" for mountain big sagebrush stands than the short composite intervals, which would be too frequent to allow mountain big sagebrush to fully recover such that these stands would have been predominantly grasslands (see Postfire recovery) [158]. Welch and Criddle [323] agreed that the 38-year fire interval would be more compatible with maintaining mountain big sagebrush dominance than the shorter fire intervals reported by Miller and Rose [214]. Because grasslands likely burned more frequently than sagebrush communities, Baker [16,18] recommended caution in applying fire frequency estimates from sites that are predominantly grasslands to sagebrush stands if the goal was to maintain sagebrush, and he recognized that the areas studied by Houston [135], Arno and Gruell [13], and Miller and Rose [214] were historically �grasslands with scattered sagebrush�.

Presence of presettlement trees indicate that conifers established in mountain big sagebrush communities periodically, likely during the long fire-free intervals recorded by fire-scarred trees in some areas [13,18,126,145,159,210]. In southwestern Montana, a mean fire interval of 37 years recorded in fire-scarred Rocky Mountain Douglas-fir trees was considered adequate to exclude the trees from mountain big sagebrush communities. However, fire intervals ranged from 2 to 84 years, so trees could have established during the longer fire-free intervals [126]. In parts of the Central Basin and Range, Colorado Plateaus, and Wasatch and Uinta Mountains ecoregions of Utah and Nevada, the maximum interval between presettlement (prior to 1850) surface fires was 72 years in patches of conifer forests and woodlands surrounded by mountain big sagebrush communities, and 65 years in conifer forests and woodlands at ecotones with mountain big sagebrush communities [160], suggesting enough time for postfire recovery of conifers in these communities (see Postfire recovery). In the mountain big sagebrush-bluebunch wheatgrass-Thurber needlegrass plant association in Lava Beds National Monument, there were no live old western juniper trees, but scattered large western juniper snags with well-developed basal fluting indicated that some fire-free intervals were long enough in the past to allow for the establishment of some large trees (>80 years between fires) but not long enough for closed woodland to develop [210].

Fire Rotation Estimates

Fire rotation is the time it takes to burn an area equal to a landscape of interest [269]. Baker [21] calculates fire rotation by adding the areas of individual fires (surface and stand-replacing fires) in a particular area over some period of time, and dividing this time period by the fraction of the total area burned. For example, a fire rotation of 100 years means that fire will burn the entire landscape over a 100-year period and that each point in the landscape will burn, on average, once during that period [17]. Fire rotation is best calculated for an area that exceeds the largest fire expected in one rotation [211], and accurate estimates of fire rotation require a period of record at least as long as the fire rotation estimates, which is seldom available [11,60]. Because fire rotations do not directly consider variation across space or time, Miller et al. [211] considered them best used to examine relative differences among regions or relative changes within a particular region, noting that a region typically encompasses a range of plant associations and ecological sites. Thus, it is important to know something about the composition of plant associations and ecological site types included within the area being studied.

Fire rotations estimated using land-survey records

Historical fire rotations estimated from vegetation reconstructions based on General Land Office survey records from the late 1800s and early 1900s suggest that presettlement fire rotations in mountain big sagebrush landscapes varied widely among ecoregions (table A6). Bukowski and Baker [59,60] and Arendt [11] used vegetation descriptions in General Land Office surveys to reconstruct historical vegetation over large landscapes, and they used these reconstructions to identify burned areas. Burned areas were then used to calculate fire rotations in mountain big sagebrush landscapes that ranged from 10s of thousands to 100s of thousands of acres and encompassed a range of soil temperature and moisture regimes. Estimates ranged from 48 to 77 years for 36,982 acres (14,966 ha) in the Eastern Cascades Slopes and Foothills and Northern Basin and Range ecoregions to 588 to 2,139 years for 176,490 acres (71,423 ha) in the Wyoming Basin ecoregion [11,59,60]. The authors stated that all of the fire rotation estimates were likely long enough to allow full postfire recovery and extended periods of dominance by mountain big sagebrush [59]; and that "no clear explanation was apparent" for the very long fire rotations in the Wyoming Basin, although they suggest that the dry climate [60], the relatively complex topography, and the sparse, fuel-limited dwarf sagebrush communities in that ecoregion [20] may have contributed (see Contemporary Fire Pattern and Size). General Land Office surveys are generally limited both spatially and temporally, and the quality and validity of surveys vary, with information in survey notes sometimes ambiguous. For example, surveys are not available for all townships, and the period of observation in available surveys is limited to a few decades, while accurate fire rotation estimates require a period of observation at least as long as the fire rotation estimates [11,60].

Fire rotations in mountain big sagebrush within a matrix of pinyon-juniper woodlands
Baker [19] suggested that small patches of mountain big sagebrush within a matrix of pinyon-juniper woodland would have burned with the same frequency as the surrounding woodland. Fire rotations and fire cycles of ~400 to 600 years were estimated for stand-replacement fires in pinyon-juniper/mountain big sagebrush communities in the Central Basin and Range [33], Colorado Plateaus [99,278], and Southern California Mountains [313] ecoregions. See table A7 for details from these studies.

Fire rotations estimated using conversion factors
In 2006, Baker [16,17] introduced the concept of using multipliers:

1. to convert composite mean fire intervals to fire rotations, based on the relationship between these metrics for contemporary fires in ponderosa pine forests studied by Fulé et al. [105] in Grand Canyon National Park, Arizona [17]; and
2. to convert fire rotations from conifer communities to fire rotations in large patches (hundreds of hectares) of adjacent sagebrush, based on contemporary fire frequency data showing that ponderosa pine and Douglas-fir communities burned more frequently than sagebrush communities [16]. In 2011, Baker [19] stated that his initial "adjacency correction" was "incorrect", and he calculated a new adjacency correction based on contemporary fire rotations in pinyon-juniper and sagebrush communities showing that pinyon-juniper burned less frequently than sagebrush.

Baker [19] applied his conversion factors to fire frequency estimates published in other studies (i.e., [13,33,66,135,214,278]) to estimate fire rotations in mountain big sagebrush communities, and he presented these data in a table (table 11.1, page 192, [19]). These data are problematic for several reasons including the following:

1. Baker applied conversion factors (3.6 and 16.0)—intended to convert composite mean fire intervals to fire rotations—to data from four published studies that assessed fire scars on adjacent and intermixed conifers to estimate fire frequency in mountain big sagebrush communities (i.e., [13,66,135,214]); however, these data were not all composite mean fire intervals (e.g., frequency estimates from Burkhardt and Tisdale [66] and Houston 1973 [135] were based on several factors including point fire intervals).
2. The upper range estimate of several fire rotations was miscalculated (i.e., multiplied by both 3.6 and 16.0).
3. The relationship between fire frequency in conifer communities and "sagebrush" communities in general likely differs from that between conifer communities and mountain big sagebrush communities in particular.
4. In his attempt to establish an adjacency correction factor for converting fire rotations in conifer communities to fire rotations in adjacent sagebrush, Baker failed to acknowledge that, because different conifer communities have fire regimes that differ substantially from one another, some conifer types probably burned more frequently while others burned less frequently than mountain big sagebrush communities. Although he initially recognized that ponderosa pine and Douglas-fir forests burned more frequently than sagebrush communities [16], he discarded his initial adjacency correction factor of 2.0 because it was not based on fire rotations. He instead used contemporary fire rotations from pinyon-juniper and sagebrush communities to calculate an "improved" adjacency correction factor of 0.57, and applied this to frequency estimates derived not only from pinyon-juniper communities [33,66,278], but also to estimates derived from Douglas-fir communities [13,135].

In addition to the above points, McAdoo et al. [193] noted that Baker's [16,19] conversion factors are based on relationships between metrics from contemporary fires in landscapes with a history of grazing and altered species compositions, and may not represent presettlement relationships.

Historical Fire Type, Severity, and Intensity

Historically, wildfires in mountain big sagebrush communities were high-severity, stand-replacement surface and crown fires [16,19] that burned at low or moderate intensity [220,264]. Mountain big sagebrush is easily killed by fire [42,55,76], and its cover and density in a stand are typically reduced by more than 75% in contemporary wildfires (e.g., [8,16,42,168,186,196,257,305]), which are therefore considered high-severity, or stand-replacement fires by LANDFIRE's definition [26,181]. Like contemporary wildfires (e.g., [139,185,199,262,264,310,358]), historical wildfires in mountain big sagebrush communities were thought to have been high-severity, stand-replacement fires [16,19]. Although fires may leave patches of unburned vegetation within fire perimeters (i.e., mosaic fires), they are not mixed-severity fires by LANDFIRE's definition [26,181].

Studies of contemporary fires in mountain big sagebrush communities typically do not report fire severity. Of those that do, most describe >75% reduction of mountain big sagebrush cover in burned areas following both wildfires [185,199,262,320,358] and prescribed fires [168,185,303] in mountain big sagebrush communities. Studies of prescribed burns that created fire mosaics in a mountain big sagebrush community in western Wyoming [257] and Wyoming big sagebrush communities in southeastern Oregon [344] reported that nearly all biomass was consumed in burned portions of the mosaics (see Historical Fire Pattern and Size for more information about mosaic fire).

Most LANDFIRE models place mountain big sagebrush steppe Biophysical Settings in replacement severity fire regime groups (II and IV) and suggest that 100% of fires were replacement severity. However, models in two map zones (1011260 and 1911260) place these Biophysical Settings in a mixed-severity fire regime group (I) and suggest that 74% of fires were mixed severity (table 1). These models may have applied mixed-severity incorrectly due to a change in LANDFIRE's fire severity definitions. Mixed-severity fires are currently defined by LANDFIRE as those that top-kill 25% to 75% of the dominant life form (e.g., shrubs in a shrubland), whereas replacement severity fires top-kill >75% of the dominant life form [177]. Our review of fire history studies in mountain big sagebrush communities and that of Baker [16] found no evidence of mixed-severity fire historically, suggesting that all mountain big sagebrush steppe Biophysical Settings should be placed in replacement severity fire regime groups.

Reviews of fire regimes in mountain big sagebrush communities describe historical fire intensity as mostly low—based on the assumption that sagebrush communities typically had abundant, continuous fine fuels and widely scattered and patchy shrub cover [220]—or moderate [264], presumably for areas with greater shrub cover. Intensity of individual contemporary fires in sagebrush communities ranges from low to high due to variation in fuel characteristics, weather, and topography [271,275]. Brown [58] quantified fuel properties and modeled fire behavior for mountain big sagebrush and Wyoming big sagebrush in Montana and Idaho to show how rate of spread and fireline intensity varied with big sagebrush height, percent cover, foliage moisture, and fraction of dead stemwood. Modeled fireline intensity for big sagebrush greater than about 24 inches (60 cm) tall was low (about 500 kW/m) when vegetation was uncured in spring and moderate (about 2,000 kW/m) when vegetation was cured in fall. However, observed fireline intensity during four prescribed fires in a variety of sagebrush communities indicated that modeled fireline intensities were 3 to 6 times lower than those observed in the field [58]. Fireline intensity in basin big sagebrush communities was moderate (880 kW/m) in a spring prescribed fire and high (6,400 kW/m) in a fall prescribed fire due to greater total aboveground biomass and lower fuel moisture content in the fall burn [271]. Fireline intensity during prescribed fires is likely to be lower than is typical in late-summer wildfires [344].

Historical Fire Pattern and Size

Introduction

Although it is difficult to reconstruct the sizes and shapes of past fires in big sagebrush communities [16,19], fire size distributions estimated using General Land Office survey records from Colorado [59], Idaho, Nevada, Oregon, and Wyoming [60] suggested that fires were mostly small (less than ~1,200 acres (500 ha)), and that large fires (>24,700 acres (10,000 ha)) were historically infrequent. Fires of all sizes were stand-replacing and left <4% of the area within burn perimeters unburned [19,59,60]. For example, using General Land Office survey records from 1872 to 1892 to reconstruct historical vegetation patterns in west-central Colorado, Bukowski and Baker [59] identified areas thought to have burned within 541,000 acres (219,000 ha) of mountain big sagebrush, Wyoming big sagebrush, mixed sagebrush-mountain shrubland, and associated grassland communities. Based on those reconstructed historical fires, they inferred a pattern of infrequent large fires and more frequent smaller fires. This fire-size distribution was inverse-J shaped with a geometric mean patch size of 380 acres (154 ha) and mean fire size of 524 acres (212 ha). Analyses also suggested that presettlement fires >1,200 acres (500 ha) had little unburned area within the burn perimeter, although the authors cautioned that the amount of unburned area may have been underestimated due to the coarse resolution of the land-survey records [59]. Using similar methods, these authors described similar historical fire patterns and sizes in >5.4 million acres (2.2 million ha) of mountain big sagebrush, Wyoming big sagebrush, and other sagebrush communities in Idaho, Nevada, Oregon, and Wyoming [60]. Few other studies provide information on presettlement fire sizes and patterns in sagebrush communities. One study in southwestern Montana found that historical surface fires ranged from 22 to 746 acres (9-302 ha) based on reconstructions from 83 fire-scarred Rocky Mountain Douglas-fir and Rocky Mountain lodgepole pine trees on a landscape historically dominated by Rocky Mountain Douglas-fir savanna and mountain big sagebrush-grassland [126]; no information was available about the burn pattern of these fires.

Simulation models of postfire recovery times suggest that presettlement fires were mostly small, and large fires were mosaic fires, with many unburned patches [159]. These models also suggest that the occurrence of mosaic fires has a pronounced effect on fire rotation estimates [95]. Models of a 1.5-mile² (4-km²) virtual landscape indicated that full recovery of mountain big sagebrush canopy cover after fire (i.e., ≥20% mountain big sagebrush cover) was only compatible with fires that were <25 acres (10 ha) when fires were simulated at 50-year fire rotations and <74 acres (30 ha) when fires were simulated at 80-year fire rotations. Larger, uniformly high-severity fires would have been infrequent because they required a much longer fire-free period for full recovery [159]. State-and-transition models of cool, relatively moist mountain big sagebrush/Idaho fescue communities in southeastern Oregon indicated that varying the probability of mosaic fire altered the fire rotation substantially. When mosaic fire was not included in the model, the fire rotation was estimated at 182 years. When mosaic fire was included in the model at the maximum probability (two times the initial probability), the fire rotation was estimated at 50 years [95].

The habitat requirements of sagebrush obligates also support the idea that mosaic fires were common. For example, greater sage-grouse prefer large, contiguous sagebrush habitats of varying cover and density with small, scattered openings [94,245], suggesting that large, uniformly stand-replacement fires were rare [153]. The relative abundance of pronghorn in some areas of the Great Basin during presettlement times suggests that fires may have been patchy historically [193], because pronghorn generally benefit from fires that create openings in dense sagebrush habitats [128,156,348]. A review of ecological literature, historical accounts, and explorer reports concluded that bird communities in sagebrush habitats depend on a mosaic of native plant communities and successional stages and that "spotty and occasional wildfire probably created a patchwork of young and old sagebrush stands across the landscape" prior to European-American settlement [241]. For information on habitat requirements of sagebrush obligates, see their FEIS Species Reviews and the Species Review about mountain big sagebrush.

In contemporary sagebrush communities, small fires are far more common than large fires [98,125]. For example, between 1992 and 2012, 33,782 fires occurred in greater sage-grouse habitat in the western United States. During this time, 53% were <1 acre (0.4 ha), 79% were <10 acres (4 ha), and 97% were <1,000 acres (400 ha); only 0.7% were >10,000 acres (4,000 ha) [125]. Analyses from national forests in Colorado suggested that small fires (<10 acres (4 ha), 91%) were more common than large fires (≥10 acres and <300 acres (120 ha), 9%) in "grass-sage" communities, and large fires accounted for only 13% of the total area of grass-sage communities burned from 1960 to 1973 (2,525 acres (6,239 ha)) [98]. Data are lacking from sagebrush communities in other regions and from mountain big sagebrush communities in particular. In addition, available data are from contemporary fires, which likely differed from historical fires because of habitat fragmentation, cheatgrass invasion, fire suppression, and livestock grazing [96,283] (see Contemporary Fire Pattern and Size).

Large Fire Frequency
Periodic large fires were likely most frequent on productive, contiguous expanses of mountain big sagebrush communities on landscapes where natural fire breaks were sparse, topography was level, fuels were dense and continuous, fuel moisture was low, multiple fire starts occurred, and winds were strong [19,47,125,153]. Presumably, large fires under these conditions would also have been less likely to have unburned patches within their perimeters (see Historical Fire Type, Severity, and Intensity). Large fires were less frequent on landscapes where mountain big sagebrush communities intermixed with natural fire breaks, such as rivers and streams, canyons, rock outcrops and talus, sand dunes, wetlands, or other areas with limited or moist fuels [19], including low sagebrush and black sagebrush communities with sparse fuels that burned only under severe weather conditions [47,175,297].

Historically, large fires in big sagebrush ecosystems may have occurred the year after one or more years with above-average precipitation that promoted fine fuel production [214]. Only one fire history study [214] examined presettlement fire-climate relationships for large fires in mountain big sagebrush. This study found that most large or "extensive" fires in mountain big sagebrush/Idaho fescue communities in the Upper Chewaucan River basin near Paisley, Oregon, occurred during years with near-average precipitation and were generally preceded by years with above-average precipitation [214]. Studies of contemporary fire-climate relationships in semiarid regions of the western United States reveal similar patterns between antecedent precipitation and widespread fires (e.g., [161,188,331]), and some suggest that large or widespread fires may have also occurred in big sagebrush communities during hot, dry summers that followed a relatively wet winter or spring (e.g., [41,118,188]).

However, this relationship may not be as strong for relatively cool, moist mountain big sagebrush sites as for relatively warm, dry Wyoming big sagebrush sites (e.g., [22]) because fine fuels are less often limiting on mountain big sagebrush sites, especially prior to widespread livestock grazing (see Amount and Continuity of Fuels). In the Great Basin from 1980 to 2000, both individual fire size and number of fires in mountain big sagebrush cover types had poor correlations to preceding year's precipitation ($r^2 = 0.02$ for both comparisons), while preceding year's precipitation explained 12% of variation in fire size ($r^2 = 0.12$) and 13% of variation in number of fires ($r^2 = 0.13$) in Wyoming big sagebrush, basin big sagebrush, and mixed sagebrush types [22]. The relationship of contemporary fire size or total area burned with antecedent precipitation is likely driven by fine fuels from nonnative annual grasses, particularly cheatgrass [22,161], which are less invasive in mountain big sagebrush communities (but see Nonnative Invasive Plants) and do not have an historical analog (see Contemporary Fire Pattern and Size).

CONTEMPORARY CHANGES IN FUELS AND FIRE REGIMES

INTRODUCTION
Since European-American settlement, fuel and fire regime characteristics in many big sagebrush communities have shifted outside the range of historical variation. Settlement generally began in the mid-1800s and caused

changes in ignition patterns and fuel characteristics, although the timing and magnitude of these changes varied among locations [216]. Since then fuels and fire regimes in many sagebrush ecosystems have changed due to a combination of interrelated factors, including livestock grazing and associated land management, land development for agriculture and energy, urbanization and infrastructure development, proliferation of nonnative invasive plants, woodland expansion, and climate changes [43,52,78,120,164,211,216,222,227,321]. In total, about a third of the land formerly occupied by sagebrush communities has been converted to nonnative grasslands, conifer woodlands, and other cover types [211], and additional areas of big sagebrush are under threat of conversion [63,284]. Of the 20.4 million acres (8.3 million ha) of sagebrush cover types present in the Great Basin region of California, Nevada, and Utah in 2005, 58% was estimated to be at moderate or high risk of displacement by cheatgrass during the next 30 years, and of the 12.0 million acres (4.8 million ha) of sagebrush cover types in the eastern Great Basin, 41% was estimated to be at moderate or high risk of pinyon-juniper expansion. Mountain big sagebrush cover types comprised only 13% of the total sagebrush area in the Great Basin, and 9% of that area was at moderate to high risk of displacement by cheatgrass. Mountain big sagebrush cover types comprised 15% of the total sagebrush area in the eastern Great Basin, and 60% of that area was at moderate to high risk of pinyon-juniper expansion. Combined, almost 90% of the area occupied by sagebrush cover types in the eastern Great Basin, including 65% of the area occupied by mountain big sagebrush types, was estimated to be at moderate or high risk from at least one of these threats [284]. Climate change scenarios predict that mountain big sagebrush communities are likely to decrease in range due, in part, to increased threat of nonnative annual grass invasion, woodland expansion, or a combination of these factors [96] (see Climate Change).

CONTEMPORARY PLANT COMMUNITIES AND FUELS

- **Woodland Expansion**
- **Nonnative Invasive Plants**
- **Changes in Herbivory**
- **Climate Change**

Woodland Expansion
Since European-American settlement, density of junipers and pinyons has increased in many sagebrush and woodland communities [208,218,268], while it has not changed or has declined in others [268]. In areas where conifer expansion into big sagebrush communities has occurred, the peak rate of expansion occurred during a relatively wet and mild period between 1850 and 1916 (e.g., [92,106,144,205,208,217,218,268,289,333,342]). In seven study areas in Idaho, Oregon, Nevada, and Utah, the area occupied by singleleaf pinyon, western juniper, or Utah juniper increased by 125% to 625% between 1860 and 2001. The period of most rapid woodland expansion was not synchronous among all sites but occurred from 1880 to 1920 in Idaho and from 1900 to 1920 in Oregon, Utah, and Nevada [218]. In the central and northern Rocky Mountains, Rocky Mountain lodgepole pine [38] and Rocky Mountain Douglas-fir [13,14,106,114,115,126] densities have also increased in mountain big sagebrush stands, but these stands are less studied. Evidence for the increase comes from descriptions of explorers and early settlers, old photographs, stand age and structure, fire-scar records, and pollen cores taken from pond sediments and woodrat middens [92,119,159,205,213,220,224].

The greatest proportion of conifer expansion has occurred on cool to warm, relatively moist sagebrush sites, particularly in mountain big sagebrush communities and low sagebrush communities on moderately deep soils. Conifer expansion has also occurred on relatively cool, moist sites in black sagebrush and Wyoming big sagebrush communities [144,208,211] (see the Species Review about mountain big sagebrush).

The combined effects of climate variability and varied fire frequency were likely the primary drivers of juniper and pinyon range expansion and contraction since prehistoric times, and they continue to be driving forces on contemporary landscapes, along with other interacting effects, including overgrazing by livestock and carbon dioxide fertilization [92,205,224,268] (see Conifer Distribution).

Some authors have attributed juniper expansion since European-American settlement to the effects of a wet, mild climate in the late 19th and early 20th centuries coincident with decreased fire frequency (e.g., [65,66,217]), while other authors debate the role of decreased fire frequency in explaining juniper expansion (e.g., [60,92]). Miller et al. [217] suggested that postsettlement western juniper expansion during the late 1800s and early 1900s was driven by mild temperatures and above-average precipitation that promoted conifer establishment and growth and decreased fire frequency that allowed western juniper trees to mature and dominate a site. Decreased fire frequency was attributed to the reduction in American Indian burning and the reduction of fine fuels by heavy livestock grazing [217]. Burkhardt and Tisdale [65,66] examined several possible causes of and contributing factors to succession of sagebrush-grasslands to western juniper woodlands, and concluded that it was directly related to the combined effects of changes in climate and reduced fire frequency and spread due to fire control and prevention, reduced fine fuels due to livestock grazing, and fragmentation of sagebrush communities due to other land uses. Bukowski and Baker [60] stated that fire regimes in sagebrush communities are primarily controlled by weather or climate, and concluded that fire rotation estimates for mountain big sagebrush communities in four areas of Idaho, Nevada, Oregon, and Wyoming were generally too long for fire to be the only factor preventing conifers from establishing (see Historical Fire Frequency: Fire rotations estimated using land-survey records). Eddleman et al. [92] considered the effects of fire suppression to be insufficient to explain western juniper expansion until after World War II, when suppression efforts became more effective. Grove [114] stated that even if fire exclusion was not a primary cause of conifer expansion, it allows it to continue unabated. Juniper and pinyon-juniper woodlands are likely to continue expanding into big sagebrush communities on susceptible landscapes [63,218,284,339] (see Climate Change).

While conifer expansion is a concern in many big sagebrush communities, tree density and canopy cover have not changed or have declined in many pinyon-juniper communities in the western United States (e.g., [53,190,268]). Romme et al. [268] cautioned that "one cannot necessarily assume that pinyon and juniper are increasing in density in any particular portion of their range without local data". In Dinosaur National Monument and the surrounding area, a comparison of historical vegetation reconstructed using General Land Office survey records from 1904 to 1911 with contemporary vegetation records showed a net decline in pinyon-juniper woodlands and mixed montane shrublands and an increase in sagebrush steppe (a combination of mountain big sagebrush, Wyoming big sagebrush, and basin big sagebrush communities). Shorter fire rotations since European-American settlement due to the high amount of prescribed burning (see Fire Rotations Estimated Using Contemporary Fire Records) appeared to be driving the decline. However, some pinyon-juniper expansion was evident near historical pinyon-juniper-sagebrush ecotones, particularly at 6,600 to 7,900 feet (2,000-2,400 m) and on 10% to 30% slopes [11].

Potential consequences of increasing tree dominance in sagebrush communities include: 1) an increase in woody fuel loads and changes in fuel structure that increase the potential for high-intensity, stand-replacing crown fires and subsequent establishment and spread of nonnative species (see Historical Fuels: Kinds of Fuels); 2) changes in plant community composition and structure, including reduced cover of sagebrush, native grasses, and forbs; 3) an increase in aboveground carbon and nutrient pools; and 4) a reduction in water infiltration and increase in soil erosion [32,87,114,208,217,248,325]. These changes result in plant communities that are less resilient to fire and other disturbances and less resistant to nonnative annual grass establishment and spread after fire [208].

Figure 8—Photographs of a) mountain big sagebrush steppe, b) midsuccessional western juniper woodland, and c) late-successional western juniper woodland in southwestern Idaho. Note changes in plant community composition and structure, including reduced cover of mountain big sagebrush, native grasses, and forbs as tree dominance increases. Images from Strand et al. [282] and used with permission.

Nonnative Invasive Plants
Of the nonnative invasive plant species present in mountain big sagebrush communities, annual grasses pose the biggest threat 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 [10,22,163,187,211,243], such that mountain big sagebrush cannot regenerate [298], a grass/fire cycle establishes, and plant communities are converted to annual grasslands [22,57,84,166,284].

Nonnative invasive annual grasses of concern in big sagebrush communities include cheatgrass, medusahead, and ventenata [80,147,270]. Among these, cheatgrass is the most widespread and has been the most harmful thus far [279], and large areas of big sagebrush—especially Wyoming big sagebrush and basin big sagebrush—have converted to cheatgrass grasslands as a consequence of frequent wildfires [22,84,166,284]. Although mountain big sagebrush communities are among the least susceptible of sagebrush communities to annual grass invasion [73,206,207], it is a growing concern (e.g., [50,147]). Cheatgrass is especially invasive on relatively warm, dry big sagebrush sites, where average annual precipitation is 8 to 12 inches (200-300 mm) [73], and predicted climate changes are likely to make additional mountain big sagebrush sites vulnerable to cheatgrass establishment and spread [242]. In addition, medusahead [253] and ventenata [147] are at the early stages of invasion in some sagebrush steppe ecosystems, and continue to expand their ranges. In the Great Basin, medusahead is most invasive in areas where mean annual precipitation exceeds 12 inches [253], and in drier areas it is most invasive and can displace cheatgrass on relatively moist sites (e.g., in soils with high clay content and in swales) [85,129,352]. A study of sagebrush steppe in eastern Oregon and southwestern Idaho [147] suggests that ventenata, like medusahead, was located primarily in relatively moist areas, including areas that received relatively more precipitation, clayey soils, and topographic positions that retain water. At elevations above 4,760 feet (1,450 m), ventenata was most abundant in areas dominated by mountain big sagebrush (which occurs in a relatively higher precipitation zone) and low sagebrush (which favors poorly drained, shallow clay soils). At elevations below 3,300 feet (1,000 m), ventenata was most abundant in areas characterized by extensive annual grass complexes dominated by medusahead. Based on these observations and additional observations in the Inland Northwest, the authors suggest that ventenata is most likely to initially establish on relatively moist sites, but that it may then spread to drier sites [147].

Factors that result in depletion of native perennial herbaceous species—such as overgrazing by livestock and establishment and growth of trees—are likely to decrease a mountain big sagebrush community's resistance to the establishment and spread of nonnative invasive annual grasses and resilience to fire and other disturbances [56,72]. For example, where dense juniper stands have established in mountain big sagebrush communities, native perennial understories are depleted, and fires are more likely to result in conversion to nonnative annual grasslands if nonnative annual grasses are present [286,287] (see Woodland Expansion).

Changes in Herbivory
Herbivory impacts have changed from prehistorical to historical to contemporary times. Prehistorically, Pleistocene megafauna heavily used sagebrush steppe and were probably the most prevalent natural disturbance in sagebrush ecosystems. These large native herbivores became extinct between 12,000 and 10,000 years ago. From about 7,000 years ago to the present, remnant medium-sized herbivores included American bison, elk, moose, deer, pronghorn, bighorn sheep, and mountain goat. American bison occurred in the Intermountain West as well as the prairies until the late 1700s or early 1800s when they became extinct in many areas [64]. The earliest historical accounts of exploration in the Intermountain West suggest that the overall landscape at the time of European-American contact at the beginning of the 1800s supported only scattered herds of remnant, medium-sized herbivores, but mule deer, elk, and pronghorn were regionally abundant [64,216]. It is unknown how these remnant herbivores affected mountain big sagebrush plant communities and fuels historically, but wild ungulates often browse heavily on contemporary mountain big sagebrush plants to the extent that they may cause injury and slow postfire recovery (e.g., [132,199,306,307,310,311]).

European-American settlers introduced new herbivores: domestic livestock [64,118,216]. Livestock grazing and associated habitat alterations have had the most widespread impact on western ecosystems of any land use [164]. Overgrazing by domestic livestock during the late 1800s and early 1900s triggered a rapid change in sagebrush plant communities, resulting in the spread of undesirable species in many areas by reducing native perennial herbaceous plants and disturbing biological soil crusts [36,80,89,118,183,261,296]. Added to the threat of livestock grazing itself was a policy of aggressive sagebrush reduction adopted by land management agencies, intended to convert sagebrush types to grasslands for seasonal grazing by livestock. The amount of area treated with prescribed fire, herbicides, and mechanical methods peaked in the late 1950s and 1960s [68,118,192,209,227] (see Ignitions by Land Managers). These efforts included seeding with nonnative grasses, primarily crested wheatgrass, which affected approximately 6.4 million acres (2.6 million ha) of sagebrush lands by the 1970s [164]. This past management has had legacy effects on the composition and diversity of sagebrush steppes, and many sites have not recovered [265].

Climate Change

Under contemporary climate conditions, both conifers and nonnative annual grasses have the potential to dominate even larger areas of the sagebrush biome [284,339], and future climate changes are likely to exacerbate this trend [81,103,211,232,273,276]. Climate change models for the sagebrush biome predict increasing temperatures, increasing atmospheric carbon dioxide, more frequent episodes of severe weather (droughts and storms), decreasing snow pack, and variable changes in precipitation [70,211]. Projected effects of climate changes on sagebrush ecosystems are varied, but many projections predict widespread vegetation shifts by the end of the century, with some locations becoming less suitable for sagebrush and others becoming more suitable [49,81,211,232,273,274]. Under most climate change projections (i.e., warmer temperatures and higher precipitation), sagebrush ecosystems are expected to recede as frost-sensitive, warm-desert vegetation expands from the south, and lower elevation boundaries of woodlands are expected to move downslope into sagebrush communities. In addition, sagebrush ranges are expected to become increasingly fragmented and threatened by nonnative grasses (e.g., [81,103,232,273,276]). If precipitation increases, sagebrush ecosystems in the Great Basin may recede as frost-sensitive, warm-desert vegetation expands from the south, and lower-elevation boundaries of woodlands move downslope into sagebrush communities. If precipitation decreases, frost-sensitive, warm-desert vegetation may still expand into sagebrush ecosystems from the south, but lower-elevation boundaries of woodlands may move upslope instead of down [232].

While few studies have examined the potential effects of projected climate changes on mountain big sagebrush communities, most suggest that they will decrease in range. Mountain big sagebrush is predicted to lose as much as 68% of its currently suitable range by the end of the 21st century under modeled climates that include warmer winter temperatures. Substantial range losses are projected under all modeled future climate conditions, largely because in some areas mountain big sagebrush does not have many high-elevation sites to retreat into [290]. Evers [96] modeled three potential future climate scenarios in southeastern Oregon: the first with warmer and drier conditions year-round, the second with warmer and wetter conditions in winter, and the third with warmer and wetter conditions in summer. All scenarios predicted a reduction or near elimination of the area covered by cool, moist mountain big sagebrush communities [96]. Simulations of climate change in mountain big sagebrush steppe, Wyoming big sagebrush-basin big sagebrush steppe, and Wyoming big sagebrush-basin big sagebrush shrublands throughout the Intermountain West predicted the greatest increases in spring soil moisture and the greatest decreases in summer soil moisture in mountain big sagebrush steppe sites. The authors stated that warmer temperatures and wetter winter and spring conditions could result in mountain big sagebrush steppe sites becoming increasingly suitable to cheatgrass establishment and spread [242].

CONTEMPORARY FIRE REGIMES

Introduction

Historical fire regimes of mountain big sagebrush communities are not fully understood because evidence and records of historical fires are limited (see Historical Fire Regimes: Introduction), which makes it difficult to assess whether fire regimes have changed. Comparison of historical and contemporary fire records are confounded by 1) an increase in reporting efforts over time, 2) different levels of reporting among regions, 3) lack of record-keeping in some districts until the 1980s, 4) lack of GIS-based fire data until the 1990s, 5) and absence of a single source of GIS-based fire data until 2004 [211,315]. Available evidence suggests that changes in fuels and fire regime characteristics since European-American settlement resulting from woodland expansion, nonnative plant invasions, changes in herbivory by livestock and wildlife, changes in fire ignitions, fire exclusion, and climate change have caused some mountain big sagebrush communities to shift outside the range of historical variation, particularly those in parts of the Colorado Plateaus, Middle Rockies, Northern Basin and Range, and Snake River Plain ecoregions [11,13,20,60,117,126,135,214,217,220]. However, little is known about changes in fuels and fire regimes in many ecoregions, and sagebrush communities differ in their resilience to stress and disturbance and their resistance to nonnative plant invasions, so it is important for managers to collect site-specific information about historical disturbance regimes and landscape dynamics prior to initiating treatments intended to restore plant communities to their historical conditions [60,208,268]. Resilience and resistance vary along climatic, elevational, and productivity gradients (e.g., [54,56,71,72,73]) (figure 3), and information on soil moisture and temperature regimes can help predict potential effects of treatments.

Contemporary Fire Ignition

American Indian Ignitions

While American Indian influence on historical fire regimes is not fully understood due to a scarcity of historical records (see Historical Fire Ignition: American Indian Ignitions), it is clear that this influence was reduced by the end of the 1700s. By that time, American Indian populations throughout the Intermountain West had been reduced by about 80% as a result of diseases introduced from Europe [92,224]. While the number of American Indian-set fires was in decline, they were still reported by early explorers and European-American settlers during the 1800s [116]. By the mid- to late 1800s, American Indians had been relocated to reservations, and their scope of influence on the landscape was severely diminished [119,126,213].

Some authors have suggested that the decrease in American Indian ignitions was largely responsible for reduced fire frequencies in sagebrush communities (see Contemporary Fire Frequency), which contributed to subsequent juniper and pinyon expansion in some areas [119,126] (see Woodland Expansion).

Ignitions by European-American Settlers

Immediately following initial settlement of the West by European-Americans, human-caused ignitions were thought to be even more common in some sagebrush communities than they were historically [23,76,92,250]. Early European-American settlers in the West burned sagebrush communities to produce more grass for domestic horses, sheep, and cattle and to clear land for farming [241,246]. In some places [353], "indiscriminant" and "excessive" burning practices, combined with the introduction of and land management for livestock, contributed to rangeland degradation and eventual conversion of many sagebrush steppe communities to nonnative annual grasslands [23,76,92,250]. Perceived increases in sagebrush after European-American settlement have been attributed in part to recovery from these burning practices [86] (see Sagebrush Distribution). Indiscriminate burning practices led to policies during the early 1900s that discouraged ignitions and required fire suppression [23,76,92]. Indiscriminant burning was gradually reduced with the establishment of the Forest Service within the U.S. Department of Agriculture in 1905 and further reduced with the formation of the U.S. Department of the Interior's Grazing Service in 1934 [23] and Bureau of Land Management in 1946 [118]. Fire suppression was considered minimally effective until after World War II, when aerial fire suppression efforts expanded [19,92].

Ignitions by Land Managers
While indiscriminant burning was reduced, land managers continued to use prescribed fire and other manipulations to reduce sagebrush cover and density in an effort to increase grass production for livestock and wildlife forage from the 1930s through the 1970s, and to a lesser extent thereafter [36]. Mountain big sagebrush communities were frequently targeted [345]. Vale [299] reported that by 1974, about 10% to 12% of 99 million acres (40 million ha) of big sagebrush rangeland in North America had been managed to reduce big sagebrush cover and increase grass production (see Changes in Herbivory). In some areas, shorter fire rotations in mountain big sagebrush communities since European-American settlement may be due to frequent prescribed burning [11] (see Fire Rotations Estimated Using Contemporary Fire Records).

Contemporary Lightning- and Human-caused Ignitions
Although humans still cause many fires, most contemporary wildfires in sagebrush communities are lightning-caused [113,125,162]. Like presettlement American Indian-set fires [27,113,119], contemporary human-caused fires are more likely to occur along travel routes, in populated areas [30,113,211], and outside of the peak fire season [113] than lightning-caused fires. For example, an analysis of fires from 1986 to 1996 in the Great Basin and surrounding mountains indicated that 67% of all fires were lightning-caused. While human-caused ignitions accounted for only 32% of fires, they accounted for 80% of ignitions between October and April. Human-caused ignitions were greatest in the northern portion of the Great Basin, particularly near populated areas such as the Wasatch Front in Utah, the Snake River Plain in Idaho, and along the highways following the Snake and Humboldt rivers in Idaho and Nevada [113]. Of 3,465 fires ignited during 2006 on or adjacent to lands managed by the Bureau of Land Management in Colorado, Idaho, Montana, Oregon, Utah, Washington, and Wyoming, 24% were caused by humans; and human-caused fires within the sagebrush range were associated with roads [211]. From 2005 to 2014, 8,028 fires burned in greater sage-grouse habitat throughout the western United States. Of these, 5,760 were lightning-caused (72%), and 2,268 were human-caused (28%) [125]. On the Modoc National Forest, where sagebrush communities are widespread, many fires were started by trains in the early 1900s and as railroad and highway traffic increased over time, so did the number of ignitions along travel corridors [264].

Nonnative annual grasses may alter lightning ignition rates on invaded sagebrush sites. Based on records of lightning-caused fires from 1980 to 1995 in native and nonnative grasslands, sagebrush steppes, and savannas in the Intermountain West—on sites where nonnative annual grass cover was high—ignition frequency increased on dry, low-elevation sites and decreased on relatively mesic, higher-elevation sites, compared to uninvaded sites. Dry, low-elevation sites historically had sparse, discontinuous fuels, and nonnative annual grass invasion increased fine fuel abundance and continuity, thus increasing ignition frequency. Relatively mesic, higher-elevation sites historically had more abundant, continuous fuels than drier sites such that annual grass invasion had less impact on fine fuel characteristics. Lower ignition frequency on invaded mesic sites was attributed to a recent history of large fires in areas dominated by nonnative annual grasses that decreased the likelihood of subsequent ignitions until sufficient fuels had accumulated [162] (see Cheatgrass and Fire Spread).

Contemporary Fire Season
Contemporary fire seasons have lengthened due to human-caused fires, annual grass invasions, and climate change. Contemporary human-caused fires lengthen the fire season in the sagebrush biome because they often occur outside the lightning season [30,113], although it is unclear how the fire season of human-caused fires differs between presettlement and postsettlement times due to the scarcity of information on American Indian burning (see Historical Fire Ignition: American Indian Ignitions). An analysis of fires from 1986 to 1996 in the Great Basin and surrounding mountains indicated that most (80%) ignitions between October and April were human-caused, while most (65%) lightning-caused fires occurred between June and September [113].

The introduction and spread of cheatgrass in sagebrush ecosystems has changed the seasonal occurrence of wildfires on sites where it has become dominant [41,247,263,329,332,350]. Because cheatgrass matures and desiccates earlier than most native herbaceous species it replaces, wildfires in cheatgrass-dominated communities tend to occur earlier in the season, when native perennials are more susceptible to injury from fire [349,350]. Cheatgrass can also carry fire 1 to 2 months later than native perennial grasses in fall [243]. Thus, cheatgrass invasion can lengthen the fire season by 1 to 3 months in sagebrush ecosystems [267].

Climate change in the late 1900s and early 2000s has been lengthening fire seasons and is likely to continue to lengthen fire seasons throughout the western United States [1,142,197]. Climate change may hasten the rate of type conversion to cheatgrass grasslands by lengthening the period during which conditions are conducive to fire ignition and growth and furthering the invasive grass/fire cycle [1].

Contemporary Fire Frequency

- **Summary**
- **Charcoal Analyses**
- **Fire-scar and Contemporary Fire Records**
- **Fire Rotations Estimated Using Contemporary Fire Records**

Summary
In most mountain big sagebrush communities, available data suggest that fire frequency has either not changed or has been reduced, with the exception of an area in the Colorado Plateaus ecoregion where fire frequency may have increased. However, data on historical fire regimes are insufficient to get a clear picture on how fire frequency has changed in most mountain big sagebrush communities, and differences among studies in the applicable scale, methods used, and metrics calculated muddle the story about changes in fire frequency. For example, a study of charcoal in sediments in the Middle Rockies indicated similar fire occurrence before and after European-American settlement [140], while studies of fire scars on trees in and adjacent to mountain big sagebrush communities identify longer fire-free periods and reduced fire frequency after European-American settlement in the Eastern Cascades Slopes and Foothills, Middle Rockies, and Northern Basin and Range ecoregions [13,117,126,135,214,220]. However, contemporary fire records suggest that the frequency of large fires may have increased in recent decades [117,118].

Fire rotations in most studied ecoregions appear unchanged, but may have increased in parts of the Colorado Plateaus, Middle Rockies, Northern Basin and Range, and Snake River Plain ecoregions [11,20,60] and decreased in Dinosaur National Monument in the Colorado Plateaus ecoregion [11]. Reduced fire frequency has been attributed to a variety of causes, particularly elimination of American Indian ignitions, removal of fine fuels by heavy livestock grazing, and fire suppression [13,20,60,117,126,135,214,220]. Less frequent fire in many ecoregions suggests that there may be proportionally less area of low-density, postfire regenerating sagebrush communities than there was historically [143].

Although mountain big sagebrush communities are less susceptible to annual grass invasion than Wyoming big sagebrush communities [73,206,207], it is a growing concern [74,93]. In southeastern Oregon, fire frequency increased as nonnative invasive annual grass cover increased on relatively cool, moist mountain big sagebrush sites [82].

Charcoal Analyses
Only one study using charcoal sediment records provides information about postsettlement fire frequencies in mountain big sagebrush communities [140], and the results of this study differ from that of a similar study in a Wyoming big sagebrush community [202], likely due to differences in the presence of nonnative annual grasses. The study that examined charcoal sediment records from three lakes and ponds surrounded by mountain big sagebrush communities in Wyoming found similar fire occurrence before and after European-American settlement [140]. This study did not mention the occurrence of nonnative annual grasses. In contrast, a similar study in Nevada that examined charcoal sediment records from a spring-fed pond surrounded by a Wyoming big sagebrush community found an increase in fire occurrence that was attributed to nonnative annual grass invasion

and increased human activity since European-American settlement. Postsettlement charcoal accumulation rates (130 years BP) in the Nevada pond were an order of magnitude higher than at any time in the previous 5,500 years [202].

Fire-scar and Contemporary Fire Records

Studies of fire scars on ponderosa pine and Rocky Mountain Douglas-fir trees intermixed with mountain big sagebrush in the Eastern Cascades Slopes and Foothills, Middle Rockies, and Northern Basin and Range ecoregions identified long fire-free periods and reduced fire frequency after European-American settlement, likely due to the reduction in American Indian ignitions, overgrazing by livestock, and fire suppression [13,117,126,135,214,220]; however, contemporary fire records suggest that the frequency of large fires has increased in sagebrush ecosystems since the 1970s (e.g., [117,118]). Several studies recorded few or no fires after European-American settlement on sites where fires were historically frequent [117,126,214,220]. For example, in mountain big sagebrush-grasslands intermixed with Rocky Mountain Douglas-fir forest near Wise River, Montana, only one small fire (79 acres (32 ha)) was recorded from 1860 to 2003, while the historical (1700–1860) composite mean fire interval for surface fires was 37 years [126]. In the Upper Chewaucan River basin of Oregon, historical composite mean fire intervals in small clusters of ponderosa pine trees within a matrix of mountain big sagebrush communities ranged from 12 to 15 years, but fire was absent from 1898 until 1996. Fire occurrence in the study area began to decline after the introduction of livestock grazing around 1870, but prior to active fire suppression, which began in the early 1900s [214]. Lengthened fire intervals and heavy livestock grazing have contributed to increased dominance by mountain big sagebrush, reduced perennial herbaceous understories [214], and woodland expansion [126,214,220] in some mountain big sagebrush communities. While heavy livestock grazing and fire suppression between 1935 and the early 1980s probably reduced the frequency of large fires on Badger Mountain in the Sheldon National Wildlife Refuge, cessation of livestock grazing since the early 1990s may have increased large fire frequency in the late 20th century [117,134]. In a review of fire history in Nevada, Gruell [118] concluded that "after European-American settlement, cessation of Indian ignitions, and removal of fine fuels by livestock, fire became an infrequent disturbance agent. With the introduction of cheatgrass, the buildup of sagebrush and other shrubs, and the recovery of grasses with more conservative (livestock) management late in the twentieth century, fire once again became a significant factor" (see Contemporary Fire Pattern and Size).

While increased fire activity following cheatgrass invasion has been documented by several researchers (e.g., [41,247,332]) and quantified by others (e.g., [22,163,187,201]), mountain big sagebrush communities are less susceptible to cheatgrass invasion than most other sagebrush types [73,206,207]. Nonetheless, where mountain big sagebrush communities are affected by annual grass invasion, fire frequency is likely to increase (e.g., [22,50,82]). For example, Creutzburg et al. [82] used fire perimeter data from 1984 to 2008 to estimate fire intervals for sagebrush sites in southeastern Oregon and detected an increase in fire frequency with increasing nonnative grass cover on sites dominated by mountain big sagebrush and low sagebrush (table 2). Similarly, across 251,000 miles^2 (650,000 km^2) of the Great Basin, fire intervals for cheatgrass-dominated grasslands (calculated as the inverse of the proportion of the total area in the cheatgrass grassland cover class that burned annually) averaged 78 years from 2000 to 2009 based on MODIS burned area data. Fires were 2 to 25 times more frequent in the cheatgrass grassland cover class than in other land cover classes, including 2.2 times more frequent than in the mountain big sagebrush and low sagebrush steppe cover class [22] (table 3). Although researchers have described fire intervals shorter than 10 years in cheatgrass communities on sites formerly dominated by Wyoming big sagebrush (e.g., [247,332]), no studies have reported fire intervals in cheatgrass communities on sites formerly dominated by mountain big sagebrush. Nonetheless, cheatgrass can dominate mountain big sagebrush sites in the first few postfire years [29,121] and impede mountain big sagebrush establishment [112,354]. Annual grasses, especially cheatgrass, medusahead, and ventenata, are a growing concern in mountain big sagebrush communities (see Nonnative Invasive Plants).

Table 2—Annual fire probabilities and corresponding fire intervals derived from Monitoring Trends in Burn Severity (MTBS) data for cool, moist and warm, dry sagebrush steppe communities in southeastern Oregon with varying cover of nonnative invasive annual grasses. The MTBS dataset includes fire perimeters and burn severity ratings for fires >1,000 acres (400 ha) that occurred from 1984–2008.

Cheatgrass was the most common nonnative annual grass; other nonnative bromes, ventenata, medusahead, and brome sixweeks grass were also present [82].

Site	Nonnative annual grass cover (%)	Annual fire probability	Fire interval[f] (years)
Cool, moist sagebrush steppe[a]	0-10[c]	0.0068	148
	10-25[d]	0.0089	112
	>25[e]	0.0173	58
Warm, dry sagebrush steppe[b]	0-10[c]	0.0063	160
	10-25[d]	0.0114	88
	>25[e]	0.0179	56

[a]Sites dominated by mountain big sagebrush, low sagebrush, Idaho fescue, and bluebunch wheatgrass.
[b]Sites dominated by Wyoming big sagebrush, basin big sagebrush, bluebunch wheatgrass, Thurber needlegrass, and needle-and-thread grass.
[c]Sites have "little to no invasion".
[d]Sites are "semi-degraded".
[e]Understories of sites dominated by nonnative grasses.
[f]The fire interval is the inverse of the annual fire probability.

Table 3—Summary of burned area and fire probabilities by land cover class in 251,000 miles² (650,000 km²) of the Great Basin based on MODIS burned area data from 2000–2009 [22].

Land cover class	Total burned area (km²)	Total land cover area (km²)	Annual fire probability[a]	Fire interval[b] (years)	Relative fire interval[c]
Cheatgrass grassland	5,258	41,208	0.0128	78	1.0
Mountain big sagebrush and low sagebrush steppe	4,634	78,353	0.0059	169	2.2
Wyoming big sagebrush, basin big sagebrush, and mixed sagebrush types[d]	8,884	173,803	0.0051	196	2.5
Desert shrubland	757	147,302	0.0005	1,946	24.9
Pinyon-juniper woodland	3,427	102,533	0.0033	299	3.8
Agriculture	2,952	49,480	0.0060	168	2.1
Total	17,961	528,263	0.0034	294	3.8

[a]Annual fire probability is the proportion of the total area in the land cover class that burned, on average, each year (total area burned during the decade, divided by the total area in the cover class, and divided by 10).
[b]The fire interval is the inverse of the annual fire probability.
[c]Relative to that observed for the cheatgrass grassland cover class [22].
[d]Includes Wyoming big sagebrush-basin big sagebrush steppe, Wyoming big sagebrush-basin big sagebrush shrubland, and xeric mixed sagebrush shrubland [51].

Fire Rotations Estimated Using Contemporary Fire Records

Estimates of contemporary fire rotations appear similar to those of historical fire rotations in most ecoregions, except for parts of the Middle Rockies, Northern Basin and Range, Snake River Plain [20,60], and Colorado Plateaus [11] ecoregions. However, comparisons between time periods are hindered by differences in location and size of sampled areas. Contemporary fire rotations in mountain big sagebrush cover types were calculated using records from 1984 to 2008 of fires (predominantly wildfires) >1,000 acres (400 ha) [20] and were compared with historical fire rotations estimated using General Land Office survey records from smaller areas [60] (see Historical Fire Frequency: Fire rotations estimated using land-survey records and table A6). Contemporary fire rotations in mountain big sagebrush types were generally within the range of historical estimates; however, fire rotations in the Snake River Plain floristic province (which covers parts of three ecoregions) were longer than estimated historical fire rotations in southeastern Idaho (table 4). Contemporary fire rotations in the Northern Great Basin floristic province (which covers parts of two ecoregions) also appeared longer than historical fire rotation estimates in southeastern Oregon, but historical fire rotation estimates were constrained by a small sample area [20,60]. Baker [20] also noted that these contemporary fire rotation estimates are "limited in accuracy because the period of study is only a small fraction of the rotations".

Table 4—Contemporary (1984–2008) [20] and historical (~1868–1910) [60] fire rotation estimates and percent unburned area inside fire perimeters for contemporary fires. Contemporary fire rotations were calculated for a total of 20.4 million acres (8.3 million ha) of mountain big sagebrush cover types; however, the area of mountain big sagebrush types within each floristic province was not provided, limiting interpretation of fire rotation estimates. Historical fire rotations are for perimeters only and cover only a portion of the area covered by mountain big sagebrush steppe in each floristic province. For more information on historical fire rotation estimates, including the area size, location, and dominant vegetation, see table A6. Blank cells indicate no available data.

Contemporary					Historical	
Floristic province	Corresponding ecoregions	Fire rotation (years)		Mean unburned area[c] (%)	Corresponding ecoregions	Fire rotation (years)
		Perimeter[a]	Black[b]			
Columbia Basin	Columbia Plateau and Blue Mountains	311	373	16.49		
Northern Great Basin	Eastern Cascades Slopes and Foothills and western portion of the Northern Basin and Range	113	141	20.16	Eastern Cascades Slopes and Foothills and western portion of the Northern Basin and Range	48-77
Silver sagebrush	Northwestern Glaciated Plains and Northwestern Great Plains	360	522	31.02		
Snake River Plain	Eastern portion of the Northern Basin and Range, Middle Rockies, and Snake River Plain	185	237	22.13	Middle Rockies and Snake River Plain	110-175
Southern Great Basin	Central Basin and Range	195	245	20.34	Central Basin and Range	130-207
Wyoming Basin	Wyoming Basin, northern portion of the Colorado Plateaus, and the northern portion of the Southern Rockies	595	842	29.40	Wyoming Basin	588-2,139

Overall	215	276	22.12		137-217

[a]Based on the area inside the fire perimeter, including any unburned area.
[b]Based only on actual burned area.
[c]The area that did not burn inside fire perimeters.

One study in the Colorado Plateaus ecoregion suggested that prescribed fires may have contributed to shorter contemporary fire rotations in mountain big sagebrush communities relative to historical fire rotations. This study examined fire perimeter data for wild and prescribed fires that occurred from 1981 to 2000 in Dinosaur National Monument and the surrounding area. Inside the monument, the fire rotation for mountain big sagebrush communities was 166 years, while in the surrounding area the fire rotation was 976 years. Historical fire rotations estimated using Government Land Office survey records from 1904 to 1911 were 458 and 729 years, respectively (table A6). The shorter contemporary fire rotation inside the monument was attributed to frequent prescribed burning; inside the monument, prescribed burns accounted for 61% of fires, and in the surrounding area they accounted for <1% of fires [11]. The relatively long fire rotation outside the monument was not discussed.

Contemporary Fire Type, Severity, and Intensity

Historically, wildfires in mountain big sagebrush communities were stand-replacement surface and crown fires that burned at low or moderate intensity (see Historical Fire Type, Severity, and Intensity). Woody fuels increase when sagebrush establishes and dominates grassland steppe communities and these woody fuels burns more intensely than perennial bunchgrasses [118]. When trees establish and dominate in mountain big sagebrush communities, fuel characteristics change because mountain big sagebrush and herbaceous plant cover decrease as tree cover increases (e.g., [25,167,205,218,260,285,316,342,346,347,357]). As mountain big sagebrush steppe succeeds to woodland, tree crowns increase in size, continuity of crown fuels increases, and surface fuel abundance, continuity, and packing ratios decrease. These changes in fuel characteristics reduce the potential for surface fires burning under moderate weather conditions and increase the potential for high-intensity crown fires burning under extreme conditions (i.e., high wind, high atmospheric instability, low humidity, and high temperatures) [208,217,282]. As prefire cover of native shrubs and herbs decreases and that of conifers increases, postfire recovery of mountain big sagebrush communities becomes slower [31] and postfire invasion by cheatgrass becomes more likely [32] (see Woodland Expansion and Nonnative Invasive Plants).

Contemporary Fire Pattern and Size

Introduction

Little is known about historical fire pattern and size in mountain big sagebrush communities (see Historical Fire Pattern and Size); however, Bukowski and Baker [59,60] suggest that the pattern and size of historical fires were similar to those of contemporary fires, and that historical fires had less unburned area within fire perimeters. Interpretations of General Land Office survey records from Colorado [59], Idaho, Nevada, Oregon, and Wyoming [60] suggested that historical fire-size and patch-size distributions were inverse J-shaped, consisting of many small fires and patches and few large ones, which is consistent with contemporary fire-size and patch-size distributions for fires >1,000 acres (400 ha) in sagebrush landscapes in the western United States from 1984 to 2008 [20]. Bukowski and Baker [59,60] estimated that unburned area within fire perimeters in mountain big sagebrush averaged <4%, historically (see Historical Fire Pattern and Size), and Baker [20] calculated an average of ~22% unburned area in contemporary mountain big sagebrush fire perimeters (table 4), which was similar to other sagebrush types. The authors cautioned that the amount of unburned area historically may have been underestimated due to the coarse resolution of the land-survey records [59]. A greater portion of unburned area within contemporary fire perimeters could facilitate faster postfire recovery [159].

In areas where livestock grazing, habitat fragmentation [20,59,60], and prescribed fire have disrupted fine fuel continuity, contemporary fires are likely to be more patchy and may leave more unburned area within fire perimeters than historical fires. In contrast, less unburned area may be expected in fire perimeters in areas where cheatgrass has invaded. Prescribed fires in sagebrush communities are often conducted in spring and fall with the objective of creating a patchy burn, which may leave more unburned area than presettlement wildfires [35,43,62,340]. Summer prescribed fires generally result in greater consumption of big sagebrush and thus less unburned area within fire perimeters than spring or fall fires [255,343], and spring fires tend to leave more unburned area in fire perimeters than fall fires [343]. Cheatgrass invasion may result in more complete and continuous fine fuels that result in fires that are often larger and more homogenous, with few unburned patches [47,153,211,247,332].

In Baker's study of contemporary fires (1984–2008) in sagebrush landscapes in the western United States [20], he concluded that mean percent unburned area within fire perimeters for all sagebrush types combined was similar among seven floristic provinces (which cover all or part of 12 ecoregions), and that contemporary fire-size distributions for all sagebrush types combined were similar among five of the seven ecoregions. More large fires (>18,500 acres (7,500 ha)) occurred in the Snake River Plain than in other floristic provinces, while more small fires (1,000-2,500 acres (400-1,000 ha)) and fewer large fires occurred in the Wyoming Basin than in other floristic provinces. Higher frequency of large fires in the Snake River Plain floristic province was attributed to extensive cheatgrass establishment and relatively flat terrain, which may have also contributed to relatively less unburned area (18%, on average) within fire perimeters in that province. Higher frequency of small fires in the Wyoming Basin floristic province was attributed to relatively complex topography and areas of sparse, fuel-limited dwarf sagebrush types, which may have also contributed to relatively more unburned area (24%, on average) within fire perimeters in that province [20].

Number of Fires and Total Burned Area

The number of fires and total area burned annually have increased since 1980 in the sagebrush biome, overall, largely due to cheatgrass establishment and spread [20,22,77,211], but also due to increased cover of sagebrush and other woody vegetation and increased grass cover following more conservative livestock management beginning late in the 20th century on some sites [118]. Available data on mountain big sagebrush communities suggest an upward trend in annual area burned in parts of the western United States during the late 20th and early 21st centuries. When contemporary fire records from 1984 to 2008 were examined by floristic province, upward trends in annual area burned in mountain big sagebrush types were significant in the Colorado Plateau ($P = 0.019$) and Southern Great Basin ($P = 0.010$) floristic provinces and "nearly so" in the Snake River Plain ($P = 0.070$) and Columbia Basin ($P = 0.059$) floristic provinces [20]. These trends may also be attributable to increases in native perennial bunchgrasses on some sites [118] (see Fire Suppression, Livestock Grazing, and Fire Size), but are more commonly attributed to increases in cheatgrass [20,22]. Data from fires in the Great Basin between 2000 and 2009 show that fires in cheatgrass grasslands are generally more frequent (table 3), spread faster, last longer, and cover more area (table 5) than fires in most other land cover classes, indicating that cheatgrass invasion has substantially altered fire regimes throughout the Great Basin [22].

Table 5—Summary of average fire data by land cover class in 251,000 miles² (650,000 km²) of the Great Basin, based on MODIS burned area data from 2000–2009. Standard errors are in parentheses; *n* is the number of fires [22].

Land cover class	*n*	Average area burned (km²)	Average fire duration (days)	Fire spread rate (km²/day)	Peak burn month
Cheatgrass grassland	1,122	4.69 (0.60)	3.07 (0.09)	0.75 (0.06)	July
Mountain big sagebrush steppe	1,681	2.76 (0.35)[b]	2.69 (0.06)[b]	0.54 (0.04)[b]	August
Wyoming big sagebrush, basin big sagebrush, and mixed sagebrush types[c]	1,910	4.65 (0.61)	2.70 (0.06)[b]	0.78 (0.06)	July
Desert shrubland	215	3.52 (1.00)	3.02 (0.18)	0.67 (0.13)	June
Pinyon-juniper woodland	1,145	2.99 (0.33)[b]	2.83 (0.08)[a]	0.62 (0.04)[a]	June
Agriculture	3,616	0.82 (0.08)[b]	2.18 (0.04)[b]	0.30 (0.01)[b]	September
Total	4,752	3.83 (0.37)	2.40 (0.03)	0.72 (0.04)	July

[a]Significantly different from cheatgrass grassland at $P < 0.10$.
[b]Significantly different from cheatgrass grassland at $P < 0.05$ [22].

[c]Includes Wyoming big sagebrush-basin big sagebrush steppe, Wyoming big sagebrush-basin big sagebrush shrubland, and xeric mixed sagebrush shrubland [51].

Fire Suppression, Livestock Grazing, and Fire Size

Heavy livestock grazing during the late 1800s and early 1900s likely reduced fire sizes by reducing fine fuels in many mountain big sagebrush communities, but cessation of heavy livestock grazing and fire suppression policies since that time have resulted in increases in fine fuels, and the number of large fires has since increased in some areas [117,118,135,217]. In the United States, 98% of wildfires reported by the U.S. Forest Service from 1970 to 2002 were suppressed before reaching 300 acres (120 ha) [67]. On the Sheldon National Wildlife Refuge from 1945 to 1967, 10 fires were suppressed. Nine of these burned <1 acre (0.4 ha), and 1 burned 100 acres (40 ha). Fire suppression efforts were thought to have been aided by the reduction in fine fuel abundance and continuity due to heavy livestock grazing on the refuge in the early 1900s. However, cessation of grazing on the refuge in the early 1980s and the resultant build-up of fine fuels were coincident with an increase in large fires on the refuge—one in 1988 (2,100 acres (840 ha)) and another in 1994 (7,500 acres (3,000 ha)) [117]. The 2006 wildfires of Elko County, Nevada, burned nearly 1 million acres (400,000 ha), most of which were mountain big sagebrush communities. These fires were attributed to "a bumper crop of perennial bunchgrasses" produced during a moist spring followed by above-average summer temperatures and periods of extreme fire weather [118]. While contemporary fire suppression efforts reduce fire sizes overall [67], wildfires in sagebrush communities that occur during hot, windy weather can reach large sizes despite aggressive fire suppression responses [97,291].

Cheatgrass and Fire Spread

When nonnative annual grasses establish and spread into big sagebrush communities, the abundance and continuity of fine surface fuels is likely to increase—especially in years or seasons following those with abundant precipitation [41,161,355]—which can increase fire activity on invaded sites [22,118,161,163]. Fire activity may increase on mountain big sagebrush sites adjacent to cheatgrass-dominated sites because fire can spread into mountain big sagebrush sites from cheatgrass-dominated sites (figure 9). In the Great Basin, 80% of fires between 2000 and 2009 that burned for more than one day (i.e., multi-date fires) and burned in cheatgrass grassland also spread into other cover types, some of which were likely mountain big sagebrush communities. Of these 379 multi-date fires, 65% started in cheatgrass grasslands [22].

Figure 9—Fire spreading from a cheatgrass grassland (a site likely formerly dominated by Wyoming big sagebrush and perennial grasses) into a mountain big sagebrush community during the 2011 Constania Fire, Long Valley, California. Photo by Nolan Preece.

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APPENDICES:

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