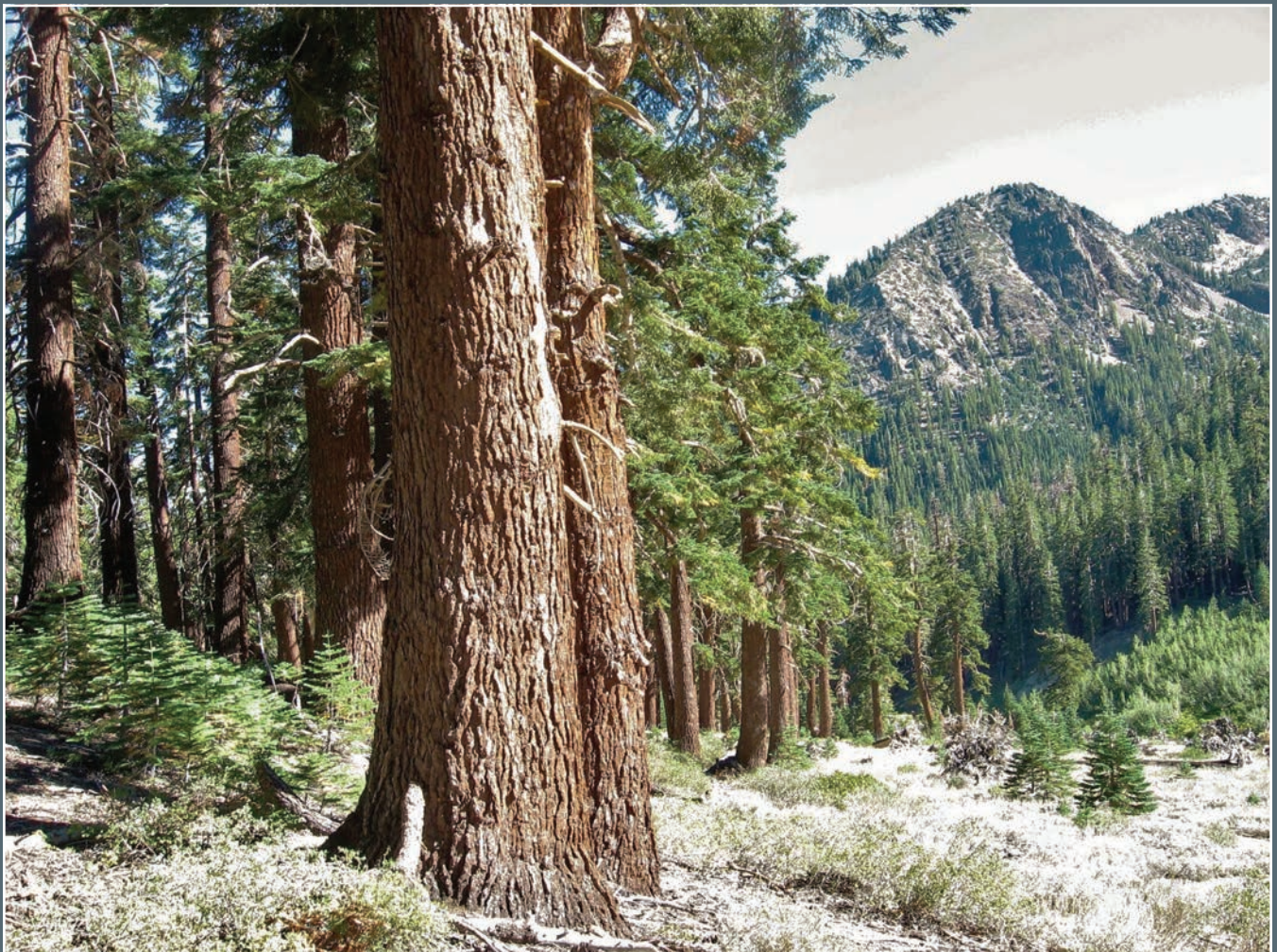




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Natural Range of Variation of Red Fir and Subalpine Forests in the Sierra Nevada Bioregion

Marc D. Meyer and Malcolm P. North



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Cover photo: Red-fir trees, Sierra Nevada, California.

Abstract

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Comparisons between historical and current conditions indicate that modern red fir (*Abies magnifica*) and subalpine forests of the Sierra Nevada bioregion are largely within their natural range of variation (NRV) with respect to compositional, functional, and some structural variables. Exceptions common to both forest types include a considerable shift in the tree size class distribution to smaller diameters, decrease in large-diameter tree densities (e.g., red fir, lodgepole pine [*Pinus contorta*], western white pine [*P. monticola*]), and greater homogenization of forest structure at both stand and landscape scales. Red fir forests had an increase in tree cover in lower canopy strata, and a lengthening of fire return intervals and fire rotations during much of the 20th century. Subalpine forests had increases in treeline growth and recruitment, and a marginal lengthening of fire return intervals and fire rotations during much of the 20th century. For both forest types, fire frequency and severity, moisture stress, the incidence of pathogens and insects, and tree mortality rates are projected to increase and likely exceed the NRV with climate change. Climate envelope models consistently project a substantial loss in suitable habitat or high climate vulnerability of both red fir and subalpine forests in the Sierra Nevada bioregion by the end of the 21st century, suggesting that the greatest changes in these forests in the coming decades will occur as a direct or indirect consequence of climate change.

Keywords: *Abies magnifica*, climate change, forest ecology, natural range of variation, historical range of variation, red fir, Sierra Nevada, subalpine forests.

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Introduction

Red fir (*Abies magnifica*) and subalpine forests dominate the upper montane ecosystems of the Sierra Nevada. These high-elevation forests share several characteristics, including high snowpack retention, low species diversity, low evapotranspiration and climatic water deficit, longer and more variable fire return intervals, and high sensitivity to changes in climate. These forests also were shaped by similar environmental (e.g., climatic) and anthropogenic changes during the Holocene, resulting in analogous contemporary features and parallel departures from their historical natural range of variation (NRV). Most notably, the low anthropogenic impact following the Euro-American settlement period has largely preserved the integrity of these forest ecosystems, especially in comparison to lower elevation forests (i.e., ponderosa pine [*Pinus ponderosa*] and mixed conifer) in the bioregion. For these reasons, we have combined red fir and subalpine forests in this assessment to emphasize their many similarities with respect to historical influences and environmental context.

Red fir and subalpine forests do possess several distinct ecosystem characteristics that warrant individual treatment of their ecological structure and function. Red fir forests contain higher biomass and occupy more productive and deeper soils than subalpine forests. Subalpine forests are more strongly influenced by energetic limitations (e.g., length of growing season) and insect and avian population dynamics than red fir forests. For these reasons, we treat red fir and subalpine forests separately in later sections of this assessment to underscore the distinctive ecological characteristics of these two high-elevation forest types in the past, present, and future.

Historical Influences

Holocene forest development—

Mid-Holocene Xerothermic period—Following a relatively cool and wet period in the early Holocene (about 10,000 to 16,000 years ago), the mid-Holocene was characterized by continual warming that reached an optimum during the Xerothermic period about 8,000 to 5,000 years ago, with peak temperatures at roughly 6,500 years before present (ybp) (table 1) (Brunelle and Anderson 2003, Potito et al. 2006). During this relatively warmer and drier period, high-elevation lake levels in the Sierra Nevada were reduced, resulting in the desiccation of Owens Lake, disconnection of Lake Tahoe from the Truckee River, and subsequent decline in Pyramid Lake (Benson et al. 2002, Mensing et al. 2004). Climate conditions were driest during three intervals of the Xerothermic period: 7,530–6,300; 5,200–5,000; and 4,700–4,300 ybp (Mensing et al. 2004).

Table 1—General overview of climate, vegetation, and environmental conditions during the Holocene in the higher elevations of the Sierra Nevada

Time period	Years before present	Climate conditions ^a	Vegetation and environmental changes ^a
Early Holocene	16,000–10,000	Cooler and moister	Open pine forests mixed with mountain hemlock and Sierra juniper Higher montane lake levels Lower fire frequencies in montane forests
Mid-Holocene Xerothermic (Hypsithermal) ^b	8,000–5,000 (or 4,000)	Warmer (~1 °C) and episodically drier	Open pine forests with shrub understory dominate Red and white fir, mountain hemlock, and subalpine conifers (whitebark pine, lodgepole pine) restricted to mesic sites Montane lake levels drop Substantial increase in fire frequencies within montane forests
Late Holocene	4,000–1,100	Relatively cooler and often moister	Red and white fir, mountain hemlock, and subalpine conifers increase Lake levels increase Decreased fire frequencies in montane forests
Medieval warm period ^b	1,100–650	Warmer (~0.25 °C) and often drier	Some increased tree establishment of subalpine conifers at treeline Lake levels moderately decrease Modest increase in fire frequencies in montane forests
Little Ice Age	650–100	Cooler and moister	Downslope movement of upper elevation limit of red fir
Current (20 th century)	100–0	Relatively cool and moist conditions with recent increases in temperatures during past three or four decades	Era of modern fire suppression and land management practices in montane forests Forest densification and homogenization Decline in density of larger trees

^a See text for data sources.^b Periods that may serve as possible analogues for climate in the near future.

During the Xerothermic period, Sierra Nevada red fir and subalpine forests (collectively referred to hereafter as high-elevation forests) were primarily dominated by pines, with montane shrubs in the understory and a notable lack of fir (table 1). Based on fossil pollen from lake deposits in the central Sierra Nevada, Anderson (1990) characterized high-elevation forests as open with abundant montane chaparral shrubs in the understory, including bush chinquapin (*Chrysolepis sempervirens*), mountain mahogany (*Cercocarpus* spp.), manzanita (*Arctostaphylos* spp.), and possibly huckleberry oak (*Quercus vacciniifolia*). Red fir, mountain hemlock (*Tsuga mertensiana*), and possibly whitebark pine (*P. albicaulis*) were rare and confined to mesic habitats, whereas limber pine (*P. flexilis*) and western white pine (*P. monticola*) demonstrated localized colonization and possible limited expansion (Anderson 1990). Lodgepole pine (*P. contorta*) was established over its present elevation range during the mid-Holocene, but subsequently disappeared from previously occupied lower elevation sites and colonized higher elevation

meadows during the Xerothermic period (Anderson 1996). Migration of lodgepole pine during the Holocene also was largely elevational rather than latitudinal in California (Anderson 1996). In Yosemite National Park, high-elevation fossil pollen deposits were dominated by pines, had increased levels of bush chinquapin and oaks (*Quercus* spp.), and contained minimal amounts of fir (red fir and white fir [*Abies concolor*]) during the Xerothermic period (Brunelle and Anderson 2003). In Lassen Volcanic National Park, high-elevation fossil pollen deposits indicated that pine forests dominated during the early- and mid-Holocene (12,500 to 3,100 ybp) with minor contributions by Taxodiaceae/Cupressaceae/Taxaceae (primarily incense cedar [*Calocedrus decurrens*]) and oaks at lower elevations (West 2003). Similarly, fossil pollen deposits in the southern Sierra Nevada indicate that pine forests dominated between 7,000 and 3,000 ybp (Davis et al. 1985).

In the neighboring Great Basin (including the Warner Mountains), climate was also warmest and possibly driest during the 7,500 to 5,000 ybp Xerothermic period. Open forests at high elevations characterized vegetation in this region, with increases in western white pine, whitebark pine, and white fir starting about 7,000 to 6,500 ybp (Minckley et al. 2007, Tausch et al. 2004). In the White Mountains, subalpine conifers such as Great Basin bristlecone pine (*P. longaeva*) shifted upward in elevation (Wells 1983). In the Sierra Nevada and Great Basin, increased charcoal deposits during the warmer periods of the Holocene indicate an increase in fire frequency during the Xerothermic and subsequent Medieval warm periods (Brunelle and Anderson 2003, Hallett and Anderson 2010, Minckley et al. 2007). In the southern Sierra Nevada, decreased charcoal deposits and fire frequency were coincident with increased abundance of red fir and lodgepole pine during the past 1,200 years (Davis et al. 1985).

Late Holocene period—At the close of the Xerothermic period, precipitation gradually increased, and cooler conditions dominated from approximately 3,000 to 2,500 ybp (table 1). Coincident with these climate changes, red fir and mountain hemlock increased in abundance and demonstrated downslope movement of their upper and lower elevation limits in the central Sierra Nevada, especially about 4,500 ybp (Anderson 1990, Brunelle and Anderson 2003). In Lassen Volcanic National Park, an abrupt increase in red fir and white fir and decline in pine abundance occurred about 3,100 ybp, suggesting cooling temperatures and increased winter snow depths during this period (West 2003). In the southern Sierra Nevada high-elevation zone, fir, incense cedar, and oaks increased substantially 3,000 ybp, during which time modern vegetation was established (Davis et al. 1985). The lower elevation limit of whitebark pine, lodgepole pine, and other subalpine conifers also moved downslope during the relatively recent cooler and wetter period, leading toward the formation of contemporary Sierra Nevada red fir and subalpine forests (Anderson 1990, 1996; Woolfenden 1996).

Medieval warm period and Little Ice Age—During the Medieval warm period, conditions were slightly warmer and drier than today as indicated by tree colonization in present-day lakes, marshes, and streams of the Sierra Nevada (table 1) (Stine 1994); lower lake levels in the Sierra Nevada and neighboring Great Basin (Benson et al. 2002, Mensing et al. 2004); and tree-ring analyses in subalpine forests (Woolfenden 1996). Evidence of warming during this period was also evident in many other parts of the world (Millar and Woolfenden 1999). Multi-year and decadal droughts and severe El Niño events occurred throughout the Medieval warm period and Little Ice Age (about 650 to 100 years ago) (Bale et al. 2011). Increased fire frequencies were evident during the Medieval warm period as documented in long-term dendrochronological records in giant sequoia (*Sequoiadendron giganteum*) (Swetnam et al. 2009) and charcoal deposits from high-elevation lakes (Beaty and Taylor 2009, Brunelle and Anderson 2003, Hallett and Anderson 2010). Evidence of downslope movement of the upper elevation limit of red fir is most evident during the Little Ice Age (Anderson 1990). Increasing tree establishment of foxtail pine (*P. balfouriana*) above treeline also indicated warmer conditions during the Medieval warm period, about 950 to 850 ybp (Scuderi 1987). However, Lloyd (1997) and Lloyd and Graumlich (1997) found a decline in the abundance, recruitment, and treeline elevation of foxtail pine during the Medieval warm period associated with multi-decadal droughts and warmer summer temperatures. Climatic controls over treeline dynamics are complex, suggesting that subalpine tree growth and recruitment patterns are primarily dependent on climatic water deficit rather than individual climate variables (Lloyd and Graumlich 1997).

Anthropogenic Influences

American Indian use—

Historically, American Indians used red fir and subalpine forests extensively during the summer for several reasons. High-elevation forests provided summer foraging and fawning habitat for mule deer (*Odocoileus hemionus*), a primary game species for American Indians (Potter 1998). Plant materials for food and basketry were available late into the summer at higher elevations, whereas these resources were desiccated or unavailable at lower elevation sites (Anderson and Moratto 1996). American Indians often targeted high-elevation meadows bordering forests as sources of food and other materials during summer months (Anderson and Moratto 1996). Additionally, well-established trans-Sierra trading routes (e.g., near Mono Pass in Yosemite National Park) crossed many higher elevation forests, and were often used seasonally (Muir 1911). These routes often included occasional bedrock grinding sites used to process acorns harvested at lower elevations (Lewis 1993).

Euro-American settlement and national forest administration (1849–1945)—

With the 1848 discovery of gold in the Sierra Nevada, Euro-American impacts greatly intensified in many parts of the range (Beesley 1996). Widespread mining operations, intensive logging, major water diversions, and other impacts (e.g., market hunting, railroad development) led to profound changes to many ecosystems in the Sierra Nevada. Red fir and subalpine forests were largely spared these impacts owing to their relative remoteness and distance from gold-bearing deposits (Leiberg 1902). There were several exceptions to this generalization, as localized areas of red fir forest in the northern and central Sierra Nevada were heavily logged during the late 19th century (Leiberg 1902). Yet overall, in their comprehensive evaluation of the ecological condition of red fir forests throughout the Sierra Nevada, Oosting and Billings (1943) noted that “these old virgin [red fir] forests of massive trees are to be found in many parts of the Sierra Nevada.” Beyond areas adjacent to early settlement, mining, railroad logging, and related impacts rarely occurred in red fir and subalpine forests throughout the late 19th and early 20th centuries.

In contrast to mining, railroad logging, and water diversion activities, widespread sheep grazing and repeated burning by sheepherders heavily affected red fir and subalpine forests in the Sierra Nevada during the late 19th and early 20th centuries. In the early 1860s, a severe drought in California brought about the summertime practice of grazing sheep in high-elevation meadows and forests of the Sierra Nevada (Ratliff 1985, Vankat 1970). By the late 19th century, more than 6 million sheep grazed in California, with an estimated 200,000 animals distributed on the Kern Plateau alone during summer and fall (McKelvey and Johnston 1992, Menke et al. 1996, Ratliff 1985, Vankat 1970). The high-elevation meadows and forests of the Sierra Nevada (primarily red fir and subalpine zones) received more grazing abuse by sheep than any other part of the range (Menke et al. 1996). Widespread and intensive sheep grazing led to permanent vegetation changes, as evidenced in stratigraphic pollen records from high-elevation meadows of the Kern Plateau of the southern Sierra Nevada (Dull 1999). Many historical accounts attest to the widespread and intensive impacts of sheep grazing in the assessment area during this period (McKelvey and Johnston 1992), including the White Mountains (Wehausen 1986).

In addition to grazing impacts, sheepherders burned extensively in high-elevation forests to promote the growth of grasses and forbs and to remove fuel and young trees from the understory (Leiberg 1902, McKelvey and Johnston 1992). Special attention was given to burning large, downed fuels and mesic areas to stimulate forage production, a pattern of burning that differed substantially from American

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Indian practices (Sudworth 1900, Vankat 1970). Such practices, combined with intensive sheep grazing, had a negative impact on red fir and subalpine regeneration in areas of the central Sierra Nevada (Leiberg 1902). However, by 1900 to 1920, sheep grazing and shepherd burning were heavily curtailed in the newly established national parks and forest reserves in the Sierra Nevada (Ratliff 1985). By 1930, sheep grazing declined in significance and was eventually replaced by cattle in Sierra Nevada national forests, coinciding with an overall decline in livestock grazing through the rest of the 20th century (Menke et al. 1996, Ratliff 1985).

Post-World War II (1945 to present)—

During the 1940s, timber harvest technology changed from railroad logging to the use of tractors and trucks (Potter 1998). Timber harvest operations and associated extensive road infrastructure began in portions of red fir forest in the mid-1950s. By the late 1960s, many red fir forests were subjected to even-age silvicultural techniques (e.g., clearcutting) (Potter 1998). By the 1990s, silvicultural practices emphasized shelterwood cutting along with other approaches such as uneven-age silvicultural systems, sanitation thinning, and salvage and “improvement” cuttings (Laacke and Tappeiner 1996). In contrast, there has never been extensive timber harvesting or silvicultural manipulation in subalpine forests.

Methods

Variables, Scales, and Information Availability

Several variables lacked sufficient historical information to include them in this assessment (table 2). However, for many of these variables, contemporary reference sites provide surrogate information that is complementary to the historical range of variation. Additionally, contemporary reference sites provide invaluable information not available from historical baseline conditions (Safford et al. 2012b). For instance, modern reference sites represent the closest approximation to the rapidly changing climate conditions currently taking place on a global scale. They also incorporate the contemporary environmental conditions (e.g., decades of fire exclusion) and the pervasive influence of humans on existing landscapes (Safford et al. 2012b). In contrast, historical information based exclusively on relatively recent cooler and wetter conditions of the recent past (see “Holocene Forest Development” section) may be less relevant when considering future conditions in the structure, function, and composition of modern ecosystems. We have used an approach similar to that used by Safford and Stevens (2017), summarizing literature and current conditions in each forest type to assess whether forest composition, structure, and function are likely within their natural range of variation.

Table 2—Variables lacking adequate historical records to quantify historical range of variation

Variable	Issue	Surrogate information source
Landscape and regional-scale patterns of disturbance (e.g., fire, insects, disease)	Historical information limited, especially pre-20 th century	Contemporary reference sites, limited historical accounts
Historical vegetation spatial structure (two and three dimensional), including structural complexity	Information rarely or not collected in historical (early 20 th century) forest inventories and surveys; primarily available with recent technology (e.g., LiDAR)	Contemporary reference sites; limited historical information on tree spatial aggregation; limited historical accounts
Understory vegetation (species composition, functional groups, diversity, cover) and soil cover (litter, duff, bare mineral soil, coarse woody debris) and fuels	Limited information in historical forest inventories and surveys; no information prior to widespread sheep grazing in the early 1860s except in few stratigraphic pollen records	Limited available sources: contemporary reference sites
Nonnative species (e.g., noxious weeds, introduced insects and pathogens)	Most species introductions have been recent and are not within the scope of this NRV assessment	Not applicable
Air quality	Historical information lacking	No available sources
Tree regeneration	Historical information lacking	Limited available sources
Snags and logs	Historical information limited	Contemporary reference sites
Nutrient cycling rates and productivity	Historical information lacking	No available sources
Forest connectivity	Historical information lacking except for biogeographic isolation from other regions	Contemporary reference sites
Grazing	Historical (Prior to ~1850) information limited or lacking	Limited historical accounts
Large-scale (landscape, regional) fire and other processes that require remote-sensing-based measures	No information prior to availability of satellite-derived information (pre-1984)	Contemporary reference sites
Physiognomic patterns: proportion of early, mid, and late seral	Historical information limited or lacking	Contemporary reference sites; estimates primarily based on LANDFIRE Biophysical Setting modeling
Metapopulation dynamics	Historical and contemporary information lacking	Limited available sources

NRV = natural range of variation.

For red fir forests, appropriate contemporary reference sites have been carefully selected based on their relatively pristine condition (e.g., national parks, wilderness areas), the absence of significant historical legacy impacts (e.g., logging), the recent reintroduction of key ecological processes (e.g., natural fire regimes), and the existence of either short- or long-term research information (e.g., experimental forests, research natural areas, natural reserves) (table 3). Much of the published scientific information on reference conditions in red fir forests has been extracted from

Table 3—Current and historical reference sites of unlogged Sierra Nevada red fir forests from north to south

Name	Location	Examples of relevant studies
Thousand Lakes Wilderness	Lassen National Forest, Southern Cascades	Bekker and Taylor (2001, 2010)
Lassen National Park	Southern Cascades	Taylor (2000)
Caribou Wilderness	Lassen National Forest, Southern Cascades	Taylor and Solem (2001)
Swain Mountain Experimental Forest	Lassen National Forest, Southern Cascades	Taylor and Halpern (1991) Taylor (1993)
Cub Creek Research Natural Area	Lassen National Forest, Southern Cascades	Beaty and Taylor (2001)
Yuba River Old Forest Emphasis Area	Tahoe National Forest, Northern Sierra Nevada	Gonzalez et al. (2010)
Lake Tahoe Basin, old-growth stands, and Desolation Wilderness	Lake Tahoe Basin Management Unit and El Dorado National Forest, Northern Sierra Nevada	Barbour et al. (2002) Beaty and Taylor (2009)
Illilouette Creek Basin, Yosemite National Park ^a	Central Sierra Nevada	Collins et al. (2007, 2009, 2016) Collins and Stephens (2010)
Yosemite National Park ^a	Central Sierra Nevada	Kane et al. (2013, 2014) Lutz et al. (2009, 2010) Miller et al. (2012) Thode et al. (2011) van Wagtenonk et al. (2002, 2012)
Devils Postpile National Monument and Valentine Camp Natural Reserve	Eastern Sierra Nevada near Mammoth Lakes	Caprio et al. (2006) Stephens (2001)
Teakettle Experimental Forest	Sierra National Forest, Southern Sierra Nevada	North et al. (2002, 2005, 2007) Smith et al. (2005)
Sugarloaf Creek Basin, Sequoia and Kings Canyon National Parks ^a	Southern Sierra Nevada	Caprio and Lineback (2002) Collins et al. (2007, 2016)
Sequoia and Kings Canyon National Parks	Southern Sierra Nevada	Pitcher (1987) Vankat and Major (1978) Westman (1987)
South Mountaineer Creek Research Natural Area, Golden Trout Wilderness	Sequoia National Forest, Southern Sierra Nevada	Potter (1998)

^a Contemporary reference sites.

contemporary reference sites that match these criteria. In a few instances, reference information was obtained from a nearby region (e.g., central Cascade Mountains), particularly when this information was unavailable for the assessment area.

In addition to contemporary reference sites, written historical accounts provide additional information regarding the historical range of variation in red fir forests of the Sierra Nevada (e.g., Leiberg 1902, Sudworth 1900). These historical accounts were based on idiosyncratic time periods, primarily by early explorers, naturalists, geologists, foresters, botanists, and other individuals who recorded their

observations in field notes, manuscripts, official reports, books, and other published sources. Although many of these historical accounts often contain an inherent bias and other limitations, they nevertheless offer a unique perspective on past conditions of red fir forests not captured in other historical information sources.

Historical Reference Period

The beginning of the historical reference period for both forest types includes much of the Holocene. For red fir forests, this period ended either shortly after the advent of the gold-rush era in California or during the mid-20th century; whereas for subalpine forests, it extended into the present era (early 21st century). The exceptions for both forest types are the areas that were subjected to early logging activities during the late 19th and early 20th centuries, especially in the northern and central Sierra Nevada (Beesley 1996, McKelvey and Johnston 1992). Additionally, beginning in the early 1860s, the widespread and intensive impacts of sheep grazing and shepherd burning practices were pervasive in the high-elevation forests of the Sierra Nevada (McKelvey and Johnston 1992, Vankat 1970). Fire suppression activities began in the mid-1920s, influencing fire regimes in many Sierra Nevada ecosystems, including red fir and subalpine forests. Consequently, information and variables pertaining to fire regimes, historical tree recruitment, understory vegetation, litter and coarse woody debris, and successional patterns in Sierra Nevada likely require a historical reference period that predates the 1860–1920 period.

In red fir forests, for ecosystem variables not strongly influenced by widespread historical grazing, historical reference conditions arguably extend into the mid-20th century (typically prior to 1950–1960), when logging activity increased within the region and led to the decline in the extent of late-seral red fir forests. This period also predates recent trends in regional climate warming and snowpack changes (Moser et al. 2009, Safford et al. 2012a). Consequently, a second historical reference period ending in 1960 was used in this assessment. The historical reference period for each variable is summarized in table 4.

In contrast, many subalpine forests in the bioregion were relatively unperturbed by extensive human impacts (e.g., arid subalpine woodlands), providing a number of likely contemporary reference sites for these forest ecosystems. More importantly, recent climate warming at high elevations (see “Climate Associations” section) indicate that the appropriate historical reference period in Sierra Nevada subalpine forests occurs before this relatively recent era of regional climate warming (i.e., prior to 1970). The historical reference period for subalpine forests is summarized in table 5.

10 **Table 4—Deviations from the natural range of variation (NRV) based on historical and modern reference information in Sierra Nevada red fir forests**

Variable(s)	Historical reference period	Modern reference site	Within NRV	Confidence	Direction of departure	Notes ^a	Pages in text
Fire return interval	1580–1900	No	No	High	Increasing	Low to moderate departure from NRV; future projections may be outside NRV	21 Table 8
Fire rotation	1650–1905	Yes	No	Moderate	Increasing	Same as above	21 Table 9
Fire size	1729–1918	Yes	Yes/no	Moderate	Increasing	Generally within NRV, but approaching values that may soon exceed NRV	24 Figs. 3 and 4
Fire type	1625–1845	Yes	Yes	Moderate	—	—	26
Fire seasonality	1650–1942	No	Yes	Moderate	—	—	27
Fire severity	1650–1930	Yes	Yes ^b	Moderate	Marginally increasing	Marginal increase in fire severity in past 25 to 30 years; this trend is likely to continue based on future projections	27 Table 10
High-severity fire patch size and size distribution	Late 1800s	Yes	Yes	Low	—	—	29 Figs. 5 through 7
Insects and pathogens	1600–1960	Yes	Yes/no	Low	Increasing mortality rates associated with pathogens	Generally within NRV, but approaching values that may soon exceed NRV	31
Wind	1874–1960	No	Yes	Low	—	—	33 Fig. 8
Volcanism	Pre-1500	No	Yes	Low	—	—	34
Annual climatic water deficit and actual evapotranspiration	1700	No	Yes	Low	Increasing	Likely within NRV but projected future range of variation will exceed NRV	35
Canopy structural classes and landscape patchiness	Current only	Yes	No	Moderate	Decreasing portion of canopy gaps and increasing structural homogenization	Canopy structural variables (includes next five variables) are based on LiDAR-derived metrics extracted from contemporary reference sites (Yosemite National Park)	36 Figs. 9 and 10
Vertical forest structural classes	Current only	Yes	No	Moderate	Shifting to lower and multistory structural classes	Lower proportion of sparse and top-story structural classes in fire-excluded landscapes	37 Fig. 11

Table 4—Deviations from the natural range of variation (NRV) based on historical and modern reference information in Sierra Nevada red fir forests (continued)

Variable(s)	Historical reference period	Modern reference site	Within NRV	Confidence	Direction of departure	Notes ^a	Pages in text
Canopy cover	Current with limited historical data	Yes	Yes/no	Moderate	Increasing especially in lower canopy strata	Canopy cover generally within NRV, but increasing cover in lower canopy strata with fire exclusion; cover decreasing in landscapes with increasing proportion of high-severity fire	38 Figs. 12 and 13
Canopy height and base height	Current only	Yes	Yes/no	Moderate	Decreasing	Likely within NRV, but decreasing canopy height and base height in landscapes experiencing fire exclusion, logging, or increasing proportion of high-severity fire	40 Fig. 14
Canopy complexity and heterogeneity	Current only	Yes	Yes/no	Moderate	Decreasing	Contemporary forest landscapes are within NRV, but landscapes with increasing proportions of high fire severity or widespread fire exclusion may approach upper or lower bounds of NRV	41 Fig. 15
Canopy fragmentation	Current only	Yes	Yes/no	Low	Increasing	Same as above	41 Fig. 16
Tree densities (all size classes)	1870–1936	Yes	No	High	Increasing	Increase in tree densities especially in the smallest size classes	43 Table 11
Average tree size and density of large diameter trees	1870–1920	Yes	No	Moderate	Decreasing	NRV departure due to recent changes in climate and 19 th century logging	43 Table 11
Tree size class distribution	pre-1870	No	No	High	Shifting to smaller size classes	Same as above	44 Fig. 17
Basal area	1870–1920	Yes	Yes	Moderate	—	—	46 Table 11
Tree spatial patterns	1870	No	Yes/no	Moderate	Increasing homogenization in smaller size classes	Large tree spatial patterns are within NRV, but small and intermediate size tree spatial patterns may be outside NRV	47
Tree regeneration	1600–1940	No	Yes	Moderate	—	—	48 Figs. 2 and 18

Table 4—Deviations from the natural range of variation (NRV) based on historical and modern reference information in Sierra Nevada red fir forests (continued)

Variable(s)	Historical reference period	Modern reference site	Within NRV	Confidence	Direction of departure	Notes ^a	Pages in text
Snag density, basal area, and average size	1899	Yes	Yes/no	Low	Increasing density and basal area	Considerable variation in snag abundance in historical and current stands may obscure trends	50 Table 12
Biomass	1920–1928	No	Yes	Low	—	—	51 Fig. 19
Understory cover	Current only	Yes	No	Low	Decreasing cover	Includes both shrub and herbaceous plant cover	52
Surface fuel loading	1873	No	Yes/no	Moderate	Some fuels likely increasing	Includes 1-hour, 10-hour, 100-hour, and 1,000-hour fuels, duff, and litter	52 Fig. 20
Seral class proportions	1600–1850	No	No	Low	Decreasing proportion of late-open seral class	Based on LANDFIRE Biophysical Settings Modeling for the southern Sierra Nevada	53 Fig. 21 Table 13
Overstory species composition	1870–1920	Yes	Yes	Moderate	—	Based on relative abundance of red fir	53 Table 11
Understory species composition	Pre–1940	No	Yes	Low	—	Based on relative abundance of shrub and herbaceous plant species	54 Table 14
Projected future distribution and climate exposure	2010–2099	—	—	Low to Moderate	Future contraction of geographic range and increasing climate vulnerability	Confidence in higher resolution spatial projections is low especially at later time intervals, but confidence in the overall degree of projected vulnerability in bioregion is moderate	56 Table 15 Figs. 22 through 24

^a Changes in variables resulting from projected future changes in climate are provided for comparison when available.^b Although the relative proportion of each fire severity class is within the NRV, the total area burned within each fire severity class (i.e., low, moderate, and high) are underrepresented in current Sierra Nevada red fir forests compared to the presettlement period; this is primarily because of fire exclusion in the assessment area during much of the 20th century.

Table 5—Deviations from the natural range of variation (NRV) based on historical and modern reference information in Sierra Nevada subalpine forests.

Variable(s)	Historical reference period	Within NRV	Direction of departure	Confidence	Notes	Pages in text
Fire return interval	1580–1942 (primarily before 1900)	Yes	Future decreases (i.e., increases in fire frequency)	Moderate	Likely within NRV for nearly all subalpine forest types except lodgepole pine forest; Projected future range of variation will exceed NRV for all subalpine forest types	71 Table 18
Fire rotation	1650–1905	Yes	Future decreases (i.e., increases in fire frequency)	Moderate	Likely within NRV but projected future range of variation will exceed NRV	71
Fire size	1729–1918	No	Increasing	Moderate	NRV departure likely due to recent changes in climate	73 Figs. 4 and 5
Fire type	1625–1845	Yes	—	Moderate	Refers to the dominant patterns in and controls over fire behavior within a vegetation type	74
Fire seasonality	1650–1942	Yes	—	High	—	76
Fire severity	1650–1930	Yes ^a	—	Low	Projected future increase in fire severity or intensity	77 Table 19
High-severity fire patch size and size distribution	Late 1800s	Yes	—	Low	Limited historical information	Fig. 6 78
Insects—mountain pine beetle	1895–1960	Yes	Future increases for whitebark, limber, lodgepole, and western white pines	Low to Moderate	Likely within NRV but projected future range of variation will exceed NRV. Current period refers to years preceding recent beetle outbreaks in the assessment area (1961–2005).	79 Fig. 7
Wind and volcanism	Variable	Yes	—	Low	Refer to red fir NRV	—
Climatic water deficit	1700	Yes	Future increases	Low	Likely within NRV but projected future range of variation may exceed NRV	81 Fig. 8
Tree growth and recruitment at treeline	1500 BCE–1960 CE	Yes/no	Variable but increasing for most species, such as bristlecone pine	High	NRV departure owing to recent changes in climate. There is a recent trend toward increased growth and recruitment at treeline that is either approaching the upper limit or exceeding the NRV	83 Table 20
Total tree densities (all size classes)	1870–1936	No	Increasing	Moderate	NRV departure owing to recent changes in climate and 19 th century logging in secondary-growth stands	83 Figs. 10 and 11

Table 5—Deviations from the natural range of variation (NRV) based on historical and modern reference information in Sierra Nevada subalpine forests. (continued)

Variable(s)	Historical reference period	Within NRV	Direction of departure	Confidence	Notes	Pages in text
Average tree diameter and density of large-diameter trees	1870–1936	No	Decreasing	Moderate	NRV departure owing to recent changes in climate and 19 th century logging in secondary-growth stands	83 Figs. 10 and 11
Tree size class distribution	1870–1936	No	Shifting to smaller size classes	Moderate to high	Same as above	85 Figs. 9 and 12
Basal area	1870–1936	Yes	—	Moderate	—	87 Fig. 11
Tree spatial patterns and structural diversity	1600–1870	No	Nondirectional pattern in tree spatial patterns	Low	Current unlogged stands similar to NRV, but lower structural diversity in current stands exposed to 19 th century logging	90 Table 17 Figs. 3 and 12
Canopy structure (canopy height, base height, and bulk density)	1600–1870	Yes/no	Lower canopy base height	Low	Based on Taylor et al. (2014) for lodgepole pine stands	90
Understory plant cover	1600–1940	Yes	—	Low	—	91
Seral class proportions	1600–1860	Yes/no	Greater proportion of early-seral class in lodgepole pine–dry forest	Low	Based on LANDFIRE Biophysical Settings Modeling for Stanislaus National Forest only; marginal changes for subalpine forest not dominated by lodgepole pine	91 Fig. 13
Tree species composition	1870–1936	Yes	—	High	Based on relative abundance of subalpine tree species	93 Fig. 21
Projected future distribution	2010–2099	—	Future contraction of geographic range and increased climate vulnerability	Low to moderate	Confidence in future projections is low especially at later time intervals, but confidence in the overall degree of projected vulnerability is moderate	93 Table 21 Figs. 14 through 16

Changes in variables resulting from projected future changes in climate are also provided for comparison.

^a Although the relative proportion of each fire severity class is within the NRV, the total area burned within each fire severity class (i.e., low, moderate, and high) are underrepresented in current Sierra Nevada subalpine forests compared to the presettlement period; this is primarily because of fire exclusion in the assessment area during much of the 20th century.

Red Fir Forests

Physical Setting and Geographic Distribution

Geographic distribution—

Red fir forests are distributed throughout the Sierra Nevada immediately above the montane mixed-conifer and below the subalpine forest zones (figs. 1 and 2) (Oosting and Billings 1943, Rundel et al. 1988). This forest generally occurs in a 300- to 500-m elevation width that extends from about 1800 to 2400 m in the northern Sierra Nevada to about 2200 to 2800 m in the southern part of the range (Fites-Kaufman et al. 2007, Potter 1998). Red fir extends from Sunday Peak in the northern edge of Kern County (Greenhorn Mountains) through the Cascade Range into southern Oregon as far north as Crater Lake National Park (Griffin and Critchfield 1972). Red fir is absent from the Warner Mountains and the Intermountain semidesert province, including the White and Inyo Mountains of eastern California (Griffin and Critchfield 1972). Red fir forests are less common on the eastern slope of the Sierra Nevada and are seldom encountered south of Mammoth Mountain to the Kern Plateau (Potter 1998).

Subspecies distributions—

Populations of red fir are represented by three different varieties in the Sierra Nevada. Shasta red fir (*Abies magnifica* var. *shastensis*) occurs from Lassen Peak to Crater Lake National Park and has cones with partly exerted bracts. The second variety, *A. m.* var. *magnifica*, exists in the northern and central Sierra Nevada and has a hidden-bract cone type. *Abies magnifica* var. *critchfieldii* occurs primarily south of the middle fork of the Kings River and is distinguished from the Shasta red fir variety by smaller cones with protruding cone bracts (Lanner 2010). Until recently, this last variety in the southern Sierra Nevada was considered to be a disjunct population of Shasta red fir. However, geographic patterns of morphological variation, artificial crossing results, and recent molecular studies indicate that Shasta red fir consists of California red fir introgressed by noble fir (*A. procera*), and that *A. m.* var. *critchfieldii* has not hybridized with noble fir (Lanner 2010). Chloroplast genetic loci indicate that both *A. m.* var. *critchfieldii* and *A. m.* var. *magnifica* share the same unique haplotype found in 100 percent of Sierra Nevada populations (Oline 2008). In contrast, the Shasta red fir variety contains multiple haplotypes, suggesting that it is probably part of a series of hybridized and introgressed California red fir and noble fir populations that are essentially a geographically widespread mature hybrid swarm (Oline 2008).

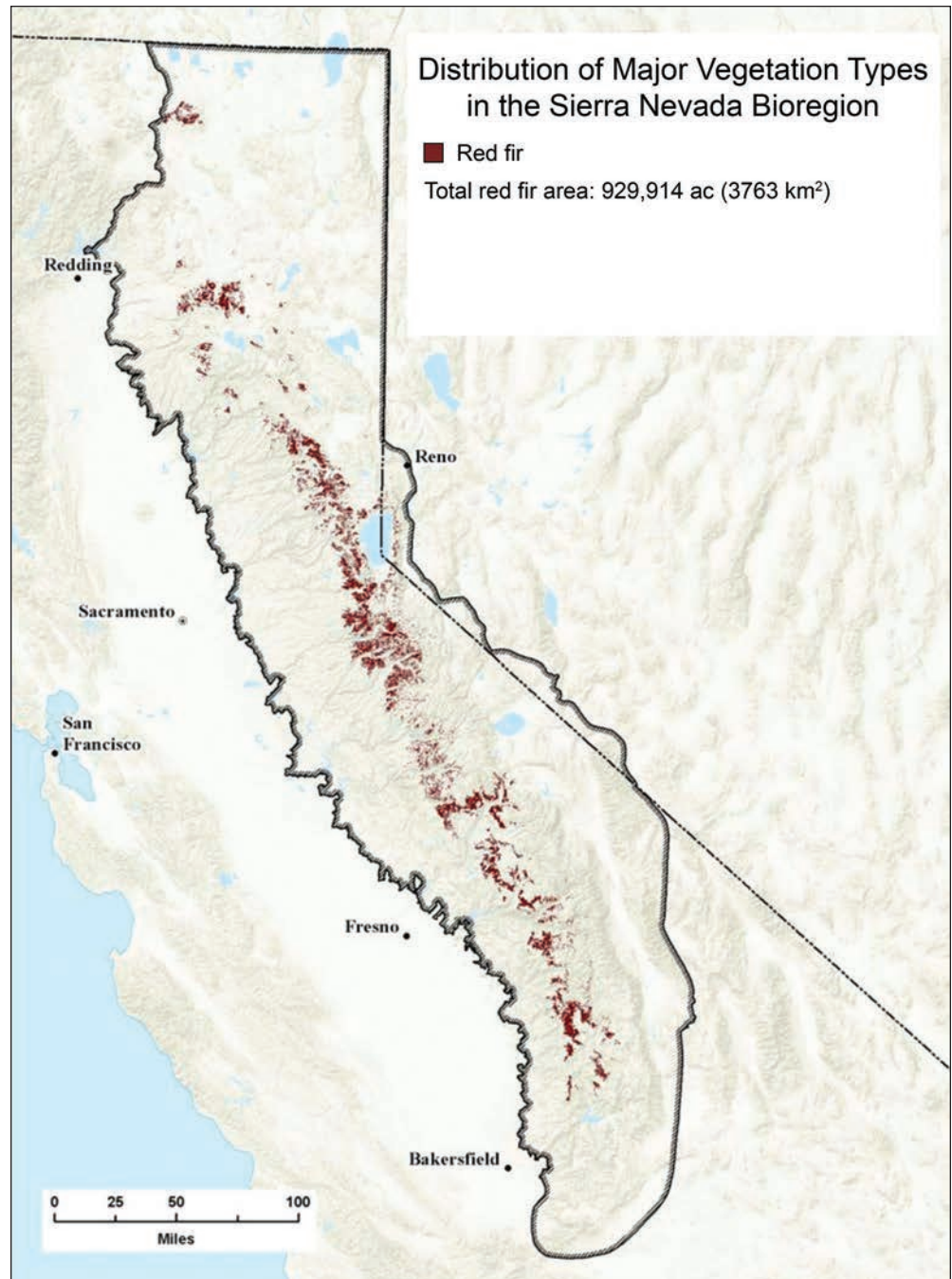


Figure 1—Distribution of red fir forest (*Abies magnifica*) in the assessment area.



Marc Meyer

Figure 2—Closed- and open-canopy late-seral red fir forests in the Illilouette Creek Basin (top and middle) and Tuolumne River watershed (bottom) of Yosemite National Park. Photos were taken in primarily low-severity, twice-burned stands about 10 years following the Hoover Fire (2001; top and middle photos) or Harden Fire (2005; bottom photo)

Red fir forests occupy cool sites with substantial winter snow.

Climatic associations—

Red fir forests occupy cool sites with substantial winter snow (table 6) (Agee 1993, Rundel et al. 1988). The distribution and dominance of red fir in the assessment area is strongly correlated with long-term, mean, late-March snow depth and snow water equivalence (Barbour et al. 1991). Growth increment is positively correlated with mean snow depth from the prior winter and spring (Dolanc et al. 2013b), although the influence of these and other climate variables may depend on latitude and elevation (Torbenenson 2014). Freezing level during late winter storms appears to be a primary indicator of regional climatic control over the lower elevation limit of red fir (North et al. 2016). Latitudinal trends indicate that red fir forests in the southern part of the assessment area are generally warmer and drier than in the northern subregion (i.e., southern Cascades, northern Sierra Nevada) (table 6) (Barbour et al. 1991, Potter 1998).

Recent climate trends indicate that the mean annual and monthly temperatures have increased in the upper elevations of the Sierra Nevada, especially within the past 30 years (Das and Stephenson 2013, Safford et al. 2012a). Moreover, the annual number of days with below-freezing temperatures at higher elevations has declined,

Table 6—Climate characteristics of red fir forests in the assessment area

Climate variable	Average (subregion) ^a
Annual precipitation (mm)	1000–1300
Precipitation (April 1 to September 30) (mm)	100–300
Precipitation as snow (percent)	75 to 95
Maximum snow depth (cm)	250–400
Snow water equivalent (mm):	
Northern	76–342
Southern	170–200
Annual streamflow discharge (mm)	708–810
Months of maximum snow depth	February through April
Mean winter temperature (°C):	
West slope	0
East slope	-5
Mean summer temperature (°C):	
West slope	16
East slope	13
Number of days mean temperature below 0 °C	240–260
July maxima (°C):	
Northern	20
Southern	26

^a Sources: Agee (1993), Barbour et al. (1991), Fites-Kaufman et al. (2007), Hunsaker et al. (2012), Oosting and Billings (1943), Potter (1998), and Rundel et al. (1988).

resulting in a 40 to 80 percent decrease in spring snowpack over the past 50 years in the northern and central Sierra Nevada (Moser et al. 2009). Snowpack (snow water equivalent) on April 1 in the southern Sierra Nevada has increased 30 to 110 percent over the same period (Moser et al. 2009), possibly owing to the relatively higher elevation terrain of the region (Safford et al. 2012a). Precipitation has remained stable or steadily increased over the past several decades in the higher elevations of the Sierra Nevada (Safford et al. 2012a).

Geology, topography, and soils—

Red fir forests occur on variable parent materials and soils, although most parent materials are granitic in the south, volcanic in the north, or either type in the central Sierra Nevada (Oosting and Billings 1943, Potter 1998). Red fir forest typically occurs on gentle to moderate slopes but also occurs on raised stream benches, terraces, steeper slopes, and ridges (Potter 1998, Sawyer et al. 2009). Soils of red fir forests are typically classified as Inceptisols (limited profile development) and Entisols (no sign of profile development) (Laacke 1990, Potter 1998). Soils are typically frigid, deep (relative to subalpine forests), and acidic (Potter 1998). Available water-holding capacity (AWC) in red fir forests is variable (average = 75 mm; range: 10 to 165 mm), with values that are relatively greater than most other nonriparian vegetation types encountered in the upper montane zone (e.g., Jeffrey pine [*Pinus jeffreyi*]) (Potter 1998). Topsoil and subsoil textures are usually sandy loams, sands, and loams, but also frequently include other texture classes (Oosting and Billings 1943, Potter 1998).

Ecological Setting

Indicator species and vegetation classification—

Red fir, Jeffrey pine, and Sierra lodgepole pine (*Pinus contorta* ssp. *murrayana*) are the primary indicator species that define the upper montane zone of the Sierra Nevada (Fites-Kaufman et al. 2007). Within this zone, red fir alone defines the occurrence of red fir forests in the region. Common associates of red fir include white fir at lower elevations and lodgepole pine, Jeffrey pine, and mountain hemlock at higher elevations (Potter 1994, 1998). Western white pine is also a common associate of red fir throughout the Sierra Nevada (Rundel et al. 1988). Current vegetation classification systems recognize as many as 14 vegetation associations of red fir forest in the assessment area (Potter 1998, Sawyer et al. 2009), including one riparian association (Potter 2005). All red fir forest stands, including those only partially dominated by red fir (e.g., mixed red fir–western white pine, red fir–white fir, red fir–mountain hemlock), were included in this NRV assessment to capture the full array of red fir associations in the Sierra Nevada.

Ecological importance of red fir—

Red fir forests provide a diverse array of ecosystem services, including watershed protection, erosion control, carbon sequestration, and habitat for a diverse array of species in the Sierra Nevada. A total of 169 vertebrate wildlife species use red fir forests for foraging or nesting/denning habitat, including 8 amphibians, 4 reptiles, 104 birds (including 15 waterbirds), and 53 mammals (Mayer and Laudenslayer 1988). These forests are particularly important for 28 birds and 26 mammals, including several uncommon and rare species such as the American marten (*Martes caurina*), great gray owl (*Strix nebulosa*), northern goshawk (*Accipiter gentilis*), Sierra Nevada red fox (*Vulpes vulpes necator*), wolverine (*Gulo gulo luteus*), white-tailed jackrabbit (*Lepus townsendii*), snowshoe hare (*Lepus americanus*), and heather vole (*Phenacomys intermedius*) (Mayer and Laudenslayer 1988, van Riper et al. 2013) (table 7). Red fir also provides important denning habitat for the

Table 7—Wildlife species that are largely or partially dependent^a on high-elevation forests in the Sierra Nevada to meet their basic habitat requirements during some part of their lifecycle; forest type includes red fir (RF) and subalpine (SA)

Common name	Scientific name	Forest type
American marten	<i>Martes caurina</i>	RF, SA
American pika	<i>Ochotona princeps</i>	SA
Black-backed woodpecker	<i>Picoides arcticus</i>	RF, SA
Bushy-tailed woodrat	<i>Neotoma cinerea</i>	RF, SA
California wolverine	<i>Gulo gulo luteus</i>	RF, SA
Cassin's finch	<i>Carpodacus cassinii</i>	SA
Clark's nutcracker	<i>Nucifraga columbiana</i>	SA
Golden-crowned kinglet	<i>Regulus satrapa</i>	RF
Great gray owl	<i>Strix nebulosa</i>	RF
Heather vole	<i>Phenacomys intermedius</i>	RF, SA
Long-tailed vole	<i>Microtus longicaudus</i>	RF, SA
Mountain bluebird	<i>Sialia currucoides</i>	RF, SA
Pine grosbeak	<i>Pinicola enucleator</i>	SA
Pine siskin	<i>Spinus pinus</i>	SA
Red crossbill	<i>Loxia curvirostra</i>	SA
Ruby-crowned kinglet	<i>Regulus calendula</i>	SA
Sierra Nevada red fox	<i>Vulpes vulpes necator</i>	RF, SA
Snowshoe hare	<i>Lepus americanus</i>	RF, SA
Sooty grouse	<i>Dendragapus fuliginosus</i>	RF
White-tailed jackrabbit	<i>Lepus townsendii</i>	RF, SA
Williamson's sapsucker	<i>Sphyrapicus thyroideus</i>	SA
Yellow-bellied marmot	<i>Marmota flaviventris</i>	RF, SA
Yosemite toad	<i>Anaxyrus canorus</i>	RF, SA

^a Red fir or subalpine forests represent primary or optimal habitat for these species based on Verner and Boss (1980) and Mayer and Laudenslayer (1988).

northern flying squirrel (*Glaucomys sabrinus*), a keystone species in many western forests, including the Sierra Nevada (Meyer et al. 2005). Red fir provides habitat for several species of arboreal lichens (Rambo 2010, 2012) and a diverse community of ectomycorrhizal fungi (Izzo et al. 2005). Red fir forests also contain some of the highest biomass and aboveground carbon pools of any forest type in the bioregion (Gonzalez et al. 2010, Swatantran et al. 2011).

Red fir forests also contain some of the highest biomass and aboveground carbon pools of any forest type in the bioregion.

NRV Descriptions and Comparisons to Current Conditions

Function—

Fire—

Fire return interval, fire rotation, and fire return interval departure—Historical fire return interval (FRI) estimates for red fir forests in the Sierra Nevada were highly variable and dependent on several factors, including elevation, forest type, and geographic location in the region (tables 8 and 22). In general, mean and median FRI values increased with elevation and latitude, and intervals tended to be longer in more mesic red fir forest types (e.g., red fir and mountain hemlock), a trend consistent with FRI patterns along elevational transects in the Sierra Nevada (e.g., Swetnam et al. 1998, Taylor 2000). Red fir forests in the eastern and southern subregions tended to have lower mean FRI values, perhaps reflecting the drier conditions of these forests, especially in the red fir and Jeffrey pine forest types; although median, minimum, and maximum FRI values for these forests were generally greater than low- and mid-elevation red fir forests on the west side of the Sierra Nevada. Estimates of FRI in the northern Sierra Nevada and southern Cascades (mean FRI = 50.8 years; range: 9 to 74 years) were generally greater than FRI estimates for the southern/central Sierra Nevada (mean FRI = 33.3 years; range: 7 to 72 years) (table 8), possibly owing to the drier conditions and more xeric red fir types at lower latitudes (Potter 1998). As an exception, the historical mean FRI in red fir forests at Crater Lake National Park in the central Cascades was 39 years (range: 15 to 71 years) (Chappell and Agee 1996).

Landscape position and context also may influence FRI patterns in Sierra Nevada red fir forests. Based on a reconstruction of the annual area burned, mean and maximum FRI estimates for red fir forests in Sequoia and Kings Canyon National Parks tended to be greater on relatively mesic north-facing slopes (mean and maximum FRI = 30 and 50 years) compared to xeric south-facing slopes (mean and maximum FRI = 15 and 25 years) (Caprio and Graber 2000, Caprio and Lineback 2002). However, Taylor (2000) found that median FRI estimates were similar across all slope aspects in red fir-mountain hemlock forests of Lassen Volcanic National Park. Fire return intervals may be longer in isolated patches of red fir than in stands with high connectivity to lower elevation forest types (North 2014).

Table 8—Average historical fire return interval (FRI) estimates for red fir forests in the Sierra Nevada

Red fir type/group (aggregation)	Mean FRI	Median FRI	Minimum FRI	Maximum FRI	Number of studies	Forest types included
----- Years -----						
West side:						
High elevation	83	66	18	85	4	Red fir–western white pine/mountain hemlock
Mid elevation	48	24	5	49	4–6	Red fir
Low elevation	27	14	7	61	7	Red fir–white fir/mixed conifer
Northern Sierra ^a	51	36	9	71	14	Red fir, red fir–white fir, red fir–western white pine/mountain hemlock
Southern and central Sierra	33	21	7	67	6	Red fir, red fir–white fir/mixed conifer
East side:						
All elevations	21	23	9	55	4	Red fir, red fir–Jeffrey pine/lodgepole pine/ mixed conifer

Individual FRI estimates and sources are presented in table 22 of the appendix.

^a Includes southern Cascade Range.

Fire rotation estimates for red fir forests were variable across the Sierra Nevada (table 9). In the southern Cascades (pre-1905 period), fire rotation ranged from 50 years in red fir–white fir forests to 147 years in red fir–mountain hemlock forests (Bekker and Taylor 2001). In Yosemite National Park, the contemporary fire rotation estimate based on lightning fires that were allowed to burn under prescribed conditions in red fir forests was 163 years (van Wagten-donk 1985, in van Wagten-donk et al. 2018). Based on recent fire severity data (1984–2009), Miller et al. (2012) calculated a fire rotation of 96 years in red fir forests of Yosemite National Park and estimated that 27 percent of these forests (27 501 ha) have burned during the 25-year period; however, remote-sensing-based mapping of red fir forests had relatively low accuracy (about 30 percent) in their study. Mallek et al. (2013) estimated a fire rotation of 61 years (range: 25 to 76 years) for red fir forests in the assessment area.

Few fires have burned during the fire suppression period in red fir forests of the Sierra Nevada (Beaty and Taylor 2009, Bekker and Taylor 2001, Hallett and Anderson 2010), with the exception of contemporary reference sites with active fire regimes (e.g., Collins et al. 2007). This absence of fire has led to an increase in FRI and fire rotation in contemporary compared to presettlement red

Table 9—Historical fire rotation estimates for red fir forests in the Sierra Nevada

Location	Forest type	Fire rotation ^a	Reference
		Years	
Thousand Lakes Wilderness, southern Cascade Range	Red fir-white fir	50	Bekker and Taylor (2001)
Thousand Lakes Wilderness, southern Cascade Range	Red fir-mountain hemlock	147	Bekker and Taylor (2001)
Caribou Wilderness, southern Cascade Range	Red fir and other upper montane forests ^b	76	Taylor and Solem (2001)
Lassen Volcanic National Park, southern Cascade Range	Red fir-western white pine	76	Taylor (2000)
Yosemite National Park, central Sierra Nevada	Red fir ^c	163	van Wagtendonk (1985)
Yosemite National Park, central Sierra Nevada	Red fir ^d	96	Miller et al. (2012)
Sierra Nevada—summary of several studies	Red fir	61	Mallek et al. (2013)
Average across studies	All	96	All

^a Fire rotation is the length of time necessary to burn an area equal to the area or landscape of interest.

^b Red fir and other upper montane forests are aggregated for estimation of fire rotation.

^c Recorded during the 1970–1985 period and includes lightning fires under prescribed conditions only.

^d Estimated for the 1984–2009 period.

fir forests (e.g., Bekker and Taylor 2001, Pitcher 1987). For example, Taylor and Solem (2001) and Taylor (2000) estimated presettlement (1735–1849), settlement (1850–1904), and fire-suppression (1905–1994) fire rotations of 76, 117, and 577 years, respectively, in red fir and other upper montane forests in the southern Cascades. The absence of fire over the past century has also increased the backlog of red fir forests that require fire for ecological benefits (e.g., surface fuels reduction, increased biodiversity and structural heterogeneity), as indicated by an increase in fire return interval departure (FRID) values in these forests (Caprio and Graber 2000, North et al. 2012, Meyer et al. 2019). However, most Sierra Nevada red fir forests have missed only one to three fire cycles (i.e., mostly low to moderate FRIDs), suggesting that the ecological effects of fire suppression in these forests are not as extreme as in the fire-frequent mixed-conifer and yellow pine forests (Miller and Safford 2012, North 2014, Safford and Van de Water 2014, van Wagtendonk et al. 2002).

Future projections in fire frequency, probability, and area—Projections of future fire frequency, probability, and total burned area are expected to increase in coming decades. Westerling et al. (2011) projected a more than 100-percent increase in annual area burned in many mid- to high-elevation forests of the western Sierra Nevada by

Most Sierra Nevada red fir forests have missed only one to three fire cycles (i.e., mostly low to moderate FRIDs), suggesting that the ecological effects of fire suppression in these forests are not as extreme as in the fire-frequent mixed-conifer and yellow pine forests.

2085 (Westerling et al. 2011). In Yosemite National Park, annual burned area is projected to increase 19 percent by 2020–2049 owing to projected decreases in snowpack in mid- and high-elevation forests (Lutz et al. 2009b). In the southern Sierra Nevada, fire probability and frequency are expected to more than double in red fir forests by the end of the century (Moritz et al. 2013). These projected increases were consistent across climate models that project hotter and drier (the Geophysical Fluid Dynamics Laboratory model) and warmer and wetter (the Parallel Climate Model) climate conditions. Additionally, these results support earlier climate models that projected increased future fire occurrence in red fir forests (Miller and Urban 1999). Increases in projected fire probability indicate that future fire frequency will increase, leading to a decrease in return intervals and fire rotations for red fir forests in the assessment area.

Fire size. There are few historical estimates of fire size in Sierra Nevada red fir forests. Mean fire size in the southern Cascades (1729–1918 period) was 151 ha (range: 34 to 372 ha) in red fir-white fir forest and 140 ha (range: 124 to 155 ha) in red fir–mountain hemlock forest (Bekker and Taylor 2001). In Lassen Volcanic National Park, mean fire size was 176 ha (median = 129 ha; range: 11 to 733 ha) in red fir–western white pine forest (Taylor 2000). In the Lake Tahoe basin, presettlement spatial patterns of fires scarred trees in red fir–western white pine forests suggested that fires in the past were small and patchy, but pulses of recruitment indicated that larger areas of moderate-severity fire also occurred on the landscape (Scholl and Taylor 2006).

Based on contemporary reference sites, sizes of suppressed fires in red fir forests vary widely but tend to be less than 4 ha in size. In the Emigrant Basin Wilderness Area between 1951 and 1973, nearly 80 percent of lightning-caused fires were less than 0.1 ha and none were larger than 4 ha (Greenlee 1973 in Potter 1998). In Sequoia and Kings Canyon National Parks between 1968 and 1973, 80 percent of unsuppressed fires were smaller than 0.1 ha and 87 percent were smaller than 4 ha (Potter 1998). In Yosemite National Park, 56 percent of fires in red fir and lodgepole pine forests between 1972 and 1993 were less than 0.1 ha, and 82 percent were smaller than 4 ha (fig. 3) (van Wagten-donk 1993). In contrast to average fire size, the highest proportion of area burned (>70 percent) in red fir forests of Yosemite National Park tended to be from fires between 4 and 400 ha in size (van Wagten-donk 1993); an additional 28 percent of burned area is attributed to fires between about 400 and 2000 ha in size (fig. 4).

There is a recent trend toward increasing fire size and total burned area in red fir forests of the Sierra Nevada. Between 1984 and 2010, annual burned area has increased (Miller and Safford 2008, 2012; Miller et al. 2009). Mean and maximum fire size have also increased during this time period in montane forests of the Sierra Nevada.

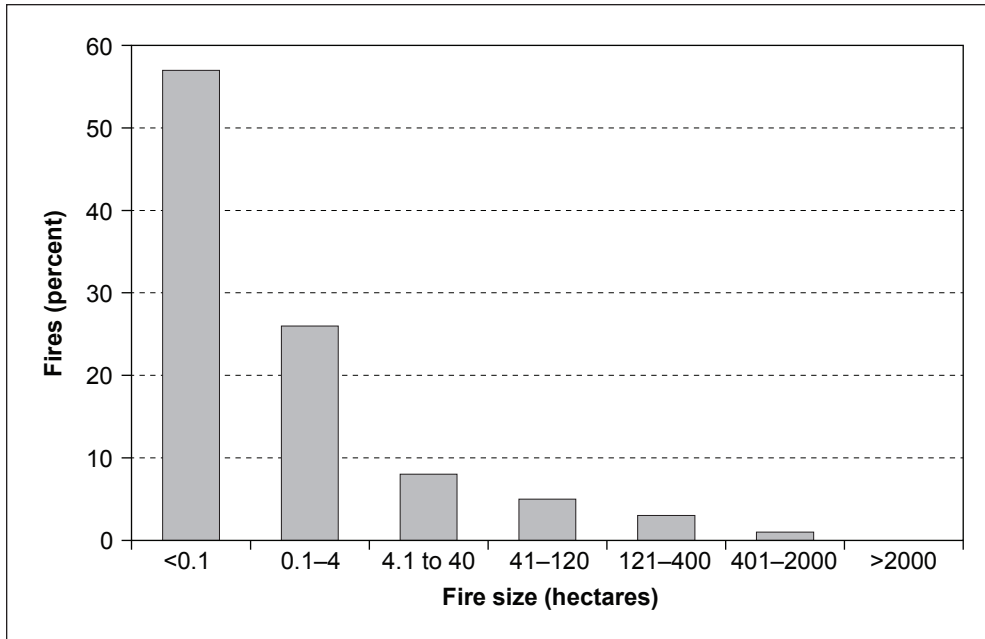


Figure 3—Percentage of fires by size class in red fir and lodgepole pine forests of Yosemite National Park between 1972 and 1993. Adapted from van Wagtenonk (1993) and Potter (1998).

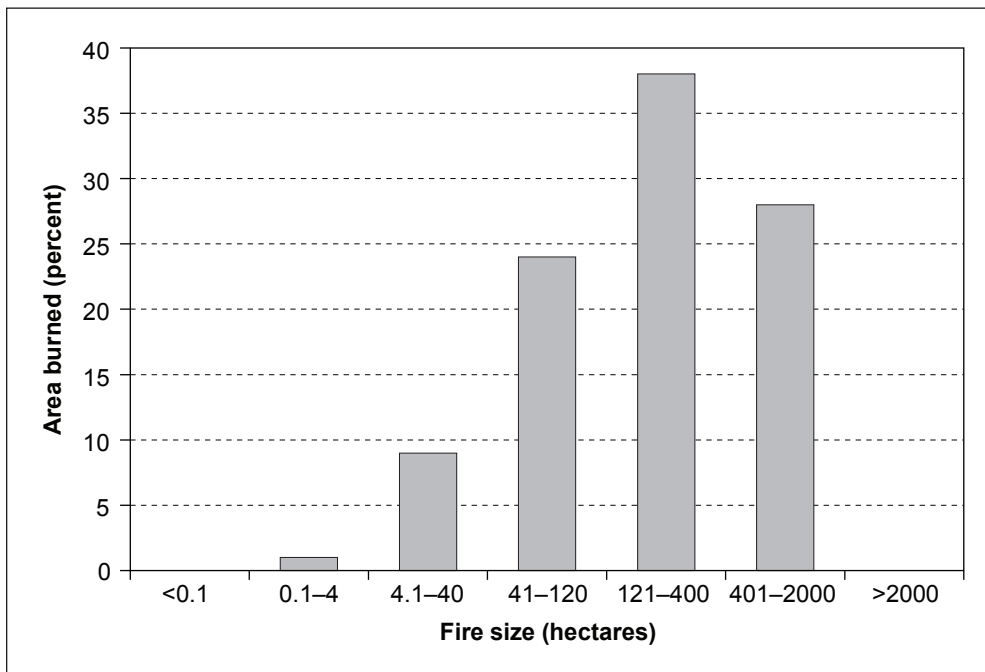


Figure 4—Percentage of total area burned by fire size class in red fir and lodgepole pine forests of Yosemite National Park between 1972 and 1993. Adapted from van Wagtenonk (1993) and Potter (1998).

Collectively, these studies indicate that current fire size is generally within the historical range of variation. However, recent (1984–2010) trends suggest that fire size may be approaching or possibly exceeding the upper limit of this historical range of variation.

Fire type. Sierra Nevada red fir forests typically experience slow-moving surface fires because of the presence of heavy and compact surface fuels, natural terrain breaks, and relatively cooler and moister conditions (van Wagtendonk et al. 2018). However, occasional, passive crown fires may occur in these forests, particularly under extreme dry and windy conditions with high fuel loading (Taylor et al. 2014). Pitcher (1987) noted the lack of evidence of extensive crown fires in red fir forests of Sequoia National Park, indicating that surface fires predominated, although localized torching and crown fires led to the creation of canopy gaps less than 0.5 ha in size. Kilgore (1971) observed that virtually all prescribed burning in red fir forests of Sequoia National Park resulted in surface fires with infrequent torching of individual trees or small groups with interlocking canopies. In the Lake Tahoe basin, modeled fire behavior in presettlement red fir stands generally produced surface fires even under the most extreme (i.e., 98th percentile) weather conditions, with passive crown fires restricted to stands with high fuel loading under the most extreme weather conditions (Maxwell et al. 2014, Taylor et al. 2014).

These fire patterns indicate a climate-limited fire regime for red fir forests, especially at mid and high elevations. Climate-limited fire regimes always have sufficient fuel to carry fire, but fire occurrence depends primarily on whether climate or weather is suitable for ignition and fire spread (Agee 1993). In a comprehensive analysis of red fir forests in California, Steel et al. (2015) found that red fir forests exhibited a fire return interval and fire severity pattern (i.e., no positive relationship) that was indicative in a climate-limited fire regime. In the upper montane mixed-conifer and red fir forests of Yosemite National Park's Illilouette Creek Basin, fire regimes are limited in both climate and fuel; the size of stand-replacing patches and total reburned area are dependent on a combination of fire weather conditions, fuel accumulation rates, and preexisting dominant vegetation (Collins and Stephens 2010, Collins et al. 2009). In addition, rates of ignition influence fire patterns in climate-limited fire regimes, and in red fir forests of Yosemite National Park these include lightning (96 percent), prescribed (1 percent), and human-induced nonprescribed (3 percent) ignition sources (van Wagtendonk et al. 2002). In the Late Holocene, fire activity in red fir and other high-elevation forests of the Sierra Nevada was driven by changes in climate, including the dynamics of the El Niño–Southern Oscillation (Hallett and Anderson 2010).

Together, these studies suggest that both historical and current fire regimes in red fir forests are climate-limited and dominated by surface fires and occasional localized crown fires. Consequently, fire regime type is likely within the historical range of variation.

Fire seasonality. Most fires in red fir forests occur during the late summer or fall (van Wagtendonk et al. 2018). In red fir–white fir forests of the southern Cascades, the position of fires on presettlement annual growth rings indicated that 77 percent of historical fires burned during the late summer and fall, and the remaining 23 percent of fires burned during the early to mid-summer (Bekker and Taylor 2001). In higher elevation red fir–mountain hemlock and red fir–western white pine stands of the southern Cascades, 99 to 100 percent of historical fires burned during late summer to fall (Bekker and Taylor 2001, Taylor 2000). In the Lake Tahoe basin, 92 percent of historical fires in red fir–western white pine forests burned during late summer to fall, and 7 percent burned in early to mid summer (Taylor 2004). In upper montane forests of Yosemite National Park, most wildfires and “wildland fire use” (i.e., wildfires managed for resource objectives) between 1974 and 2005 burned during the months of July, August, and September (van Wagtendonk and Lutz 2007). These collective studies demonstrate that fire season has not changed between historical and current periods.

Fire severity. Fire regimes of red fir forests in contemporary reference sites have been classified as “mixed” or “moderate” severity (Agee 1993, Brown and Smith 2000, van Wagtendonk et al. 2018), although there is ambiguity associated with this terminology (Collins and Stephens 2010). Overall, fire severity estimates based on historical data or contemporary reference sites were dominated by three fire severity classes: unburned or unchanged, low severity, and moderate severity, but with low severity as the predominant class (tables 10 and 23). For instance, Thode et al. (2011) concluded that the red fir fire regime type burned between 1984 and 2003 in Yosemite National Park had a “low-severity fire regime distribution.” The proportion of area burned at high severity in red fir forests was 16 percent based on historical reference information from Taylor and Solem (2001) in the southern Cascades. The proportion of area burned at high severity in contemporary reference sites in Yosemite, Sequoia, and Kings Canyon National Parks averaged 7 percent (range: <1 to 15 percent). Reburned red fir stands in Yosemite National Park tended to burn at higher severity when initial burn severity was high (van Wagtendonk et al. 2012) (table 23). Wildfires managed under suppression objectives also tended to burn at greater severity relative to prescribed fires and “wildland fire use” fires across upper and lower montane forests in Yosemite National Park during 1974–2005 (van

Overall, fire severity estimates based on historical data or contemporary reference sites were dominated by three fire severity classes: unburned or unchanged, low severity, and moderate severity, but with low severity as the predominant class.

Wagtendonk and Lutz 2007). In Crater Lake National Park, Chappell and Agee (1996) found that mature and old-growth red fir stands (>100 years old) burned at lower severity and had lower proportions of high-severity burned areas (4.5 percent) than young red fir stands (50 to 80 years old; 24 percent burned at high severity). Miller et al. (2009) found that fire severity in Sierra Nevada red fir forests was negatively correlated with spring precipitation. In the northern Sierra Nevada, Leiberg (1902) estimated that 8 percent of red fir forests (primarily below 3120 m elevation) had historically burned at stand-replacing severity (>95 percent tree mortality), and at least 28 percent of red fir forests in the 19th century had burned at moderate to high severity (>50 percent tree mortality). However, Leiberg's estimates may have overestimated these fire severity proportions owing to the ubiquitous presence of burning activities from early placer mining camps and sheepherders.

Although the proportion of high-severity fire has not changed in recent decades in Sierra Nevada red fir forests, the total area of high-severity fire has increased during this period. Miller et al. (2009) and Miller and Safford (2008, 2012) examined trends (1984–2004 and 1984–2010, respectively) in the percentage of high severity and high-severity fire area for all fires ≥ 80 ha in the Sierra Nevada and found a marginally significant increase in total area of high-severity fire in red fir forests; this pattern was best explained by decreases in spring precipitation (Miller et al. 2009). Interestingly, red fir forests that burned between 1984 and 2009 have significantly lower proportions of high-severity fire in Yosemite National Park (average = 7 percent) than the national forests of the Sierra Nevada (average: 12, 16, and 32 percent in west-side Sierra Nevada, east-side Sierra Nevada, and southern Cascade subregions, respectively) (Miller et al. 2012). Despite these recent trends, Mallek et al. (2013) estimated that modern rates of burning in Sierra Nevada red fir forests for all severity classes (i.e., low-moderate and high) were currently underrepresented compared to the presettlement period (Mallek et al. 2013). Consequently, current Sierra Nevada red fir forests may be deficient (i.e., outside or approaching the upper limit of the NRV) in all fire severity classes (except unburned) at the bioregional scale.

Future projections in fire severity and intensity. Projections of future climate suggest that fire severity or intensity may increase in many parts of the Sierra Nevada during the mid-21st century, especially in high-elevation forests such as red fir (Lenihan et al. 2003, 2008). In Yosemite National Park, the total area burned at high severity in mid- and high-elevation forests is projected to increase 22 percent between the current (1984–2005) and mid-21st century (2020–2049) periods, owing to declines in snowpack (April 1 snow water equivalent) (Lutz et al. 2009b).

High-severity and unburned patch size. Information related to high-severity patch size was based almost exclusively on contemporary reference sites, primarily in Yosemite National Park, by using remote-sensed estimates of high severity based on a 95 percent tree mortality threshold value (fig. 5). In the Illilouette Creek Basin of Yosemite National Park, the mean patch size of stand-replacing, high-severity burned patches (>95 percent tree mortality) following the Hoover Fire (2001) and Meadow Fire (2004) was 9.1 ha (median = 2.2 ha) (Collins and Stephens 2010). Most (>60 percent) of the stand-replacing patches in their study were ≤ 4 ha in size, but a few large patches accounted for about 50 percent of the total stand-replacing patch area (fig. 6). In addition, the median patch size of stand-replacing patches was an order of magnitude greater in red fir–white fir–lodgepole pine forests than either red fir–white fir forests or stands dominated exclusively by lodgepole pine. In another study that used light detection and ranging (LiDAR) to examine structural patterns in burned stands of Yosemite National Park, the frequency distribution of canopy gap sizes in red fir forest generally shifted toward the right (increased gap sizes) with increasing fire severity (Kane et al. 2013) (fig. 7). In addition, most (>60 percent) canopy gaps were greater than 10 ha in size within high-severity burned red fir stands.

Historical accounts of high-severity patch size in Sierra Nevada red fir forests are limited. Leiberg (1902) noted that a few older burns from the early 19th century were stand replacing and covered “large tracts” of area in red fir forests of the northern Sierra Nevada, as indicated by the presence of older montane chaparral. He also estimated that 30 percent of the total area of stand-replacing fires was attributed to burns exceeding about 30 ha. However, a large proportion of these burned areas was attributed to the activity of early placer-mining camps and sheepherders (Leiberg 1902), inferring that these early 20th-century estimates do not accurately reflect presettlement conditions.



Figure 5—High-severity burned patch in a red fir and Jeffrey pine forest, about 20 years following the Rainbow Fire (1992) located within Devils Postpile National Monument. High-severity burned patches were defined as areas exceeding 95 percent tree mortality with high to complete mortality of vegetation.

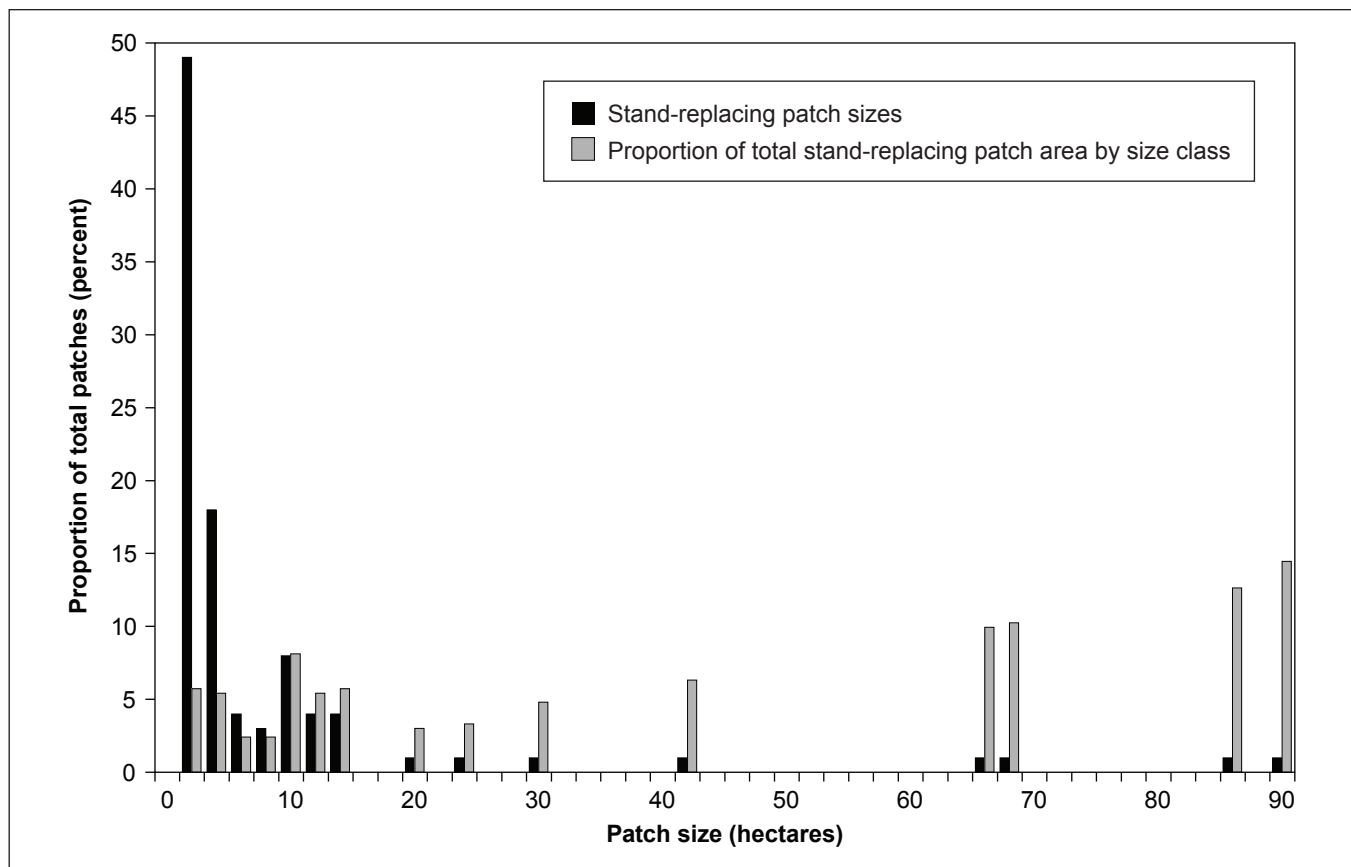


Figure 6—Frequency distribution of stand-replacing patch sizes (black bars) and proportion of total stand-replacing patch area by size class (gray bars) within the Hoover (2001) and Meadow (2004) fires from Collins and Stephens (2010). The authors used a minimum patch size of 0.5 ha and a total number of 72 high-severity patches in their analysis. Adapted from Collins and Stephens (2010).

Miller et al. (2012) found that lower and upper montane forests (including red fir forest) had a mean high-severity patch size of 4.2 ha (median = 0.45 ha; range: 0.09 to 999 ha) in Yosemite National Park, but a mean high-severity patch size of 9.0 to 16.5 ha (median = 0.45 to 0.63 ha; range: 0.09 to 4752 ha) in the Sierra Nevada national forests. The average size of high-severity patches tended to be smaller following prescribed fires (1.8 ha) and wildland fire use fires (2.3 ha) compared to wildfires (6.8 ha) in lower and upper montane forests of Yosemite National Park (van Wagtendonk and Lutz 2007). The average size of high-severity patches in resource objective wildfires of the southern Sierra Nevada was 2.8 ha, which was similar to an estimated NRV average patch size of 3.4 ha (Meyer 2015). Agee (1998) found an average high-severity patch size of 1.3 ha (median = 0.4 ha) in red fir forests of Crater Lake National Park.

Unburned patch size in lower and upper montane forests of Yosemite National Park (including red fir forests) averaged 19.5 ha, with an unburned patch density of 12 patches per 100 ha (Kolden et al. 2012). The total proportion of unburned area

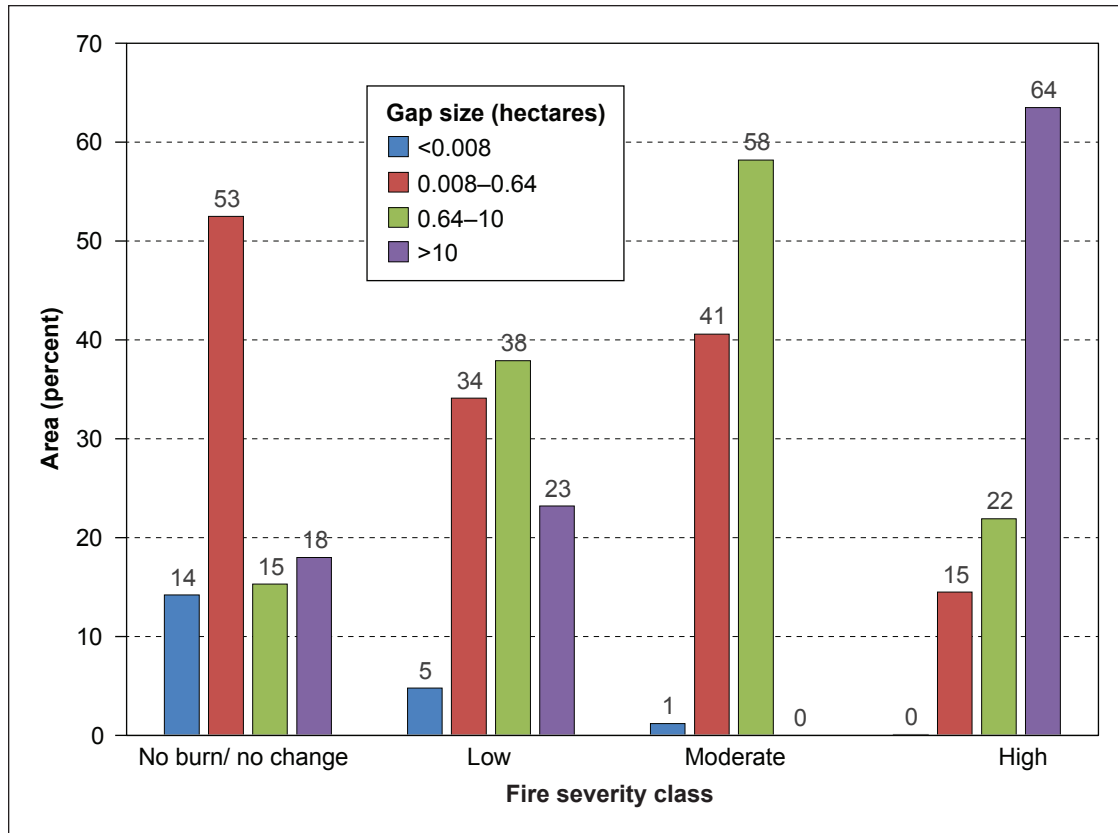


Figure 7—Kane et al. (2013) gap size distribution in different fire severity classes in red fir forests of Yosemite National Park. Adapted from Kane and Lutz (2012) and Kane et al. (2013). Fire severity classes are based on the Relativized differenced Normalized Burn Ratio (RdNBR) from Miller and Thode (2007). Note the relatively even distribution of gap sizes in the low-severity-fire class.

within fire perimeters in their study was 35 percent, and the average unburned proportion per fire was 52 percent (range: 8 to 97 percent).

It is likely that current averages for high-severity and unburned patch size are within the historical range of variation, but historical information is limited with respect to these variables. However, contemporary reference site studies indicate that high-severity patch size may be increasing in red fir and other fire-excluded forest landscapes within the assessment area.

Insects and pathogens—Several native insects and pathogens can affect red fir growth and survivorship in the assessment area, including fir engraver beetle (*Scolytus ventralis*), flatheaded fir borer (*Melanophila drummondi*), roundheaded fir borer (*Tetropium abietis*), Heterobasidion root disease (*Heterobasidion occidentale*), Cytospora canker (*Cytospora abietis*), and dwarf mistletoe (*Arceuthobium abietinum* f. sp. *magnificae*) (Ferrell 1996, Scharpf 1993). These mortality agents often interact to compromise the health of red fir trees, especially during periods of stress associated with extended drought or following disturbance such as mechanical

thinning operations (Ferrell 1996, Maloney et al. 2008b). Most of these insects and pathogens also are found in the lower montane zone (Safford and Stevens 2017).

Based on sedimentary pollen records, dwarf mistletoe has been a persistent component of Sierra Nevada red fir forests for the past 3,000 years, likely fluctuating with changes in canopy cover and density (Anderson and Davis 1988, Brunelle and Anderson 2003). Historical records by 19th and early 20th century botanists and plant pathologists identified dwarf mistletoe as a significant pathogen in coniferous forests of the Western United States, including the Sierra Nevada (Hawksworth 1978). In the late 1950s, about 45 percent of trees in Sierra Nevada red fir stands were infected with dwarf mistletoe, especially in older and denser forests and often associated with *Cytospora* canker (California Forest Pest Council 1960, Scharpf 1993). Dwarf mistletoe incidence in white fir was 50 percent (range: 17 to 100) in the relatively active fire regime landscapes of the Sierra San Pedro Martir in Baja, Mexico (Maloney and Rizzo 2002). Contemporary pollen records in the central Sierra Nevada indicate that dwarf mistletoe occurs in 48 percent of upper montane stands below 3000 m elevation (Anderson and Davis 1988).

Based on these studies and reports, dwarf mistletoe occurrence in Sierra Nevada red fir forests is generally similar between historical (1600–1960) and current (1960–2005) periods. However, recent trends (1983–2012) indicate that the impacts of dwarf mistletoe, *Cytospora* canker, and other pathogens in red fir forests may be increasing in many parts of the assessment area. In California, red fir mortality rates have increased based on a comparison of recent Forest Inventory and Analysis (FIA) plots between 2005 and 2010 (Mortenson et al. 2015). Similarly, mortality rates in coniferous forests (including red fir) have increased in Yosemite, Sequoia, and Kings Canyon National Parks between 1983 and 2004 (van Mantgem and Stephenson 2007). The primary factors associated with the increased red fir mortality were increased temperatures associated with climatic water deficit and the occurrence of dwarf mistletoe (19 percent on red fir) and associated *Cytospora* canker, although the role of other mortality factors (e.g., fir engraver, *Heterobasidion* root disease) was not clear (Mortenson et al. 2015). These findings suggest that the occurrence of dwarf mistletoe, *Cytospora*, and other native pathogens or insects may be increasing within red fir stands of the Sierra Nevada, possibly driven by recent increases in temperature, drought stress, and climatic water deficit (California Forest Pest Council 2011, Meyer et al. 2019, Mortenson et al. 2015, van Mantgem and Stephenson 2007) even though the current population structure of red fir is stable in California (Mortenson et al. 2015). These trends are consistent with future projected increases in climatic water deficit that are expected to increase tree mortality rates in Sierra Nevada red fir forests during the 21st century (Das et al. 2013).

The occurrence of dwarf mistletoe, *Cytospora*, and other native pathogens or insects may be increasing within red fir stands of the Sierra Nevada, possibly driven by recent increases in temperature, drought stress, and climatic water deficit.

Wind, volcanism, and avalanches—Wind, volcanism, and avalanches can have substantial impacts on red fir and other high-elevation forests. Wind-related disturbances in red fir forests are highly variable both spatially and temporally, but can result in extensive, severe blowdown events that cause breakage of boles and limbs and tree uprooting (Potter 1998) and widespread dieback of shrubs (Nelson and Tiernan 1983). John Muir observed a major blowdown event with extensive damage in forests of the Sierra Nevada in December 1874 (Muir 1894). In the northern Sierra Nevada, sustained windspeeds of 44 to 48 km per hour (kph) were recorded during the Columbus Day storm of October 12, 1962, that caused substantial damage in red fir forests (Potter 1998). On November 30 and December 1, 2011, the Devil’s Windstorm event in the eastern Sierra Nevada caused the toppling of 400,000 trees in red fir and upper montane forests of the Red’s Meadow Valley of the Inyo National Forest and Devils Postpile National Monument (USDA FS 2012). During the event, winds gusted to an estimated 100 to 110 kph and may have exceeded 145 kph on the Mammoth Mountain summit. Large trees were disproportionately uprooted (86 percent) and snapped (14 percent) during the Devil’s Windstorm event, creating variable-sized canopy gaps in red fir forests with heavy postdisturbance fuel loading (fig. 8) (Hilimire et al. 2013). Taylor and Halpern (1991) measured radial growth patterns in red and white fir stands of the southern Cascades and found growth releases related to two windstorm events that occurred between 1960 and 1990. Gordon (1973) found that wind (based on two extreme events) accounted for 60 percent of tree damage and 77 percent of gross stand volume loss within intact red fir-white fir stands adjacent to clearcut stands in the Swain Mountain Experimental Forest. The direct effects of wind (i.e., bole and limb breakage, uprooted trees) accounted for 71 percent of tree mortality in their study; indirect effects (e.g., tree struck by another wind-damaged tree) accounted for the remaining 29 percent mortality. Wind had a disproportionate impact on larger trees in the dominant and codominant crown classes (Gordon 1973).



Marc Meyer

Figure 8—Red fir stand that experienced an extreme wind “blowdown” event in the Reds Meadow area (Inyo National Forest) and Devils Postpile National Monument. Photo was taken about 8 months after this extreme weather event.

Volcanism has historically been more common on the east side of the Sierra Nevada, in areas such as the Long Valley Caldera region near Mammoth Lakes. Within this area, a 10-km-long chain of domes and craters, the Inyo Craters, was formed by the repeated expulsion of rhyolitic lava over the past 6,000 years. Volcanic events occurred at North Deadman Creek dome (about 6,000 years ago), Wilson Butte (1,350 years ago), and at several other domes along the Inyo Craters chain (1369, 1433, and 1469 CE) (Hill 2006). These volcanic events directly (e.g., lava flows) and indirectly (e.g., volcano-induced forest fires) caused substantial tree mortality in subalpine and upper montane forests, including areas currently occupied by red fir (Millar and Woolfenden 1999, Millar et al. 2006). In addition to volcanic eruptions, subsurface magma can cause localized tree mortality through the production of excessive carbon dioxide gas in soils. In the 1990s, about 50 ha of tree mortality occurred in upper montane forest stands with a red fir component near Horseshoe Lake below Mammoth Mountain (Hill 2006).

Avalanches may occur in red fir and other high-elevation Sierra Nevada forests, especially on slopes exceeding 30 to 40 percent (Potter 1998). Most large avalanches occur during years of high snowpack and following heavy snowfall events, often coupled with high windspeeds (Davis et al. 1999). Avalanches can occur frequently in steep gullies and “chutes,” or, on rare occasions, can have major impacts on slopes that show no evidence of past activity (e.g., older forested stands on lower slope positions located beneath open slopes with few trees [Potter 1998]). The 1860–1864 Brewer expedition (Brewer 1930) noted evidence of avalanches in subalpine forests of the southern Sierra Nevada, and Muir (1894) observed the complete removal of an older upper montane forest stand by avalanches.

Despite past and recent observations of avalanches in high-elevation forests of the Sierra Nevada, post-avalanche successional dynamics remain poorly documented in the region. In the European Alps, where post-avalanche successional dynamics have received more research attention, subalpine forests affected by avalanche are characterized by smaller and shorter trees, reduced stem densities, shade-intolerant species, and greater structural heterogeneity at the landscape scale (Bebi et al. 2009). In western North America and Europe, increased landscape heterogeneity from avalanches can enhance the diversity of plants and wildlife habitat, benefiting such species as brown bear (*Ursus arctos*) and wolverine (*Gulo gulo*) (Bebi et al. 2009). Johnson (1987) estimated avalanche return intervals from 2 to 20 years (maximum: 130 years) in the Canadian Rocky Mountains, with return intervals below 15 to 20 years resulting in a shift from tree- to shrub-dominated vegetation, including short-statured broad-leaved trees (e.g., willows and birch; *Salix* and *Betula* spp., respectively).

Historical rates of wind, volcanism, and avalanches are difficult to compare to current rates owing to the highly infrequent or unpredictable nature of these natural processes. Nevertheless, current rates of wind, volcanism, and avalanches in Sierra Nevada red fir forests are broadly considered within the historical range of variation. Interestingly, projected declines in snowpack in the Sierra Nevada in the 21st century could result in reduced probability of avalanches and increased landslide activity in coming decades (Huggel et al. 2012). However, reductions in snowpack could be offset in the near future by potential increases in precipitation variability and the frequency of heavy, unpredictable snowfall events that could elevate avalanche probability, especially at higher elevations (Bebi et al. 2009).

Climatic water deficit—Water balance relations are important for evaluating climate controls on species distributions across spatial scales, including red fir (Stephenson 1998). Annual actual evapotranspiration (AET) and annual climatic water deficit (CWD) are two water balance variables that can be used to model vegetation presence (Stephenson 1998). In Yosemite National Park, AET and CWD values indicated that red fir tended to occupy sites that were cooler and snowier than common associates such as white fir (*A. concolor*) (Lutz et al. 2010), consistent with the relatively low drought tolerance of red fir in California's montane forests (North et al. 2016). Lutz et al. (2010) also found that values of AET/potential evapotranspiration (PET), a measure of the relative sensitivity of species ranges to increases in CWD, for red fir stands in Yosemite National Park were clustered near the arid end for its entire geographic range, indicating moderately high sensitivity to changes in CWD. In the Sierra Nevada, annual rates of climatic water deficit tend to increase with decreasing elevation (Stephenson 1998), indicating greater moisture deficit in red fir stands at lower elevations.

Modeled CWD averages for red fir forests in Yosemite National Park were 10 percent lower during the Little Ice Age (about 1700 CE; deficit = 114 mm) than the present (1971–2000; deficit = 126 mm) (Lutz et al. 2010). This suggests that CWD may be approaching or exceeding the upper threshold for the historical range of variation for red fir in the central portion of the assessment area. Modeled CWD averages for red fir forests in Yosemite National Park were projected to be 24 percent greater in the near future (2020–2049; deficit = 157 mm) compared to the present (1971–2000; CWD = 126 mm) (Lutz et al. 2010), indicating an increasing trend of moisture stress in red fir forests. This future projected trend will likely increase tree mortality rates in red fir forests of the Sierra Nevada, especially if mortality rates are related to relative changes in CWD (Das et al. 2013). Accordingly, increased CWD and reduced canopy water content during the extreme 2012–2016 drought resulted in high percentages of recently dead trees (approximately 18

percent) in red fir forests of the Sierra Nevada, particularly in areas of increased topographic dryness (i.e., lower elevations, south-facing slopes of decreased soil moisture) (Brodrick and Asner 2017, Meyer et al. 2019, Paz-Kagan et al. 2017).

Structure—

Canopy structural classes and landscape patchiness—

Several recent studies (e.g., Kane et al. 2012, 2013, 2014) have used airborne LiDAR technology in contemporary reference sites of Yosemite National Park to provide new insights into landscape-scale, three-dimensional canopy structural information for late-seral coniferous forests. Kane et al. (2012, 2013) categorized red fir forest landscapes (2900 ha total) into three distinct canopy structural classes: canopy-gap, clump-gap, and open patch (fig. 9). Canopy-gap arrangements (typically referred to as “closed canopy” forest) were characterized by continuous canopy punctuated by frequent and small gaps across the landscape. These arrangements typically occurred in unburned and undifferentiated (no satellite-detected change in postfire vegetation) red fir forests. Patch-gap arrangements (i.e., “spatially heterogeneous partially open canopy forest”) had alternating tree clumps and canopy gaps in roughly equal proportions across the landscape. This patch-gap pattern was typical of low-severity burned red fir forests. In contrast, open-patch arrangements (i.e., “large canopy gaps”) occurred on landscapes where trees were scattered across large open areas, which was typical following moderate- and high-severity fire. Overall, the proportion of the landscape containing canopy patches decreased and the proportion of canopy gaps increased with increasing fire severity in red fir stands of Yosemite National Park (fig. 10) (Kane et al. 2013, 2014).

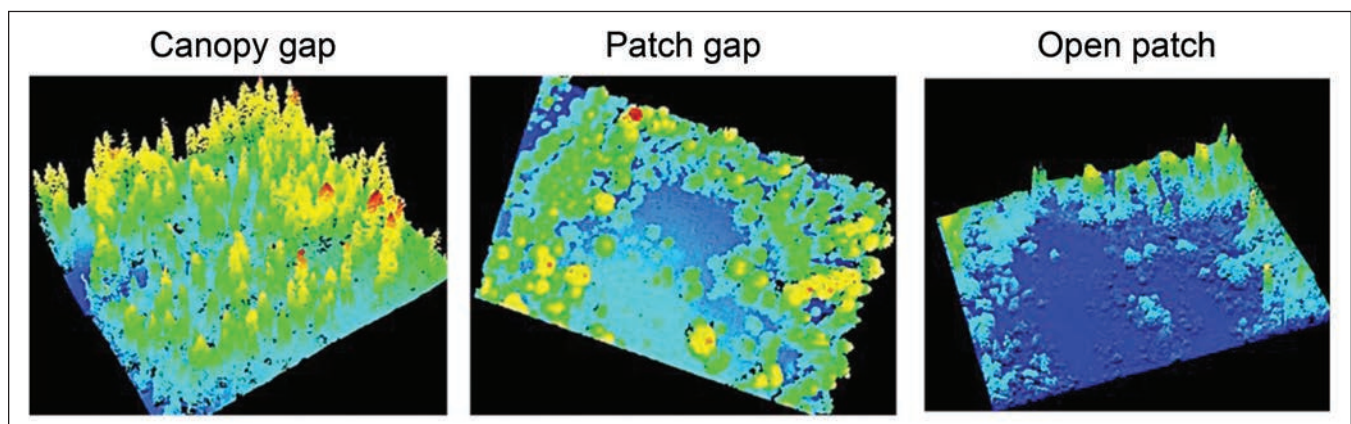


Figure 9—Landscape-scale canopy structural classes in burned and unburned red fir forests of Yosemite National Park from Kane et al. (2013). Structural classes included (1) canopy-gap arrangements in which continuous canopy was punctuated by frequent and small gaps across the landscape (typically in unburned and undifferentiated areas), (2) patch-gap arrangements in which tree clumps and canopy gaps alternated and neither dominated (typically following low-severity fire), and (3) open-patch arrangements in which trees were scattered across large open areas (typically following moderate- or high-severity fire). Figure was created with FUSION software (McGaughey 2010).

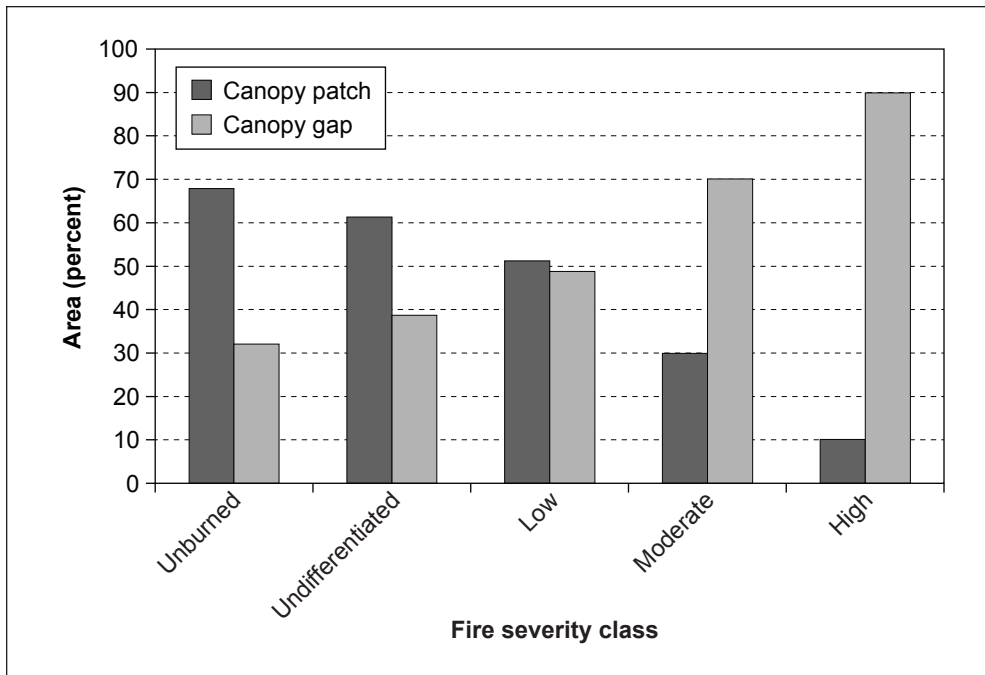


Figure 10—Percentage of landscape occupied by canopy patches or gaps in burned and unburned red fir forest landscapes of Yosemite National Park from Kane et al. (2013). Only vegetation >2 m in height are included in estimation of canopy patches.

These results suggest that, in the absence of fire over the past century, current red fir forests landscapes have (1) shifted from a spatially heterogeneous partially open canopy to a closed canopy structure, and (2) experienced substantial canopy ingrowth that led to a reduction in the portion of canopy gaps (Kane et al. 2013).

Vertical forest structural classes—

At the individual patch scale, vertical forest structure of red fir forests were classified into five structural classes: open, sparse, shorter, multistory, and top story (Kane et al. 2013). The open forest class was characterized by few or no erect trees, with trees and shrubs mostly under 2 m in height. The sparse forest class was characterized by low tree densities separated by relatively large areas where most vegetation did not exceed 2 m in height. The shorter forest class was characterized as predominantly tree covered, but with smaller trees. The multistory forest class was characterized by trees of variable height, typical of fire-excluded stands. The top story forest class was characterized by low densities of larger trees with distinct vertical separation between tall trees and lower forest strata, typical of stands with a low biomass of ladder fuels and subcanopy trees (Kane et al. 2013). Increasing fire severity in red fir forests increased the proportion of open and sparse structural classes and decreased the proportion of top story, multistory, and shorter structural classes (fig. 11). In addition, low-severity

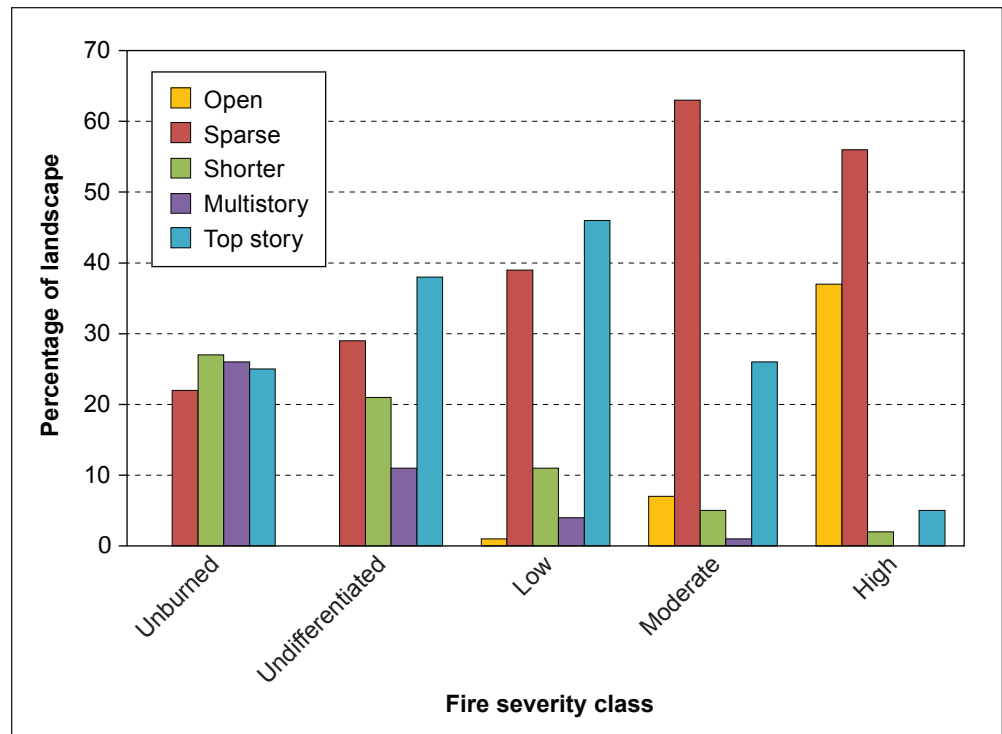


Figure 11—Proportion of five forest structural classes that occur at the individual patch scale within burned and unburned red fir forest landscapes of Yosemite National Park.

and undifferentiated fire severity classes had a greater proportion of the top story structural class compared to unburned patches and high- to moderate-severity classes, demonstrating the capacity of low-severity fire to remove understory ladder fuels while retaining larger trees (Kane et al. 2013). These results show that modern fire-excluded red fir forests have a relatively lower proportion of top story and sparse structural classes and greater proportion of multistory and shorter (and denser) structural classes than contemporary reference landscapes burned within the past 26 years.

Canopy cover and height—

Although canopy cover estimates show a high degree of overlap between contemporary reference sites and current stands across the entire assessment area, there was a tendency for fire-excluded late-seral stands to have greater canopy cover (fig. 12). Similarly, field-based estimates of canopy cover from red fir stands in active fire regime landscapes of Yosemite and Kings Canyon National Parks (38 ± 17 percent) were generally lower than neighboring unburned areas (64 ± 16 percent) (Meyer et al. 2019). Cover in the upper (>16 m) and lower (2 to 16 m) canopy strata of red fir forests in Yosemite National Park was negatively related with fire severity (fig. 13) (Kane et al. 2013). The upper canopy stratum (i.e., overstory canopy cover) was substantially reduced following moderate- or high-severity fire, suggesting

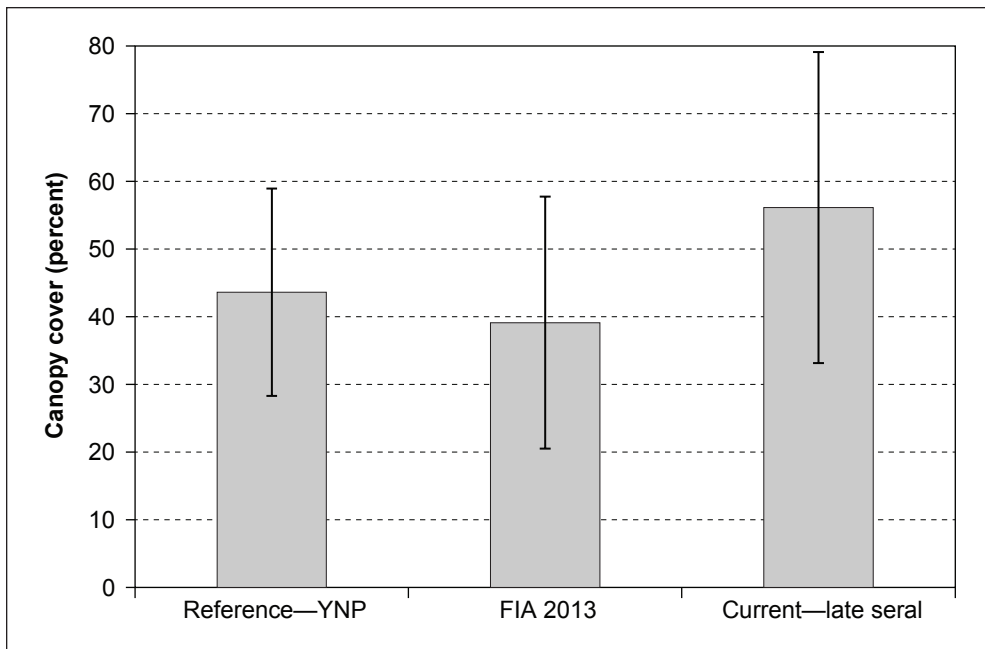


Figure 12—Mean ($\pm$ standard deviation) percentage canopy cover in contemporary reference and current red fir stands of the assessment area. Historical mean canopy cover represents a landscape-scale estimate using a combination of LiDAR-derived canopy cover values from Yosemite National Park (YNP) for each fire severity class (based on data presented in fig. 10) and average fire severity proportions calculated from reference site and model-derived estimates presented in table 26 in the appendix. Stand-scale canopy cover estimates in current red fir forests are represented by bioregional Forest Inventory and Analysis (FIA) data (collected 2001—2009 from logged and unlogged stands) and current late-seral (unlogged) stands based on 13 studies presented in table 24 of the appendix. Error bars for contemporary reference stands are based on canopy cover estimates for red fir forests of YNP exclusively and do not represent the full range of variation in canopy cover for the entire assessment area.

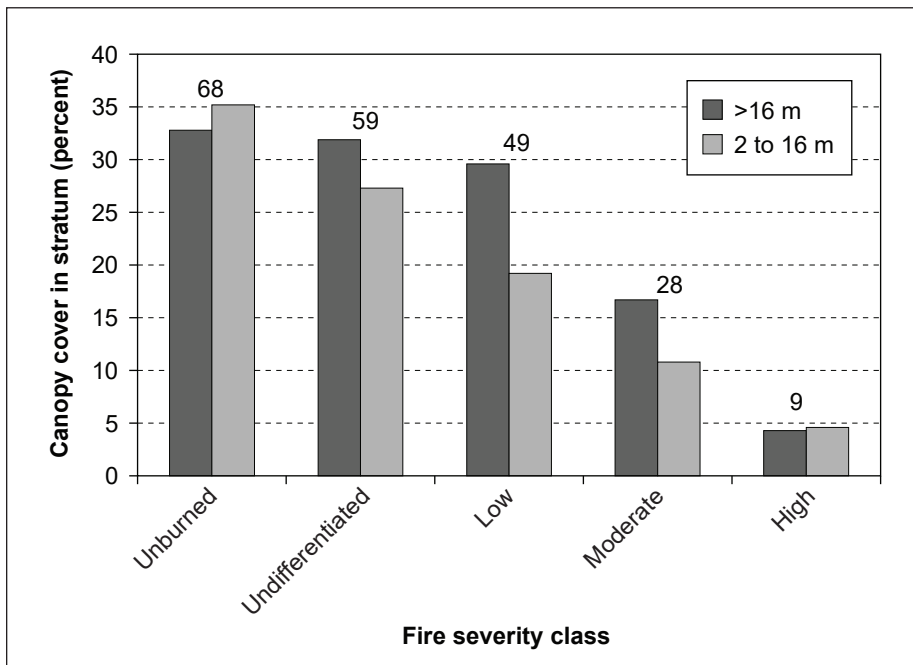


Figure 13—Mean percentage cover in canopy strata >16 m (overstory canopy) and 2 to 16 m (subcanopy) in height. Values above bars indicate total canopy cover from both canopy strata.

high mortality rates in larger red fir trees possibly resulting from increased postfire insect or pathogen activity (Maloney et al. 2008b). Dominant tree height (95th percentile) and dominant lower foliage height (25th percentile; related to canopy base height) also declined with increasing fire severity, although heights were greatest following low-severity fire (fig. 14). Lower fire severities may eliminate understory ladder fuels and raise canopy base height, whereas higher severities may induce shrub growth and tree regeneration in upper montane forests (Collins and Stephens 2010). In red fir stands of the Lake Tahoe basin, canopy height and canopy base height were greater, and canopy bulk density was lower in presettlement than contemporary secondary-growth stands (Taylor et al. 2014). These combined results suggest that modern unburned red fir forest landscapes have considerably more cover in the lower strata, lower canopy base heights, greater canopy bulk density, and reduced dominant tree heights than either contemporary reference landscapes that burned at low-severity or presettlement reference stands. In addition, landscapes that burned at lower severity have greater canopy cover in higher strata and greater canopy base and dominant tree heights than those burned predominantly at high to moderate severity.

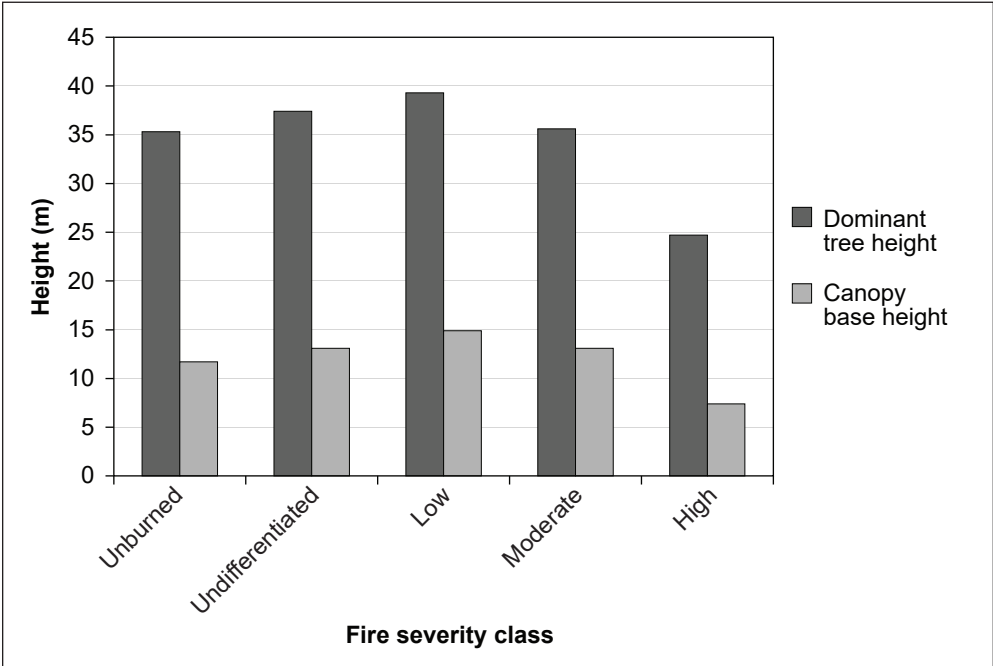


Figure 14—Mean dominant tree height and canopy base height in burned and unburned red fir forest landscapes of Yosemite National Park from Kane et al. (2013). Dominant tree height and canopy base height estimates are based on the 95th and 25th percentile LiDAR return heights, respectively.

Canopy structural complexity, forest heterogeneity, and fragmentation—

In red fir–western white pine stands of the Lake Tahoe basin, Taylor (2004) used Shannon’s diversity index to estimate the richness and evenness of diameter size classes in presettlement and current stands that had been logged in the late 19th century. Current stands had significantly lower structural diversity than presettlement stands.

Kane et al. (2013, 2014) used rumple as an estimate of canopy surface rugosity, which measures canopy structural complexity and forest heterogeneity. Their results indicated that low-severity and undifferentiated fire severity classes (the most frequently occurring in red fir forests based on NRV) (table 10) led to the greatest canopy structural complexity in red fir forest landscapes, exceeding that of fire-excluded landscapes (fig. 15).

Kane et al. (2014) also evaluated forest fragmentation in red fir forest landscapes by estimating the total number of canopy clumps or patches within each sample unit (90 × 90 m), with higher counts of disconnected canopy clumps indicating increasing forest fragmentation. Their results show that increasing fire severity results in greater forest fragmentation (fig. 16). Red fir forest landscapes burned at high severity had a high proportion of the landscape (94 percent) containing many (>20) canopy clumps, suggesting an elevated level of forest fragmentation. In contrast, aggregation of canopy clump strata (a measure of whether adjacent cells tended to be of a similar class type) showed little change with fire, suggesting that landscape clumpiness was not influenced by fire severity (Kane et al. 2014).

Table 10—Average proportion of fire severity classes in Sierra Nevada red fir forests based on historical and contemporary reference site information

Aggregation/ group	Locations	Unchanged/ unburned	Low	Moderate	High	Forest types
----- Percent -----						
Historical estimates	Northern Sierra ^a	—	49	38	13	Red fir, red fir–white fir/ western white pine
Reference sites	Yosemite, Sequoia and Kings Canyon National Parks	28	42	22	8	Red fir, red fir–mixed conifer
Modeled ^b	Sierra Nevada	—	62	18	21	Red fir

Individual fire severity estimates and sources are presented in table 23 of the appendix.

— = no estimate available.

^a Includes the southern Cascade Range.

^b Based on LANDFIRE Biophysical Setting Model estimates of historical reference conditions.

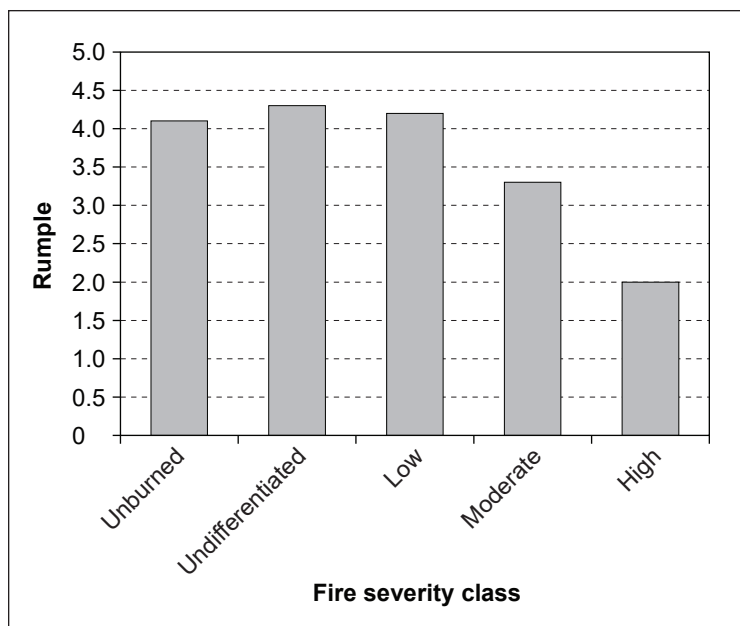


Figure 15—Mean rumple values for burned and unburned red fir forest landscapes of Yosemite National Park from Kane et al. (2013). Rumble is a measure of canopy surface rugosity and an indicator of canopy structural complexity and heterogeneity. All fire severity classes are statistically distinguishable ($P < 0.05$) from each other.

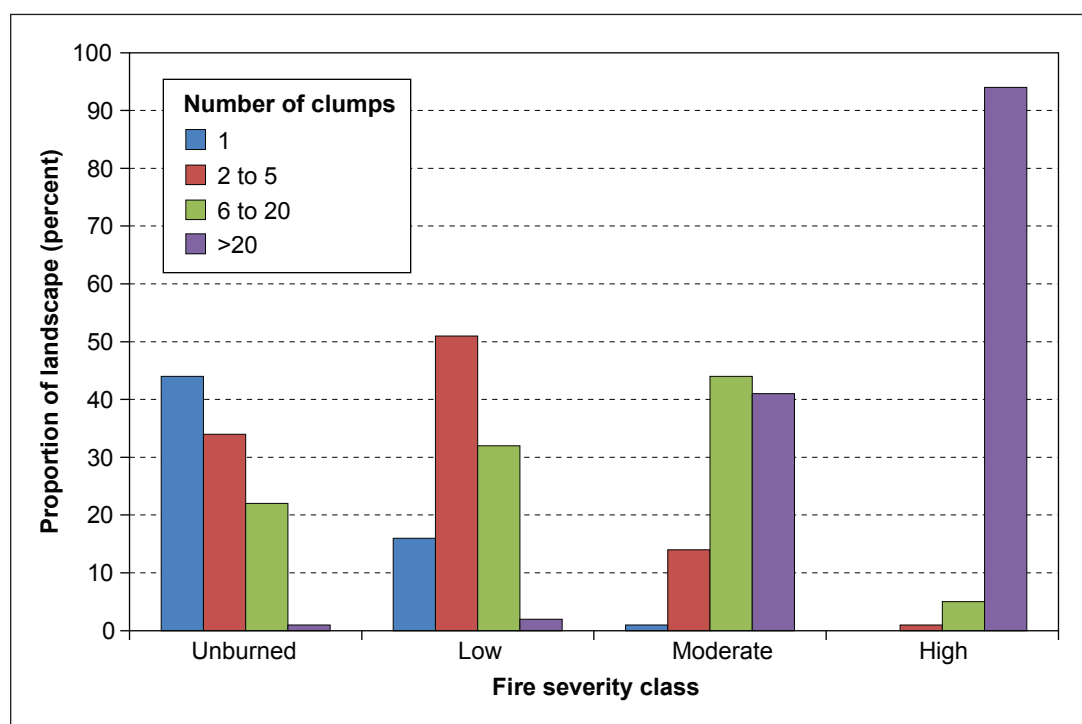


Figure 16—Forest fragmentation in burned and unburned red fir forest landscapes of Yosemite National Park. Increasing proportion of the landscape with a greater number of canopy clumps or patches indicates that the total red fir forest canopy was more fragmented. The number of clumps was calculated by determining the minimum number of clumps within each sample area that were ≥ 75 percent of the total canopy cover.

Collectively, these results suggest that (1) presettlement red fir forests were structurally more complex than current secondary-growth forests (Taylor 2004), (2) contemporary red fir landscapes experiencing low-severity fire have greater structural heterogeneity than unburned landscapes (Kane et al. 2013, 2014), and (3) increasing fire severity in these landscapes results in less structural complexity and greater homogenization and fragmentation (Kane et al. 2013, 2014). Consequently, patterns of increased total area burned at high severity in red fir forests (see the “Fire severity” section on page 27) implicates a potential trend toward increasing structural homogenization and fragmentation in severely burned red fir forest landscapes over the past few decades.

Tree density, size, and size class distribution—

Average tree densities (all species pooled) were lower in historical (pre-1940) or contemporary reference landscapes compared to current, fire-excluded red fir forests based on a broad comparison of all unlogged stands across the entire assessment area (tables 11 and 24). In the Lake Tahoe basin, presettlement (pre-1870) tree densities in historical red fir–western white pine forests (average = 161; range: 118 to 208 trees/ha) were substantially lower than modern forests that were intensively logged in the late 19th century (average = 538; range: 214 to 842 trees/ha) (Taylor 2004, Taylor et al. 2014). Overall tree density increased by about 23 to 51 percent between historical (1929–1936) and current (2001–2010) red fir stand inventories of the northern and central Sierra Nevada (Dolanc et al. 2014a, 2014b). Bouldin (1999) also found modest increases in tree densities in red fir forests of the central and northern Sierra Nevada. The average size of trees (red fir, western white pine, and lodgepole pine) in red fir–western white pine forests was greater in presettlement than contemporary stands (table 24).

The density of larger diameter red fir trees in Sierra Nevada red fir forests was often greater in historical than contemporary periods. Dolanc et al. (2014b) compared extensive historical (early 1930s) and modern (FIA) forest inventories in the northern and central Sierra Nevada and found that the density of large (>60 cm diameter at breast height [d.b.h.]) red fir trees had declined by 36 percent (from 64 to 41 trees/ha) and the density of smaller (10 to 30 cm d.b.h.) red fir trees had increased by about 70 percent (from 91 to 154 trees/ha) over a 70-year period. In a related study, Dolanc et al. (2013a) estimated that the density of smaller diameter red fir trees had increased 91 percent, and the density of larger (61 to 91 cm d.b.h.) red fir trees marginally decreased by about 20 percent over a 73-year period in unlogged upper elevation (2300 to 3400 m) forests of the central Sierra Nevada. The average density of moderately large diameter (61 to 91 cm d.b.h.) red fir trees declined between historical (1932–1936) and contemporary (1988–1999)

Size class distribution in red fir forests has shifted to smaller size classes between historical and current periods.

Overall, there has been an increase in total tree densities of Sierra Nevada red fir forests over the past century, especially in stands that experienced intensive logging impacts and long-term fire exclusion.

sampling periods in upper montane forests of Yosemite National Park, although declines in the largest trees (>92 cm d.b.h.) was not significant possibly owing to limited sample size (Lutz et al. 2009a). Patterns of increased mortality rates in large-diameter trees were also apparent in late-seral forests of the southern Sierra Nevada (Smith et al. 2005, van Mantgem and Stephenson 2007) and throughout the Western United States (van Mantgem et al. 2009). These changes in the density of red fir trees were frequently attributed to recent increases in temperature and climatic water deficit associated with climate change (Dolanc et al. 2013a, 2014b; van Mantgem et al. 2009).

Size class distribution in red fir forests has shifted to smaller size classes between historical and current periods. The presettlement size class distribution of trees in red fir–western white pine forests of the Lake Tahoe basin was dominated by red fir and western white pine trees ranging from 30 to 110 cm d.b.h., but current secondary-growth stands were dominated by significantly smaller size classes of lodgepole pine (fig. 17) (Taylor 2004, Taylor et al. 2014). Presettlement size class distribution also varied among 66 percent of sampled plots, demonstrating high variation in size class structure among stands. These size class distribution patterns indicate that historical red fir forests were structurally more diverse and lacked the characteristic structure of even-aged or uneven-aged stands (Taylor and Halpern 1991). In contrast to historical stands, contemporary unlogged red fir forests after a century of fire exclusion consistently had reverse J-shaped or irregular diameter distributions, with most trees occurring in the smallest size classes (typically 3 to 30 cm d.b.h.) (Oosting and Billings 1943, Potter 1998). Such a diameter distribution approximates an uneven-aged stand structure (e.g., Bekker and Taylor 2010, Taylor 2004, Taylor and Halpern 1991), which is notably different than presettlement patterns (Taylor 2004). North et al. (2007) also found that size class distribution patterns changed between presettlement (relatively flat distribution) and contemporary (reverse J-shaped) mixed-conifer–red fir forests of the southern Sierra Nevada.

Overall, there has been an increase in total tree densities of Sierra Nevada red fir forests over the past century, especially in stands that experienced intensive logging impacts and long-term fire exclusion. These increased tree densities are attributed to an increase in the density of small-diameter (<30 cm d.b.h.) trees. In contrast, there has been a relatively consistent decline in the density of larger diameter red fir trees over the past century. Also, the size class distribution of red fir forests has generally shifted toward smaller size classes, resulting in reduced structural diversity. Collectively, these patterns indicate a loss of large trees and accumulation of small trees in red fir forests of the assessment area

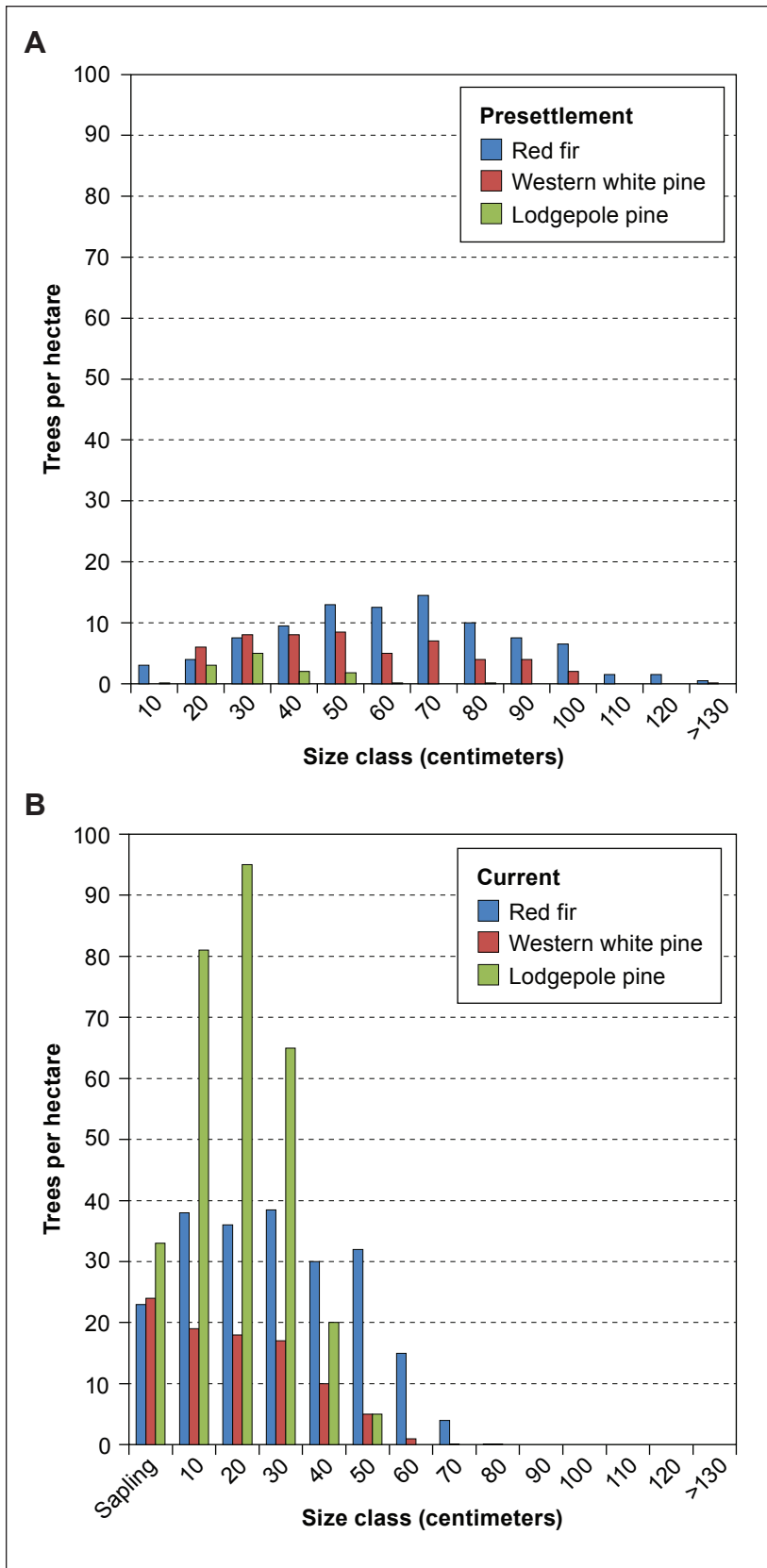


Figure 17—Size class distribution of presettlement and current secondary-growth red fir–western white pine stands in the Lake Tahoe basin. Note the large increase in the density of lodgepole pine between periods. The Y-axes are scaled to a maximum of 100 trees per hectare to emphasize differences in tree densities between periods. Adapted from Taylor (2004).

over the past 70 to 150 years. These changes are coincident with (1) increases in daily minimum temperatures and precipitation over the past several decades that may favor increased regeneration, recruitment, and large-tree mortality rates in red fir and other upper montane tree species (Dolanc et al. 2013a, 2014b); (2) 19th century logging impacts in secondary growth stands (e.g., Maxwell et al. 2014, Taylor 2004); and (3) fire exclusion, especially at elevations below 2500 m (Dolanc et al. 2014b).

Basal area—

Basal area varied widely across both historical and current late-seral red fir forests of the Sierra Nevada (tables 11 and 24). Most modern forests were within the historical range of variation, but basal area averaged 42 percent greater in current unlogged and fire-excluded red fir forests compared to historical or contemporary reference red fir forests (based on a grand average across studies) (table 11). Basal area was similar between historical and contemporary red fir–western white pine forests of the Lake Tahoe basin (Taylor 2004, Taylor et al. 2014).

Table 11—Average (weighted by sampling effort) and standard deviation (SD) of total and relative red fir tree densities, basal area, and tree diameter in historical or contemporary reference and current red fir stands, including Forest Inventory and Analysis (FIA) data (collected 2001 to 2009)

Summary statistic	Tree density ^a			Basal area			Mean d.b.h.	Number of plots
	Total	Red fir	Red fir	Total	Red fir	Red fir		
	<i>Number per hectare</i>		<i>Percent</i>	<i>Square meters per hectare</i>		<i>Percent</i>		
						<i>Centimeters</i>		
Historical (pre-1940) or contemporary reference red fir stands: ^b								
Mean	260	187	72	58	41	71	70	1,304
SD	92	78	13	76	50	7	10	
Contemporary (post-1940) red fir stands:								
Mean	895	664	74	71	58	82	31	279
SD	357	284	20	22	19	15	8	
Contemporary (2001–2009) FIA red fir stands: ^c								
Mean	527	254	49	41	21	51	20	342
SD	537	—	—	25	—	—	—	

d.b.h. = diameter at breast height.

— = no estimate available.

Individual stand structure variables and sources are presented in table 24 of the appendix.

All sampled stands are unlogged with the exception of current FIA stands.

^a Tree density estimates are based predominantly on trees ≥ 3 or ≥ 5 cm d.b.h.

^b Reference red fir stands are located within contemporary, active fire regime landscapes.

^c All FIA estimates are based on FIA plots throughout the entire assessment area, including trees only ≥ 5 cm d.b.h. Inclusion of mixed red fir–white fir forests in the FIA summary may have resulted in the lower relative density and basal area estimates of red fir in red fir forest stands. Average tree density of red fir stands is 685 ± 697 (SD) based on all trees ≥ 3 cm d.b.h. in FIA plots.

Tree spatial patterns—

Tree spatial patterns in historical and contemporary late-seral red fir stands are characterized by a high degree of structural heterogeneity, especially in the larger size classes. In presettlement red fir stands of the Lake Tahoe basin, large trees (≥ 40 cm diameter at stump height) were most frequently clumped at small spatial scales (< 9 m) but were randomly distributed at larger scales (Taylor 2004). In contemporary red fir stands, large trees (> 40 cm d.b.h.) were also clumped at the smallest spatial scales (3 to 9 m) and randomly distributed at larger scales. Small and intermediate size trees (< 40 cm d.b.h.) were usually randomly distributed at all spatial scales in presettlement red fir stands but had a clumped distribution at all scales in contemporary stands. In addition, current red fir regeneration often exhibited positive spatial autocorrelation at short (3 to 12 m) and intermediate (36 to 75 m) distances (Scholl and Taylor 2006).

Similar to fire-adapted mixed-conifer and yellow-pine-dominated forests, red fir forests often contain a mosaic of single trees, canopy gaps, and clumps of trees with adjacent or interlocking crowns (Larson and Churchill 2012). Muir (1911) observed the regularity of canopy gaps and tree clumps in historical red fir forests of Yosemite National Park:

The principal tree for the first mile or two from camp is the magnificent [red] fir, which reaches perfection here both in size and form of individual trees, and in the mode of grouping in groves with open spaces between... A few noble specimens two hundred feet high occupy central positions in the groups with younger trees around them; and outside of these another circle of yet smaller ones, the whole arranged like tastefully symmetrical bouquets, every tree fitting nicely the place assigned to it as if made especially for it; small roses and eriogonums are usually found blooming on the open spaces about the groves, forming charming pleasure grounds.

Muir (1898) also noted the occurrence of large, isolated red fir trees with surrounding regeneration patches:

Some venerable patriarch [red fir] may be seen heavily storm-marked, towering in severe majesty above the rising generation, with a protecting grove of hopeful saplings pressing close around his feet, each dressed with such loving care that not a leaf seems wanting. Other groups are made up of trees near the prime of life, nicely arranged as if Nature had carved them with discrimination from all the rest of the woods.

Tree spatial patterns in historical and contemporary late-seral red fir stands are characterized by a high degree of structural heterogeneity, especially in the larger size classes.

Similar to fire-adapted mixed-conifer and yellow-pine-dominated forests, red fir forests often contain a mosaic of single trees, canopy gaps, and clumps of trees with adjacent or interlocking crowns

Leiberg (1902) observed a similar high degree of spatial variation in red fir forests and upper montane forest landscapes in the northern and central Sierra Nevada:

The tendency of the [red fir] tree in the region is toward open, park-like groves...The type as a whole is scattering and patchy. Everywhere along the main divide of the Sierra it is made of blocks of forest, separated by sedgy or weed-covered openings or by tracts of naked rock. In the central district the stands form long thin lines, here widening into a fairly compact or heavy body of timber a few hundred acres in extent, there narrowing into irregular, straggling groups or lines of trees. The great expanses of chaparral which occur almost everywhere throughout this district break and interrupt the stands of the type at frequent intervals. Wet glades and expanses of bare rock are common in these areas, and contribute toward the patchy character of these forests.

These historical observations, coupled with the spatial structure information from Taylor (2004), suggest that historical red fir forests of the Sierra Nevada were characterized by a high degree of spatial heterogeneity, especially in the large size classes. Moreover, this spatial variation was also evident across the larger forest landscape, with small to large patches of montane chaparral, bare rock, canopy gaps, and montane meadows embedded within the red fir forest matrix.

Based on historical and contemporary stand information, large tree spatial patterns are within the historical range of variation. However, small- and intermediate-size trees may be more spatially homogeneous (i.e., more clumped than random pattern) in modern red fir forests than occurred historically, possibly as a consequence of long-term fire exclusion (Taylor 2004).

Tree regeneration—

Average tree regeneration varied by more than an order of magnitude in historical (about 1940) and contemporary red fir forests of the Sierra Nevada (fig. 18). This variation in red fir regeneration occurred both within and among contemporary red fir forest associations (Barbour and Woodward 1985, Potter 1998). An average of 76 percent of total tree regeneration in red fir forests was attributed to red fir across studies (fig. 18). In Sequoia and Kings Canyon National Parks, density of red fir regeneration declined with elevation and had higher seedling-to-parent tree ratios in recently burned forests than unburned forests (van Mantgem et al. 2006). Chappell and Agee (1996) found that the density of red fir seedlings was greatest in low- and moderate-severity burned patches (fig. 2, middle photo) and lowest in high-severity burned and unburned patches. Comparing mixed-conifer and red fir regeneration following fire, Meng et al. (2015) suggested that moisture availability and cooler

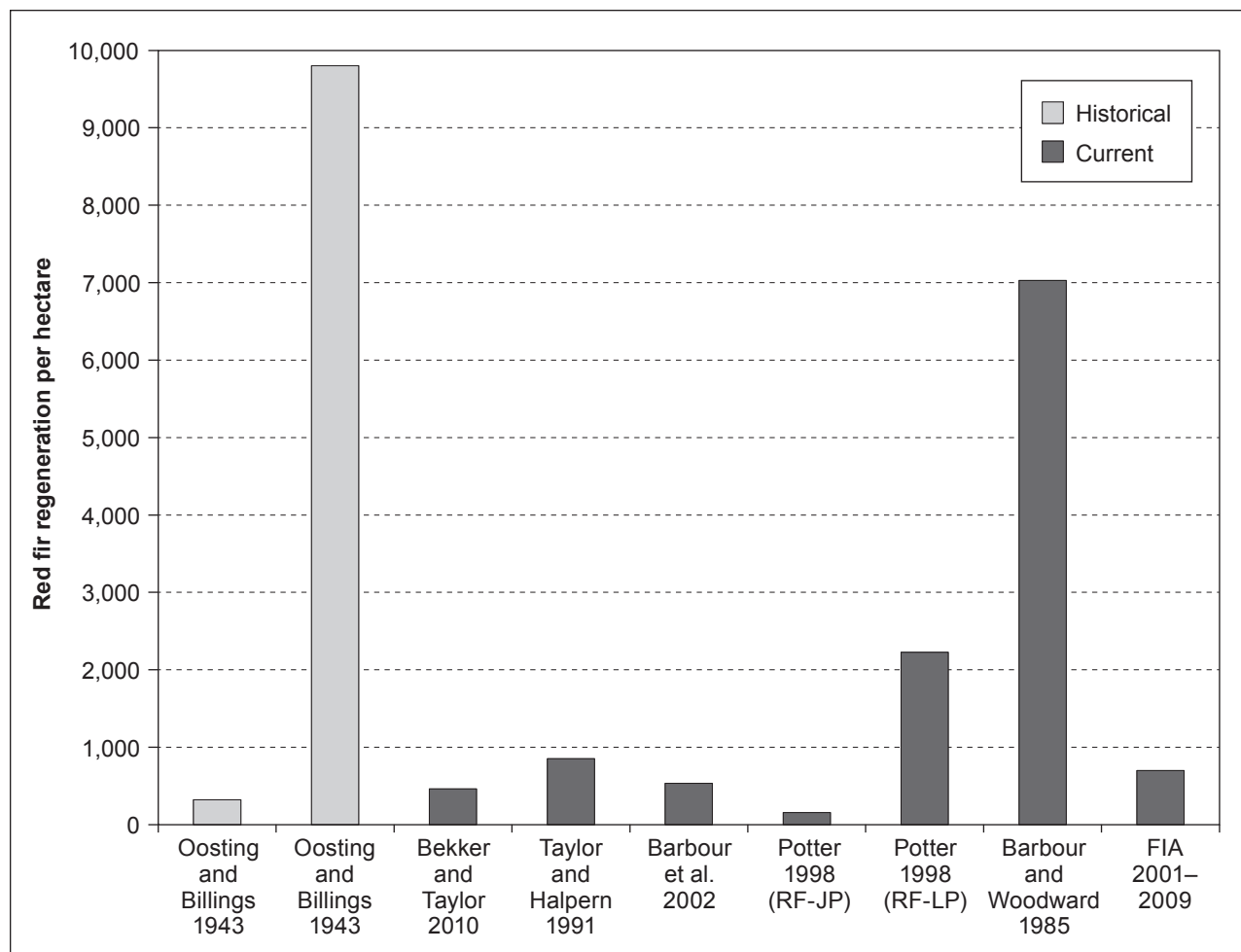


Figure 18—Mean estimates of red fir regeneration in (A) historical (about 1940) and (B) current (1990–2012) red fir forests of the Sierra Nevada. Light gray bars represent the historical range of variation based on Oosting and Billings (1943), and dark gray bars represent contemporary red fir stands based on current studies. Potter (1998) includes estimates from red fir–Jeffrey pine (RF–JP) and red fir–lodgepole pine (RF–LP) forest associations. Forest Inventory and Analysis (FIA) data collected from 2001 to 2009 include 342 red fir forest plots from the entire assessment area. All estimates are based on late-seral stands with the exception of FIA data, which include both logged and unlogged red fir forests.

minimum January temperatures, respectively, influence regeneration establishment and growth in each forest type. Increasing minimum temperatures associated with climate change are likely to reduce or shift areas favorable for red fir regeneration. In complex mountainous topography, this may not always mean a distribution shift toward northern latitudes. With higher elevations in the southern part of the range, Loarie et al. (2008) showed that, for plants in the Sierra Nevada, movement to higher elevation climatic niches often means taking a southward path. This may explain why Serra-Diaz et al. (2015), in a statewide analysis using FIA plots, found the distribution of red fir regeneration to be decreasing geographically (primarily owing to a reduction in northern Sierra Nevada extent) but increasing climatically

(owing to a broadening elevational distribution in the southern Sierra Nevada). These combined studies indicate that red fir regeneration is within the historical range of variation, although postfire patterns suggest that decades of fire exclusion may have reduced regeneration densities over time. Stage-transition modeling suggests that current red fir regeneration is sufficient to balance the impacts of recent increases in red fir tree mortality rates, but longer term data are needed to evaluate robust population trends in the bioregion (Mortenson et al. 2015).

Snags—

Based on historical forest inventories of four red fir stands of the central Sierra Nevada (i.e., Sudworth 1899), the average density of snags was 17.5 per ha (range: 0 to 60), the basal area of snags was 4.5 m²/ha, and average snag diameter was 57 cm (Stephens 2000). In comparison, average snag densities across contemporary, late-seral red fir forests in the southern and central Sierra Nevada was 33.4 ± 22.6 (standard deviation [SD]) per hectare (table 12) and average snag diameter was 50 cm in the red fir forest association (Potter 1998). In red fir forests of the southern Sierra Nevada, average snag basal area was 12.4 m²/ha (approximate range: 0 to 32 m²/ha) (North et al. 2002). These collective results suggest that snags may have been less abundant in historical than current unlogged red fir forest stands that have experienced decades of fire exclusion, although considerable variation exists in current stands (table 12). Average snag diameter was similar between historical and current red fir forests.

Table 12—Average snag densities in historical and current Sierra Nevada red fir forests

Red fir forest association	Snag density
	<i>Number per hectare</i>
Historical red fir forests: ^a	
Mean	17.5
Range	0 to 60
Current red fir forests (Potter 1998): ^b	
Mean	34.4
Range	3 to 65
Current red fir forests (FIA 2001–2009): ^b	
Mean	38.0
Standard deviation (±)	0 to 94

^a Historical values are based on Stephens (2000).
^b Current values are based on late-seral stands in the southern and central Sierra Nevada from Potter (1998) and red fir stands throughout the assessment area (logged and unlogged) from Forest Inventory and Analysis data (2001–2009).

Biomass—

Early 20th century stand inventories of older red fir forests (>100 years) estimated total biomass to be an average of 802 Mg/ha (range: 327 to 1720 Mg/ha; values adjusted for aboveground biomass only) (Rundel et al. 1988). In comparison, aboveground biomass in modern red fir forests averaged 510 ± 120 [SE] Mg/ha in the northern Sierra Nevada (Gonzalez et al. 2010) and 298 to 666 Mg/ha in Sequoia National Park (fig. 19) (Westman 1987). On the Sierra National Forest in the southern Sierra Nevada, remote-sensing and field-based estimates of secondary-growth and old-growth red fir forest biomass varied between 50 and 600 Mg/ha (Swatantran et al. 2011). Collectively, these estimates indicate that current red fir forests are within the historical range of variation, although there was a general trend toward lower levels of biomass in contemporary managed and unlogged forests than historical stands, possibly because of the lower density of large-diameter trees.

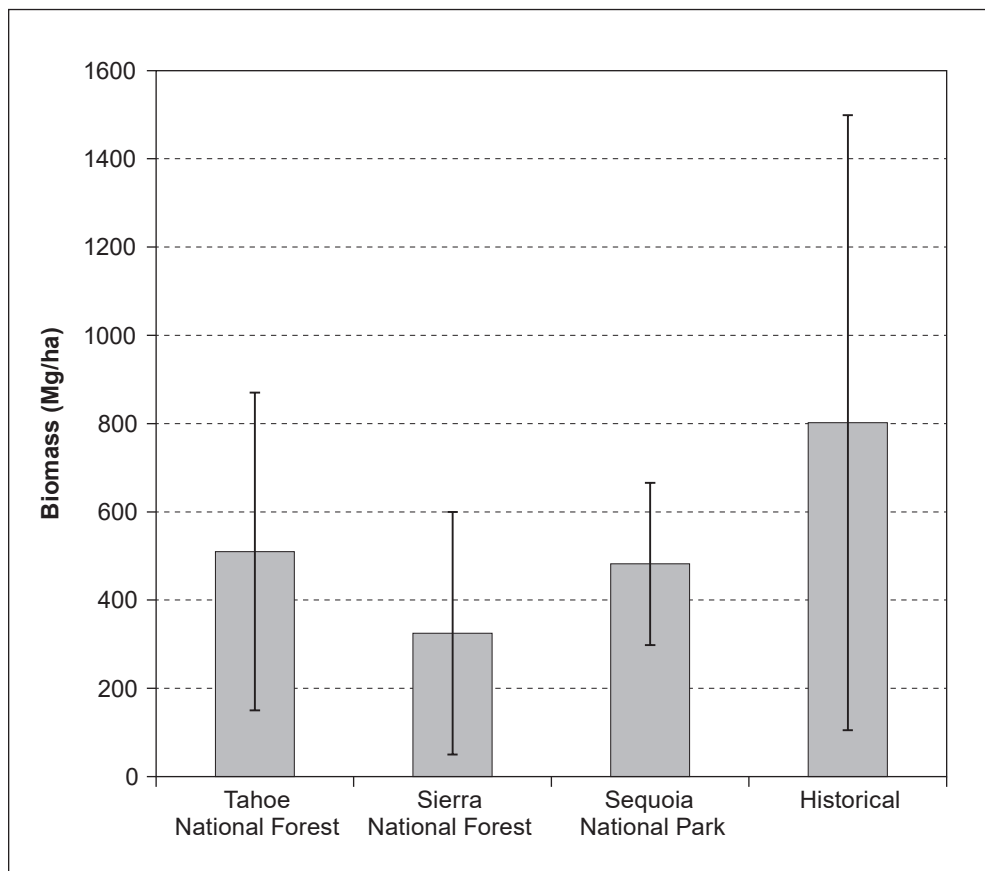


Figure 19—Mean ($\pm$ range) biomass estimates of red fir forests of the Sierra Nevada. Contemporary sites include Tahoe National Forest (late seral), Sierra National Forest (second growth and late seral), Sequoia National Park (late seral), and historical estimates for the assessment area. Sources: Gonzalez et al. (2010), Swatantran et al. (2011), Westman (1987), and Schumacher (1928) in Rundel et al. (1988), respectively.

Understory vegetation cover and surface fuels—

Shrub cover tended to be greater in red fir stands within contemporary, active fire regime landscapes (9 ± 15 percent [SD]) than fire-excluded landscapes (2 ± 8 percent) of Yosemite and Kings Canyon National Parks with high variation throughout (Meyer et al. 2019). Collins et al. (2016) found similar amounts of shrub cover in red fir–white fir stands of active fire regime landscapes of Yosemite and Kings Canyon National Parks (average: 11 percent). Similarly, herbaceous plant cover was generally greater in these contemporary fire-adapted landscapes (10 ± 19 percent) than fire-excluded landscapes (5 ± 7 percent) with high variation among red fir stands. Surface fuels were lower in presettlement than contemporary red fir stands of the Lake Tahoe basin based on Forest Vegetation Simulator estimates (fig. 20) (Taylor et al. 2014). Total surface fuel loading was also generally similar between active-fire regime than fire-excluded red fir forests in Yosemite and Kings Canyon National Parks, although coarse woody debris cover and litter depth were greater in fire-excluded stands (Meyer et al. 2019).

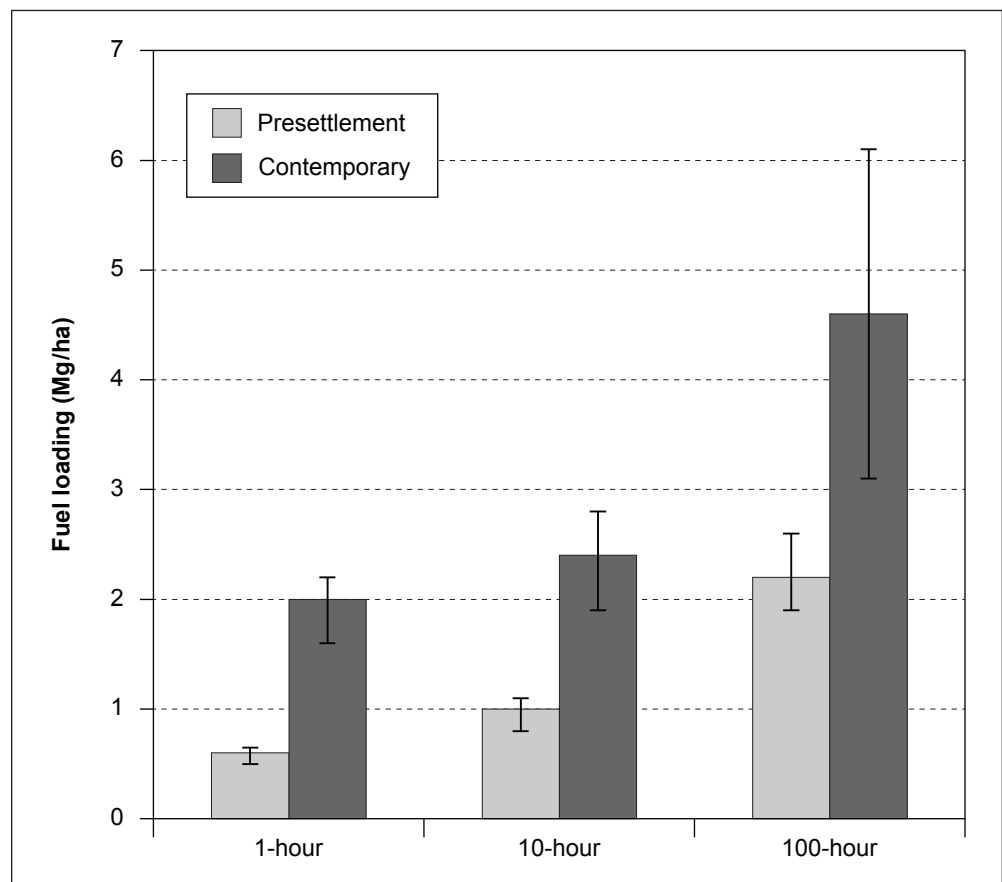


Figure 20—Surface fuel loading in presettlement and contemporary red fir stands in the Lake Tahoe basin. Fuel estimates are based on Taylor et al. (2014) using the Fire and Fuels Extension of the Forest Vegetation Simulator.

Physiognomic patterns—seral class proportions—

LANDFIRE Biophysical Setting (BpS) modeling indicated that historical reference conditions in red fir forests of the assessment area were dominated by mid- and late-seral classes (fig. 21). In general, red fir forests of the southern Sierra Nevada had a greater proportion of mid- and late-seral classes that contained relatively open canopies (<50 percent cover) than forests of the southern Cascades (Safford and Sherlock 2005a, 2005b). LANDFIRE BpS modeling of the southern Sierra Nevada national forests (Inyo, Sequoia, Sierra, and Stanislaus National Forests) at the sub-forest scale indicated that current red fir–western white pine forests contained a greater proportion of closed-canopy late-seral forests, a lower proportion of open-canopy late-seral forests, and generally similar or variable proportions of other seral classes (table 13) (Southern Sierra Nevada Wildfire Risk Assessment 2015). These results suggest that there may be a current deficit of the open-canopy late-seral class, a surplus of closed-canopy late-seral class, and either a surplus or similar amount of early-seral red fir forests in the southern half of the assessment area compared to the NRV.

Composition—

Overstory species composition—

Red fir maintains a high relative density and basal area in both historical and current late-seral red fir forests of the Sierra Nevada (tables 11 and 24). This

Figure 21—(A) Percentage of red fir forest landscape in different seral classes based on LANDFIRE biophysical setting models for the southern Cascade Range and southern Sierra Nevada; (B) open and closed canopy subclasses within mid- and late-seral classes. Sources: Safford and Sherlock (2005a, 2005b).

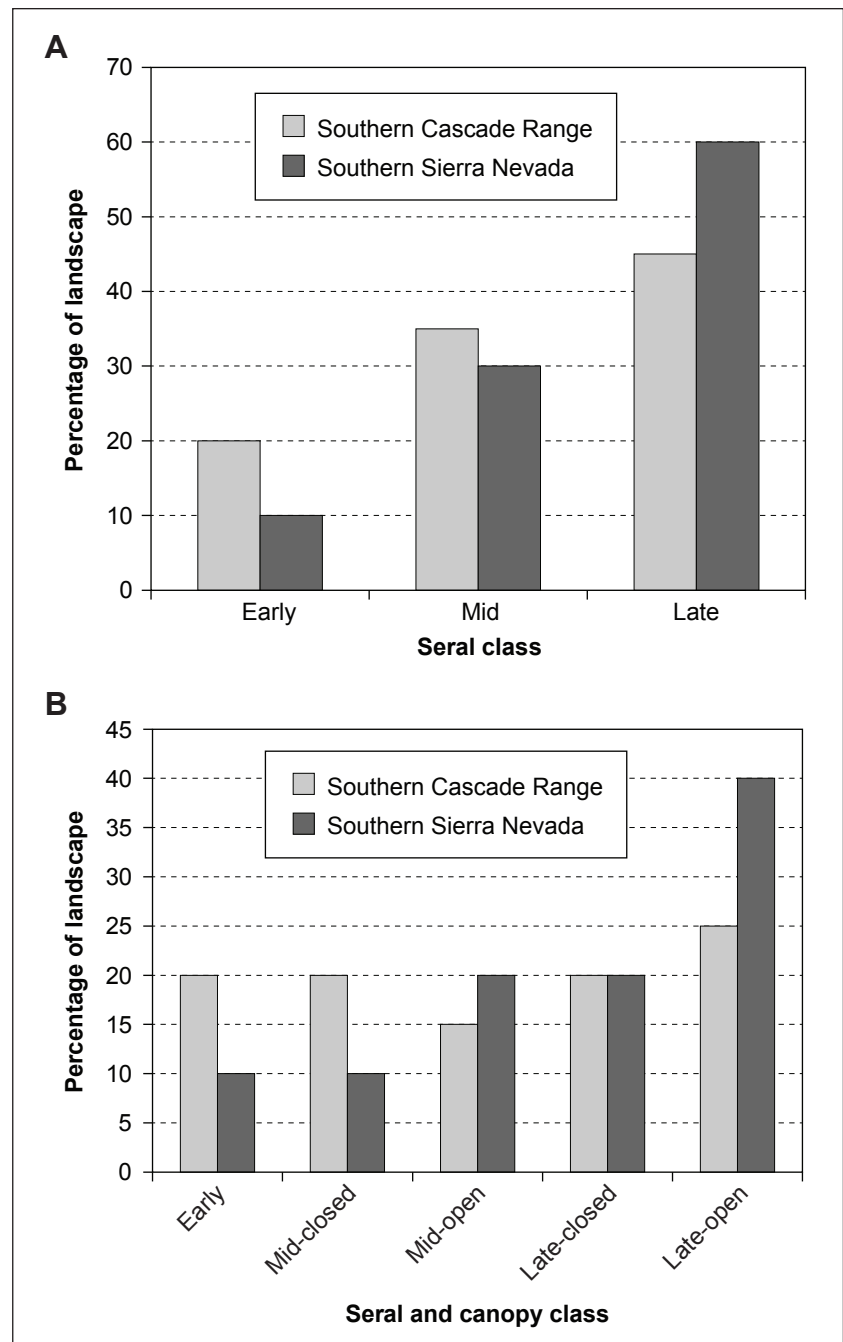


Table 13—Comparisons of reference (i.e., historical) versus current red fir forest landscapes for different seral classes based on “Southern Sierra” LANDFIRE Biophysical Setting model (red fir and western white pine) for the southern Sierra Nevada national forests

Landscape	Seral class ^a				
	Early	Mid-open	Mid-closed	Late-open	Late-closed
Inyo National Forest, south	Surplus	Surplus	Similar	Deficit	Similar
Inyo National Forest, north	Similar	Similar	Similar	Deficit	Surplus
Sequoia National Forest, south	Surplus	Deficit	Deficit	Deficit	Surplus
Sequoia National Forest, north	Similar	Similar	Deficit	Deficit	Surplus
Sierra National Forest, south	Similar	Similar	Similar	Deficit	Surplus
Sierra National Forest, north	Surplus	Deficit	Similar	Deficit	Surplus
Stanislaus National Forest, south	Similar	Deficit	Deficit	Deficit	Surplus
Stanislaus National Forest, north	Surplus	Deficit	Surplus	Deficit	Surplus
All landscapes ^b	Surplus/similar	Deficit/similar	Multiple	Deficit	Surplus

^a Seral class comparison of reference and current conditions on a specific landscape, whereby “deficit” refers to a current shortage of a particular seral class, “surplus” represents a current excess amount of a seral class, and “similar” refers to an equivalent seral class representation compared to reference conditions.

^b “All landscapes” represents the combined information from all eight landscapes, including largely surplus (late-closed), deficit (late-open), similar to surplus (early), or multiple (mid-closed and mid-open) conditions relative to reference conditions (i.e., natural range of variation).

Data source is the Southern Sierra Nevada Wildfire Risk Assessment (2015) based on the Inyo, Sequoia, Sierra, and Stanislaus National Forests.

includes mixed red fir–white fir, red fir–mountain hemlock, and red fir–western white pine forests that generally have a lower and more variable relative contribution and dominance of red fir than pure red fir stands. These patterns indicate that the relative proportion of red fir in unlogged red fir forests either did not change or slightly increased between historical and current periods in the assessment area (Dolanc et al. 2014a, 2014b), suggesting that species composition in Sierra Nevada red fir forests has not changed substantially over the past century. However, within some of these mixed red fir stands there is evidence that the relative density of red fir may have shifted when exposed to intensive logging practices or high-severity wildfires that initially favor shade-intolerant species (e.g., lodgepole pine) (Rundel et al. 1988). In a comparison of historical and current red fir–western white pine stands of the Lake Tahoe basin, for example, there is evidence of an increase in the relative density of lodgepole pine following late-19th century logging (fig. 17) (Taylor 2004, Taylor et al. 2014). Although these changes in tree species composition in mixed red fir forests may not be within the historical range of variation for the assessment area, successional processes may favor the reestablishment of red fir dominance over many decades (Oosting and Billings 1943, Rundel et al. 1988).

Understory species composition—

Historical red fir forests in the northern and central Sierra Nevada had a relatively high frequency of 6 shrub and 11 herbaceous plant species (table 14) (Oosting and Billings 1943). These understory species were also relatively common in current red fir forests

of the southern and central Sierra Nevada, based on Potter (1998). Exceptions included a relatively higher frequency of bush chinquapin and lower frequency of pinyon groundsmoke (*Gayophytum ramosissimum*) in current versus historical surveys. However, pinyon groundsmoke is restricted to the northern Sierra Nevada, which would explain the low frequency of this species in current surveys focused on the southern half of the range (i.e., Potter 1998). Additionally, Wieslander et al. (1933) found that bush chinquapin occurred relatively frequently in red fir forests of the northern and central Sierra Nevada, suggesting that perhaps Oosting and Billings (1943) were unable to detect this species because of their limited number of survey plots. Collectively, these results indicate that understory species abundance has changed but that composition in red fir forests is generally similar between historical and current stands.

Table 14—Relative frequency of understory species in historical (1940) and current (1990s) surveys of Sierra Nevada red fir forests

Group/species	Historical ^a	Current ^b
----- Percent -----		
Shrubs:		
<i>Ribes viscosissimum</i>	100	47
<i>Symphoricarpos rotundifolius</i>	54	87
<i>Arctostaphylos nevadensis</i>	31	100
<i>Lonicera conjugialis</i>	23	13
<i>Quercus vaccinifolia</i>	16	67
<i>Ribes montigenum</i>	62	33
<i>Chrysolepis sempervirens</i> ^c	0	100
Herbaceous plants:		
<i>Eucephalus breweri</i>	100	56
<i>Pedicularis semibarbata</i>	94	100
<i>Pyrola picta</i>	94	58
<i>Gayophytum ramosissimum</i> ^d	94	2
<i>Mondardella odoratissima</i>	94	56
<i>Phacelia hydrophylloides</i>	80	53
<i>Poa bolanderi</i>	80	49
<i>Arabis platysperma</i>	80	78
<i>Corallorhiza maculata</i>	80	47
<i>Thalictrum fendleri</i>	73	24
<i>Hieracium albiflorum</i>	67	49

^a Based on relative frequency of occurrence in 16 red fir forest plots in the northern and central Sierra Nevada. Source: Oosting and Billings (1943).

^bBased on about 172 upper montane plots focused on red fir in the central and southern Sierra Nevada. Source: Potter (1998).

^c*Chrysolepis sempervirens* was detected in other historical surveys of the northern and central Sierra Nevada by Wieslander et al. (1933).

^d *Gayophytum ramosissimum* is restricted in distribution to the northern Sierra Nevada, which was not covered in current surveys by Potter (1998).

Projected Future Conditions and Trends

Background—

Future climatic change is often projected from statistical or dynamical downscaled global climate models (GCMs). Assumptions inherent to each alternative greenhouse gas emission scenario and GCM (based on the type of atmospheric general circulation model) influence model projections. The use of multiple GCMs or emission scenarios provides a more comprehensive outlook of the future effects of climate change on a region, biome, or species of interest. For example, the National Center for Atmospheric Research Parallel Climate Model (PCM) projects warmer and similar (no significant change in) precipitation conditions in California, whereas the National Oceanic and Atmospheric Administration Geophysical Fluid Dynamics Laboratory (GFDL) model projects hotter and drier conditions for the state (Cayan et al. 2006). The spatial resolution of these models usually ranges from 160 to 800 km per side for GCMs to 800 m through 50 km for downscaled models, although much higher resolutions are available. The relatively lower resolution of GCMs necessitates analysis at regional or large landscape scales. Temporally, model projections are typically presented in 10-, 20-, or 30-year intervals, such as the future periods of 2010–2039, 2040–2079, and 2070–2099.

In addition to projections in future climate, ecological response models may assess the response of ecological variables to climate change. These models range from qualitative conceptual models to quantitative niche-based (e.g., Maximum Entropy or Maxent) and dynamic vegetation models (e.g., MC1). Model outputs may project changes in the climatic envelope of an individual species (e.g., red fir), vegetation type (e.g., red fir forest), or biome (e.g., evergreen conifer forest). Several ecological response models have focused on red fir or red fir forests at the scale of the assessment area (table 15). These ecological response models provide many insights into the potential broad-scale impacts of climate change to tree species (e.g., McKenney et al. 2007, Shafer et al. 2001), but results from these models should be interpreted with caution owing to the many assumptions and limitations associated with them (Clark et al. 2011, Rowland et al. 2011).

Model projections—

Projected changes in the distribution of red fir or red fir forests are summarized in table 15. All studies used the A2 emissions scenario (regionally oriented economic development), with the exception that McKenney et al. (2007) used a combination of the A2 (regional development) and B2 (local environmental sustainability) emissions scenarios. Ecological response models included species distribution models (BioMove, ANUCLIM, Maxent, Bioclim) in four studies, but also included

Table 15—Projected future changes in the distribution of red fir or red fir forests based on climate envelope (species distribution) and dynamic vegetation (MC1) models

Unit of analysis	Geographic scope	GCM and trends (model type)	Decrease ^a	Stable ^a	Increase ^a	Time period	Reference
----- Percent -----							
Species	California	CCSM—warmer and wetter	77	23	1	2080	FRAP (2010)
Species	California	Hadley Centre—hotter and drier	99.9	0.1	<0.1	2080	FRAP (2010)
Species ^b	Species range	Ensemble of three models—full dispersal	77	23	—	2071–2100	McKenney et al. (2007)
Species ^b	Species range	Ensemble of three models—no dispersal	87.5	12.5	—	2071–2100	McKenney et al. (2007)
Biome ^c	California	PCM—warmer and possibly wetter (MC1)	5	—	—	2071–2100	Lenihan et al. (2008)
Biome ^c	California	GFDL—hotter and drier (MC1)	52	—	—	2071–2100	Lenihan et al. (2008)
Species ^d	Southern Sierra Nevada	Ensemble of 11 models	28	49	17	2040–2065	SSP (2010)
Species ^d	California	Ensemble of 11 models	56	27	10	2040–2065	SSP (2010)
Vegetation type ^e	Southern Sierra Nevada	PCM—warmer and possibly wetter (Bioclim, Flint)	66	33	—	2070–2099	Schwartz et al. (2013)
Vegetation type ^e	Southern Sierra Nevada	GFDL—hotter and drier (Bioclim, Flint)	85	15	—	2070–2099	Schwartz et al. (2013)
Vegetation type ^f	Species range	GFDL—warmer and drier (FVS)	>99	<1	—	2090	Crookston et al. (2011)
Average across studies: ^g			84.6	14.4	0.5	2071–2100	—

GCM = global climate model; — = no estimate available; CCSM = community climate system model; PCM = parallel climate model; GFDL = Geophysical Dynamics Fluid Laboratory

^a Percentage decrease, increase, or stable indicates the percentage change in the area covered by red fir within the geographic scope and time period of each study.

^b Estimates for percentage stable and percentage increase (“percent remaining”) are pooled. Includes models that assume full dispersal or no dispersal.

^c Projections are for conifer forest biome, which includes mixed-conifer forest, red fir forest, and other conifer-dominated forest types.

^d Decrease is defined as percentage of red fir distribution that is “stressed.” Projected estimates also include an uncertain category defined as areas lacking model agreement (range: 6 to 7 percent). Source: Southern Sierra Partnership (SSP 2010).

^e Based on U.S. Forest Service Pacific Southwest Region CALVEG red fir alliance vegetation type. Percentage of decrease estimate includes moderate, high, and extreme climate exposure categories (outside 66th percentile bioclimatic distribution for red fir), and percentage of stable estimate is equal to the percentage in the low-exposure category (inside the 66th percentile bioclimatic distribution). Climate exposure estimates are for red fir forests on national forest lands of the southern Sierra Nevada (Inyo, Sequoia, and Sierra National Forests and southern half of Stanislaus National Forest).

^f Decrease is defined as percentage of red fir distribution that has low viability (i.e., viability score <0.5) using the Forest Vegetation Simulator (FVS) model.

^g Includes Crookston et al. (2011), FRAP (2010), McKenzie et al. (2006), and Schwartz et al. (2013).

the MC1 vegetation dynamic model for biome projections in Lenihan et al. (2003, 2008). Models projected a 66 to 99.9 percent range reduction in red fir across a range of geographic scales (subregional to entire species geographic range) by the end of the 21st century. Projected loss of red fir in the southern Sierra Nevada was nearly twice that for the entire state of California (Southern Sierra Partnership 2010), indicating that red fir forests may be more prone to climate change impacts toward the southern end of their geographic distribution (e.g., the Kern Plateau). Nevertheless, several model projections (e.g., Lenihan et al. 2008) suggest that the southern Sierra Nevada may serve as a future climate refugium for high-elevation conifers and retain a greater total area of red fir forests in the late 21st century.

Schwartz et al. (2013) used a climatic envelope modeling approach based on two GCMs (PCM, GFDL) and two climate surface models (ensemble of Bioclim and Flint Regional Water Balance model; downscaled to 270 m) to evaluate the exposure of red fir and other vegetation types to climate change in the southern Sierra Nevada. Their results indicate that by the end of the century, red fir will be highly to extremely vulnerable (i.e., outside the 90th percentile of the current bioclimatic distribution for the vegetation type) in 66 percent (PCM) or 85 percent (GFDL) of red fir forests in the southern Sierra Nevada national forests (Sequoia, Sierra, and Inyo National Forests and southern half of Stanislaus National Forest (fig. 22). The total area of low climate exposure for red fir forest will be 20 percent (PCM) and 7 percent (GFDL) by the end of the century (table 15). These areas of low climate exposure under the PCM model are generally concentrated within the higher elevation, eastern portions of Sierra and Stanislaus National Forests and Yosemite National Park, the Mammoth Lakes area of Inyo National Forest, and most portions of Sequoia and Kings Canyon National Parks (fig. 23). Under the GFDL model, the only geographic areas of red fir low-climate exposure by the end of the century include limited portions of Kings Canyon National Park and some high-elevation and eastern portions of Stanislaus National Forest (fig. 24) (Schwartz et al. 2013).

Most red fir forest in the assessment area will be outside its past and present climate envelope by the end of the century.

Most red fir forest in the assessment area will be outside its past and present climate envelope by the end of the century. Projected changes in the distribution of red fir forests consistently show a pronounced reduction in their geographic extent within the assessment area by 2070–2100. Several models also project a relatively high degree of climate vulnerability for red fir forests within the southern extent of their geographic distribution, at lower elevations, and in isolated populations. These projections support theoretical models that predict greater loss of populations at geographic range margins, especially at the low latitude limit (Hampe and Petit 2005). Ultimately, the degree of climate vulnerability and adaptive capacity in red

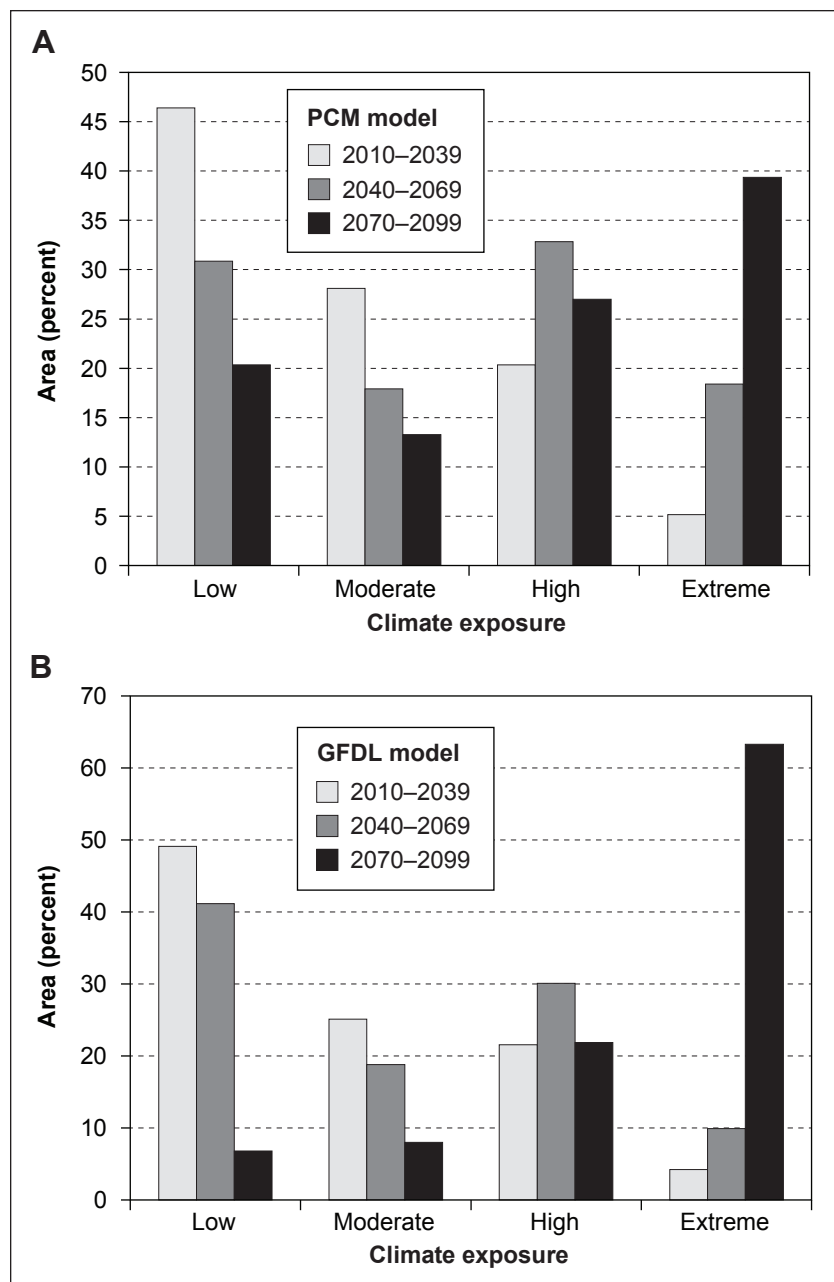


Figure 22—Future projections of climate exposure for red fir forest in the southern Sierra Nevada national forests (primarily Sequoia, Sierra, and Inyo National Forests). Projections are based on (A) the Parallel Climate Model (PCM) and (B) the General Flow Dynamics Laboratory (GFDL) global climate model used by Schwartz et al. (2013). Projections include three future time periods: 2010–2039 (near future), 2040–2069 (mid-century), and 2070–2099 (end of century). Levels of climate exposure indicate red fir bioclimatic areas that are projected to be (1) inside the 66th percentile (low exposure), (2) in the marginal 67–90th percentile (moderate exposure), (3) in the highly marginal 90–99th percentile (high exposure), or (4) outside the 99th percentile (extreme exposure) of the current regional bioclimatic envelope for the species.

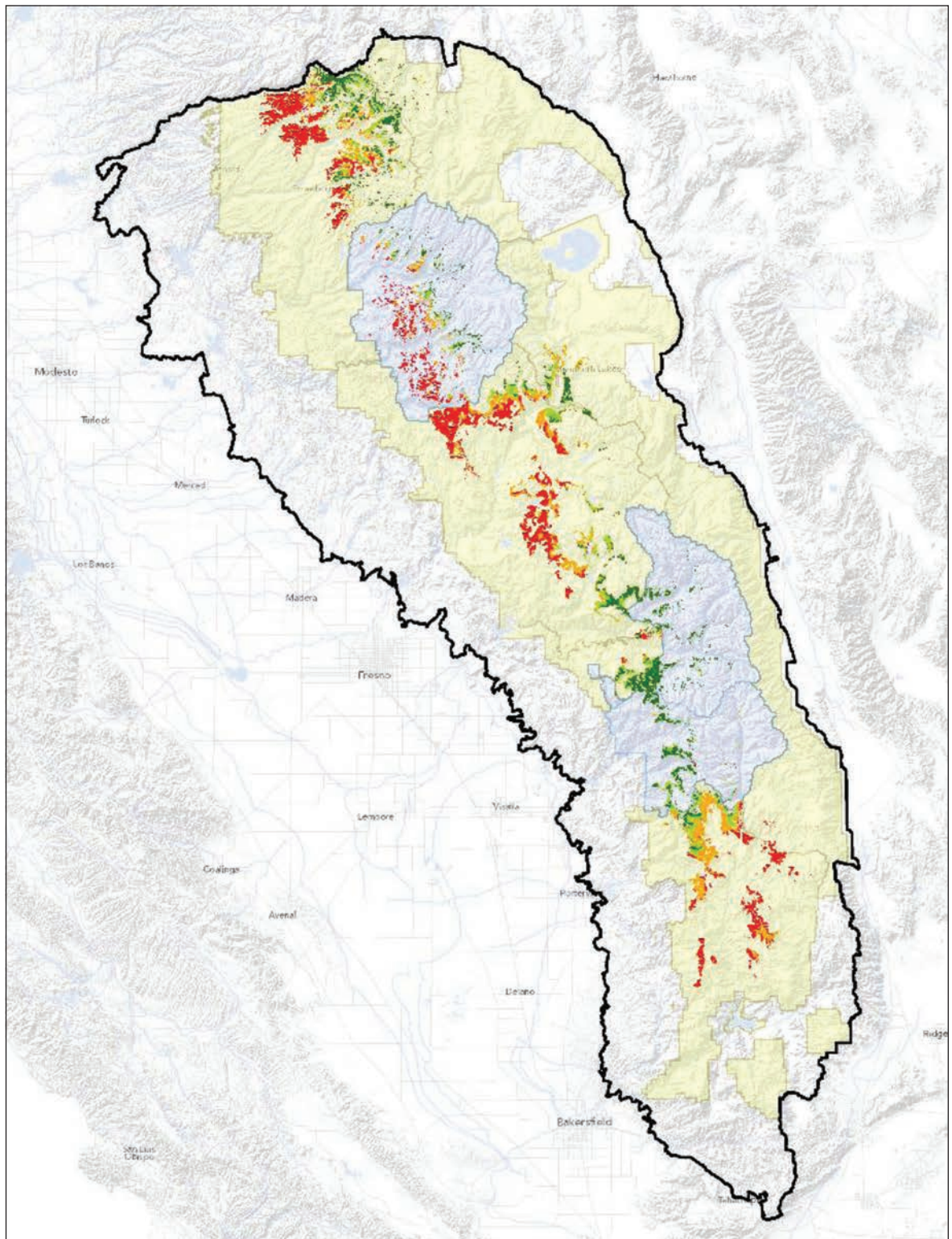


Figure 23—Future projections (end of century: 2070–2099) of climate exposure for red fir forest in the southern Sierra Nevada based on the Parallel Climate Model (warmer and similar precipitation) used by Schwartz et al. (2013). Levels of climate exposure indicate bioclimatic areas that are projected to be (1) inside the 66th percentile (dark green), (2) in the marginal 67–90th percentile (light green), (3) in the highly marginal 90–99th percentile (yellow), or (4) outside the extreme 99th percentile (red) for the bioclimatic distribution of the vegetation type. Areas in green are suggestive of climate refugia for red fir forests by the end of the century.

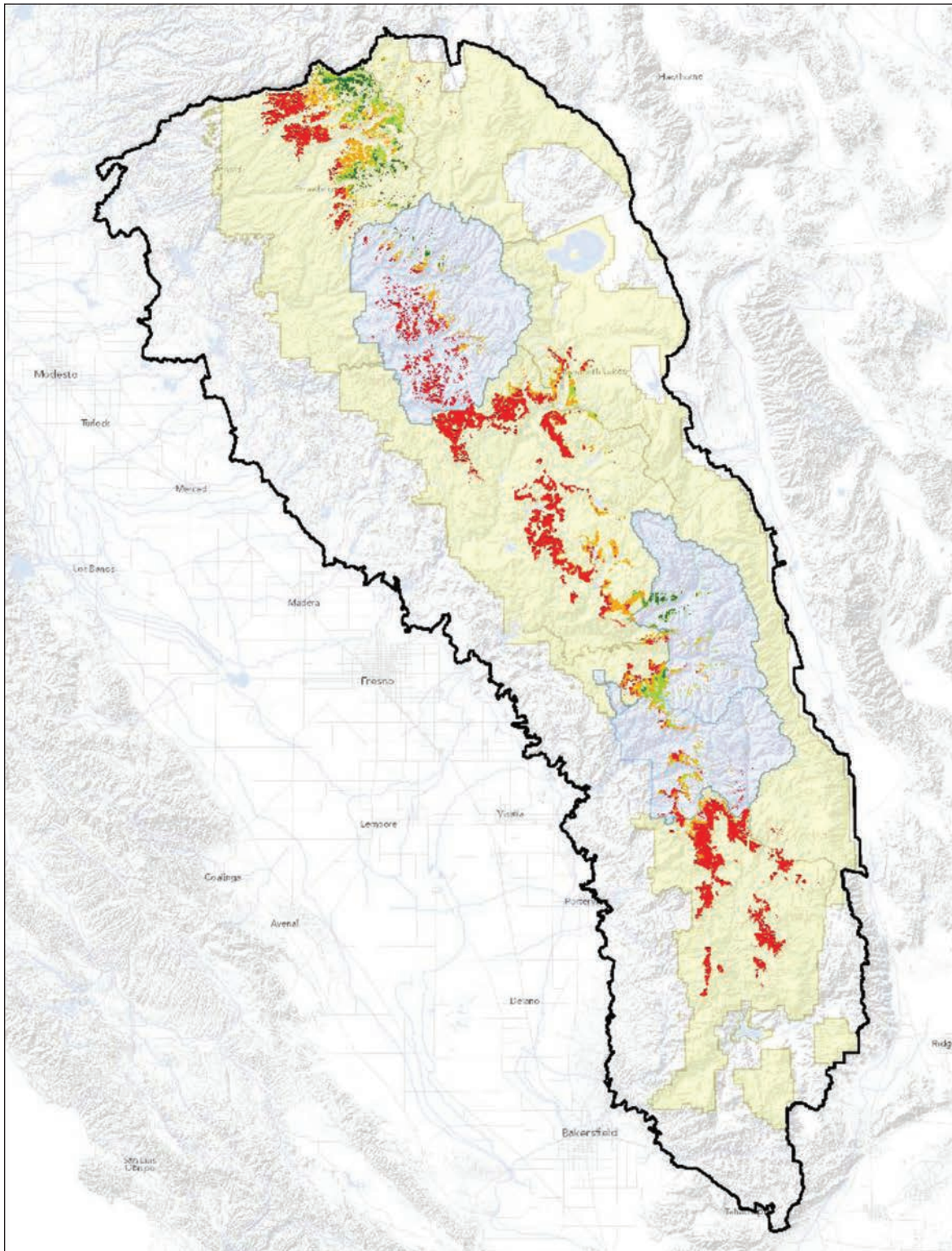


Figure 24—Future projections (end of century: 2070–2099) of climate exposure for red fir forest in the southern Sierra Nevada based on the General Flow Dynamics Laboratory model (hotter and drier) used by Schwartz et al. (2013). Levels of climate exposure are described in figure 23.

fir will be contingent on several factors not covered by most species distribution models, including dispersal rates, biotic interactions, evolutionary processes (e.g., adaptation, genetic drift), physiological tolerances, edaphic constraints, interacting stressors, and forest management actions (Clark et al. 2011, Kuparinen et al. 2010, Rowland et al. 2011, Zhu et al. 2012). For example, projected climate-wildfire interactions in the Sierra Nevada resulted in a 50 percent decrease in the spatial extent of red fir recruitment but a 5 to 18 percent increase in the extent of red-fir-dominated forests by the end of the 21st century (Liang et al. 2016). Similarly, fire-based restoration efforts resulted in reduced fire severity and carbon emissions in Sierra Nevada red fir and mixed-conifer forests under projected climate-wildfire interactions (Krofcheck et al. 2017). Consequently, red fir forests may persist in or adapt to areas of moderate climate exposure despite ominous model projections for red fir forests in the Sierra Nevada.

Subalpine Forests

Physical Setting and Geographic Distribution

Geographic distribution—

Subalpine forests and woodlands (hereafter collectively referred to as “subalpine forests”) are distributed throughout the Sierra Nevada immediately above the red fir and upper montane forest zone and below the alpine vegetation belt (fig. 25) (Rundel et al. 1988). The elevational distribution of this forest type generally extends from approximately 2450 to 3100 m in the northern Sierra Nevada to about 2900 to 3660 m in the southern part of the range (Fites-Kaufman et al. 2007). On the east side of the Sierra Nevada, the lower elevation limit of subalpine and upper montane forests typically extends an additional 50 to 450 m upward in elevation in the northern and southern portions of the range, respectively; upper elevation limits may extend an additional 20 to 100 m in elevation (Potter 1998). In the Sierra Nevada bioregion, subalpine forest extends from the higher elevations of the Warner Mountains of the Modoc National Forest to the Tulare County–Kern County border on the Kern Plateau of the Sequoia National Forest (Griffin and Critchfield 1972). Subalpine forests also occur in the White and Inyo Mountains and Glass Mountain of the Intermountain Semi-Desert province (Miles et al. 1997), typically at 2620 to 3540 m elevation (Rundel et al. 1988). On the western slope of the Sierra Nevada, subalpine forests form a relatively contiguous belt from Tulare County to Nevada County with more isolated populations to the north and south of this region.

Research has shown that globally the tree/alpine ecotone occurs where average growing season temperature is 6.4 °C (43.5 °F) (Körner 2012, Körner and Paulsen 2004). The worldwide occurrence of this isotherm has been associated with the

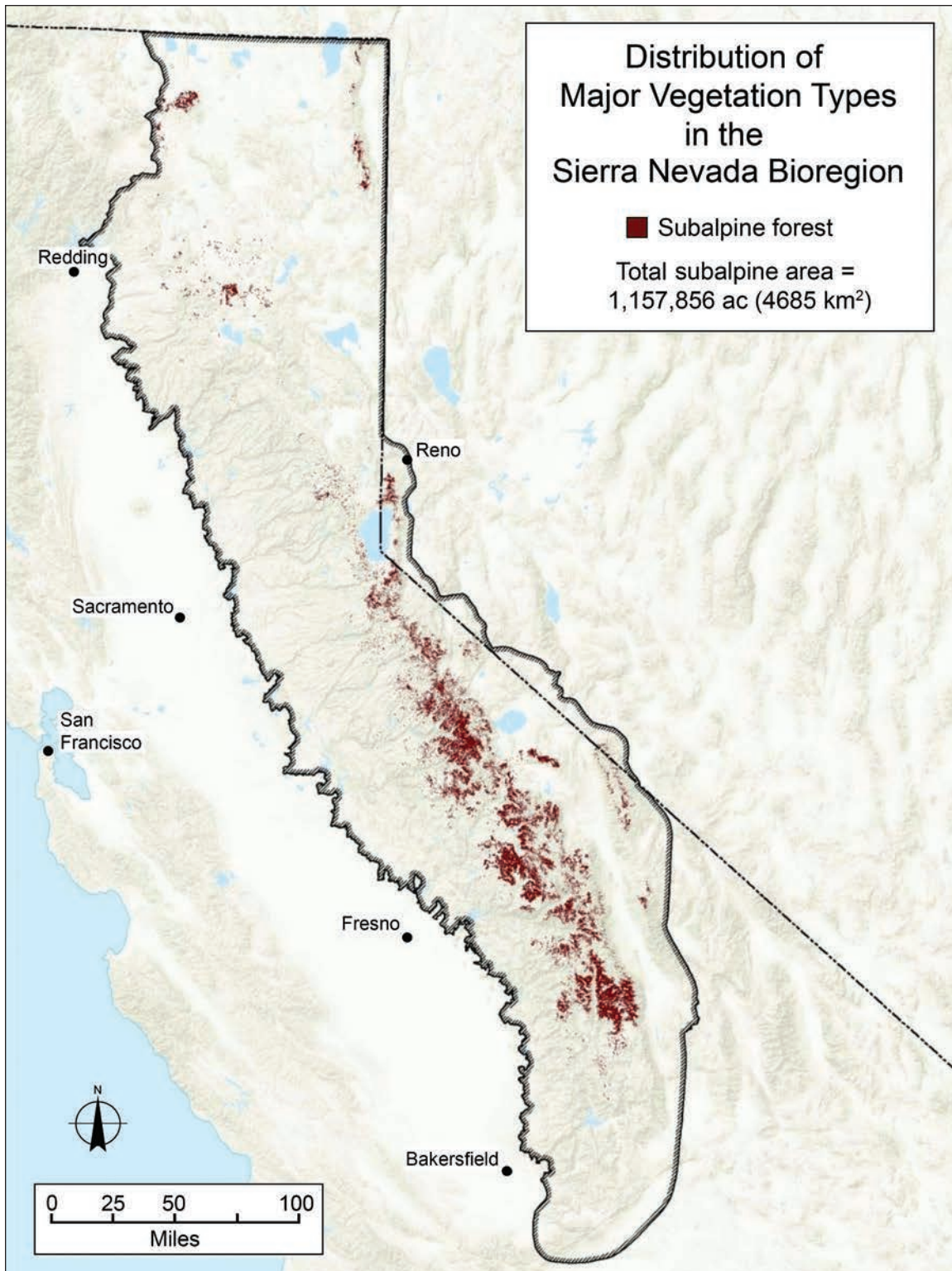


Figure 25—Distribution of subalpine forests in the assessment area.

Climate change is likely to have a more significant influence on the distribution, extent, and condition of subalpine forests than perhaps any other forest type within the assessment area.

interaction of abiotic (i.e., rooting zone temperatures, solar radiation, etc.) and physiological (i.e., plant tissue capacity, primary production, etc.) factors that limit the development and height of a “tree” (defined as a woody structure ≥ 3 m tall). This relationship means that, at a broad scale, treeline temporally changes with climate, and at a fine scale, spatially varies with local microclimate conditions (Millar and Rundel 2016). For these reasons, climate change is likely to have a more significant influence on the distribution, extent, and condition of subalpine forests than perhaps any other forest type within the assessment area.

Several tree species in subalpine forests have restricted or unique geographic distribution patterns in the Sierra Nevada bioregion. Foxtail pine is a California endemic with disjunct populations located in the Klamath Mountains and southern Sierra Nevada (Rundel et al. 1988); core southern populations are located in the upper South Fork of the Kern River drainage (Griffin and Critchfield 1972). Limber pine is primarily restricted to the east side of the southern and central Sierra Nevada, and does not occur farther north than the Sweetwater Mountains in Mono County on the Toiyabe National Forest. This species also occurs in the White and Inyo Mountains and Glass Mountain of the Inyo National Forest (Miles and Goudey 1997). Great Basin bristlecone pine (hereafter referred to as “bristlecone pine”) is restricted to the higher elevations of the White, Inyo, and Panamint Mountains of the western Great Basin. Mountain hemlock is primarily restricted to the northern and central Sierra Nevada and is not found south of Silliman Lake in Sequoia National Park (Griffin and Critchfield 1972, Parsons 1972). Both western white pine and lodgepole pine occur throughout the upper elevations of the Sierra Nevada, although western white pine gradually declines in occurrence south of Kings River on the west slope and south of Twin Lakes on the east slope (Griffin and Critchfield 1972). Whitebark pine is primarily located in the central and southern Sierra Nevada, especially north of the Kings River watershed and Kings–Kern Divide in Sequoia National Park (Vankat and Major 1978). Only small and isolated populations of whitebark pine exist in the northern portion of the assessment area, located primarily in the Lassen Volcanic National Park area and higher elevations of the Warner Mountains, owing to the limited amount of high-elevation habitat in the northern subregion. The southern Sierra Nevada represents the southern extent of the geographic distribution of whitebark pine, western white pine, foxtail pine, and mountain hemlock. Bristlecone pine populations in the White, Inyo, and Panamint Mountains represent the western extent of the geographic range of the species (Griffin and Critchfield 1972).

Subspecies distributions and genetic structure—

Subalpine conifer populations in the Sierra Nevada bioregion, especially the southern Sierra Nevada, are unique and distinct from other regions in western North America. Throughout its distribution, whitebark pine is clustered by genetic similarity into three main groups: Sierra Nevada, the greater Yellowstone region, and other areas, including the northern Cascade Range, southern Oregon, and central and northern Idaho (Richardson et al. 2002). Of these three groups, Sierra Nevada populations have the highest degree of genetic divergence, suggesting that they may be considered a contemporary refugia (i.e., an area where climate and vegetation type have remained relatively unchanged while surrounding areas have changed markedly). Similarly, limber pine populations in California are genetically distinct from all other populations in western North America, and the southern Sierra Nevada likely represents a regional refugium for California populations (Mitton et al. 2000). Sierra Nevada populations of western white pine also show a relatively high degree of genetic differentiation compared to other more northerly populations throughout the species range (Kim et al. 2011). The Sierra Nevada subspecies of lodgepole pine (*P. contorta* ssp. *murrayana*) occurs only in the Sierra Nevada, southern California mountains, Klamath Mountains, and high Cascade Range (Anderson 1996). The southern Sierra Nevada subspecies of foxtail pine (*P. balfouriana austrina*) is morphologically, genetically, and ecologically distinct from the northern California subspecies (*P. b. balfouriana*) (Maloney 2011, Mastrogiuseppe and Mastrogiuseppe 1980), and molecular evidence suggests a divergence of these subspecies in the early to mid-Pleistocene (0.13 to 2.45 million years ago) (Eckert et al. 2008). Population genetic differentiation within the southern subspecies of foxtail pine tends to be lower than the northern subspecies, presumably because of lower degrees of topographic isolation in the southern Sierra Nevada (Oline et al. 2000).

Overall, high-elevation pines in the assessment area exhibit moderate to high levels of genetic diversity, comparable to other pine species in western North America (Lee et al. 2002, Maloney et al. 2014, Rogers et al. 1999) and relatively greater than other conifers with restricted ranges in California (Eckert et al. 2008). Westfall and Millar (2004) and Eckert et al. (2008) proposed that this genetic diversity within populations may be a consequence of the complex interaction between cyclic climatic variation, biogeographical processes (e.g., dispersal into glacial refugia), and the nonequilibrium evolutionary response of high-elevation conifers, underscoring the dynamic distributional patterns within these forests.

Subalpine conifer populations in the Sierra Nevada bioregion, especially the southern Sierra Nevada, are unique and distinct from other regions in western North America.

Climatic associations—

Subalpine forests are characterized by a prolonged winter snowpack, a short growing season, and cool summer and cold winter temperatures (table 16) (Agee 1993, Fites-Kaufman et al. 2007, Millar and Rundel 2016). Precipitation mainly occurs as winter snow and during the summer months is limited to locally intense convective storms (Fites-Kaufmann et al. 2007). Recent climate trends indicate that the mean annual and monthly temperatures have increased in the higher elevations (>2200 m) of the Sierra Nevada, especially within the past 30 years (Das and Stephenson 2013, Diaz and Eischeid 2007, Edwards and Redmond 2011, Safford et al. 2012). Moreover, the annual number of days with below-freezing temperatures at higher elevations has declined, resulting in a 40 to 80 percent decrease in spring snowpack over the past 50 years in the northern and central Sierra Nevada (Moser et al. 2009). Snowpack in the southern Sierra Nevada has increased 30 to 100 percent

Table 16—Climate characteristics of subalpine forests in the assessment area

Climate variable ^a	Average (subregion)
Annual precipitation (mm):	
Sierra Nevada	750–1250
White and Inyo Mountains	320
Precipitation as snow (percent)	70–99
Mean snow depth (cm):	
Southern	160
Northern	210
Maximum annual snow depth (cm)	140–500
Snow water equivalent (mm):	
Southern	50–160
Northern	70–190
Month of maximum snow depth	April
Snowpack duration (days)	>200
Daily snow-covered area (3000 m elevation) (percent)	70
Mean winter temperature (°C)	-4
Mean summer temperature (°C)	12
January minima (°C)	-11
July maxima (°C)	16
Growing season length (weeks)	8
Lightning (strikes/year/100 km ²)	33.6

Source: Agee (1993), Barbour et al. (2002), Fites-Kaufman et al. (2007), Jepsen et al. (2012), Lloyd and Graumlich (1997), Munz and Keck (1959), USDC NOAA (2013), Potter (1998, 2005), Rice et al. (2011), Rundel et al. (1988), van Wagtenonk and Cayan (2007), van Wagtenonk and Fites-Kaufman (2006).

^a Snow variables are primarily based on April 1 averages.

over the same period, possibly owing to the relatively higher elevation terrain of the region. Precipitation has remained stable or steadily increased over the past several decades in the higher elevations of the Sierra Nevada (Edwards and Redmond 2011, Safford et al. 2012). Growth increments of most subalpine tree species are positively correlated with cool and wet conditions in the year prior to growth and warm springs with sufficient moisture during the year of growth (Dolanc et al. 2013b).

Geology, topography, and soils—

Subalpine forests occur on variable parent materials and soils, although most parent materials are granitic in the south, volcanic in the north, or of either type in the central Sierra Nevada (Potter 1998, Sawyer et al. 2009). Topographic, edaphic, and microclimate associations of subalpine forests are highly variable, but in general, most subalpine conifers (especially high-elevation white pines) are restricted to less productive sites on drier soils (table 17). Soils of subalpine forests are typically classified as Inceptisols (limited profile development) and Entisols (no sign of profile development) (Laacke 1990, Potter 1998). Soils are typically frigid, shallow, acidic, xeric, and variable in texture and available water-holding capacity. In general, subalpine soils tend to be shallow owing to repeated glaciation during the Pleistocene (Fites-Kaufman et al. 2007). Available water-holding capacity (AWC; top 100 cm of soil profile) in subalpine forest is typically between 70 to 80 mm (Lutz et al. 2010, Potter 1998, USDA NRCS 2013). Topsoil and subsoil textures are usually sandy loams, sands, and loams, but include other texture classes (Potter 1998).

Landscape patterns—

Subalpine landscapes consist of a mosaic of subalpine forests and woodlands, rock outcrops, scrub vegetation, meadows, and riparian ecosystems (figs. 26 and 27) (Fites-Kaufman et al. 2007). Subalpine forests typically comprise less than half of this landscape, especially at higher elevations. Granitic and other rock outcrops can constitute a substantial proportion of subalpine forest landscapes, creating large patches of open and treeless areas that support sparse vegetation cover. This is particularly apparent at higher elevations (>3000 m) and in the drier eastern Sierra Nevada, where harsher environmental conditions limit forest productivity and biomass. The underlying physical template and corresponding soil development and moisture patterns largely drive this variation within subalpine landscapes, resulting in a heterogeneous mixture of contiguous groves, open woodlands, individual tree clusters, shrub patches, wet and dry meadows, tree islands, and riparian corridors (Keane et al. 2012, Potter 1998). These conditions favor the coexistence of both shade-tolerant and shade-intolerant subalpine conifer species in high-elevation landscapes (table 17) (Rundel et al. 1988).

Subalpine landscapes consist of a mosaic of subalpine forests and woodlands, rock outcrops, scrub vegetation, meadows, and riparian ecosystems.

Table 17—Characteristic ecological features of subalpine conifers in the Sierra Nevada

Feature	Whitebark pine	Foxtail pine	Limber pine	Bristlecone pine	Western white pine	Lodgepole pine	Mountain hemlock
Topographic, soil, and microclimate associations	Harsh, cold, dry slopes	Cool and dry sites on well-drained, decomposed granite soils	Dry, steep, and rocky slopes with well-drained soils	Limestone, low-nutrient soils on dry sites	Sunny sites with unfertile and shallow soils	Hydric (meadows) to moderately xeric, postfire environments	Moist and cold sheltered canyons, ravines, and lake benches
Sites of successional replacement ^a	Productive sites at lower elevation	Mesic and productive sites	Mesic sites	Mesic and productive sites	Productive sites	Productive sites at lower elevation	Postfire environments
Shade tolerance	Moderate	Intolerant	Intolerant	Intolerant	Intolerant	Moderate	High
Fire tolerance	Some fire adaptations, postfire colonizer	Fire avoider	Fire avoider	Fire avoider	Some fire adaptations, postfire colonizer	Fire sensitive, postfire colonizer but cones not serotinous	Fire avoider
Spatial pattern	Clustered	Single stem	Clustered	Clustered	Both	Single stem	Single stem
Primary seed dispersal agent ^b	Animal	Unknown	Animal	Animal and wind	Animal and wind	Wind and animal	Wind

^a Indicates environments where species may establish and grow but are either replaced by more competitive species over time or are less suited at exploiting early-seral environments (e.g., mountain hemlock).

^b Animal dispersed seeds are mainly the result of seed caching activity by Clark's nutcracker, but may include significant dispersal by chipmunks and squirrels. Seed dispersal mechanisms in foxtail pine are poorly understood but currently assumed to be primarily via wind.

Source: Agee (1993), Beasley and Klemmedson (1973, 1976, 1980), Billings and Thompson (1957), Bunn et al. (2005), Burns and Honkala (1990), Caprio (2006, 2008), Coop and Schoettle (2009), Ernst et al. (2003), Fites-Kaufman et al. (2007), Harris (1939), Hiebert and Hamrick (1984), Keane et al. (2012), Keifer (1991), Lanner (1988), Lanner et al. (1984), Maloney (2014), Maloney et al. (2011), Parker (1986, 1988), Pierce and Taylor (2011), Potter (1994, 1998), Rourke (1988), Rundel et al. (1988), Sawyer et al. (2009), Taylor (1995), Tomback et al. (1993), Vander Wall (2008), Vankat (1970), van Wagendonk and Fires-Kaufman (2006), and Wright and Mooney (1965).



Marc Meyer

Figure 26—Subalpine forests in the Sierra Nevada, including (top) lodgepole pine and western white pine forest, (middle) lodgepole pine and mountain hemlock forest, and (bottom) high-elevation landscape dominated by whitebark pine and lodgepole pine with limber pine situated on steeper slopes. Top and middle photos: Ansel Adams Wilderness, Sierra National Forest; bottom photo: John Muir Wilderness, Inyo National Forest.



Marc Meyer



Figure 27—Foxtail pine forests in the Cottonwood Lakes Basin, Inyo National Forest, southern Sierra Nevada.

Ecological Setting

Indicator species and vegetation classification—

The primary indicator species that define subalpine forests of the Sierra Nevada bioregion include whitebark pine, foxtail pine, limber pine, bristlecone pine, western white pine, lodgepole pine, and mountain hemlock (figs. 26 and 27) (Fites-Kaufman et al. 2007). Common associates of subalpine forests include red fir, Sierra juniper (*Juniperus occidentalis*) and Jeffrey pine at lower elevations. Uncommon associates may include mid-elevation forest species such as white fir, especially in the southern Cascades (Rundel et al. 1988). The California Wildlife Habitat Relationships (CWHR) system recognizes two vegetation types (subalpine conifer, lodgepole pine) that are considered subalpine forests in the assessment area (Mayer and Laudenslayer 1988). There are eight CALVEG types that are included as subalpine forests, including bristlecone pine, foxtail pine, limber pine, mountain hemlock, whitebark pine, western white pine, lodgepole pine, and subalpine conifers (USDA FS 2013). Sawyer et al. (2009) recognizes eight vegetation alliances and 52 associations of subalpine forests in the Sierra Nevada. Subalpine alliances include both subalpine forests (whitebark pine, lodgepole pine, western white pine, and mountain hemlock alliances) and woodlands (foxtail pine, limber pine, and bristlecone pine alliances).

Ecological importance of subalpine forests—

Subalpine forests provide a diverse array of ecosystem services, including watershed protection, soil formation, erosion control, carbon sequestration, and habitat for a diverse array of species in the Sierra Nevada (Keane et al. 2012). Subalpine tree species such as whitebark pine are also considered a keystone and foundation species in many high-elevation ecosystems throughout the Western United States (Tomback and Achuff 2010). Although subalpine forests support a less diverse fauna than lower elevation terrestrial ecosystems, a number of wildlife species depend on subalpine forests for foraging, nesting, or denning (Mayer and Laudenslayer 1988). Subalpine forests are particularly important for several uncommon and rare species such as American marten (*Martes caurina*), great gray owl (*Strix nebulosa*), Sierra Nevada red fox (*Vulpes vulpes necator*), California wolverine (*Gulo gulo luteus*), white-tailed jackrabbit (*Lepus townsendii*), snowshoe hare (*Lepus americanus*), and heather vole (*Phenacomys intermedius*) (Mayer and Laudenslayer 1988) (table 7). Clark's nutcracker, Douglas' squirrel (*Tamiasciurus douglasii*), lodgepole chipmunks (*Neotamias speciosus*), and other seed-caching wildlife species are important seed dispersers and predators of subalpine tree species in the assessment area (table 7) (Tomback 1982, Vander Wall 2008).

NRV Descriptions and Comparisons to Current Conditions

Function—

Fire—

Fire return interval, fire rotation, and fire return interval departure—

Historical fire return interval (FRI) estimates for subalpine forests in the Sierra Nevada were highly variable (range: 19 to 187 years) and largely dependent on forest type (table 18). In general, mean and median FRI values were longest in undefined “subalpine forest,” moderately long in whitebark pine and mixed red fir–western white pine–mountain hemlock forests, and shortest in the lodgepole pine and western white pine forests. Mean FRI estimates for foxtail pine and bristlecone pine varied up to an order of magnitude (table 18), possibly owing to the relatively larger survey areas used by North et al. (2009). FRI estimates tend to decrease with increased survey area (Agee 1993). Limited fire scar or contemporary fire history data from foxtail pine stands in the southern Sierra Nevada suggest FRI estimates between 130 and 260 years (Keifer 1991, Rourke 1988), which supports model estimates (about 250 years) for these xeric subalpine forests (Stephenson et al. 2005). Based on a reconstruction of the annual area burned, Caprio and Graber (2000) noted that mean and maximum FRI estimates for subalpine forests in Sequoia and Kings Canyon National Parks tended to be greater on relatively mesic north-facing slopes (mean FRI = 374; max FRI = 1,016 years) compared to xeric south-facing slopes (mean FRI = 187; max FRI = 508 years). However, Taylor (2000) found that median FRI estimates were similar across all slope aspects in red fir–mountain hemlock forests of Lassen Volcanic National Park.

Fire rotation estimates for historical subalpine forests were variable across the Sierra Nevada. In the southern Cascades (pre-1905 period), fire rotation differed between 46 years for lodgepole pine forests and 147 years for red fir–mountain hemlock forests (Bekker and Taylor 2001). Taylor and Solem (2001) and Taylor (2000) estimated a presettlement (1735–1849) fire rotation of 76 years in lodgepole

Table 18—Average historical fire return intervals (FRI) for subalpine forests in the Sierra Nevada bioregion

Subalpine type/group (aggregation)	Mean FRI	Median FRI	Minimum FRI	Maximum FRI	Number of studies	Subregions
----- Years -----						
Lodgepole pine	43	56	14	150	7	Northern, Southern, Eastern
Subalpine	160	156	57	338	4	All
Red fir–western white pine– mountain hemlock ^a	83	66	18	75	4	Northern

Individual fire return interval estimates and sources are presented in table 25 of the appendix.

^a Fire return interval estimates were extracted from red fir NRV chapter for comparison.

pine, red fir, and other upper montane forests in the southern Cascades. In Yosemite National Park, the contemporary (1980–2000) fire rotation estimate based on lightning fires that were allowed to burn under prescribed conditions was 579 years in dry lodgepole pine forests (van Wagtendonk et al. 2018). In foxtail pine stands of the southern Sierra Nevada, the contemporary fire rotation estimate was 2,100 years based on all fires and 7,200 years for lightning fires only (Rourke 1988).

Few fires of notable size (>10 ha) have burned during the fire suppression period in subalpine forests of the Sierra Nevada (Beaty and Taylor 2001, 2009; Hallett and Anderson 2010), with the exception of contemporary reference sites with active fire regimes (e.g., Collins et al. 2007). This absence of fire has led to an increase in FRI and fire rotation in contemporary compared to presettlement subalpine forests (e.g., Bekker and Taylor 2001, Taylor and Solem 2001). Moreover, the absence of fire has also increased the backlog of subalpine forests that require fire for ecological benefits, as indicated by an increase in fire return interval departure (FRID) values in these forests (Caprio and Graber 2000, North et al. 2012). This pattern may already be starting to change as the annual average and highest elevation burned by wildfire in the Sierra Nevada has been increasing as changes in minimum nighttime temperatures increased over the past three decades (Schwartz et al. 2015). However, most Sierra Nevada subalpine forests have missed only one or two fire cycles at most (i.e., mostly low to moderate FRID), suggesting that the ecological effects of fire suppression in these forests are relatively minor or negligible compared to the fire-frequent mixed-conifer and yellow pine forests (Long et al. 2013, Miller and Safford 2012, Safford and Van de Water 2014, van Wagtendonk et al. 2002).

Future projections in fire frequency, probability, and area. Projections of future fire frequency, probability, and total burned area are expected to increase in coming decades. Westerling et al. (2011) projected a more than 100 percent increase in annual area burned in many mid- to high-elevation forests of the western Sierra Nevada by 2085 (Westerling et al. 2011). In Yosemite National Park, annual burned area is projected to increase 19 percent by 2020–2049 owing to projected decreases in snowpack in mid- and high-elevation forests (Lutz et al. 2009b). Projections of future fire probability and frequency are expected to more than double by the end of the century (Mortiz et al. 2013). These projected increases were consistent across climate models that project hotter and drier (GFDL) and warmer and similar precipitation (PCM) climate conditions. Additionally, these results support earlier climate models that projected increased future fire occurrence in subalpine forests (Miller and Urban 1999). Increases in projected fire probability indicate that fire frequency will increase, leading to a decrease in return intervals and fire rotations for subalpine forests in the assessment area.

Most Sierra Nevada subalpine forests have missed only one or two fire cycles at most (i.e., mostly low to moderate FRID), suggesting that the ecological effects of fire suppression in these forests are relatively minor or negligible compared to the fire-frequent mixed-conifer and yellow pine forests.

Projections of future fire frequency, probability, and total burned area are expected to increase in coming decades.

Fire size. There are few historical estimates of fire size in Sierra Nevada subalpine forests. Mean fire size in the southern Cascades (1729–1918 period) was 405 ha (range: 295 to 460 ha) in lodgepole pine forest and 140 ha (range: 124 to 155 ha) in red fir–mountain hemlock forest (Bekker and Taylor 2001). In Lassen Volcanic National Park, mean fire size was 176 ha (median = 129 ha; range: 11 to 733 ha) in red fir–mountain hemlock forest (Taylor 2000). In the Lake Tahoe basin, presettlement spatial patterns of fire-scarred trees in red fir–western white pine forests suggested that historical fires were small and patchy, but pulses of recruitment indicated that larger areas of moderate-severity fire also occurred on the landscape (Scholl and Taylor 2006).

Based on contemporary reference sites, the size of unsuppressed fires in subalpine forests vary widely but tend to be less than 4 ha in size. In upper montane and subalpine forests of the Emigrant Basin Wilderness Area between 1951 and 1973, nearly 80 percent of lightning-caused fires were less than 0.1 ha, and none were larger than 4 ha (Greenlee 1973 in Potter 1998). In Sequoia and Kings Canyon National Parks between 1968 and 1973, 80 percent of unsuppressed fires were smaller than 0.1 ha, and 87 percent were smaller than 4 ha (Potter 1998). In Yosemite National Park, 56 percent of unsuppressed fires in red fir and lodgepole pine forests between 1972 and 1993 were less than 0.1 ha, and 82 percent were smaller than 4 ha (fig. 28) (van Wagtendonk 1993). In contrast to average fire size, the highest proportion of area burned (>70 percent) in red fir and lodgepole pine forests of Yosemite National Park tends to be from fires between 4 and 400 ha in size (van Wagtendonk 1993); an additional 28 percent of burned area is attributed to fires between approximately 400 and 2000 ha in size (fig. 29).

There is a recent trend toward increasing fire size and total burned area in moister and higher elevation forests of the Sierra Nevada. Between 1984 and 2004, total annual burned area has increased in red fir, white fir, and subalpine forests of the Sierra Nevada (Miller and Safford 2008, Miller et al. 2009). Mean and maximum fire size have also increased during this time period in higher elevation forests of the Sierra Nevada.

Fire type. Sierra Nevada subalpine forests are currently split into two general fire types, based on contemporary reference site information. In the first type, both high-elevation white pine forests (i.e., whitebark pine, foxtail pine, limber pine, and bristlecone pine) and open western white pine–Jeffrey pine forests typically experience slow-moving surface fires because of the presence of sparse surface and canopy fuels, natural terrain breaks, and relatively drier conditions that support

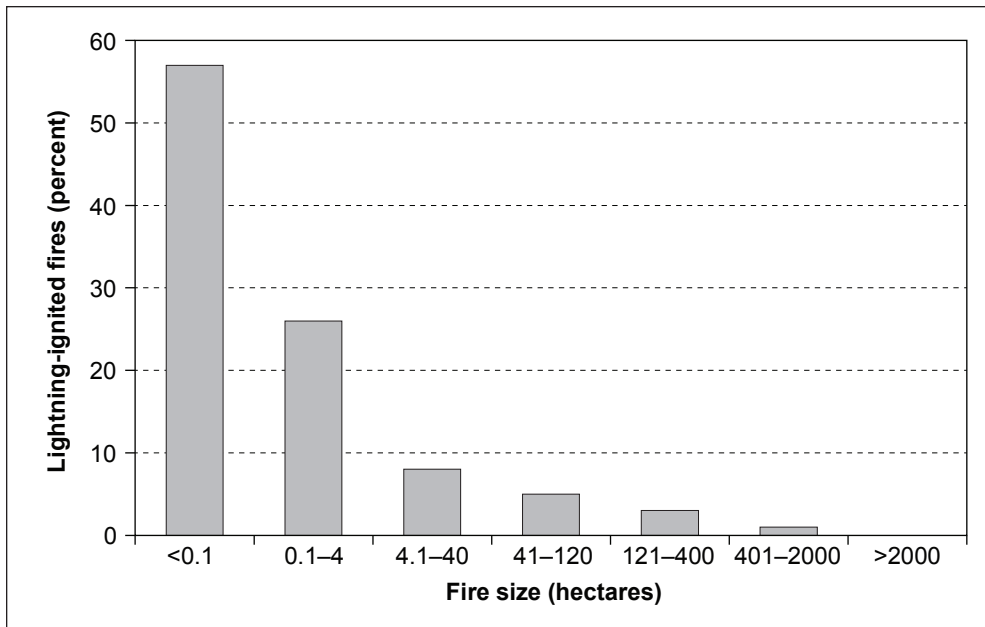


Figure 28—Percentage of lightning-ignited fires by size class in red fir and lodgepole pine forests of Yosemite National Park, 1972–1993. Figure is redrawn from van Wagtendonk (1993) and Potter (1998).

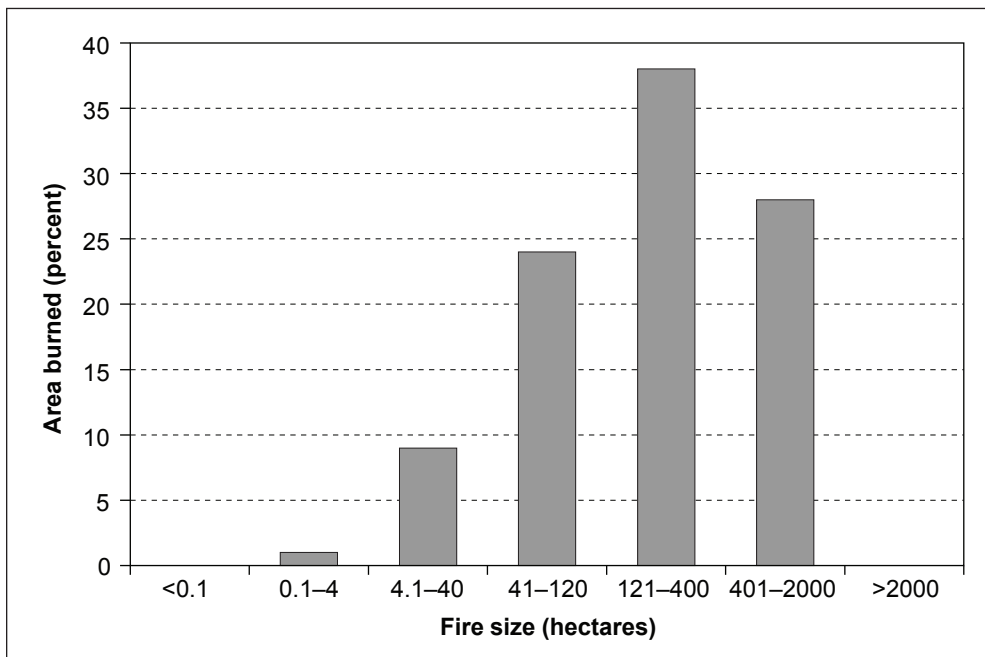


Figure 29—Percentage of total area burned by fire size class in red fir and lodgepole pine forests of Yosemite National Park between 1972 and 1993. Adapted from van Wagtendonk (1993) and Potter (1998).

lower tree densities and biomass (Keane et al. 2012, van Wagtendonk et al. 2018). Occasional local torching of individual tree or tree clumps does occur in these forests, particularly under extreme dry and windy conditions. The second general fire type is represented by subalpine forests dominated by lodgepole pine or mountain hemlock. These relatively mesic forests are characterized by a mixture of semi-frequent surface fires with occasional crown fires, resulting in “multiple” fire types that are dependent on localized fire weather and fuel loading conditions (Agee 1993, van Wagtendonk et al. 2018). The relatively higher frequency of crown fires in these forests are supported by the presence of heavy and compact surface fuels, higher tree densities, and greater rates of litter and woody fuel deposition (van Wagtendonk and Moore 2010, van Wagtendonk et al. 2018). Sustained crown fires in these forests often occur only under extreme dry and windy conditions (Keifer 1991, van Wagtendonk et al. 2018). In the Lake Tahoe basin, modeled fire behavior in presettlement lodgepole pine stands generally produced surface fires, with active crown fires largely restricted to stands with high fuel loading under the most extreme weather conditions (98th percentile) (Maxwell et al. 2014, Taylor et al. 2014). Regarding high-elevation lodgepole pine forests of Yosemite National Park, Muir (1894) remarked:

During the calm season and Indian summer the fire creeps quietly along the ground, feeding on the needles and cones; arriving at the foot of a tree, the resin bark is ignited and the heated air ascends in a swift current, increasing in velocity and dragging the flames upward. Then the leaves catch, forming an immense column of fire, beautifully spired on the edges and tinted a rose-purpose hue. It rushes aloft thirty or forty feet above the top of the tree, forming a grand spectacle, especially at night. It lasts, however, only a few seconds, vanishing with magical rapidity, to be succeeded by other along the fire-line at irregular intervals, tree after tree, upflashing and darting, leaving the trunks and branches scarcely scarred.

These observations support current studies in contemporary reference sites that these forests were characterized by relatively frequent surface fires interspersed with occasional wind-driven crown fires (e.g., Caprio 2006, Keifer 1991). Interestingly, fire type roughly parallels fire tolerance of subalpine tree species, with more tolerant species usually associated with surface fire types (table 17).

Subalpine forests are generally characterized by a climate-limited fire regime at landscape and regional scales, although fuels can limit fire spread at localized scales in patchy, sparsely vegetated subalpine stands (Brown and Smith 2000, van Wagtendonk et al. 2018). Climate-limited fire regimes typically have sufficient

fuel to carry fire, but fire occurrence depends primarily on whether climate or weather is suitable for ignition and fire spread (Agee 1993). In the Late Holocene, fire activity in subalpine forests of the Sierra Nevada was driven by changes in climate, including the dynamics of the El Niño–Southern Oscillation (Hallett and Anderson 2010).

Together, these studies suggest that historical and current fire regimes in subalpine forests are both climate-limited and dominated by either surface fires or a combination of surface fires with occasional crown fires. Consequently, fire regime types of subalpine forests are likely within the historical range of variation.

Fire seasonality. Most fires in subalpine forests historically occurred during late summer or fall (van Wagtendonk et al. 2018). In lodgepole pine and red fir–western hemlock forests of the southern Cascades, the position of fires on presettlement annual growth rings indicated that 99 to 100 percent of historical fires burned during late summer and fall (Bekker and Taylor 2001, Taylor 2000). In the Lake Tahoe basin, 92 percent of historical fires in red fir–western white pine forests burned during late summer to fall, and 7 percent burned in early to mid summer (Taylor 2004). Whitebark pine forests burned throughout the growing season, but most fires (especially large fires) occurred late in the season (Agee 1993). In high-elevation forests of Yosemite National Park, most wildfires and wildland use fires between 1974 and 2005 burned during the months of July, August, and September (van Wagtendonk and Lutz 2007). Together, these studies indicate that fire season has not changed substantially between historical and current periods.

Fire severity. Fire regimes of subalpine forests in contemporary reference sites have been classified as either low severity or mixed severity (generally characterized by “multiple” fire severity classes). High-elevation white pine forests typically experience low-severity fire (often <25 percent tree mortality), and mesic lodgepole pine or mountain hemlock forests are generally characterized as mixed severity (table 19) (Agee 1993, Brown and Smith 2000, Keane et al. 2012, van Wagtendonk et al. 2018). For instance, Thode et al. (2011) concluded that the whitebark pine–mountain hemlock had a low-severity fire regime distribution and lodgepole pine had a multiple fire regime distribution based on fires that burned between 1984 and 2003 in Yosemite National Park. The proportion of area burned at high severity (>75 to 95 percent tree mortality with high to complete mortality of vegetation) averaged 27 and 7 percent across studies in lodgepole pine and other subalpine forests, respectively (table 19). Reburned lodgepole pine stands in Yosemite National Park tended to burn at higher severity compared to stands not recently burned (van Wagtendonk et al. 2012). Suppression wildfires also tended to burn at greater severity relative to

Table 19—Average fire severity proportions in Sierra Nevada subalpine forests based on historical and contemporary reference site information

Aggregation/group ^a	Locations	Fire severity class				Number of studies
		Unchanged	Low	Moderate	High	
		----- Percent -----				
Lodgepole pine	Multiple	19	29	28	24	5
Other subalpine	Multiple	52	22	19	7	2

Individual fire severity estimates and sources are presented in table 25 of the appendix.
Averages do not include estimates based on LANDFIRE biophysical setting models.
^a Fire severity averages are adjusted such that the sum of fire severity classes for each group equals 100 percent.

Projections of future climate suggest that fire severity or intensity may increase in many parts of the Sierra Nevada during the mid-21st century, especially in subalpine forests.

prescribed fires and “wildland fire use” fires (i.e., wildfires managed for resource objectives) across upper and lower montane forests in Yosemite National Park during 1974–2005 (van Wagtendonk and Lutz 2007).

Miller et al. (2009) found that fire severity in Sierra Nevada subalpine forests was negatively correlated with spring precipitation, but temporal trends (1984–2006) in fire severity were not apparent owing to insufficient data for the subalpine zone. Mallek et al. (2013) estimated that modern rates of burning in Sierra Nevada subalpine forests for any severity class (i.e., low-moderate and high) was currently underrepresented compared to the presettlement period (Mallek et al. 2013). Accordingly, current subalpine forests may be deficient in all fire severity classes at the bioregional scale.

Future projections in fire severity and intensity. Projections of future climate suggest that fire severity or intensity may increase in many parts of the Sierra Nevada during the mid-21st century, especially in subalpine forests (Lenihan et al. 2003, 2008). In Yosemite National Park, the total area burned at high severity in mid- and high-elevation forests is projected to increase 22 percent between the 1984–2005 and 2020–2049 periods because of declines in snowpack (April 1 snow water equivalent) (Lutz et al. 2009b).

High-severity patch size. Presettlement information related to high-severity patch size is limited to sparse historical accounts. Muir (1894) observed that high-elevation stands of lodgepole pine experienced stand-replacing fire events that were frequently small and patchy but sometimes “miles in extent...leaving a forest of bleached spires...encumbering the ground until, dry and seasoned, they are consumed by another fire.” In addition, he emphasized “during strong winds whole forests are destroyed, the flames surging and racing onward above the bending woods,

like the grass-fire of a prairie.” In combination with related observations (see quote in “Fire type” section), Muir’s various accounts suggest that some presettlement lodgepole pine forests in Yosemite endured rare wind-driven fire events that resulted in large stand-replacing patches.

Stand-replacing high-severity patches in contemporary reference subalpine forests were typically areas exceeding 95 percent tree mortality, with high to complete mortality of vegetation (Miller and Safford 2008) (fig. 30). In montane forests of the Illilouette Creek Basin of Yosemite National Park (including lodgepole pine forests), the mean patch size of stand-replacing, high-severity burned patches following the Hoover Fire (2001) and Meadow Fire (2004) was 9.1 ha (median = 2.2 ha) (Collins and Stephens 2010). The median patch size of stand-replacing patches in lodgepole pine forests was approximately 1.5 ha, although median patch size increased to about 20 ha in mixed stands of red fir–white fir–lodgepole pine. Most (>60 percent) of the stand-replacing patches in montane forests in the Illilouette Creek Basin were ≤ 4 ha in size, but a few large patches accounted for approximately 50 percent of the total stand-replacing patch area.

Collectively, historical accounts and contemporary reference site information suggest that presettlement stand-replacing patches in subalpine lodgepole pine forests were primarily small in size but also included occasional large-size patches as a consequence of extreme fire weather conditions (e.g., high winds, low fuel moisture). Conditions in other subalpine forest types are uncertain. Current temporal trends in high-severity patch size are not available owing to insufficient information in current nonreference subalpine forests (Miller and Safford 2008, Miller et al. 2009).



Figure 30—High-severity burned patch in a lodgepole pine forest in the Illilouette Creek Basin, Yosemite National Park. Photo was taken about 8 years after the Meadow Fire (2004).

Insects—

Native insect outbreaks have occurred within the Sierra Nevada in almost every decade of the 20th century (Ferrell 1996, FRAP 2010). Mountain pine beetle (*Dendroctonus ponderosae*) was responsible for a significant portion of this historical tree mortality in subalpine forests, often acting in concert with drought, pathogens, and other stressors (Ferrell 1996). Subalpine host species of mountain pine beetle includes lodgepole pine, whitebark pine, western white pine, limber pine, foxtail pine, and bristlecone pine (Furniss and Carolin 2002). Coevolved plant defenses differ in these host species, with more resin production and higher concentrations of toxic monoterpenes found in lower elevation species (e.g., lodgepole pine) than higher-elevation species (e.g., whitebark pine) (Raffa et al. 2014). Other native insects and pathogens in subalpine forests are covered in the “Red fir” section and in Safford and Stevens (2017).

Both historical records and long-term paleoecological records indicate that significant mountain pine beetle outbreaks in western North America occurred at irregular intervals, initiated by regional drought or rapid climate transitions.

Both historical records and long-term paleoecological records indicate that significant mountain pine beetle outbreaks in western North America occurred at irregular intervals, initiated by regional drought (Gibson et al. 2008) or rapid climate transitions (Brunelle et al. 2008). In contrast, Ferrell (1996) reviewed forest insect damage reports for the Sierra Nevada from 1917 to 1993 and found that mountain pine beetle outbreaks in subalpine forests were infrequent and usually limited to small clumps of trees, although larger outbreaks in dense stands did occasionally occur (California Forest Pest Council 1951–1993). It is not clear, however, whether historical insect damage surveys for the Sierra Nevada were effective at detecting mountain pine beetle outbreaks within high-elevation subalpine forests, owing to their relatively low economic importance and inaccessibility (Gibson et al. 2008). Consequently, historical information is inconclusive with respect to the frequency and extent of mountain pine beetle outbreaks in subalpine forests of the assessment area.

Recent modeling studies of mountain pine beetle activity throughout the Western United States (including the assessment area) have provided insights into the natural range of variation in bark beetle outbreaks. Hicke et al. (2006) modeled past (1895–1960), then current (1961–2005), and future (2006–2100) mountain pine beetle outbreaks in forests of the Western United States by using climate factors closely associated with the synchronous emergence of adults from host trees at an appropriate time of year (termed “adaptive seasonality”). Their results indicate that the adaptive seasonality of mountain pine beetle was similar between historical and current periods for many parts of the Western United States, including higher elevations of the Sierra Nevada. However, future projections in adaptive seasonality at high elevations (>3000 m) demonstrated that the

total area susceptible to bark beetle attack would initially increase between 2005 and 2050, then steadily decline but remain above current levels between 2060 and 2100 (fig. 31) (Hicke et al. 2006). Bentz et al. (2010) found similar results comparing current and projected future adaptive seasonality with a similar population model. These results suggest that future projections in mountain pine beetle outbreaks in subalpine forests of the Sierra Nevada will be outside the historical range of variation.

Several recent studies and reports lend support to model projections in mountain pine beetle activity within the assessment area. Since 2006, mountain pine beetle activity in subalpine forests dominated by western white pine and lodgepole pine has increased substantially above background levels, especially on the Modoc National Forest (California Forest Pest Council 2011). Whitebark pine and limber pine have recently experienced significant increases in mortality from mountain pine beetle, drought, and other stressors in the eastern Sierra Nevada on the Inyo (both species) and Modoc (whitebark pine only) National Forests (California Forest Pest Council 2011; Millar et al. 2007, 2012). Such outbreaks have led to significant changes in the structure, regeneration, and

Future projections in mountain pine beetle outbreaks in subalpine forests of the Sierra Nevada will be outside the historical range of variation.

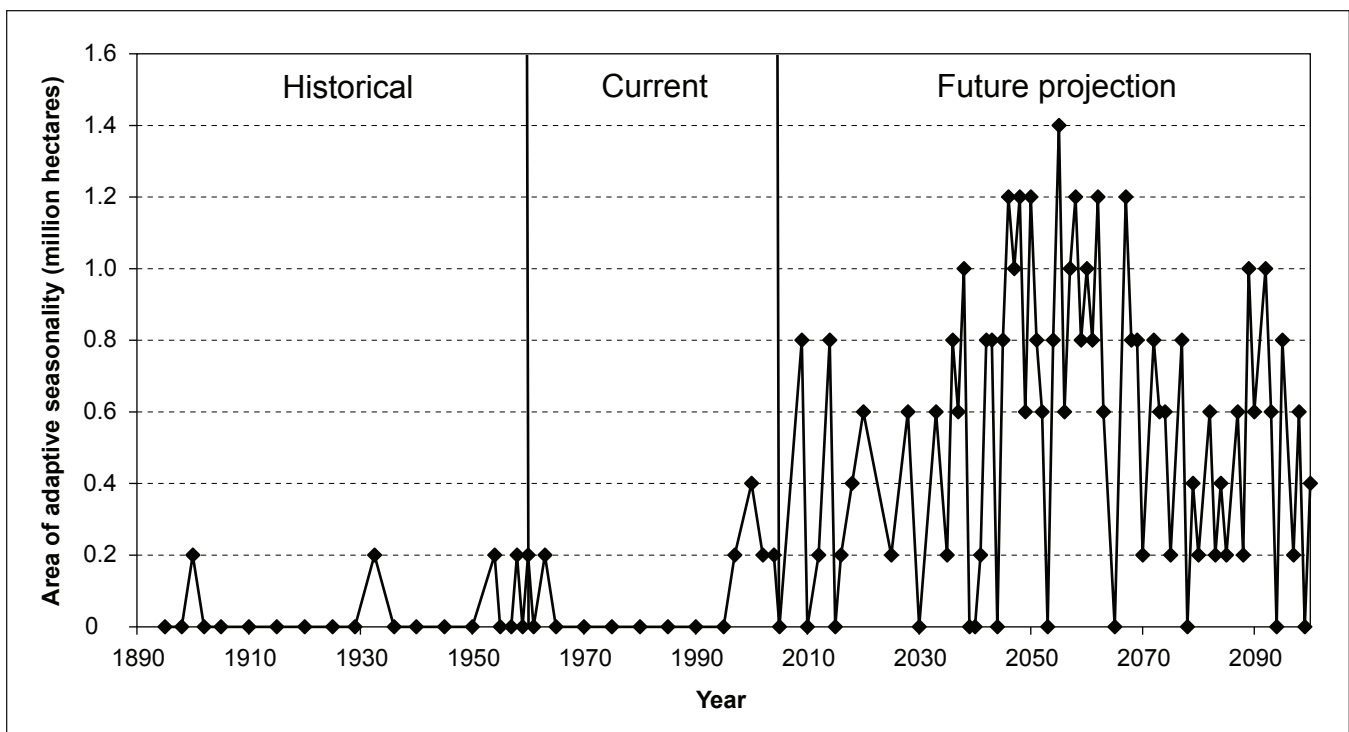


Figure 31—Area of mountain pine beetle adaptive seasonality from 1895 to 2100 in subalpine forests (3000–3500 m elevation) of the Western United States, including the Sierra Nevada. Time periods include historical (1895–1960), current (1961–2005), and projected future under a warming climate (2006–2100). Adaptive seasonality is a measure of the synchronous and successful emergence of adult beetles and is an estimate of the climate conditions associated with outbreaks. Adapted from Hicke et al. (2006).

Increased mountain pine beetle activity has been clearly linked to increases in temperature and climatic water deficit, decreases in precipitation, and greater stand densities or tree diameters.

dominance of whitebark pine stands (Meyer et al. 2016). In many of these cases, increased mountain pine beetle activity has been clearly linked to increases in temperature and climatic water deficit, decreases in precipitation, and greater stand densities or tree diameters (Meyer et al. 2016; Millar et al. 2007, 2012), further implying that future outbreaks in high-elevation subalpine stands are likely in the near future.

Collectively, these studies and reports indicate that mountain pine beetle outbreaks are currently within the historical range of variation for the assessment area, at least before the recent 2006–2012 outbreak events in high-elevation white pine stands of the Inyo and Modoc National Forests. However, near future (2006–2050) projections for high-elevation white pine forests in the assessment area suggest that increased frequency and extent of outbreaks may greatly exceed the historical range of variation by the early- to mid-21st century. This projected increase in mountain pine beetle activity will have substantial cascading impacts on subalpine forest ecosystems of the assessment area similar to those observed recently in the central and northern Rocky Mountains (Edlburg et al. 2012).

Wind, volcanism, and avalanche—

Refer to the “NRV Descriptions and Comparisons to Current Conditions” section for red fir on page 33.

Climatic water deficit—

Water balance relations are important for evaluating climate controls on species distributions across spatial scales, including subalpine forests (Stephenson 1998). In Yosemite National Park, subalpine tree species occupied areas with the lowest evapotranspiration and CWD values relative to other montane tree species (Lutz et al. 2010). Lutz et al. (2010) also found that values of AET/PET (a measure of the relative sensitivity of species ranges to increases in CWD) for subalpine tree species in Yosemite were either well within the North American water balance envelope for each species (e.g., whitebark pine, lodgepole pine) or were clustered near the extreme arid end for its entire geographic range (e.g., mountain hemlock, western white pine), indicating high sensitivity of these species to changes in CWD in Yosemite. In the Sierra Nevada, annual rates of AET for subalpine conifers generally tended to increase with latitude (with corresponding decrease in CWD), from approximately 225 mm (deficit $\approx$ 110 mm) in Sequoia National Park (Stephenson 1998) to 248 mm (deficit $\approx$ 63 mm) in Yosemite National Park (Lutz et al. 2010). This trend indicates greater moisture deficit in subalpine forest stands

toward the southern portion of its range in the Sierra Nevada. In the southern Sierra Nevada, foxtail pine basal area was positively correlated with AET and negatively correlated with water vapor deficit during summer in Sequoia National Park (Rourke 1988).

Modeled CWD averages for subalpine forests in Yosemite National Park were generally similar between the Little Ice Age (about 1700 CE) and the present (1971–2000) (fig. 32) (Lutz et al. 2010). This suggests that CWD is generally within the historical range of variation for subalpine tree species in the central Sierra Nevada. However, CWD was projected to be 24 to 30 percent greater in the near future (2020–2049) compared to the period 1971–2000 (Lutz et al. 2010), indicating an increasing trend of moisture stress in subalpine tree species particularly for species (i.e., mountain hemlock and western white pine) near the arid extreme of their distribution. Future moisture stress in the Sierra Nevada is likely to inhibit subalpine tree growth and increase tree mortality rates, especially in areas not characterized by deep and persistent snowpack (Das et al. 2013, Dolanc et al. 2013b). This will likely lead to a decreased representation of subalpine forests in the Sierra Nevada with progressive water stress (Brodrick and Asner 2017).

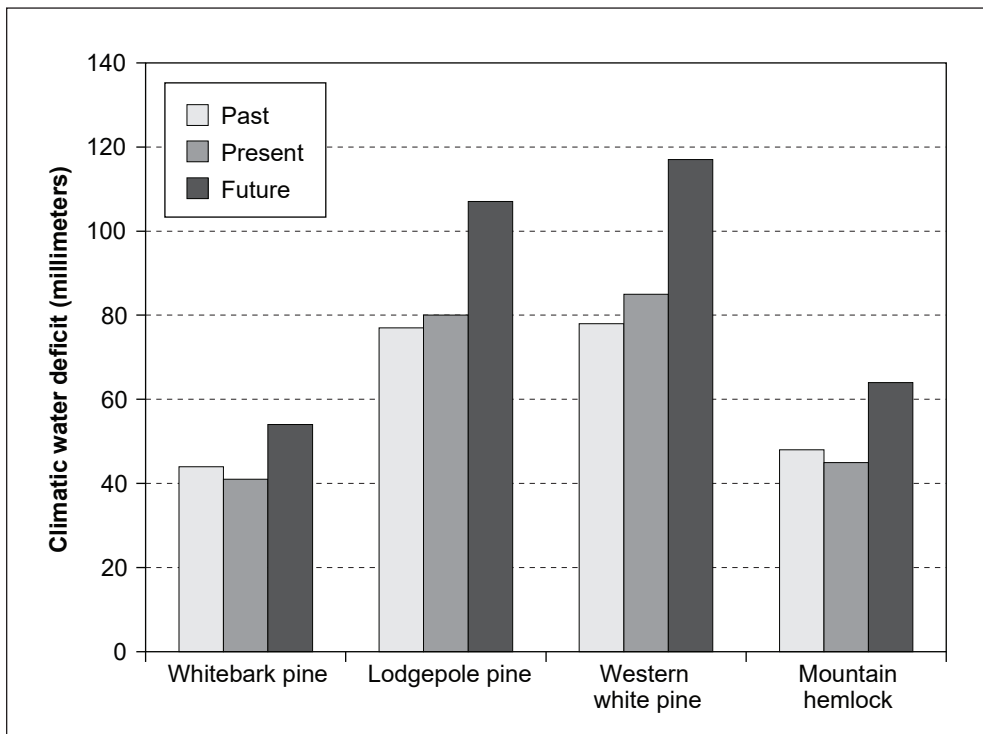


Figure 32—Mean values of climatic water deficit for modeled climate in the past (about 1700; Little Ice Age), present (1971–2000), and near future (2020–2049). Data source is Lutz et al. (2010).

Forest dynamics at treeline or ecotonal boundaries—

Subalpine forests at or near treeline or ecotonal boundaries (e.g., lower elevation limit) are highly sensitive to changes in climate in the Sierra Nevada, although these patterns and their mechanisms are complex and often species specific (table 20) (Fites-Kaufman et al. 2006, Körner 1998, LaMarche 1973). Overall, these climate-dependent patterns indicate that treeline populations are generally within the broad historical range of variation, especially when comparing 20th century records with a historical reference period that spans both the Little Ice Age and Medieval Warm Period (tables 1 and 20). However, there is a general trend of increased growth, density, recruitment, and treeline elevation within subalpine tree populations located at or near treeline within the past 40 to 50 years (table 20). For example, bristlecone pine tree-ring growth near treeline in the White Mountains (which was positively correlated with temperature) was greater during 1960–2010 than any other period during the past 3,700 years (Salzer et al. 2009). In contrast, lower elevation stands of bristlecone pine had decreased growth associated with increased temperatures and decreased precipitation, indicating greater moisture limitations within lower elevation stands. Foxtail pine populations may be an exception to these general trends for subalpine forests, with recent declines in recruitment and regeneration in foxtail pine treeline populations of the southern Sierra Nevada, possibly because of an increased climatic water deficit resulting from higher temperatures and lower precipitation (e.g., Lloyd 1997, Lloyd and Graumlich 1997). Irrespective of these trends, potential upslope movement of subalpine forests with climate change is likely to be limited by unsuitable growing substrates and altered disturbance regimes at elevations above current treelines (Donato 2013, although see Smithers et al. 2018).

Structure—***Tree densities and size class distribution—***

Tree densities and tree size class distribution are highly variable among subalpine forests owing to the complex topography and variable species composition of subalpine landscapes (Rundel et al. 1988). For instance, size class distributions of high-elevation white pine stands differ considerably across tree species (Maloney 2011, Maloney et al. 2008a), although current subalpine forests as a whole have a relatively even distribution excluding the regeneration class (fig. 33). However, several general patterns have emerged from recent studies examining changes in subalpine forest stand structure over the past century based on the comparison of historical inventories (e.g., Wieslander Vegetation Type Mapping) with modern surveys (e.g., U.S. Forest Service FIA) or historical stand reconstructions. In the central Sierra Nevada, tree density in subalpine forests increased by a net value of 30 percent, including a 63 percent (range: 44 to 91) increase in small tree (<30.4 cm d.b.h.) density for

Table 20—Growth and tree recruitment associations with climate in subalpine forests near treeline or ecotonal boundaries in the assessment area

Subalpine species (region)	Climate association(s)	Reconstruction period (years)	Reference(s)
Bristlecone pine (White Mountains)	Increase in tree growth at treeline was positively associated with increased temperature and weakly associated with precipitation. Growth in lower elevation sites was negatively associated with increased temperature and decreased precipitation.	3,700	Salzer et al. (2009)
Foxtail pine (southern Sierra Nevada)	Decreased tree recruitment and density and treeline elevation was associated with multi-decadal droughts coupled with warmer temperatures, implicating the importance of water balance relations.	1,000–3,500	Lloyd (1997), Lloyd and Graumlich (1997)
Foxtail pine (southern Sierra Nevada)	Tree growth and recruitment was positively associated with temperature in relatively mesic plots, but positively correlated with precipitation in relatively xeric plots.	600	Bunn et al. (2005)
Foxtail pine (southern Sierra Nevada)	Tree growth was limited by drought stress in years of low precipitation and cool temperatures limit growth during high winter precipitation years.	850	Graumlich (1991)
Lodgepole pine (southern Sierra Nevada)	Tree growth was positively correlated with winter precipitation and secondarily by summer temperature, with optimal growth during moderate temperatures coupled with high precipitation.	400	Graumlich (1991)
Mountain hemlock (southern Cascade Range)	Tree expansion into previously unoccupied higher elevation sites was positively associated with increased temperature, lower snowpack, and periods of higher moisture.	150	Taylor (1995)
Whitebark pine, lodgepole pine, red fir, western white pine, mountain hemlock (central Sierra)	Tree growth across subalpine zone was positively correlated with cool, wet conditions in the year preceding growth and warm springs with sufficient moisture during the year of growth. Overall, warm and dry conditions lead to reduced radial growth.	110	Dolanc et al. (2014)
Whitebark pine, western white pine, lodgepole pine (eastern Sierra Nevada)	Annual branch growth and invasion of snowfields was positively associated with increased minimum temperature and the Pacific Decadal Oscillation index.	100	Millar et al. (2004)

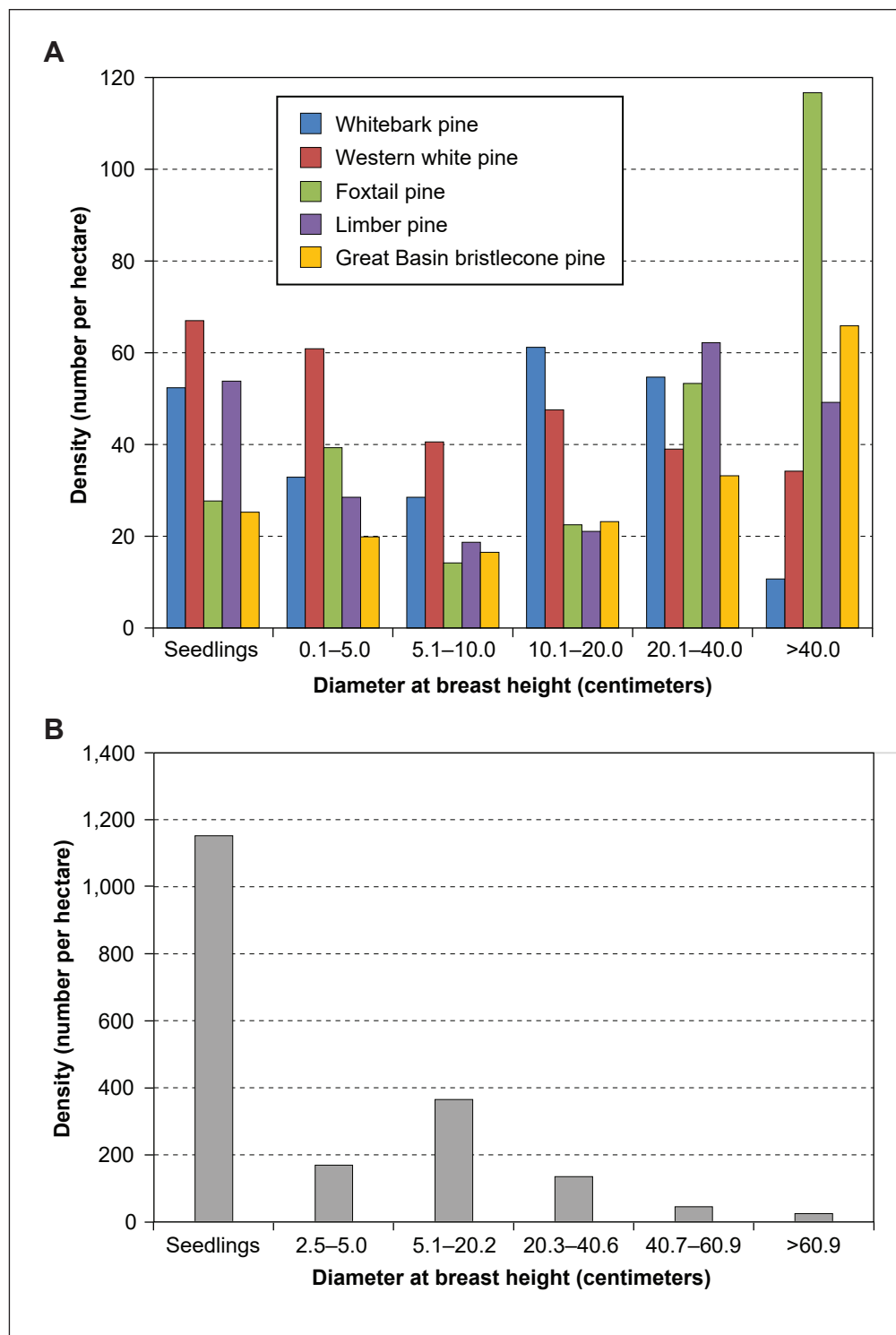


Figure 33—Tree size class distributions of subalpine stands in the assessment area: (A) high-elevation white pine forests, from Maloney et al. (2008a) and Maloney (2011); (B) total of 301 Forest Inventory and Analysis plots (2012) of subalpine forests (all types) covering the entire assessment area.

whitebark pine, lodgepole pine, mountain hemlock, and red fir between 1929–1936 and 2007–2009 (Dolanc et al. 2013a). In contrast to small tree density, large tree (≥ 61 cm d.b.h.) density declined an average of 20 percent in high-elevation species such as western white pine, lodgepole pine, and red fir (fig. 34) (Dolanc et al. 2013a). These same tree density patterns were observed in subalpine forests of the northern and central Sierra Nevada based on a comparison of historical and current forest inventory data (Dolanc 2014b). Lutz et al. (2009) estimated a 49 percent reduction in the density of large-diameter (≥ 61 cm d.b.h.) lodgepole pine over roughly the same period in Yosemite National Park. Several other subalpine species showed large tree declining trends in Yosemite, but these were not significant. In secondary-growth lodgepole pine forests of the Lake Tahoe basin, total tree density increased but average tree diameter decreased between presettlement and current periods based on stand reconstructions by Taylor (2004) and Taylor et al. (2014) (fig. 35), resulting in a significant shift in the size class distribution to smaller diameter trees (fig. 36). Using a landscape-scale analysis, Maxwell et al. (2014) also found relatively low tree densities (median: 289; lower and upper quartiles: 160 to 420 stems/ha) in presettlement

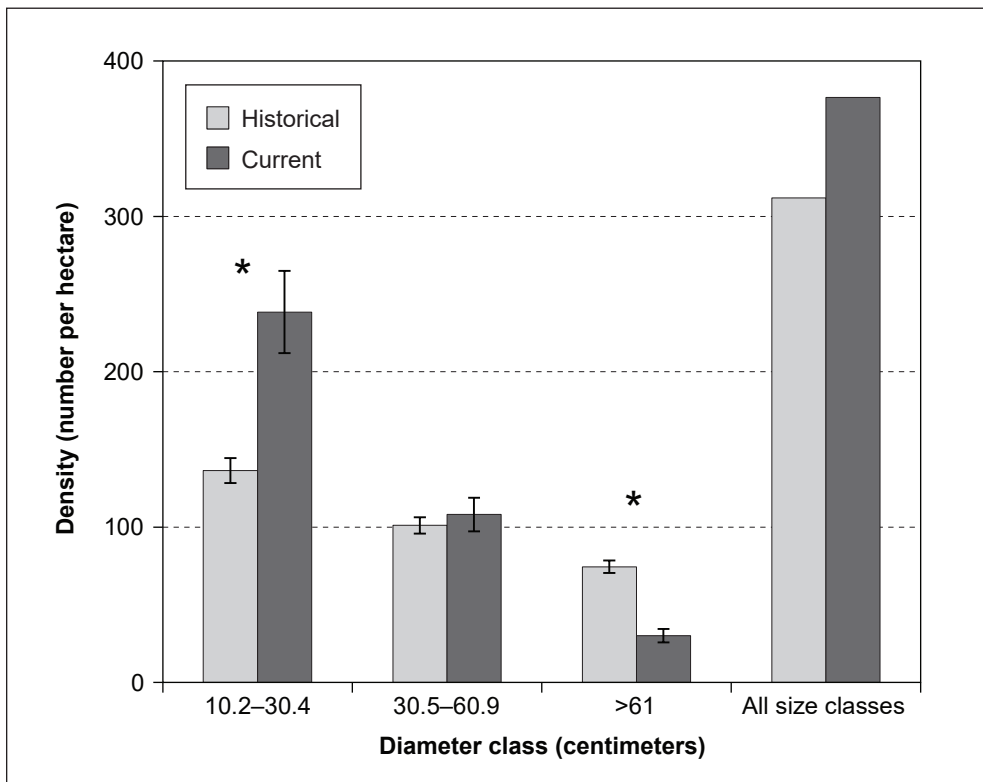


Figure 34—Mean ($\pm$ standard error) tree density in historical (1929–1936) and current (2001–2010) subalpine forests (>2500 m elevation) of the central and northern Sierra Nevada. Adapted from Dolanc et al. (2014b). Asterisks represent statistically significant differences ($P < 0.001$) between historical and current periods.

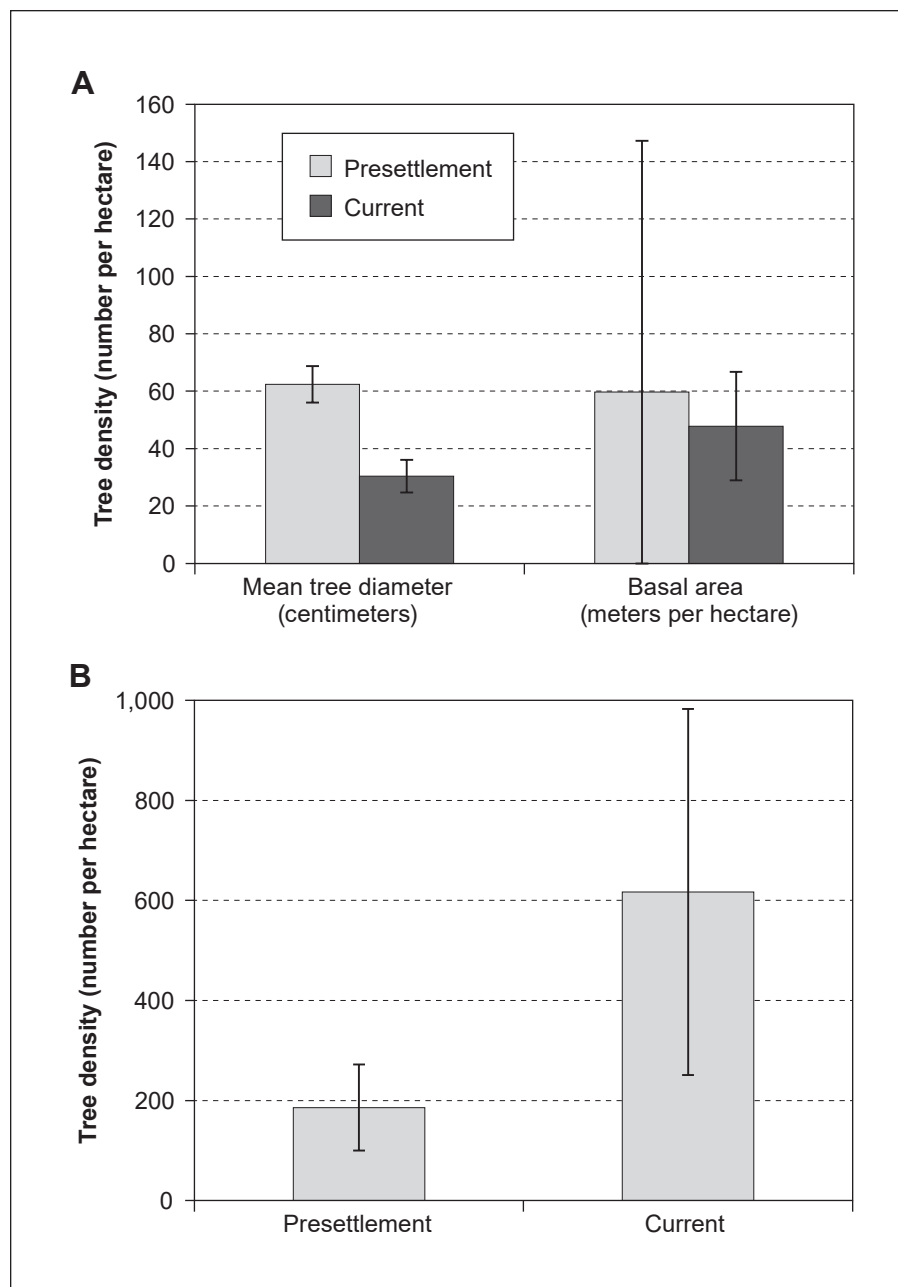


Figure 35—(A) Mean tree diameter and basal area, and (B) mean ($\pm$ standard deviation) tree density in presettlement (before 1870) and current (about 2000) lodgepole pine forests of the Lake Tahoe basin. From Taylor (2004).

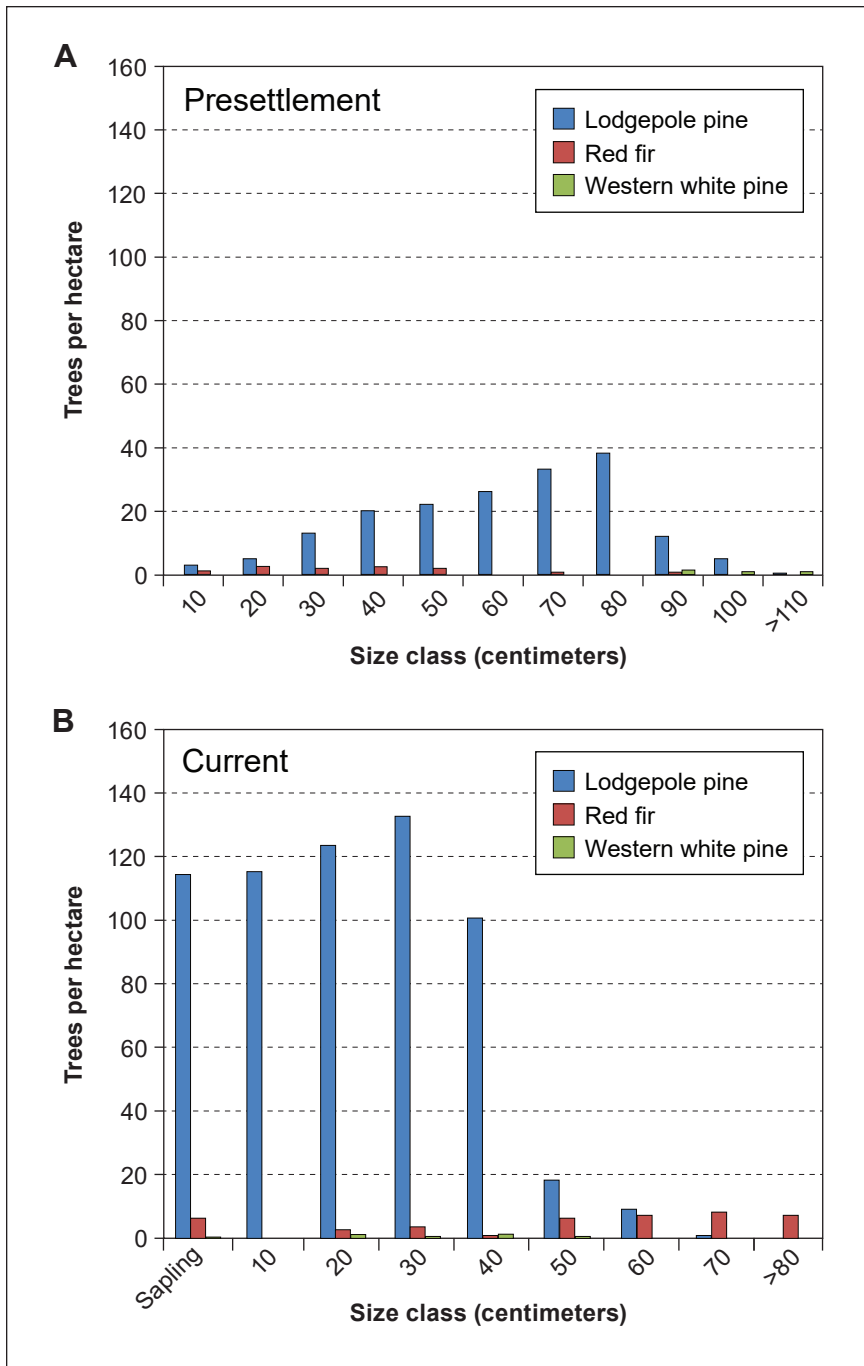


Figure 36—Tree species composition and size class distribution of (A) presettlement and (B) current lodgepole pine stands that were heavily logged in the late 19th century in the Lake Tahoe basin. The Y-axis scale was fixed at a maximum of 160 trees per hectare to emphasize differences in tree densities between periods. Adapted from Taylor (2004).

lodgepole pine stands in the Lake Tahoe basin. In Sequoia National Park, Vankat and Major (1978) compared historical and modern photos in subalpine forests, including foxtail pine and lodgepole pine stands, and found an apparent increase in tree density and cover between 1912 and 1978. Gruell (2001) also observed increased tree densities and cover while comparing historical (1867–1900) and contemporary (1990s) photos taken in subalpine forests throughout the Sierra Nevada.

William Brewer (Brewer 1930) observed large-diameter trees and low tree densities in subalpine forests of modern-day Sequoia and Kings Canyon National Parks:

Our route lay along the divide between the head branches of the Kings and Kaweah rivers, over steep ridges, some of them nearly ten thousand feet high, and then along ridges covered with forests of subalpine pines and firs...All grow to a rather large size, say four to five feet in diameter, but are not high. All are beautiful, the fir especially so, but there is difference enough in the color of the foliage and habit of the trees to give picturesque effect to these forests, which are not dense.

This historical account supports historical stand inventories documenting the low density of subalpine forest stands that were dominated by large-diameter (120 to 150 cm) trees.

Based on the historical–current stand inventory comparisons, stand reconstructions, and historical observations, it is likely that subalpine forests have increased in tree density and experienced a shift in their size class distribution to smaller size classes over the past 70 to 140 years. These changes are coincident with (1) 19th-century logging impacts in secondary growth stands (e.g., Maxwell et al. 2014, Taylor 2004), and (2) increases in daily minimum temperatures and precipitation over the past several decades that may favor increased regeneration, recruitment, and large-tree mortality rates in subalpine tree species (Dolanc et al. 2013a, 2014b).

Basal area—

Although there is limited information on historical basal area in subalpine forests of the Sierra Nevada, evidence suggests that basal area has not changed between historical and current periods. Taylor (2004) and Taylor et al. (2014) found that basal area was not different between presettlement and current lodgepole pine stands in the Lake Tahoe basin (fig. 36). Landscape-scale estimates of basal area in lodgepole pine and subalpine forests of the Lake Tahoe basin tended to be similar between presettlement and current periods (Maxwell et al. 2014).

Tree spatial patterns and structural diversity—

Both historical and current tree spatial patterns in subalpine stands show distinct spatial patterns among subalpine tree species, partially contingent on seed dispersal mechanism (table 17). Harris (1939) observed “scattered” foxtail pine stands

It is likely that subalpine forests have increased in tree density and experienced a shift in their size class distribution to smaller size classes over the past 70 to 140 years.

in Sequoia National Park where “the spacing between the mature old foxtails is uniform,” a pattern that reflects the random-to-uniform tree spacing patterns in current foxtail pine stands (fig. 27) (Keifer 1991). Both Muir (1894) and Leiberg (1902) remarked that whitebark pine had a “scattered” distribution in the Sierra Nevada that is similar to current clumped spatial patterns in the range (Keane et al. 2012, Meyer et al. 2016, Tomback 1982). Muir (1894) also observed that western white pine trees “grow in clusters of from three to six or seven.” Historical photos by Wieslander et al. (1933) show generally similar clumped spatial patterns for whitebark pine, limber pine, and western white pine in historical subalpine stands.

In contrast to unlogged subalpine stands, high-elevation forests logged during the late 19th century are dissimilar to presettlement stands with respect to tree spatial patterns and structural diversity. Taylor (2004) analyzed tree spatial patterns in presettlement and current secondary-growth lodgepole pine stands in the Lake Tahoe basin. Presettlement lodgepole pine forests were characterized by heterogeneity in tree spatial patterns; large- to intermediate-diameter trees (>40 cm d.b.h.) were clumped at all spatial scales, and small-diameter (10 to 40 cm d.b.h.) trees were randomly distributed (Taylor 2004). In comparison, current lodgepole pine forests contained small-diameter trees that were clumped at all spatial scales, but large trees were randomly distributed. These results suggest that the underlying structural patterns of presettlement and current secondary-growth lodgepole pine stands are different, despite relatively high structural heterogeneity in both periods. Structural diversity, defined as the dispersion and evenness of diameter size classes, was greater in presettlement than current secondary-growth lodgepole pine stands of the Lake Tahoe basin (fig. 36), suggestive of a frequent, low-severity fire regime (Taylor 2004).

Canopy structure—

In the Lake Tahoe basin, canopy bulk density and stand height were similar between presettlement and contemporary lodgepole pine stands (Taylor et al. 2014). However, canopy base height was greater in presettlement stands (mean: 7.3 m; range: 5.5 to 9.8 m) than contemporary stands (mean: 0.8 m; range: 0.6 to 0.9 m; Taylor et al. 2014).

Understory plant cover—

Historical information pertaining to understory vegetation and groundcover is primarily limited to historical accounts that predate the period of extensive sheep grazing in the high-elevation forests of the Sierra Nevada. In his extensive travels of montane forests in the Sierra Nevada, Brewer (1930) remarked that “the ground under the [subalpine] tree is generally nearly bare. There is but little grass or undergrowth of either herbs or bushes.” In describing the subalpine landscapes,

including “upper pine forests” and “glacier meadow gardens” in Yosemite National Park, Muir (1894) reported that “in some places the sod is so crowded with showy flowers that the grasses are scarce noticed, in others they are rather sparingly scattered.” Historical surveys and photos by Harris (1939) indicated that outside riparian areas and mesic microsites, understory shrub cover (especially *Ribes*) in pure and mixed foxtail pine stands of Sequoia National Park was “intermittent” to “practically devoid of vegetation.” Wieslander et al. (1933) historical forest inventories indicated low average coverage of understory vegetation in foxtail pine stands (1.3 ± 2.4 percent) but moderate coverage in whitebark pine stands (24 ± 31 percent) of the Sierra Nevada. These accounts suggest that presettlement understory plant cover was spatially variable and relatively sparse in many subalpine stands, especially outside of subalpine meadows, riparian areas, and mesic microhabitats. Current understory patterns largely mirror these trends (Potter 1998, Rundel et al. 1988, Vankat and Major 1978), and are driven to a large extent by variability in the underlying substrate and soil moisture (see “Landscape patterns” section). For example, understory cover averages 13.4 ± 14.5 (SD) for herbaceous plants and 8.2 ± 12.8 percent for shrubs, based on an analysis of a total of 301 FIA plots in subalpine forest plots of the assessment area. This general consistency between presettlement and current conditions implies that understory cover in contemporary subalpine forests is within the historical range of variation.

Physiognomic patterns—seral class proportions—

LANDFIRE biophysical setting (BpS) modeling estimated that historical reference conditions in subalpine forests of the assessment area were dominated by mid- and late-seral classes. As an exception, the southern Sierra subalpine forest, or Mediterranean California subalpine woodland BpS model (which is dominated by whitebark pine, mountain hemlock, and red fir but may include foxtail pine, western white pine, and lodgepole pine), was defined only by mid- and early-seral classes (fig. 37). In general, reference subalpine forests had a greater proportion of mid- and late-seral classes with open canopies (<50 percent cover) than other montane forests in the assessment area, with the exception of wet lodgepole pine forests, which were dominated by the late-seral closed-canopy seral class (Caprio 2005a, 2005b, Richardson and Howell 2005; Stephenson et al. 2005; van Wagtenonk et al. 2005).

Recent LANDFIRE BpS modeling of the southern Sierra Nevada national forests (Inyo, Sequoia, Sierra, and Stanislaus National Forests) at the subforest scale indicated that current subalpine forests exhibited low departure from reference conditions (Southern Sierra Nevada Wildfire Risk Assessment 2015). These patterns were especially evident in the Mediterranean California subalpine woodland and Intermountain basins subalpine limber-bristlecone pine woodland.

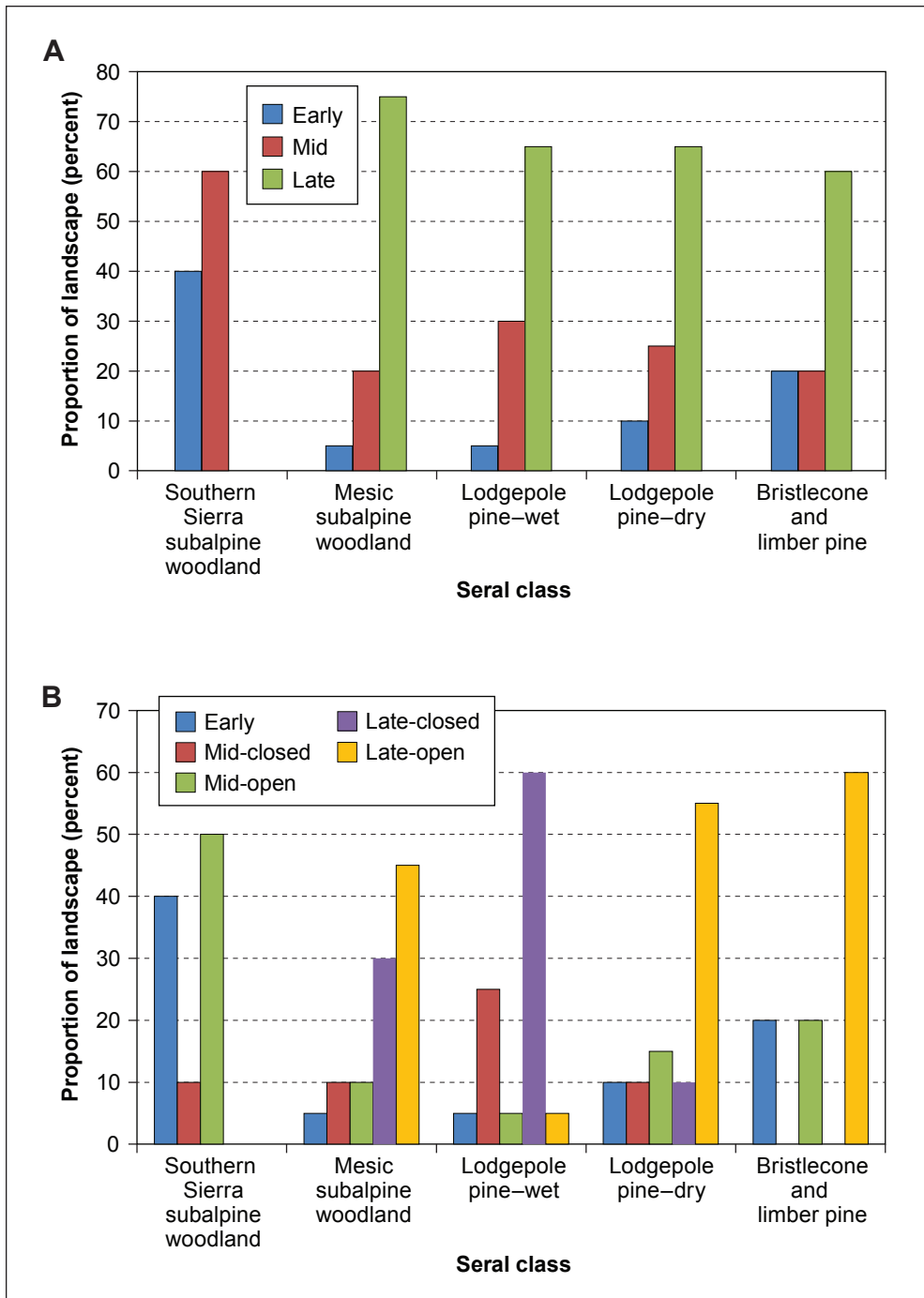


Figure 37—Percentage of subalpine landscape in different seral classes based on LANDFIRE biophysical setting models for the Sierra Nevada: (A) early-, mid-, and late-seral classes for five subalpine forest types; (B) open and closed canopy subclasses in mid- and late-seral classes. Southern Sierra “dry” subalpine woodland is typically dominated by whitebark pine or foxtail pine but may include western white pine, lodgepole pine, mountain hemlock, and red fir. Mesic subalpine woodland is dominated by mountain hemlock, lodgepole pine, western white pine, and red fir. (Caprio 2005a, 2005b; Richardson and Howell 2005; Stephenson et al. 2005; van Wagtendonk et al. (2005).

Composition—

Subalpine tree species composition—

Historical stand inventory and stand reconstruction studies indicate that tree species composition in subalpine forests is generally similar between past and present subalpine forests. In the northern and central Sierra Nevada, modern stand composition was indistinguishable from historical composition based on stand inventory comparisons over a 65- to 80-year period, with the exception that red fir density increased 103 percent within subalpine forests (Dolanc et al. 2014a). In the Lake Tahoe basin, lodgepole pine forests at the lower elevational limit of subalpine forests did not change significantly in tree species composition between presettlement and current periods (fig. 36) (Taylor 2004, Taylor et al. 2014). Dolanc (2013a) also found that changes in the relative frequency of high-elevation tree species in the central Sierra Nevada was relatively minor, supporting the conclusion that species composition has remained relatively unchanged over the past 70 to 140 years.

Projected Future Conditions and Trends

Background—

Refer to the “NRV Descriptions and Comparisons to Current Conditions” section for red fir on page 21.

Model projections—

Projected changes in the distribution of subalpine forests are summarized in table 21. All studies used the A2 emissions scenario (high emissions), with the exception that Gonzalez (2012) used an ensemble of the B1 (lower emissions), A1B (moderate emissions), and A2 emissions scenarios with two GCMs (PCM, GFDL). Southern Sierra Partnership (2010) used only the A2 emissions scenario but included an ensemble of 11 GCMs. Ecological response models included species distribution models (BioMove, ANUCLIM, Maxent, Bioclim) in four studies but also included the MC1 vegetation dynamic model for biome projections in Lenihan (2003, 2008). Statistical procedures used to project changes in bristlecone pine distribution incorporated geol-

Table 21—Average projected future changes in the distribution of subalpine forests and tree species based on climate envelope (species distribution) and dynamic vegetation (MC1) models

Forest type or species	Decrease ^a	Stable ^a	Number of studies
Subalpine forest	78	12	3
Whitebark pine	95	5	3
All subalpine conifer vegetation types	85	15	5

Individual projection estimates and sources are presented in table 27 of the appendix.

^a Projected percentage decrease or lack of change (“stable”) in the area occupied by subalpine conifers at the end of the century (2071–2100). Projections are based primarily on the arallem Climate Model (warmer and similar precipitation) and Geophysical Dynamics Fluid Laboratory (hotter and drier) global climate models.

ogy and topography but did not include information regarding the types of GCMs, emission scenarios, or species distribution models used (Van de Ven et al. 2007).

Models projected a substantial 55 to 100 percent reduction in the geographic range size of all subalpine forests in the assessment area (table 21). Reductions in the range size of specific subalpine species included an 83 to 100 percent reduction in foxtail pine, 75 to 100 percent reduction in bristlecone pine, and 82 to 100 percent range reduction in whitebark pine across a range of geographic scales (subregional to entire species' geographic range). Projected proportional loss of lodgepole pine (by 2040–2065) in the southern Sierra Nevada was more than twice that for the entire state of California (Southern Sierra Partnership 2010), suggesting that lodgepole pine and possibly other subalpine conifers will be more prone to climate change impacts toward the southern end of its geographic distribution (e.g., Kern Plateau). However, several model projections (e.g., Lenihan et al. 2008) suggest that the southern Sierra Nevada may serve as a future climate refugium for high-elevation conifers and retain a greater total area of subalpine forests in the late 21st century. Projected declines are also anticipated for western white pine in the Sierra Nevada, although suitable climate space is projected to increase approximately 160 and 330 m in elevation for western white pine and whitebark pine, respectively (Richardson et al. 2008). The projected rate of climate exposure for foxtail pine is similar between the mid and late 21st century, but this projected rate is more variable for lower elevation tree species (Serra-Diaz et al. 2014).

Projected future climate vulnerability of Clark's nutcracker in the Sierra Nevada under the GFDL climate model (Siegl et al. 2014) suggests potential indirect negative impacts of climate change on subalpine tree species. Whitebark pine, limber pine, and bristlecone pine are especially dependent on Clark's nutcracker for seed dispersal and colonization of unoccupied sites (table 17) (Coop and Schoettle 2009, Lanner 1988, Tomback 1982). Consequently, the loss or reduction of Clark's nutcracker populations in high-elevation forests may limit localized dispersal potential and further exacerbate future environmental conditions for these high-elevation white pine species. Additionally, severe, climate-induced mortality in white pine stands (similar to that observed in stands heavily affected by white pine blister rust) may induce increased seed predation by Clark's nutcracker, resulting in heavily reduced dispersal potential and regeneration densities (McKinney and Tomback 2007). Alternatively, potential upslope movement of Clark's nutcracker could facilitate the migration of these white pine species to higher elevations or other future suitable habitats. Understanding future range shifts resulting from climate change will require careful consideration of altered species interactions (Van der Putten et al. 2010).

Schwartz et al. (2013) used a climatic envelope modeling approach based on two GCMs (PCM, GFDL) and two climate surface models (ensemble of Bioclim and Flint Regional Water Balance model; downscaled to 270 m) to evaluate the

exposure of subalpine forest and individual subalpine tree species (e.g., whitebark pine, foxtail pine, lodgepole pine) to climate change in the southern Sierra Nevada. Their results indicate that, by the end of the century, subalpine forests will be highly to extremely vulnerable (outside the 90th percentile of the current bioclimatic distribution for the vegetation type) in 72 percent (PCM) or 95 percent (GFDL) of subalpine forests and 56 percent (PCM) and 83 percent (GFDL) of whitebark pine forests in the southern Sierra Nevada national forests (Sequoia, Sierra, and Inyo National Forests and southern half of the Stanislaus National Forest) (fig. 38). The total area of low climate exposure for subalpine forests in the southern Sierra Nevada will only be 18 percent (PCM) and 0 percent (GFDL) by the end of the century; values for foxtail pine, whitebark pine, and lodgepole pine reflect these trends (table 21). By the end of the century, geographic areas of low climate exposure (i.e., climatic refugia) for subalpine forests under the PCM model are generally scattered along the higher elevations within the entire study area, with core areas of low exposure in (1) the central portion of the Inyo National Forest, and (2) eastern portions of Sierra National Forest and Sequoia, Kings Canyon, and Yosemite National Parks (fig. 39). Under the GFDL model, climatic refugia are primarily limited to the highest elevations of Sequoia and Kings Canyon National Parks (especially in the Kern River drainage) and Sierra and Inyo National Forests (fig. 40). End-of-century climate projections suggest high degrees of climate exposure and pronounced range reductions for subalpine conifers in the southern Sierra Nevada (Schwartz et al. 2013). Climate model forecasts for the state of California suggest that these drastic reductions in subalpine forests may occur across the entire assessment area.

Most subalpine forests in the assessment area will be outside their historical and contemporary climate envelope by the end of the century.

Based on these collective modeling results, most subalpine forests in the assessment area will be outside their historical and contemporary climate envelope by the end of the century. Projected changes in the distribution of subalpine forests consistently show a pronounced reduction in their geographic extent within the assessment area by 2070–2100. Several models also project a relatively high degree of climate vulnerability for subalpine forests within the southern extent of its geographic distribution, at lower elevations, and within isolated populations. These projections support theoretical models that predict greater loss of populations at geographic range margins and low latitude limits (Hampe and Petit 2005). Ultimately, the degree of climate vulnerability in subalpine conifers will be contingent on several factors not covered by most species distribution models, including migration rates, biotic interactions, evolutionary processes (e.g., adaptation, genetic drift), physiological tolerances, edaphic constraints, interacting stressors, and forest management actions (Clark et al. 2011, Kuparinen et al. 2010, Rowland et al. 2011, Zhu et al. 2012). For example, projected climate-wildfire interactions in the Sierra Nevada resulted in only a slight decrease in the spatial extent and recruitment of

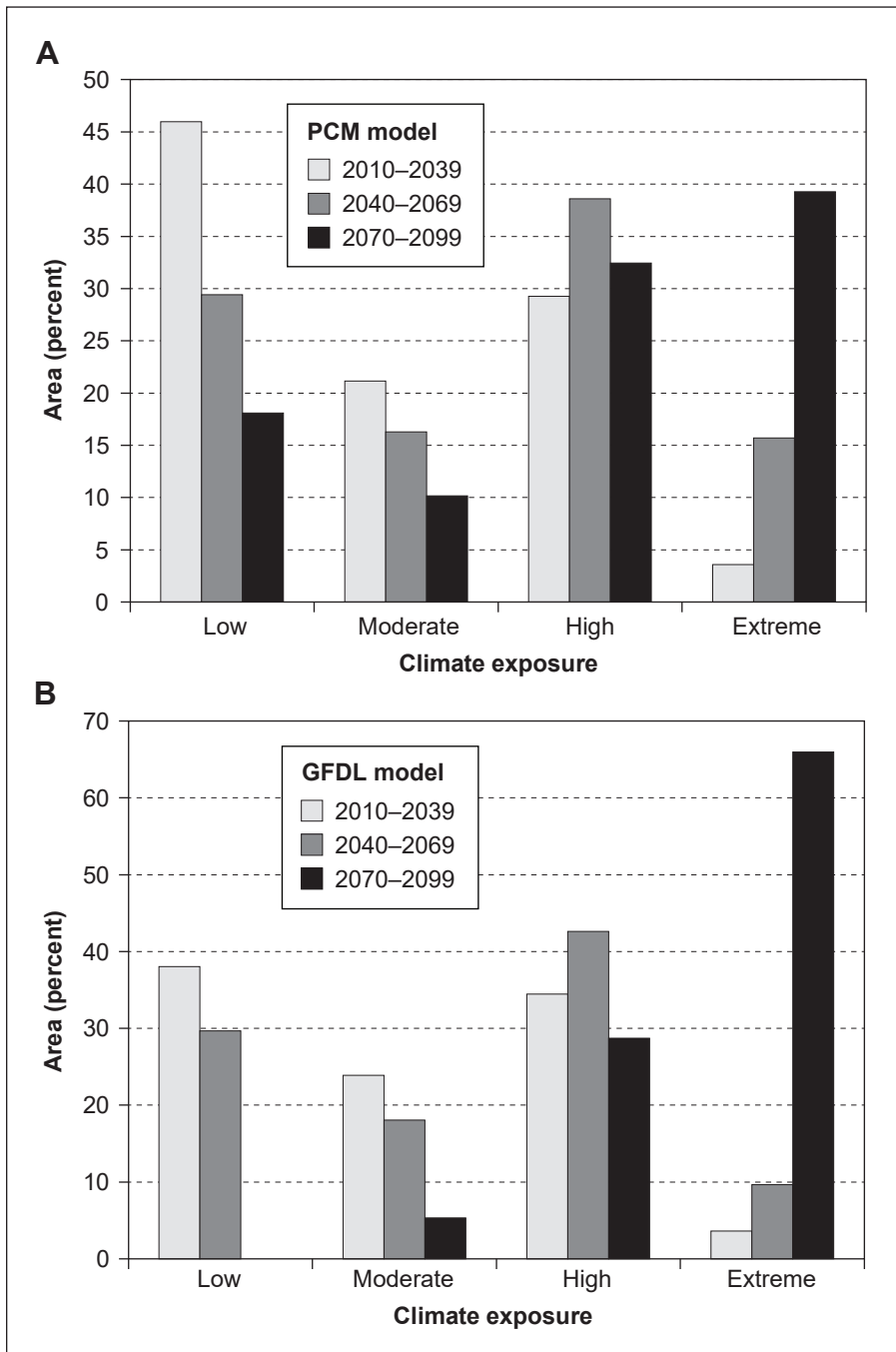


Figure 38—Future projections of climate exposure for subalpine forest in the southern Sierra Nevada national forests (primarily Sequoia, Sierra, and Inyo National Forests). Projections are based on the (A) Parallel Climate Model (PCM) and (B) General Fluid Dynamics Laboratory (GFDL) global climate model used by Schwartz et al. (2013). Projections include three future periods: 2010–2039 (near future), 2040–2069 (mid-century), and 2070–2099 (end of century). Levels of climate exposure indicate red fir bioclimatic areas that are projected to be (1) inside the 66th percentile (low exposure), (2) in the marginal 67–90th percentile (moderate exposure), (3) in the highly marginal 90–99th percentile (high exposure), or (4) outside the 99th percentile (extreme exposure) of the current regional bioclimatic envelope for subalpine conifers.

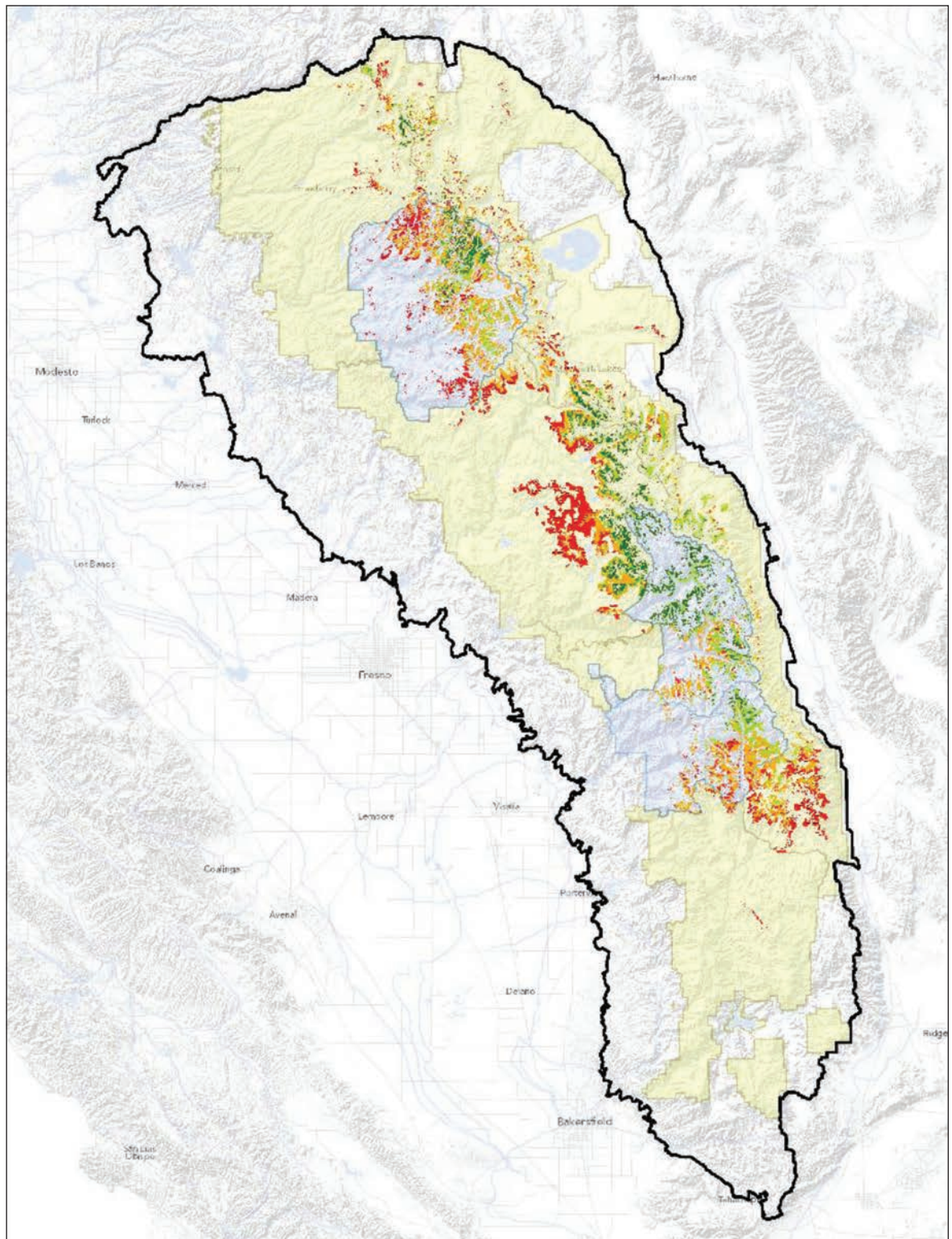


Figure 39—Future projections (end of century: 2070–2099) of climate exposure for subalpine forest in the southern Sierra Nevada based on the Parallel Climate Model (warmer and similar precipitation) produced by Schwartz et al. (2013). Levels of climate exposure indicate bioclimatic areas that are projected to be (1) inside the 66th percentile (dark green), (2) in the marginal 67–90th percentile (light green), (3) in the highly marginal 90–99th percentile (yellow), or (4) outside the extreme 99th percentile (red) for the bioclimatic distribution of the vegetation type. Areas in green are suggestive of climate refugia for subalpine conifers by the end of the century.

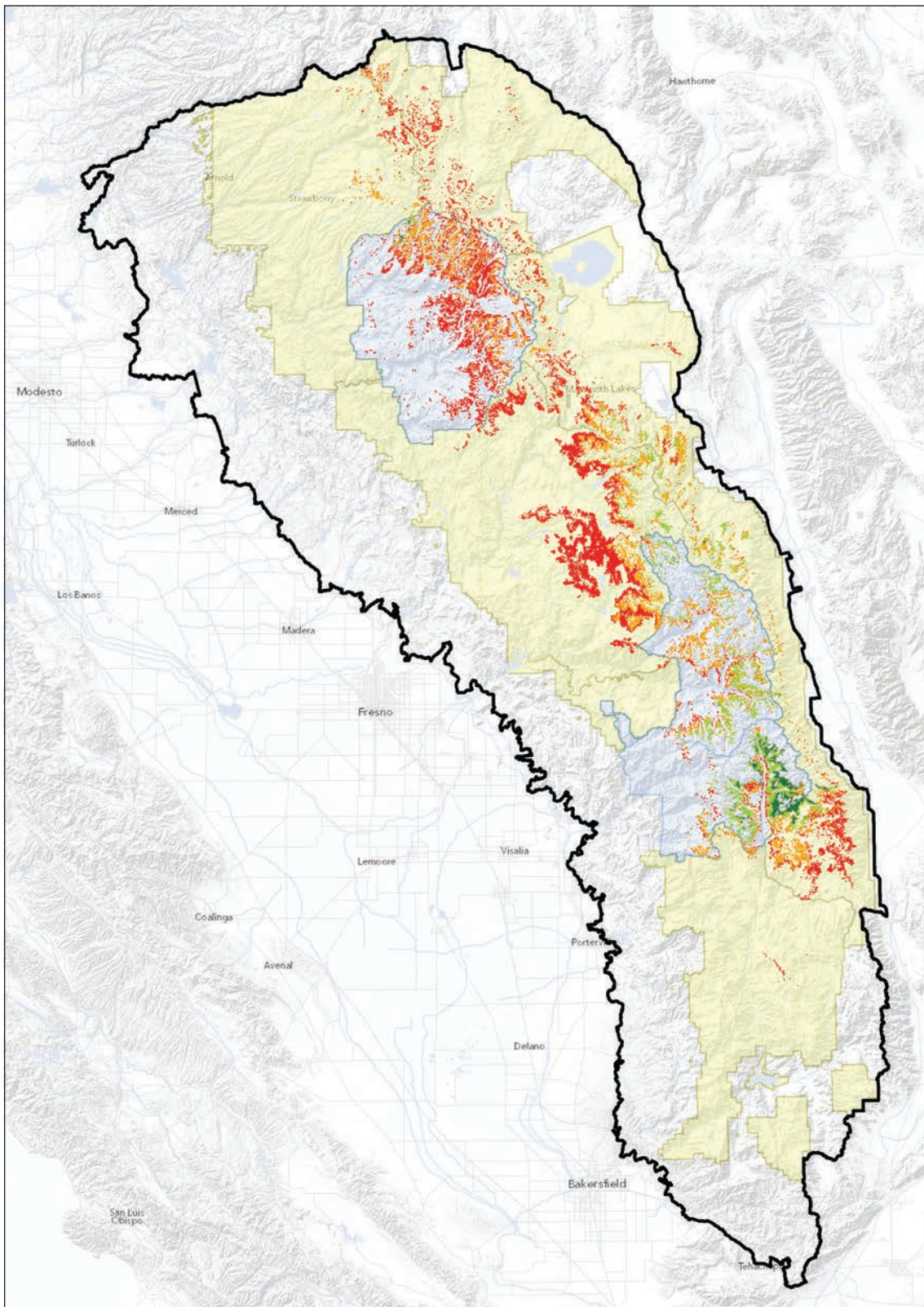


Figure 40—Future projections (end of century: 2070–2099) of climate exposure for subalpine forest in the southern Sierra Nevada based on the General Fluid Dynamics Laboratory model (hotter and drier) produced by Schwartz et al. (2013). Levels of climate exposure are described in figure 39.

subalpine forests by the end of the 21st century (Liang et al. 2016). Consequently, subalpine forests may persist in or adapt to areas of projected high climate exposure (Iglesias et al. 2015), especially in the higher elevation environments of the southern Sierra Nevada.

Red Fir and Subalpine Forests Summary

- Comparisons between historical and current conditions indicate that modern red fir and subalpine forests of the assessment area are largely within the natural range of variation with respect to compositional, functional, and some structural variables (tables 4 and 5)
- For both forest types, exceptions include a considerable shift in the tree size class distribution to smaller diameters, greater homogenization of forest structure at stand and landscape scales, increased cover in lower canopy strata, increased density of small-diameter trees, and decreased density of the largest diameter fir, lodgepole pine, and western white pine trees. These changes have likely occurred primarily from 19th century logging within secondary-growth stands, decades of fire exclusion, and recent climatic warming within the entire assessment area.
- Fire regimes in red fir forests have changed significantly, as fire return intervals and fire rotations have generally lengthened during much of the 20th century as a result of fire suppression activities. In contrast, fire regimes in subalpine forests have not changed significantly.
- In both forest types, the total burned area has increased since 1984 and future fire frequency, annual burned area, and fire severity are all projected to increase with climate change.
- In red fir forests, the incidence of pathogens and insects, such as dwarf mistletoe and *Cytospora* canker, likely have not changed considerably from historical (1600–1960) to contemporary (1961–2005) periods. However, recent (2006–2012) increases in tree mortality rates in red fir forests associated with pathogens, insects, and moisture stress suggest increased potential for these mortality agents to exceed the historical range of variation in the coming decades.
- In subalpine forests, mountain pine beetle outbreaks likely have not changed considerably during historical (1890–1960) and contemporary (1961–2005) periods. However, future projections and recent beetle eruptions in subalpine forests (especially 2006–2012) suggest increased potential for large-scale outbreaks over the next 50 years that will exceed the historical range of variation.

- Treeline growth and recruitment of some subalpine species, such as bristlecone pine, have increased beyond the historical range of variation within the past 40 to 50 years, likely owing to increases in temperature.
- Climate envelope models consistently project a substantial loss (average: 85 percent in both cases) or high climate vulnerability of red fir and subalpine forests in the assessment area by the end of the 21st century. This suggests that the greatest changes in Sierra Nevada red fir and subalpine forests during the 21st century will occur as a consequence of climate change.

Plant Species Identified in This Report

Scientific name	Common name
<i>Abies concolor</i> (Gord. & Glend.) Lindl. ex Hildebr.	White fir
<i>Abies magnifica</i> A. Murray bis	Red fir
<i>Abies magnifica</i> A. Murray bis var. <i>magnifica</i>	California red fir
<i>Abies magnifica</i> A. Murray bis var. <i>shastensis</i> Lemmon	Shasta red fir
<i>Abies magnifica</i> A. Murray bis var. <i>critchfieldii</i> Lanner	Critchfield's red fir
<i>Abies procera</i> Rehder	Noble fir
<i>Arceuthobium abietinum</i> f. sp. <i>Magnificae</i> Engelm. ex Munz	Red fir dwarf mistletoe
<i>Arctostaphylos</i> Adans.	Manzanita
<i>Calocedrus decurrens</i> (Torr.) Florin	Incense cedar
<i>Cercocarpus</i> Kunth	Mountain mahogany
<i>Chrysolepis sempervirens</i> (Kellogg) Hjelmqvist	Bush chinquapin
<i>Gayophytum ramosissimum</i> Torr. & A. Gray	Pinyon groundsmoke
<i>Juniperus occidentalis</i> Hook.	Sierra juniper
<i>Pinus albicaulis</i> Engelm.	Whitebark pine
<i>Pinus flexilis</i> James	Limber pine
<i>Pinus longaeva</i> Engelm.	Great basin bristlecone pine
<i>Pinus balfouriana</i> Balf.	Foxtail pine
<i>Pinus balfouriana</i> Balf. ssp. <i>austrina</i> R.J. Mastrog & J.D. Mastrog.	Sierra foxtail pine
<i>Pinus balfouriana</i> Balf. ssp. <i>balfouriana</i>	Klamath foxtail pine
<i>Pinus contorta</i> Douglas ex Loudon	Lodgepole pine
<i>Pinus contorta</i> Douglas ex Loudon var. <i>latifolia</i> Engelm. ex S. Watson	Lodgepole pine
<i>Pinus contorta</i> Douglas ex loudan var. <i>murrayana</i> (Balf.) Engelm.	Sierra lodgepole pine
<i>Pinus jeffreyi</i> Balf.	Jeffrey pine
<i>Pinus monticola</i> Douglas ex D. Don	Western white pine
<i>Pinus ponderosa</i> Lawson & C. Lawson	Ponderosa pine
<i>Quercus vaccinifolia</i> Kellogg	Huckleberry oak
<i>Sequoiadendron giganteum</i> (Lindl.) J. Buchholz	Giant sequoia
<i>Tsuga mertensiana</i> (Bong.) Carrière	Mountain hemlock

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U.S. Equivalents

When you know:	Multiply by:	To get:
Millimeters (mm)	0.0394	Inches
Centimeters (cm)	2.54	Inches
Meters (m)	3.28	Feet
Kilometers (km)	.621	Miles
Hectares (ha)	2.47	Acres
Square meters per hectare (m ² /ha)	4.37	Square feet per acre
Megagrams per hectare (Mg/ha)	.446	Tons per acre
Degrees Celsius (°C)	1.8 (°C+32)	Degrees Fahrenheit

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Appendix

Table 22—Historical fire return interval (FRI) estimates for red fir forests in the Sierra Nevada^a

Vegetation type	Subregion	Mean FRI				Maximum FRI				Years sampled	Sample type ^b	Reference
		Low	Mid	High	Composite	Low	Mid	High	Composite			
Red fir	State of California	40	33	15	130	—	—	—	—	—	—	Van de Water and Safford (2011)
Red fir–western white pine	Southern Cascade Range	—	69	14	109	—	—	—	—	—	Single	Taylor (1995) ^c
Red fir	Southern Cascade Range	—	20	8	35	—	—	—	—	—	Composite	McNeil and Zobel (1980) ^b
Red fir	Southern Cascade Range	—	11	1	47	—	—	—	—	—	Composite	Taylor (1993) ^c
Red fir–white fir	Southern Cascade Range	—	9.5	3	37	—	—	—	—	1650–1899	Composite	Bekker and Taylor (2001)
Red fir–white fir	Southern Cascade Range	—	24	4	55	—	—	—	—	1650–1899	Single	Bekker and Taylor (2001)
Red fir–mountain hemlock	Southern Cascade Range	—	20	9	91	—	—	—	—	1650–1942	Composite	Bekker and Taylor (2001)
Red fir–white fir	Southern Cascade Range	10	8	—	—	—	—	—	—	1650–1918	Composite	Bekker and Taylor (2010)
Red fir–mountain hemlock	Southern Cascade Range	100	100	—	—	—	—	—	—	1650–1918	Composite	Bekker and Taylor (2010)
Red fir	Southern Cascade Range	41	—	5	65	—	—	—	—	1830–1930	Composite	Taylor and Halpern (1991)
Red fir–white fir	Southern Cascade Range	41	—	—	—	—	—	—	—	1735–1874	Composite	Taylor and Solem (2001)
Red fir–western white pine	Southern Cascade Range	66	—	—	—	—	—	—	—	1768–1874	Composite	Taylor and Solem (2001)
Red fir–white fir	Southern Cascade Range	47	—	14	127	—	—	—	—	—	Composite	Taylor (1993)
Red fir–western white pine	Southern Cascade Range	—	27	9	46	—	—	—	—	—	Composite	Taylor (2000)
Red fir–western white pine	Southern Cascade Range	—	70	26	109	—	—	—	—	—	Single	Taylor (2000)
Red fir–mixed conifer	Northern Sierra	21	20	12	34	—	—	—	—	1616–1893	Composite	Beatty and Taylor (2009)
Red fir–western white pine	Northern Sierra	—	76	25	175	—	—	—	—	1580–1853	Single	Scholl and Taylor (2006)
Red fir–white fir	Central Sierra	—	12	5	69	—	—	—	—	—	Composite	Bahro (1993) ^c
Red fir	Central Sierra	—	30	9	92	—	—	—	—	—	—	van Wagtendonk et al. (2002)
Red fir	Southern Sierra	65	—	—	—	—	—	—	—	1600–1886	Composite	Pitcher (1987)
Red fir	Southern Sierra	30	—	—	50	—	—	—	—	—	—	Caprio and Lineback (2002) ^c
Mixed conifer–red fir	Southern Sierra	17	—	3	115	—	—	—	—	1692–1865	Single	North et al. (2005) ^d
Red fir–lodgepole pine	Eastern (central)	25	24	13	38	—	—	—	—	—	Composite	Stephens (2001)
Red fir	Eastern (south)	—	27	9	91	—	—	—	—	—	Composite	Hawkins (1994) ^e
Red fir–Jeffrey pine	Eastern (south)	—	17	5	56	—	—	—	—	—	Composite	Hawkins (1994) ^e
Red fir–mixed conifer	Eastern (central)	16	—	8	33	—	—	—	—	1645–1875	Composite	Caprio et al. (2006) ^f

^a Summary values for aggregated red fir forest types based on elevation (low, mid, high) and geographic location are provided in table 5. Sample areas in FRI studies were nearly all less than 2 ha in size, with a few exceptions (e.g., 48 ha in North et al. 2002).

^b Refers to whether estimates were derived from a single tree or composite sample.

^c References and estimates were extracted from Skinner and Chang (1996).

^d References and estimates were extracted from Skinner and Chang (1996).

^e Contained a minor component of red fir that contributed to 5 percent of fire-scarred sample trees.

^f Hawkins, R. 1994. Fire intervals in an eastern Sierra mixed conifer forest, preliminary results. Unpublished report. On file with: U.S. Department of the Interior, Forest Service, Inyo National Forest, Bishop, CA.

^g Mean maximum FRI was calculated by using a randomization algorithm drawing from the pooled fire chronology data from a specific collection site to yield a more conservative estimate than the mean.

Table 23—Proportion of fire severity classes in Sierra Nevada red fir forests based on historical and contemporary reference site information

Forest type	Location	Unchanged/ unburned	Low severity	Moderate severity	High severity	Reference
----- Percent -----						
Contemporary reference sites and stand reconstructions:						
Red fir–white fir	Southern Cascade Range	—	43	44	13	Taylor and Solem (2001)
Red fir–western white pine	Southern Cascade Range	—	33	48	19	Taylor and Solem (2001)
Red fir–mixed conifer	Yosemite National Park	28	28	29	15	Collins and Stephens (2010) ^a
Lower–upper montane Red fir	Yosemite National Park	35	—	—	—	Kolden et al. (2012)
Red fir—1 st burn	Yosemite National Park	—	—	—	8	Miller et al. (2012)
Red fir—1 st burn	Yosemite National Park	46	41	12	1	van Wagtendonk et al. (2012)
Red fir—2 nd burn (reburn)	Yosemite National Park	12	45	30	13	van Wagtendonk et al. (2012)
Red fir	Yosemite National Park	20	45	30	5	Thode et al. (2011) ^b
Red fir	Yosemite National Park	16	50	21	13	Kane et al. (2013)
Red fir–mixed conifer	SEKI ^d	43	44	12	<1	Collins et al. (2007) ^c
LANDFIRE biophysical setting model ^e :						
Red fir	Southern Cascade Range	—	58	19	23	Safford and Sherlock (2005)
Red fir	Southern Sierra	—	66	16	18	Safford and Sherlock (2005)
Historical accounts:						
Red fir	Northern Sierra	—	72	20	8	Leiberg (1902) ^f

Summary fire severity proportions for aggregated red fir forest types are provided in table 8.

^a Values for unchanged/unburned and low-severity classes were assumed to be one-half the total pooled value (55.5 percent).

^b Fire severity estimates are approximated.

^c Based on satellite-derived differenced Normalized Burn Ratio (dNBR) estimates rather than relative dNBR (RdNBR) used in other studies presented.

^d Sequoia and Kings Canyon National Parks.

^e Based on LANDFIRE biophysical setting model estimates of historical reference conditions.

^f Historical estimates of moderate- and high-severity classes by Leiberg (1902) may be overestimated owing to the occurrence of early placer mining and sheepherder burning activities that were difficult to distinguish from natural ignition sources. Estimates for moderate severity were roughly based on 50 to 75 percent tree mortality.

Table 24—Average total and relative red fir tree densities, basal area, and mean tree diameter in historical, contemporary reference, and current red fir plots

Subregion of Sierra Nevada ^a	Tree density ^b			Basal area			Mean d.b.h.	Number of plots	Reference
	Total	Red fir	Red fir	Total	Red fir	Red fir			
	<i>Number per hectare</i>		<i>Percent</i>	<i>Square meters per hectare</i>		<i>Percent</i>	<i>Centimeters</i>		
California	318	310	97	—	—	—	—	6	Schumacher 1928 ^c Historical
Northern	1,285	740	58	69	38	55	—	24	Bekker and Taylor 2001 ^d
Northern	868	736	85	81	64	79	—	35	Taylor 2000 ^d
Northern	1,404	1,088	77	106	74	70	—	31	Taylor and Solem 2001 ^d
Northern	294	231	79	85	70	82	—	2	Taylor and Halpern 1991
Northern	419	130	31	33	18	54	—	4	Talley 1977a
Northern	599	467	78	72	58	80	—	9	Talley 1977b
N & C	873	794	91	98	96	98	—	5	Oosting and Billings 1943 ^e
N & C	317	231	73	—	—	—	—	408	Dolanc et al. 2014a historical ^f
Central	433	275	63	202	136	67	77	4	Stephens 2000 historical ^g
Central	228	164	72	55	—	—	—	787	Maxwell et al. 2014 historical
Central	374	241	64	53	47	89	—	14	Barbour et al. 2002
Central	161	94	58	56	40	72	74	6	Taylor 2004 historical ^h
Central	538	184	34	49	24	50	42	6	Taylor 2004 current ^h
Central	743	594	80	85	71	83	—	4	Barbour 1985
Central	579	533	92	47	39	84	—	11	Talley 1976
C & S	—	—	—	92	88	96	25	16	Potter 1998 ⁱ
C & S	—	—	—	51	41	81	25	28	Potter 1998 ⁱ
C & S	—	—	—	45	28	63	25	31	Potter 1998 ⁱ
C & S	264	189	72	84	64	76	58	55	Meyer et al. 2017 burned ^j
C & S	1,010	767	73	99	78	79	31	19	Meyer et al. 2017 unburned ^j
C & S	275	—	—	65	—	—	—	38	Collins et al. 2016 burned ^j
Southern	340	289	85	100	48	48	—	10	Griffin 1975
Southern	370	345	93	69	65	94	37	352	North et al. 2002
Southern	—	—	87	81	70	87	—	10	Vankat 1970, 1982
Southern	—	—	88	93	80	86	—	3	Vankat and Major 1978
Southern	507	431	85	57	51	89	—	3	Pitcher 1981
Southern	—	283	—	92	58	63	—	14	Barbour and Woodward 1985

d.b.h. = diameter at breast height.

Summary stand structure values for aggregated red fir forest types are provided in table 9. All stands are unlogged with the exception of current stands from Taylor (2004). Values are extracted from Barbour and Woodward (1985) and other sources. Studies arranged from north to south.

^a Northern subregion includes areas within the southern Cascade Range. N and C = North and Central; C and S = Central and Southern.

^b Tree density estimates are based on trees ≥ 3 or ≥ 5 cm d.b.h.

^c Estimates are based on the oldest (≥ 160 years) red fir stands with a diameter distribution that most closely approximated presettlement conditions.

^d Estimates are based on red fir–white fir stands (Bekker and Taylor 2001), red fir–mountain hemlock stands (Taylor 2000), or red fir–western white pine (Taylor and Solem 2001).

^e Values based on Oosting and Billings (1943) are not considered “historical” or current.

^f Dolanc et al. (2014a) is based on Wieslander Vegetation Type Mapping data collected between 1929 to 1936 and includes all trees >10.1 cm d.b.h. in the red fir forests.

^g Stephens (2000) used red fir forest stand structure data from four plots surveyed by Sudworth (1899). Average tree diameter includes only trees >30.5 cm d.b.h.

^h Taylor (2004) based stand estimates on presettlement (pre-1870; “historical”) or contemporary (“current”) conditions following 19th-century logging.

ⁱ Potter (1998) included red fir (upper row), red fir/pinemat manzanita (middle row), and red fir–western white pine/pinemat manzanita associations.

^j Meyer et al. (2017) included unlogged red fir stands from Yosemite and Kings Canyon National Parks that are located in active fire regime landscapes (i.e., burned; no departure from historical fire return interval [FRI]) and fire-excluded stands (i.e., unburned; missed two or more historical FRIs).

Collins et al. (2016) included unlogged red fir–white fir stands from Yosemite and Kings Canyon National Parks located in active fire regime landscapes.

Table 25—Historical fire return interval (FRI) estimates for subalpine forests in the Sierra Nevada bioregion

Vegetation type	Subregion	Mean FRI	Median FRI	Minimum FRI	Maximum FRI	Years sampled	Sample type ^a	Reference
		----- Years -----						
Subalpine	California	113	132	100	420	—	—	Van de Water and Safford (2011)
Western white pine	California	50	42	15	370	—	—	Van de Water and Safford (2011)
Lodgepole pine	California	37	36	15	290	—	—	Van de Water and Safford (2011)
Lodgepole pine	Northern	—	37	6	48	1650–1883	Composite	Bekker and Taylor (2001)
Lodgepole pine	Northern	43	48	—	—	—	—	Bekker and Taylor (2010)
Lodgepole pine	Northern	67	—	—	—	1735–1929	Composite	Taylor and Solem (2001)
Subalpine ^b	Central (western)	—	230	40	290	500 BCE–1985 CE	Paleofire	Hallett and Anderson (2010)
Subalpine ^b	Central (eastern)	—	105	30	135	500 BCE–1985 CE	Paleofire	Hallett and Anderson (2010)
Lodgepole pine	Southern	102	—	4	163	—	—	van Wagendonk et al. (2002) ^c
Subalpine	Southern	187	—	—	508	—	—	Caprio and Lineback (2002) ^d
Lodgepole pine	Southern	50	—	31	98	1455–1860	Composite	Caprio (2008)
Bristlecone pine	Eastern (southern)	46	—	—	—	1460–1871	Composite	North et al. (2009) ^e
Bristlecone pine	Eastern (southern)	143	—	—	—	1500–1850	—	Richardson and Howell (2005)
Foxtail pine	Eastern (southern)	28	—	—	—	1578–2008	Composite	North et al. (2009) ^e
Foxtail pine	Southern	250	—	—	—	1578–2008	Composite	Stephenson et al. (2005)
Lodgepole–foxtail pine	Eastern (southern)	39	—	—	—	1490–2008	Composite	North et al. (2009) ^e
Lodgepole pine	Eastern (southern)	19	—	—	—	1676–2006	Composite	North et al. (2009) ^e
Whitebark pine	Central Cascade Range	85	—	—	—	—	—	Murray (2007)
Whitebark–lodgepole pine	Central Cascade Range	73	—	—	—	—	—	Murray (2007)

Summary values for aggregated subalpine forest types are provided in table 18.

^a Refers to whether estimates were derived from a composite sample, or estimated using paleofire reconstruction methods. Sample areas in FRI studies were nearly all less than 2 ha in size, with a few exceptions (e.g., 18 to 44 ha in North et al. 2009).

^b Contemporary subalpine forest site included the following dominant species at the central site: lodgepole pine, mountain hemlock, red fir, and limber pine. Species at the eastern site included lodgepole pine, mountain hemlock, western white pine, and whitebark pine.

^c Values from van Wagendonk et al. (2002) were extracted from Caprio and Lineback (2002) and other sources from sites primarily in the southern Sierra Nevada.

^d FRI estimates based primarily in foxtail pine and whitebark pine stands of Sequoia National Park. Mean maximum FRI was calculated by using a randomization algorithm drawing from the pooled fire chronology data from a specific collection site to yield a more conservative estimate than the mean.

^e The larger survey area for North et al. (2009) likely resulted in a relatively low FRI estimate, especially for foxtail pine and bristlecone pine stands, where mean reference (historical) FRI estimates based on other sources are 250 years for foxtail pine and 143 years for bristlecone pine in the assessment area.

Table 26—Proportion of fire severity classes in Sierra Nevada subalpine forests based on historical and contemporary reference site information

Forest type	Location	Fire severity class				Reference
		Unchanged/ unburned	Low	Moderate	High	
		----- Percent -----				
Contemporary reference sites and stand reconstructions:						
Lodgepole pine	Southern Cascade Range	—	8	17	75	Taylor and Solem (2001) ^a
Lodgepole pine–red fir	Southern Cascade Range	—	10	52	38	Taylor and Solem (2001) ^a
Red fir–western white pine	Southern Cascade Range	—	33	48	19	Taylor and Solem (2001) ^a
Lodgepole pine—1 st burn	Yosemite National Park	28	56	15	<1	van Wagtendonk et al. (2012)
Lodgepole pine – 2 nd burn	Yosemite National Park	7	24	46	23	van Wagtendonk et al. (2012)
Whitebark pine–mountain hemlock	Yosemite National Park	70	27	3	0	Thode et al. (2011) ^b
Lodgepole pine	Yosemite National Park	25	30	37	8	Thode et al. (2011) ^b
Lodgepole pine	Kings Canyon National Park	—	75	23	2	Caprio (2006)
LANDFIRE Biophysical Setting Model: ^c						
Mountain hemlock–lodgepole pine–red fir	Sierra Nevada	—	0	36	64	van Wagtendonk et al. (2005)
Whitebark pine–mountain hemlock–red fir	Southern Sierra Nevada	—	0	50	50	Stephenson et al. (2005)
Bristlecone and limber pine	White–Inyo Mountains	—	29	—	71	Richardson and Howell (2005)
Lodgepole pine (wet)	Sierra Nevada	—	71	7	22	Caprio (2005a)
Lodgepole pine (dry subalpine)	Sierra Nevada	—	45	45	11	Caprio (2005b)

Summary fire severity proportions for aggregated subalpine forest types are provided in table 19.

^aBased on historical reference information.^bFire severity estimates are approximated.^cBased on LANDFIRE Biophysical Setting Model estimates of historical reference conditions.

Table 27—Projected future changes in the distribution of subalpine forests and tree species based on climate envelope (species distribution) and dynamic vegetation (MC1) models

Unit of analysis	Geographic scope	GCM (model type)	Decrease ^a ----- Percent -----	Stable ^a -----	Time period	Reference
Subalpine/alpine ^b	California	PCM (MC1)	55	—	2071–2100	Lenihan et al. (2008)
Subalpine/alpine ^b	California	GFDL (MC1)	77	—	2071–2100	Lenihan et al. (2008)
Subalpine	Southern Sierra Nevada	Ensemble	78 (11) ^c	22 (89) ^c	2071–2100	Gonzalez (2012)
Bristlecone pine	White and Inyo Mountains	Ensemble ^d	75–99	1–25	2071–2100	Van de Ven et al. (2007)
Lodgepole pine	Southern Sierra Nevada	Ensemble	26	60	2040–2065	SSP (2010)
Lodgepole pine ^e	California	Ensemble	58	34	2040–2065	SSP (2010)
Lodgepole pine ^f	Southern Sierra Nevada	PCM (Bioclim, Flint)	96	4	2070–2099	Schwartz et al. (2013)
Lodgepole pine ^f	Southern Sierra Nevada	GFDL (Bioclim, Flint)	100	0	2070–2099	Schwartz et al. (2013)
Subalpine forest ^f	Southern Sierra Nevada	PCM (Bioclim, Flint)	82	18	2070–2099	Schwartz et al. (2013)
Subalpine forest ^f	Southern Sierra Nevada	GFDL (Bioclim, Flint)	100	0	2070–2099	Schwartz et al. (2013)
Foxtail pine ^f	Southern Sierra Nevada	PCM (Bioclim, Flint)	83	17	2070–2099	Schwartz et al. (2013)
Foxtail pine ^f	Southern Sierra Nevada	GFDL (Bioclim, Flint)	100	0	2070–2099	Schwartz et al. (2013)
Whitebark pine ^f	Southern Sierra Nevada	PCM (Bioclim, Flint)	82	18	2070–2099	Schwartz et al. (2013)
Whitebark pine ^f	Southern Sierra Nevada	GFDL (Bioclim, Flint)	100	0	2070–2099	Schwartz et al. (2013)
Whitebark pine	Entire species range	Unknown	97	3	2090	Warwell et al. (2007)
Whitebark pine	Southern Sierra Nevada	CCCM ^g	99.97	0.03	2060–2090	Anderson et al. (2012)

GCM = global climate model; PCM = parallel climate model; GFDL = Geophysical Fluid Dynamics Laboratory; — = no estimate available.

Note: Average values for projected future changes in subalpine forest types are provided in table 21.

^a Percentage decrease or stable indicates the percent change in the area covered by subalpine conifers within the geographic scope and time period of each study.^b Projections are pooled for subalpine forest and alpine biomes.^c Values in parentheses indicate percent change in subalpine forests of the White and Inyo Mountains and Glass Mountain.^d Specific GCMs were not provided, but estimates were based on projected temperature increases (3 to 5 °C) from Hayhoe et al. (2004), Lenihan et al. (2003), and other sources.^e Decrease is the percentage of subalpine conifer distribution that is “stressed.” Projected estimates also include an uncertain category defined as areas lacking model agreement (range: 7–12 percent). Reference refers to the Southern Sierra Partnership (2010).^f Based on U.S. Forest Service Pacific Southwest Region CALVEG subalpine conifers or whitebark pine alliance vegetation types. Percentage decrease estimate includes moderate, high, and extreme climate exposure categories (outside 66th percentile bioclimatic distribution), and percentage stable estimate is equal to the percentage in the low-exposure category (inside the 66th percentile bioclimatic distribution). Projection estimates are based on subalpine forests on national forest lands of the southern Sierra Nevada (Inyo, Sequoia, and Sierra National Forests and southern half of Stanislaus National Forest).^g Canadian Center for Climate Modeling GCM.

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