Natural Range of Variation of Red Fir Forests in the Bioregional Assessment Area

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Introduction

Physical setting and geographic distribution

Geographic Distribution

Red fir (*Abies magnifica*) forests are distributed throughout the Sierra Nevada immediately above the montane mixed-conifer and below the subalpine forest zones (Figures 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 approximately 1800–2400 m in the northern Sierra Nevada to about 2200–2800 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 and north of 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. critchfieldi* and *A. m. magnifica* share the same unique haplotype found in 100% 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).

Climatic Relationships

Red fir forests occupy cool sites with substantial winter snow (Table 1; 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). Freezing level during late winter storms appears to be a primary indicator of regional climatic control over the lower elevation limit of red fir. 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 1; 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, resulting in a 40–80% decrease in spring snowpack over the last 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 30–110% 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. 2008). 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: 10–165 mm), with values that are relatively greater than most other non-riparian 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 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 (*Abies concolor*) at lower elevations and lodgepole pine, Jeffrey pine, and mountain hemlock (*Tsuga mertensiana*) at higher elevations (Potter 1994, 1998). Western white pine (*P. monicola*) is also a common associate of red fir throughout the Sierra Nevada (Rundel et al. 1988). Current vegetation classification systems recognize 11 vegetation associations of red fir forest in the assessment area (Potter 1998, Sawyer et al. 2008), 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 variation 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 sensitive and rare species such as 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). Red fir also provides important denning habitat for the northern flying squirrel (*Glaucomys sabrinus*), a keystone and management indicator 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).

Holocene Forest Development

Mid-Holocene Xerothermic period

Following a relatively cool and wet period in the early Holocene (~10,000 to 16,000 years ago), the mid-Holocene was characterized by continual warming that reached an optimum during the xerothermic period about 8000 to 5000 years ago, with peak temperatures at roughly 6500 years before present (ybp) (Table 2; 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 periods of the xerothermic: 7530 to 6300, 5200 to 5000 and 4700 to 4300 ybp (Mensing et al. 2004).

Sierra Nevada upper montane and subalpine forests (collectively referred to hereafter as high-elevation forests) during the xerothermic were primarily dominated by pines with montane shrubs in the understory and a notable lack of fir (Table 2). 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*), manzanita (*Arctostaphylos*), and possibly huckleberry oak (*Quercus vacciniifolia*). Red fir, mountain hemlock, and possibly whitebark pine were rare and confined to mesic habitats, while limber pine (*P. flexilis*) and western white pine demonstrated localized colonization and possible limited expansion (Anderson 1990). Lodgepole pine 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) during the xerothermic period (Brunelle and Anderson 2003). In Lassen National Park, high-elevation fossil pollen deposits indicated that pine forests dominated during the early- and mid-Holocene (12,500 to 3100 ybp) with minor contributions by Taxodiaceae/Cupressaceae/Taxaceae (primarily incense cedar) and oaks at lower elevations (West 2003). Similarly, fossil pollen deposits in the southern Sierra Nevada indicate that pine forests dominated between 7000 and 3000 ybp (Davis et al. 1985).

In the neighboring Great Basin (including the Warner Mountains), climate was also warmest and possibly driest during the 7500 to 5000 ybp xerothermic period. Vegetation in this region was characterized by open forests at high elevations with increases in western white pine, whitebark pine, and white fir starting approximately 7000 to 6500 ybp (Minckley et al. 2007, Tausch et al.

2004). In the White Mountains, subalpine conifers such as 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 period (Brunelle and Anderson 2003, Hallett and Anderson 2010, Minckley et al. 2007). In the southern Sierra Nevada, decreased charcoal deposits and fire frequency was coincident with increased abundance of red fir and lodgepole pine during the last 1200 years (Davis et al. 1985).

Late Holocene period

At the close of the xerothermic period, precipitation gradually increased, and cooler conditions dominated about 3000 to 2500 years ago (Table 2). 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 approximately 4500 ybp (Anderson 1990, Brunelle and Anderson 2003). In Lassen National Park, an abrupt increase in red fir and white fir and decline in pine abundance occurred approximately 3100 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 3000 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 2; 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 Nino events occurred throughout the Medieval warm period and Little Ice Age (~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 (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, approximately 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).

Cultural and Socioeconomic Setting

Cultural and Socioeconomic Significance of Red Fir Forests

Red fir in the Sierra Nevada has both cultural and socioeconomic importance. Red fir may be harvested for the wood products and provide a diverse array of recreational resources (Laacke 1990). Historically, Native Americans 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 Native Americans (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). Native Americans often targeted high elevation meadows bordering forests as sources of food and other materials during the 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, such as red fir, 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).

Historical Setting

European-American Settlement and National Forest Administration (1849-1945)

With the discovery of gold in 1848 in the Sierra Nevada, European-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 forests were largely spared these impacts due to their relative remoteness and distance from gold-bearing deposits in the Sierra Nevada (Leiberg 1902). However, there were many exceptions to this generalization, as areas of the northern and central Sierra Nevada were heavily logged during the late 19th century (Leiberg 1902). Outside of this region, however, mining, railroad logging, and related impacts rarely occurred in red fir forests throughout the late 19th and early 20th centuries. In their comprehensive evaluation of the ecological condition of red fir forests throughout the Sierra Nevada, Oosting and Billings (1943) noted "these old virgin [red fir] forests of massive trees are to be found in many parts of the Sierra Nevada. The present relative abundance of undisturbed stands of the species is due in large part to the comparative inaccessibility of the type to lumbering."

In contrast to mining, railroad logging, and water diversion activities, red fir forests were heavily impacted by widespread sheep grazing and repeated burning by sheepherders in the Sierra Nevada during the late 19th and early 20th centuries. In the early 1860s, a severe drought in California, initiated the practice of summer sheep grazing in high elevation meadows and forests of the Sierra Nevada (Vankat 1970, Ratliff 1985). 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 the 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 the greatest grazing abuse by sheep of 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 historic 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 Native American practices (Sudworth 1900, Vankat 1970). Such practices combined with intensive sheep grazing had a negative impact on red fir regeneration in areas of the central Sierra Nevada (Leiberg 1902). However, by 1900–1920 sheep grazing and sheepherder 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 the 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-aged silvicultural techniques (e.g., clearcutting; Potter 1998). By the 1990s, sivlicultural practices emphasized shelterwood cutting along with other approaches such as uneven-aged silvicultural systems, sanitation thinning, and salvage and improvement cuttings (Laacke and Tappiener 1996).

Methods

Variables, Scales, and Information Availability

There were several variables that lacked sufficient historical information for their inclusion in this assessment (Table 3). However, for many of these variables contemporary references sites provide surrogate information that is complementary to the historic range of variation. Additionally, contemporary reference sites provide invaluable information not available from historic 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. Appropriate contemporary reference sites for red fir forests 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 regime), and the existence of either short- or long-term research information (e.g., Experimental Forests, Research Natural Areas, Natural Reserves; Table 4). Much of the published science information on reference conditions in red fir forests have been extracted from contemporary reference sites that match these criteria. In a few instances, reference information was obtained from a nearby region (e.g., Central Cascades), particularly when this information was unavailable for the assessment area.

In addition to contemporary reference sites, historic written accounts provide additional information regarding the historic range of variation in red fir forests of the Sierra Nevada. These historic accounts were based on idiosyncratic time periods, primarily by early explorers, naturalists, geologists, foresters, botanists, and other individuals that recorded their observations in field notes, manuscripts, official reports, books, and other published sources. Although many of these historic accounts often contain an inherent bias and other limitations, they nevertheless offer a unique perspective on the historic conditions of red fir forests not captured in other historical information sources.

Historic Reference Period

The historic reference period of Sierra Nevada red fir forests includes much of the Holocene and ends either shortly after the advent of the gold rush era in California or during the mid-20th century. As noted in the Historical Setting section, the reference period ends in 1860 for most of the northern and central Sierra Nevada and parts of the southern Sierra Nevada that were subjected to early European-American logging and mining activities in the late 19th and early 20th centuries (Beesley 1996, McKelvey and Johnston 1992). Additionally, beginning in the early 1860s, the widespread and intensive impacts of sheep grazing and sheepherder burning practices were pervasive in the high elevation forests of the Sierra Nevada. Fire suppression activities begin in the mid-1920s, influencing fire regimes in many Sierra Nevada ecosystems, including red fir 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 red fir forests likely requires a historic reference period that predates the 1860–1920 period. However, for other variables not strongly influenced by widespread historic grazing, historic reference conditions for many unlogged red fir forests 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 historic reference period ending in 1960 was used in this assessment. The historic reference period for each variable is summarized in Table 12.

NRV Descriptions and Comparisons to Current Conditions

Function

Fire

Fire Return Interval, Fire Rotation, and Fire Return Interval Departure

Historic 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 (Table 5). 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 type; 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. Estimates of FRI in the northern Sierra Nevada and southern Cascades (Mean FRI = 50.8 years; range: 9–71 years) were generally greater than FRI estimates for the southern/central Sierra Nevada (Mean FRI = 41.7 years; range: 5–60 years; Table 5), possibly owing to the drier conditions and more xeric red fir types at lower latitudes (Potter 1998). As an exception, the historic mean FRI in red fir forests at Crater Lake National Park in the central Cascades was 39 years (range: 15–71 years; Chappell and Agee 1996). 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 median FRI estimates were similar across all slope aspects in red fir-mountain hemlock forests of Lassen National Park.

Fire rotation estimates for red fir forests were variable across the Sierra Nevada (Table 6). In the southern Cascades (pre-1905 period), fire rotation varied 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, contemporary fire rotation estimates based on lightning fires that were allowed to burn under prescribed conditions in red fir forests was 163 years (van Wagtendonk 1985 in van Wagtendonk and Fites-Kaufman 2006). 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 estimates that 27% of these forests (27,501 ha total) have burned during the 25 year period; however, remote-sensing based mapping of red fir forests had relatively low accuracy (~30%) in their study. Mallek et al. (in review) estimated a fire rotation of 61 years (range: 25–76 years) for red fir forests in the assessment area.

Few fires have burned during the fire suppression time 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 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, as indicated by an increase in Fire Return Interval Departure (FRID) values in these forests (Caprio and Graber 2000, North et al. 2012). However, most Sierra Nevada red fir forests have missed only one to three fire cycles (i.e., mostly low to moderate FRID), 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 (Long et al. 2013, Miller and Safford 2012, 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 the coming decades. Westerling et al. (2011) projected a more than 100% 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% by 2020–2049 due 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 (Figure 3; Mortiz et al. 2013). These projected increases were consistent across climate models that project hotter and drier (GFDL) and warmer and wetter (PCM) 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 historic estimates of fire size in Sierra Nevada red fir forests. Mean fire size in the southern Cascades (1729–1918 period) was 151 ha (range: 34–347 ha) in red fir-white fir forest and 140 ha (range: 124–155) in red fir-mountain hemlock forest (Bekker and Taylor 2001). In Lassen National Park, mean fire size was 176 ha (median = 129 ha; range: 11–733 ha) in red fir-mountain hemlock forest (Taylor 2000). In the Lake Tahoe Basin, presettlement spatial patterns of fires scarred trees in red fir–western white pine forests suggested that historic 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, size 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% 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% of unsuppressed fires were smaller than 0.1 ha and 87% were smaller than 4 ha (Potter 1998). In Yosemite National Park, 56% of fires in red fir and lodgepole pine forests between 1972 and 1993 were less than 0.1 ha and 82% were smaller than 4 ha (Figure 4; van Wagtendonk 1993). In contrast to average fire size, the highest proportion of area burned (>70%) in red fir forests of Yosemite National Park tends to be from fires between 4 and 400 ha in size (van Wagtendonk 1993); an additional 28% of burned area is attributed to fires between ~400 and 2000 ha in size (Figure 5).

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 in red fir forests of the Sierra Nevada (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.

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

Fire Type

Sierra Nevada red fir forests typically experience slow-moving surface fires due to the presence of heavy and compact surface fuels, natural terrain breaks, and relatively cooler and moister conditions (van Wagtendonk and Fites-Kaufman 2006). However, occasional crown fires occur in these forests, particularly under extreme dry and windy conditions. 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.

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 the upper montane mixed conifer and red fir forests of Yosemite National Park's Illilouette Creek Basin, fire regimes are both climate- and fuel-limited; 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 et al. 2009, Collins and Stephens 2010). 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%), prescribed (1%), and human induced (3%) ignition sources (van Wagtendonk et al. 2002). In Late Holocene, fire activity in the 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 historic 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 historic range of variation.

Fire Seasonality

Most fires in red fir forests occur during the late summer or fall (van Wagtendonk and Fites-Kaufman 2006). In red fir-white fir forests of the southern Cascades, the position of fires on presettlement annual growth rings indicated that 77% of historic fires burned during the late summer and fall, and the remaining 23% 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, 99–100% of historic fires burned during the late summer to fall (Bekker and Taylor 2001, Taylor 2000). In the Lake Tahoe Basin, 92% of historic fires in red fir–western white pine forests burned during the late summer to fall, and 7% burned in the early to mid-summer (Taylor 2004). In upper montane 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). These collective studies demonstrate that fire season has not changed between historic 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 and Fites-Kaufman 2006), although there is ambiguity associated with this terminology (Collins and Stephens 2010). Overall, fire severity estimates based on historic data or contemporary reference sites were dominated by three fire severity classes: unburned or unchanged, low-severity, and moderate-severity (Table 7). 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% based on historic 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% (range: <1–15%). Re-burned red fir stands in Yosemite National Park tended to burn at higher severity compared to stands not recently burned (van Wagtendonk et al. 2012; Table 7). Unmanaged wildfires 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 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%) than young red fir stands (50 to 80 years old; 24% burned at high severity). Miller et al. (2009) found that fire severity in red fir forests of the Sierra Nevada was negatively correlated with spring precipitation. In the northern Sierra Nevada, Leiberg (1902) estimated that 8% of red fir forests (primarily below 3120 m elevation) had historically burned at stand-replacing severity (>95% tree mortality), and at least 28% of red fir forests in the 19th century had burned at moderate to high severity (>50% tree mortality). However, Leiberg's estimates may have overestimated these fire severity proportions due 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 percent 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%) than the national forests of the Sierra Nevada (average: 12, 16, and 32% in the west-side Sierra Nevada, east-side Sierra Nevada, and southern Cascade subregions, respectively; Miller et al. 2012).

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% between the current (1984–2005) and mid-21st century (2020–2049) periods, due 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, using remote-sensed estimates of high-severity based on a 95% tree mortality threshold value (Figure 6). In the Illilouette Creek Basin of Yosemite National Park, the mean patch size of stand-replacing, high-severity burned patches (>95% 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%) of the stand-replacing patches in their study were ≤4 ha in size, but a few large patches accounted for ~50% of the total stand-replacing patch area (Figure 7). 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 using 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; Figure 8). In addition, the majority (>60%) of canopy gaps were greater than 10 ha in size within high severity burned red fir stands.

Historic 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% of the total area of stand-replacing fires was attributed to burns exceeding approximately 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 pre-settlement conditions.

Miller et al. (2012) found that lower and upper montane forests (including red fir forest) had a mean patch size of 4.2 ha (median = 0.45 ha; range: 0.09–999 ha) in Yosemite National Park, but a mean 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). 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 within fire perimeters in their study was 35%, and the average unburned proportion per fire was 52% (range: 8–97%).

It is likely that current averages for high-severity and unburned patch size are within the historic range of variation, but historic 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 impact 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 annosum*), Cytospora canker (*Cytospora abietis*), and dwarf mistletoe (*Arceuthobium abietinum* f. sp. *magnificae*; Scharpf 1993, Ferrell 1996). These mortality agents often interact together to compromise the health of red fir trees, especially during periods of stress associated with extended drought or following disturbance (Ferrell 1996). Most of these insects and pathogens are covered in the Yellow Pine and Mixed Conifer Forest NRV Chapter.

Based on sedimentary pollen records, dwarf mistletoe has been a persistent component of Sierra Nevada red fir forests for the past 3000 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, approximately 45% 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% (range: 17–100) 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 dwarf mistletoe occurs in 48% 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 historic (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 the Sierra Nevada, red fir mortality rates have increased based on a comparison of recent Forest Inventory and Analysis plots between 2005 and 2010 (Mortenson 2011). 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 and possibly Cytospora canker, although the role of other mortality factors (e.g., fir engraver, Heterobasidion root disease) was not clear (Mortenson 2011). 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, Mortenson 2011, van Mantgem and Stephenson 2007).

Wind and Volcanism

Wind and volcanism can have substantial impacts on red fir forests, although their effects are often limited in spatial extent. 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 of 1874 (Muir 1894). In the northern Sierra Nevada, sustained wind speeds of 44 to 48 kilometers 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 of 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 2012). During the event, winds gusted at an estimated 100 to 110 kph and may have exceeded 145 kph on the Mammoth Mountain summit. Large trees were disproportionately uprooted (86%) and snapped (14%) during the Devil's Windstorm event, creating variable-sized canopy gaps in red fir forests with heavy post-disturbance fuel loading (Figure 9; Hilimire et al.

2012). 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% of tree damage and 77% 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% of tree mortality in their study and indirect effects (e.g., tree struck by another wind-damaged tree) accounted for the remaining 29% mortality. Wind had a disproportionate impact on larger trees in the dominant and co-dominant crown classes (Gordon 1973).

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, Inyo Craters, was formed by the repeated expulsion of rhyolitic lava over the past 6000 years. Volcanic events occurred at North Deadman Creek dome (~6000 years ago), Wilson Butte (1350 years ago), and at several other domes along the Inyo Craters chain (1369, 1433, and 1469 A.D.; Hill 2006). These volcanic events directly (e.g., lava flows) and indirectly (e.g., volcanic-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 the volcanic eruptions, subsurface magna can cause localized tree mortality through the production of excessive carbon dioxide gas in soils. In the 1990s, approximately 50 ha of tree mortality occurred in subalpine forest stands with a red fir component near Horseshoe Lake below Mammoth Mountain (Hill 2006).

Historic rates of wind and volcanism are difficult to compare to current rates due to the highly infrequent or unpredictable nature of these climatic and geologic processes. However, current rates of wind and volcanism in Sierra Nevada red fir forests are broadly considered within the historic range of variation.

Climatic Water Deficit

Water balance relationships 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 (Deficit) are two water balance variables that can be used to model vegetation presence (Stephenson 1998). In Yosemite National Park, AET and Deficit 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). Lutz et al. (2010) also found that values of AET/PET (a measure of the relative sensitivity of species ranges to increases in climatic water deficit) for red fir stands in Yosemite were clustered near the arid end for its entire geographic range, indicating moderately high sensitivity of red fir stands in Yosemite to changes in Deficit. 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 climatic water deficit (Deficit) averages for red fir forests in Yosemite National Park was 10% lower during the Little Ice Age (~1700 A.D.; Deficit = 114 mm) than the present (1971–2000; Deficit = 126 mm; Lutz et al. 2010). This suggests that Deficit may be approaching or exceeding the upper threshold for the historic range of variation for red fir in the central portion of the assessment area. Modeled climatic water deficit (Deficit) averages for red fir forests in Yosemite National Park was projected to be 24% greater in the near future (2020–2049; Deficit = 157 mm) compared to the present (1971–2000; Deficit = 126 mm; Lutz et al. 2010), indicating an increasing trend of moisture stress in red fir forests.

Structure

Canopy Structural Classes and Landscape Patchiness

Several recent studies (e.g., Kane et al. 2012, 2013, in review) have used airborne Light Detection and Ranging (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 gap (Figure 10). 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 post-fire 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 (Figure11; Kane et al. 2013).

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 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. 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 (Figure 12). In addition, low-severity 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 structural classes than contemporary reference landscapes burned within the past 26 years.

Canopy Cover and Height

Canopy cover estimates based on a product of LiDAR-based values from Kane et al. (2013) and fire severity sources presented in Table 7 show a high degree of overlap between contemporary reference sites and current stands across the entire assessment area (Figure 13). Cover in the upper (>16 m) and lower (2–16 m) canopy strata of red fir forests in Yosemite National Park was negatively related with fire severity (Figure 14; Kane et al. 2013). The upper canopy stratum (i.e., overstory canopy cover) was substantially reduced following moderate or high severity fire, suggesting high mortality rates in larger red fir trees. 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 (Figure 15). 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. in press). 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 burned at lower severity have greater canopy cover across strata and greater canopy base and dominant tree heights than those burned predominantly at high to moderate severity.

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) used rumple as an estimate of canopy surface rugosity, which measures canopy structural complexity and forest heterogeneity. Their results indicated that low-severity fire (including the undifferentiated fire severity class) led to the maximum canopy structural complexity in red fir forest landscapes (Figure 16).

Kane et al. (in review) 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, as indicated by an increasing proportion of the landscape containing higher canopy clump counts (Figure 17). Red fir forest landscapes burned at high-severity had a high proportion of the landscape (94%) containing many (>20) canopy clumps, suggesting an elevated level of forest fragmentation. In contrast, aggregation (measure of overall landscape clumpiness or the tendency of cells of similar class type to be aggregated) of canopy clump strata showed little change with fire, suggesting that landscape clumpiness (or the spatial evenness of forest structural conditions) was not influenced by burning regardless of fire severity class (Kane et al. in review).

Collectively, these results suggest: (1) presettlement red fir forests were structurally more complex than current secondary-growth forests (Taylor 2004), (2) unburned (>80 years) and low-severity burned contemporary red fir landscapes have roughly similar degrees of structural heterogeneity and fragmentation (Kane et al. 2013), and (3) increasing fire severity in these landscapes results in reduced structural complexity and greater homogenization and fragmentation (Kane et al. 2013). Consequently, patterns of increased total area burned at high severity in red fir forests (refer to Fire Severity section below) implicates a potential trend toward increasing structural homogenization and fragmentation in severely-burned red fir forest landscapes over the past few decades.

Tree Densities, Size, and Size Class Distribution
Average tree densities (all species pooled) were similar between historic and current red fir forests based on a broad comparison of all unlogged stands across the entire assessment area (Table 8, Figure 18). Overall tree density increased by a marginal ~8% between historic (early 1930s) and current (2001–2010) red fir stand inventories of the northern and central Sierra Nevada (Dolanc et al. in review). In the Lake Tahoe Basin, however, presettlement (pre-1870) tree densities in historic red fir–western white pine forests (average = 161; range: 118–208) were substantially lower than modern forests that were intensively logged in the late 19th century (average = 538; range: 214–842; Taylor 2004, Taylor et al. in press). 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 8). Bouldin (1999) found modest increases in tree densities in red fir forests of the central and northern Sierra Nevada.

The density of larger-diameter red fir trees in Sierra Nevada red fir forests was often greater in historic than contemporary periods. Dolanc et al. (in review) compared extensive historic (early 1930s) and modern (USFS Forest Inventory and Analysis; FIA) forest inventories in the northern and central Sierra Nevada and found that the density of large (>60 cm dbh) red fir trees had declined by 40% (68 to 41 trees/ha) and the density of smaller (10–30 cm dbh) red fir trees had increased by approximately 60% over a 70-year time period. Large red fir trees also experienced the greatest decline of all 17 tree species analyzed in their study. In similar study, Dolanc et al. (2012) estimated that the density of smaller diameter red fir trees had increased 91% and the density of larger (61–91 cm dbh) red fir trees marginally decreased by ~20% over a 73-year period in unlogged upper elevation (2300–3400 m) forests of the central Sierra Nevada. The average density of moderately large diameter (61–91 cm dbh) red fir trees declined between historic (1932–1936) and contemporary (1988–1999) sampling periods in upper montane forests of Yosemite National Park, although declines in the largest trees >92 cm dbh was not significant possibly due to limited sample size (Lutz et al. 2009a). Patterns of increased mortality rates in large diameter trees were also apparent in late-seral forests in the southern Sierra Nevada (Smith et al. 2005, van Mantgem and Stephenson 2007) and throughout the western United States (van Mantgem et al. 2009). In most cases, these changes in the density of red fir trees were attributed to recent increases in temperature and climatic water deficit (Dolanc et al. 2012, in press; van Mantgem et al. 2009).

Size class distribution in red fir forests have shifted to smaller size classes between historic 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 dbh, but current secondary-growth stands were dominated by significantly smaller size classes of lodgepole pine (Figure 19; Taylor 2004, Taylor et al. in press). Presettlement size class distribution also varied among 66% of sampled plots, demonstrating high variation in size class structure among stands. These size class distribution patterns indicate that historic 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 historic 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 3–30 cm dbh; 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) found similar size class distribution patterns in presettlement and contemporary mixed conifer–red fir forests of the southern Sierra Nevada.

Overall, there has been a marginal and inconsistent increase in total tree densities in Sierra Nevada red fir forests over the past century, but current tree densities remain within the historic range of variation. In comparison, there has been a relatively consistent and significant decline in the density of large-diameter red fir trees and an increase in the density of small-diameter red fir trees over this period. Also, the size class distribution of red fir forests has generally shifted towards smaller size classes, resulting in lower structural diversity. Collectively, these patterns indicate a loss of large trees and accumulation of small trees in red fir forests of the assessment area 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 subalpine tree species (Dolanc et al. 2012, in review), and (2) 19th century logging impacts in secondary growth stands (e.g., Taylor 2004).

Basal Area

Basal area varied widely across both historic and current late-seral red fir forests of the Sierra Nevada (Table 8). Basal area averaged 43% greater in historic reference than modern red fir forests, but most modern forests were within the historic range of variation (Table 8, Figure 18). Basal area was similar between historic and contemporary red fir–western white pine forests of the Lake Tahoe Basin (Taylor 2004, Taylor et al. in press), but average basal area was substantially greater based on historic inventories in the central Sierra Nevada than in any contemporary red fir stands (Stephens 2000).

Tree Spatial Patterns

Tree spatial patterns in historic and contemporary late-seral red fir forests are characterized by a high degree of structural heterogeneity, especially in the larger size classes. In presettlement red fir forests 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 dbh) were also clumped at the smallest spatial scales (3–9 m) and randomly distributed at larger scales. Small and intermediate sized trees (<40 cm dbh) 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 (3–12 m) and intermediate (36–75 m) distances (Scholl and Taylor 2006).

Similar to fire-frequent 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 historic 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."*

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 historic observations, coupled with the spatial structure information from Taylor (2004) suggest that historic 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 historic and contemporary stand information, large tree spatial patterns are within the historic range of variation. However, small and intermediate sized 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 historic (~1940) and contemporary red fir forests of the Sierra Nevada (Figure 20). 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% of total tree regeneration in red fir forests was attributed to red fir across studies (see Figure 20 for references). 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 than unburned forests (van Mantgem et al. 2006). Chappell and Agee (1996) found the density of red fir seedlings was greatest in low- and moderate-severity burned patches (Figure 2 – middle photo) and lowest in high-severity burned and unburned patches. These combined studies indicate that red fir regeneration is within the historic range of variation, although post-fire patterns suggest that decades of fire exclusion may have reduced regeneration densities over time.

Snags

Based on historic 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: 0–60), the basal area of snags was 4.5 m^2/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 (SD) per ha (Table 9) 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 m^2/ha (approximate range: 0–32 m^2/ha; North et al. 2002). These collective results suggest that snags may have been less abundant in historic than current unlogged red fir forest stands that have experienced decades of fire exclusion, although considerable variation exists in current stands (Table 9). Average snag diameter was similar between historic and current red fir forests.

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: 327–1720 Mg/ha; values adjusted for above ground biomass only; Rundel et al. 1988). In comparison, above-ground 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 (Figure 21; 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 historic range of variation, although there was a general trend towards lower levels of biomass in contemporary managed and unlogged forests than historic stands, possibly due to the lower density of large-diameter trees (see Tree densities, size, and size class distribution section).

Physiognomic Patterns – Seral Class Proportions
LANDFIRE Biophysical Setting (BpS) modeling indicated that historic reference conditions in red fir forests of the assessment area were dominated by mid- and late-seral classes (Figure 22). 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% cover) than forests of the southern Cascades (Safford and Sherlock 2005a, b). LANDFIRE BpS modeling of the Stanislaus National Forest based on analyses at the subwatershed scale (7th field HUCs; ~800 to 2800 ha) indicated that current red fir–white fir and red fir–western white pine forests contained a greater proportion of mid-seral classes (34 and 48% increase, respectively) and a lower proportion of late-seral (30 and 41% decrease) and early-seral classes (marginal 4 and 7% decrease) than historic conditions (Figure 23; Safford and Schmidt 2006). Assuming that the Stanislaus National Forest is generally representative of the larger assessment area, these results suggest that there may be a current deficit of late-seral classes, surplus of mid-seral classes, and minor deficit of early-seral classes in red fir forests of the Sierra Nevada. However, analyses from additional national forests in the Sierra Nevada will be required to more thoroughly evaluate seral class trends within the assessment area.

Composition

Overstory Species Composition
Red fir maintains a high relative density and basal area in both historic and current late-seral red fir forests of the Sierra Nevada (Table 8, Figure 24). This 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 was similar between historic and current stands in the assessment area, supporting conclusions by Dolanc et al. (2012, in press) that species composition in Sierra Nevada red fir forests has not changed over the past several decades. 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 historic 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 (Figure 19; Taylor 2004, Taylor et al. in press). However, these changes in tree species composition in mixed red fir forests are likely within the historic range of variation for the assessment area, since successional processes favor dynamic shifts in tree species dominance over many decades (Oosting and Billings 1943, Rundel et al. 1988).

Understory Species Composition
Historic red fir forests in the northern and central Sierra Nevada had a relatively high frequency of 6 shrub and 11 herbaceous plant species (Table X; 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 *Chrysolepis sempervirens* (bush chinquapin) and lower frequency of *Gayophytum ramosissimum* (pinyon groundsmoke) in current versus historic surveys. However, *G. ramosissimum* 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 *C. sempervirens* occurred relatively frequently in red fir forests of the northern and central Sierra Nevada, suggested that perhaps Oosting and Billings (1943) were unable to detect this species due to their limited number of survey plots. Collectively, these results indicate that understory species composition in red fir forests is generally similar between historic and current stands.

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 (NCAR) Parallel Climate Model (PCM) projects warmer and similar (no significant change in) precipitation conditions in California, while the National Oceanic and Atmospheric Administration (NOAA) 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 varies from 160 to 800 km per side for GCMs to 800 m to 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 vary 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 10). These ecological response models provide many insights in 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 due 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 on Table 11. 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 and B2 emissions scenarios (local environmental sustainability). 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). Models projected a 66–99.9% range reduction in red fir across a range of geographic scales (subregional to entire species geographic range). 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 its geographic distribution.

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% (PCM) or 85% (GFDL) of red fir forests in the southern Sierra Nevada national forests (Sequoia, Sierra, and Inyo national forests and southern half of the Stanislaus National Forest; Figure 25). The total area of low climate exposure for red fir forest will be 20% (PCM) and 7% (GFDL) by the end of the century (Table 11). By the end of the century, geographic areas of red fir low climate exposure under the PCM model are generally concentrated within the higher elevation, eastern portions of the Sierra and Stanislaus national forests and Yosemite National Park, the Mammoth Lakes area of the Inyo National Forest, and most portions of the Sequoia and Kings Canyon National Parks (Figure 26). 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 the Stanislaus National Forest (Figure 27; Schwartz et al. 2013).

Most red fir forests in the assessment area will be outside its historic and contemporary 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 its 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 in subalpine conifers 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, and interacting stressors (Clark et al. 2011, Kuparinen et al. 2010, Rowland et al. 2011, Zhu et al. 2012).

Summary

- Comparisons between historic and current conditions indicate that modern red fir stands of the assessment area are largely within the natural range of variation with respect to their composition, structure, and function (Table 12).

- Exceptions include a considerable shift in the tree size class distribution to smaller diameters, greater homogenization of forest structure at both stand and landscape scales, and a decrease in the density of large-diameter red fir trees. These changes have likely occurred primarily as a result of 19th century logging within secondary-growth stands and recent climatic warming within the entire assessment area.

- Fire regimes in red fir forests have also changed significantly, as fire return intervals and fire rotations have generally lengthened during much of the 20th century due to fire suppression activities, and total burned area has increased since 1984. In addition, future fire frequency, annual burned area, and fire severity are projected to increase in red fir forests with climate change.

- The incidence of pathogens and insects, such as dwarf mistletoe and Cytospora canker, likely have not changed considerably from historic (1600–1960) to contemporary (1961–2005) periods. However, recent (2006-2012) increases in tree mortality in red fir forests associated with pathogens, insects, and moisture stress suggest increased potential for these mortality agents to exceed the historic range of variation in the coming decades.
- Climate envelope models consistently project a substantial loss (average: 82%) or high climate vulnerability of red fir forests in the assessment area by the end of the 21st century. This suggests that the greatest changes in Sierra Nevada red fir forests during the 21st century will occur as a consequence of climate change.

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Literature Cited

Agee, J.K. 1993. Fire Ecology of Pacific Northwest Forests. Island Press, Washington, D.C.

Anderson, R. 1990. Holocene forest development and paleoclimates within the central Sierra Nevada, California. Journal of Ecology. 78: 470-489.

Anderson, R. 1996. Postglacial biogeography of Sierra lodgepole pine (*Pinus contorta* var *murrayana*) in California. Ecoscience. 3: 343-351.

Anderson, R.S.; Davis, O.K. 1988. Contemporary pollen rain across the central Sierra Nevada, California, USA: relationships to modern vegetation types. Arctic and Alpine Research. 20: 448–60.

Anderson, M.K.; Moratto, M.J. 1996. Native American land-use practices and ecological impacts. In: Erman, D.C., ed. Sierra Nevada Ecosystem Project: Final Report to Congress, Volume II. University of California, Davis, Wildland Resources Center Report. 187-206. Chapter 9.

Bale, R., I. Robertson, M. Salzer, N. Loader, S. Leavitt, M. Gagen, T. Harlan, and D. McCarroll. 2011. An annually resolved bristlecone pine carbon isotope chronology for the last millennium. Quaternary Research 76:22-29.

Barbour, M.; Berg, N.; Kittel, T.; Kunz, M. 1991. Snowpack and the distribution of a major vegetation ecotone in the Sierra Nevada of California. Journal of Biogeography. 18: 141-149.

Barbour, M.; Kelley, E.; Maloney, P.; Rizzo, D.; Royce, E.; Fites-Kaufmann, J. 2002. Present and past old-growth forests of the Lake Tahoe Basin, Sierra Nevada, US. Journal of Vegetation Science. 31: 461-472.

Barbour, M.; Woodward, R. 1985. The Shasta red fir forest of California. Canadian Journal of Forest Research. 15: 570-576.

Beaty, R.; Taylor, A. 2001. Spatial and temporal variation of fire regimes in a mixed conifer forest landscape, Southern Cascades, California, USA. Journal of Biogeography. 28: 955-966.

Beaty, R.; Taylor, A. 2009. 14,000 year sedimentary charcoal record of fire from the northern Sierra Nevada, Lake Tahoe. Holocene. 19: 347-358.

Beesley, D. 1996. Reconstructing the Landscape: An Environmental History, 1820–1960. In: Erman, D.C., ed. Sierra Nevada Ecosystem Project: Final Report to Congress, Volume II. University of California, Davis, Wildland Resources Center Report. 3-24. Chapter 1.

Bekker, M.; Taylor, A. 2001. Gradient analysis of fire regimes in montane forests of the southern Cascade Range, Thousand Lakes Wilderness, California, USA. Plant Ecology. 155: 15-28.

Bekker, M.; Taylor, A. 2010. Fire disturbance, forest structure, and stand dynamics in montane forests of the southern Cascades, Thousand Lakes Wilderness, California, USA. Ecoscience. 17: 59-72.

Benson, LV.; Kashgarian, M.; Rye, R.O.; Lund, S.P.; Paillet, F.L.; Smoot, J.; Kester, C.; Mensing, S.; Meko, D.; Lindstrom, S. 2002. Holocene multidecadal and multicentennial droughts affecting northern California and Nevada. Quaternary Science Reviews 21: 659–682.

Bouldin, J. 1999. Twentieth-century changes in forests of the Sierra Nevada, California. Ph.D. dissertation, University of California, Davis. 222 p.

Brown, J.K.; Smith, J.K., eds. 2000. Wildland fire in ecosystems: effects of fire on flora. General Technical Report RMRS-GTR-42-vol. 2. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 257 p.

Brunelle, A.; Anderson, R.S. 2003. Sedimentary charcoal as an indicator of late Holocene drought in the Sierra Nevada, California, and its relevance to the future. The Holocene. 13: 21–28.

California Forest Pest Council. 1960. Forest pest conditions in California 1960. Prepared by Forest Health Protection, USDA Forest Service, Pacific Southwest Region, in cooperation with the California Department of Forestry and Fire Protection, and other member organizations. < http://www.fs.fed.us/r5/spf/publications/pestconditions/index. shtml >. Accessed 7 March 2013.

California Forest Pest Council. 2011. California forest pest conditions 2011. Prepared by Forest Health Protection, USDA Forest Service, Pacific Southwest Region, in cooperation with the California Department of Forestry and Fire Protection, and other member organizations. < http://www.fs.fed.us/r5/spf/publications/pestconditions/index.shtml >. Accessed 7 March 2013.

Caprio, A.C.; Keifer, M.; Webster, K. 2006. Long-term effects of the 1992 rainbow fire, Devils Postpile National Monument, California. National Park Service Internal Report. Three Rivers, CA. 6 p.

Caprio, A.C., and D.M. Graber. 2000. Returning fire to the mountains: can we successfully restore the ecological role of pre-Euro-American fire regimes to the Sierra Nevada? In: Cole, D.N.; McCool, S.F..; Borrie, W.T..; O'Loughlin, J., comps. Proceedings: Wilderness science in a time of change - Vol. 5 wilderness ecosystems, threats, and management; 1999 May 23-27; Missoula, MT. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. Proceedings RMRS-P-15-VOL-5. 233-241.

Caprio, A.C.; Lineback, P. 2002. Pre-Twentieth Century fire history of Sequoia and Kings Canyon National Park: a review and evaluation of our knowledge. In: Fire in California Ecosystems: Integrating Ecology, Prevention, and Management, November 17-20, 1997. San Diego, California.

Cayan, D.; Luers, A.L.; Hanemann, M.; Franco, G.; Cores, B. 2006. Scenarios of climate change in California: an overview. California Climate Change Center Report CEC-500-2005-186-SF. Sacramento, CA.

Chappell, C.; Agee, J. 1996. Fire severity and tree seedling establishment in *Abies magnifica* forests, southern Cascades, Oregon. Ecological Applications. 6: 628-640.

Clark, J.S., D.M. Bell, M.H. Hersh, and L. Nichols. 2011. Climate change vulnerability of forest biodiversity: climate and competition tracking of demographic rates. Global Change Biology 17:1834-1849.

Collins, B.; Kelly, M.; van Wagtendonk, J.; Stephens, S. 2007. Spatial patterns of large natural fires in Sierra Nevada wilderness areas. Landscape Ecology. 22: 545-557.

Collins, B.M.; Miller, J.D.; Thode, A.E.; Kelly, M.; van Wagtendonk, J.W.; Stephens, S.L. 2009. Interactions among wildland fires in a long-established Sierra Nevada natural fire area. Ecosystems. 12: 114–128.

Collins, B.; Stephens, S. 2010. Stand-replacing patches within a 'mixed severity' fire regime: quantitative characterization using recent fires in a long-established natural fire area. Landscape Ecology. 25: 927-939.

Das, A.J.; Stephenson, N.L. 2013. Climate change. Appendix 22 of the Sequoia and Kings Canyon National Parks Natural Resource Report NPS/SEKI/NRR—2013/XXX. 23 p.

Davis, O.; Anderson, R.; Fall, P.; Orourke, M.; Thompson, R. 1985. Palynological evidence for early Holocene aridity in the Southern Sierra Nevada, California. Quaternary Research. 24: 322-332.

Dolanc, C.R.; Thorne, J.H.; Safford, H.D. 2012. Widespread shifts in the demographic structure of Sierra Nevada subalpine forests over the last 80 years. Global Ecology and Biogeography. 13 p.

Dolanc, C.R.; Safford, H.D.; Dobrowski, S.Z.; Thorne, J.H. In review. Seven decades of forest change in the Sierra Nevada, California, USA. Manuscript in review in Forest Ecology and Management.

Dull, R.A. 1999. Palynological evidence for 19th century grazing induced vegetation change in the southern Sierra Nevada, California, U.S.A. Journal of Biogeography. 26: 899-912.

Fire and Resource Assessment Program. 2010. California's forests and rangelands: 2010 assessment. California Department of Forestry and Fire Protection, Fire and Resource Assessment Program. June 2010. Chapter 3.7. 251-272.

Fites-Kaufmann, J., P. Rundel, N. Stephenson, and D.A. Weixelman. 2007. Montane and subalpine vegetation of the Sierra Nevada and Cascade Ranges. In: M.G. Barbour, T. Keeler-Wolf and A.A. Schoenherr, eds. Terrestrial vegetation of California. University of California Press, Berkeley. 456-501. Chapter 17.

Gonzalez, P.; Asner, G.P.; Battles, J.J.; Lefsky, M.A.; Waring, K.M.; Palace, M. 2010. Forest carbon densities and uncertainties from Lidar, QuickBird, and field measurements in California. Remote Sensing of Environment. 114: 1561-1575.

Gordon, D.T. 1973. Damage from wind and other causes in mixed white fir-red fir stands adjacent to clearcuttings. General Technical Report PSW-GTR-90. Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 23 p.

Griffin, J.B.; Critchfield, W.B. 1972. The distribution of forest trees in California. General Technical Report PSW-GTR-82. Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 120 p.

Hallett, D.; Anderson, R. 2010. Paleofire reconstruction for high-elevation forests in the Sierra Nevada, California, with implications for wildfire synchrony and climate variability in the late Holocene. Quaternary Research. 73: 180-190.

Hampe, A.; Petit, R.J. 2005. Conserving biodiversity under climate change: the rear edge matters. Ecology Letters. 8: 461-467.

Hilimire, K.; Nesmith, J.; Caprio, A. Milne, R.; Mutch, L. 2012. Winds of change: characterizing windthrown trees in a Sierra Nevada mixed conifer forest. CIRMOUNT Mountain Views. 6(2): 44-46.

Hill, M. 2006. Geology of the Sierra Nevada. University of California Press, Berkeley, CA.

Hunsaker, C.T.; Whitaker, T.W.; Bales, R.C. 2012. Snowmelt runoff and water yield along elevation and temperature gradients in California's southern Sierra Nevada. Journal of the American Water Resources Association 48:667-678.

Izzo, A.D.; Meyer, M.; Trappe, J.; North, M.; Bruns, T. 2005. Hypogeous ectomycorrhizal fungal species on roots and in small mammal diet in a mixed-conifer forest. Forest Science. 51: 243–254.

Kane, V.R.; Lutz, J.A. 2012. Combining Landsat and LiDAR remote sensing data to refine fire management objectives for forest structural heterogeneity in Yosemite National Park. Pacific Northwest Cooperative Ecosystem Studies Unit Task Agreement J8W07100018. Final Report to Yosemite National Park, National Park Service, February 8, 2012. 50 p.

Kane, V.R.; Lutz, J.A.; Roberts, S.L.; Smith, D.F.; McGaughey, R.J.; Povak, N.A.; Brooks, M.L. 2013. Landscape-scale effects of fire severity on mixed-conifer and red fir forest structure in Yosemite National Park. Forest Ecology and Management. 287: 17-31.

Kane, V.R.; North, M.; Lutz, J.A.; Churchill, D.; Roberts, S.L.; Smith, D.F.; McGaughey, R.J.; Kane, J.T..; Brooks, M.L. In review. Assessing fire-mediated change to forest spatial structure using a fusion of Landsat and airborne LiDAR data in Yosemite National Park. Article in review in Remote Sensing of Environment.

Kilgore, B.M. 1971. The role of fire in red fir forests. In: Transactions of the Thirty-Sixth, North. American Wildlife and Natural Resources Conference, March 7-10, 1971. Wildlife Management Institute, Washington, D.C.

Kolden, C.A., J.A. Lutz, C.H. Key, J.T. Kane, and J.W. van Wagtendonk. 2012. Mapped versus actual burned area within wildfire perimeters: Characterizing the unburned. Forest Ecology and Management 286:38-47.

Kuparinen, A., O. Savolainen, and F.M. Schurr. 2011. Increased mortality can promote evolutionary adaptation of forest trees to climate change. Forest Ecology and Management 259:1003-1008.

Laacke, R.J. 1990. *Abies magnifica* A. Murr. California red fir. In: Burns, R.M.; Honkala, B.H., technical coordinators. Silvics of North America. Volume 1. Conifers. Agriculture Handbook 654. Washington, DC: U.S. Department of Agriculture, Forest Service: 71-79.

Laacke, R.J.; Tappeiner, J.C. 1996. Red fir ecology and management. In: Erman, D.C., ed. Sierra Nevada Ecosystem Project: Final Report to Congress, Volume III. University of California, Davis, Wildland Resources Center Report. 1-10. Chapter 10

Lanner, R.M. 2010. *Abies magnifica* var. *Critchfieldii*, a new California red fir variety from the Sierra Nevada. Madroño 57:141-144.

Leiberg, J. B. 1902. Forest conditions in the northern Sierra Nevada, California. Professional Paper 8, Series H, Forestry, 5. Washington, D.C.: U.S. Geological Survey, Government Printing Office.

Lenihan, J.M.; Drapek, R.; Bachelet D.; Neilson, R.P. 2003. Climate change effects on vegetation distribution, carbon, and fire in California. Ecological Applications. 13: 1667-1681.

Lenihan, J.M.; Bachelet, D.; Neilson, R.P.; Drapek, R. 2008. Response of vegetation distribution, ecosystem productivity, and fire to climate change scenarios for California. Climate Change. 87 (Suppl. 1): S215-S230.

Lewis, H.T. 1993. Patterns of Indian burning in California: Ecology and ethnohistory. In: Blackburn, T.C.; Anderson, M.K., eds. Before the wilderness: Native Californians as environmental managers. Ballena Press, Menlo Park, CA. 55–116.

Lloyd, A. 1997. Growth of foxtail pine seedlings at treeline in the southeastern Sierra Nevada, California, USA. Ecoscience 5:250-257.

Lloyd, A.H.; Graumlich, L.J. 1997. Holocene dynamics of treeline forests in the Sierra Nevada. Ecology 78:1199-1210.

Long, J; Skinner, C.; North, M. (and 18 other authors). 2013. Science synthesis to support land and resource management plan revision in the Sierra Nevada and Southern Cascades. USDA Forest Service Pacific Southwest Research Station Report to the USDA Forest Service Pacific Southwest Region. January 2013. Davis, CA. 504 p.

Lutz, J.A.; van Wagtendonk, J.W.; Franklin, J.F. 2009a. Twentieth-century decline of large-diameter trees in Yosemite National Park, California, USA. Forest Ecology and Management. 257: 2296–2307.

Lutz, J.; van Wagtendonk, J.; Franklin, J. 2010. Climatic water deficit, tree species ranges, and climate change in Yosemite National Park. Journal of Biogeography. 37: 936-950.

Lutz, J.A.; van Wagtendonk, J.W.; Thode, A.E.; Miller, J.D.; Franklin, J.F. 2009b. Climate, lightning ignitions, and fire severity in Yosemite National Park, California, USA. International Journal of Wildland Fire. 18: 765–774.

Mallek, C. et al. In review.

Maloney, P.E.; Rizzo, D.M. 2002. Pathogens and insects in a pristine forest ecosystem: the Sierra San Pedro Martir, Baja, Mexico. Canadian Journal of Forest Research 32: 448-457.

Mayer, K.E.; Laudenslayer, W.F. 1988. A guide to wildlife habitats of California. State of California, Department of Forestry and Fire Protection, Sacramento, CA.

McGaughey, R.J. 2010. FUSION/LDV: Software for LIDAR Data Analysis and Visualization. USDA Forest Service, Pacific Northwest Research Station, Seattle, WA. 150 p.

McKelvey, K.S.; Johnston, J.D. 1992. Historical perspectives on forests of the Sierra Nevada and the Transverse Ranges of Southern California: forest conditions at the turn of the century. General Technical Report PSW-GTR-133. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station: 225-246. Chapter 11.

McKenney, D.W., J.H. Pedlar, K. Lawrence, K. Campbell, and M.F. Hutchinson. 2007. Potential impacts of climate change on the distribution of North American trees. BioScience, Vol. 57:939-948.

Menke, J.W.; Davis, C.; Beesley, P. 1996. Rangeland assessment. In: Erman, D.C., ed. Sierra Nevada Ecosystem Project: Final Report to Congress, Volume III. University of California, Davis, Wildland Resources Center Report. 1-56. Chapter 22.

Mensing, S.A.; Benson, L.V.; Kashgarian, M.; Lund, S. 2004. A Holocene pollen record of persistent droughts from Pyramid Lake, Nevada, USA. Quaternary Research 62:29-38.

Meyer, M.D.; Kelt, D.A.; North, M.P. 2005. Nest trees of northern flying squirrels in the Sierra Nevada. Journal of Mammalogy. 86: 275–280.

Millar, C.I.; Woolfenden, W.B. 1999. The role of climate change in interpreting historical variability. Ecological Applications. 9: 1207-1216.

Millar, C.I.; King, J.C.; Westfall, R.D.; Alden, H.A.; Delany, D.L. 2006. Late Holocene forest dynamics, volcanism, and climate change at Whitewing Mountain and San Joaquin Ridge, Mono County, Sierra Nevada, CA, USA. Quaternary Research. 66: 273–287.

Miller, J.D.; Safford, H. 2008. Sierra Nevada fire severity monitoring 1984-2004. R5-ECOL-TP-003. Vallejo, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Region. 102 p.

Miller, J.D.; Safford, H. 2012. Trends in wildfire severity: 1984 to 2010 in the Sierra Nevada, Modoc Plateau, and southern Cascades, California, USA. Fire Ecology. 8(3): 41-57.

Miller, J.D.; Collins, B.M.; Lutz, J.A.; Stephens, S.L.; van Wagtendonk, J.W.; Yasuda, D.A. 2012. Differences in wildfires among ecoregions and land management agencies in the Sierra Nevada region, California, USA. Ecosphere. 3: art80.

Miller, J.; Safford, H.; Crimmins, M.; Thode, A. 2009. Quantitative evidence for increasing forest fire severity in the Sierra Nevada and Southern Cascade Mountains, California and Nevada, USA. Ecosystems. 12: 16-32.

Moritz, M.; Batllori, E.; Krawchuk, M.; Schwartz; M.D.; Nydick, K. 2013. Southern Sierra ecoregional fire management exercise based on modeling plausible future scenarios: future fire occurrence section. Report in preparation for Sequoia and Kings Canyon National Parks and Sequoia National Forest. California Cooperative Ecosystem Studies Unit, National Park Service, Task Agreement No. J8C07100024.

Moser, S.; Franco, G.; Pittiglio, S.; Chou, W.; Cayan, D. 2009. The future is now: an update on climate change science impacts and response options for California. California Climate Change Center Report CEC-500-2008-071. Sacramento, CA: California Energy Commission. 91 p.

Muir, J. 1894. The Mountains of California. The Century Company, New York. 398 p.

Muir, J. 1911. My First Summer in the Sierra. Houghton Mifflin Company, Boston, MA. 272 p.

Nelson, D.L.; Tiernan, C.F. 1983. Winter injury of sagebrush and other wildland shrubs in the Western United States. Gen. Tech. Rep. INT-GTR-314. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 18 p.

North, M.; Collins, B.; Stephens, S. 2012. Using fire to increase the scale, benefits, and future maintenance of fuels treatments. Journal of Forestry. 110: 392-401.

North, M.; Hurteau, M.; Fiegener, R.; Barbour, M. 2005. Influence of fire and El Niño on tree recruitment varies by species in Sierran mixed conifer. Forest Science. 51: 187-197.

North M; Innes, J.; Zald, H. 2007. Comparison of thinning and prescribed fire restoration treatments to Sierran mixed-conifer historic conditions. Canadian Journal of Forest Research. 37: 331–42.

North, M.; Oakley, B.; Chen, J.; Erickson, H.; Gray, A.; Izzo, A.; Johnson, D.; Ma, S.; Marra, J.; Meyer, M.; Purcell, K.; Rambo, T.; Rizzo, D.; Roath, B.; Schowalter, T. 2002. Vegetation and ecological characteristics of mixed-conifer and red-fir forests at the Teakettle Experimental Forest. Gen. Tech. Rep. PSW-GTR-186. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 52 p.

Oline, D. K. 2008. Geographic variation in chloroplast haplotypes in the California red fir-noble fir species complex and the status of Shasta red fir. Canadian Journal of Forest Research. 38: 2705–2710.

Oosting, H.J.; Billings, W.D. 1943. The red fir forest of the Sierra Nevada: Abietum magnificae. Ecological Monographs. 13: 259-274.

Pitcher, D. 1987. Fire history and age structure in red fir forests of Sequoia National Park, California. Canadian Journal of Forest Research. 17: 582-587.

Potito, A.P.; Porinchu, D.F.; MacDonald, G.M.; Moser, K.A. 2006. A late Quaternary chironomid-inferred temperature record from the Sierra Nevada, California, with connections to northeast Pacific sea surface temperatures. Quaternary Research. 66: 356-363.

Potter, D.A. 1994. Guide to the forested communities of the upper montane in the central and southern Sierra Nevada. R5-ECOL-TP-003. San Francisco, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Region. 164 p.

Potter, D.A. 1998. Forested communities of the upper montane in the central and southern Sierra Nevada. Gen. Tech. Rep. PSW-GTR-169. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 319 p.

Potter, D.A. 2005. Riparian plant community classification: west slope, central and southern Sierra Nevada, California. Gen. Tech. Rep. R5-TP-022. Albany, CA: U.S. Department of Agriculture, Forest Service. Pacific Southwest Region. 630 p.

Rambo, T. 2010. Structure and composition of corticolous epiphyte communities in a Sierra Nevada old-growth mixed-conifer forest. The Bryologist. 113: 55-71.

Rambo, T. 2012. Association of the arboreal forage lichen *Bryoria fremontii* with *Abies magnifica* in the Sierra Nevada, California. Canadian Journal of Forest Research. 42: 1587-1596.

Ratliff, R.D. 1985. Meadows of the Sierra Nevada of California: state of knowledge. General Technical Report PSW-84. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture. 52 p.

Rowland, E.L., J.E. Davidson, and L.J. Graumlich. 2011. Approaches to evaluating climate change impacts on species: a guide to initiating the adaptation planning process. Environmental Management 47:322-337.

Rundel, P.W., Parsons, D.J.; Gordon, D.T. 1988. Montane and subalpine vegetation of the Sierra Nevada and Cascade Ranges. In: Barbour, M.G., Major, J. eds. Terrestrial vegetation of California. California Native Plant Society Special Publication no. 9, Sacramento, CA. 559–599.

Safford, H.J.; Schmidt. D. 2006. Fire Regime Condition Class – Stanislaus National Forest. USDA Forest Service Pacific Southwest Region and The Nature Conservancy. Vallejo, CA. 17 p.

Safford, H.; J. Sherlock. 2005a. LANDFIRE biophysical setting model 0610321 Mediterranean California red fir forest—Cascades. <http://www.landfire.gov>. Accessed 28 February 2013.

Safford, H.; J. Sherlock. 2005b. LANDFIRE biophysical setting model 0610322 Mediterranean California red fir forest—southern Sierra. <http://www.landfire.gov>. Accessed 28 February 2013.

Safford, H.D.; North, M.; Meyer, M.D. 2012a. Climate change and the relevance of historical forest conditions. In: North, M., ed. Managing Sierra Nevada forests. General Technical Report PSW-GTR-237. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 23-46. Chapter 3.

Safford, H.D.; Hayward, G.D.; Heller, N.E.; Wiens, J.A. 2012b. Historical ecology, climate change, and resource management: can the past still inform the future? In: Wiens, J.A.; Hayward, G.D.; Safford, H.D.; Giffen, C.M., eds. Historical environmental variation in conservation and natural resource management. Wiley-Blackwell, Oxford, U.K. 46-62.

Sawyer, J.O.; Keeler-Wolf, T.; Evens, J.M. 2008. A manual of California vegetation, second edition. California Native Plant Society, Sacramento, CA. 1300 p.

Scharpf, R.F. 1993. Diseases of Pacific Coast conifers. U.S. Department of Agriculture Forest Service, Agricultural Handbook 521. Albany, CA. 199 p.

Scholl, A.; Taylor, A. 2006. Regeneration patterns in old-growth red fir-western white pine forests in the northern Sierra Nevada, Lake Tahoe, USA. Forest Ecology and Management. 235: 143-154.

Schwartz, M.D.; Nydick, K.R.; Thorne, J.H.; Holguin, A.J. 2013. Southern Sierra ecoregional fire management exercise based on modeling plausible future scenarios: vegetation climate vulnerability section. Report in preparation for Sequoia and Kings Canyon National Parks and Sequoia National Forest. California Cooperative Ecosystem Studies Unit, National Park Service, Task Agreement No. J8C07100024.

Skinner, C.N.; Chang, C. 1996. Fire regimes, past and present. In: Erman, D.C., ed. Sierra Nevada Ecosystem Project: Final Report to Congress, Volume II. University of California, Davis, Wildland Resources Center Report. 1041-1070. Chapter 38.

Shafer S.L., P.J. Bartlein, and R.S. Thompson. 2001. Potential changes in the distributions of western North America tree and shrub taxa under future climate scenarios. Ecosystems 4: 200–215.

Southern Sierra Partnership. 2010. Framework for cooperative conservation and climate adaptation for the southern Sierra Nevada and Tehachapi Mountains, California, USA. Report prepared by The Nature Conservancy, Audubon Society, Sequoia Riverlands Trust, and Sierra Business Council. October, 2010. 275 p.

Stephens, S.L. 2000. Mixed conifer and red fir forest structure and uses in 1899 from the central and northern Sierra Nevada, California. Madroño. 47: 43-52.

Stephens, S. 2001. Fire history differences in adjacent Jeffrey pine and upper montane forests in the eastern Sierra Nevada. International Journal of Wildland Fire. 10: 161-167.

Stephenson, N.L. 1998. Actual evapotranspiration and deficit: biologically meaningful correlates of vegetation distribution across spatial scales. Journal of Biogeography. 25: 855–870.

Stine, S. 1994. Extreme and persistent drought in California and Patagonia during mediaeval time. Nature. 369: 546–549.

Swatantran, A.; Dubayah, R.; Roberts, D.; Hofton, M.; Blair, J.B. 2011. Mapping biomass and stress in the Sierra Nevada using lidar and hyperspectral data fusion. Remote Sensing of Environment. 115:2917-2930.

Swetnam, T.W.; Baisan, C.H.; Caprio, A.C.; Brown, P.M.; Touchan, R.; Anderson, R.S.; Hallett. D.J. 2009. Multi-millennial fire history of the Giant Forest, Sequoia National Park, California, USA. Fire Ecology. 5(3): 120-150.

Swetnam, T.W.; Baisan, C.H.; Morino, K.; Caprio, A.C. 1998. Fire history along elevational transects in the Sierra Nevada, California. University of Arizona Laboratory of Tree Ring Research and Fire History Final Report to Sierra Nevada Global Change Research Program, U.S. Geological Survey, Biological Resources Division, Sequoia, Kings Canyon, and Yosemite National Parks. Tuscon, AZ. 40 p.

Taylor, A. 1993. Fire history and structure of red fir (*Abies magnifica*) forests, Swain Mountain Experimental Forest, Cascade Range, northeastern California. Canadian Journal of Forest Research. 23: 1672-1678.

Taylor, A. 2000. Fire regimes and forest changes in mid and upper montane forests of the Southern Cascades, Lassen Volcanic National Park, California, USA. Journal of Biogeography. 27: 87-104.

Taylor, A. 2004. Identifying forest reference conditions on early cut-over lands, Lake Tahoe Basin, USA. Ecological Applications. 14: 1903-1920.

Taylor, A.; Halpern, C. 1991. The structure and dynamics of *Abies magnifica* forests in the Southern Cascade Range, USA. Journal of Vegetation Science. 2: 189-200.

Taylor, A., Solem, M., 2001. Fire regimes and stand dynamics in an upper montane forest landscape in the southern Cascades, Caribou Wilderness, California. Journal of the Torrey Botanical Society 128, 350-361.

Taylor, A.H.; Vandervlug, A.M.; Maxwell, R.S.; Beaty, R.M.; Catherine, A.; Skinner, C.N. In press. Changes in forest structure, fuels, and potential fire behavior since 1873 1 in the Lake Tahoe Basin, USA. In press in Applied Vegetation Science.

Thode, A.; van Wagtendonk, J.; Miller, J.; Quinn, J. 2011. Quantifying the fire regime distributions for severity in Yosemite National Park, California, USA. International Journal of Wildland Fire. 20: 223-239.

Thornthwaite, C.W.; Mather, J.R. 1955. The water balance. Publications in Climatology, 8: 1–104.

United States Department of Agriculture, Forest Service. 2012. Forest Service recreation and natural resource briefing paper. Bishop, CA. October 12, 2012. 20 p.

van de Water, K.M.; Safford, H.D. 2011. A summary of fire frequency estimates for California vegetation before Euro-American settlement. Fire Ecology. 7(3): 26-58.

Vankat, J. 1970. Vegetation change in the Sequoia National Park, California. Ph.D. dissertation, University of California, Davis. 197 p.

Vankat, J.; Major, J. 1978. Vegetation changes in Sequoia National Park, California. Journal of Biogeography. 5: 377-402.

van Mantgem, P.J.; Stephenson, N.L. 2007. Apparent climatically induced increase of tree mortality rates in a temperate forest. Ecology Letters. 10: 909-916.

van Mantgem, P.J.; Stephenson, N.L.; Byrne, J.C.; Daniels, L.D.; Franklin, J.F.; Fule, P.Z.; Harmon, M.E.; Larson, A.J.; Smith, J.M.; Taylor, A.H.; Veblen, T.T. 2009. Widespread increase of tree mortality rates in the western United States. Science. 323: 521–524.

van Wagtendonk, J.W. 1993. Spatial patterns of lightning strikes and fires in Yosemite Park. In: Proceedings of the 12th conference on fire and forest meteorology. 1993 October 26-28; Jekyll Island, GA.

van Wagtendonk, J. W.; J. Fites-Kaufman. 2006. Sierra Nevada bioregion. In: Sugihara, N. G.; van Wagtendonk, J.W.; Fites-Kaufman, J.; Shaffer, K.E.; Thode, A.E., eds. Fire in California's ecosystems. University of California Press, Berkeley, CA. 264-294. Chapter 12.

van Wagtendonk, J.W., and J.A. Lutz. 2007. Fire regime attributes of wildland fires in Yosemite National Park, USA. Fire Ecology 3(2): 34-52.

van Wagtendonk, J.W.; van Wagtendonk, K.A.; Thode, A.E. 2012. Factors associated with the severity of intersecting fires in Yosemite National Park, California, USA. Fire Ecology. 8(1): 11-31.

van Wagtendonk, J.W.; van Wagtendonk, K.A.; Meyer, J.B.; Paintner, K.J. 2002. The use of geographic information for fire management planning in Yosemite National Park. The George Wright Forum 19: 19-39.

Wehausen, J D. 1986. Bighorn sheep in the White Mountains: past and recent history. In: Hall, C.A.; Young, D.J, (eds). Natural history of the White-Inyo Range, eastern California and western Nevada and high altitude physiology. University of California White Mountain Research Station Symposium 1, Bishop, CA. p. 180-182

Wells, P. 1983. Paleobiogeography of montane islands in the great-basin since the last glaciopluvial. Ecological Monographs. 53: 341-382.

West, G.J. 2003. A Late Pleistocene-Holocene pollen record of vegetation change from Little Willow Lake, Lassen Volcanic National Park, California. PACLIM Conference Proceedings (2003). 65-80 p.

Westerling, A.L.; Bryant, B.P.; Preisler, H.K.; Holmes, T.P.; Hidalgo, H.G.; Das, T.; Shrestha, S.R. 2011. Climate change and growth scenarios for California wildfire. Climatic Change. 109:445-463.

Westman, W. 1987. Aboveground biomass, surface-area, and production relations of red fir (*Abies magnifica*) and white fir (*A. concolor*). Canadian Journal of Forest Research. 17: 311-319.

Wieslander, A.E., H.S. Yates, A.E. Jensen, and P.L. Johannsen. 1933. Manual of field instructions for vegetation type map of California. USDA Forest Service Pacific Southwest Region and University of California Berkeley Marian Koshland Bioscience and Natural Resources Library, Berkeley, CA.

Woolfenden, W.B. 1996. Quaternary vegetation history. In: Erman, D.C., ed. Sierra Nevada Ecosystem Project: Final Report to Congress, Volume II. University of California, Davis, Wildland Resources Center Report. 47-70. Chapter 4.

Zhu, K., C.W. Woodall, and J.S. Clark. 2012. Failure to migrate: lack of tree range expansion in response to climate change. Global Change Biology 18:1042-1052.

Figure Captions

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

Figure 2 – Photo of red fir forest in Illilouette Creek Basin, Yosemite National Park. This photo was taken in a low-severity burned stand approximately ten years following the Hoover Fire (2001).

Figure 3 –Projected increase in fire probability for red fir forests in the southern Sierra Nevada under the GFDL (warmer-drier) and PCM (warmer-wetter) climate models by the end of century (2070–2099). Frequency distributions represent future projected (red, green) and current (gray) climate conditions. Y-axis represents the number of model simulations. Graphics courtesy of Moritz et al. (2013).

Figure 4 – Percent of fires by size class in red fir and lodgepole pine forests of Yosemite National Park between 1972 and 1993. Figure redrawn from van Wagtendonk (1993) and Potter (1998).

Figure 5 – Percent of total area burned by fire size class in red fir and lodgepole pine forests of Yosemite National Park between 1972 and 1993. Figure redrawn from van Wagtendonk (1993) and Potter (1998).

Figure 6 – Photo of a high severity burned patch in a red fir and Jeffrey pine forest, approximately 20 years following the Rainbow Fire (1992) located within Devils Postpile National Monument. High-severity burned patches were defined as areas exceeding 95% tree mortality with high to complete mortality of vegetation.

Figure 7 – 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 their analysis. Figure redrawn from Collins and Stephens (2010).

Figure 8 – Kane et al. (2013) gap size distribution in different fire severity classes in red fir forests of Yosemite National Park. Figure redrawn 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 fire severity class.

Figure 9 – Photo of a 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 approximately eight months following this extreme weather event.

Figure 10 – 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).

Figure11 – Percent 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.

Figure 12 – 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.

Figure 13 – Mean (± SD) percent canopy cover in contemporary reference and current red fir stands of the assessment area. Historic mean canopy cover is estimated as a product of LiDAR-derived canopy cover values from Yosemite National Park (YNP) for each fire severity class (based on data presented in Figure 13) and fire severity class estimates based on reference sites and models presented in Table 7. Current red fir forests are represented by Forest Inventory and Analysis data (FIA 2013; includes logged and unlogged stands) and current late-seral (unlogged) stands based on 13 studies presented in Table 8. Error bar for contemporary reference stands are based on canopy cover estimates for red fir forests of YNP exclusively and does not represent the full range of variation in canopy cover for the entire assessment area.

Figure 14 – Mean percent cover in canopy strata >16 m (overstory canopy) and 2–16 m (sub-canopy) in height.

Figure 15 – 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 95^{th} and 25^{th} percentile LiDAR return heights, respectively.

Figure 16 – Mean rumple values for burned and unburned red fir forest landscapes of Yosemite National Park from Kane et al. (2013). Rumple 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 17 – 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% of the total canopy cover.

Figure 18 – Mean (± SD) tree densities (top graph) and basal area (bottom graph) in historic and current unlogged red fir forests of the Sierra Nevada. Data sources are presented on Table 8.

Figure 19 – 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. Y-axis scale was fixed at a maximum of 100 trees per ha to emphasize differences in tree densities between periods. Figure redrawn from Taylor (2004).

Figure 20 – Mean estimates of red fir regeneration in historic (~1940) and current (1990–2012) red fir forests of the Sierra Nevada. Blue bars represent the historic range of variation based on Oosting and Billings (1943), and 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. FIA (2013) includes 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 includes both logged and unlogged red fir forests.

Figure 21 – Mean (± 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 historic estimates for the assessment area. Respective data sources include Gonzalez et al. (2010), Swatantran et al. (2011), Westman (1987), and Schumacher (1928) in Rundel et al. (1988).

Figure 22 – Percent of red fir forest landscape in different seral classes based on LANDFIRE biophysical setting models for the southern Cascades and southern Sierra Nevada. Bottom figure displays the open and closed canopy subclasses within mid- and late-seral classes. Data source is Safford and Sherlock (2005a, b).

Figure 23– Percent of reference (i.e., historic) and current red fir forest landscapes in different seral classes based on LANDFIRE Biophysical Setting (BpS) models for the Stanislaus National Forest. Bottom figure displays the open and closed canopy subclasses within mid- and late-seral classes. Data source is Safford and Schmidt (2006).

Figure 24 – Relative density and basal area of red fir in historic and contemporary unlogged red fir forests of the Sierra Nevada. Data sources are presented on Table 8.

Figure 25 – 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 the PCM (top graph) and GFDL (lower graph) 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 66^{th} percentile (low exposure), (2) in the marginal 67–90^{th} percentile (moderate exposure), (3) in the highly marginal 90–99^{th} percentile (high exposure), or (4) outside the 99^{th} percentile (extreme exposure) of the current regional bioclimatic envelope for the species.

Figure 26 – Future projections (end of century: 2070–2099) of climate exposure for red fir forest in the southern Sierra Nevada based on the **PCM** 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 66^{th} percentile (Dark Green), (2) in the marginal 67–90^{th} percentile (Light Green), (3) in the highly marginal 90–99^{th} percentile (Yellow), or (4) outside the extreme 99^{th} 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 27 – Future projections (end of century: 2070–2099) of climate exposure for red fir forest in the southern Sierra Nevada based on the **GFDL** model (hotter and drier) used by Schwartz et al. (2013). Levels of climate exposure are described in Figure 25.

Tables

Table 1. Climate characteristics of red fir forests in the assessment area.

Climate Variable	Average (Subregion)[1]
Annual Precipitation (mm)	1000–1300
Precipitation (April 1to September 30) (mm)	100–300
Precipitation as Snow (%)	75–95%
Maximum Snow Depth (cm)	250–400
Snow Water Equivalent (mm)	76–342 (Northern) 170–200 (Southern)
Annual Streamflow Discharge (mm)	708–810
Months of Maximum Snow Depth	Early February to late April
Mean Winter Temperature (° C)	0 (West slope) -5 (East slope)
Mean Summer Temperature (° C)	16 (West slope) 13 (East slope)
Number of Days Mean Temperature Below 0° C	240–260
July° Maxima (° C)	20 (Northern) 26 (Southern)

[1] Data sources include Oosting and Billings (1943), Potter (1998), Rundel et al. (1988), Fites-Kaufman et al. (2007), Hunsaker et al. (2012), Agee (1993), and Barbour et al. (1991).

Table 2. General overview of climate, vegetation, and environmental conditions during the Holocene in the higher elevations of the Sierra Nevada. See text for data sources.

Time Period	Years Before Present	Climate conditions	Vegetation and Environmental Changes
Early Holocene	16,000 to 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)[1]	8000 to 5000 (or 4000)	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	4000 to 1100	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[1]	1100 to 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 to 100	Cooler and moister	Downslope movement of upper elevation limit of red fir
Current (20th century)	100 to 0	Relatively cool and moist conditions with recent increases in temperatures during past three decades	Era of modern fire suppression and land management practices in montane forests

[1] Periods that may serve as possible analogues for climate in the near future.

Table 3. Variables lacking adequate historic records to quantify historic range of variation.

Variable	**Issue**	**Surrogate information source**
Historic vegetation spatial structure (two and three dimensional), including structural complexity	Information rarely or not collected in historic (early 20th century) forest inventories and surveys; primarily available using recent technology (e.g., LiDAR)	Contemporary reference sites; limited historic information on tree spatial aggregation; limited historic 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 historic forest inventories and surveys; no information prior to widespread sheep grazing in the early 1860s except in few stratigraphic pollen records	No available sources
Non-native species (e.g., noxious weeds, introduced insects and pathogens)	Most species introductions to subalpine forests have been recent and are not within the scope of this NRV assessment	Not applicable
Air quality	Historic information lacking	No available sources
Tree regeneration	Historic information lacking	No available sources
Nutrient cycling rates and productivity	Historic information lacking	No available sources
Forest Connectivity	Historic information lacking except for biogeographic isolation from other regions	Contemporary reference sites
Grazing	Historic information limited or lacking	Limited historic 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	Historic information limited or lacking	Contemporary reference sites Estimates primarily based on LANDFIRE Biophysical Setting modeling
Metapopulation dynamics	Historic and contemporary information lacking	No available sources

Table 4. Current and historic reference sites of unlogged Sierra Nevada red fir forests from north to south. Contemporary reference sites are noted in bold.

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	Central Sierra Nevada	Collins et al. (2007, 2009) Collins and Stephens (2010)
Yosemite National Park	Central Sierra Nevada	Kane et al. (2013) Lutz et al. (2009, 2010) Miller et al. (2012) Thode et al. (2011) van Wagtendonk 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**	Southern Sierra Nevada	Caprio and Lineback (2002) Collins et al. (2007)
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)

Table 5. Historic Fire Return Interval (FRI) estimates for red fir forests in the Sierra Nevada. Summary values for aggregated red fir forest types based on elevation (low, mid, high) and geographic location are provided at the bottom. 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).

Vegetation Type	Subregion	Mean FRI	Median FRI	Min. FRI	Max. FRI	Years Sampled	Sample Type[1]	Reference
Red fir	State of California	40	33	15	130	—	—	Van de Water & Safford (2011)
Red fir-western white pine	Southern Cascades	—	69	14	109	—	single	Taylor (1995)[2]
Red fir	Southern Cascades	—	20	8	35	—	comp.	McNeil & Zobel (1980)[2]
Red fir	Southern Cascades	—	11	1	47	—	comp.	Taylor (1993)[2]
Red fir-white fir	Southern Cascades	—	9.5	3	37	1650-1899	comp.	Bekker & Taylor (2001)
Red fir-white fir	Southern Cascades	—	24	4	55	1650-1899	single	Bekker & Taylor (2001)
Red fir-mountain hemlock	Southern Cascades	—	20	9	91	1650-1942	comp.	Bekker & Taylor (2001)
Red fir-white fir	Southern Cascades	10	8	—	—	1650-1918	comp.	Bekker & Taylor (2010)
Red fir-mountain hemlock	Southern Cascades	100	100	—	—	1650-1918	comp.	Bekker & Taylor (2010)
Red fir	Southern Cascades	41	—	5	65	1830-1930	comp.	Taylor & Halpern (1991)
Red fir-white fir	Southern Cascades	41	—	—	—	1735-1874	comp.	Taylor & Solem (2001)
Red fir-western white pine	Southern Cascades	66	—	—	—	1768-1874	comp.	Taylor & Solem (2001)
Red fir-white fir	Southern Cascades	47	—	14	127	—	comp.	Taylor (1993)
Red fir-western white pine	Southern Cascades	—	27	9	46	—	comp.	Taylor (2000)
Red fir-western white pine	Southern Cascades	—	70	26	109	—	single	Taylor (2000)
Red fir-mixed conifer	Northern Sierra	21	20	12	34	1616-1893	comp.	Beaty & Taylor (2009)
Red fir-western white pine	Northern Sierra	—	76	25	175	1580-1853	single	Scholl & Taylor (2006)

Vegetation Type	Subregion	Mean FRI	Median FRI	Min. FRI	Max. FRI	Years Sampled	Sample Type[1]	Reference
Red fir-white fir	Central Sierra	—	12	5	69	—	comp.	Bahro (1993)[2]
Red fir	Central Sierra	—	30	9	92	—	—	van Wagtendonk et al. (2002)
Red fir	Southern Sierra	65	—	—	—	1600-1886	comp.	Pitcher (1987)
Red fir	Southern Sierra	30	—	—	50	—	—	Caprio and Line-back (2002)[3]
Mixed coni-fer-Red fir[4]	Southern Sierra	17	—	3	115	1692-1865	single	North et al. (2005)
Red fir-lodge-pole pine	Eastern (Central)	25	24	13	38	—	comp.	Stephens (2001)
Red fir	Eastern (South)	—	27	9	91	—	comp.	Hawkins (1994)[2]
Red fir-Jeffrey pine	Eastern (South)	—	17	5	56	—	comp.	Hawkins (1994)[2]
Red fir-mixed conifer	Eastern (Central)	16	—	8	33	1645-1875	comp.	Caprio et al. (2006)
Red fir type/group (aggregation)		**Mean FRI**	**Me-dian FRI**	**Min. FRI**	**Max. FRI**	**No. of studies**	**Forest types included**	
High-elevation red fir (west side)		83	66	18	78	4	Red fir–western white pine Red fir–mountain hemlock	
Mid-elevation red fir (west side)		48	16	5	49	4	Red fir	
Low-elevation red fir (west side)		27	14	7	61	7	Red fir–mixed conifer Red fir–white fir	
Southern Cascades and Northern Sierra Nevada		51	36	9	71	14	Red fir, Red fir–white fir, Red fir-western white pine Red fir–mountain hemlock	
Southern and Central Sierra Nevada		33	21	7	67	6	Red fir, Red fir–white fir, Red fir-mixed conifer	
East-side red fir		21	23	9	55	4	Red fir Red fir–Jeffrey pine Red fir–lodgepole pine Red fir–mixed conifer	

[1] Refers to whether estimates were derived from a single tree or composite (comp.) sample.

[2] References and estimates were extracted from Skinner and Chang (1996).

[3] Mean maximum FRI was calculated 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.

[4] Contained a minor component of red fir which contributed to 5% of fire-scarred sample trees.

Table 6. Historic fire rotation estimates for red fir forests in the Sierra Nevada.

Location	**Forest type**	**Fire Rotation (years)[1]**	**Reference**
Thousand Lakes Wilderness, Southern Cascades	Red fir-white fir	50	Bekker & Taylor 2001
Thousand Lakes Wilderness, Southern Cascades	Red fir-mountain hemlock	147	Bekker & Taylor 2001
Caribou Wilderness, Southern Cascades	Red fir and other upper montane forests[2]	76	Taylor & Solem 2001
Lassen National Park, Southern Cascades	Red fir-western white pine	76	Taylor 2000
Yosemite National Park, Central Sierra Nevada	Red fir (1970-1985 period; lightning fires under prescribed conditions only)	163	van Wagtendonk (1985)
Yosemite National Park, Central Sierra Nevada	Red fir (1984-2009 period)	96	Miller et al. (2012)
Sierra Nevada – summary of several studies	Red fir	61	Mallek et al. (in review)
	Average across studies:	**96**	

[1] Fire rotation is the length of time necessary to burn an area equal to the area or landscape of interest.

[2]Red fir and other upper montane forests are aggregated for estimation of fire rotation.

Table 7. Proportion of fire severity classes in Sierra Nevada red fir forests based on historic and contemporary reference site information.

Forest type	**Location**	**Unchanged/ Unburned (%)**	**Low Severity (%)**	**Moderate Severity (%)**	**High Severity (%)**	**Reference**
Red fir-white fir	Southern Cascades	—	43	44	13	Taylor & Solem (2001)
Red fir-western white pine	Southern Cascades	—	33	48	19	Taylor & Solem (2001)
Red fir-mixed conifer	Yosemite NP	27.8	27.8	29.5	15.0	Collins & Stephens (2010)[1]
Lower and upper montane forests	Yosemite NP	35	—	—	—	Kolden et al. (2012)
Red fir	Yosemite NP	—	—	—	8	Miller et al. (2012)
Red fir – 1st burn	Yosemite NP	46	41	12	1	van Wagtendonk et al. (2012)
Red fir – 2nd burn (reburn)	Yosemite NP	12.4	44.7	29.8	13	van Wagtendonk et al. (2012)
Red fir	Yosemite NP	20	45	30	5	Thode et al. (2011)[2]
Red fir	Yosemite NP	16.5	49.8	20.7	12.7	Kane et al. (2013)
Red fir-mixed conifer	Sequoia and Kings Canyon NP (SEKI)	43	44	12	<1	Collins et al. (2007)[3]
LANDFIRE Biophysical Setting Model[4]:						
Red fir	Southern Cascades	—	58	19	23	Safford & Sherlock (2005)
Red fir	Southern Sierra	—	66	16	18	Safford & Sherlock (2005)
Historic Accounts:						
Red fir	Northern Sierra	—	72	20	8	Leiberg (1902)[5]
Aggregation/ Group	**Locations**	**Unchanged/ Unburned (%)**	**Low (%)**	**Moder-ate (%)**	**High (%)**	**Forest types**
Historic esti-mates (mean)	Southern Cascades and Northern Sierra	—	49	38	13	Red fir-white fir Red fir-western white pine Red fir
Contemporary reference sites (mean)	Yosemite and SEKI	28	42	22	8	Red fir Red fir-mixed conifer
LANDFIRE BpS (mean)	Sierra Nevada	—	62	18	21	Red fir

[1] Since estimates for unchanged and low severity burn classes were pooled, values for these two classes were assumed to be one-half the total pooled value (55.5%).
[2] Fire severity estimates are approximated.
[3] Based on satellite-derived differenced Normalized Burn Ratio (dNBR) estimates rather than relative dNBR (RdNBR) used in other studies presented.
[4] Based on LANDFIRE Biophysical Setting Model estimates of historic reference conditions.
[5] Historic estimates of moderate and high severity classes by Leiberg (1902) may be overestimated due 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 50–75% tree mortality.

Table 8. Average total and relative red fir tree densities, basal area (BA), and tree diameter in historic and current red fir stands, including Forest Inventory and Analysis (FIA) data (2013). All stands are unlogged with the exception of current stands from Taylor (2004) and FIA data. Values are extracted from Barbour and Woodward (1985) and other sources. Studies arranged from north to south.

Subregion of Sierra Nevada[1]	Tree Density (no/ha)[2]			BA (m²/ha)			Mean dbh (cm)	No. of Stands	Reference
	Total	Red Fir	% Red Fir	Total	Red Fir	% Red Fir			
California	970	—	—	112	—	—	—	—	Schumacher (1928)[3]
Northern	1285	740	58	69	38	55	—	24	Bekker & Taylor (2001)[4]
Northern	868	736	85	81	64	79	—	35	Taylor (2000)[6]
Northern	1404	1088	77	106	74	70	—	31	Taylor & Solem (2001)[4]
Northern	294	231	79	85	70	82	—	2	Taylor & 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 & Billings (1943)[5]
Central	433	275	63	202	136	67	77	4	Stephens (2000) Historic[6]
Central	324	241	74	53	47	89	—	14	Barbour et al. (2002)
Central	161	94	58	56	40	72	74	6	Taylor (2004) Historic[7]
Central	538	184	34	49	24	50	42	6	Taylor (2004) Current[7]
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)[8]
C & S	—	—	—	51	41	81	25	28	Potter (1998)[8]
C & S	—	—	—	45	28	63	25	31	Potter (1998)[8]
Southern	340	289	85	100	48	48	—	10	Griffin (1975)
Southern	370	345	93	69	65	94	37	352	North et al. (2002)[9]
Southern	—	—	87	81	70	87	—	10	Vankat (1970, 1982)
Southern	—	—	88	93	80	86	—	3	Vankat & Major (1978)
Southern	507	431	85	57	51	89	—	3	Pitcher (1981)
Southern	—	283	—	92	58	63	—	14	Barbour & Woodward (1985)
Historic (pre-1950) red fir stands:									
Mean	609	388	71	117	91	79	76	>10	—
SD	379	363	18	61	48	17	2	—	—
Contemporary (post-1950) red fir stands:									
Mean	658	472	74	72	54	74	31	229	—
SD	363	284	19	22	20	16	8	—	—
Contemporary (2013) FIA red fir stands[9]:									
Mean	527	254	49	41	21	51	20	342	—
SD	537	—	—	25	—	—	—	—	—

[1] Northern subregion includes areas within the southern Cascades. N & C = North and Central; C & S = Central and Southern.

[2] Tree density estimates are based on trees ≥3 or ≥5 cm dbh.

[3] Estimates extracted from Rundel et al. (1988) based on trees >10 cm dbh.

[4] Estimates are based on red fir–white fir stands (Bekker & Taylor 2001), red fir–mountain hemlock stands (Taylor 2000), or red fir–western white pine (Taylor & Solem 2001).
[5] Values based on Oosting and Billings (1943) are considered "historic" rather than current.
[6] Stephens (2000) used red fir forest stand structure data from 4 plots surveyed by Sudworth (1899). Average tree diameter only includes trees >30.5 cm dbh.
[7] Taylor (2004) based stand estimates on presettlement (pre-1870; "historic") or contemporary ("current") conditions following 19th century logging.
[8] Potter (1998) includes Red fir (upper row), Red fir/Pinemat manzanita (middle row), and Red fir–Western white pine/Pinemat manzanita associations.
[9] All Forest Inventory and Analysis (FIA) estimates are based on FIA plots throughout the entire assessment area using only trees ≥5 cm dbh. Inclusion of mixed red fir–white fir forests in 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 684 ± 697 (SD) based on all trees ≥3 cm dbh in FIA plots.

Table 9. Average snag densities in historic and current Sierra Nevada red fir forests. Historic values are based on Stephens (2000). 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 FIA data (2013).

Red Fir Forest Association	**Snag Density (no./ha)**
Red fir	36.1
Red fir/Pinemat manzanita	6.9
Red fir–Lodgepole pine/White-flowered hawkweed	51.2
Red fir–Western white pine	32.4
Red fir–Western white pine/ Pinemat manzanita	11.1
Red fir–Western white pine/Bush chinquapin	3.2
Red fir–Western white pine–Lodgepole pine	12.8
Red fir–White fir	64.7
Red fir–White fir–Jeffrey pine	44.2
Red fir–White fir–Sugar pine	58.3
Jeffrey pine–Red fir	57.1
Historic red fir forests (Stephens 2000):	
Mean	17.5
Range	0–60
Current red fir forests (Potter 1998):	
Mean	34.4
Range	3–65
Current red fir forests (FIA 2013):	
Mean	38.0
±Standard Deviation	0–94

Table 10. Relative frequency of understory species in historic (1940) and current (1990s) surveys of Sierra Nevada red fir forests.

Group/Species	**Historic (% Relative Frequency)[1]**	**Current (% Relative Frequency)[2]**
Shrubs:		
Ribes viscosissimum	100	47
Symphoricarpos rotundifolius	54	87
Arctostaphylos nevadensis	31	100
Lonicera conjugialis	23	13
Quercus vaccinifolia	16	67
Ribes montigenum	62	33
Chrysolepis sempervirens[3]	0	100
Herbaceous plants:		
Eucephalus breweri	100	56
Pedicularis semibarbata	94	100
Pyrola picta	94	58
Gayophytum ramosissimum[4]	94	2
Mondardella odoratissima	94	56
Phacelia hydrophylloides	80	53
Poa bolanderi	80	49
Arabis platysperma	80	78
Corallorhiza maculata	80	47
Thalictrum fendleri	73	24
Hieracium albiflorum	67	49

[1] Based on relative frequency of occurrence in 16 red fir forest plots in the northern and central Sierra Nevada. Data source is Oosting and Billings (1943).

[2] Based on approximately 172 upper montane plots focused on red fir in the central and southern Sierra Nevada. Data source is Potter (1998).

[3] *Chrysolepis sempervirens* was detected in other historic surveys of the northern and central Sierra Nevada by Wieslander et al. (1933).

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

Table 11. Projected future changes in the distribution of red fir or red fir forests based on climate envelope (species distribution) and dynamic vegetation (MC1) models. Percent decrease, increase, or stable indicates the percent change in the area covered by red fir within the geographic scope and time period of each study.

Unit of analysis	Geographic scope	GCM and trends (model type)	Decrease (%)	Stable (%)	Increase (%)	Time Period	Reference
Species	California	CCSM – warmer & wetter	77	23	1	2080	FRAP (2010)
Species	California	Hadley Centre – hotter & drier	99.92	0.07	0.01	2080	FRAP (2010)
Species[1]	Species range	Ensemble of 3 models – full dis.	77	23	—	2071-2100	McKenney et al. (2007)
Species[1]	Species range	Ensemble of 3 models – no dis.	87.5	12.5	—	2071-2100	McKenney et al. (2007)
Biome[2]	California	PCM – warmer & possibly wetter (MC1)	5	—	—	2071-2100	Lenihan et al. (2008)
Biome[2]	California	GFDL – hotter & drier (MC1)	52	—	—	2071-2100	Lenihan et al. (2008)
Species[3]	Southern Sierra Nevada	Ensemble of 11 models	28	49	17	2040-2065	SSP (2010)
Species[3]	California	Ensemble of 11 models	56	27	10	2040-2065	SSP (2010)
Veg type[4]	Southern Sierra Nevada	PCM – warmer & possibly wetter (Bioclim, Flint)	66	33	—	2070-2099	Schwartz et al. (2013)
Veg type[4]	Southern Sierra Nevada	GFDL – warmer & possibly wetter (Bioclim, Flint)	85	15	—	2070-2099	Schwartz et al. (2013)
Average across studies for red fir[5]:			**82.1**	**17.9**	**0.5**	**2071-2100**	**—**

[1] Estimates for percent stable and percent increase ("percent remaining") are pooled. Includes models that assume full dispersal (full dis.) or no dispersal (no dis.).

[2] Projections are for conifer forest biome, which includes mixed conifer forest, red fir forest, and other conifer-dominated forest types.

[3] 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: 6–7%). Data source is the Southern Sierra Partnership (SSP 2010).

[4] Based on U.S. Forest Service Region 5 Calveg red fir alliance vegetation type. Percent decrease estimate includes moderate, high, and extreme climate exposure categories (outside 66th percentile bioclimatic distribution for red fir), and percent stable estimate is equal to the percentage in the low exposure category (inside the 66th percentile bioclimatic distribution). Projection estimates are based on 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).

[5] Includes FRAP (2010), McKenney et al. (2006), and Schwartz et al. (2013).

Table 12 – Deviations from the Natural Range of Variation (NRV) based on historical and modern reference information in Sierra Nevada red fir forests. Changes in variables resulting from projected future changes in climate are also provided for comparison.

Variable(s)	Historic Reference Period	Modern Reference Site	Within NRV	Confidence	Direction of Departure	Notes	Pages in discussion
Fire Return Interval	1580–1900	No	No	High	Increasing	Relatively low departure from NRV, but future projections may be outside NRV	Pg. 9–11 Table 5 Fig. 3
Fire Rotation	1650–1905	Yes	No	Moderate	Increasing	Same as above	Pg. 9–11 Table 6
Fire Size	1729–1918	Yes	Yes/No	Moderate	Increasing	Generally within NRV, but approaching values that may soon exceed NRV	Pg. 11 Fig. 4, 5
Fire Type	1625–1845	Yes	Yes	Moderate	—	—	Pg. 11–12
Fire Seasonality	1650–1942	No	Yes	Moderate	—	—	Pg. 12
Fire Severity	1650–1930	Yes	Yes	Moderate	Marginally increasing	Marginal increase in fire severity in past 25 to 30 years, and this trend is likely to continue based on future projections	Pg. 12–13 Table 7
High Severity Fire Patch Size and Size Distribution	Late 1800s	Yes	Yes	Low	—	—	Pg. 13–14 Fig. 6–8
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	Pg. 14–15
Wind	1874–1960	No	Yes	Low	—	—	Pg. 15–16 Fig. 9

Variable(s)	Historic Reference Period	Modern Reference Site	Within NRV	Confidence	Direction of Departure	Notes	Pages in discussion
Volcanism	Pre–1500	No	Yes	Low	—	—	Pg. 16
Annual Climatic Water Deficit and Actual Evapo-transpiration	1700	No	Yes	Low	Increasing	Likely within NRV but projected future range of variation may exceed NRV	Pg. 16
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 5 variables) are based on LiDAR-derived metrics extracted from contemporary reference site (Yosemite NP)	Pg. 17 Fig. 10, 11
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	Pg. 17 Fig. 12
Canopy Cover	Current with limited historic data	Yes	Yes	Moderate	Increasing in lower canopy strata	Overall canopy cover within NRV but increasing cover in lower canopy strata with fire exclusion; also decreasing in landscapes with increasing proportion of high-severity fire	Pg. 18 Fig. 13, 14
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	Pg. 18 Fig. 15

Variable(s)	Historic Reference Period	Modern Reference Site	Within NRV	Confidence	Direction of Departure	Notes	Pages in discussion
Canopy Complexity and Heterogeneity	Current only	Yes	Yes/No	Moderate	Decreasing	Contemporary unburned forest landscapes are within NRV, but landscapes with increasing proportions of high fire severity may approach values outside NRV	Pg. 18–19 Fig. 16
Canopy Fragmentation	Current only	Yes	Yes/No	Low	Increasing	Same as above	Pg. 18–19 Fig. 17
Tree Densities (all size classes)	1870–1928	No	Yes/No	High	Increasing	Marginal increase in tree densities in unlogged forests but substantial increase in 19th century logged stands	Pg. 19–20 Table 8 Fig. 18
Average Tree Size and Density of Large Diameter Trees	1870–1928	No	No	Moderate	Decreasing	NRV departure due to recent changes in climate and 19th century logging	Pg. 19–20 Table 8
Tree Size Class Distribution	pre–1870	No	No	High	Shifting to smaller size classes	Same as above	Pg. 19–20 Fig. 19
Basal Area	1870–1928	No	Yes	Moderate	—	—	Pg. 20 Table 8 Fig. 18
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 sized tree spatial patterns are outside NRV	Pg. 20–21
Tree Regeneration	1600–1940	No	Yes	Moderate	—	—	Pg. 21–22 Fig. 2, 20

Variable(s)	Historic Reference Period	Modern Reference Site	Within NRV	Confidence	Direction of Departure	Notes	Pages in discussion
Snag Density, Basal Area, and Average Size	1899	No	Yes/No	Low	Increasing density and basal area	Considerable variation in snag abundance in historic and current stands may obscure trends	Pg. 22 Table 9
Biomass	1920–1928	No	Yes	Low	—	—	Pg. 22 Fig. 21
Seral Class Proportions	1600–1850	No	No	Low	Greater proportion of mid-seral and lower proportion of late-seral	Based on LANDFIRE Biophysical Settings Modeling for Stanislaus National Forest only	Pg. 22–23 Fig. 22, 23
Overstory Species Composition	1870–1928	No	Yes	Moderate	—	Based on relative abundance of red fir	Pg. 23 Table 8 Fig. 24
Understory Species Composition	Pre–1940	No	Yes	Low	—	Based on relative abundance of shrub and herbaceous plant species	Pg. 23 Table 10
Projected Future Distribution	2010–2099	—	—	Low to Moderate	Future contraction of geographic range and greater climate vulnerability	Confidence in future projections is low especially at later time intervals, but confidence in the overall degree of projected vulnerability is moderate	Pg. 24–25 Table 11 Fig. 25–27

Figures

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

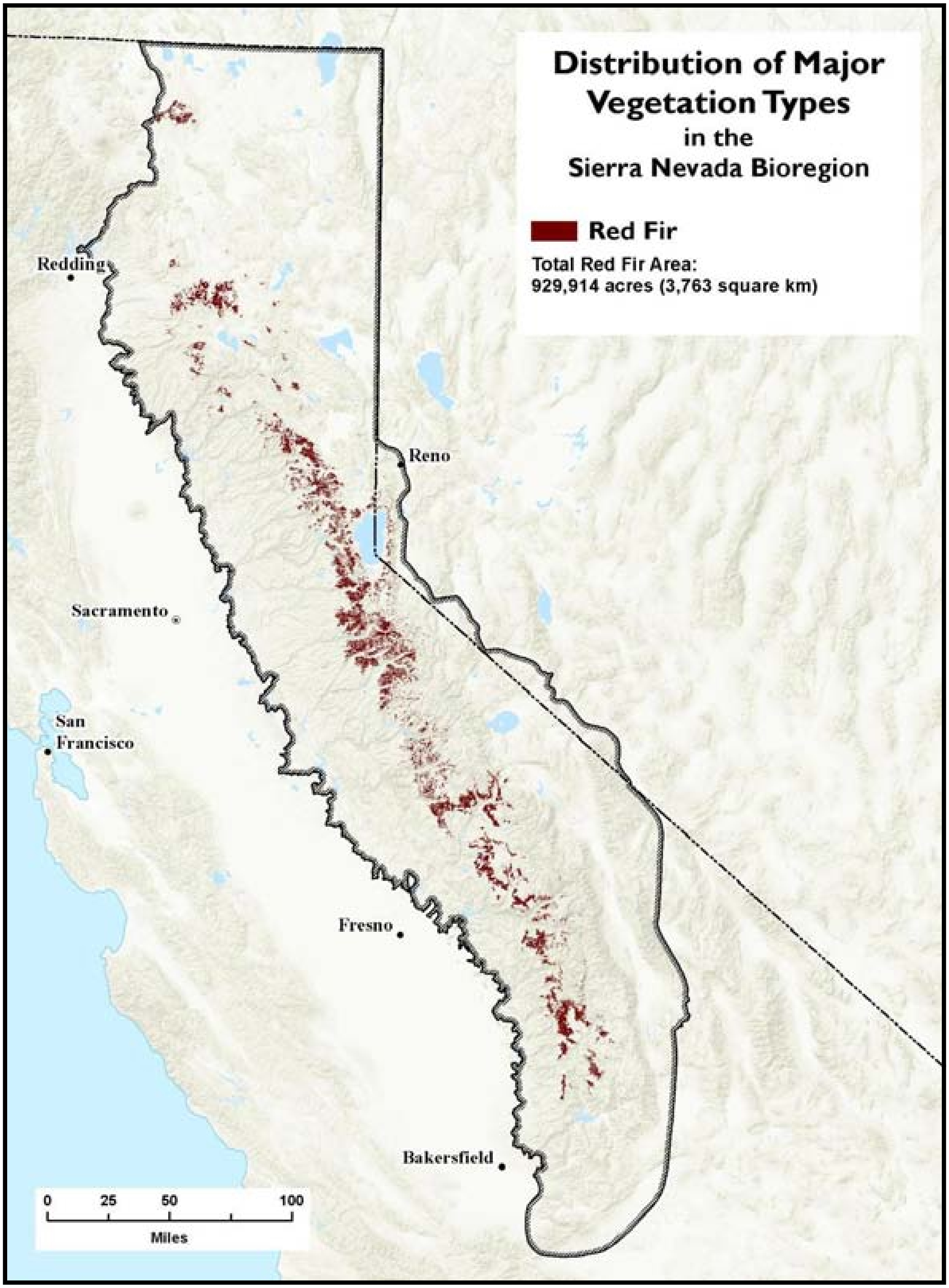


Figure 2 – Photos of late-seral red fir forest in the Illilouette Creek Basin of Yosemite National Park (top and middle) and Owens River Headwaters Wilderness of the Inyo National Forest, eastern Sierra Nevada (bottom). This Illilouette Creek Basin photos were taken in a low-severity burned stand approximately ten years following the Hoover Fire (2001). Image Credit: Marc Meyer, USFS.

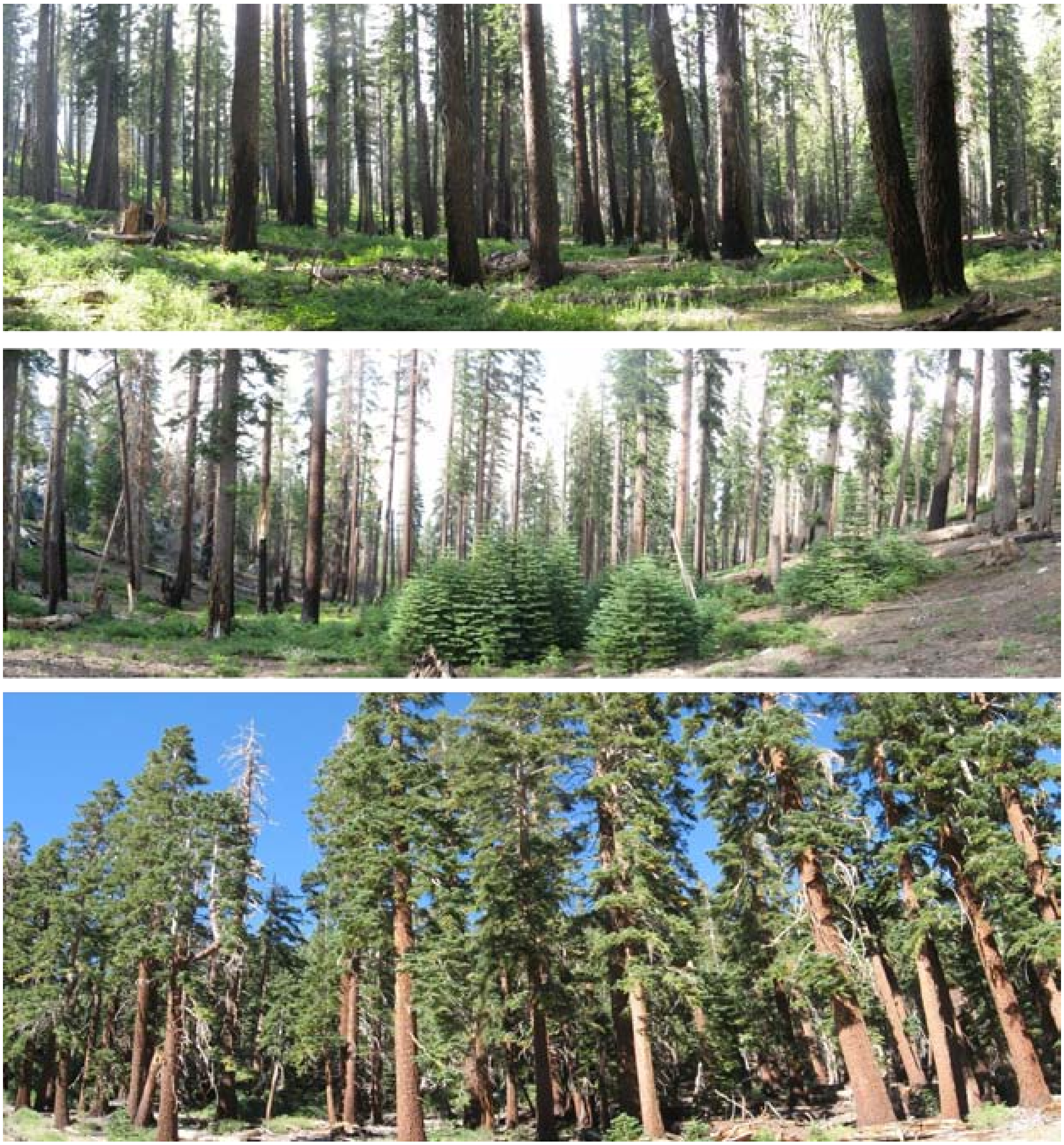


Figure 3 –Projected increase in fire probability for red fir forests in the southern Sierra Nevada under the GFDL (warmer-drier) and PCM (warmer-wetter) climate models by the end of century (2070–2099). Frequency distributions represent future projected (red, green) and current (gray) climate conditions. Y-axis represents the number of model simulations. Graphics courtesy of Moritz et al. (2013).

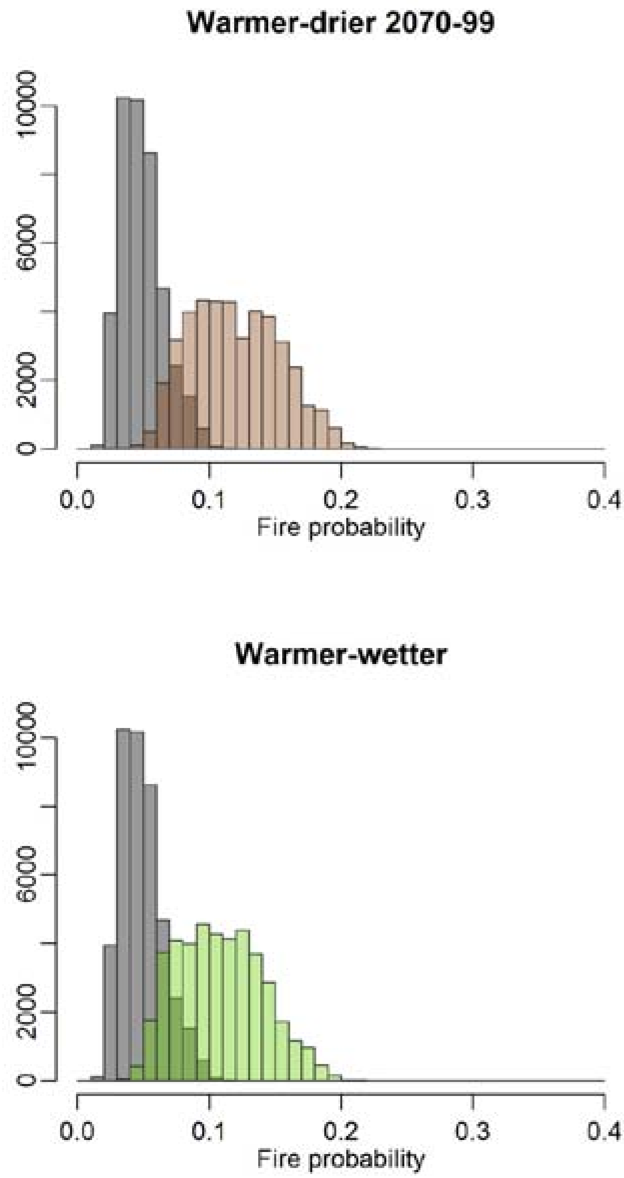


Figure 4 – Percent of fires by size class in red fir and lodgepole pine forests of Yosemite National Park, 1972–1993. Figure redrawn from van Wagtendonk (1993) and Potter (1998).

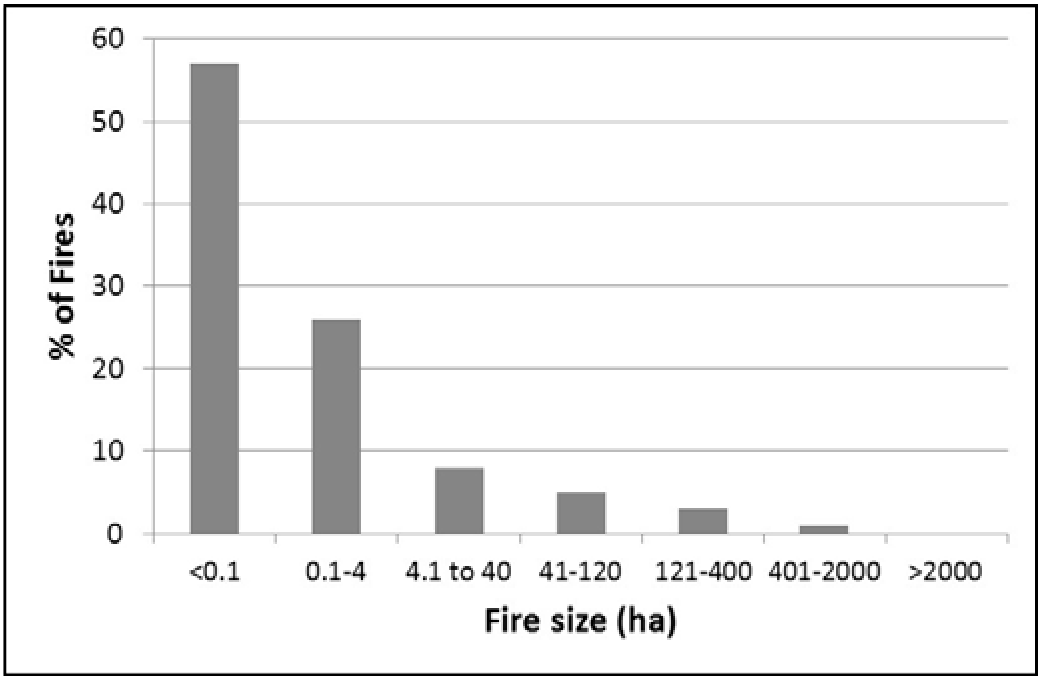


Figure 5 – Percent of total area burned by fire size class in red fir and lodgepole pine forests of Yosemite National Park, 1972–1993. Figure redrawn from van Wagtendonk (1993) and Potter (1998).

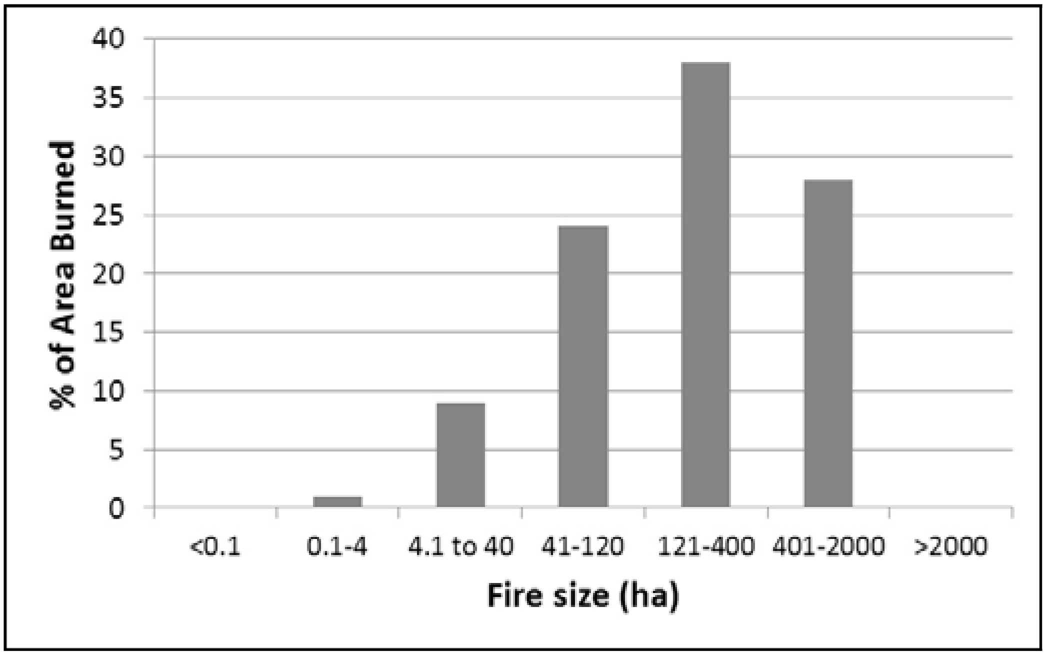


Figure 6 – Photo of a high severity burned patch in a red fir and Jeffrey pine forest, approximately 20 years following the Rainbow Fire (1992) located within Devils Postpile National Monument. High-severity burned patches were defined as areas exceeding 95% tree mortality with high to complete mortality of vegetation. Image Credit: Marc Meyer, USFS.

Figure 7. – 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 analyzed a total number of 72 high-severity patches and used a minimum patch size of 0.5 ha and their analysis. Figure redrawn from Collins and Stephens (2010).

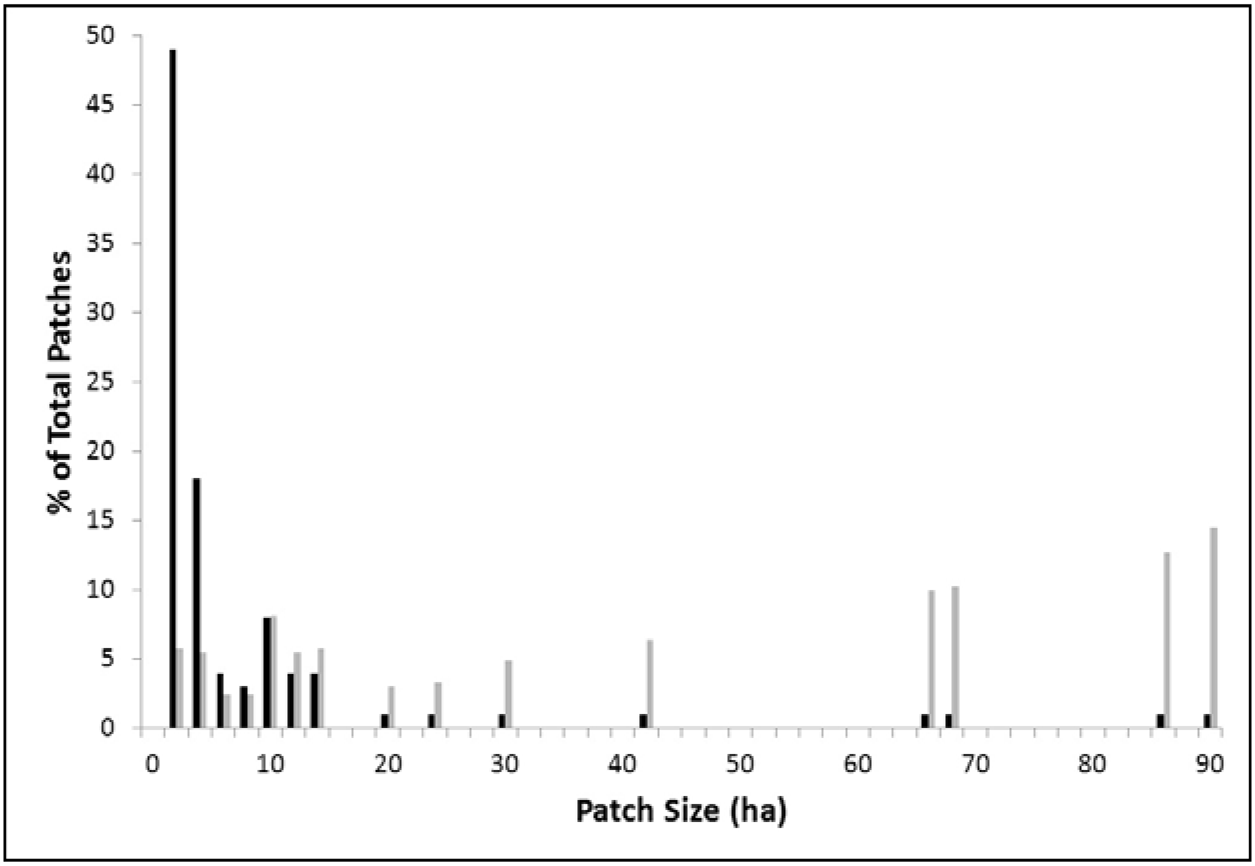


Figure 8 – Canopy gap size distribution in different fire severity classes in red fir forests of Yosemite National Park. Figure redrawn from Kane and Lutz (2012) and Kane et al. (2013). Fire severity classes are based on the Relativized differenced Normalized Burn Ratio (RdNBR) from Miller and Thode (2007). The undifferentiated class includes areas within recent (1984–2010) fire perimeters where there was no detectable change in fire severity class as measured using remote-sensing (i.e., RdNBR) techniques. Note the relatively even distribution of gap sizes in the low fire severity class.

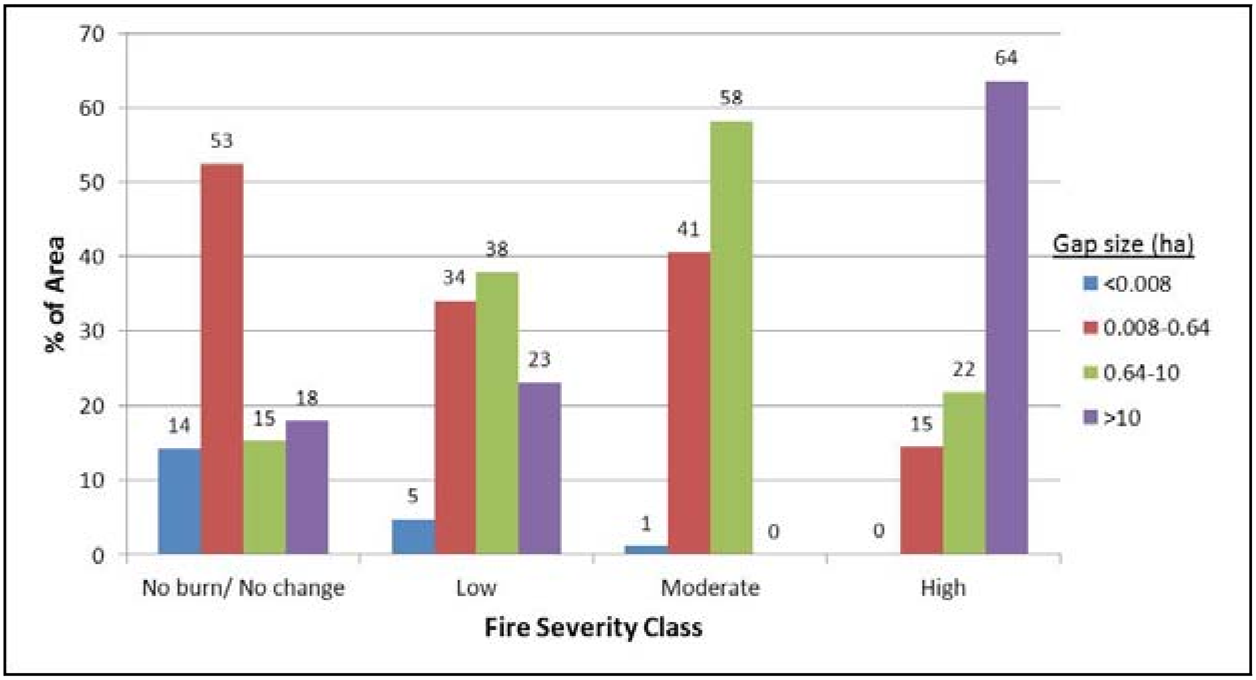


Figure 9 – Photo of a red fir stand that experienced an extreme wind "blowdown" event in the Reds Meadow area (Inyo National Forest) and Devils Postpile National Monument. Photo was taken approximately eight months following this extreme wind event. Image Credit: Marc Meyer, USFS.

Figure 10 – 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 (usually after moderate or high severity fire). Figure created using FUSION software (McGaughey 2010).

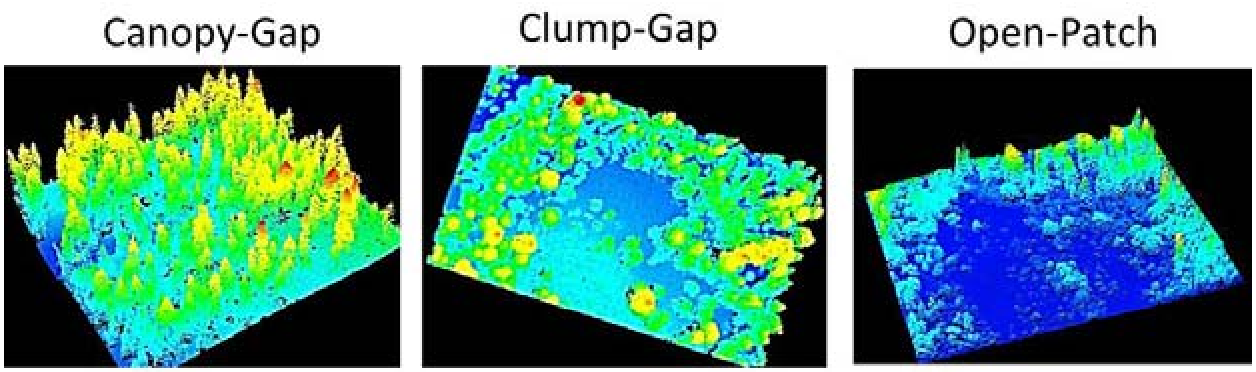


Figure 11 – Percent of landscape occupied by canopy patches or gaps in burned and unburned red fir forest landscapes of Yosemite National Park from Kane et al. (2013). Only vegetation >2 m in height are included in the estimation of canopy patches. The unburned fire severity class represents landscapes outside fire perimeters that burned prior to 1930.

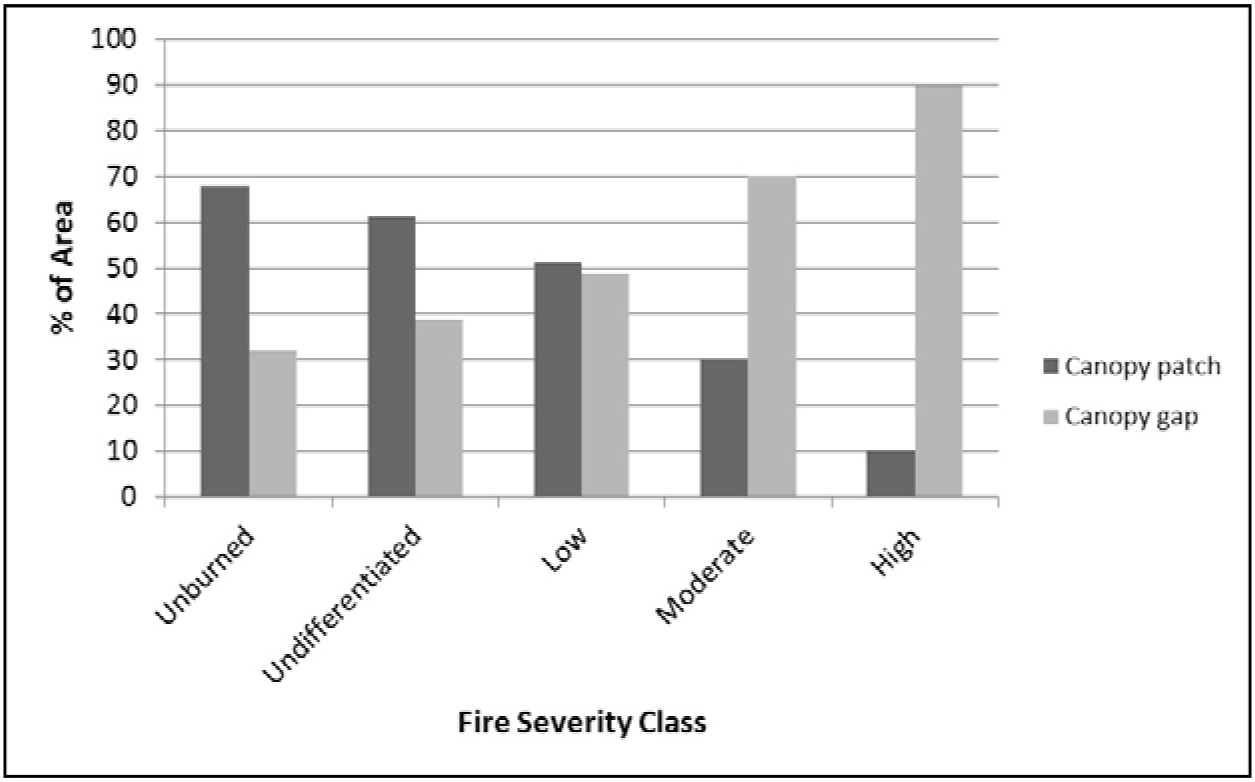


Figure 12 – Proportion of five forest structural classes that occur at the individual patch scale within burned and unburned red fir forest landscapes of Yosemite National Park. Data source is Kane et al. (2013).

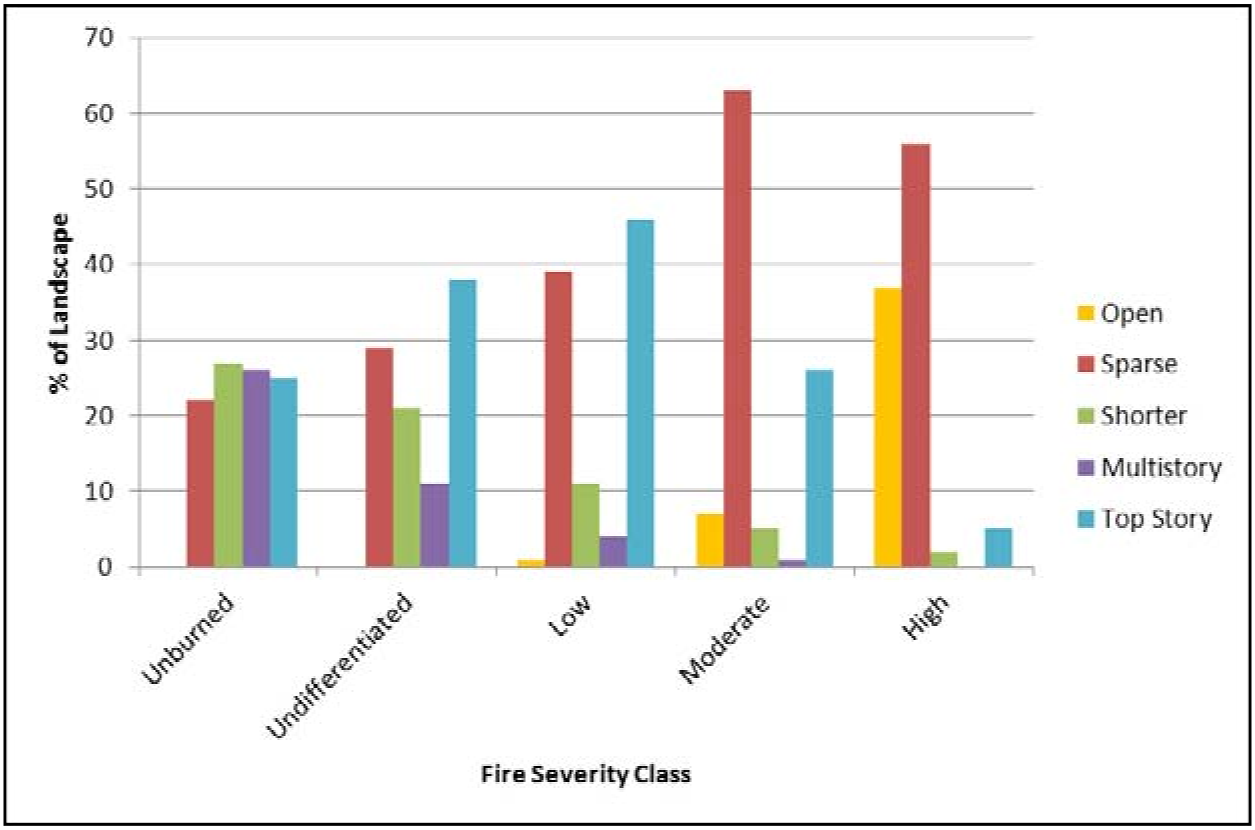


Figure 13 – Mean (± SD) percent canopy cover in contemporary reference and current red fir stands of the assessment area. Historic mean canopy cover is estimated as a product of LiDAR-derived canopy cover values from Yosemite National Park (YNP) for each fire severity class (based on data presented in Figure 13) and fire severity class estimates based on reference sites and models presented in Table 7. Current red fir forests are represented by Forest Inventory and Analysis data (FIA 2013; includes logged and unlogged stands) and current late-seral (unlogged) stands based on 13 studies presented in Table 8. Error bar for contemporary reference stands are based on canopy cover estimates for red fir forests of YNP exclusively and does not represent the full range of variation in canopy cover for the entire assessment area.

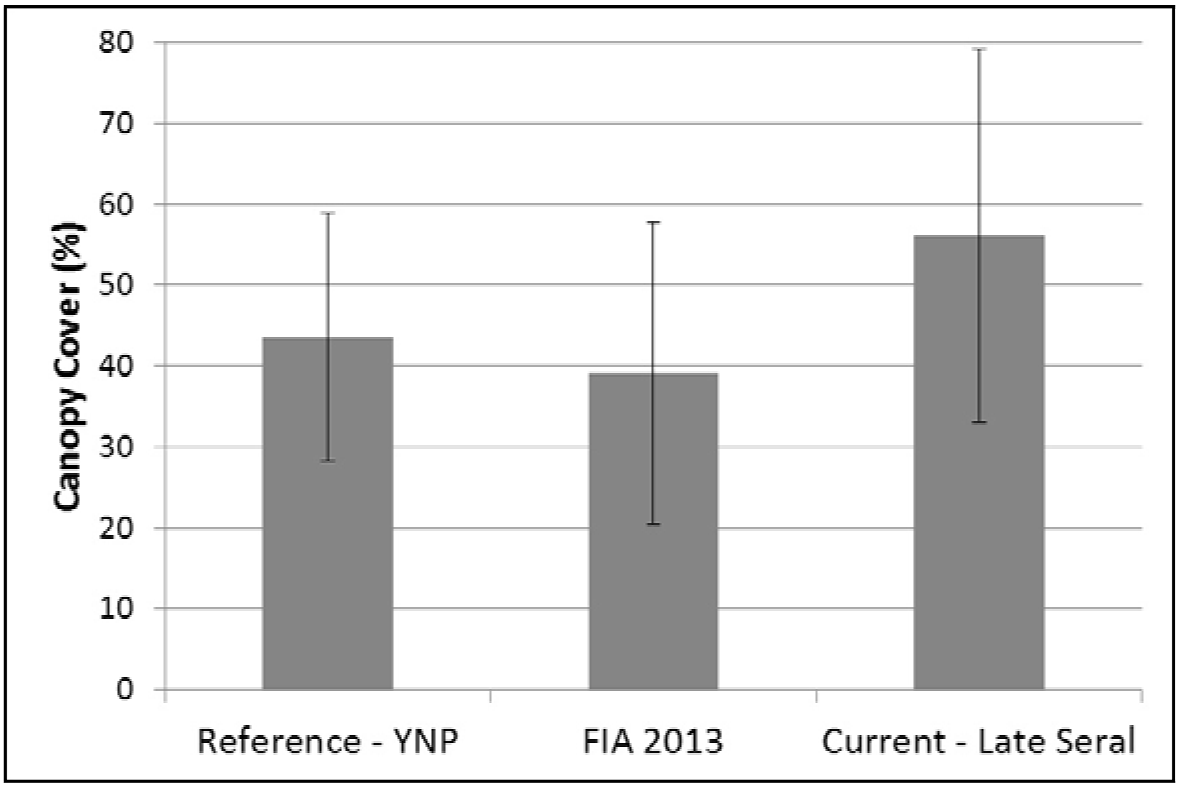


Figure 14 – Mean percent cover in canopy strata >16 m (overstory canopy) and 2–16 m (subcanopy) in height. Numbers above bars represent the total (additive) percent canopy cover for each fire severity class. Data source is Kane et al. (2013).

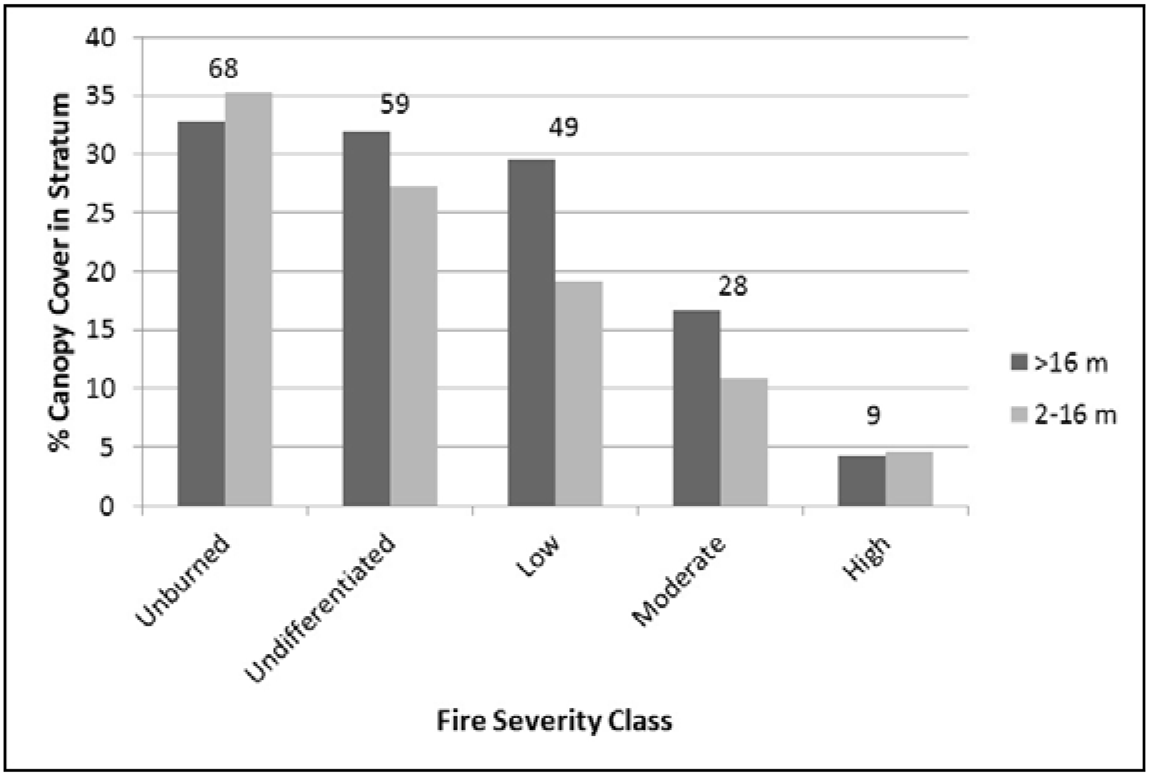


Figure 15 – Mean dominant tree height and canopy base height in burned and unburned red fir forest landscapes of Yosemite National Park from Kane et al. (2013). Dominant tree height and canopy base height estimates are based on the 95th and 25th percentile LiDAR return heights, respectively.

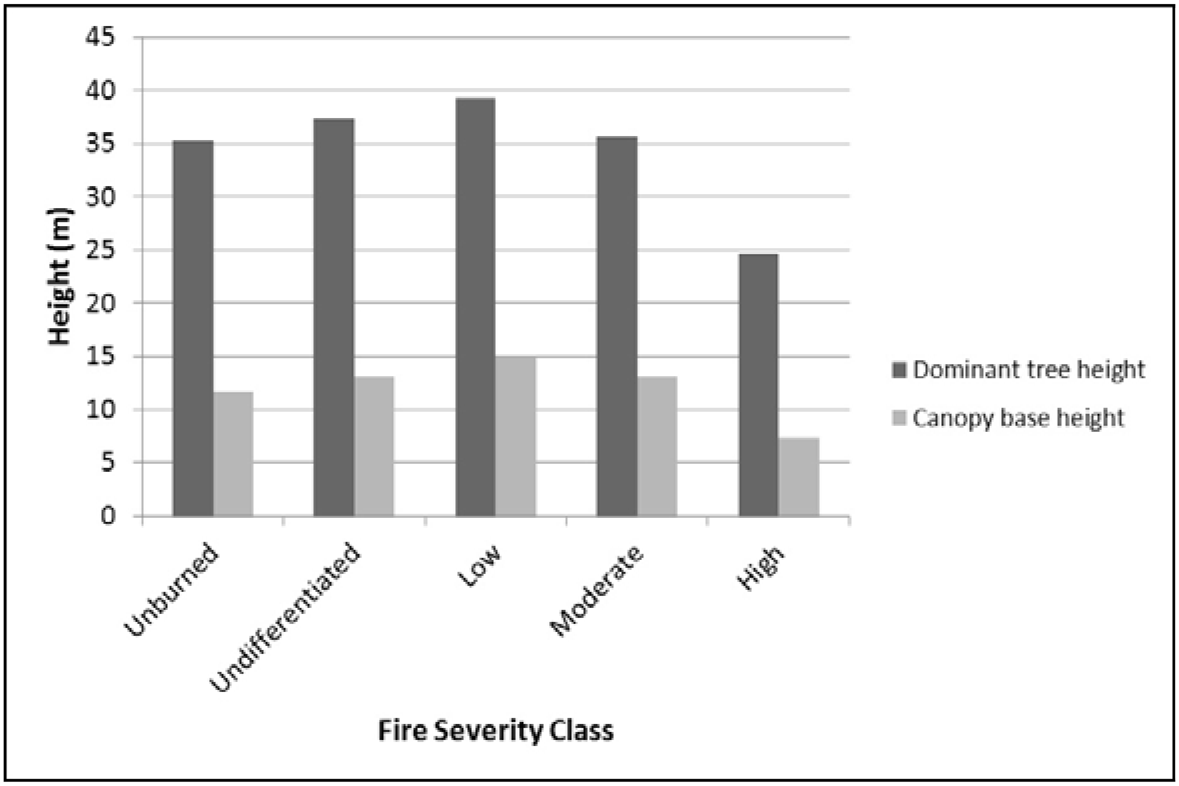


Figure 16 – Mean rumple values for burned and unburned red fir forest landscapes of Yosemite National Park from Kane et al. (2013). Rumple is a measure of canopy surface rugosity and an indicator of canopy structural complexity and heterogeneity. All fire severity classes are statistically distinguishable ($P < 0.05$) from each other.

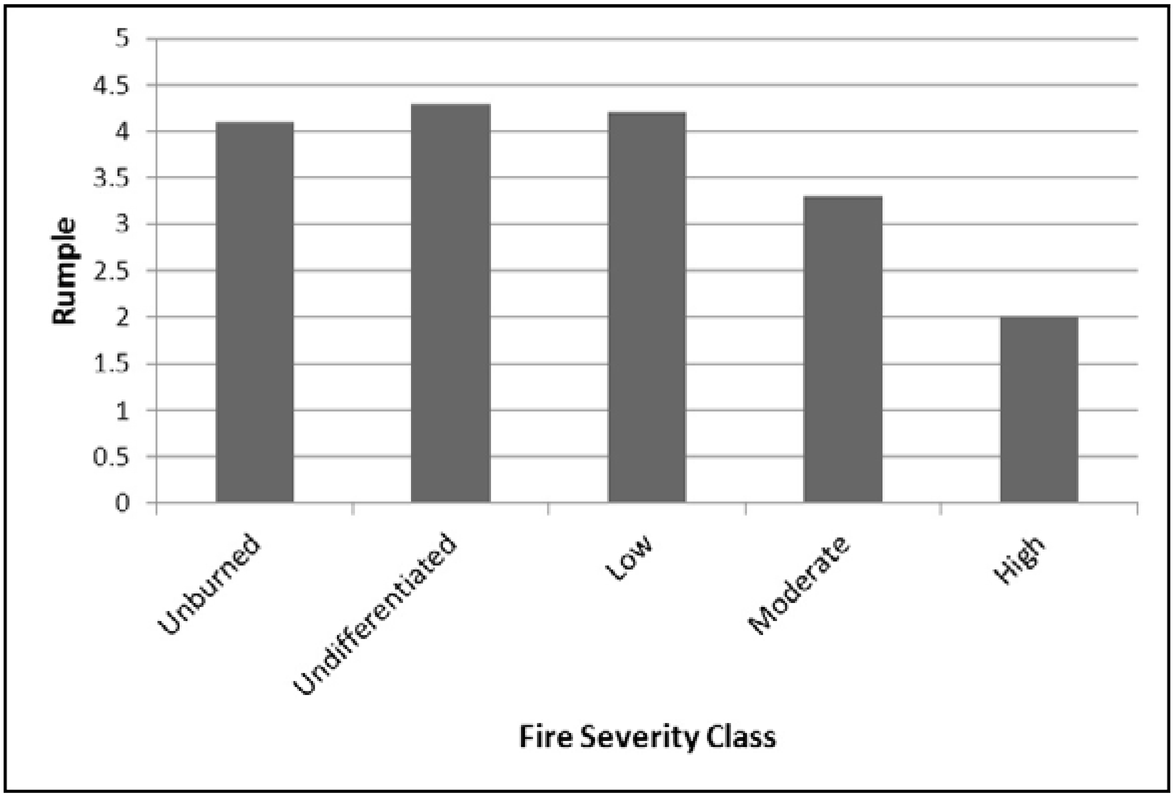


Figure 17 – Forest fragmentation in burned and unburned red fir forest landscapes of Yosemite National Park. Increasing proportion of the landscape with a greater number of canopy clumps or patches indicates that the total red fir forest canopy was more fragmented. The number of clumps was calculated by determining the minimum number of clumps within each sample area that were ≥75% of the total canopy cover. Data source is Kane et al. (in review).

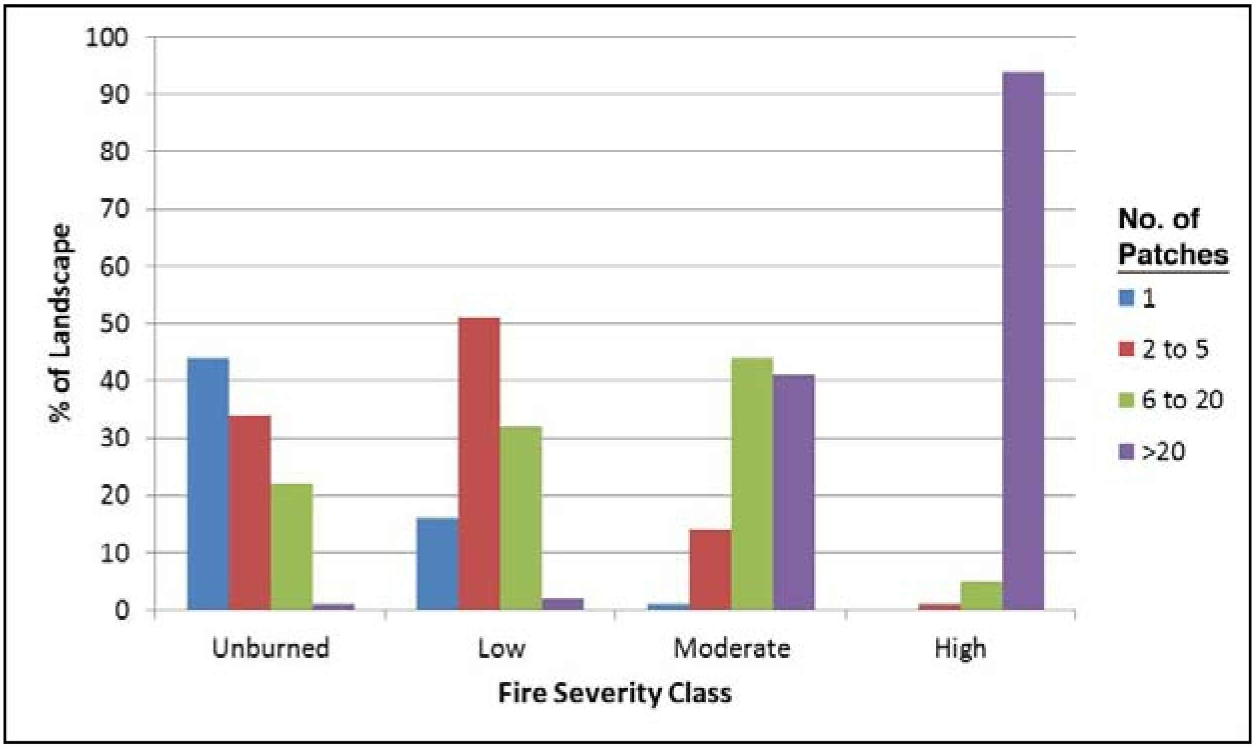
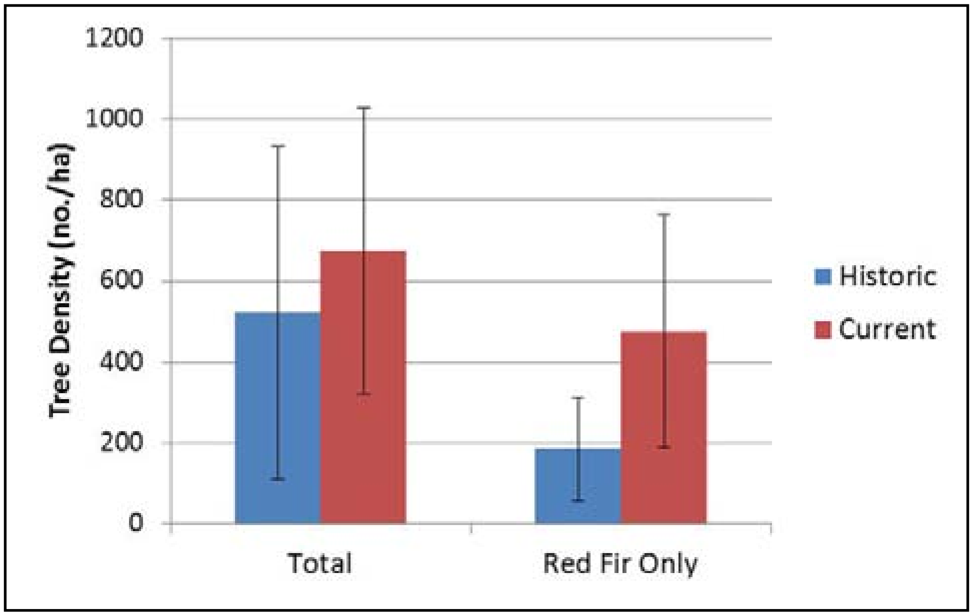


Figure 18 – Mean (± SD) tree densities (top graph) and basal area (bottom graph) in historic and current unlogged red fir forests of the Sierra Nevada. Data sources are presented on Table 6.



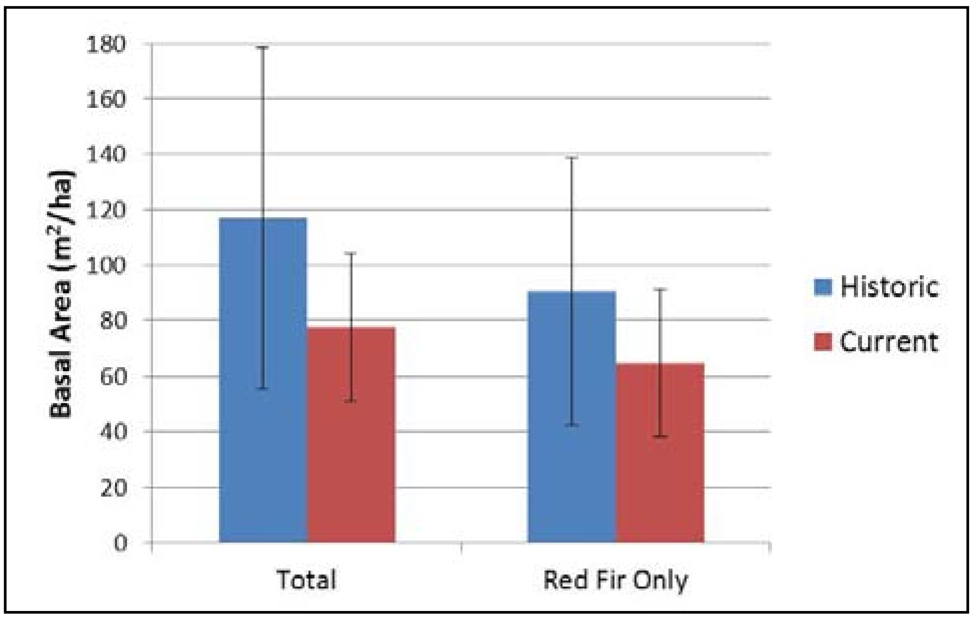


Figure 19 – Size class distribution of presettlement and current secondary-growth red fir–western white pine stands in the Lake Tahoe Basin. Note the large increase in the density of lodgepole pine between time periods. Y-axis scale was fixed at a maximum of 100 trees per ha to emphasize differences in tree densities between periods. Figure redrawn from Taylor (2004).

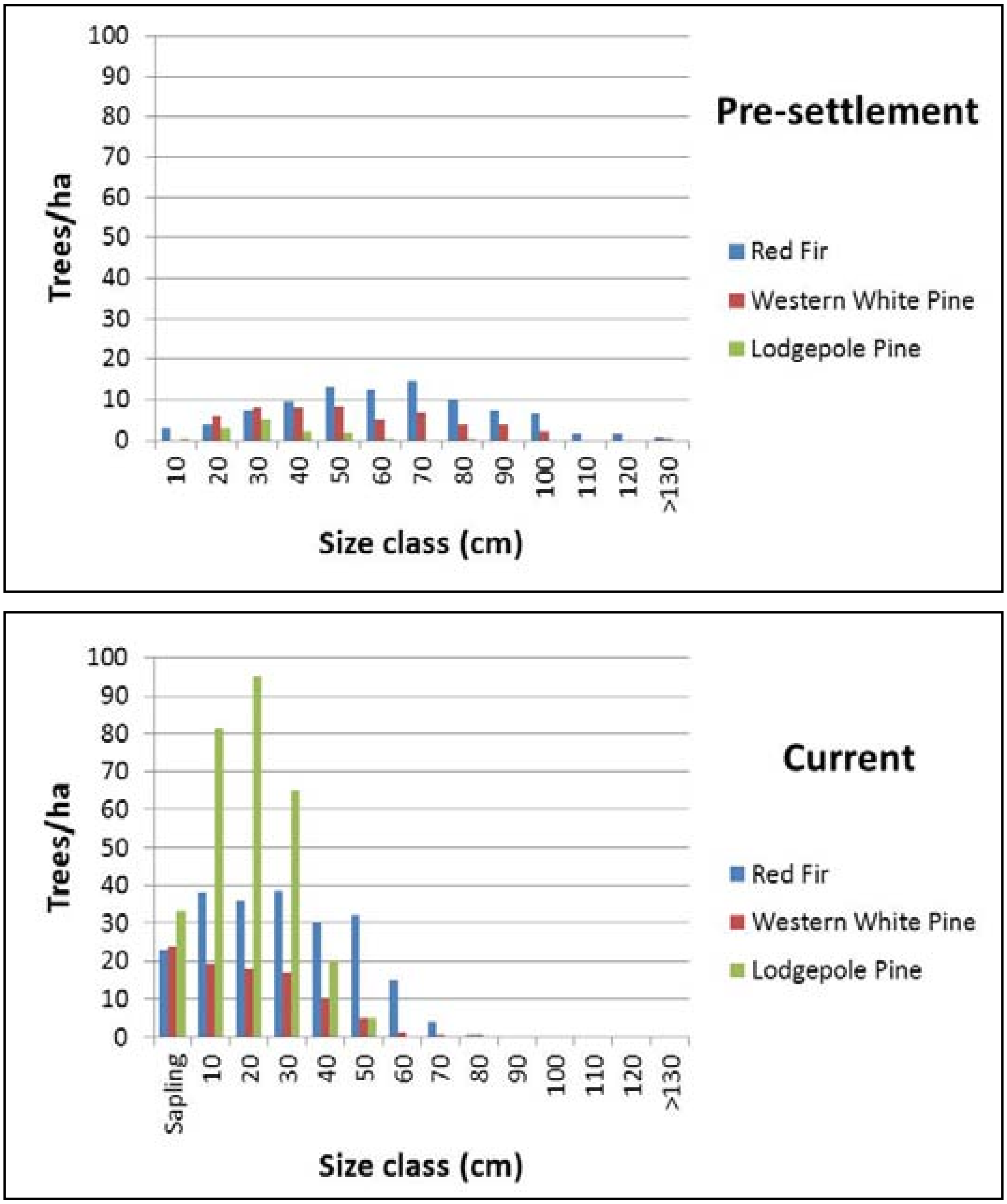


Figure 20 – Mean estimates of red fir regeneration in historic (~1940) and current (1990–2012) red fir forests of the Sierra Nevada. Blue bars represent the historic range of variation based on Oosting and Billings (1943), and gray bars represent contemporary red fir stands based on current studies. Potter (1998) includes estimates from red fir–Jeffrey pine (RF–JP) and red fir-lodgepole pine (RF–LP) forest associations. FIA (2013) includes 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 includes both logged and unlogged red fir forests.

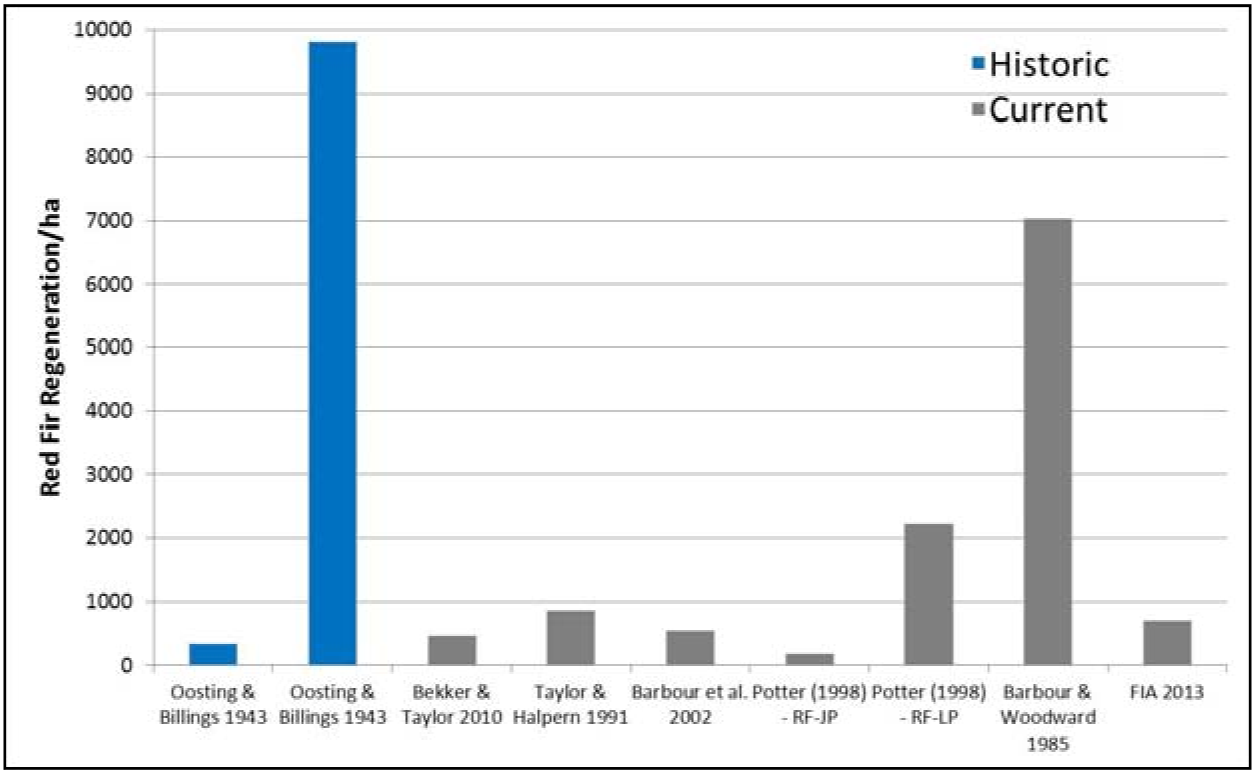


Figure 21 – Mean (± range) biomass estimates of red fir forests of the Sierra Nevada. Contemporary sites include Tahoe National Forest (late-seral), Sierra National Forest (second-growth and late seral), Sequoia National Park (late-seral), and historic estimates for the assessment area. Respective data sources include Gonzalez et al. (2010), Swatantran et al. (2011), Westman (1987), and Schumacher (1928) in Rundel et al. (1988).

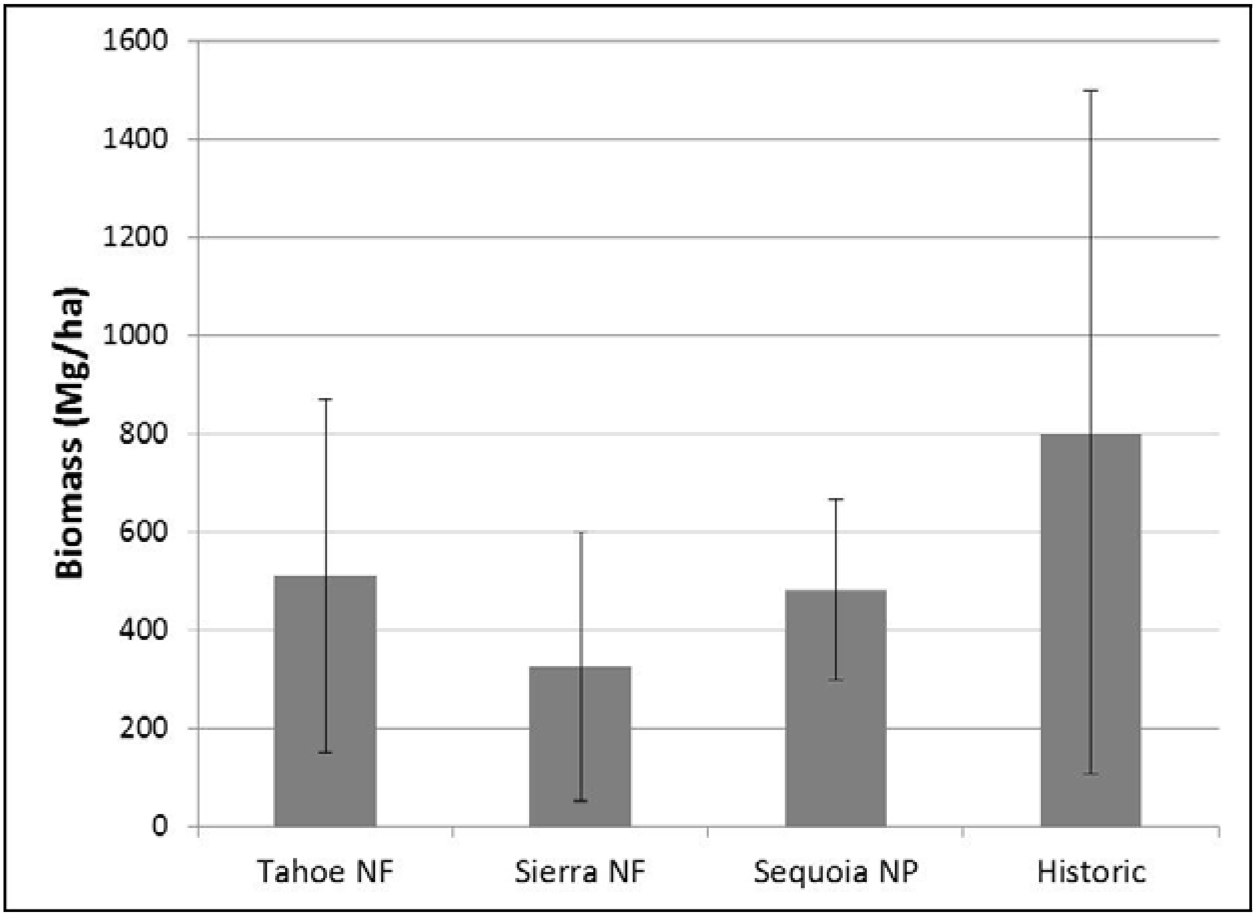
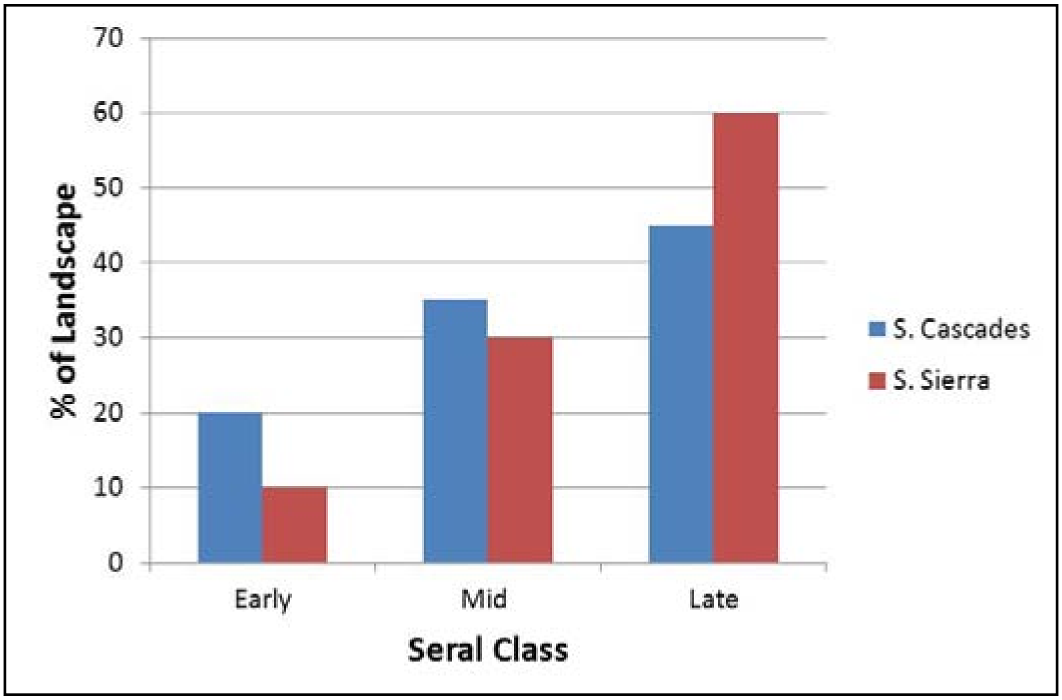


Figure 22 – Percent of red fir forest landscape in different seral classes based on LANDFIRE Biophysical Setting (BpS) models for the southern Cascades and southern Sierra Nevada. Bottom figure displays the open and closed canopy subclasses within mid- and late-seral classes. Data sources are Safford and Sherlock (2005a, b).



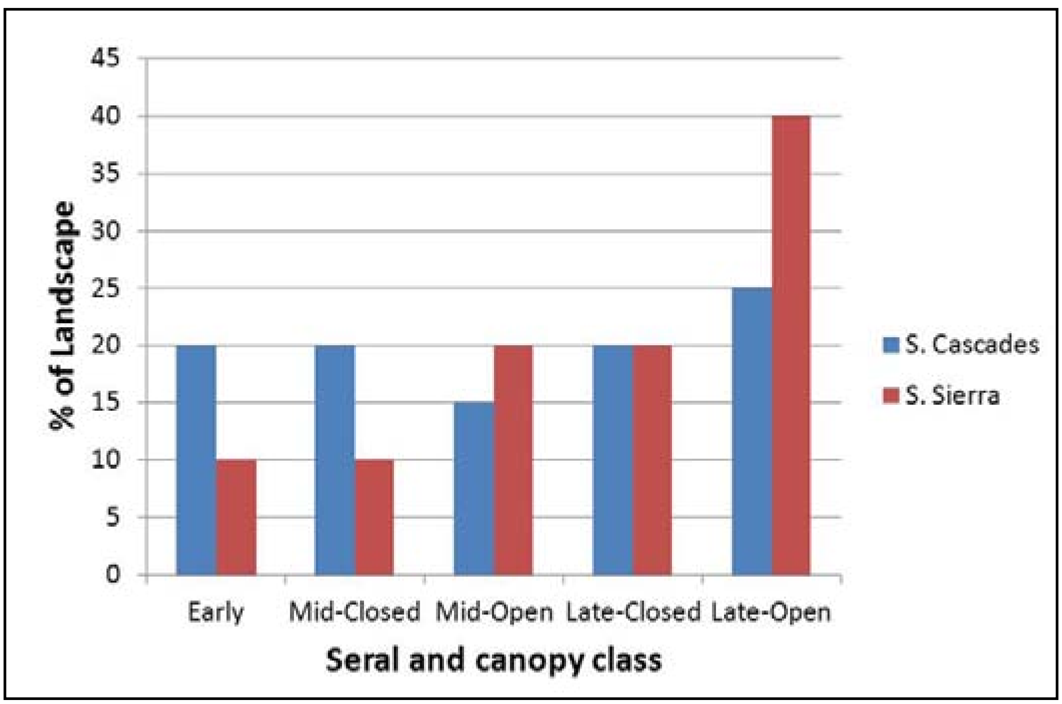
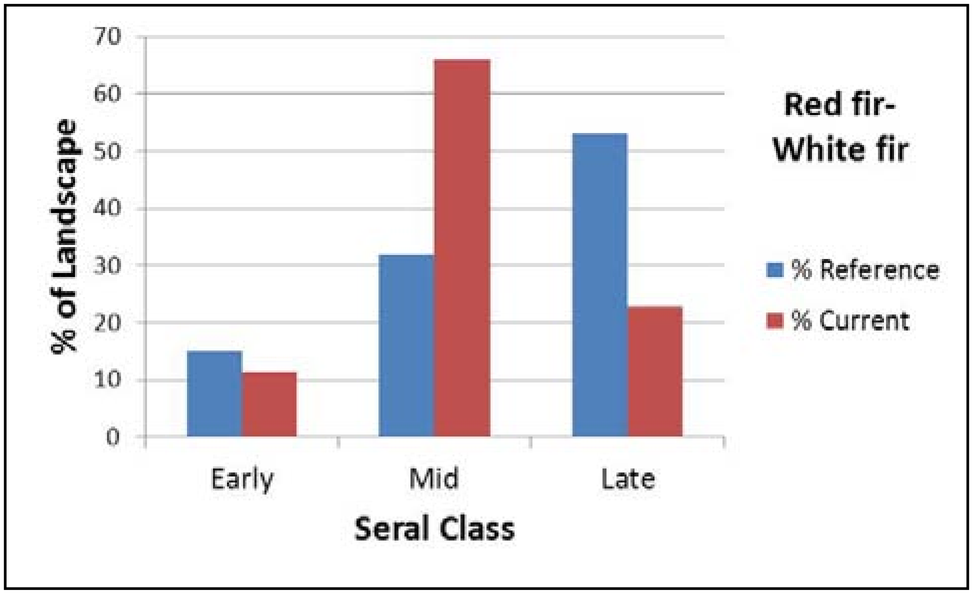


Figure 23 – Percent of reference (i.e., historic) and current red fir forest landscapes in different seral classes based on LANDFIRE Biophysical Setting (BpS) models for the Stanislaus National Forest. Data source is Safford and Schmidt (2006) and Safford and Sherlock (2005a, b).



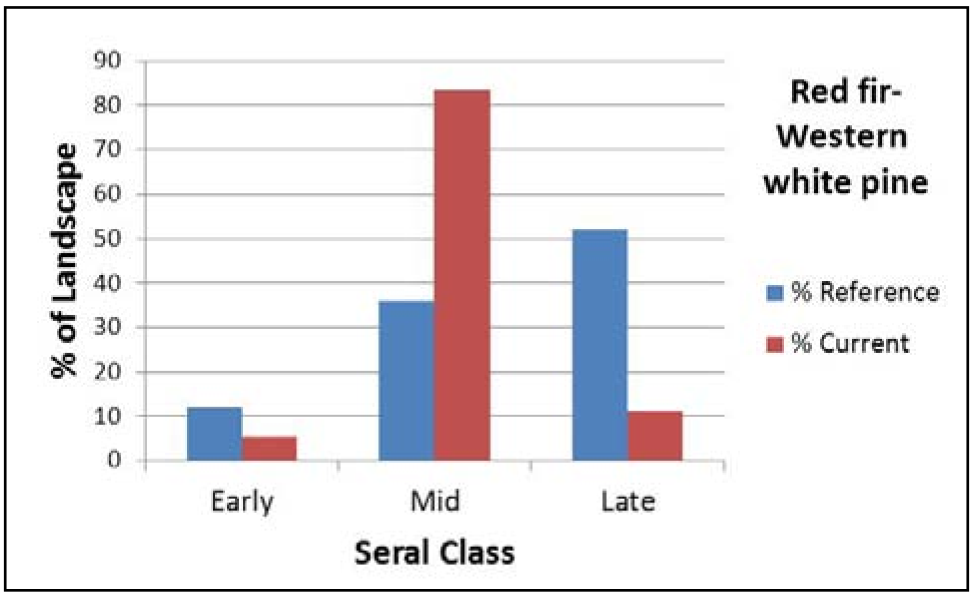


Figure 24 – Relative density and basal area (± SD) of red fir in historic and contemporary un-logged red fir forests of the Sierra Nevada. Data sources are presented on Table 6.

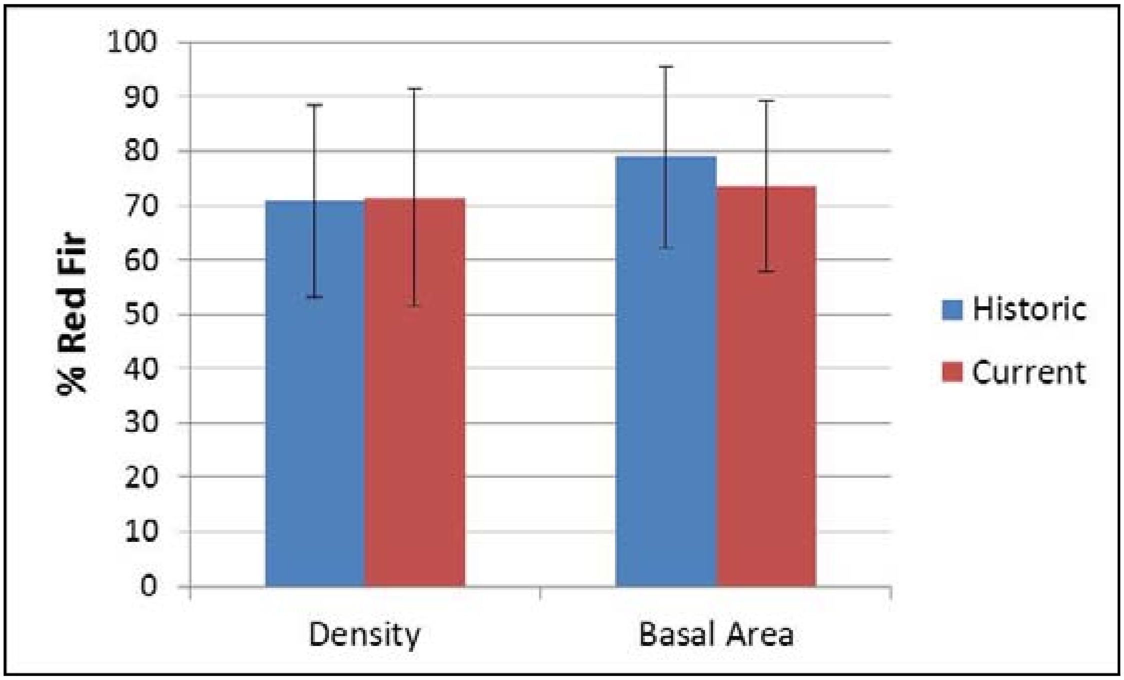
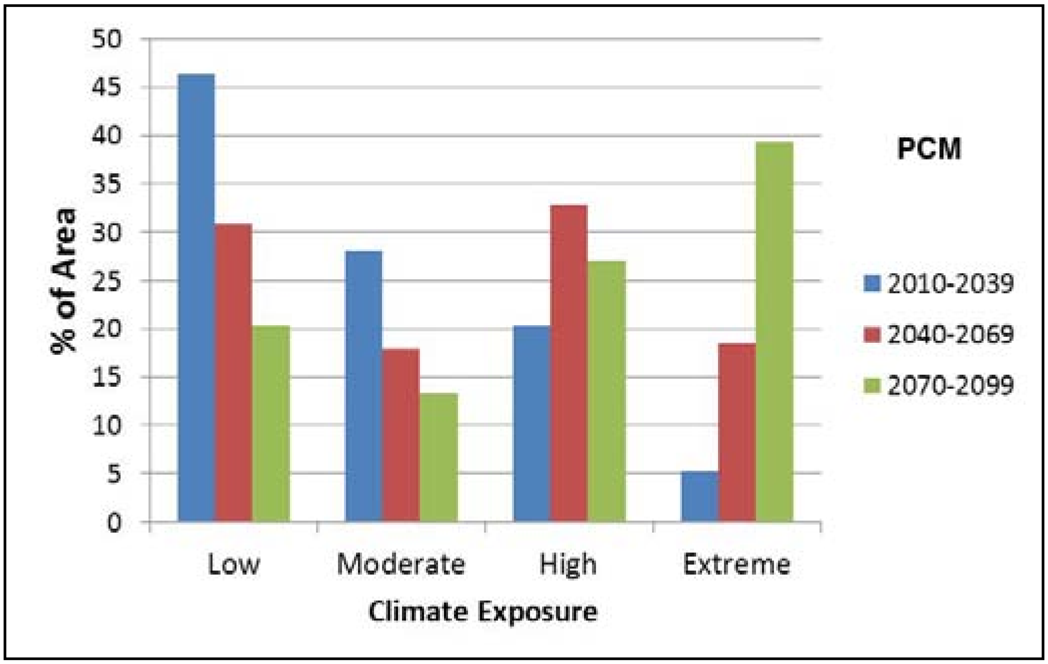


Figure 25 – Future projections of climate exposure for red fir forest in the southern Sierra Nevada national forests (primarily Sequoia, Sierra, and Inyo national forests). Projections by Schwartz et al. (2013) are based on the PCM (top graph) and GFDL (lower graph) global climate models, including three 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.



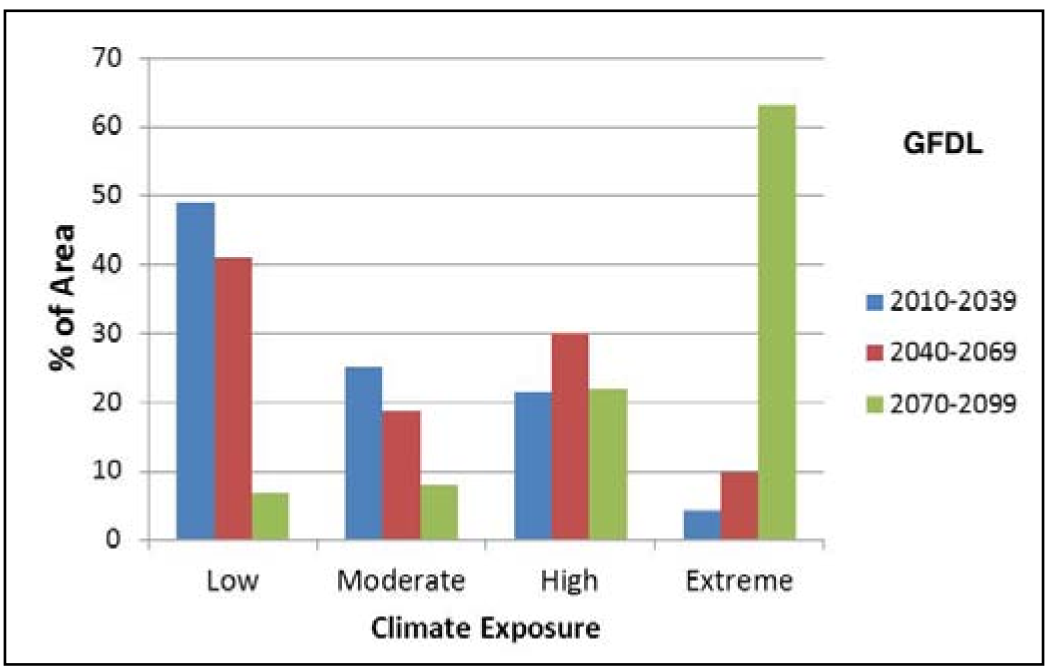


Figure 26 – Future projections (end of century: 2070–2099) of red fir forest climate exposure in the southern Sierra Nevada based on the **PCM** model (warmer and similar precipitation). Levels of climate exposure indicate bioclimatic areas that are projected to be: (1) inside the 66th percentile (Dark 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 current bioclimatic distribution. Areas in green are suggestive of climate refugia for red fir forests by the end of the century. Data source and graphic courtesy of Schwartz et al. (2013).

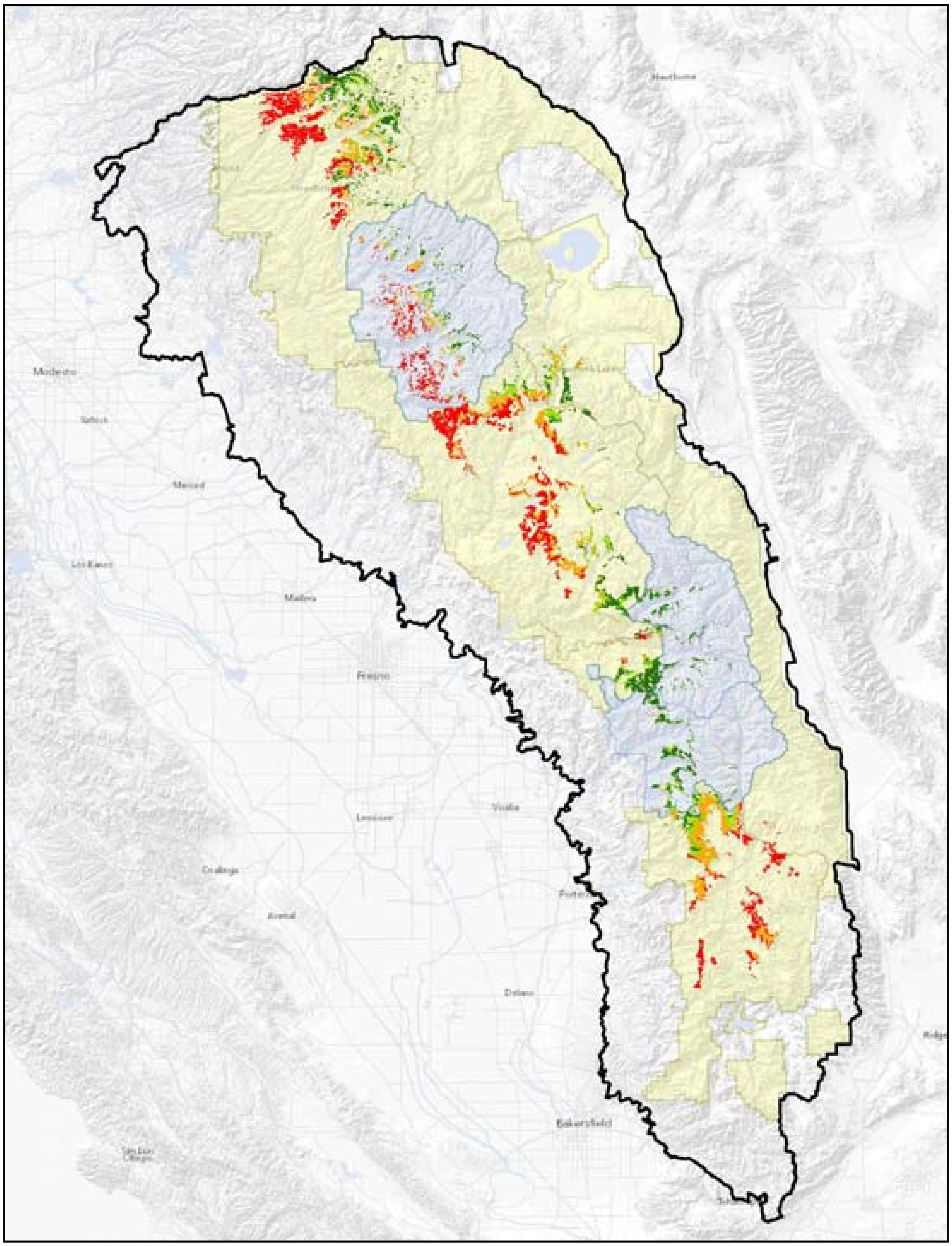


Figure 27 – Future projections (end of century: 2070–2099) of climate exposure for red fir forest in the southern Sierra Nevada based on the **GFDL** model (hotter and drier) used by Schwartz et al. (2013). Levels of climate exposure are described in Figure 25. Data source and graphic courtesy of Schwartz et al. (2013).