CHAPTER FOURTEEN

Sierra Nevada Bioregion

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> In the main forest belt of California, fires seldom or never sweep from tree to tree in broad all-enveloping sheets . . . Here the fires creep from tree to tree, nibbling their way on the needle-strewn ground, attacking the giant trees at the base, killing the young, and consuming the fertilizing humus and leaves.
>
> MUIR (1895)

The Sierra Nevada is one of the most striking features of the state of California, extending from the southern Cascade Mountains in the north to the Tehachapi Mountains and Mojave Desert 620 km (435 mi) to the south (Map14.1). The Central Valley forms the western boundary of the Sierra Nevada bioregion, and the Great Basin is on the east. The bioregion includes the central mountains and foothills of the Sierra Nevada Section and the Sierra Nevada Foothills Section of Miles and Goudey (1997). The area of the bioregion is 69,560 km^2 (26,442 mi^2), approximately 17% of the state. Significant features along the length of the range include Lake Tahoe, Yosemite Valley, and Mount Whitney.

Description of the Bioregion

The natural environment of the Sierra Nevada is a function of the physical factors of geomorphology, geology, and regional climate interacting with the resident biota. These factors are inextricably linked to the abiotic and biotic ecosystem components including local climate, hydrology, soils, plants, and animals. The nature and the distribution of the Sierra Nevada's ecological zones are directly influenced by these interactions. The ecological role of fire in the bioregion varies with changes in the natural environment.

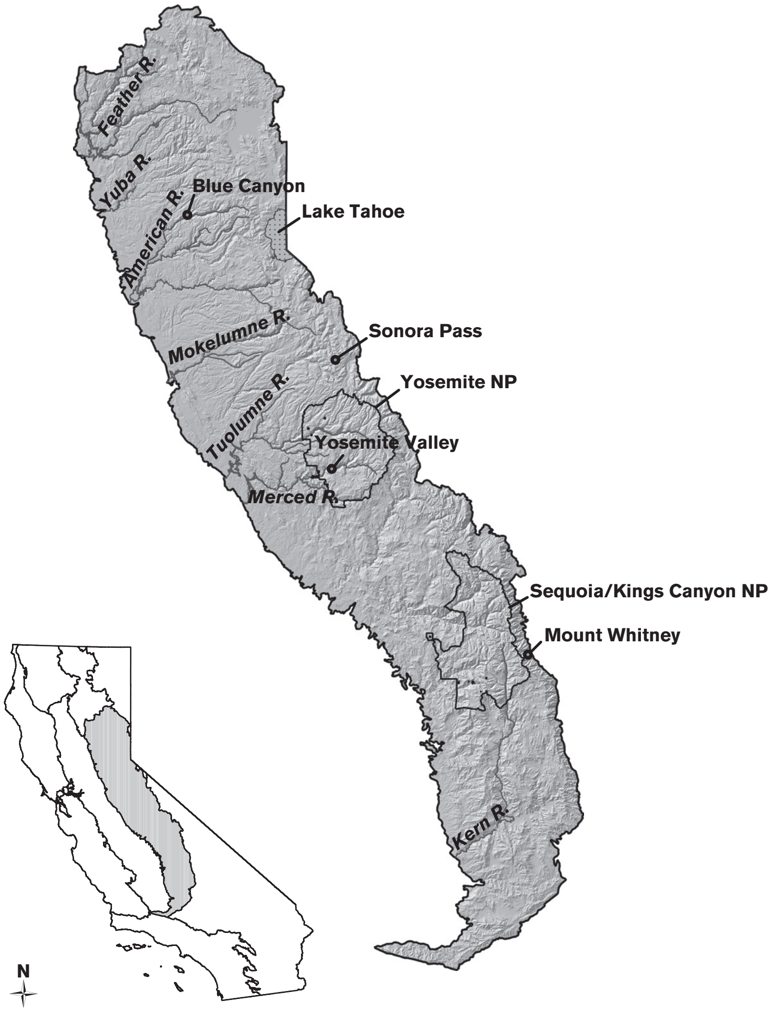
Physical Geography

The Sierra Nevada is a massive block mountain range that tilts to the west-southwest and has a steep eastern escarpment that culminates in the highest peaks. Elevations range from 150 m (492 ft) on the American River near Sacramento to 4,421 m (14,505 ft) at Mount Whitney. The moderately inclined western slope of the Sierra Nevada is incised with a series of steep river canyons from the Feather River in the north to the Kern River in the south. The western foothills are gently rolling with relatively narrow valleys. At the mid-elevations, landforms include deep canyons and broad ridges that run primarily from east-northeast to west-southwest. Rugged mountainous terrain dominates the landscape at the higher elevations. The eastern slope is steep and in some places precipitous, with the relative height of the mountain front increasing greatly as one moves south.

The oldest rocks of the Sierra Nevada were metamorphosed from sediments deposited on the sea floor during the early Paleozoic Era (Huber 1987). Granitoid rocks began to form 225 million years ago with the beginnings of the Nevada Orogeny, and pulses of magma continued for more than 125 million years, forming the granite and grandiorite core of the range (Schweickert 1981). During the Cretaceous Period, mountains were uplifted and erosion stripped the metamorphic rocks from above the granite and exposed large expanses of the core throughout the range. Meandering streams became deeply incised as gradients became steeper. By the Eocene Epoch, about 55 million years ago, this high "proto-Sierra Nevada" had been eroded into a chain of low mountains. Volcanic eruptions during the second half of the Tertiary Period blanketed much of the subdued landscape of the northern Sierra Nevada and portions of the central Sierra Nevada with lava and ash (Hill 1975). Today volcanic and metamorphic rocks occur primarily in the northern and central Sierra Nevada, although outcrops can be seen throughout the range. The sharp relief and high altitude of the modern Sierra Nevada are the products of Late Cenozoic uplift, and periodic earthquakes are a sign that the uplift continues today.

During the Pleistocene Epoch, snow and ice often covered most of the high country, and glaciers filled many of the river valleys. Several glaciations are recognized to have occurred in the Sierra Nevada. These glaciers further deepened valleys and scoured ridges, leaving the exposed granite landscape so prevalent today. Glaciers appear to have more or less disappeared from the Sierra Nevada by the Early Holocene. Modern glaciers scattered on high peaks between Yosemite and Sequoia national parks grew as the climate cooled and water balance rose over the last 4,000 years (Konrad and Clark 1998).

Geology primarily influences fire activity through its influence on soil formation, which in turn influences vegetation. Hard rock types such as granites and quartzites weather slowly, especially where glaciation has stripped soils and removed vegetation. As a result, glaciated ridges in the Sierra Nevada often support relatively little biomass. Valleys and catchments in canyons accumulate sediment, and deep soils



MAP 14.1 The Sierra Nevada bioregion. Locations mentioned in the text are shown on the map.

can develop and support dense forests and grasslands. Differences in topography and glacial history and subtle changes in rock chemistry affect erodibility and nutrient availability, creating a patchwork of forested swales and rocky outcrops and peaks (Hahm et al. 2014). This highly heterogeneous patchwork of vegetation, fuels, and natural barriers affects fire spread. North of Yosemite, rock lithology becomes progressively more dominated by metamorphic and volcanic rocks, and the time for soil formation has been much longer. Forest cover thus tends to be denser and more continuous, and fires can run more easily through the landscape.

Climatic Patterns

The pattern of weather in the Sierra Nevada is influenced by its topography and geographic position relative to the Central Valley, the Coast Ranges, the Pacific Ocean, and the Southeastern Deserts. Winters are dominated by low pressure in the northern Pacific Ocean while summer weather is influenced by high pressure in the same area. The climate type is primarily Mediterranean, with a wet winter and dry summer, but the influence of the Southeastern Deserts is important east of the Sierra Nevada crest, where rainfall from summer monsoons originating in the Gulf of California can be substantial.

FIRE CLIMATE VARIABLES

The primary sources of precipitation are winter storms that move from the north Pacific and cross the Coast Ranges and Central Valley before reaching the Sierra Nevada. Over the long term 30–40% of all precipitation comes in the form of "atmospheric rivers," which arrive as long, linear storm systems carrying large amounts of atmospheric water, often from subtropical sources (Dettinger et al. 2011). Lower coastal mountains catch some of the arriving moisture, but the gap in the mountains near San Francisco Bay allows storms to pass with relatively little orographic loss, producing heavy precipitation in the Sierra Nevada to the east and north. As air masses move up the western slope, precipitation increases and, at the higher elevations, falls as snow. Once across the crest, precipitation decreases sharply. This decrease is less prominent in the northern Sierra Nevada where the crest is not as high as in the central and southern parts of the range. Precipitation also decreases from north to south with nearly twice as much falling in the northern Sierra Nevada as does in the south. Mean annual precipitation ranges from a low of 25 cm (10 in) at the western edge of the southern foothills to over 200 cm (79 in) north of Lake Tahoe. More than half of the total precipitation falls in January, February, and March, much of it as snow. Summer precipitation is associated with afternoon thunder-

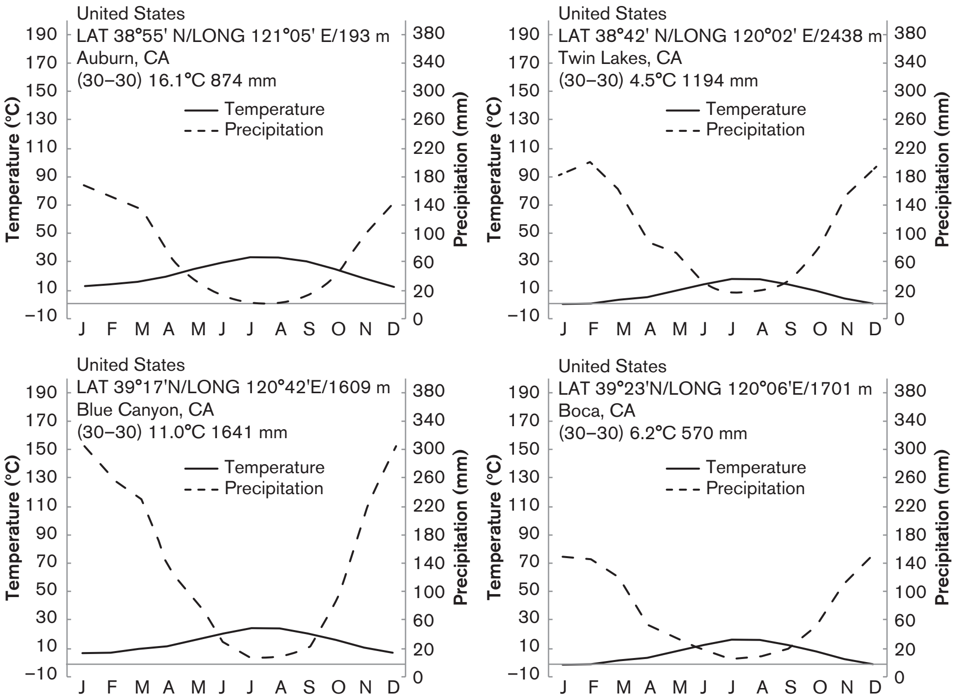


FIGURE 14.1 Annual precipitation and temperature patterns for four stations along a transect from the foothills to the eastern side of the Sierra Nevada.

storms and subtropical storms moving up from the Gulf of California.

Sierra Nevada temperatures are warm in the summer and cool in the winter. Temperatures decrease as latitude and elevation increase, with a temperature lapse rate of approximately 4.5°C with each 1,000 m of elevation (2.5°F in 1,000 ft) (Major 1988). Normal 10:00 am relative humidity is highest in January and lowest in July. Extremely low relative humidity is common in the summer. Sustained wind speeds are variable, averaging up to 10 km hr^{-1} (6 mi hr^{-1}) but have been recorded as high as 100 km hr^{-1} (70 mi hr^{-1}) or more out of the north during October or across high mountain ridges during winter storms.

Fig. 14.1 shows the annual pattern of precipitation and temperature for four stations along a transect in the northern Sierra Nevada. Auburn is located at the upper edge of the foothills and has the hottest summer temperatures. Midway up the slope, Blue Canyon receives the greatest amount of precipitation and slightly cooler temperatures. Twin Lakes is located near the crest with the coldest temperatures and decreasing amounts of precipitation. On the eastern side of the crest, Boca has cool temperatures and scant precipitation.

Monthly precipitation and temperature, in conjunction with soil water holding capacity and snow cover, can be used to calculate annual potential evapotranspiration, actual evapotranspiration, and annual climatic water deficit (Stephenson 1998). Deficits occur when the potential evapotranspiration demand exceeds the water supply (rain plus snowmelt). Both actual evapotranspiration and deficit have been shown to affect the distribution of forest species in the Sierra Nevada (Lutz et al. 2010), and deficits during the summer months can affect fire ignitions and fire severity (Lutz et al. 2009, van Wagtendonk and Smith 2016). Fig. 14.2 shows the water balance for three locations in Yosemite National Park at 1,680 m (5,512 ft), 2,426 m (7,959 ft), and 3,018 m (9,902 ft) elevation. In the ponderosa pine (*Pinus ponderosa*) forest, where temperatures are mostly above 0°C (32°F), a large deficit occurs during the summer and provides opportunities for fire ignitions. In the red fir (*Abies magnifica* var. *magnifica*) forest, precipitation peaks in May, mean monthly temperature is below 0°C (32°F) from mid-November to March, and the resulting deficit is relatively small. Abundant snowmelt and low temperatures limit ignitions in the whitebark pine (*Pinus albicaulis*) forest.

Lightning is pervasive in the Sierra Nevada, occurring in every month (van Wagtendonk and Cayan 2008). There is, however, important spatial and temporal variation. Most strikes occur between noon and 4:00 pm during July and August. Map 14.2 shows the spatial distribution of the average annual number of lightning strikes for the 16-year period from1985 through 2000. The highest concentration of lightning strikes occurs across the crest east of Sonora Pass. In the Sierra Nevada, there is a strong correlation between the number of lightning strikes and elevation, with strikes increasing with elevation up to about 3,200 m (10,500 ft) (Fig. 14.3). Nearly a third of strikes occur in mid-afternoon during July and August.

WEATHER SYSTEMS

Fires tend to be associated with critical fire weather patterns that occur with regularity during the summer (Hull et al. 1966). The Pacific High Postfrontal type is a surface type where air from the Pacific moves in behind a cold front and causes northerly to northwesterly winds in northern and central California. A föhn effect is produced by steep

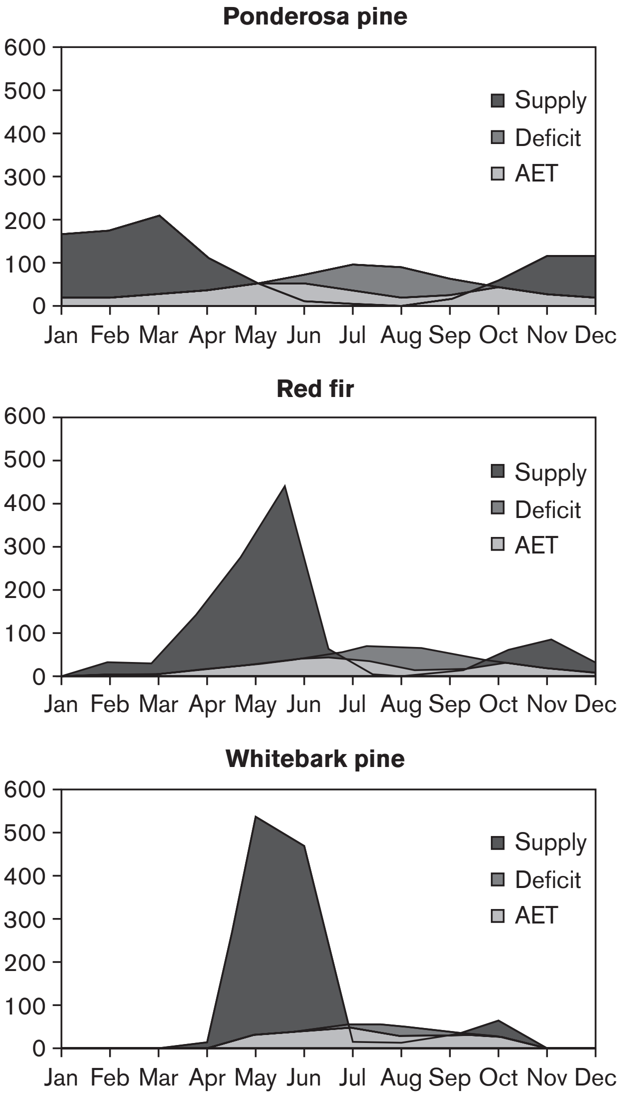
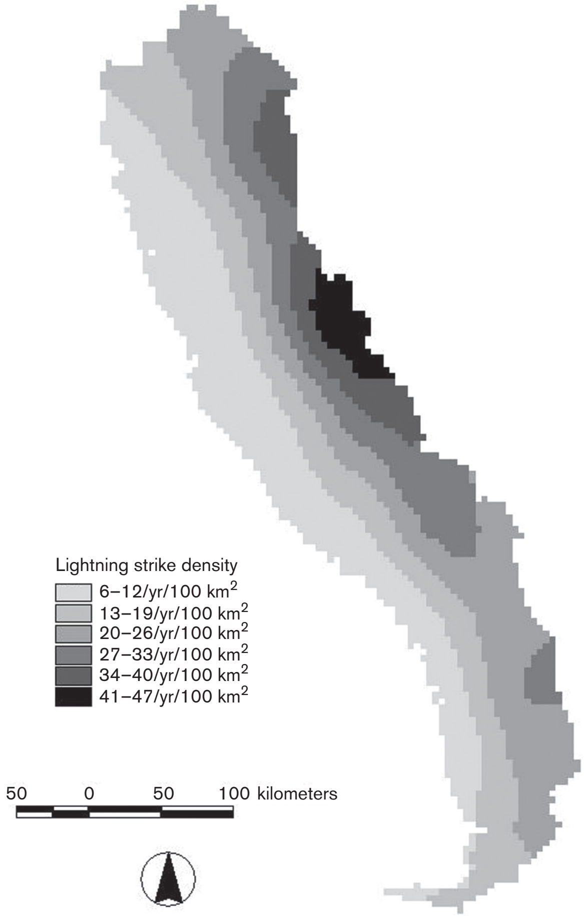


FIGURE 14.2 Water balance relationships for three species in Yosemite National Park in the central Sierra Nevada. Winter temperatures, spring water supply, and soil water capacity combine to determine Deficit and AET. Species water balance curves were based on the means of the plots where these species were present. Among species at similar elevations, increased soil water capacity results in higher AET. Deficits occur when evaporative demand has exhausted stored water and exceeds water supply (from Lutz et al. 2010).



MAP 14.2 Spatial distribution of lightning strikes in the Sierra Nevada bioregion, 1985–2000. The density increases from west to east and reaches a maximum just east of the crest north of Sonora Pass.

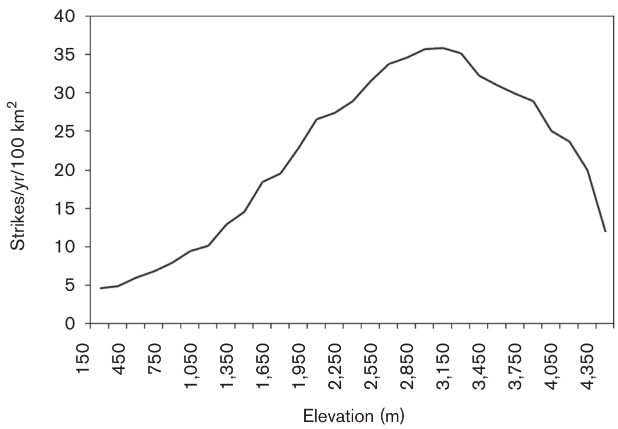


FIGURE 14.3 Lightning strikes by elevation in the Sierra Nevada bioregion, 1985–2000. The density of strikes is greatest at 3,000 m and decreases as elevation increases above that point.

pressure gradients behind the front causing strong winds to blow downslope. The Great Basin High often follows the Pacific High Postfrontal type with air stagnating over the Great Basin. Combined with a surface thermal trough off the California coast, the Great Basin High creates strong pressure gradients and easterly or northeasterly winds across the Sierra Nevada. Although this type is often present during winter months when fires are uncommon, the Great Basin High can produce extreme fire weather during the summer.

During the Subtropical High Aloft type, the belt of westerly winds is displaced northward and a stagnant air pattern effectively blocks advection of moist air from the Gulf of Mexico. High temperature and low relative humidity are associated with this type. The Meridional Ridge with Southwest Flow pattern requires a ridge to the east and a trough to the west, allowing marine air penetration in coastal and inland areas. Above the marine layer in the Sierra Nevada, temperatures are higher and relative humidities are lower as short wave troughs and dry frontal systems pass over the area (Hull et al. 1966).

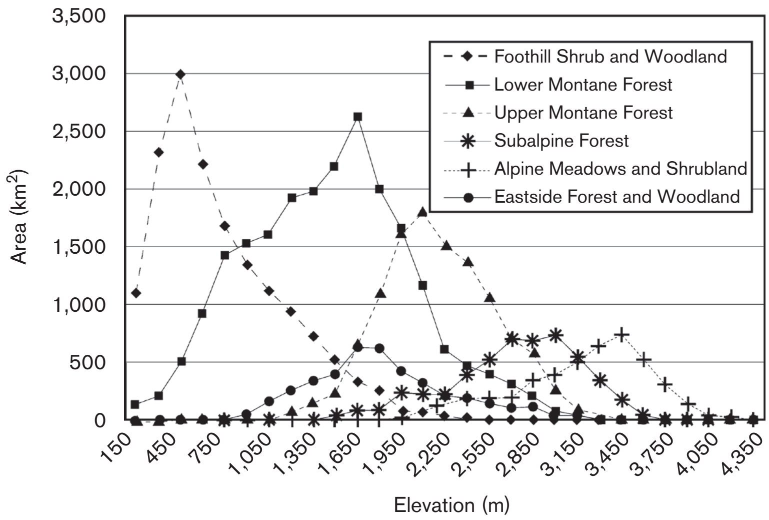


FIGURE 14.4 Area of ecological zones by 500 m elevation bands summed for the entire Sierra Nevada. Each zone is found at progressively higher elevations from the northern Sierra Nevada to the south, hence the broad elevational distributions shown in the figure.

Recent fires such as the Rim fire in 2013 and the King fire in 2014 burned under these conditions.

Ecological Zones

The vegetation of the Sierra Nevada is as variable as its topography and climate. In response to actual evapotranspiration and deficit, the vegetation forms six broad ecological zones that roughly correspond with elevation (Stephenson 1998). These zones include (1) the foothill shrubland and woodland zone, (2) the lower montane forest zone, (3) the upper montane forest zone, (4) the subalpine forest zone, (5) the alpine meadow and shrubland zone, and (6) the eastside forest and woodland zone. These zones are arranged in elevation belts from the Central Valley up to the Sierra Nevada crest and back down to the Great Basin (Fig. 14.4). Because of the effects of latitude on temperature, the belts increase in elevation from the northern to southern Sierra Nevada.

FOOTHILL SHRUBLAND AND WOODLAND

The foothill shrubland and woodland zone covers about 16,000 km² (6,200 mi²) from the lowest foothills at 142 m (466 ft) to occasional stands at 1,500 m (5,000 ft). The primary vegetation types in this zone are foothill pine-interior live oak (*Pinus sabiniana*-*Quercus wislizeni*) woodlands, mixed hardwood woodlands and chaparral shrublands. Blue oak (*Q. douglasii*) woodlands and annual grasslands occur at lower elevations and are treated in chapter 15.

LOWER MONTANE FOREST

The lower montane forest is the most prevalent zone in the Sierra Nevada bioregion, occupying about 22,000 km² (8,500 mi²) primarily on the west side of the range above the foothill zone. Major vegetation types include California black oak (*Quercus kelloggii*), ponderosa pine, white fir (*Abies concolor*) mixed conifer, Douglas-fir (*Pseudotsuga menziesii* var. *menziesii*) mixed conifer, and mixed evergreen forests. Interspersed within the forests are chaparral stands, riparian forests, and meadows.

UPPER MONTANE FOREST

This ecological zone covers about 11,500 km² (4,400 mi²) and extends from as low as 750 m (2,500 ft) in the northernmost Sierra Nevada to as high as 3,450 m (11,500 ft) in the southern Sierra Nevada. The upper montane forest is most widespread above 1,950 m (6,500 ft), the elevation at which most winter precipitation transitions from rain to snow. Forests within this zone include extensive stands of California red fir accompanied by variable densities of western white pine (*Pinus monticola*) and lodgepole pine (*P. contorta* subsp. *murrayana*). Woodlands with Jeffrey pine (*P. jeffreyi*) and Sierra juniper (*Juniperus grandis*) occupy exposed ridges and warm dry slopes, and meadows and quaking aspen (*Populus tremuloides*) stands occur in moist areas.

SUBALPINE FOREST

The subalpine forest zone ranges from a low of 1,650 m (5,500 ft) in the northern Sierra Nevada to a high of 3,450 m (11,500 ft) in the southern Sierra Nevada. The subalpine zone comprises about 5,000 km² (1,930 mi²) and consists of forests and woodlands of lodgepole pine, and mountain hemlock (*Tsuga mertensiana*), whitebark pine, limber pine (*P. flexilis*), and foxtail pine (*P. balfouriana* subsp. *austrina*), with numerous large meadow complexes.

ALPINE MEADOW AND SHRUBLAND

Sitting astride the crest of the Sierra Nevada is the 4,400-km² (1,700-mi²) alpine meadow and shrubland ecological zone. The zone extends from as low as 2,000 m (7,000 ft) in the northern Sierra Nevada to as high as 4,421 m (14,505 ft) in the southern Sierra Nevada. Willow (*Salix* spp.) shrublands and alpine fell fields containing grasses, sedges, and herbs are the dominant vegetation types.

EASTSIDE FOREST AND WOODLAND

On the eastern side of the Sierra Nevada, forest and woodlands cover a total of about 3,900 km^2 (1,500 mi^2). Single-leaf pinyon pine (*Pinus monophylla*) and western juniper (*Juniperus occidentalis*) woodlands are extensive, as are woodlands and forests dominated by Jeffrey pine and ponderosa pine, often with some component of white fir where moisture is sufficiently available. Shrublands dominated by sagebrush (*Artemisia tridentata*), bitterbrush (*Purshia tridentata*), and other associated species are also widespread. The zone ranges in elevation from a low of 1,050 m (3,500 ft) in the northern Sierra Nevada up to a high of 2,850 m (9,500 ft) in the south.

Overview of Historical Fire Occurrence

Fire has been an ecological force in the Sierra Nevada for millennia. A Mediterranean climate, flammable fuels, abundant ignition sources, and hot, dry summers combine to produce conditions conducive for an active fire role. Fire activity has varied over time, with different patterns characterizing the Early, Middle, and Late Holocene Epochs.

Prehistoric Period

The earliest charcoal evidence of fire in the Sierra Nevada is found in lake sediments between 11,000 and 17,000 years old (Smith and Anderson 1992, Brunelle and Anderson 2003). These records are from glacially scoured lakes and are no older than the time of deglaciation after the Last Glacial Maximum. Core samples from meadow sediments also record fire back to the beginning of the Holocene (Anderson and Smith 1997). Fire scar studies are constrained by the durability of wood, but in the Sierra Nevada the large size and old age of many tree species allows records as far back as 3,000 years before present. The first fire scar studies in the western Sierra Nevada were conducted by Show and Kotok (1924). Since then, numerous fire scar studies have been published studies (Wagener 1961a, Kilgore and Taylor 1979, Taylor 2000, 2004, Stephens and Collins 2004, Collins and Stephens 2007, Moody et al 2006, Vaillant and Stephens 2009, Scholl and Taylor 2010, Van de Water and North 2010). Additional studies have developed fire histories for the eastern Sierra Nevada including the Lake Tahoe Basin (Gill and Taylor 2009, North et al. 2009, Taylor et al. 2013).

Pollen and macrofossils in lake and meadow cores and fire scars show broadly similar trends in climate, vegetation, and fire in the Sierra Nevada since the beginning of the Holocene Epoch. The Early Holocene (11,700 BP to 8,200 BP) was a period of postglacial warming, with general conditions somewhat cooler and moister than today. At the beginning of the epoch, elevations that currently support lower montane forests were dominated by sagebrush and grass species, with minor presence of pines and juniper (Woolfenden 1996). By the middle of the Early Holocene, however, conifer forests had established themselves in most of these areas (Minnich 2007, Hallett and Anderson 2010). Most paleo records suggest that fires were common, but generally less frequent than during the remainder of the Holocene.

During the Middle Holocene (8,200 BP to 4,200 BP) climate became much warmer and drier, with the warmest and driest conditions of the Holocene occurring between 6,500 BP and 6,000 BP. Fire frequency increased markedly during the Middle Holocene, although some places saw reduced frequencies because they were too dry to support much plant cover (Woolfenden 1996, Beaty and Taylor 2009). The pollen data show that forests of pine and fir were replaced by oak, sagebrush, and juniper in many areas, and forest structure was likely very open, with abundant understory shrubs. Conifers invaded former moist areas of meadow, and desert plant and animal taxa migrated upslope (Anderson 1990, Minnich 2007).

The Late Holocene (4,200 BP to present) has been characterized by general cooling, with some warmer periods. Precipitation increased, and small glaciers began to form again in the Sierra Nevada. According to Millar and Woolfenden (1999), the spatial and compositional outlines of modern Sierra Nevada ecosystems developed by the beginning of the Late Holocene. As temperatures cooled, available moisture rose, fir and incense cedar (*Calocedrus decurrens*) abundance began to increase, and giant sequoias (*Sequoiadendron giganteum*) colonized their current groves. At high elevations, firs and hemlock supplanted pine and chaparral (Anderson 1990). White fir increased in abundance, and oaks and sagebrush declined since the end of the Middle Holocene. Fire frequency dropped from its mid-Holocene high, allowing the development of denser forest types in moist locations.

The last 1,000 years of the Holocene have been marked by short-term changes in temperature and precipitation that have had marked impacts on Sierra Nevada ecosystems (Woolfenden 1996, Millar and Woolfenden 1999, Minnich 2007). Between about 900 and 1100 AD and 1200 to 1350 AD, two long "Medieval Droughts" led to very low levels in lakes and streams and increased fire frequencies. This was followed by a shift to cooler temperatures known as the "Little Ice Age" that lasted from about 1400 to 1880; the period between 1650 and 1850 was the coolest since the Early Holocene (Stine 1974). Glaciers expanded in the Sierra Nevada, tree line dropped, and fire frequencies moderated.

Van de Water and Safford (2011) reviewed all of the available fire scar literature and provided a comprehensive summary of pre-Euro-American settlement fire return intervals for fire regime types as they existed in California before major Euro-American settlement (i.e., before 1850). Their data for the mean, median, mean minimum, and mean maximum fire return intervals for Sierra Nevada vegetation types and characteristic species are included in Table 14.1. Median fire return intervals ranged from 7 years for yellow pine forest and woodland to 132 years for subalpine forest.

Although lightning ignitions would have been present for millennia prior to charcoal appearing in lake sediments 17,000 years ago, ignitions by Native Americans probably did not occur until about 9,000 years ago (Hull and Moratto 1999). Their use of fire was extensive and had specific cultural purposes (Anderson and Rosenthal 2015). It is currently not possible to determine whether charcoal deposits or fire scars were caused by lightning fires or by fires ignited by Native Americans. However, Anderson and Carpenter (1991) attributed a decline in pine pollen and an increase in oak pollen coupled with an increase in charcoal in sediments in Yosemite Valley to expanding populations of Native Americans 650 years ago. Similarly, Anderson and Smith (1997) could not rule out burning by Native Americans as the cause of the change in fire regimes beginning 4,500 years ago. It is reasonable to assume that their contribution to ignitions was significant but varied over the spectrum of inhabited landscapes (Vale 2002), grading from high levels of fire use in the foothill chaparral and woodland belt to little or no use in subalpine forests.

TABLE 14.1

Mean, median, mean minimum, and mean maximum historical fire return intervals for major Sierra Nevada vegetation types (from Van de Water and Safford 2011). Van de Water and Safford summarized fire history records for the entire state of California. Local and regional deviations from the listed means and medians are common, but values will be found between the mean minima and maxima

Ecological zone	Vegetation type[a] (characteristic species)	Mean	Median	Mean min	Mean max
Foothill woodland	Chaparral and serotinous conifers (chamise, manzanita, California lilac, knobcone pine)	55	59	30	90
	Oak woodland (blue oak, interior live oak, foothill pine)	12	12	5	45
Lower montane forest	Mixed evergreen forest (canyon live oak, interior live oak, black oak, tan oak, madrone, California bay, Douglas-fir)	29	13	15	80
	Yellow pine forest and woodland (ponderosa pine, sugar pine, black oak)	11	7	5	40
	Dry mixed conifer forest (ponderosa pine, sugar pine, incense cedar, white fir, black oak)	11	9	5	50
	Moist mixed conifer forest (white fir, D ouglas-fir, incense cedar, ponderosa pine, sugar pine, lodgepole pine, giant sequoia)	16	12	5	80
	Montane chaparral (huckleberry oak, California lilac, manzanita, bitter cherry, chinquapin)	27	24	15	50
Upper montane forest	Red fir forest (red fir, western white pine, lodgepole pine)	40	33	15	130
	Western white pine forest	50	42	15	370
	Lodgepole pine woodland	37	36	15	290
	Aspen forest	19	20	10	90
	California juniper	83	77	5	335
Subalpine forest	Subalpine forest (mountain hemlock, lodgepole pine, whitebark pine, limber pine, foxtail pine, western white pine)	133	132	100	420
Eastside woodland and forest	Yellow pine forest and woodland (Jeffrey pine, ponderosa pine)	11	7	5	40
	Pinyon-juniper woodland (single-leaf pinyon pine, juniper)	151	94	50	250
	Big sagebrush (big sagebrush, bitter brush, rabbit brush)	35	41	15	85

[a] Some types occur in more than one vegetation zone, and most of them are listed only once in the zone in which they are most prevalent.

Historic Period

The arrival of Euro-Americans in the Sierra Nevada affected fire regimes in several ways. Native Americans were often driven from their homeland, and diseases brought from Europe decimated their populations. As a result, use of fire by Native Americans was greatly reduced. Settlers further modified fire regimes by introducing cattle and sheep to the Sierra Nevada, setting fires in attempts to improve the range, and suppressing fires to protect timber. Extensive fires occurred as a result of loggers who burned slash, prospectors who burned large areas to enhance the discovery of mineral outcrops, and shepherds who burned to increase forage and ease travel (Leiberg 1902, Vankat and Major 1978, Safford and Stevens 2017).

The effect of Euro-Americans on fire in the Sierra Nevada was to severely reduce its frequency. Evidence of the changed fire regimes is found in charcoal deposits and fire scars. The meadow sediments examined by Anderson and Smith (1997) showed a drop in charcoal particles during the most recent century, which they attributed to fire suppression. Beaty and Taylor (2009) documented a similar pattern in lake sediments from near Lake Tahoe. Essentially all fire scar studies in the Sierra Nevada document the near complete elimination of fire by the beginning of the twentieth century (Wagener 1961a, Kilgore and Taylor 1979, Swetnam 1993, Stephens and Collins 2004, Taylor 2004, North et al. 2005).

Of all the activities affecting fire regimes, the exclusion of fire by suppression forces has had the greatest effect. Beginning in the late 1890s, the US Army attempted to extinguish all fires within the national parks in the Sierra Nevada (van Wagtendonk 1991b). When the Forest Service was established in 1905, it developed both a theoretical basis for systematic fire protection and considerable expertise to execute that theory on national forests (Show and Kotok 1923). This expertise was expanded to the fledgling National Park Service when it was established in 1916. Fire control remained the dominant management practice throughout the Sierra Nevada until the late 1960s.

Fire exclusion resulted in an increase in accumulated surface debris and density of shrubs and understory trees. Although the number of fires and the total area burned decreased between 1908 and 1968, the proportion of the yearly area burned by the largest fire each year increased (McKelvey and Busse 1996). Suppression forces were able to extinguish most fires while they were small but, during extreme weather conditions, they were unable to control the large ones.

Current Period

The National Park Service changed its fire policy in 1968 to allow the use of prescribed fires deliberately set by managers, and to allow fires of natural origin to burn under prescribed conditions (van Wagtendonk 1991b). The Forest Service followed suit in 1974, changing from a policy of fire control to one of fire management (DeBruin 1974). As a result, fire was reintroduced to national parks in the Sierra Nevada through programs of prescribed burning and managed wildfires (Kilgore and Briggs 1972, van Wagtendonk 2007). Similarly, the Stanislaus, Sierra, Sequoia, and Inyo national forests have managed some wilderness wildfires for resource benefit since 2003 (Meyer 2015).

For much of the Sierra Nevada, however, routine fire suppression is still the rule. For lower montane and foothill forests, where most fires occurred before fire exclusion, vegetation structure and fire regimes have been greatly altered. Fire frequencies in these forest types have shifted from frequent to very infrequent (Safford and Van de Water 2014), in contrast forests in the Sierra de San Pedro Mártir, Mexico, have experienced fire through much of the twentieth century and are therefore important reference sites (see sidebar 14.1). Steel et al. (2015) estimated that 74% of mixed-conifer forests in California had not experienced a fire in the last century. When fire does occur, there are much greter proportions of high severity relative to the historical period (Miller et al. 2009, Mallek et al. 2013, Lydersen et al. 2014, Harris and Taylor 2015, Safford and Stevens 2017). Some headway is being made in wilderness areas and areas where prescribed fire can be applied safely and effectively, but the overall deficit in fire is huge and widening (North et al. 2012).

Widespread harvesting, primarily targeting overstory trees, beginning in the early twentieth century also contributed to contemporary fire patterns. Large accumulations of slash and vigorous tree establishment and growth resulted in stands that became overstocked with much greater horizontal and vertical fuel continuity than existed prior to harvesting and fire exclusion (Knapp et al. 2013). Consequently many forests now have so much fuel that most fires are likely to move into the canopy, crowning out and killing many overstory trees (Stephens and Moghaddas 2005, Ritchie et al. 2007, Valliant et al. 2009). Under these conditions, prescribed fire without antecedent thinning is difficult to use unless fuel moistures are high, and even then multiple applications may be needed to reduce fuels sufficiently to restore surface burning conditions.

Major Ecological Zones

The six ecological zones of the Sierra Nevada are comprised of different vegetation types and species. Each species has different adaptations to fire and varies in its relation to fire. Similarly, the fire regimes and plant community interactions of the zones vary.

Foothill Shrubland and Woodland

The foothill shrubland and woodland zone is bounded below by the valley grasslands and blue oak woodlands, and above the lower montane zone, which is conifer dominated. The terrain is moderately steep with deep canyons. Metasedimentary, metavolcanic, and granitic rocks form the substrate, and soils are generally thin and well drained. The climate is subhumid with hot, dry summers and cool, moist winters. Lightning is relatively infrequent averaging only 8.25 strikes yr^{-1} 100^{-1} km^{-2} (75.9 strikes yr^{-1} 100^{-1} mi^{-2}).

The vegetation is a mix of large areas of chaparral and live oak woodland with patchy foothill or ponderosa pines (Fig. 14.5); annual grasslands are also common. Except on very unproductive soils, chaparral forms dense continuous stands of vegetation and fuels. Chamise (*Adenostoma fasciculatum*), manzanita (*Arctostaphylos* spp.), and California-lilac (*Ceanothus* spp.) dominate the chaparral. Interior live oaks and canyon live oaks (*Quercus chrysolepis*) are extensive on steep slopes of large canyons, and can be accompanied by Pacific madrone (*Arbutus menziesii*), big-leaf maple (*Acer macrophyllum*), California buckeye (*Aesculus californica*), and Douglas-fir on north-facing slopes or where moisture and soil conditions permit. This forest type is commonly referred to as mixed evergreen. Tall deciduous shrubs or forests dominate riparian areas with dense vertical layering and a cooler microclimate.

FIRE RESPONSES OF IMPORTANT SPECIES

Many foothill species of the Sierra Nevada have fire responses and characteristics that are similar to those of the interior South Coast zone described in chapter 17. Chaparral includes several sprouting shrub species and some that require heat or other fire cues for seed germination. As in southern California, many herb species are strongly benefitted by fire. The two live oaks are vigorous sprouters. The most prevalent conifers are fire resistant, such as ponderosa pine, or have serotinous cones, such as foothill pine and knobcone pine (*Pinus attenuata*). Establishment, survival, and abundance of many species are enhanced by fire. The fire responses for knobcone pine, ponderosa pine, and chamise are covered in more detail in the North Coast (chapter 10), Northeast Plateaus (chapter 13), and South Coast (chapter 17) chapters, respectively. Table 14.2 lists the fire responses of the important species in the foothill zone.

Most chaparral shrubs sprout following fire. These include chamise, birch-leaf mountain-mahogany (*Cercocarpus betuloides* var. *betuloides*), yerba santa (*Eriodictyon californicum*), California coffeeberry (*Frangula californica*), and toyon (*Heteromeles arbutifolia*). Nonsprouting shrubs can be locally dominant, with seeds that are heat resistant and have fire-enhanced germination—such as whiteleaf manzanita (*Arctostaphylos viscida*), chaparral whitethorn (*Ceanothus leucodermis*), and buckbrush (*C. cuneatus* var. *cuneatus*). Some species like chamise, yerba santa, greenleaf manzanita (*A. patula*),

SIDEBAR 14.1 FORESTS IN THE SIERRA DE SAN PEDRO MÁRTIR, BAJA CALIFORNIA, MEXICO

S.L. Stephens and H.D. Safford

FIGURE 14.1.1 Jeffrey pine forest in the Sierra de San Pedro Mártir, Baja California, Mexico.

Fire suppression and harvesting have impacted the majority of California's ponderosa pine, mixed conifer, and Jeffrey pine forests. These changes have made it difficult to derive reference conditions for management, conservation, and restoration, particularly at landscape scales. One Jeffrey pine-mixed-conifer forest exists where fire suppression did not begin until the 1970s and harvesting was confined to an area less than 10 ha (25 ac); the Sierra de San Pedro Mártir (SSPM) in Baja California, Mexico (Minnich and Franco 1998, Fry et al. 2014) (Fig. 14.1.1). This region includes approximately 20,000 ha (50,000 ac) of Jeffrey pine and mixed conifer forests that are floristically similar to forests of the eastern Sierra Nevada (Dunbar-Irwin and Safford 2016) and southern California mountains (Minnich et al. 1995). Climatic analysis of the SSPM and 17 meteorological stations in the range of Jeffrey pine determined that the SSPM clearly belongs to the general class of Jeffrey pine-dominated yellow pine-mixed-conifer (YPMC) forests (Dunbar-Irwin and Safford 2016).

Recent research measured forest structure, fuels, and vegetation and ground cover in the SSPM and in multiple National Forests along the eastern slope of the Sierra Nevada (Dunbar-Irwin and Safford 2016). Live tree density was nearly twice as high in the eastern Sierra Nevada as in SSPM, and dead tree density was 2.6 times higher. Basal area was about 30% higher in the eastern Sierra Nevada even though average tree size was larger in SSPM. Fuel loads and coarse woody debris were very similar between the two sites, and fine fuels (1-h fuels) were actually higher in SSPM. Logging and fire suppression have resulted in denser YPMC forests dominated by smaller trees in California, but Dunbar-Irwin and Safford's (2016) results suggest that fire suppression in SSPM over the last 40 years has increased surface fuel loads. Nonetheless, the Baja California forests still retain an overstory structure created and maintained by centuries of frequent fire.

Fire severity trends in the SSPM and the Sierra Nevada are very different over the last several decades

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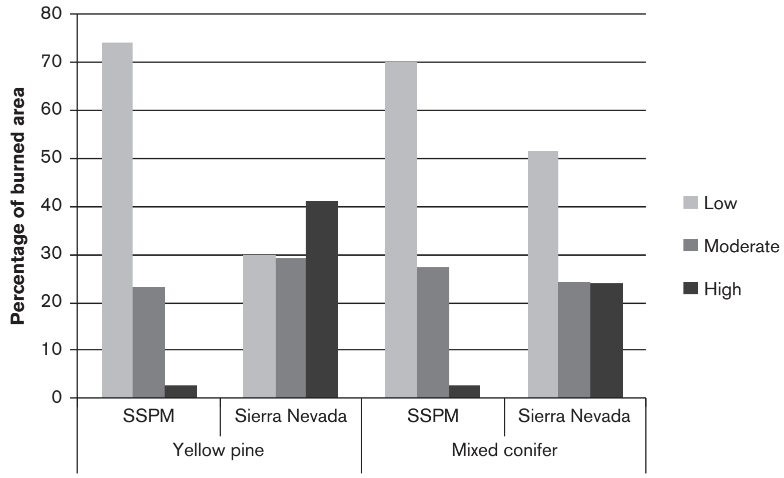

FIGURE 14.1.2 Fire severity distribution in the Sierra de San Pedro Mártir, Baja California, Mexico, versus distribution from the Sierra Nevada, California, USA. Data from 1984 to 2010. The measured variable is % basal area mortality, categorized as low (<25% mortality), moderate (25–90% mortality), and high (>90% mortality). Data from Rivera et al. (2015).

(Rivera-Huerta et al. 2015). LANDSAT data were used to identify 32 fires that burned 26,529 ha (66,555 ac) in the SSPM from 1984 to 2010, of this, 1,993 ha (4,925 ac) burned in YPMC forests in 17 fires. No temporal trends in forest burned area or in the proportion of high severity fire were found in the SSPM, but the mean size of high-severity patches within fires is rising. In the SSPM, the overall proportion of fire area burned at high severity averaged 3% (average high-severity patch = 2.9 ha [7.1 ac], median = 0.6 ha [1.5 ac], largest high-severity patch = 11.3 ha [27.9 ac]) in both yellow pine and mixed-conifer forests (Fig. 14.1.2), similar to severity values found in much of the Sierra Nevada historically (Stephens et al. 2015, Safford and Stevens 2017). In the SSPM, there was no correlation between burned area and proportion of high-severity fire; Rivera-Huerta et al (2015) interpreted this to mean that differences in fuels in the SSPM were more important to fire behavior than weather condition. This is in stark contrast to similar forests in California, which are experiencing fires of sizes and severities that fall far outside the historical range of variation.

Resilience to drought followed by fire has also been demonstrated in SSPM forests (Stephens et al. 2008, 2018). Fire effects were moderate especially considering that a 2003 wildfire occurred at the end of a severe, multiyear (1999–2003) drought. Shrub consumption was an important factor in tree mortality and the dominance of Jeffrey pine increased after fire. The SSPM wildfire enhanced or maintained a patchy forest structure, in contrast to large high-severity fires in California that produce homogeneous structures in large high-severity patches. The cumulative impact of 4 years of severe drought followed by wildfire only killed 20% of the trees (Stephens et al. 2008) in the SSPM demonstrating that YPMC can be very resilient to stressors if properly restored and managed.

and deer brush (*C. integerrimus*) are facultative, and regenerate after fire both by sprouting and by fire-enhanced germination. Many chaparral species produce seed at an early age that can remain viable in the soil for many decades. Buckbrush and deer brush produce seeds at around 4 to 7 years of age. Growing in dominantly single species patches, such species resist burning until decadent or foliar moistures are extremely low. Many years' worth of seeds are often produced before fire returns, enhancing postfire dominance.

Depending on nutrient and water availability, chaparral stands can recover biomass very rapidly after fire. This is especially true where resprouting species dominate the stand. As chaparral stands age, overall biomass levels off and the proportion of dead biomass increases (Oechel and Reid 1983). For

FIGURE 14.5 Foothill shrub and woodland. Foothill pine and interior live oak are dominant overstory species in this stand with nonnative grasses and species of manzanita and California-lilac in the understory. Grazing, thin soils, and periodic fire help keep the understory relative clear.

TABLE 14.2
Fire response types for important species in the foothill shrub and woodland ecological zone

	Type of fire response			
Lifeform	Sprouting	Seeding	Individual	Species
Conifer	None	None	Resistant, killed	Ponderosa pine
	None	Fire-stimulated (seed release)	Resistant, killed	Foothill pine, knobcone pine
Hardwood	Fire-stimulated	None	Top-killed or branch killed	Blue oak, interior live oak, canyon live oak
Shrub	Fire-stimulated	None or unknown	Top-killed	Poison oak, flannelbush, coyote bush, birch-leaf mountain-mahogany, yerba santa, California coffeeberry, Christmas berry
	Fire-stimulated	Fire-stimulated	Top-killed	Chamise, redbud
	None	Fire-stimulated	Killed	Whiteleaf manzanita, chaparral whitethorn, buckbrush
	None	None	Killed	
Forb	Fire-stimulated	None	Top-killed	Soap plant, death camas, mariposa lilies
	None	None		
Grass	Fire-stimulated	None	Top-killed	Deergrass
	None	None	Killed	Cheat grass

example, by the time chamise stands reach about 9 years in age, the combination of dead branches and live resinous foliage make them extremely flammable.

Chaparral supports numerous species of geophytes, or bulb bearing plants that show increased flowering and growth following fire. Common examples are soap plant (*Chlorogalum pomeridianum*), death camas (*Zigadenus* spp.), and mariposa lilies (*Calochortus* spp.) (Tyler and Borchert 2007). Most plant species in the postfire flora are annuals, some of which are postfire endemics with fire-enhanced germination. The annuals are responding to the sudden availability of light and nutrients and can recruit either from the soil seed bank or from offsite sources. Nonnative annual species invariably increase after fire, but they tend to disappear as shrubs recover dominance.

Interior and canyon live oaks sprout both from root and canopy crowns following fire. Canyon live oak bark resists low-intensity fires (Paysen and Narog 1993), whereas the relatively thin bark of interior live oak results in top-kill with all but lowest intensity fires (Plumb 1980). Both species can also sprout new branches from epicormic buds on the stem.

Foothill pines are sensitive to fire and the oldest individuals in a chaparral stand are a minimum indication of the time since last burn. Pitch running down the bole is common and increases crown torching (Lawrence 1966). Foothill pines develop cones and seeds at an early age. Their large cones are partially serotinous and the annual accumulation of cones results in a large seed crop available when fire arrives, ready to germinate on open mineral soil. Foothill pine is relatively drought tolerant and grows well in rocky, thin soils, including serpentine soils. In such low productivity conditions fuels are not heavy and fire frequency and intensity may be reduced, enhancing foothill pine survival. Foothill pine seeds are large and wingless, and long distance dispersal of seeds is dependent on rodents and birds.

FIRE REGIME–PLANT COMMUNITY INTERACTIONS

Fire regimes in the foothill zone vary with topography and vegetation (Appendix 1). Fire season is long, beginning in early summer, and lasting through late fall. In the lower areas of the zone, oak grassland savannah areas burned frequently and with low to moderate intensity as described in the Central Valley chapter (chapter 15). Areas dominated by chaparral burned less frequently because lightning is infrequent, especially in the fall when fuel moistures become critically low. On a statewide basis, pre-Euro-American settlement fire return intervals in foothill chaparral probably averaged between 30 years and 90 years (Van de Water and Safford 2011).

Persistence of obligate-seeding shrubs on the landscape can be potentially threatened by long fire return intervals (Zedler 1995). For example, California-lilac species are relatively short-lived (40 to 50 years is common), and fire-free intervals much longer than this could result in both the plants and the majority of the seed pool dying before the return of fire necessary for seed germination. However, other species have seeds that remain viable for very long periods, even after the plants have died (Knapp et al. 2012). As Zedler (1995) noted though, this threat may be more theoretical than real. Keeley et al. (2005) tested this hypothesis in the southern Sierra Nevada and found that even 150-year old chaparral stands in which most of the buckbrush component had died regenerated after fire with densities of over 14,000 seedlings ha^{-1} (5,566 ac^{-1}). A more real threat is the risk of very frequent fire (<15 years) outpacing the ability of either seeding or sprouting species to recover enough seeds or viable buds to remain in the landscape (Zedler 1995).

In Yosemite, Thode et al. (2011) found that the greatest proportion of area burned in the foothill chaparral type was of high severity. Live oaks also burned with high severity, conifer patches with moderate severity, and oak woodlands with low severity. Islands of trees in chaparral landscapes can survive fire by occupying rocky or moist areas such that flames are avoided or attenuated, but longer periods without fire might lead to invasion by chaparral and subsequent stand loss under a more severe fire regime (Lombardo et al. 2009). Where severe fires occur at the upper end of the foothill shrubland zone, the boundary between the shrublands and the lower montane forest may shift. Reestablishment of conifers in such areas may take decades to centuries, and frequent recurring high-severity fires may perpetuate the shrub species.

Frequent fire in foothill grasslands, in part from burning by Native Americans, reduced encroachment by chaparral and expanded the area supporting important herbaceous species that were used for many cultural purposes (Anderson and Rosenthal 2015). The mosaic of vegetation in the foothills is very dynamic. In areas that have soils that are sufficiently fertile and stable to support woody biomass, grasslands would have required frequent fire to persist on the landscape. Such areas dominated by chaparral could be reduced to grassland by frequent fire, or they might succeed to woodland and then forest with the very long absence of fire. On the other hand, oak or pine woodlands that experienced a long fire-free interval might see invasion by chaparral shrubs, with subsequent fire being severe enough to extirpate the oaks (Cocking et al. 2014).

Ponderosa pine occurred at much lower elevations in the Sierra Nevada when Euro-Americans arrived, and the uphill movement of its lower distribution has been primarily driven by logging and changes in land-use (Thorne et al. 2008). Ponderosa pine remains in the foothills in limited patches on more mesic north-facing slopes. Natural reestablishment of ponderosa pine in the foothills is limited by the reduction in fires, which maintained canopy openings and provided mineral soil for successful recruitment and also prevented invasion by chaparral. Warming temperatures, which increase the summer water deficit, could also limit reproduction (Lutz et al. 2010). The increase in large, high-severity fires over the last few decades has also reduced conifer cover in some areas and greatly increased the distance to living sources of seed. In the foothills to the west of Yosemite National Park, recurrent, large and overlapping fires with large stand-replacing patches have resulted in establishment of vast shrubfields and annual grasslands. The 5-year drought from 2012 through 2016 has resulted in almost complete elimination of ponderosa pine in the southern Sierra Nevada foothills (Stephens et al. 2018).

Foothill pine stands respond to the fire regimes of the surrounding chaparral and live oak stands, surviving those of low severity and succumbing to moderate- to high-severity fires. Partial serotiny allows reestablishment after stand-replacing fires. Woody and duff fuel loads are among the lowest of any Sierra Nevada conifer and do not contribute significantly to fire spread and intensity (van Wagtendonk et al. 1998a). Although relatively uncommon, patches of knobcone pine exist in the Sierra Nevada foothills surrounded by chaparral. Like foothill pine, knobcone pine shows a notable tolerance for low productivity soils, which lowers fuel accumulation rates and reduces the probability of fire before stands have amassed sufficient seed to regenerate after fire (Safford and Harrison 2004). Knobcone is more completely serotinous

FIGURE 14.6 Lower montane forest. This open stand of ponderosa pine, incense cedar, and sugar pine with mountain misery in the understory burned in 1978 and in 1996.

than foothill pine and grows in dense mostly single-aged stands that promote high-intensity fires. Current practices of fire exclusion may reduce the persistence of some knobcone pine patches, but counteracting this is the recent increase in large severe fires in the Sierra Nevada.

Lower Montane Forest

The lower montane forest ecological zone is the first continuous zone of conifers as one ascends the Sierra Nevada. The foothills are below with the upper montane forest above. The relatively gentle western slope consists of an alternating series of often flat-topped ridges and river canyons. Metavolcanic, metasedimentary, and granitic rocks form the majority of the geologic substrates and soils are relatively deep and well drained. Summers are hot and dry, and winters are cold and wet. Lightning is moderately frequent, averaging 15.6 strikes yr^{-1} 100^{-1} km^{-2} (40.3 strikes yr^{-1} 100^{-1} mi^{-2}).

Vegetation and fire within the lower montane zone vary with elevation, landscape position, and latitude. At the lowest elevations, California black oak and ponderosa pine dominated large areas before Euro-American settlement, but many stands have been logged or developed, and others have succeeded to mixed-conifer forest dominated by Douglas-fir and incense cedar due to selective logging and fire exclusion (Dolanc et al. 2014b). Intermixed with these forests are various-sized patches of chaparral and canyon live oak. Manzanita and California-lilac species dominate chaparral, whereas canyon live oak is extensive on steep slopes of large canyons. As elevation increases, moist sites and north slopes are dominated by Douglas-fir at lower elevations and white fir at higher elevations. Incense cedar and sugar pine (*Pinus lambertiana*) are found throughout. Fig. 14.6 shows a stand of ponderosa pines, incense cedars, and sugar pines with an understory of mountain misery (*Chamaebatia foliolosa*). Giant sequoia groves are concentrated in several river basins in the central and southern Sierra Nevada, occupying sites where soils are moist and deep. At the highest elevations, at the boundary with upper montane forests, white fir often becomes dominant on all aspects except where soils are shallow or very rocky, where pine or shrub communities often dominate.

Throughout the zone, riparian plant communities characterized by deciduous trees, shrubs, herbs, and grasses occur with varied proportions of conifers. White alder (*Alnus rhombifolia*), mountain alder (*A. incana*), or black cottonwood (*Populus trichocarpa*) dominate larger streams or wetter sites. Big-leaf maple and mountain dogwood (*Cornus nuttallii*) occur along smaller or intermittent streams or where soil moisture is high, especially in the northern Sierra Nevada. Small patches of quaking aspen (*P. tremuloides*) occur in the higher elevation mixed-conifer forests but are more prevalent in the upper montane zone and on the eastside of the range (Potter 2006). Meadows and seeps are mostly small and scattered throughout.

Partly due to increasing precipitation, Douglas-fir becomes important in the north. Mixed-evergreen forests comprised of tanoak (*Notholithocarpus densiflorus* var. *densiflorus*), Pacific madrone, and other montane hardwoods and conifers (especially Douglas-fir and ponderosa pine) occupy large areas in the western Yuba and Feather River basins where precipitation exceeds 152 cm (60 in) annually.

FIRE RESPONSES OF IMPORTANT SPECIES

The majority of lower montane species have characteristics resulting in resistance to fire and often have favorable responses to fire. Sprouting hardwood trees, shrubs, vines, herbs, and grasses are common and mostly fire-enhanced; conifers have at least some fire resistant characteristics.

Giant sequoia, ponderosa pine, sugar pine, Douglas-fir, and white fir have thick bark when mature (Table 14.3). The trees vary in their level of resistance to low- and moderate-intensity fires (Safford and Stevens 2017). Ponderosa pine has a thicker bark as a young tree and is more resistant to fire than the other lower montane conifers. As ponderosa pine grows older, it also self-prunes lower branches, which raises the crown above typical surface flame heights. In addition, ponderosa pine's large, protected buds provide further fire resistance. Ponderosa pine leaf litter is among the most flammable of all

TABLE 14.3
Fire response types for important species in the lower montane ecological zone

	Type of fire response			
Lifeform	Sprouting	Seeding	Individual	Species
Conifer	None	None	Resistant, killed	Ponderosa pine, Douglas-fir, white fir, sugar pine, incense cedar
	None	Fire-stimulated (seed release)	Resistant, killed except sprouts when young	Giant sequoia
	None	None	Low resistance, killed	Pacific yew
Hardwood	Fire-stimulated	None	Top-killed	Black oak, tanoak, canyon live oak, big-leaf maple, Pacific madrone, white alder
Shrub	Fire-stimulated	None	Top-killed	Mountain misery, greenleaf manzanita, poison oak, hazelnut, , willow
	Fire-stimulated	Fire-stimulated	Top-killed	Deer brush, mountain whitethorn
	None	Fire-stimulated	Killed	Whiteleaf manzanita
Forb	Fire-stimulated	None	Top-killed	Penstemon, many lilies, iris, starflower, trail plant, sanicle
				Lady's slipper orchid
Grass	Fire-stimulated	None	Top-killed	Red fescue, melic, sedges
	None	None	Killed	Cheat grass

North American conifers (van Wagtendonk et al. 1998a), which may represent an adaptation to frequent fires that kill less fire-tolerant competitors. Rapid growth of giant sequoia seedlings produces early fire resistance. Douglas-fir, white fir, and incense cedar have thick bark when mature, but are killed by fire when young because of thin bark, low, flammable crowns, and small, unprotected buds. Sugar pine is intermediate in fire resistance with thick bark and high crowns but potentially more susceptible to cambial or root damage from heat (Haase and Sackett 1998).

Giant sequoias have serotinous cones that are exposed by heat and show increased seedling density with higher intensity fire (Kilgore and Biswell 1971). Giant sequoia and white fir are the only major Sierra Nevada conifers that epicormically (none sprout basally) sprout, but this response is apparently limited to younger trees (Weatherspoon 1986, Hanson and North 2006). More information on the responses of giant sequoias to fire is provided in sidebar 14.2. Pacific yew (*Taxus brevifolia*) and California nutmeg (*Torreya californica*) are uncommon, relict conifers that have thin bark, and they sprout prolifically. They have survived in the fire-prone landscape by their restricted habitats in wet, mostly riparian areas and can apparently survive low-intensity fire, as evidenced by observed fire scars and sprouting (Fites-Kaufman 1997).

The montane hardwoods, including tanoak, Pacific madrone, California black oak, canyon live oak, California bay (*Umbellularia californica*), mountain dogwood, big-leaf maple, white alder, and black cottonwood, all sprout from basal burls or root crowns following fire. Sprouting can be vigorous with up to 100 sprouts produced on individual California black oak stumps (McDonald 1981). Epicormic sprouting from the stem following low-intensity fire was observed in California black oak, tanoak, and mountain dogwood (Kauffman and Martin 1990). California black oak is the only oak species that develops bark sufficiently thick to resist low- to moderate-intensity fire in larger trees (Plumb 1980). Like ponderosa pine, black oak leaf litter is highly flammable (Engber and Varner 2012) but decomposes rapidly. Frequent fires in oak litter kill competitors and maintain open canopy conditions. Riparian hardwoods all sprout following fire. Native Americans burned riparian areas to enhance shoot production of big-leaf maple and hazelnut (*Corylus cornuta*) shrubs (Anderson 1999).

Most shrub species resprout prolifically after fire and some also have heat-stimulated seeds (Kauffman and Martin 1990) (Table 14.3). Sprouters include mountain misery, deer brush, greenleaf manzanita, bush chinquapin (*Chrysolepis sempervirens*), mountain whitethorn (*Ceanothus cordulatus*), and riparian shrubs like hazelnut, thimbleberry (*Rubus parviflorus*), and mountain alder. The burning season can affect sprouting response. Bush chinquapin, Sierra gooseberry (*Ribes roezlii*), deer brush, greenleaf manzanita, and thimbleberry all showed greater sprouting following early spring burns than fall or late spring burns (Kauffman and Martin 1990). Overall, mountain whitethorn showed the greatest postfire sprouting after higher intensity fall burns. Sprouting occurs from burls, root crowns, and rhizomes.

SIDEBAR 14.2 GIANT SEQUOIAS AND FIRE

One is in no danger of being hemmed in by sequoia fires, because they never run fast, the speeding winds flowing only across the treetops, leaving the deeps below calm, like the bottom of the sea. Furthermore, there is no generally distributed fire food in sequoia forests on which fires can move rapidly. Fire can only creep on the dead leaves and burrs, because they are solidly packed. —MUIR (1878)

Probably better than any other species, giant sequoia exemplifies a truly fire-adapted species. Not only does it have thick bark that protects it from periodic surface fires, but also its cones are opened by heat and its regeneration is dependent on exposed mineral soil, such as occurs after a moderately severe fire. Biswell (1961) was one of the first scientists to explore the relationships between giant sequoias and fire. He reported fire scar dates in the Mariposa Grove in Yosemite National Park from as early as 450 AD with periods between fire scars averaging 18 years. He also looked at the number of lightning fires in 93 km^{-2} (36 mi^{-2}) areas surrounding sequoia groves and found that during the years from 1950 through 1959, 36 fires had been suppressed in the Mariposa Grove and 39 in the Tuolumne Grove. These data along with observations of dense thickets of white firs and incense cedars and large increases in forest floor debris led him to conclude the groves should be managed with fire as part of the environment.

Hartesveldt (1964) conducted the first detailed scientific study of giant sequoias and fire in the Mariposa Grove and concluded that the greatest threat to the survival of the big trees was catastrophic fire burning through accumulated surface and understory fuels as a result of decades of fire exclusion. His recommendation was to reintroduce fire to the giant sequoia ecosystem through the use of prescribed burning.

Subsequently, Hartesveldt and Harvey (1967) and Harvey et al. (1980) studied factors associated with giant sequoia reproduction in the Redwood Mountain Grove of Kings Canyon National Park. Using experimental fires and mechanical manipulations, they measured seedling survival and growth and investigated the role of vertebrate animals and arthropods in giant sequoia reproduction. Seedlings established on areas burned the hottest survived at a higher rate than those on other soils. Fire did not greatly affect vertebrate populations, and only one species had a significant effect on sequoia reproduction. The Douglas squirrel (*Tamiasciurus douglasii*) feeds on the scales of 2-year to 5-year-old giant sequoia cones and cuts and caches literally thousands of cones each year. This greatly aids the distribution of cones and, subsequently, seedlings because the squirrels could not relocate most cached cones. Although over 150 arthropods were found to be associated with giant sequoias only two significantly affected regeneration. The gelechiid moth (*Ghelechia* spp.) feeds on one-year old cones, while the small long-horned beetle (*Phymatodes nitidus*) mines the main axis of cones older than five years, which causes them to dry and drop their seeds.

Based on these findings, the national Park Service began a program of prescribed burning and research in giant sequoia groves in Yosemite, Sequoia, and Kings Canyon national parks (Kilgore 1972). Detailed information on fires and minerals (St. John and Rundel 1976), fuel accumulation (Parsons 1978), and fire history (Kilgore and Taylor 1979) added to the knowledge about the role of fire in these forests.

Burning in sequoia groves was not without controversy, however. Charred bark from a prescribed burn in Sequoia National Park prompted an investigation and a report on the burning programs in the groves (Cotton and McBride 1987). As a result, additional research was conducted to refine the scientific basis for the programs (Parsons 1994). Fire history studies extended the fire scar record back to 1125 B.C. with an average interval between fires from 2 to 30 m years (Swetnam 1993). Pollen and charcoal in sediments cores taken in the groves indicated that giant sequoias became more prevalent about 5,000 years ago and that fires occurred throughout the record (Anderson 1994, Anderson and Smith 1997).

Studies on the effects of fire on fungi and insect relationships with giant sequoias led Piirto (1994) to conclude that fire does influence the types and population levels of numerous organisms but that their interactions are not well understood. Other studies looked at the role of fire severity in establishing and maintaining giant sequoia groves. Of particular interest was the finding that patchy, intense fires existed in presettlement times and that these fires were important determinants of grove structure and composition (Stephenson et al. 1991). Leading to these intense fires in giant sequoia groves are the heaviest woody fuel loads found for any Sierra Nevada conifer species (van Wagtendonk et al. 1998b).

All the research to date indicates that fires have always played an important role in giant sequoia ecology and that the survival of the species depends on the continued presence of fire. Management programs must recognize this fact and must be designed to include fire in as natural a role as practicable. Restoration targets must include process goals as well as structural goals based on sound science (Stephenson 1999). Only through such a program can we ensure the survival of this magnificent fire species.

Shrubs sprouting from deeply buried rhizomes, such as mountain misery, can readily dominate sites with frequent and intense fire. Mountain misery occupies large areas, 4–40 ha (10–100 ac) through extensive networks of rhizomes protected from heat over 20 cm (8 in) below the soil surface. With highly flammable foliage containing volatile oils, mountain misery promotes burning. Rundel et al. (1981) found that regrowth was stimulated by spring and fall burns but that summer burns inhibited resprouting for at least two years. Further enhancing its competitive advantage, mountain misery is able to fix nitrogen from nodules that develop after burning (Heisey et al. 1980).

Heat-stimulated seed of deer brush, buckbrush, or mountain whitethorn can produce extensive dense seedling patches. Seeds produced by these species can persist in the soil for decades or centuries (Knapp et al. 2012). The fire-stimulated sprouting and seed germination responses of deer brush make it particularly successful in rapidly colonizing burned sites. Deer brush germination with wet seed can be greater than from dry heat (Kauffman and Martin 1990). This could explain its greater prevalence, especially after fires, on moister portions of the landscape, such as north and east aspects or lower slopes. Deer brush gains height rapidly but can be limited by deer browsing (Kilgore and Biswell 1971). In the Sierra Nevada, deer brush and mountain whitethorn can dominate postfire habitats in lower montane forest that burns at high severity, reaching heights of 2–4 m (6–12 ft) in 5 years. As shade-tolerant trees succeed in growing through the overlying shrub canopy, sometimes many decades after fire, these shrub species can continue to persist for some years in the understory in a decadent, highly flammable state (Oakley et al. 2006).

The postfire herbaceous flora of lower montane forests supports few species whose germination is enhanced by fire (Keeley et al. 2003). The general lack of a fire-following endemic flora is the result of the long-term absence of widespread high-severity fires in these forests. Certainly many species respond positively to the increase in understory light, moisture availability, and nutrients that fire brings (Collins et al. 2007, Wayman and North 2007, Abella and Springer 2015). However, very severe fire in these forests reduces understory species diversity at scales larger than the plot due to strong homogenization of the flora (Stevens et al. 2015). Numerous perennial plants with underground rhizomes, corymbs, or stolons have been observed to increase in abundance following fire. These include Pacific starflower (*Trientalis latifolia*), trail plant (*Adenocaulon bicolor*), western blue flag (*Iris missouriensis*), Bolander's bedstraw (*Galium bolanderi*), bear-grass (*Xerophyllum tenax*), sanicles (*Sanicula* spp.), many-stemmed sedge (*Carex multicaulis*), Ross' sedge (*C. rossii*), needle grasse (*Stipa* spp.), oniongrass (*Melica bulbosa*), and red fescue (*Festuca rubra*). Other plants exhibit sprouting or enhanced flowering following fire, such as Mariposa lilies and penstemons (*Penstemon* spp.). Severe fire also increases the presence of nonnative species in the postfire flora.

FIRE REGIME–PLANT COMMUNITY INTERACTIONS

Fire regime attributes for major vegetation types of the lower montane ecological zone are shown in Appendix 1. Most fires occur between mid-summer and early fall. The fire season is longer in the southern portion of the Sierra Nevada because of drier conditions, and the proportion of fire scars in the growing season is greater (Skinner 2002). Some fires have always occurred in the spring and early summer and occasionally in the winter, but the prevalence of such "out of season" fires is increasing as climates warm.

Before Euro-American settlement, fire was generally frequent in the lower montane zone, with stand-scale fire return intervals averaging 10 to 20 years, and ranging from 5 to 80 years (Van de Water and Safford 2011). At the landscape scale, fire rotations averaged 22 to 31 years in ponderosa pine and mixed-conifer forest, ranging from 11 to 70 years (Mallek et al. 2013). There was noticeable variation in fire pattern with latitude and elevation. Drier areas with longer fire seasons experienced the most frequent and regular fires. These areas are most prevalent in the southern and central Sierra Nevada and throughout the range on south aspects, ridges, and lower elevations. These areas tend to be dominated or codominated by ponderosa pine and California black oak. Throughout the zone, relatively cooler and wetter sites have had somewhat less frequent fire and are more likely to have a presence or dominance of Douglas-fir and white fir. Forests around smaller, headwater streams have similar fire regimes to adjacent uplands, whereas larger streams with cooler, more mesic microclimate have longer fire return intervals and higher fuel loading (Van de Water and North 2010, 2011). Fire severity is also variable throughout the lower montane forest zone. In a summary of 20 years of fire in Yosemite National Park, Thode et al. (2011) found mostly low to moderate severity in ponderosa pine stands, mostly low severity in white fir and California black oak stands, and high severity in riparian and chaparral stands. Under severe fire weather conditions, high-severity patches in white fir did reach 60 ha (148 ac) in size (Collins and Stephens 2010).

Frequent fire creates forest structural diversity at stand and landscape scales associated with several ecosystem processes. The within-stand structure has been characterized as containing three main conditions: individual trees, clumps of trees, and openings or gaps (Lydersen et al. 2013). Stand-level average canopy cover under frequent-fire conditions is typically low (20–45%) compared to modern fire-excluded conditions (typically 55–85%) (Collins et al. 2011). However, within a stand, individual, clump and opening conditions produce heterogeneity such that canopy closure (North and Stine 2012) is highly variable, providing a scattering of areas for plants and animals associated with dense forest conditions. Several studies suggest this fine-scale heterogeneity affects ecosystem conditions and functions, producing a wide range of microclimates (Rambo and North 2009, Ma et al. 2010), a diversity of understory plants (Wayman and North 2007) and soil invertebrates (Marra and Edmonds 2005), variation in soil respiration (Concilio et al. 2005), and limits on pest and pathogen spread (Maloney et al. 2008). The spatial variability also makes these stand conditions more resistant to crown fire because groups of trees are separated by low fuel gaps reducing crown fire spread potential (Agee and Skinner 2005, Stephens and Moghaddas 2005).

At a landscape level, fire often burned with greater intensity associated with changes in topography and species composition (Taylor and Skinner 2003, Lydersen and North 2012). Topography has a direct effect on fire intensity on steeper and drier slopes and an indirect effect on mesic north-facing slopes and canyon bottoms where fuel loads are higher because of greater forest productivity (Lydersen and North 2012, Kane et al. 2014). Diverse and variable species in both the tree and shrub layers result in variable fuel and fire patterns. For example, ponderosa pine fuels are both more energy rich and more loosely packed than those of white fir, allowing the pine fuels to burn more readily (van Wagtendonk et al. 1998a). In addition, ponderosa pine has one of the highest annual deposition rates of both litter and small branches (van Wagtendonk and Moore 2010).

High levels of variation slope, aspect, elevation, and weather, as well as topographically controlled diurnal changes in fire behavior, overlap with variable fuel patterns to create fine-scale patterns of variation in forest density, structure, and understory vegetation. With fire exclusion, density and uniformity in structure and composition have increased (Lydersen et al. 2013, Safford and Stevens 2017). Across many sites in the mid-elevations of the Sierra Nevada, white fir and incense cedar have increased, shifting composition away from ponderosa pine and sugar pine and creating more uniformly dense forests (Vankat and Major 1978, Parsons and deBenedetti 1979, North et al. 2007, Dolanc et al. 2014a, 2014b). Douglas-fir responds similarly in the northern Sierra Nevada (Fites-Kaufman 1997). At lower elevations bordering the foothills, these shade-tolerant species are less common and ponderosa pine has decreased in density (Parsons and deBenedetti 1979, Fites-Kaufman 1997). Similarly, at higher elevations, white fir dominates but with increased uniformity and density attributed to fewer fires (Parsons and deBenedetti 1979).

Historically, open or more variable forest structure occurred as a result of more frequent fire. Not only did fire favor different species, it also affected forest structure by thinning the young trees leaving a patchier or more open forest, and selectively retaining larger, more fire resistant trees (van Wagtendonk 1985). Exactly how forest and understory vegetation conditions varied across historical landscapes is unknown, but a close reading of early observers' writings (Safford and Stevens 2017) suggests a very heterogeneous landscape dominated by mostly open canopied forests with scattered dense patches in certain landscape positions (Sudworth 1900, Leiberg 1902). These observations are supported by historical photographs (Gruell 2001) and analyses of historical forest inventories conducted in both the central and southern Sierra Nevada (Collins et al. 2015, Stephens et al. 2015). The original inventories were conducted systematically in 1911 across large landscapes greater than 10,000 ha (>25,000 ac), allowing for robust characterization of historical forest conditions in the lower montane zone. Areas with moderate- to high-density forests historically had greater proportions of white fir and Douglas-fir and tended to be associated with higher elevations and topographic settings with greater moisture availability (Collins et al. 2015, Stephens et al. 2015). In addition to heterogeneous forest overstory conditions, understory vegetation was highly variable, including stands with high mountain misery cover (50–80%) and moderate cover of taller shrubs (25–50%).

Montane chaparral patches also appear to have been a distinct feature of historical landscapes that contributed to overall heterogeneity. These patches likely occurred at relatively low proportions (<10%) and small patch sizes (<20 ha [<50 ac]) across landscapes with intact fire regimes (Show and Kotok 1923, Collins and Stephens 2010). In some areas of upper montane forest there has been a loss of chaparral due to tree invasion in the absence of fire (Nagel and Taylor 2005). This is consistent with observations from Show and Kotok (1924) that frequent fire facilitated shrub persistence or expansion, which was one of several justifications for early fire exclusion policies. At the same time, the increasing size and severity of wildfires in the lower montane zone is leading to the origin, maintenance, and expansion of very large areas of montane chaparral that may never succeed to forest given current trends (Safford and Stevens 2017).

Questions remain concerning the intensity and severity of presettlement fires in lower montane forests, but almost all evidence points to fires that were typified by low and moderate severity, with higher severity occurring in areas of heavier fuels or under extreme weather conditions (Collins et al. 2015, Stephens et al. 2015, Safford and Stevens 2017). Steel et al. (2015) showed that time since last fire was positively related to fire severity in lower montane forests, substantiating the general maxim that fuel accumulations in these forests due to a century of fire exclusion is changing modern fire behavior. Various sources of evidence suggest that high-severity patches in lower montane fires were generally small (Sudworth 1900, Stephenson et al. 1991, Collins et al. 2015, Stephens et al. 2015, Safford and Stevens 2017). There is certainly evidence of historical large high-severity fires in the Sierra Nevada, but such fires were the exception rather than the rule. Characteristics of modern fires burning >20,200 ha (>50,000 ac) at a time with >30% high severity and high-severity patches of >400 ha (>1,000 ac) appear to have no analogue in the Late Holocene, at least over the period of the tree-ring record.

There is a lack of historical information on the size or distribution of high-severity fires in the lower montane zone. It is likely that they occurred infrequently and were related to drought cycles, which would create larger areas of highly flammable vegetation. The northern Sierra Nevada experiences higher average annual rainfall than the southern Sierra Nevada and supports denser forest and a higher component of relatively fire-intolerant species. As a result historic fire return intervals in the north tend to be somewhat longer than in the south, and fires probably burned at higher severity (Fites-Kaufman 1997). There is evidence from historical inventories that indicates high proportions of shrub-dominated vegetation within and adjacent to major canyons. These shrubfields could be attributed to centuries of recurring fires perpetuating the shrubs or forests that were converted to shrubs by high-severity fires that occurred after Euro-American settlement (Collins et al. 2015, Airey Lauvaux et al. 2016).

Sierra Nevada lower montane forests are some of the most productive fire-prone forests in the western United States. This results in increased stand densities and reduced decomposition rates that produce high fuel accumulations (Kilgore 1973, Vankat and Major 1978, Agee et al. 2000). This increases the tendency for high-intensity and high-severity fire through increased fuels and increased susceptibility of dense smaller vegetation, especially when fire intervals are increased. Various studies have documented large increases over the last three decades in fire size and severity in the lower montane zone of the Sierra Nevada (Miller et al. 2009, Miller and Safford 2012, Mallek et al. 2013). This trend has not been seen in Yosemite National Park, however, where extensive prescribed burning and managed wildfire programs begun in the 1970s have reduced fuels (van Wagtendonk and Lutz 2007).

Upper Montane Forest

The upper montane forest is located above the lower montane forest and occurs on both sides of the crest of the Sierra Nevada. On the west side elevations are generally lower than on the east, with the differences greater in the south than in the north (Potter 1998). The terrain is relative moderate on the west side but drops precipitously on the east. The geology underlying this zone is primarily volcanic in the north and granitic in the south. Soils are weakly developed and are

FIGURE 14.7 Upper montane forest. This stand is characterized by large red fir, western white pine, and Jeffrey pine in the overstory with an understory of prostrate and erect manzanita and California-lilac species. Fire is infrequent but can burn extensive areas.

typically medium to coarse textured and often lack a clay-rich subsoil (Potter 1998). The large expanses of exposed rock and shallow soils in the southern Sierra Nevada provide a discontinuous landscape that inhibits fire spread.

The climate of the upper montane forest is characterized by cool summers and cold winters. The transition from the lower montane zone to the upper montane zone is found approximately at the elevation of maximum overall precipitation, where the percentage of precipitation falling as snow rises above 50%, the average freezing-level occurs in winter storms, and the winter snowpack is at its deepest (Major 1988, Barbour et al. 1991, Safford and Van de Water 2014). The upper montane forest zone receives as many lightning strikes as might be expected by chance (van Wagtendonk 1991a). The average number of lightning strikes that occurred in the zone between 1985 and 2000 was 29.3 strikes yr^{-1} 100^{-1} km^{-2} (75.9 strikes yr^{-1} 100^{-1} mi^{-2}) (van Wagtendonk and Cayan 2008).

The vegetation of the upper montane forest is characterized by the presence of California red fir (Potter 1998). Fig. 14.7 shows a stand of California red fir and western white pine with a sparse understory of montane chaparral. Besides thee two species, other species include western white pine, quaking aspen, Sierra juniper, Jeffrey pine, and tufted hair grass (*Deschampsia cespitosa*). Interspersed in the forests are meadows and stands of montane chaparral.

FIRE RESPONSES OF IMPORTANT SPECIES

Many upper montane species have fire resistant characteristics and respond favorably to fire (Table 14.4). Shrubs and hardwood trees typically sprout, whereas herbs and grasses either reseed or regrow quickly after fire. Conifers are protected from fire heat by thick bark layers.

The conifers in the upper montane ecological zone vary in their resistance to fire. California red fir has thin bark when it is young, making it susceptible to fire. As California red fir matures, its bark becomes thicker and it is able to survive most fires (Kilgore 1971). Like ponderosa pine, Jeffrey pine has thicker bark when young than its competitors, which—along with self pruning of lower branches and highly flammable litter—gives it an advantage in resisting frequent fire. Western white pine and Sierra juniper are more susceptible to fire at a young age than California red fir or Jeffrey pine. The percent crown scorch that a species can sustain is also variable. Up to 50% of the buds of a Jeffrey pine can be killed and still survive (Wagener 1961b). The other upper montane conifers can sustain only 30–40% scorch (Kilgore 1971).

Quaking aspen is the primary hardwood species in the upper montane forest and occurs in small stands where moisture is available. It is a vigorous and a profuse sprouter after fire (Brown and DeByle 1987). It becomes increasingly resistant to fire as its diameter increases beyond 15 cm (6 in).

Bush chinquapin, mountain whitethorn, and huckleberry oak (*Quercus vaccinifolia*) form extensive stands in the open and underneath conifers. They are all sprouters and are top-killed by fire (Conard et al. 1985). Mountain whitethorn is also a relatively prolific seeder after fire. Pinemat manzanita (*Arctostaphylos nevadensis* subsp. *nevadensis*) and greenleaf manzanita are usually killed by intense heat, but Sierra Nevada populations of greenleaf mazanita grow lignotunber and can resprout after fire. Both species are able to reestablish by seed the first year after fire. Although these nonsprouting manzanitas are killed by intense heat, they are able to reestablish by seed the first year after fire.

Woolly mule's ears (*Wyethia mollis*) apparently resprouts after fire (Mueggler and Blaisdell 1951). The density of mule's ears has been noted to increase after fire (Young and Evans 1978). Tufted hair grass is one of many grass and sedge species common in wet meadows. Although it burns infrequently, tufted hair grass generally survives all but the most intense fires and sprouts from the root crown, as do most sedges.

FIRE REGIME-PLANT COMMUNITY INTERACTIONS

Although the upper montane forest receives a proportionally higher number of lightning strikes on a per area basis than the lower montane forest, fewer fires result (van Wagtendonk 1994). Lightning is often accompanied with rain, and the

TABLE 14.4
Fire response types for important species in the upper montane forest ecological zone

Lifeform	Type of fire response: Sprouting	Seeding	Individual	Species
Conifer	None	None	Resistant, killed	Red fir, Jeffrey pine, western white pine, Sierra juniper
Hardwood	Fire-stimulated	None	Resistant, top-killed	Quaking aspen
Shrub	Fire-stimulated	Abundant seed production	Top-killed	Bush chinquapin, mountain whitethorn, huckleberry oak
	None	Fire-stimulated	Killed	Whiteleaf manzanita, pinemat manzanita
Forb	Fire-stimulated	None	Top-killed	Western mule's ears
	None	None	Top-killed	Corn lily
Grass	Fire-stimulated	Off-site	Top-killed	Tufted hair grass
	Tillers	Off-site	Top-killed	Western needlegrass

compact fuelbeds are not easily ignited. Those fires that do occur are usually of low intensity and spread slowly through the landscape except under extreme weather conditions. Natural fuel breaks such as rock outcrops and moist meadows limit the development of extensive fires (Kilgore 1971).

California red fir fuelbeds are among the heaviest and most compact found for conifers in the Sierra Nevada. Whereas duff weight was just above average, woody fuel weight is surpassed only by giant sequoia (van Wagtendonk et al. 1998a). Relatively high annual deposition of large woody fuels contribute to woody fuel weight (van Wagtendonk and Moore 2010). The bulk density of California red fir duff fuels is above average and the fuelbed bulk density, including woody and litter fuels, is only exceeded by limber pine. Such dense fuels ignite and carry fire only under extremely dry and windy conditions.

Fire regimes tend to be more variable in frequency and severity than those in the lower montane forest (Appendix 1) (Skinner and Chang 1996). Van de Water and Safford (2011) reported mean, median, mean minimum, and mean maximum fire return intervals for red fir of 40, 33, 15, and 130 years, respectively. The mean presettlement fire rotation for Sierra Nevada red fir was 61 years, ranging from 25 years to 76 years (Mallek et al. 2013). The wide range of values may be due to variability in red fir forest conditions and locations. Studies at lower elevations, where the tree species composition suggests drier site conditions, have generally found shorter historical fire return intervals and age structures that suggest frequent pulses of regeneration. In contrast, higher elevation and more mesic site studies often document a fire regime of mixed severities with distinct recruitment pulses following fire events (Taylor 2004, Scholl and Taylor 2006). One study documented a strong linear relationship between fire return interval and elevation, possibly driven by snowpack and its effect on fuel moistures (Bekker and Taylor 2001). Montane chaparral stands in Yosemite National Park burned with high severity, whereas red fir, Jeffrey pine-shrub, Jeffrey pine-western white pine, and aspen stands all burned with low to moderate severity (Thode et al. 2011).

At the higher elevations in the upper montane zone, fire has an important role in the successional relationship between California red fir and lodgepole pine (Kilgore 1971, Taylor 2000). Where lodgepole pine occurs under a California red fir canopy, without fire it is eventually succeeded by California red fir. Pitcher (1987) concluded that fire was necessary for creating openings where young California red fir trees could get established. In areas where crown fires have burned through California red fir forests, montane chaparral species such as mountain whitethorn and bush chinquapin become established. Within a few years, however, California red fir and Jeffery pine begin to overtop the chaparral.

Fires in Jeffrey pine, Sierra juniper, and western white pine stands are usually moderate in intensity, burning through litter and duff or, if present, through huckleberry oak or greenleaf manzanita. Older trees survive these fires, although occasionally an intense fire may produce enough heat to kill an individual tree (Wagener 1961b). Fuelbed bulk density and woody fuels weights are comparable for the three species, but Jeffrey pine has three times as much litter and twice as much duff (van Wagtendonk et al. 1998a). Jeffrey pine also accumulates more fuel annually than either western white pine or Sierra juniper (van Wagtendonk and Moore 2010). As a result, surface fires tend to be more intense in Jeffrey pine stands. Jeffrey pine will be replaced by huckleberry oak and greenleaf manzanita if fires of high severity occur frequently, or by California red fir if the period between fires is sufficiently long (Bock and Bock 1977).

Although quaking aspen stands in the Sierra Nevada usually burn only if a fire from adjacent vegetation occurs at a time when the stands are flammable, the decline of quaking aspen stands has been attributed to the absence of natural fire regimes (Lorentzen 2004). Quaking aspen stands burn in late summer when the herbaceous plants underneath the trees have dried sufficiently to carry fire. Because quaking aspen is a vigorous sprouter, it is able to recolonize burns immediately at the expense of nonsprouting conifers. Recent research has found that aspen seedling establishment is more common than has been assumed, suggesting the species may be able to thrive even with changing climate and fire regime conditions (Krasnow and Stephens 2015). Similarly, meadows consisting primarily of tufted hair grass burn if fires in adjacent forests occur during the late summer. Occasional fires reduce encroachment into the meadows by conifers (deBenedetti and Parsons 1979).

Subalpine Forest

The subalpine forest lies between the upper montane forest and the alpine meadows and shrublands. Extensive stands of subalpine forest occur on the west side of the Sierra Nevada and a thin band exists on the east side of the range. Like the upper montane zone below, the terrain is moderate on the west side and steep on the east. Volcanic rocks are prevalent in the north and granitic rocks occur throughout the zone. Soils are poorly developed.

The climate of the subalpine forest is characterized by cool summers and extremely cold winters. Whereas growth and other ecological processes are more moisture limited in lower elevation forests, growth in the subalpine zone is largely energy limited driven by low temperatures and a short growing season. Other than occasional summer thundershowers, precipitation falls as snow. The snow-free period is short, from mid-June to late October, and the frost-free period is much shorter. Lightning is pervasive in the subalpine forest with many more lightning strikes than might be expected by chance (van Wagtendonk 1991a). Between 1985 and 2000, the average number of strikes was 33.6 strikes yr^{-1} 100^{-1} k^{-2} (87.1 strikes yr^{-1} 100^{-1} mi^{-2}) (van Wagtendonk and Cayan 2008).

In central and southern Sierra Nevada, the subalpine forest is dominated by lodge pole pine. As tree line is approached, lodgepolepine is replaced by mountain hemlock and whitebark pine (Fig. 14.8). In the northern Sierra Nevada, the forest is dominated by mountain hemlock, western white pine, and whitebark pine. Lodgepole pine also occurs in the north, but there it is more of a riparian or lacustrine fringe species. On the east side of the Sierra Nevada, limber pine occurs with whitebark pine, and in Sequoia National Park, foxtail pine is found at tree line. Extensive meadows of sagebrush sedge (*Carex filifolia* var. *erostrata*) are mixed within the forest.

FIRE RESPONSES OF IMPORTANT SPECIES

Subalpine trees are easily killed by fire at a young age but increase their resistance as they grow older (Table 14.5). Unlike the Rocky Mountain lodgepole pine (*Pinus contorta* var. *latifolia*), the cones of the Sierra Nevada lodgepole are not fully serotinous (some of the cones will hold onto seeds for a few years [Lotan 1975]), and seeding from off-site survivors is often necessary to regenerate a stand lost to high severity fire. Parker (1986) concluded that fire was not necessary for the perpetuation of lodgepole pine, but fire-induced openings supplemented those created by tree-falls. When surface fires occur in Sierra Nevada lodgepole pine forests, individual

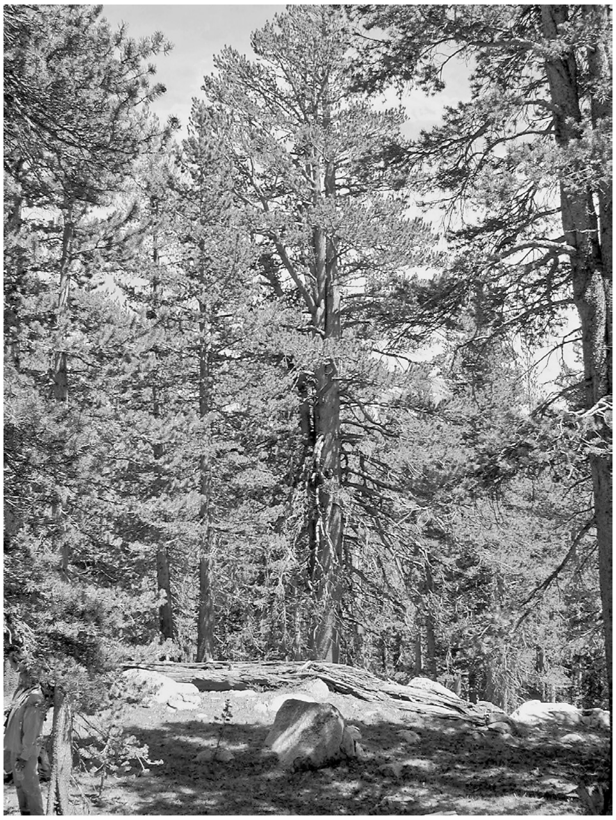

FIGURE 14.8 Subalpine forest. Lodgepole pine forms extensive stands in this zone. Fire is infrequent but when it occurs it burns from log to log or creeps through the sparse understory vegetation and litter.

trees may be killed (deBenedetti and Parsons 1984), while others survive.

The combination of thin bark, flammable foliage, low hanging branches, and growth in dense groups make mountain hemlocks susceptible to fire (Fischer and Bradley 1987). As the trees mature, the bark thickens giving them some protection. Whitebark pine survives fires because trees grow in rocky or sandy habitats and are scattered in areas of patchy fuels (Keane and Arno 2001). Clark's nutcrackers (*Nucifraga columbiana*) facilitate postfire seedling establishment (Tomback 1986). Bark thickness is moderate and mature trees usually survive low and sometimes moderate-intensity surface fires, whereas smaller trees do not. Limber pines also have moderately thin bark, and young trees often do not survive surface fires (Keeley and Zedler 1998). Terminal buds are protected from the heat associated with crown scorch by the tight clusters of needles around them. Foxtail pine occurs where fuels to carry fires are practically nonexistent (Parsons 1981). The charred remains of trees struck by lightning are evidence that periodic fires do occur, although they seldom spread over large areas.

FIRE REGIME–PLANT COMMUNITY INTERACTIONS

Fire regime attributes for the subalpine zone are listed in Appendix 1. Although lightning strikes are plentiful in the subalpine forest zone, ignitions are infrequent. Between 1930 and 1993, lightning caused only 341 fires in the zone in Yosemite National Park (van Wagtendonk 1994). Those fires

TABLE 14.5
Fire response types for important species in the subalpine forest ecological zone

	Type of fire response			
Lifeform	Sprouting	Seeding	Individual	Species
Conifer	None	Fire-enhanced	Killed	Lodgepole pine
	None	None	Resistant, killed	Mountain hemlock
	None	None	Resistant, killed	Whitebark pine, limber pine, foxtail pine
Grass	Fire-stimulated	None	Top-killed	Brewer's reedgrass

burned only 2,448 ha (5,953 ac) primarily in the lodgepole forest. During the period between 1972 and 1993 when lightning fires were allowed to burn under prescribed condition, only six fires in lodgepole pine grew larger than 123 ha (300 ac).

Lodgepole pine fuelbeds are relatively shallow and compact (van Wagtendonk et al. 1998a). Often herbaceous plants occur in the understory precluding fire spread except under extreme dry conditions. Annual deposition of litter and woody fuels are about average among common Sierra Nevada conifers (van Wagtendonk and Moore 2010). When fires do occur, encroaching California red firs and mountain hemlocks are replaced by the more prolific seeding lodgepole pines. In areas where lodgepole pines have invaded meadows, fires will often kill the trees and halt or reverse the invasion (deBenedetti and Parsons 1984). Stand-replacing fires are rare, but when they do occur, lodgepole pines become reestablished from the released seeds.

Data from fires that have burned in the managed wildfire zone in Yosemite suggest a fire rotation of 579 years (van Wagtendonk 1995). Caprio (2008), however, reported that prior to 1860, widespread fires were recorded in 1751, 1815, and 1846 in lodgepole pine stands in Sequoia National Park. Mallek et al. (2013) found that presettlement fire rotations in Sierra Nevada subalpine forest ranged from 75 years to 721 years, with an average of 394 years. Two fire-scar studies in the Sierra Nevada found that lodgepole had a mean fire return interval of 19 years to 39 years on the eastside (North et al. 2009) and 31 years to 98 years in Sequoia National Park (Caprio 2008). Both studies suggested that unlike many Rocky Mountain populations, Sierra Nevada lodgepole pine forests have a fire regime characterized by a mix of fire severities and that stand regeneration may not be largely dependent on serotinous seed dispersal. In Yosemite, lodgepole pine burned predominantly at low severity, although some high severity occurred (Thode et al. 2011). Severity of white bark pine and mountain hemlock fires was barely detectable.

Little information exists for the role of fire in mountain hemlock forests in the Sierra Nevada. In Montana, however, fires in the cool wet mountain hemlock forests generally occur as infrequent, severe stand-replacing crown fires (Fischer and Bradley 1987). Fire return intervals are estimated to be between 400 and 800 years (Habeck 1985). During the 28-year period prior to 1972, no fires burned in hemlock forests in the managed wildfire zone of Yosemite National Park (van Wagtendonk et al. 2002). Litter and duff fuels of mountain hemlocks were some of the deepest, heaviest, and most compact of any Sierra Nevada conifer, indicating long periods between fires (van Wagtendonk et al. 1998a). For mature stands, mountain hemlock had the highest annual deposition of small diameter twigs among eleven common Sierra Nevada conifers (van Wagtendonk and Moore 2010). Mountain hemlock is replaced by lodgepole pine in areas where both are present before a fire. Seeding from adjacent areas is possible but can take several years to be successful.

Fire seldom burns in the pine stands that occur at tree line. There have been only 25 lightning fires in whitebark pine during the past 70 years in Yosemite (van Wagtendonk 1994). Only four of these fires grew larger than 0.1 ha (0.25 ac), and they burned a total of 4 ha (9 ac). Based on the area burned in the type, van Wagtendonk (1995) calculated a fire rotation of over 27,000 years. Although no records exist showing fires in limber pine stands in the Sierra Nevada, it is reasonable to assume equally long fire return intervals for that species. Scattered pockets of fuel beneath both whitebark pine and limber pine attest to the long period between fires. Limber pine recorded the heaviest litter and duff load of any Sierra Nevada conifer (van Wagtendonk et al. 1998a). On the other hand, foxtail pine had hardly any fuel beneath it. Keifer (1991) found only occasional evidence of past fires in foxtail stands. She noted sporadic recruitment in stands that did not appear to be related to fire and suggested that the thick bark on the mature trees protected them from low-intensity fires.

Little is known about fire in subalpine meadows. These meadows are sometimes ignited when adjacent forests are burning. Short hair reedgrass (*Calamagrostis breweri*) can become reestablished after fire from seeds and rhizomes. Meadow edges are maintained by fire as invading lodgepole pines are killed (deBenedetti and Parsons 1984, Vale 1987).

Alpine Meadow and Shrubland

The alpine meadow and shrubland zone consists of fell fields and riparian willows. The short growing season produces little biomass and fuels are sparse. Lighting strikes occur regularly in the alpine zone but result in few fires (van Wagtendonk and Cayan 2008). Weather, coincident with lightning, is usually not conducive for fire ignition or spread. Fires are so infrequent that they probably did not play a role in the evolutionary development of the plants that occur in the alpine zone. The 70-year record of lightning fires in Yosemite includes only eight fires, burning a total of 12 ha (28 ac), primarily in a single fire (van Wagtendonk 1994).

Eastside Forest and Woodland

The width of the eastside montane zone of the Sierra Nevada varies from 30 to 40 km (18 mi) in the northern and central Sierra Nevada to as little as 1 km (0.6 mi) or in the far south. The area to the north and east of Lake Tahoe basin comprises large expanses of eastside forest and woodland vegetation, as does the area around Mammoth Lakes. Lightning is common in the eastside zone with 28.9 strikes yr^{-1} 100^{-1} k^{-2} (74.8 strikes yr^{-1} 100^{-1} mi^{-2}) for the period between 1985 and 2000 (van Wagtendonk and Cayan 2008). Proportionally more lightning strikes occur in the central part of the zone than in any other zone in the Sierra Nevada.

The vegetation of the eastside of the Sierra Nevada is often transitional between upper montane and lower elevation Great Basin species. A variable, but often coarse-scale mosaic of open woodlands, forests, shrublands, or grasslands, is characteristic. The most prevalent tree-dominated types include Jeffrey pine or mixed Jeffrey and ponderosa pine woodlands, mixed white fir and pine forests, and quaking aspen groves (Fig. 14.9). In some locations, particularly in the central and southern portions, pinyon pine occurs. Douglas-fir occur in small amounts in the northern Sierra Nevada and California black oak is scattered throughout the entire range. Shrublands can be extensive and variable, ranging from typical Great Basin species of sagebrush and bitterbrush to chaparral comprised of snow brush (*Ceanothus velutinus*), greenleaf manzanita, bearbrush (*Garrya fremontii*), and bush chinquapin. Curl-leaf mountain-mahogany (*Cercocarpus ledifolius*) occurs in patches on rocky and dry sites. Riparian and wetland areas occur throughout, and meadows can be extensive. Quaking aspen, black cottonwood, and various willow species dominate the overstory of riparian communities of larger streams. Lodgepole pine is also common in riparian areas or localized areas with cold air drainage.

Because of similarities with the Southern Cascades (chapter 12) and the Northeastern Plateaus (chapter 13) bioregions, the focus of this chapter is on the Jeffrey pine woodlands, mixed Jeffrey pine-white fir forests, and montane chaparral. Additional information on communities dominated by desert species can be found in the Southeastern Deserts chapter (chapter 18).

FIRE RESPONSES OF IMPORTANT SPECIES

Species in this zone tend to be a mixture of those with fire resistant or enhanced characteristics and those that are fire inhibited (Table 14.6). Jeffrey pine has thick, fire resistant bark, and large well-protected buds, self-pruning that often results in high crowns, and highly flammable foliage. Pinyon pine is not very fire resistant, with crowns low to the ground, relatively thin bark, and a tendency to have pitchy bark, making it flammable. In this zone, pinyon pine often occupies rocky sites with sparse vegetation and fuels that decrease the likelihood of frequent fire. After severe fires, pine stands can be replaced by sprouting hardwood species. For example, in the northeastern Sierra Nevada, California black oak woodlands now occur where there were Jeffrey pine forests before the 1987 Clark Fire (Carl Skinner, Redding, California, USA, Pers. comm.).

Shrub species vary from those that have enhanced sprouting or seed germination following fire to those that have little fire resistance. Greenleaf manzanita, bearbrush, bush chinquapin, and snow brush all sprout from basal burls following

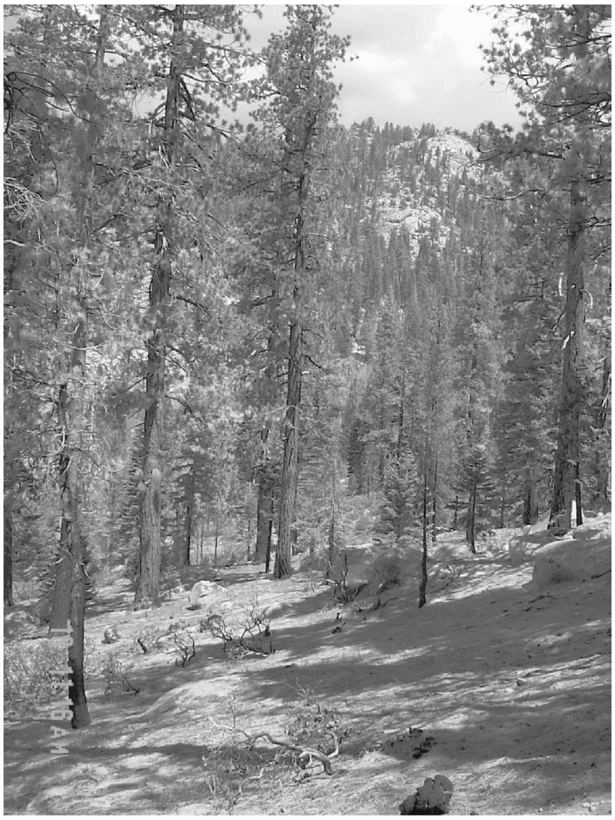

FIGURE 14.9. Eastside forest and woodland. This stand of Jeffrey pine and red fir was recently thinned.

fire. Where branches are pressed against the soil from snow, layering results in sprouting; however, these sprouts can be more susceptible to fire mortality. Snow brush also has enhanced germination from fire.

FIRE REGIME–PLANT COMMUNITY INTERACTIONS

Fire regimes vary with both vegetation type and landscape location (Appendix 1). Several fire history studies have been conducted in the eastern montane zone. In an area east of the crest near Yosemite, Stephens (2001) found median fire return intervals of 9 years for Jeffrey pine and 24 years for adjacent upper montane forest consisting of California red fir, lodgepole pine, and western white pine. Taylor's (2004) work on the east shore of Lake Tahoe showed a mean fire return interval of 11.4 years for presettlement mixed Jeffrey pine and white fir stands. Sampling 10 different eastside Jeffrey pine forests, North et al. (2009) found fire return intervals that ranged from 9 years to 36 years and suggested that some of the variability was related to how isolated or connected stands were to larger forested areas. As recent, severe fires have burned on the lower slopes of the eastside forests, the boundary between forests and sagebrush has retreated upslope. On the eastern slope of the northern Sierra Nevada, Gill and Taylor (2009) determined that the grand mean and grand median composite fire return intervals for all sites were 12.1 years and 10.4 years, respectively.

The most frequent fires and lowest intensity fires occur in the lower elevation, open pine-dominated areas of this zone with responses similar to that described in the Northeastern Plateaus (chapter 13). On less productive or more southern portions, Jeffrey pine woodlands likely had a fire regime

TABLE 14.6
Fire response types for important species in the eastside forest and woodland ecological zone

	Type of fire response			
Lifeform	Sprouting	Seeding	Individual	Species
Conifer	None	None	Resistant, killed	Jeffrey pine, ponderosa pine
	None	None	Low resistance, killed	Pinyon pine
Hardwood	Fire-stimulated	None	Top-killed	Quaking aspen, black cottonwood, willow
Shrub	Fire-stimulated	None	Top-killed	Bush chinquapin, greenleaf manzanita, huckleberry oak, Fremont silk tassel, snowberry, willow, bitterbrush*
	Fire-stimulated	Fire-stimulated	Top-killed	Tobacco brush
	None	None	killed	Sagebrush, bitterbrush*
Herb	Fire-stimulated	None	Top-killed	Woolly mule's ears
	None	None		
Grass	Fire-stimulated	None	Top-killed	Sedges
			killed	Cheat grass

* Bitterbrush has a variable sprouting response to fire.

similar to those described for upper montane Jeffrey pine woodlands, with a range of fire return intervals from 5 years to 47 years (Taylor 2004). White fir forests occur in a mosaic with chaparral on the more mesic sites on north slopes and at higher elevations. The fire regimes included a greater variety of severities, due, in part, to less consistent fire intervals and patterns. The fire season was primarily from summer through fall, with longer seasons at lowest elevations in open pine forests.

The fire regime for the white fir-chaparral type apparently included some high-severity fires in the past (Russell et al. 1998), although the importance of settlement activities on contributing to these types of fires is unclear. Regeneration of white fir is continuous (Bock et al.1978, Conard and Radosevich 1982) until a crown fire occurs. Subsequently, portions of the forest are converted to chaparral dominated by sprouting greenleaf manzanita and both sprouting and heat-stimulated germination of snow brush (Conard and Radosevich 1982). The duration of this fire-generated chaparral can last for over 50 years (Russell et al. 1998). Under current projected climate change, these conversions could become permanent (Airey Lauvaux et al. 2016). Numerous sites in locations conducive to high-severity fire may have supported chaparral stands in the past, but, in the absence of fire over the last century, have succeeded to conifer stands, often dominated by white fir, which can survive for decades in the dense shade of the chaparral understory (Nagel and Taylor 2005). The relative amounts of pine and white fir regeneration are affected by fire. Pine regeneration can increase from 25% in forests with no fire to greater than 93% in forests with fire (Bock and Bock 1969). Fire can also serve to control regeneration by limiting the density of white fire recruitment (Bock et al. 1976), but white fir can also regenerate well under the shade of chaparral (Conard and Radosevich 1982).

Management Issues

Private property owners, land managers, and the public in the Sierra Nevada face many issues as a result of changed fire regimes and population growth. Primary among the issues is the accumulation of fuels both on the ground and in tree canopies. Dealing with these fuels has become more complicated by increased urbanization, at risk species, air quality and high densities of dead trees from drought and beetle infestations.

Urbanization

The population of the Sierra Nevada more than doubled between 1970 and 1990 (Duane 1996). Much of this growth has occurred in the foothills of the Sierra Nevada. In particular, the central Sierra Nevada contains one of the largest areas of intermixed urban and wildlands in California. This creates changes in fire patterns and restricts restoration and fuels reduction activities. The relatively high productivity chaparral in the foothills means that the maintenance of fuel reduction areas needs to be more frequent and are more costly. There are two contrasting fire management conditions in the montane and eastern portions of the Sierra Nevada. One is where communities are adjacent to and mixed with wildlands, and the second is where vast areas are undeveloped, often bordering higher elevation wilderness. The former creates conditions where intensive and frequent fuels reduction treatments around communities are important. Property owners demand that fire suppression forces protect their homes first, thus diverting them from protecting resources. In contrast, more remote forests are well suited for managed wildfire, a program that restores naturally occurring fires in a less intensive and expensive means.

Fire and Fuels Management

Each new catastrophic fire increases the clamor to do something about fuels. Homeowners expect fire and land management agencies to act, yet are often unwilling to accept some of the responsibility themselves. The most immediate problem exists around developments and other areas of high societal values. Mechanical removal of understory trees followed by some sort of surface fuel treatment—prescribed burning is ideal from the standpoint of reducing fuels and restoring ecological process—is the most likely to succeed in these areas. Where houses have encroached into shrublands, removal of shrubs up to 30 m (100 ft) may be necessary. Less compelling are treatments in remote areas where there is less development and access is difficult. Prescribed burning and the use of naturally occurring fires are more appropriate in areas beyond the urban wildland interface.

The call to thin forests to prevent catastrophic fires has confused the issue. Only in rare occasions can a fire move independently through the crowns of trees without treating surface fuels is likely to increase surface fuels and thus increase severity (Vaillant et al. 2009, McIver et al. 2013). A combination of treatments including thinning from below and prescribed fire will probably be most productive.

Climate Change

Under most climate change projections, fire is projected to increase in frequency, size, and severity (Westerling 2011). These fire regime attributes are already increasing in many places (Miller et al 2009, Miller and Safford 2012, chapter 26), and fire is likely to influence changes in forest cover types. Some site type changes from repeated high-severity fire are already occurring (Stephens et al. 2013). Long-term climate change coupled with decades of fire exclusion is likely to exacerbate the problem. Young et al. (2017) found that forest mortality in California during the first four years of the drought that began in 2012 increased disproportionately in response to increases in climatic water deficit and stand basal area.

Although current efforts to reduce fuel loads and wildfire severity have been marginal at best, climate change is likely to exacerbate this situation (chapter 26). Greater use of prescribed fire and managed wildfire may be a more effective way to significantly increase the pace and scale of fuels reduction and mitigate the impacts of climate change. For example, van Mantgem et al. (2016) found that in Yosemite, Sequoia, and Kings Canyon national parks, common conifers in plots burned by prescribed fires or managed wildfires had significantly reduced drought-related mortality than in unburned plots.

Species at Risk

All species living in the Sierra Nevada evolved with fire and its effects on habitat vegetation and prey populations. Several at-risk animal species, including the Pacific fisher (*Martes pennanti pacifica*), American marten (*M. americana*), northern goshawk (*Accipiter gentilis*), and California spotted owl (*Strix occidentalis occidentalis*), are associated with habitat characterized by older, dense forest stands with high canopy cover. As a result of fire exclusion, these conditions often have high fuel loads that produce high-severity fire killing most of the large, overstory trees. A challenge of Sierra Nevada forest management is to provide this habitat while reducing landscape-level fuels sufficiently to reduce wildfire severity (North et al. 2010). Current and projected future trends in climate are likely to accelerate forest change due to fire, especially the loss of older forest and the expansion of early seral habitats (McKenzie et al. 2004, Scheller et al. 2011, Safford and Stevens 2017).

Research has identified the amount, size, and location of dense, high-canopy cover habitat in historical and modern forests with active fire regimes. These conditions are often associated with wetter, more productive sites that burned at lower frequencies, as well as lower severities under moderate weather conditions, but the probability of high severity fire was increased in such stands under severe fire weather conditions (Lydersen and North 2012, Collins et al. 2015, Kane et al. 2015). One study of California spotted owl and Pacific fisher in the southern Sierra Nevada found significantly higher than expected use of these areas given their proportion of the landscape (Underwood et al. 2010). There is also evidence that although these species may rest, den, and nest in these conditions, they often forage in variable forest conditions that include less dense, open canopy stands (Irwin et al. 2007, Roberts et al. 2008, Truex and Zielinski 2013). The forest heterogeneity created by low- to moderate-severity burns is associated with greater evenness in small mammal communities, possibly providing more consistent prey base abundances for higher predators such as the California spotted owl and Pacific fisher (Roberts et al. 2015).

The question becomes how to restore natural fire regimes and forest structures without adversely affecting at risk species and their habitats. To do nothing threatens to make the already tenuous situation worse, predisposing the species and habitats to destruction by catastrophic fire. These species evolved with fire and the answer must include fire (Jones et al. 2016).

Air Quality

Air quality is one of the biggest impediments to conducting prescribed burns and managing wildfires in the Sierra Nevada. Lower to mid-elevation forests inevitably burn and produce smoke. When a wildfire escapes suppression under extreme weather conditions, it often produces heavy concentrations of smoke lasting weeks that winds may direct into rural communities or urban cities. With prescribed burning, local residents can be forewarned and the area burned when wind direction will disperse smoke away from population centers (Rappold et al. 2014). Although air quality regulations exempt wildfire emissions, prescribed and managed wildfires are considered anthropogenic and only permitted when their emissions will not exceed regulatory limits (Engel 2013). Current air regulations and acceptable pollutant concentrations are based on a concept of pristine air quality that does not consider pre-Euro-American settlement levels of burning (chapter 23). Another problem with current regulations is that burn projects are evaluated based on burn area rather than on smoke emissions and do not consider actual impacts to human health (Long et al. 2018).

Model projections suggest smoke emissions are likely to double by the end of the century, but a greatly expanded program of prescribed burning could mitigate much of that effect (Hurteau et al. 2014). Society is faced with deciding to accept periodic episodes of low concentrations of smoke from managed fires or heavy, long duration doses from wildfires. Either reduced emission restrictions for wildland management activities or exemptions for Federal agencies from air pollution control district regulations will be necessary if fire is to be allowed to again play its natural role in the Sierra Nevada.

Research Needs

Skinner and Chang (1996) developed a comprehensive list of research needs during the Sierra Nevada Ecosystem Project. They identified topics in three general areas: (1) spatial and temporal dynamics of fire, (2) presettlement forest conditions, and (3) effects of fire on ecosystem processes. Much has been accomplished on these topics and new issues have arisen. These include forest heterogeneity, smoke dynamics, and post-burn forest restoration.

Forest Heterogeneity

Fire exclusion tends to make forests more homogeneous as trees fill in forest openings and create high, uniform canopy cover. When these forests burn, particularly during high-intensity wildfire, they often perpetuate that homogeneity by creating large areas of dead trees and subsequently uniform areas of high brush cover. A challenge has been to reestablish heterogeneous forests conditions that were historically created by frequent fire and that may have been self-reinforcing. Although there is a general sense of how forest and fuel conditions may have varied with topography and water availability, specific management prescriptions are still vague for creating variable conditions that could be self-perpetuating under an active fire regime. Tree spatial patterns such as clumps and openings likely varied with topography, as did fuels loads in different size classes. Research is needed to identify general target levels for these conditions that would help managers set objectives at site, stand, and landscape scales.

Smoke Dynamics

Current models of the total amount, concentration, and dispersal of smoke produced by wildland fires are fairly general. Many unknowns still limit prediction accuracy such as the amount of fuel consumed, wind patterns at different elevations affecting dispersal, local diurnal weather patterns, and how these affect concentrations of different smoke pollutants such as particulate matter of and ozone. Furthermore, a network of established pollutant sensors is needed to measure where smoke actually accumulates. The concern with wildland fire smoke is human exposure and yet current assessments are based on crude estimates of total production rather than concentration, exposure, and duration.

Post-Burn Forest Restoration

Many wildfires escape suppression and burn with high severity during extreme weather events in fuels-loaded forests. These fires often produce large patches (>250 ha [>1,000 ac]) with near 100% tree mortality. Historically this was a rare occurrence and may now produce relatively novel conditions for vegetation succession, wildlife habitat, and microclimate. Research is needed on how forest regeneration, carbon cycling, and water quality and quantity respond to these conditions. In the past, high-severity areas have been replanted at high density (>80 trees ha^{-1} [>200 trees ac^{-1}]) often with regularly spaced pines. Many of these plantations have burned at high severity in subsequent wildfires. There is also concern that such densities may be too high given drying and warming climate conditions and that the regular spacing does not mimic forest patterns produced by frequent fire. The size and severity of modern wildfires raise many questions about how best to manage these post-burn landscapes and help set them on a trajectory toward recovery. How is the forest to fare if nothing is done in large areas of high severity—will it be able to recover in a reasonable time or will the vegetation likely shift to nonforest vegetation? If the latter is the case, then would planting with other treatments help to mitigate?

Summary

John Muir named the Sierra Nevada the Range of Light; a better name might have been the Range of Fire. Fires have been a part of the Sierra Nevada for millennia and will continue to be so in the future. In this chapter we surveyed the factors that make fire an important process in the ecological zones of the range and the interactions fire has with the vegetation in each zone. The success of our management of the Sierra Nevada is contingent upon our ability and willingness to maintain fire as an integral part of these ecosystems. To not do so is to consign ourselves to failure: fire in the Sierra Nevada is inevitable, and the only real questions are when and under what conditions an area will burn.

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