CHAPTER 12

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.
>
> JOHN 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 700 km (435 mi) to the south (Map 12.1). 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 as described by 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 of California. Significant features along the length of the range include Lake Tahoe, Yosemite Valley, and Mount Whitney.

Description of the Bioregion

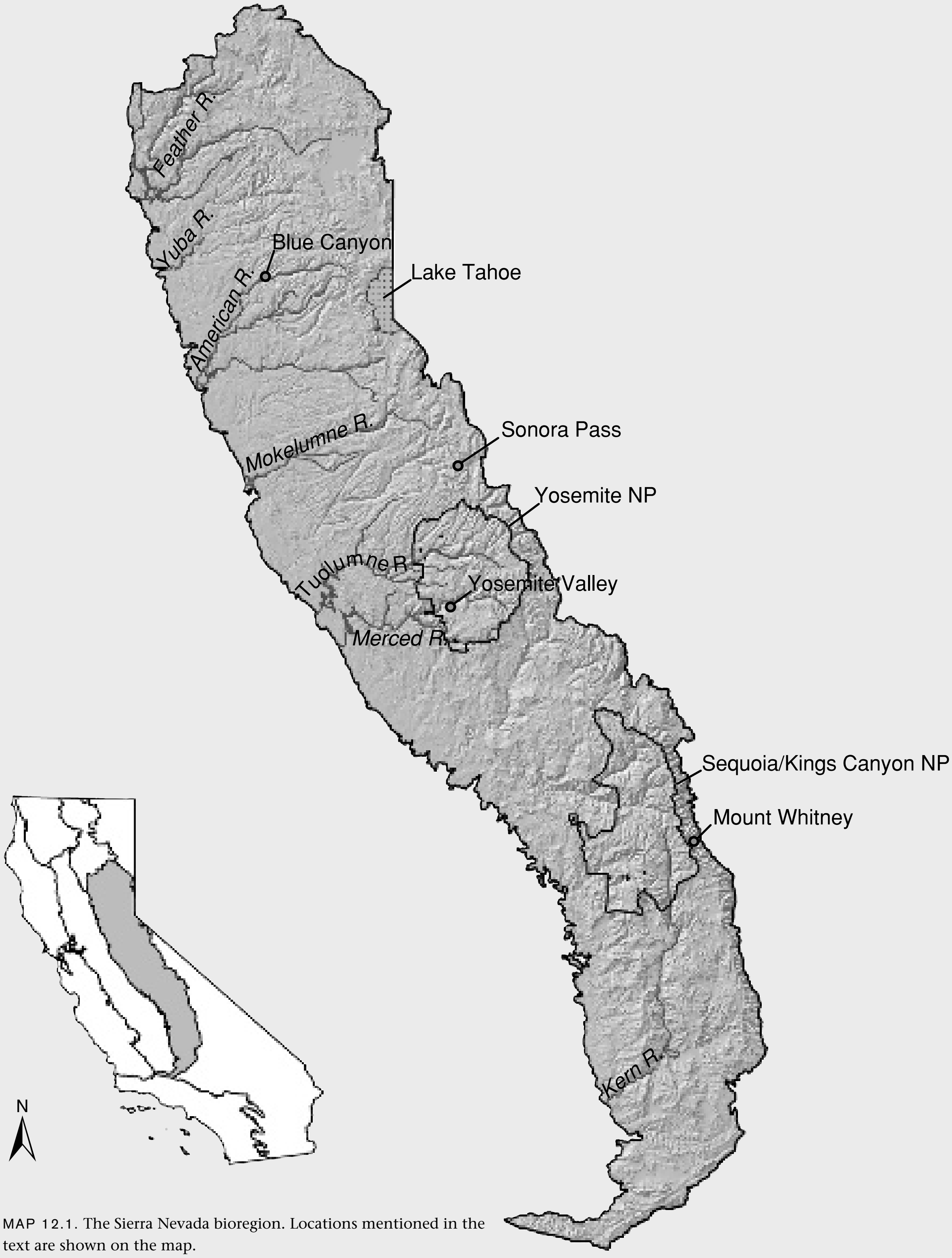
The natural environment of the Sierra Nevada is a function of the physical factors of geomorphology, geology, and regional climate interacting with the available biota. These factors are inextricably linked to the abiotic and biotic ecosystem components including local climate, hydrology, soils, plants, and animals. The distribution and abundance of the ecological zones of the Sierra Nevada 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 slightly to the south of west and has a steep eastern escarpment that culminates in the highest peaks. This block of the Earth's crust broke free along a bounding fault line and has been uplifted and tilted (Huber 1987). Elevations range from 150 m (492 ft) on the American River near Sacramento to 4,418 m (14,495 ft) at Mount Whitney.

The relatively moderate 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. As the mountain block was uplifted, the rivers cut deeper and deeper into underlying rock (Huber 1987). The foothills are gently rolling with both broad and narrow valleys. At the mid elevations, landforms include canyons and broad ridges that run primarily from east-northeast to west-southwest. Rugged mountainous terrain dominates the landscape at the higher elevations.

The oldest rocks of the Sierra Nevada were metamorphosed from sediments deposited on the sea floor that collided with the continent during the early Paleozoic Era (Huber 1987). These rocks grade into early Mesozoic Era metasediments and metavolcanics west of the crest of the Sierra Nevada. Granites began to form 225 million years ago, and pulses of liquid rocks continued for more than 125 million years, forming the granite core of the range (Schweickert 1981). During the first half of the Tertiary Period, mountains were uplifted and erosion stripped the metamorphic rocks from 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 an Appalachian-like chain of low mountains. Violent 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 higher central Sierra Nevada with ash that dammed streams, filled narrow valleys, and covered passes (Hill 1975). Today, volcanic rocks occur primarily in the northern and central Sierra Nevada, although small outcrops can be seen throughout the range. The sharp relief and high altitude of the modern Sierra Nevada are the products of recent uplift associated with extension of the Great Basin. This uplift began 2 to 3 million years ago and continues today.



MAP 12.1. The Sierra Nevada bioregion. Locations mentioned in the text are shown on the map.

TABLE 12.1
Normal maxima, normal minima, record high, and record low temperatures at Blue Canyon, elevation 1,609 m (5,391 ft), northern Sierra Nevada

	Normal Daily Maximum (°C)	*Normal Daily Minimum (°C)*	*Record High (°C)*	*Record Low (°C)*
January	6.4	−0.8	21.7	−15.0
February	6.3	−0.7	22.8	−14.4
March	7.9	0.4	22.2	−12.8
April	11.7	3.3	25.6	−8.3
May	15.7	6.7	30.0	−6.1
June	19.6	10.6	33.3	−2.2
July	25.0	15.0	32.8	4.4
August	24.8	13.8	33.3	1.7
September	22.2	12.2	33.9	−1.7
October	16.8	7.4	29.4	−5.6
November	12.1	3.1	25.6	−0.6
December	8.6	0.6	23.9	−2.8

During the Pleistocene Epoch, snow and ice covered most of the high country, and glaciers filled many of the river valleys (Hill 1975). Several glaciations are recognized to have occurred in the Sierra Nevada, but only two can be reconstructed with confidence (Huber 1987). The Tahoe glaciation reached its maximum extent about 60,000 to 75,000 years ago, whereas the Tioga glaciation peaked about 15,000 to 20,000 years ago. These glaciers further deepened valleys and scoured ridges, leaving the exposed granite landscape so prevalent today. Modern glaciers are scattered on high peaks between Yosemite and Sequoia National Parks.

Seven soil orders occur in the Sierra Nevada. *Alfisols* are formed under forest cover with the bulk of the annual production of organic matter delivered above ground. *Andisols* most commonly occur on steep slopes formed by volcanic activity. *Aridisols* occur in semi-arid areas where local conditions impose aridity. *Entisols* and *Inceptisols* are found where climate or bedrock limits soil development. Most *Mollisols* have formed under meadow or grassland vegetation. Deeply weathered *Ultisols* develop in moist, cold areas under acidic conditions. The different soil orders occur in combination with wet, frigid or frozen soil temperature regimes and dry to aquatic soil moisture regimes.

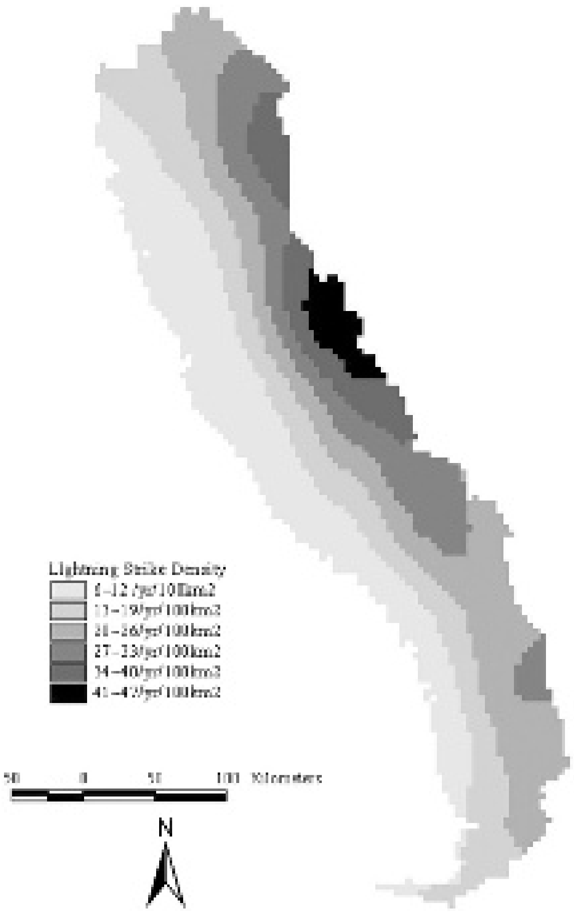
Climatic Patterns

The pattern of weather in the Sierra Nevada is influenced by its topography and geographic position relative to the Central Valley, the Coast Ranges, and the Pacific Ocean. Winters are dominated by low pressure in the northern Pacific Ocean while summer weather is influenced by high pressure in the same area.

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. The coastal mountains catch some of the moisture, but the gap in the mountains near San Francisco Bay allows storms to pass through producing the heaviest precipitation to occur in the Sierra Nevada in areas to the east and north. As the air masses move up the gentle western slope, precipitation increases and, at the higher elevations, falls as snow. Once across the crest, most of the moisture has been driven from the air mass and precipitation decreases sharply. 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 foothills to more than 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 thunderstorms and subtropical storms moving up from the Gulf of California.

Sierra Nevada temperatures are generally warm in the summer and cool in the winter. Table 12.1 shows normal monthly maxima and minima and highest and lowest temperatures recorded for the Blue Canyon weather station at 1,609 m (5,391 ft) in the northern Sierra Nevada. Temperatures decrease as latitude and elevation increase, with a temperature lapse rate of approximately 6.5°C with each 1,000 m of elevation (3.3°F in 1,000 ft). At Blue Canyon, normal 10:00 am relative humidity is highest in January at 60% and lowest in July at 30%. Extremely low relative humidity is common in the summer. Wind speeds are variable, averaging



MAP 12.2. 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.

up to 11 km hr^{-1} (7 mi hr^{-1}) but have been recorded as high as 113 km hr^{-1} (70 mi hr^{-1}) out of the north at Blue Canyon during October.

Lightning is pervasive in the Sierra Nevada, occurring in every month and on every square kilometer with over 210,000 strikes occurring from 1985 through 2000 (van Wagtendonk and Cayan 2007). However, there are spatial and temporal patterns. Map 12.2 shows the spatial distribution of the average annual number of lightning strikes for the 16-year period. The highest concentration of lightning strikes occurs 15 km (9.3 mi) northeast 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 (Fig. 12.1) (van Wagtendonk 1991a). Summer afternoon heating of slopes causes uplift in the mountains and results in the development of thunderstorms. Ridge tops receive more strikes than valley bottoms, but there is no significant relationship between strikes and either slope steepness or aspect. The temporal distribution of lightning strikes is shown in Table 12.2. The greatest number of strikes occurs in the afternoon in July and August.

WEATHER SYSTEMS

Fires are associated with critical fire weather patterns that occur with regularity during the summer (Hull et al. 1966). For California, there are four types of patterns: (1) the Pacific High–Post-Frontal, (2) the Great Basin High, (3) the Subtropical High Aloft, and (4) the Meridional Ridge with Southwest Flow Aloft. The Pacific High–Post-Frontal type is a surface type where air from the Pacific moves in behind a cold front and causes north to northwest winds in northern and central California (Hull et al. 1966). A foehn effect is produced by steep pressure gradients behind the front causing strong winds to blow down slope. The Great Basin High type often follows the Pacific High–Post-Frontal 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 (Hull et al. 1966). Although this type is often present during winter months when fires are not expected to occur, 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 temperatures and low relative humidities 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). Table 12.3 shows the percentage of days each month that would be expected to have each critical fire weather pattern based on records from the Blue Canyon station. During June, July, and August, the maximum temperatures associated with each of these types range from 27°C to 33°C (81°F–91°F) and the relative humidity from 8% to 21%.

Ecological Zones

The vegetation of the Sierra Nevada is as variable as its topography and climate. In response to actual evapotranspiration and the available water budget, 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. 12.2). The ecological zones increase in elevation from the north to southern Sierra Nevada.

FOOTHILL SHRUBLAND AND WOODLAND

The foothill shrubland and woodland zone covers 15,777 km^2 (5,993 mi^2) from the lowest foothills at 142 m (466 ft) to occasional stands at 1,500 m (5,000 ft), reaching a maximum

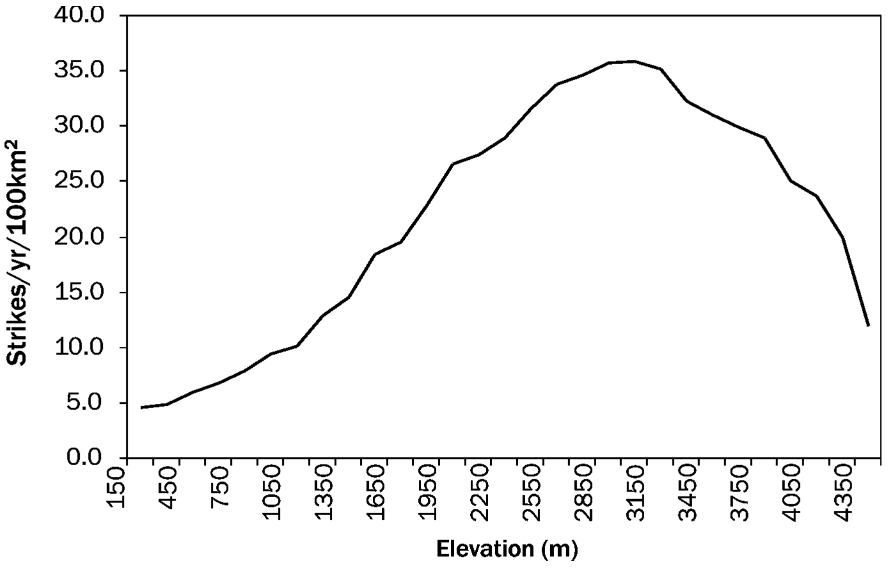


FIGURE 12.1. Lightning strikes by elevation in the Sierra Nevada bioregion, 1985–2000. The density of strikes is greatest at 3,000 m and decreases as elevation increases above that point.

TABLE 12.2
Temporal distribution of lightning strikes by 2-month and 4-hour periods for the Sierra Nevada, 1985–2000

	Number of Strikes						
Hour	Jan–Feb	Mar–Apr	May–Jun	Jul–Aug	Sep–Oct	Nov–Dec	*Total*
0–4	88	159	1,661	3,645	1,505	156	7,214
4–8	61	111	858	6,402	1,919	39	9,390
8–12	105	610	7,946	21,902	4,204	85	34,852
12–16	665	3,688	28,124	64,692	17,430	377	114,976
16–20	482	1810	10,025	15,344	6,685	762	35,110
20–24	162	434	3,344	2271	1723	801	8,735
Total	1,565	6,812	51,958	114,256	33,466	2,220	210,277

extent between 150 m and 300 m (1,000–1,500 ft). The primary vegetation types in this zone are foothill pine–interior live oak *(Pinus sabiniana-Quercus wislizenii)* woodlands, mixed hardwood woodlands, and chaparral shrublands. Blue oak *(Quercus douglasii)* woodlands occur at the lower end of the zone and are treated in Chapter 13 (Central Valley Bioregion).

LOWER-MONTANE FOREST

The lower montane forest is the most prevalent zone in California and in the Sierra Nevada bioregion, occupying 21,892 km^2 (8,316 mi^2) primarily on the west side of the range just above the foothill zone. Ninety-five percent of the stands occur below 2,400 m (8,000 ft), and the greatest occupied area is between 1,500 and 1,650 m (5,000–5,500 ft). Major vegetation types include California black oak *(Quercus kelloggii)*, ponderosa pine *(Pinus ponderosa)*, 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 and seeps.

UPPER MONTANE FOREST

This ecological zone covers 11,383 km^2 (4,324 mi^2) and extends from as low as 750 m (2,500 ft) to 3,450 m (11,500 ft). The upper-montane forest is most widely spread between 1,950 and 2,100 m (6,500–7,000 ft) where it covers 1,800 km^2 (695 mi^2). Forests within this zone include extensive stands of California red fir *(Abies magnifica* var. *magnifica)* along with occasional stands of western white pine *(Pinus monticola)*. Woodlands with Jeffrey pine *(Pinus jeffreyi)* and Sierra juniper *(Juniperus occidentalis* ssp. *australis)* occupy exposed ridges, whereas meadows and quaking aspen *(Populus tremuloides)* stands occur in moist areas.

TABLE 12.3

Percent of days each month with critical fire weather types for Blue Canyon, 1951–1960

	Percentage of Days Per Month									
Weather Type	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec–Feb
Pacific High, Post-frontal	6.8	8.0	5.2	7.0	3.2	4.5	5.7	7.4	5.3	4.9
Great Basin High (Pacific)	16.1	12.0	11.3	11.0	7.4	6.1	12.3	18.7	15.7	16.1
Subtropical High Aloft	0.0	0.0	0.0	10.3	32.3	24.8	16.3	1.6	0.0	0.0
Meridional Ridge SW Flow Aloft	3.9	6.3	11.6	17.0	16.5	27.4	17.3	9.0	7.7	1.9

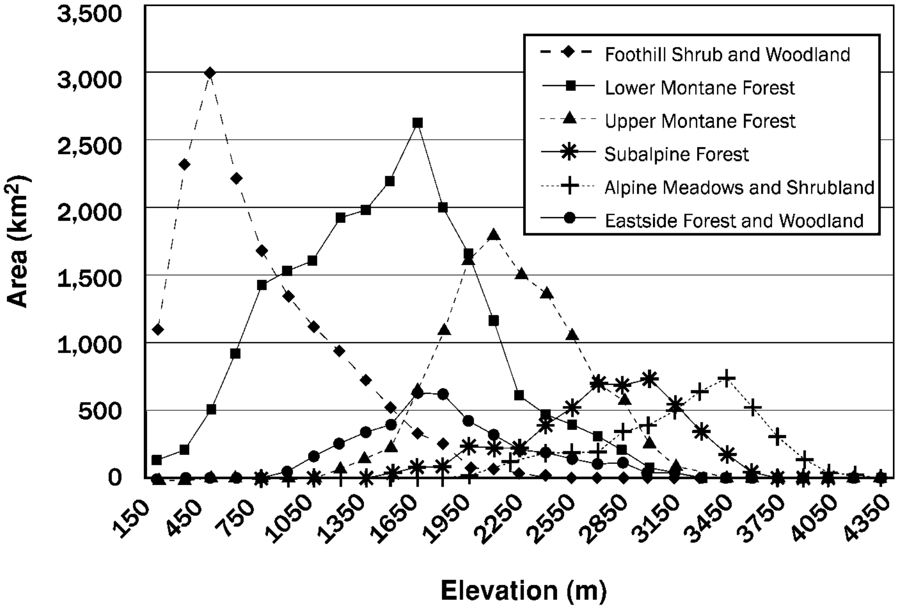


FIGURE 12.2. Area of ecological zones by 500-m elevation bands. The elevational distribution of ecological zones is evident as area cover by each zone increases and then decreases as elevation increases.

SUBALPINE FOREST

The subalpine forest zone ranges from 1,650 m (5,500 ft) to 3,450 m (11,500 ft) and reaches its maximum extent between 3,000 m to 3,450 m (9,500–10,000 ft). The subalpine zone encompasses 5,047 km^2 (1,917 mi^2) and consists of lodgepole pine *(Pinus contorta* ssp. *murrayana)*, mountain hemlock *(Tsuga mertensiana)* forests and limber pine *(Pinus flexilis)*, foxtail pine *(Pinus balfouriana* ssp. *balfouriana)*, and whitebark pine *(Pinus albicaulis)* woodlands, with numerous large meadow complexes.

ALPINE MEADOW AND SHRUBLAND

Sitting astride the crest of the Sierra Nevada is the 4,423-km^2 (1680-mi^2) alpine meadow and shrubland ecological zone. The zone extends from 2,000 m (7,000 ft) to 4,350 m (14,500 ft), with the largest area between 3,300 m and 3,450 m (11,000–11,500 ft). 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 3,907 km^2 (1,484 mi^2). The woodlands are comprised of single-leaf pinyon pine *(Pinus monophylla)*, while the forests consist of Jeffrey pine, white fir, and mixed white fir and pine. The zone ranges in elevation from 1,050 m to 2,850 m (3,500–9,500 ft) and is most prevalent between 1500 m and 1,650 m (5,000–5,500 ft).

Overview of Historic Fire Occurrence

Fire has been an ecological force in the Sierra Nevada since the retreat of the Tioga glacier more than 10,000 years ago. Flammable fuels, abundant ignition sources, and hot, dry summers combine to produce conditions conducive to an active fire role. Whereas this role has varied over the millennia as climate has changed, fire continues to shape vegetation and other ecosystem components. Fire's role is also influenced by the elevation gradient of the Sierra Nevada, which affects fuels, ignition sources, and climate.

Prehistoric Period

The earliest evidence of the presence of fire in the Sierra Nevada can be seen in lake sediments more than 16,000 years old in Yosemite National Park (Smith and Anderson 1992). Charcoal does not appear in meadow sediments until about 10,000 B.P. (Anderson and Smith 1997). Six separate peaks in charcoal deposits were recorded between 8,700 and 800 years B.P. in seven meadows from Yosemite south to Sequoia National Park. Such increases in charcoal abundance above the background level indicate large individual fires or fire periods. With the exception of the peak between 8,700 and 9,500 years B.P., charcoal was less prevalent in the early Holocene Epoch than in the late Holocene, suggesting that the climate was drier during the earlier period (Anderson and Smith 1997).

Pollen and macrofossils in the sediments indicate that the forests were more open during the early Holocene, possibly producing less fuel and less extensive fires. Anderson and Smith (1997) hypothesized that, during the late Holocene, climatic changes and possible increases in winter storms or El Niño-like conditions led to denser forests with greater fuel loads and more intense fires. Pollen data from sediment cores taken from subalpine lakes confirmed the meadow data showing open, dry vegetation consisting of pines and chaparral during the early Holocene and closed, wet forests of firs and hemlocks during the late Holocene (Anderson 1990).

Fire scars are another source of information for documenting the historical role of fire. Wagener (1961b) reexamined fire scar records from mixed conifer stands on the western slope of the Sierra Nevada between the Feather River on the north and the San Joaquin River on the south. Included in his analysis were five stands originally investigated by Boyce (1920) and two additional stands north and south of Yosemite. Based on all seven of those stands, fire-return intervals ranged from seven to nine years. In a study area 50 km (31 mi) west of Lake Tahoe, Stephens et al. (2004) recorded fires between 1649 and 1921 with median fire intervals between 5 and 15 years. For the mountains just to the southeast of Lake Tahoe, Taylor (2004) reported a mean presettlement fire return interval of 10.4 years. Further south in Kings Canyon National Park, Kilgore and Taylor (1979) found that fires scarred trees every 7 years on west-facing slopes and every 16 years on east-facing slopes.

Fire scar records from five giant sequoia *(Sequoiadendron giganteum)* groves located from Yosemite to south of Sequoia National Park confirm the presence of fire in the Sierra Nevada for the past 3,000 years with the earliest recorded fire occurring in 1125 B.C. (Swetnam 1993). Based on independent climate reconstructions, years with low precipitation amounts were likely to have fires occur synchronously across the region. The scars showed that extensive fires burned every 3.4 to 7.7 years during the cool period between A.D. 500 and A.D. 800 and every 2.2 years to 3.7 years during the warm period from A.D. 1000 to A.D.1300. After 1300, fire-return intervals increased, except for short periods, during the 1600s for one grove and during the 1700s for two other groves (Swetnam 1993). Fire-free intervals ranged from 15 to 30 years during the long-interval period and were always less than 13 years during the short-interval years.

Although lightning would have been present for millennia prior to charcoal appearing in late sediments 16,000 years ago, ignitions by Native Americans probably did not occur until 9,000 years ago (Hull and Moratto 1999). Their use of fire was extensive and had specific cultural purposes (Anderson 1999). 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 aboriginal inhabitants 650 years ago. Similarly, Anderson and Smith (1997) could not rule out burning by aboriginals as the cause of the change in fire regimes beginning 4,500 years ago. It is reasonable to assume that the contribution of ignitions by Native Americans was significant but varied over the spectrum of inhabited landscapes (Vale 2002).

Historic Period

The arrival of European 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 exacerbated the situation by introducing cattle and sheep to the Sierra Nevada, setting fires in attempts to improve the range, and excluding fires from other areas to protect timber and watershed values. Extensive fires occurred as a result of slash burning associated with logging activities and prospectors who burned large areas to enhance the discovery of mineral outcrops (Lieberg 1902).

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. Giant sequoias also showed a reduction in fire scars after 1850, assumed by Swetnam (1993) to be the result of sheep grazing, elimination of fires set by Native Americans, and fire suppression. Similar decreases in fire scars were noted by Wagener (1961b) throughout the Sierra Nevada and by Kilgore and Taylor (1979) in the southern part of the range.

Of all the activities affecting fire regimes, the exclusion of fire by organized government suppression forces has had the greatest effect. Beginning in the late 1890s, the U.S. 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

Based on early work by Biswell (1959) and Hartesvelt (1962), 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 the Sierra Nevada landscape through programs of prescribed burning and wildland fire use (Kilgore and Briggs 1972, van Wagtendonk 1986). Giant sequoias recorded the new program with fire scars from two prescribed burns in 1969 and 1971 and a wildfire in 1988 (Caprio and Swetman 1995).

For much of the Sierra Nevada, however, routine fire suppression is still the rule. Fire regimes are altered with a shift from frequent, low-intensity fires to less frequent, large fires (McKelvey and Busse 1996). Fuel accumulations, brush, small trees, and dense forests produce very different conditions for the inevitable fire that occurs, whether from lightning or from human sources. Some headway is being made in wilderness areas and areas where prescribed fire can be applied safely and effectively.

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 dependency on fire. Similarly, the fire regimes and plant community interactions of the zones vary.

Foothill Shrubland and Woodland

The foothill shrubland and woodland zone is the first ecological zone above the Central Valley bioregion. It is bounded below by the valley grasslands and blue oak woodlands and above by the montane, conifer-dominated zone. The terrain is moderately steep with deep incised canyons. Sedimentary, metavolcanic, and granitic rocks form the substrate and soils are 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 km^{-2} (75.9 strikes yr^{-1} 100 mi^{-2}).

The vegetation is a mix of large areas of chaparral, live oak woodland with scattered or patchy foothill or ponderosa pines (Fig. 12.3). These species form dense continuous stands of vegetation and fuels. Chamise *(Adenostoma faciculatum)*, manzanita *(Arctostaphylos* spp.*)*, and California-lilac *(Ceanothus* spp.*)* dominate the chaparral. Interior live oaks or canyon live oaks *(Quercus chrysolepis)* are extensive on steep slopes of large canyons. 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 15. Some species are dominant, such as chamise in extensive chaparral areas and stands of interior live oak. Chaparral includes many sprouting species but few that require heat for seed germination. The two live oaks are vigorous sprouters. The most prevalent conifers, such as ponderosa pine, are fire resistant or have serotinous cones, such as gray pine and knobcone pine. There has been less research in Sierra Nevada chaparral than in southern California and the proportion of species with fire-dependent characteristics is unknown. Establishment, survival, and abundance of many species are enhanced by fire. The fire responses for knobcone pine *(Pinus attenuata)*, ponderosa pine, and chamise are covered in more detail in the North Coast (Chapter 8), Northeastern Plateaus (Chapter 11), and South Coast (Chapter 15) chapters, respectively. Table 12.4 lists the fire responses of the important species in the foothill zone.

Numerous chaparral shrubs sprout following fire. These include chamise, flannelbush *(Fremontodendron californicum)*, poison oak *(Toxicodendron diversilobum)*, coyote brush *(Baccharis pilularis)*, birch-leaf mountain-mahogany *(Cercocarpus betuloides* var. *betuloides)*, redshank *(Adenostoma sparsifolium)*, yerba santa *(Eriodictyon californicum)*, California coffeeberry *(Rhamnus californica)*, and Christmas berry *(Heteromeles arbutifolia)* (Biswell 1974). Non-sprouting shrubs can be dominant as well, with seeds that are heat resistant and have fire-enhanced germination—such as whiteleaf manzanita *(Arctostphylos viscida)*, Mariposa manzanita *(Arctostaphylos viscida* spp. *mariposa)*, chapparal whitethron *(Ceanothus leucodermis),* and buck brush *(Ceanothus cuneatus* var. *cuneatus)*. Exposure to heat can more than double germination rates. Laurel sumac *(Malosma laurina)*

FIGURE 12.3. Foothill shrub and woodland. Foothill pine and interior live oak are dominant overstory species in this stand with non-native grasses and species of manzanita and California-lilac in the understory. Fire is common and keeps the understory relatively clear.

seed germination increased from 17% to more than 50% with exposure to 100°C (212°F) (Wright 1931). Many chaparral species produce seed at an early age that can remain viable in the soil for decades or more. Buck brush produces seeds from age 5 to 7 years. Growing in dominantly single-species patches, buck brush resists burning until decadent or foliar moistures are extremely low. Several crops of seed are often produced before fire returns, enhancing post-fire dominance.

Sierra Nevada chaparral can be more productive than its southern California counterparts, with four times the biomass accumulation over 37 years (Rundel and Parsons 1979). As stands age, the proportion of dead biomass increases. By the time chamise stands reach 16 years of age, the combination of dead branches and live resinous foliage make them extremely flammable.

Numerous geophytes, or bulb-bearing plants, that show an increased flowering and growth response following fire are scattered in chaparral. Common examples are soap plant *(Chlorogalum pomeridianum)*, death camas *(Zigadenus* spp.*)*, and mariposa lilies *(Calochortus* spp.*)*. Annual plants respond to fire by prolific seeding.

Interior and canyon live oaks sprout both from root and canopy crowns following fire and their seedlings develop burls early. 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 persist after high-intensity fires in surrounding chaparral by developing cones and seeds at an early age, producing plentiful seeds (Fowells 1979), and by having cones that are opened by heat (Sudworth 1908) and seedlings that survive well on mineral soil. Pitch running down the bole is common and increases crown torching (Lawrence 1966). The tolerance of foothill pine for rocky, thin soils and drought conditions also enables it to avoid burning because fuels are scattered and fire infrequent. Because foothill pine seeds are large and wingless, dispersal of seeds is dependent on seed caching by rodents and birds.

Native Americans maintained small patches of native grasslands such as deergrass *(Muhlenbergia rigens)*, which is a large, coarse-leaved perennial bunchgrass (Anderson 1996). It responds to periodic burning with vigorous growth. Fires, particularly if set in the fall, favored native species, including fire-stimulated flowers of bulb-species like brodiaea *(Brodiaea* spp.*)* (York 1997). Fire exclusion has led to invasion of these patches by annual, non-native grasses such as cheat grass *(Bromus tectorum)*.

FIRE REGIME–PLANT COMMUNITY INTERACTIONS

Fire regimes in the foothill zone vary with topography and vegetation. In the lower portions with more gentle topography, the oak grassland savannah areas burned frequently and with low to moderate intensity as described in the Central Valley chapter (Chapter 11). Fire season would have begun in early summer extending to fall. Steeper areas dominated by chaparral and scattered trees or pockets of conifers burned less frequently and with higher-intensity crown fires, resulting in highly severe effects to vegetation (Table 12.5). These are among the driest areas in the bioregion, with less than 62.5 cm (25 in) average annual precipitation being characteristic. Fire season is long and begins in early summer. Given the high numbers of species with fire-enhanced responses, the vegetation overall is resilient to high-severity fires. Where severe fires

TABLE 12.4
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, redshank, yerba santa, California coffeeberry, Christmas berry
	Fire stimulated	Fire stimulated	Top-killed	Chamise, redbud
	None	Fire stimulated	Killed	Whiteleaf manzanita, chaparral whitethorn, buck brush
	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

have occurred at the upper end of the foothill shrubland zone, the boundary between the shrublands and the lower-montane forest has shifted. Reestablishment of the conifers in those areas could take decades to centuries, and frequent recurring fires may perpetuate the shrub species.

Little direct information exists on the patterns of historic vegetation shaped by fire. Biswell (1974) described three different kinds of California chaparral, of which two occur in the Sierra Nevada foothills. One is on shallow soils and steep slopes with chamise, California-lilac, manzanita, and scrub oaks; and the second is on deeper productive soils, often developed from grasslands when fires become less frequent. Other species occur such as flannelbush and coyote brush. This type of chaparral has increased with fire suppression and development in the foothills.

Recurrent fire and dominance by sprouters tend to perpetuate large patches of single-species dominated chaparral or oak forest. Chamise dominates large areas, particularly on dry, shallow soil sites with both post-fire sprouting and heat-enhanced germination. But not all chamise plants resprout, and these openings allow California-lilac to germinate and persist in mixed chamise patches. Similarly, live oak often dominates large areas and sprouts vigorously with rapid growth following fire (Biswell 1974).

Frequent fire in the grasslands of the foothills, in part from burning by Native Americans, reduced encroachment by chaparral. With fire suppression and elimination burning by Native Americans, chaparral has increased in extent. Chaparral has also increased on sites where it previously co-occurred with ponderosa pine. Ponderosa pine remains in the foothills in limited patches on more mesic north-facing slopes. It has a reduced distribution due to preferential logging during European settlement. Natural re-establishment of ponderosa pine in the foothills is limited by the reduction in fires, which provided canopy openings and mineral soil for successful survival. In some locations, the boundary for conifer communities is rising in elevation due, in part, to current patterns of fire. In the foothills to the west of Yosemite National Park, recurrent, large, high-intensity fires have resulted in establishment of vast shrub fields and annual grasslands. Ponderosa pine is at its lower limit in the foothills as moisture becomes less available, especially in large open areas. Establishment of ponderosa pine is difficult since seed sources are somewhat distant.

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

TABLE 12.5
Fire regime attributes for vegetation types of the foothill shrub and woodland ecological zone

Vegetation type	Chaparral	Oak woodlands/ grasslands	Conifer forest patches
Temporal			
Seasonality	Summer–fall	Summer–fall	Summer–fall
Fire-return interval	Medium	Short	Medium
Spatial			
Size	Large	Large	Small
Complexity	Low	Low	Low
Magnitude			
Intensity	High	Low	High
Severity	High	Low	High
Fire type	Crown	Surface	Crown

NOTE: Fire regime terms used in this table are defined in Chapter 4.

any Sierra Nevada conifer and do not contribute significantly to fire spread and intensity (van Wagtendonk et al. 1998). Although relatively uncommon, patches of knobcone pine exist in the Sierra Nevada foothills surrounded by chaparral. Locations are typically steep on large canyon walls. These patches are dependent on high-intensity fire because of their serotinous cones. Current practices of fire exclusion may reduce the persistence of some knobcone pine patches.

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 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 km^{-2} (40.3 strikes yr^{-1} 100 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 dominate large areas, particularly in the southern Sierra Nevada. Intermixed with the oak-pine forests are various-sized patches of chaparral and canyon live oak—extensions of foothill types. Manzanita and California-lilac species dominate chaparral, whereas canyon live oak is extensive on steep slopes of large canyons. With increasing elevation, the proportion of white fir or Douglas-fir increases on mesic slopes they can dominate. Incense-cedar *(Calocedrus decurrens)* and sugar pine *(Pinus lambertiana)* are found throughout. Figure 12.4 shows a stand of ponderosa pines, incense-cedars, and sugar pines with an understory of mountain misery *(Chamaebatia foliolosa)*. Giant sequoia–mixed conifer forests are concentrated in several river basins in the central and southern Sierra Nevada, occupying sites where soils are wet. At the highest elevation, at the boundary with upper montane forests, white fir often becomes dominant on all aspects except where soils are shallow or very rocky. Here, pine or shrub communities often dominate.

Throughout the zone, riparian plant communities characterized by deciduous trees, shrubs, large herbs, and grasses occur with varied proportions of intermixed conifers. White alder *(Alnus rhombifolia)*, gray alder *(Alnus incana)*, or black cottonwood *(Populus balsamifera* ssp. *trichocarpa)* dominate larger streams or wetter sites. Bigleaf maple *(Acer macrophyllum)* and mountain dogwood *(Cornus nuttallii)* occur along smaller or intermittent streams. Small patches of quaking aspen occur in the higher-elevation white-fir–dominated forests but are more prevalent in the upper-montane zone. Meadows and seeps tend to be small and scattered.

Partly due to increasing precipitation, Douglas-fir becomes important from the Mokelumne River basin to the north. Mixed-evergreen forests comprised of tanoak *(Lithocarpus densiflorus)*, Pacific madrone *(Arbutus menziesii)*, and other montane hardwoods and conifers occupy large areas in the western Yuba and Feather River basins further north 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,

FIGURE 12.4. 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.

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 12.6). The trees vary in their level of resistance to low- and moderate-intensity fires. Ponderosa pine has a thicker bark as a seedling and is more resistant to fire than the other lower-montane conifers. As ponderosa pine grows older, its high crowns and large, protected buds provide additional fire resistance. 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).

All conifers show improved establishment with mineral soil. Giant sequoias have serotinous cones that are exposed by heat or by small mammals and show increased seedling density with higher-intensity fire (Kilgore and Biswell 1971). Giant sequoia is the only Sierra Nevada conifer that sprouts, but this response is apparently limited to younger trees (Weatherspoon 1986). See sidebar on giant sequoias for more information about responses of this species to fire. Pacific yew (*Taxus brevifolia)* and California nutmeg *(Torreya californica)* are uncommon, relict conifers that have thin bark. 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, bigleaf 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). Sprouting can also can change with tree size. Tanoak sprouts are smaller when originating from smaller trees (Tappenier et al. 1984). Epicormic sprouting from the stem following low-intensity fire was observed in California black oak, tan oak, and mountain dogwood (Kauffman and Martin 1990). California black oak is the only species that develops bark sufficiently thick to resist low- to moderate-intensity fire in larger trees (>16 cm [6.3 in] dbh) (Plumb 1980). Riparian hardwoods all sprout following fire. Native Americans

TABLE 12.6

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, tan oak, 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, Scotch broom
	None	Fire stimulated	Killed	Whiteleaf manzanita
Forb	Fire stimulated	None	Top-killed	Penstemon, many lilies, iris, Pacific starflower, trail plant, sanicle, mountain lady's slipper
Grass	None	None		
	Fire stimulated	None	Top-killed	Red fescue, melic, sedges
	None	None	Killed	Cheat grass

burned riparian areas to enhance shoot production of bigleaf maple and hazelnut *(Coylus cornuta)* shrubs (Anderson 1999).

Many shrubs have fire-enhanced regeneration with both sprouting and heat-stimulated seeds (Kauffman and Martin 1990) (Table 12.6). Sprouters include mountain misery, deer brush *(Ceanothus intergerrimus)*, greenleaf manzanita *(Arctostaphylos patula)*, bush chinquapin *(Chrysolepis sempervirens)*, mountain whitethorn *(Ceanothus cordulatus)*, and riparian shrubs hazelnut, thimbleberry *(Rubus parviflorus)*, and gray 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). But mountain whitethorn showed the greatest post-fire sprouting after higher-intensity fall burns. Sprouting occurs from burls, root crowns, and rhizomes.

Shrubs sprouting from deeply buried rhizomes, such as mountain misery, can readily dominate sites with frequent and intense fire. Mountain misery occupies extensive areas, 4 to 40 ha (10–100 ac), through extensive networks of rhizomes protected from heat more than 20 cm (8 in) below the soil surface. With highly flammable foliage containing volatile oils and with highly dissected leaves, 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).

Some shrubs, particularly California-lilac, have heat-stimulated seed germination. Heat-stimulated seed of deer brush can produce extensive seedling patches, as dense as 15,800 seedlings ha^{-1} (6,500 seedlings ac^{-1}) after burning (Kilgore and Biswell 1971). Mountain whitethorn also produces many seeds that can persist in the soil for decades or centuries. The dual fire-enhanced sprouting and seed germination responses of the native deer brush and non-native Scotch broom *(Cytisus scoparius)* make them particularly successful in rapidly colonizing burned sites. Scotch broom is an aggressive, non-native shrub that has animal-dispersed and fire-stimulated seed, vigorous sprouting, and rapid early

SIDEBAR 12.1. 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.*
>
> —JOHN 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 A.D. 450 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 (1962) 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 (Hartesveldt 1964).

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 the hottest areas burned 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 feeds on the scales of two- to five-year-old giant sequoia cones and cuts and caches 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 more than 150 arthropods were found to be associated with giant sequoias, only two significantly affected regeneration. The gelechiid moth *(Gelechia* spp.*)* feeds on one-year-old cones, while the small long-horned beetle 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 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. 1998).

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.

growth and seed production. It is taller than mountain misery and can out-compete deer brush and even mountain misery at times.

Deer brush is one of the most ubiquitous shrubs throughout the lower montane zone. 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. It gains height rapidly but can be limited by deer browsing (Kilgore and Biswell 1971). It persists under shaded canopies, but in a decadent, highly flammable state.

Little formal research has been conducted on fire response of herbs and grasses in the Sierra Nevada. But observations of morphology and fire responses indicate many understory species are enhanced by fire. Numerous perennial plants with sprouting structures including rhizomes, corymbs, or stolons exist and have been observed sprouting 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 *(Carex rossii)*, needlegrasses *(Achnantherum* spp.*)*, oniongrass *(Melica bulbosa)*, and red fescue *(Festuca rubra)*. On the other hand, some species like the Mountain lady's slipper *(Cypripedium montanum)* are killed outright by fire. Other plants exhibit sprouting or enhanced flowering following fire. Mariposa lilies and penstemons *(Penstemon* spp.*)* are two examples.

FIRE REGIME–PLANT COMMUNITY INTERACTIONS

Fire regime attributes for major vegetation types of the lower montane ecological zone are shown in Table 12.7. Fire was generally frequent in the lower-montane zone, ranging from 2 to 20 years on average at the stand or landscape scale (Wagener 1961b, Skinner and Chang 1996). There was noticeable variation in fire pattern with latitude and elevation related to shifts in fire season and in precipitation. 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 co-dominated by ponderosa pine and California black oak. Throughout the zone, relatively cooler and wetter sites have had frequent but less regular fire and are more likely to have a presence or dominance of Douglas-fir and white fir. Fire patterns and vegetation interactions also varied at fine-spatial scales for all portions of this zone.

The interrelationships between vegetation and fire regimes make it difficult to distinguish which pattern drives the other. Fire-return interval estimates for this zone vary by the size of area examined. Average fire-return intervals reported for larger sample areas (more than 50 ha [122 ac]) generally fall under 10 years and are often as short as 4 years (Caprio and Swetnam 1995). Fire-return intervals for smaller areas (fewer than several ha) are more variable, ranging from 5 to more than 30 years (Kilgore and Taylor 1979, Fites-Kaufman 1997).

TABLE 12.7

Fire regime attributes for major vegetation types of the lower montane ecological zone

Vegetation type	Ponderosa pine/ black oak	Douglas-fir/ white fir	Tanoak-mixed evergreen
Temporal			
Seasonality	Summer–fall	Summer–fall	Summer-fall
Fire-return interval	Short (regular)	Short (variable)	Medium (variable)
Spatial			
Size	Large	Large	Medium
Complexity	Low	Multiple	Multiple
Magnitude			
Intensity	Low	Low–moderate	Multiple
Severity	Low–moderate	Low–moderate	Multiple
Fire type	Surface	Surface–multiple	Multiple

NOTE: Fire regime terms used in this table are defined in Chapter 4.

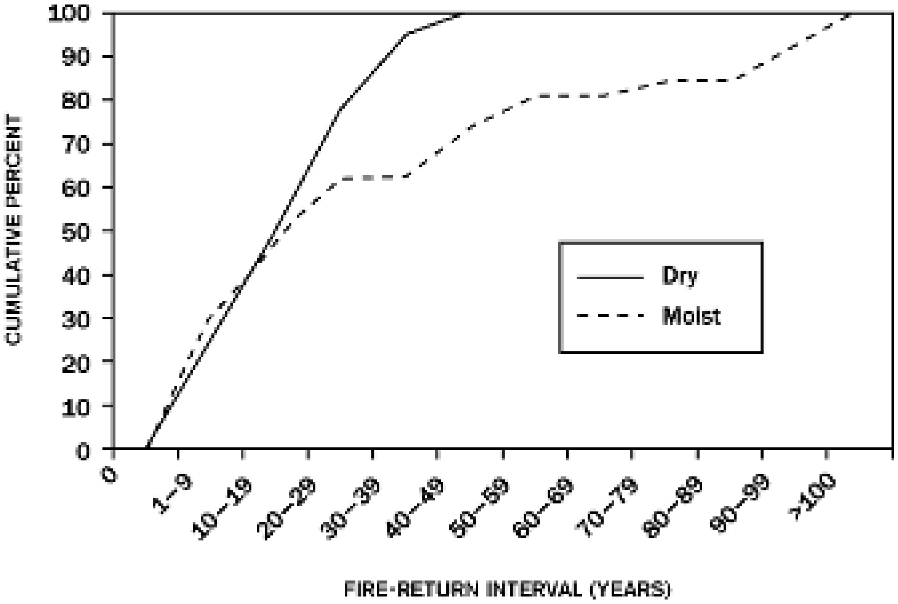


FIGURE 12.5. Distribution of fire-return intervals from small sample areas (1–3 ha, 2.5–7.5 ac) showing variation between moist and dry sites. Return intervals for dry sites peak at 50 years, whereas moist sites can have intervals of more than 100 years. (Adapted from Fites Kaufman 1996.)

North–south gradients in climate and vegetation parallel changes in fire patterns. Fire seasons are longer and precipitation lower in the southern portions of the westside lower montane zone. In ponderosa pine–California black oak forests of the southern Sierra Nevada, fire-return intervals increased with increasing elevation (Caprio and Swetnam 1995). In the northern Sierra Nevada, mean fire-return intervals were shorter (5–15 years) on drier, south- and west-facing upper slopes than on mesic, north- and east-facing lower slopes (15–25 years) (Fites-Kaufman 1997). More important than the average fire-return intervals, the distribution of fire-return intervals can vary substantially among locations in the landscape (Fig. 12.5), with associated differences in forest composition. The distribution of return intervals for xeric sites is more skewed toward small return intervals than for mesic sites. The more frequent, regular fire pattern is more often associated with ponderosa pine-dominated sites. Ponderosa pine develops resistance to fire at a young age and can best tolerate frequent, regular fire. The less regular fire pattern is more often associated with the presence of Douglas-fir or white fir. These latter species require more time for young trees to develop fire resistance. Spatial complexity of vegetation within forest stands has been linked to fire (Bonnickson and Stone 1982, Fites-Kaufman 1997, Knight 1997).

Diverse and variable species in both the tree and shrub layers resulted in variable fuel and fire patterns. For example, ponderosa pine fuels are more loosely packed than those of white fir, allowing the pine fuels to burn more readily (van Wagtendonk et al. 1998). High levels of contrasting fire environments, such as varying 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, height, tree sizes, and understory vegetation. With fire suppression, density and uniformity in structure and composition have increased. Across many sites in the mid-elevations of the central and southern Sierra Nevada, white fir and incense cedar have increased, shifting composition away from ponderosa pine and creating more uniformly dense forests (Vankat and Major 1978, Parsons and deBenedetti 1979, Minnich et al.1995, Bouldin 2000). Douglas-fir responds similarly in the northern Sierra Nevada (Fites-Kaufman 1997). At lower elevations, bordering the foothills, these shade-tolerant species are scarce or absent but ponderosa pine has increased in density (Parsons and deBenedetti 1979, Fites-Kaufman 1997). Similarly, at higher elevations, white fir dominates but with increased uniformity and density attributed to lack of fire (Parsons and deBenedetti 1979).

Historically, open or more variable forest structure occurred as a result of more frequent fire (Gruell 2001). Not only did fire favor different species with different return interval patterns, but also it affected forest structure by thinning the young trees, leaving a patchier or more open forest, and selectively retaining larger, fire-resistant trees (Bonnickson and Stone 1982, van Wagtendonk 1985). Exactly what the landscape was like overall and what proportion was low density are unknown. Early observers emphasized open, park-like pine-dominated forests (Muir 1895, Jepson 1921) but also noted dense patches (Sudworth 1900, Leiburg 1902). Gruell (2001) chronicled the ecological changes since 1849 through a series of repeat photographs. Portions of the landscape that exhibited more variable fires included north and east aspects and higher elevations. These areas had greater portions of the landscape with moderate to high cover forests, evidenced by the historic prevalence of shade-tolerant white fir and Douglas-fir (Fites-Kaufman 1997).

Questions remain concerning the intensity and severity of presettlement fires. All sites in the lower-montane zone experienced fire frequently enough to reduce fuel accumulations and vegetation density, and, as a result, these fires were primarily of low to moderate intensity and severity. Long-term evidence in giant sequoia suggests that high-severity fires occurred in small patches (Stephenson et al. 1991). Large patches of California black oak or chaparral persist, evidently the result of large, severe fires. Some patches may have originated or expanded during the last century of suppression (Vankat and Major 1978), but others were apparently from earlier fires (Leiburg 1902).

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. It is also possible that locations in the northern Sierra Nevada with high average annual rainfall (more than 203 cm [80 in] mean annual precipitation) and continuous fuels (conifer and tan oak) would have a higher proportion of high-severity fires (Fites-Kaufman 1997). Moister conditions and higher foliar water content reduce fire in many years but allow more fuels to accumulate. These locations also overlap with steep terrain. When the canyons are aligned with prevailing southwest winds, the likelihood of larger, severe fire increases.

Currently, most of the area burned does so with fires of high intensity and severity. The Sierra Nevada contains some of the most productive fire-prone areas in the western United States (Franklin and Agee 2003). The increased stand densities and reduced decomposition rates result in accumulated fuels (Kilgore 1973, Vankat and Major 1978, Agee et al. 2000). This increases the tendency for high-intensity and high-severity fire through both increased fuels and increased susceptibility of dense smaller vegetation. It is unknown if current fires are larger but the extent of high-severity fire has certainly increased (Skinner and Chang 1996).

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. Some fires have always occurred in the spring and early summer and occasionally in the winter. Historic fire patterns in lower-elevation and drier landscapes maintained open pine and California black oak woodlands with resprouting shrubs and perennial grasses and herbs. Suppression of fire in combination with harvest patterns has resulted in an increase in the density of these forests (Parsons and deBenedetti 1979) but not always in changes of pine dominance (Parsons and deBenedetti 1979, Fites-Kaufman 1997). At higher elevations, trees with greater shade tolerance and less fire-resistant seedlings such as white fir, Douglas-fir, and incense-cedar, have become established and form dense understories (Parsons and deBenedetti 1979, van Wagtendonk 1985, Vale 1987,). Lower light levels and possibly lack of fire have resulted in sparse shrub and herb presence. On more mesic north or east slopes at mid-elevations, white fir and Douglas-fir were historically present but have also increased in density (Fites-Kaufman 1997). High-elevation white fir–mixed conifer forests have often retained similar composition but increased in density (Parsons and deBennedetti 1979).

Historically, Sierra Nevada lower-montane forests were more heterogeneous with clumps or patches of shrubs present in varying amounts. Fire promoted a greater distribution of younger, more vigorous sprouting shrubs. Deer brush is able to persist in the forest through changes in density until fire or some other activity opens the overstory and heats the soil, stimulating germination or sprouting. Current low levels of fire have resulted in increasingly tall and decadent deer brush, slowly being shaded out under dense forest cover. Thick patches of mountain misery decrease ponderosa pine regeneration, precluding dense stands of pines from

FIGURE 12.6. 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.

developing. This has resulted in the maintenance of relatively open pine stands over mountain misery, even with fire suppression. Fire restoration in these settings has been achieved in only two applications in Yosemite National Park.

Upper-Montane Forest

The upper-montane forest is located just above the lower-montane forest and occurs on both sides of the crest of the Sierra Nevada. The forest ranges in elevation with latitude. On the west side of the crest, elevations are generally lower than on the east side, with the differences greater in the south than in the north (Potter 1998). The terrain is relatively 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 typically medium to coarse textured and often lack a clay zone (Potter 1998).

The climate of the upper-montane forest is moderate with warm summers and cold winters. Total annual precipitation, although less than that which occurs in the lower montane forest, is still relatively high with 65% to 90% falling as snow (Major 1988). Barbour et al. (1991) propose that the ecotone between the lower and upper-montane zones is determined by the winter-long snowpack. 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 km^{-2} (75.9 strikes yr^{-1} 100 mi^{-2}) (van Wagtendonk and Cayan 2007).

The vegetation of the upper-montane forest is characterized by the presence of California red fir (Potter 1998). Figure 12.6 shows a stand of California red fir and western white pine with a sparse understory of montane chaparral. Other alliances include western white pine, quaking aspen, western juniper, Jeffrey pine, and tufted hairgrass *(Deschampsia cespitosa* ssp. *holciformus)*. Interspersed in the forests are wet 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 12.8). Shrubs and hardwood trees typically sprout, whereas herbs and grasses either reseed or regrow quickly after fire. Conifers are protected from the heat from fire 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). Similarly, mature Jeffrey pines have thick bark, and a slightly thicker bark when young that allows them to survive low-intensity fires. Western white pine and western juniper are more susceptible to fire at a young age than California red fir or Jeffrey pine. The percentage of crown scorch that a species can sustain is also variable. Like ponderosa pine, up to 50% of the buds of a Jeffrey pine can be killed and it can still survive (Wagener 1961a). The other upper-montane conifers can sustain only 30% to 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 (DeByle 1985). It becomes increasingly resistant to fire as

TABLE 12.8

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

	Type of Fire Response			
Lifeform	Sprouting	Seeding	Individual	*Species*
Conifer	None	None	Resistant, killed	Red fir, Jeffrey pine, western white pine, western 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	Woolly mule's ears
	None	None	Top-killed	Corn lily
Grass	Fire stimulated	Off-site	Top-killed	Tufted hairgrass
	Tillers	Off-site	Top-killed	Western needlegrass

its diameter increases beyond 15 cm (6 in) (Brown and DeByle 1987).

Bush chinquapin, mountain whitehorn, and huckleberry oak *(Quercus vaccinifolia)* form extensive stands in the open and underneath conifers. They are all sprouters and are top-killed by fire (Biswell 1974, Conard et al.1985). Mountain whitethorn is also a relatively prolific seeder after fire. Pinemat manzanita *(Arctostaphylos nevadensis)* and greenleaf manzanita are usually found in the understory. Although these non-sprouting manzanitas are killed by intense heat, they are able to reestablish by seed the first year after fire. Both species may be obligate seeders, requiring fire and/or charred wood leachate to break seed dormancy (Kruckeberg 1977).

Woolly mule's ears *(Wyethia mollis)* apparently resprouts after fire but the sprouting might not be fire dependent (Mueggler and Blaisdell 1951). The density of mule's ears has been noted to increase after fire (Young and Evans 1978). Corn lily *(Veratrum californicum)* grows in wet meadows and is not usually affected by fire. Based on its ability to resprout each year after being top-killed by frost, it is reasonable to assume that corn lily would sprout the year after being burned.

Western needlegrass *(Achnantherum occidentalis)* occurs in the understory of the conifer forests and is a tussock-forming grass that seeds into burns from off-site (Brown and Smith 2000). The above-ground biomass is consumed, and intense fires can kill the rootstock. Tufted hairgrass is one of many grass and sedge species common in wet meadows. Although it burns infrequently, tufted hairgrass 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 compact fuel beds 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 prevent extensive fires from occurring (Kilgore 1971).

California red fir fuel beds are among some of the heaviest and most compact found for conifers in the Sierra Nevada. Although duff weight was just above average, woody fuel weight was surpassed only by giant sequoia (van Wagtendonk et al. 1998). The bulk density of California red fir duff fuels was above average, and the fuel bed bulk density, including woody and litter fuels, was 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 (Table 12.9) (Skinner and Chang 1996). Median fire-return interval estimates from fire scars range from 12 to 69 years (Skinner and Chang 1996). Based on lightning fires that were allowed to burn under prescribed conditions in Yosemite National Park, van Wagtendonk (1995) calculated the fire rotation in California red fir to be 163 years. Occasional crown fires occur in California red fir stands, but normally fires spread slowly because of compact surface fuels and the prevalence of natural terrain breaks.

TABLE 12.9

Fire regime attributes for major vegetation types of the upper montane forest ecological zone

Vegetation type	Red fir	Jeffrey pine, western white pine, mountain juniper	Tufted hairgrass
Temporal			
Seasonality	Late summer–fall	Summer–fall	Late summer–fall
Fire-return interval	Medium	Medium	Long
Spatial			
Size	Medium	Truncated small	Small
Complexity	Multiple	Low	Low
Magnitude			
Intensity	Multiple	Low	Low
Severity	Multiple	Low	Low
Fire type	Multiple	Surface	Surface

NOTE: Fire regime terms used in this table are defined in Chapter 4.

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). Fire creates canopy openings by killing mature lodgepole pine and some mature California red fir. Where lodgepole pine occurs under a California red fir canopy, 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 Jeffrey pine begin to overtop the chaparral.

Fires in Jeffrey pine, western 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 1961a). Fuel bed 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. 1998). 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). Western juniper is slow to return to burned areas and, like Jeffrey pine and western white pine, will seed in from adjacent stands.

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 quaking aspens have dried sufficiently to carry fire. Because quaking aspen is a vigorous sprouter, it is able to recolonize burns immediately at the expense of non-sprouting conifers. Similarly, meadows consisting primarily of tufted hairgrass burn if fires in adjacent forests occur during the late summer. Occasional fires reduce encroachment into the meadows by conifers (deBennedetti 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 moderate with cool summers and extremely cold winters. Other than occasional thundershowers, precipitation falls as snow. The snow-free period is short, from mid June to late October. 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 k^{-2} (87.1 strikes yr^{-1} 100 mi^{-2}) (van Wagtendonk and Cayan 2007).

The vegetation of the subalpine forest is dominated by lodgepole pine (Fig. 12.7). As tree line is approached, lodgepole pine is replaced by mountain hemlock and whitebark pine. On the east side of the Sierra Nevada, limber pine

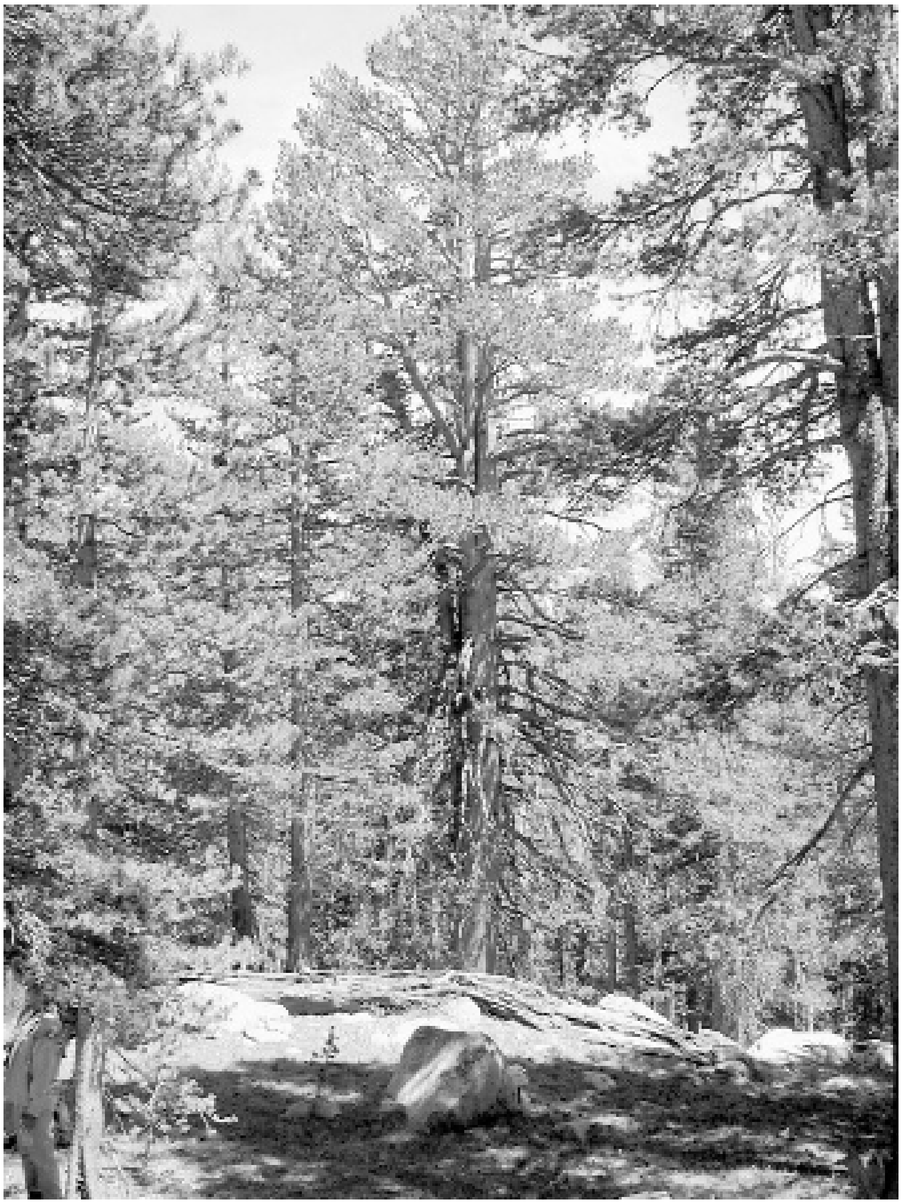


FIGURE 12.7. Subalpine forest. Lodgepole pine forms extensive stands in this zone. Fire is infrequent but when it occurs it burns from log to log or creeps through the sparse understory vegetation and litter.

occurs with whitebark pine, and in Sequoia National Park, foxtail pine is found at tree line. Extensive meadows of shorthair sedge *(Carex filifolia* var. *erostrata)* and Brewer's reedgrass *(Calamagrostis breweri)* 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 12.10). Clements (1916) was one of the first ecologists to consider lodgepole pine to be a fire type. Its thin bark, flammable foliage, and serotinous cones all fit into the classical definition of a fire-adapted species. The cones of the Sierra Nevada subspecies, however, are not fully serotinous, open at maturity, and are dispersed over a two-year period (Lotan 1975). 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 lodgepole pine forests, individual trees are killed (deBennedetti and Parsons 1984). Occasional crown fires can consume entire stands, which are quickly recolonized by released seed.

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 large refugia trees are scattered in areas of patchy fuels (Keane and Arno 2001). Clark's nutcrackers *(Nucifraga columbiana)* facilitate post-fire 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

TABLE 12.10

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

	Type of Fire Response			
Lifeform	Sprouting	Seeding	Individual	*Species*
Conifer	None	Fire stimulated	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

TABLE 12.11

Fire regime attributes for vegetation types of the subalpine forest ecological zone

Vegetation type	Lodgepole pine	Mountain hemlock	Whitebark pine, limber pine, foxtail pine
Temporal			
Seasonality	Late summer–fall	Late summer–fall	Late summer–fall
Fire-return interval	Long	Long	Truncated long
Spatial			
Size	Small	Small	Small
Complexity	Low	Low	Low
Magnitude			
Intensity	Multiple	Low	Low
Severity	Multiple	Low	Low
Fire type	Multiple	Surface	Surface

NOTE: Fire regime terms used in this table are defined in Chapter 4.

(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

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 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 conditions, only six fires in lodgepole pine grew larger than 123 ha (300 ac).

Lodgepole pine fuel beds are relatively shallow and compact (van Wagtendonk et al. 1998). Often herbaceous plants occur in the understory, precluding fire spread except under extremely dry conditions. 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 kill back the trees (deBennedetti and Parsons 1984). Stand-replacing fires are rare, but when they do occur, lodgepole pines become reestablished from the released seeds.

Keeley (1981) estimated the fire-return interval in lodgepole pine to be several hundred years. Data from fires that have burned in the wildland fire-use zone in Yosemite suggest a fire rotation of 579 years (van Wagtendonk 1995). Caprio (2002), however, found that prior to 1860, widespread fires were recorded in 1751, 1815, and 1846 in lodgepole pine stands in Sequoia National Park. In any case, fires are relatively rare and usually light to moderately severe. (Table 12.11)

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 wildland fire-use 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. 1998). 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 more than 23,000 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 as well. 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. 1998). 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 those 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. Brewer's reedgrass can become re-established after fire from seeds and rhizomes. Meadow edges are maintained by fire as invading lodgepole pines are killed (deBenndetti and Parsons 1984, Vale 1987).

Alpine Meadow and Shrubland

The alpine meadow and shrubland zone consists of fell fields and willows along riparian areas. 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 2007). The 16-year average number of strikes in the Sierra Nevada is 32.2 yr^{-1} 100 k^{-2} (83.5 strikes yr^{-1} 100 mi^{-2}). Weather, coincident with lightning, is usually not conducive to 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 north to south. In the north, the width of the zone is more than 12.5 km (20 mi), but to the south it quickly becomes less than 1 km (0.6 mi) due to the high elevation of the crest, increased importance of the rain shadow effect, and the sharp gradient from upper montane to Great Basin vegetation. In the northern Sierra Nevada, the eastside montane zone increases in width, as the crest of the Sierra Nevada becomes lower and less distinct. The area to the north and east of Lake Tahoe basin comprises large expanses of eastside forest and woodland vegetation. Some of the species, such as Jeffrey pine, are at the eastern edge of their distribution. Others, such as pinyon pine and sagebrush, are at their western edge of distribution (Fig. 12.8). Small climatic shifts may have resulted in dramatic shifts in vegetation, fire, and plant community–fire interactions. Lightning is common in the eastside zone with 28.9 strikes yr^{-1} 100 k^{-2} (74.8 strikes yr^{-1} 100 mi^{-2}) for the period between 1985 and 2000 (van Wagtendonk and Cayan 2007). Proportionally more lightning strikes occur in the northern 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 or forests and shrublands or grasslands, is characteristic. This is similar to the east side of the Cascades or northeastern California. The most prevalent tree-dominated types include Jeffrey pine or mixed Jeffrey and ponderosa pine woodlands, mixed white fir and pine forests, white fir, and quaking aspen groves. In some locations, particularly in the central and southern portions, pinyon pine occurs. Typically, westside species (i.e., Douglas-fir and black oak) occur in small amounts in the northern Sierra Nevada. The shrublands can be extensive and variable, ranging from typical Great Basin species of sagebrush *(Atemisia* spp.*)* and bitterbrush *(Purshia* spp.*)* to chaparral comprised of tobacco brush *(Ceanothus velutinus* var. *velutinus)*, greenleaf manzanita, bearbrush *(Garrya fremontia)*, and bush chinquapin. Curl-leaf mountain-mahogany *(Cercocarpus ledifolia)* occurs in patches on rocky and particularly dry sites. Riparian and wetland areas occur throughout, and, although this is the most xeric portion of the Sierra Nevada, 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 the Sierra Nevada bioregion's similarities with the Northeastern Plateaus (Chapter 11) and Southern Cascades (Chapter 10) 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 Great Basin or desert species

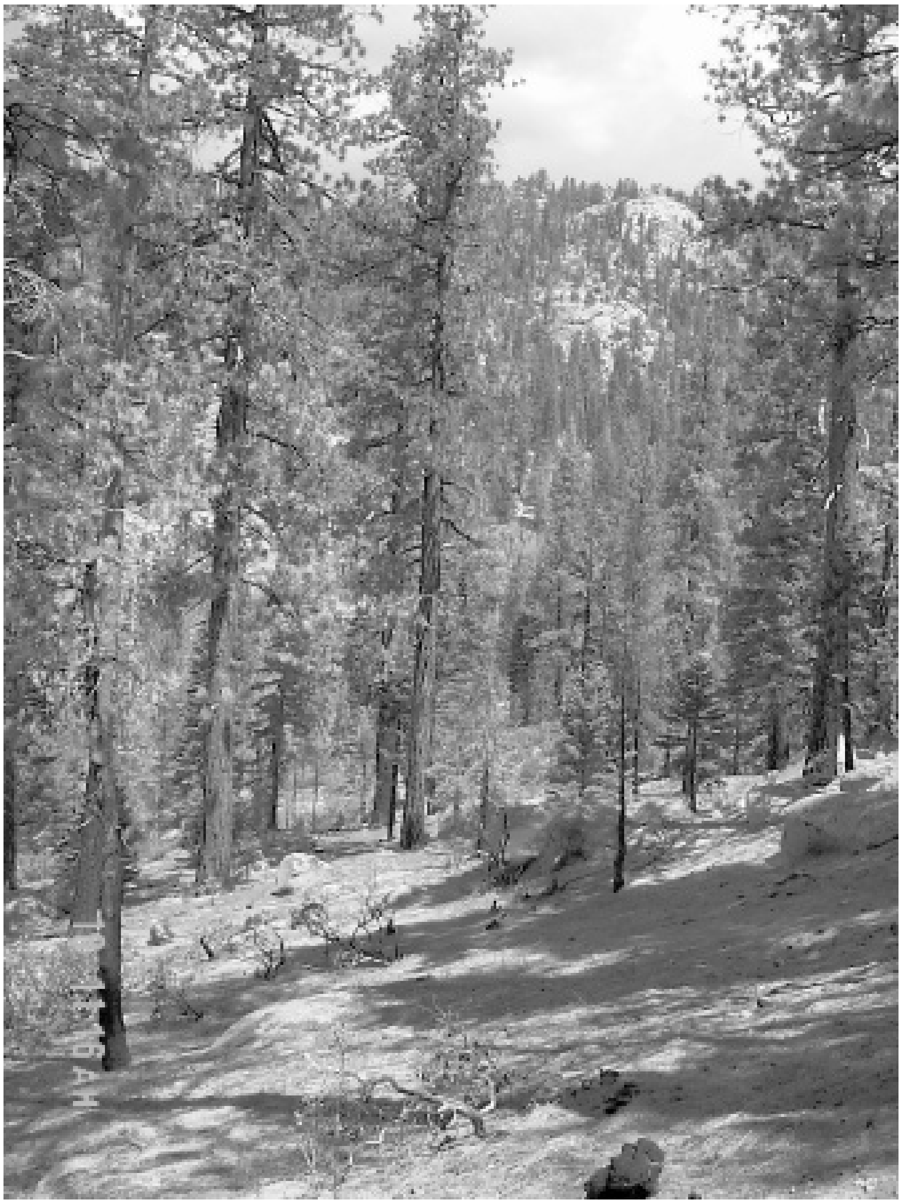


FIGURE 12.8. Eastside forest and woodland. This stand of Jeffrey pine and red fir was recently burned and shows evidence of manzanita mortality.

such as juniper, pine, and sagebrush or bitterbrush, can be found in the Northeastern Plateaus chapter (Chapter 11) and Southeastern Deserts chapter (Chapter 16).

FIRE RESPONSES OF IMPORTANT SPECIES

Some of the dominant species in this zone are also prevalent in the upper montane or adjacent lower montane zones and are only described as they co-occur in this zone. Species in this zone tend to be a mixture of those with fire-resistant or fire-enhanced characteristics and those that are fire inhibited (Table 12.12). Jeffrey pine has thick, fire-resistant bark; large, well-protected buds; and self-pruning that often results in high crowns. Pinyon pine is not very fire resistant, with crowns low to the ground; relatively thin bark; and a tendency to have pitchy bark, branches, and foliage, making it flammable. In this zone, pinyon pine often occupies rocky sites with sparse vegetation and fuels that decrease the likelihood of frequent fire. Seeds of both ponderosa pine and lodgepole pine show a high tolerance to heat, showing germination over 50% after 5-minute exposures to heat as high as 930°C (200°F) (Wright 1931).

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 tobacco brush all sprout from basal burls following fire. Where branches are pressed against the soil from snow, layering results in sprouting; however, these sprouts can be more susceptible to fire mortality. Tobacco brush also has enhanced germination from fire.

TABLE 12.12

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, snowberry, willow, bitterbrush[a]
	Fire stimulated	Fire stimulated	Top-killed	Tobacco brush
	None	None	Killed	Sagebrush, bitterbrush[a]
Herb	Fire stimulated	None	Top-killed	Woolly mule's ears
	None	None		
Grass	Fire stimulated	None	Top-killed	Sedges
			Killed	Cheat grass

[a] Bitterbrush has a variable sprouting response to fire.

TABLE 12.13

Fire regime attributes for vegetation types of the eastside forest and woodland ecological zone

Vegetation type	Jeffrey pine, ponderosa pine	White fir and mixed conifer	Chaparral
Temporal			
Seasonality	Summer–fall	Summer–fall	Summer–fall
Fire-return interval	Short	Medium	Medium
Spatial			
Size	Small–Medium	Medium	Medium
Complexity	Multiple	Multiple	Low
Magnitude			
Intensity	Low	Multiple	High
Severity	Low	Multiple	High
Fire type	Surface	Multiple	Crown

NOTE: Fire regime terms used in this table are defined in Chapter 4.

FIRE REGIME–PLANT COMMUNITY INTERACTIONS

Only a few 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 southeast of Lake Tahoe showed a mean fire return interval of 11.4 years for presettlement mixed Jeffrey pine and white fir stands. As recent, severe fires have burned on the lower slopes of the eastside forests, the boundary between forests and sagebrush has retreated up slope.

Fire regimes vary with both vegetation type and landscape location (Table 12.13). The most-frequent fires and lowest-intensity fires occurred in the lower elevation, open pine-dominated areas of this zone, with responses similar to that described in the Northeastern Plateaus (Chapter 11). On less productive or more southern portions, Jeffrey pine woodlands likely had a fire regime similar to those described for upper montane Jeffrey pine woodlands, with a range of intervals from 5 to 47 years (Taylor 2004). White fir forests occurred 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. The structure of white fir forests leads to higher crown-fire potential (Conard and Radosevich 1982). Branch retention, high stand densities, and low and uniform crowns are all common. Regeneration of white fir is continuous (Bock et al.1978, Conard and Radosevich 1982) until a fire occurs. Subsequently, portions of the forest are converted to chaparral dominated by sprouting greenleaf manzanita and both sprouting and heat-stimulated germination of tobacco brush (Conard and Radosevich 1982). The duration of this fire-generated chaparral can last for more than 50 years (Russell et al. 1998). 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 as a control over 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, and air quality considerations.

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 or fuels reduction. The relatively higher productivity chaparral of the Sierra Nevada foothills means that growth rates are higher and maintenance of fuel-reduction areas more frequent and costly. There are two contrasting fire management conditions in the montane and eastern portions of the Sierra Nevada: one where communities are adjacent to and mixed with wildlands; the second where vast areas are undeveloped, often bordering higher-elevation wilderness. The former creates conditions in which intensive and frequent fuel-reduction treatments around communities are important because of the frequent occurrence of fire in this area. The latter is well suited for wildland fire use, a program that restores naturally occurring fires through less intensive and expensive means. The situation in the intermix areas has serious ramifications for fire management. Property owners demand that fire suppression forces protect their homes first, thus diverting them from protecting resources.

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 prescribed burning is the most likely treatment 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. As we have learned in Chapter 3, only in rare occasions can a fire move independently through the crowns of trees without a surface fire to feed it. Thinning forests to prevent crown fires without treating surface fuels is ecologically inappropriate and economically unjustifiable. A combination of treatments including understory thinning and prescribed fire will probably be most productive.

Species at Risk

Several species at risk occur in the Sierra Nevada, and many of these, including the Pacific fisher *(Martes pennanti pacifica)*, American marten *(Martes americana)*, and California spotted owl *(Strix occidentalis occidentalis)*, evolved in fire-dependent or fire-maintained habitats. Concurrent changes in fire regimes and vegetation in the lower-elevation portions of the Sierra Nevada foothill and lower montane zones have resulted in region-wide changes in vegetation and wildlife habitats, including the stability of those habitats. Low-severity fire regimes made low-contrast changes to previous regional patterns of vegetation and habitat. Today, moderate- to high-severity fires produce high-contrast changes. These changes have implications for wildlife habitat that varies with vegetation. Habitat with denser forests was more distributed and less widespread. Currently, however, denser forests dominate but are punctuated with large, non-forest openings created by severe fires.

The question becomes how to restore natural fire regimes without adversely affecting at-risk species and their habitats. To do nothing only makes the situation worse, predisposing the species and habitats to destruction by catastrophic fire. These species evolved with fire and the answer must include fire. Care must be taken, however, to ensure that fragmented populations are not adversely affected by fire treatment activities.

Air Quality

One of the biggest impediments to conducting prescribed burns or using wildland fires to achieve resource benefits in the Sierra Nevada is restrictions on air quality. Smoke is a byproduct of burning, whether it comes from a prescribed fire, a wildland fire burning under prescribed conditions, or a wildfire. Catastrophic wildland fires produce extreme concentrations of smoke that exceed public health standards (see Chapter 21 for additional information). Society is faced with deciding to accept periodic episodes of low concentrations of smoke from managed fires or heavy doses from wildfires. Either reduced emission restrictions for wildland management activities or exemptions for federal agencies from the local air pollution control district regulations will be necessary if fire is to be allowed to 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 six research topics, which we have grouped into three general areas: (1) spatial and temporal dynamics of fire, (2) presettlement forest conditions, and (3) effects of fire on ecosystem processes.

Spatial and Temporal Dynamics of Fire

Although much has already been learned about the dynamics of fire and Sierra Nevada ecosystems, several specific topics still need to be addressed. Fire history data are sparse through much of the Sierra Nevada. Isolated studies are the rule, although comprehensive data sets exist for the national parks and the area around Lake Tahoe. Complete fire histories would elucidate the spatial and temporal aspects of landscape-level fire interactions. Related studies on the spatial and temporal interactions of climate, vegetation, and fire are needed.

There is also a need for more information about the effects of frequent low- to moderate-severity fires on vegetation patterns. Most information available today is on low-severity prescribed fire or high-severity wildfires. Naturally occurring low- to moderate-intensity fires were probably the norm, and their ecological role is not well understood. Similarly, little is known about the interaction of fire with some of the other dynamic ecosystem processes, such as insect and fungi population fluctuations. These processes combine to affect fire behavior and subsequent fire effects and vegetation responses.

Presettlement Forest Conditions

Researchers have been uncertain about the vegetation conditions of the Sierra Nevada in presettlement times. Understanding those conditions and the factors that led to them gives insights into possible management targets and methods to reach those targets. Comparative photos have proven useful, but detailed re-measurement of historic vegetation surveys holds the greatest promise. Several of these surveys were conducted in the late 1800s and early 1900s in many parts of the Sierra Nevada and should prove productive if they can be relocated. Information derived from resurveys would give the best estimate of what have been called "old forest" or "late successional" conditions because the original surveys included the effects of naturally occurring ecological processes such as fire.

Effects of Fire on Ecosystem Properties

Although it will never be possible to know all of the effects of fire, investigators should continue to determine those effects of greatest importance to society and to ecosystem function. These include the effects of fire on coarse woody debris including logs and snags. The role fire plays in the dynamics of these structural habitat components is not well understood.

Smoke is another ecosystem process that warrants additional study. Some preliminary investigations have looked at the interactions of smoke with fungi and bacteria in forested ecosystems. Attempts need to be made to determine the presettlement air quality conditions for comparison to those now experienced with wildland fire use, suppressed wildland fires, and prescribed fires.

Summary

John Muir named the Sierra Nevada the Range of Light; an even 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. This chapter has looked at the factors that have contributed to make fire an important process in the ecological zones of the range and how fire has interacted with vegetation in each zone. The success of our management of the Sierra Nevada is contingent on our ability and willingness to keep fire an integral part of these ecosystems. To not do so is to doom ourselves to failure; fire is inevitable and we must try to manage only in harmony with fire.

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