PART II

THE HISTORY AND ECOLOGY OF FIRE IN CALIFORNIA'S BIOREGIONS

Part II of this book describes nine bioregions and their fire regimes, beginning in the humid northwest and ending in the arid southeast. We start in Chapter 8 with the North Coast bioregion in northwestern portion of the state where numerous valleys and steep coastal and interior mountains create moisture gradients in response to numerous winter storms. In Chapter 9, we describe the Klamath Mountains bioregion, a complex group of mountain ranges and a diverse flora. Tall volcanoes and extensive lava flows characterize the Southern Cascades (Chapter 10) and Northeastern Plateaus (Chapter 11) bioregions. Immediately south of the Cascades is the Sierra Nevada bioregion (Chapter 12), extending nearly half the length of the state. The Sacramento and San Joaquin rivers flow through broad interior valleys with extensive, nearly flat alluvial floors that constitute the Central Valley bioregion (Chapter 13). Coastal valleys and mountains and interior mountains are also typical of the Central Coast bioregion (Chapter 14). Southern California with its coastal valleys and the prominent Transverse and Peninsular Ranges are included in Chapter 15 on the South Coast bioregion. Finally, in Chapter 16, we discuss the vast southeast corner of California that constitutes the Southeastern Deserts bioregion. Each bioregion is divided in ecological zones, which are defined by the interaction of biotic communities and soil, hydrology, climate, elevation, topography, and aspect. Within ecological zones can be found vegetation alliances, defined by existing dominant or co-dominant plant species. Part II chapters describe ecological zones and discuss fire regimes in different alliances.

CHAPTER 8

North Coast Bioregion

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In the early days of forestry we were altogether too dogmatic about fire and never inquired into the influence of fire on shaping the kind of forests we inherited.

EMANUEL FRITZ, 1951

Description of Bioregion

Physical Geography

The North Coast California bioregion is classified as being within the California Coastal Steppe, Mixed Forest, and Redwood Forest Province of the Mediterranean Division of the Humid Temperate Domain (Bailey 1995). Specifically, it is composed of the Northern California Coast and the Northern California Coast Ranges Sections (Map 8.1) (Miles and Goudey 1997). The bioregion ranges from southwestern Oregon to north of the Golden Gate in Marin County. Its eastern boundary is adjacent to the Klamath Mountains in the north and the Northern California Interior Coast Ranges in the central and southern portions. The North Coast section stretches from San Francisco Bay to the Oregon border. Other notable landmarks include Humboldt Bay, Cape Mendocino, Clear Lake, and Point Reyes. The North Coast Ranges are bounded by the North Coast section, the Interior Ranges, and the Klamath Mountains.

Sedimentary rocks from the Franciscan Formation dominate in the bioregion. Sandstone, shale, and mudstone are most common with lesser amounts of chert, limestone, and ultramafic rocks. Basalt, andesite, rhyolite, and obsidian can be found in the volcanic fields of Sonoma, Napa, and Lake Counties, whereas granitic rocks similar to those found in the Sierra Nevada are located west of the San Andreas Fault near Point Reyes and Bodega Bay (Harden 1997). Soils in the northwestern California ecological units have been classified as Alfisols, Entisols, Inceptisols, Mollisols, Spodosols, Ultisols, and Vertisols (Miles and Goudey 1997).

The bioregion is topographically diverse. Elevations range from sea level to around 1,000 m (3,280 ft) in the Northern California Coast Section and from around 100 to 2,470 m (328 to 8,100 ft) in the Northern California Coast Ranges (Miles and Goudey 1997). Slope gradients vary from flat in valley bottoms to moderate to steep on mountain slopes. Gradients of over 50% are common in the mountains. Mountain ranges are generally parallel to each other and are oriented in a northwesterly direction. Mountains and ridges are typically long and separate parallel river valleys and steep, narrow canyons. Prominent mountain ranges include the Kings Range, South Fork Mountain, Yolla Bolly Mountains, and the Mayacamas Mountains. The North Coast is home to the Smith, Klamath, Mad, Van Duzen, Mattole, Eel, Noyo, Navarro, Gualala, Russian, and Napa Rivers, as well as Redwood Creek.

Climatic Patterns

Three predominant climatic gradients help determine the vegetation patterns in northwestern California: (1) a west–east gradient extending from a moist, cool coastal summer climate to a drier, warmer interior summer climate; (2) a north–south gradient of decreasing winter precipitation and increasing summer temperatures; and (3) a montane elevational gradient of decreasing temperature and increasing precipitation. These gradients, although important individually, interact in a complex fashion, especially away from the coast.

The bioregion enjoys a mediterranean climate with cool, wet winters and cool to warm, dry summers. Over 90% of the annual precipitation falls between October and April (Elford and McDonough 1964). Annual precipitation varies from 500 to 3,000 mm (20 to 118 in.) (Miles and Goudey 1997). The Pacific Ocean greatly moderates temperature, resulting in sharp west to east temperature gradients. The mean maximum monthly temperature at Fort Ross, for example, varies from 13.8ºC in January to 20.2ºC in September, a difference of only 6.4ºC. In contrast, the mean maximum monthly temperature at Angwin, near the Napa Valley, varies from 11.2ºC in January to 30.5ºC in July, a difference of 19.3ºC

TABLE 8.1

Number of days of temperature and relative humidity observations in Prairie Creek Redwoods State Park (coastal redwood forest) and Humboldt Redwoods State Park (interior redwood forest)

	Coastal Flat	*Coastal Slope*	*Interior Flat*	*Interior Slope*
No. days maximum temperature >21°C	4	23	106	208
No. days maximum temperature >27°C	0	0	16	78
No. days relative humidity <50%	0	27	46	172
No. days relative humidity <35%	0	0	2	37

NOTE: Data were collected between July 1986 and November 1987. (After Pillers 1989.)

(Western Region Climate Center 2001). Most coastal forests, and especially coast redwood *(Sequoia sempervirens)* forests, experience summer fog. Fog can be an important source of water for trees, boosting soil moisture and reducing plant moisture stress (Azevedo and Morgan 1974, Dawson 1998). Summer relative humidity and temperature are strongly influenced by proximity to the Pacific Ocean and the presence of summer fog. Pillers (1989) found that coastal redwood forests in Humboldt County had many fewer days with temperatures above 21ºC and relative humidity lower than 50% than comparable interior sites (Table 8.1).

Although lightning does occur during the fire season, it is much less prevalent than on the higher ridges and mountains to the east (Elford and McDonough 1964, Keeley 1981, Automated lightning detection system 1999). Notwithstanding lightning's potential to ignite fires in northwestern California, Native American ignitions likely accounted for most fires (Fritz 1931, Agee 1993, Lewis 1993).

Synoptic weather systems in northwestern California influence critical fire danger (Hull et al. 1966). Gripp (1976), in a study of critical fire weather in northwestern California, found that 37.5% of fires larger than 120 ha (300 ac) were associated with the Pacific High (Postfrontal) Type. The Great Basin High Type accounted for 29.7% of the fires, the Subtropical High Aloft Pattern was linked with 21.9%, and other miscellaneous types were associated with 10.9%. The Pacific High (Postfrontal) and the Great Basin High Types produce warm, dry east winds *(foehn winds)* that displace the marine air mass off the coast (Hull et al. 1966). The Subtropical High Aloft Pattern produces abnormally high temperatures and low humidity (Hull et al. 1966). The most hazardous weather pattern is the Pacific High (Postfrontal) Type, having produced an average of 1.4 fires larger than 120 ha (300 ac) every ten days it occurs. The Great Basin High Type was associated with 0.5 fires/10 days and the Subtropical High Aloft Pattern had 0.3 large fires/10 days (Gripp 1976).

Between 1955 and 1974 there were 64 fires larger than 120 ha (300 ac) in Humboldt and Del Norte Counties. Twelve of these fires occurred in cool, moist coastal areas, and 52 fires were located in warm, dry interior regions. All of the large fires in coastal areas and 86% of those in interior regions were associated with the Pacific High (Postfrontal) Type, the Great Basin High Type, or the Subtropical High Aloft Pattern (Gripp 1976).

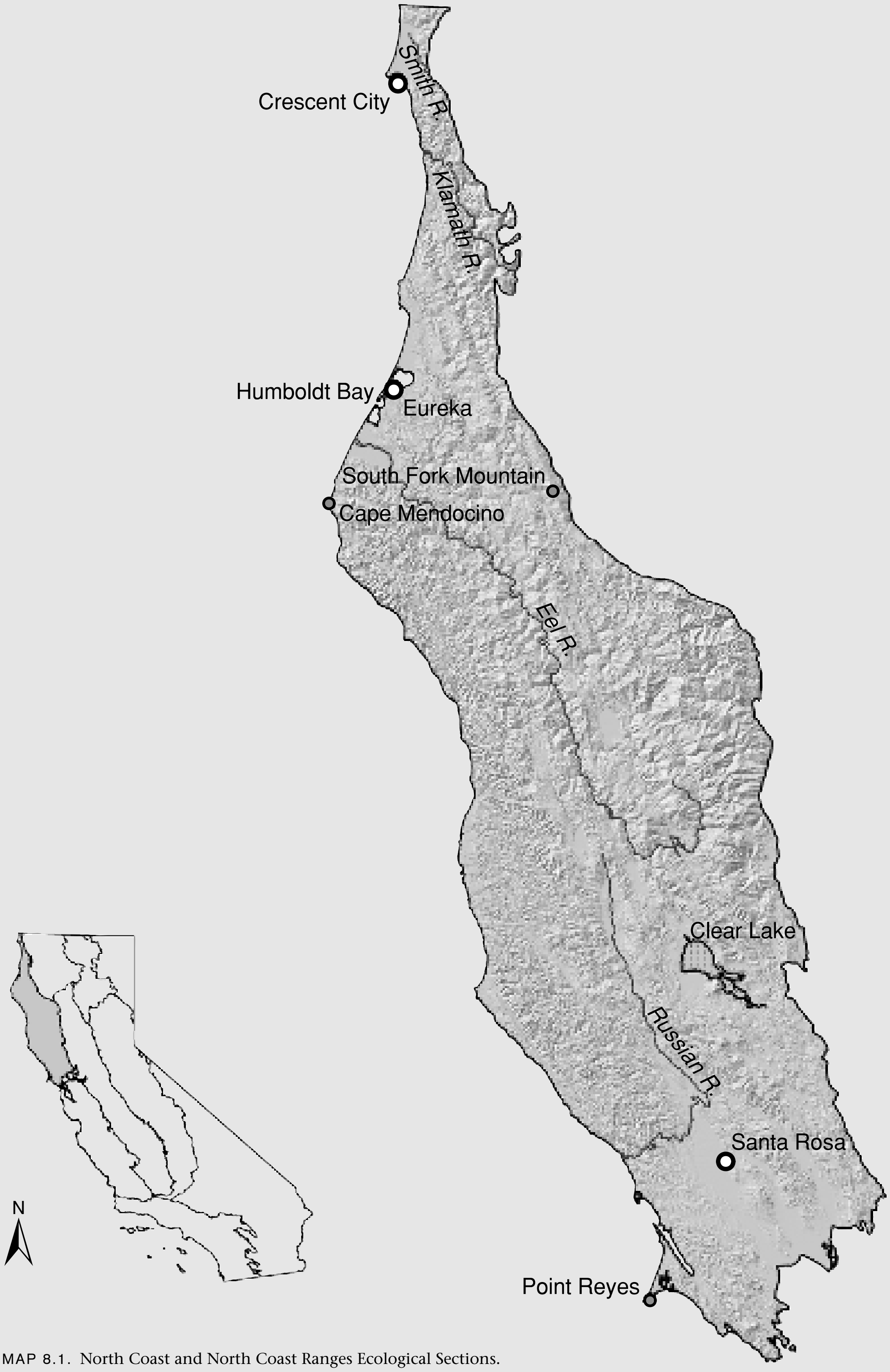
Ecological Zones

In general, low-elevation conifer forests dominate along the coast and in the northern part of the bioregion. Woodlands and montane forests increasingly dominate to the south and east. Interspersed among these vegetation types and along the coast can be found grasslands and shrublands. Montane scrubs are found at higher elevations in the Northern California Coast Ranges, whereas chaparrals are more common on volcanic soils in the southeastern part of the bioregion. These plant communities can be described as occurring in six broad ecological zones.

The north coastal scrub and prairie zone (Fig. 8.1) is found in the fog belt along the California coast in a discontinuous band below 1,000 m elevation from Santa Cruz north to the Oregon border (Heady et al. 1988). Its distribution along the north coast varies from locally extensive to sporadic to absent. North Coastal Scrub is found immediately inland of the coastal strand in a narrow strip extending from southern Oregon to the Bay Area. The vegetation is characteristically compact having been sculpted by strong salt-laden ocean winds. North Coastal Scrub was described by Munz (1959) and is variously dominated by species such as coyotebrush *(Baccharis pilularis)*, yellow bush lupine *(Lupinus arboreus)*, salal, and evergreen huckleberry *(Vaccinium ovatum)*. Scrubs dominated by salal *(Gaultheria shallon)*, evergreen huckleberry, ferns, and blackberry are more common in the northern part of the bioregion and are more likely to form two-layered communities. One-layered communities are more common to the south (Heady et al. 1988). Coastal Prairie is dominated by an assortment of grass and herbaceous species and may have the greatest plant diversity of any North American grassland type (Stromberg et al. 2001).

The north coastal pine forest zone (Fig. 8.2) is made up of isolated stands along the north coast. Principal species include beach pine *(Pinus contorta* ssp. *contorta)*, Bishop pine *(Pinus muricata)*, Bolander pine *(Pinus contorta* ssp. *bolanderi)*, and pygmy cypress *(Cupressus goveniana* ssp. *pigmaea)*.

The Sitka spruce *(Picea sitchensis)* forest zone (Fig. 8.3) is generally found inland of the north coastal scrub and prairie zone in a narrow strip approximately 1 to 2 km (0.6 to 1.2 mi) wide (Zinke 1988) extending south from the Oregon border and terminating near Fort Bragg. Along rivers and in the Wildcat Hills south of Ferndale, Sitka spruce forests can extend inland as far as 25 km (15.5 mi) (Zinke 1988).



MAP 8.1. North Coast and North Coast Ranges Ecological Sections.

FIGURE 8.1. North coastal scrub and prairie zone. Coastal prairie at Sea Ranch, Sonoma County. (Photograph by Rand Evett.)

FIGURE 8.2. North coastal pine forest zone. Bishop pine forest regeneration following fire. (Photograph by Scott Stephens.)

The redwood forest zone (Fig. 8.4) is inland of the Sitka spruce forest zone. Redwood is intolerant of salt spray and strong, desiccating winds (Olson et al. 1990). On the north, east, and south, the redwood zone is mostly limited by inadequate soil moisture and excessive evapotranspiration (Mahony and Stuart 2001). Redwood forests occur in an irregular narrow strip, ranging in width from 8 to 56 km (5 to 35 mi) (Olson et al. 1990). Stands in Napa County are 68 km (42 mi) from the coast (Griffin and Critchfield 1972). The tallest and largest trees are confined to moist, wind-protected canyons and lower slopes.

Increased evapotranspiration inland limits the coastal conifers allowing for complex mixtures of Douglas-fir *(Pseudotsuga menziesii)* and a variety of evergreen and deciduous broadleaved trees defining the Douglas-fir–tanoak *(Lithocarpus densiflorus)* forest zone (Fig. 8.5). Notable among the tree species present are tanoak, Pacific madrone *(Arbutus menziesii)*, Oregon white oak *(Quercus garryana)*, and California black oak *(Quercus*

FIGURE 8.3. Sitka spruce forest zone. Young Sitka spruce forest at Patrick's Point State Park. (Photograph by John Stuart.)

FIGURE 8.4. Redwood forest zone. Old-growth redwood forest in Redwood National Park. (Photograph by John Stuart.)

FIGURE 8.5. Douglas-fir–tanoak forest zone. Young Douglas-fir–tanoak forest in Humboldt County. (Photograph by John Stuart.)

kelloggii) (Zinke 1988, Stuart and Sawyer 2001). Douglas-fir and tanoak forests dominate inland lower montane forests. Montane forests characteristically have Douglas-fir mixed with ponderosa pine *(Pinus ponderosa),* and then at higher elevations Douglas-fir is intermixed with white fir *(Abies concolor).*

The Oregon white oak woodland zone (Fig. 8.6) occurs sporadically throughout the North Coast and North Coast Ranges. In the redwood forest zone and the Douglas-fir–tanoak forest zone, Oregon white oak woodlands often occur in patches of a few to hundreds of hectares in size, usually near south- and west-facing ridges. In the warmer, drier parts of the North Coast and North Coast Ranges, Oregon white oak can form open savannas or be interspersed with other broadleaved trees or conifers.

A few of the higher mountains support red fir *(Abies magnifica)* forests and on the highest peaks, foxtail pine *(Pinus balfouriana* spp. *balfouriana)* and Jeffrey pine *(Pinus jeffreyi)* woodlands can be found. These are discussed in the Klamath Mountains chapter (Chapter 9). Blue oak *(Quercus douglasii)* woodlands, chaparrals, and grasslands are found in the interior lowlands on the eastern border of the region (Stuart and Sawyer 2001) and are discussed in the Central Valley chapter (Chapter 13).

Overview of Historic Fire Occurrence

Prehistoric Period

Holocene fire history reconstructions from lake sediments in western Oregon (Long et al. 1998, Long and Whitlock 1999) and the Klamath Mountains (Mohr et al. 2000) indicate relatively frequent fire during the warm, dry early to mid Holocene and less frequent fire as climate became cooler and wetter. Pollen analyses reveal increased levels of fire-adapted vegetation concomitant with thicker charcoal deposits and a warm, dry climate (Long and Whitlock 1999). Similar patterns, presumably, apply to California's North Coast and North Coast Ranges.

The North Coast Ranges have experienced three major climatic periods since the end of the Pleistocene: a cool, somewhat continental climate from the early Holocene to about 8,500 years B.P.; a warmer period with presumably drier summers from 8,500 to about 3,000 years B.P.; and a cool, moist climate since about 3,000 years B.P. (Keter 1995). Native Americans are known to have lived in the region since around 8,200 to 8,600 years B.P., and by the middle of the Holocene, humans lived throughout the North Coast region (Sawyer et al. 2000). The pollen record demonstrates that vegetation differed during the three periods. Open pine forests with sparse shrubs and herbs dominated during the early Holocene in parts of the North Coast Ranges. As the climate warmed and dried, pine pollen counts remained high and oak counts increased while Douglas-fir pollen decreased. The cool, moist climate in the late Holocene enabled Douglas-fir, tanoak, and true fir pollen counts to increase and oak counts to decrease (Keter 1995). Fire was presumably more frequent during the warm, dry period and less frequent during the cool, moist period.

Fire history studies from the last 1,000 years reveal a variable pattern of fire frequencies throughout northwestern California. The most frequently burned landscapes were ignited on a nearly annual basis by Native Americans (Lewis 1993, Keter 1995) and were generally near villages, or were in vegetation cultured for food and basketry materials such as in grasslands and oak woodlands. Vegetation adjacent to Native American use areas experienced more frequent fire than would be found in the same vegetation type farther away (Vale 2002, Whitlock and Knox 2002). In general, the

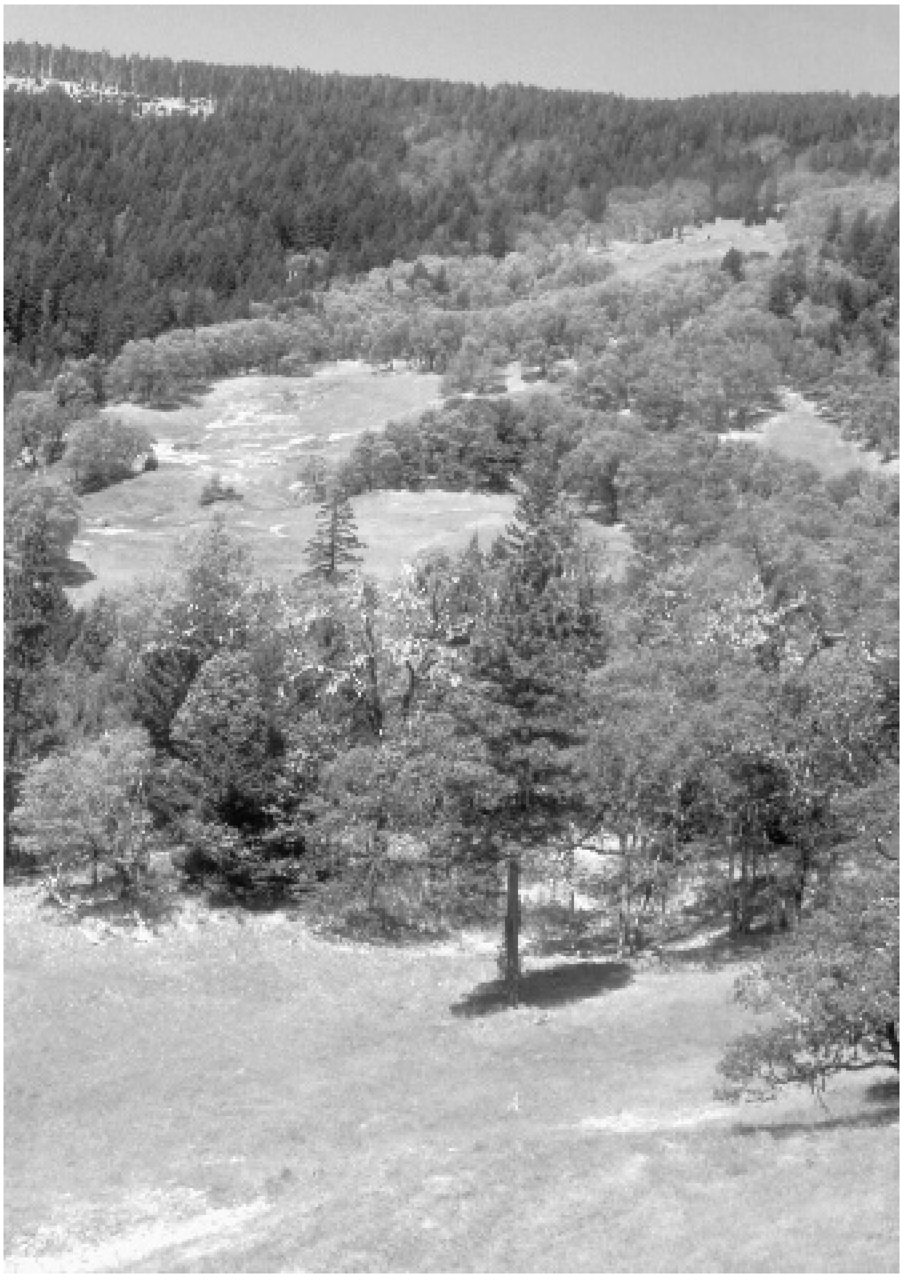


FIGURE 8.6. Oregon white oak woodland zone. Oregon white oak woodland in Humboldt County. (Photograph by John Stuart.)

most frequent fire occurred in grasslands and oak woodlands, with decreasing fire frequencies in chaparral, mixed evergreen, and montane mixed conifer. The least frequent fire occurred in moist, coastal conifer forests.

Native American ignitions presumably accounted for the most fire starts in the coastal region, as lightning is infrequent during the summer months (Automated lightning detection system 1999, Stephens and Libby 2006). Lightning fires are more numerous at higher elevations in the North Coast Ranges than the in coastal regions, but not as numerous as in the Klamath, Shasta, or Trinity National Forests (Show and Kotok 1923, Keeley 1981). Van Wagtendonk and Cayan (2007) found that lightning strike density increased with distance from the Pacific Ocean (Fig. 8.7) and increasing elevation for the period between 1985 and 2000. The number of lightning strikes per year per 100 km^2 (39 mi^2) in northwestern California during this period ranged from 0.9 to 9.3 (median = 1.7, mean = 3.0, SD = 2.5).

Historic Period

The prevention of Native-American–ignited fires, the introduction of cattle and sheep by ranchers, and logging altered fire regimes during the historic period. New fire regimes were created as Euro-American settlement moved north from the Bay Area in the early nineteenth century to the northern counties in the mid to late nineteenth century. Coastal areas were usually settled earlier than inland areas.

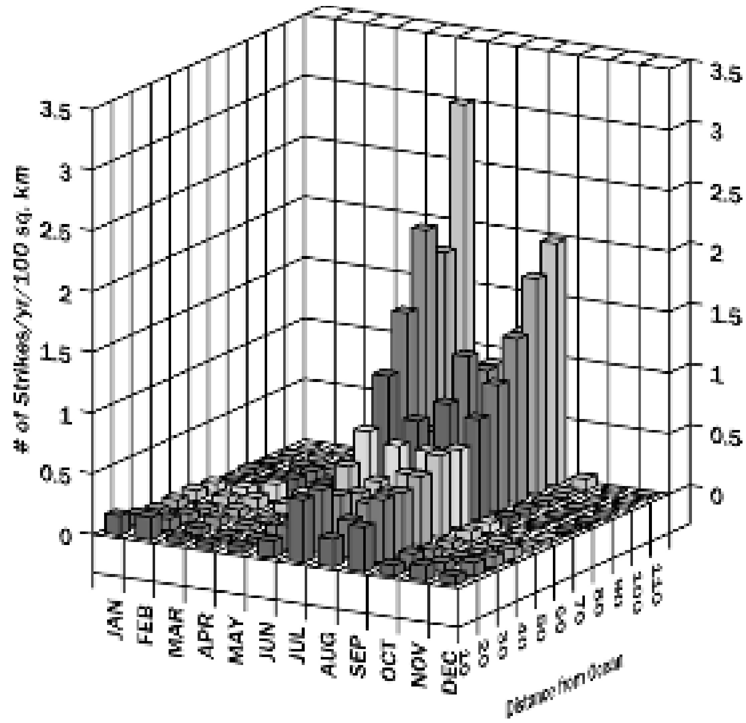


FIGURE 8.7. Average annual lightning strike density as a function of distance from the Pacific Ocean in the North Coast bioregion, 1985–2000. (Data from van Wagtendonk and Cayan 2007.)

Indian burning was interrupted in the early 1800s near the Bay Area, in the 1830s to 1840s near Clear Lake, and the mid 1860s in northern Mendocino and Humboldt Counties (Keter 2002). Traditional burning practices were curtailed as Indian populations were decimated by disease and warfare and as survivors were relocated to reservations (Keter 1995).

Early settler fires either originated from escaped campfires or were deliberately set to improve forage for livestock (Barrett 1935, Gilligan 1966). Ranchers primarily grazed cattle during the early to mid nineteenth century with sheep grazing increasing in the mid to late nineteenth century. Sheepherders were notorious as indiscriminate users of fire. Barrett (1935) wrote, "[T]he largest percentage of the most destructive fires in the mountains of California were caused by sheepmen during the thirty years preceding the establishment of the National Forests." Fire use by ranchers was not as skillfully employed as by Indians. Rather than burning for a single reason, Indians burned for multiple purposes at different times of the year and with variable intensities and severities (Lewis 1993).

Loggers during the mid to late nineteenth century regularly burned recently cut lands to remove bark and facilitate log extraction by draft animals. The potential for fire to escape and burn into unlogged forests was high. Fortunately, most of the early logging was done in cool, moist coastal forests where fire hazards were generally low (O'Dell 1996). By the late nineteenth century and through the 1920s, mechanical yarding systems and railroads enabled logging of whole watersheds in coastal and interior drainages. Following logging, many timberland owners attempted to convert forestland to grassland by repeatedly burning the logging slash and sowing grass seed (O'Dell 1996). Fire frequency, intensity, and severity were high throughout this period.

Large fires were frequent in northwestern California during the historic period. For example, Gripp (1976) conducted an extensive review of northwestern California newspapers and various other documents and found that large fires in Humboldt and Del Norte Counties from about 1880 to 1945 were common with an average interval between severe fire seasons of 3 years.

Fire suppression began on National Forest Land in northwestern California in 1905 (Keter 1995, Stephens and Ruth 2005). Fire suppression on private and state land, in the latter part of the nineteenth century through the early twentieth century, was largely the responsibility of the counties and various landowner associations. During the 1920s, fire wardens used their power of conscription to recruit firefighters and by the early 1930s, the California Division of Forestry assumed the role of fire suppression (Clar 1969). Effective fire suppression on private, state, and federal land, however, did not begin until after 1945 when the State Forest Practice Act curtailed logging activities, more effective firefighting equipment became available, and returning soldiers from World War II helped to suppress fires.

Current Period

Fire records dating back to around 1915 exist for the bioregion, although reasonably complete records for large fires are only available since 1945, and complete records in digital format for fires of all sizes are available for only the past couple of decades. The records for fires larger than approximately 120 ha (300 ac) (CDF-FRAP 2001) reveal that two to three times as many fires occurred in the 1950s as in subsequent decades. In addition, there were consistently more fires in the

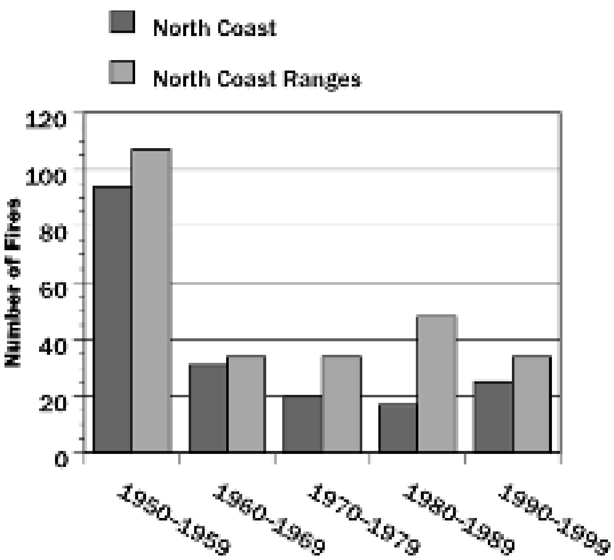


FIGURE 8.8. Number of fires larger than 120 ha (300 ac) by decade in the North Coast and North Coast Ranges Ecological Sections.

North Coast Ranges Section than in the North Coast Section (Fig. 8.8). The vast majority of fire records did not identify fire cause, although the large number of fires in the 1950s coincided with a period of increased logging. Fewer large fires in ensuing decades can be attributed to more effective fire prevention and suppression.

The North Coast has experienced a consistent decrease in cumulative hectares burned since the 1950s, and the North Coast Ranges similarly experienced progressively fewer hectares burned from 1950 through the 1970s; but in the past two decades cumulative fire size has dramatically increased, possibly due to fuel load and structural changes associated with fire suppression (Fig. 8.9) (Talbert 1996, Stuart and Salazar 2000).

The *natural fire rotation,* a measure of fire frequency defined as "the length of time necessary for an area equal in size to the study area to burn" (Agee 1993), in northwestern California has lengthened appreciably since fire prevention and suppression were initiated. Overall, the North Coast had a natural fire rotation from 1950 through 1999 of 485 years, and the North Coast Ranges had a value of 261 years. When analyzed by latitude, the North Coast had longer natural fire rotations in the central and southern parts of the ecological section, while the North Coast Ranges had a longer natural fire rotation in the north (Fig. 8.10).

Major Ecological Zones

North Coastal Scrub and Prairie Zone

North coastal scrub extends from Monterey County into Oregon in a narrow strip generally ranging in width from tens to hundreds of meters. Belsher (1999) found that scrubs north of Sonoma County were variously dominated by coyotebrush, yellow bush lupine, salal, evergreen huckleberry, and various blackberry species. Salal in combination with blackberry species and a rich mix of other shrubs, subshrubs, and herbaceous species often forms thickets and brambles. Yellow bush lupine stands, in contrast, can be monotypic (Heady et al. 1988). A transition zone between north coastal scrub and coastal sage scrub lies in Marin and San Mateo Counties. Tolerance to salt spray is the dominant ecological factor in these communities.

Prior to European settlement, the North Coastal Prairie was probably dominated by native perennial grasses, including California oatgrass *(Danthonia californica)*, purple needlegrass *(Nassella pulchra)*, Idaho fescue *(Festuca idahoensis),* and tufted hairgrass *(Deschampsia cespitosa)* (Heady et al. 1988). Highly susceptible to invasion, coastal prairie now includes many mediterranean annual species as well as non-native perennial grasses, notably velvetgrass *(Holcus lanatus)* and sweet vernalgrass *(Anthoxanthum odoratum)* (Hektner and Foin 1977).

FIRE ECOLOGY

Salal, evergreen huckleberry, coyotebrush, thimbleberry *(Rubus parviflorus)*, salmonberry *(Rubus spectabilis)*, and California blackberry *(Rubus ursinus)* are all fire-neutral, facultative sprouters (Table 8.2). Although regeneration is not fire dependent, these species have the capability to aggressively recolonize burned landscapes through sprouting, seeding, or germination from buried seed.

Because the pre-European settlement prairie community composition is speculative, and the present communities have been significantly altered by invasion, fire responses must be examined for each species individually. The only published study of coastal prairie native bunchgrass fire responses showed no significant changes in foliar cover or frequency for California oatgrass, purple needlegrass, and foothill needlegrass *(Nassella lepida)* after burning (Hatch et al. 1999). Tufted hairgrass in other plant communities is resistant to all but the highest intensity fires and recovers to pre-burn levels in a few years (Walsh 1995). Idaho fescue is resistant to low-intensity burning but can be killed at higher intensities (Zouhar 2000). A small unpublished study at The Sea Ranch in Sonoma County showed temporary decreases in the cover of velvetgrass and sweet vernalgrass following prescribed burns with little effect on tufted hairgrass (Evett 2002).

FIRE REGIME–PLANT COMMUNITY INTERACTIONS

Fire is relatively uncommon in North Coastal Scrub because of its proximity to the cool, humid climate of the Pacific Ocean. Native Americans would most likely have ignited any fires that did burn and fire spread would have been probably dependent on warm, dry east winds. Pre-European fire intervals are unknown, but may have varied from a few years near Native American habitations to hundreds of years. North Coastal Scrub is capable of self-perpetuating with or without fire.

The role of fire in maintaining coastal prairie prior to European settlement is poorly documented but is likely to have included widespread burning (Blackburn and Anderson

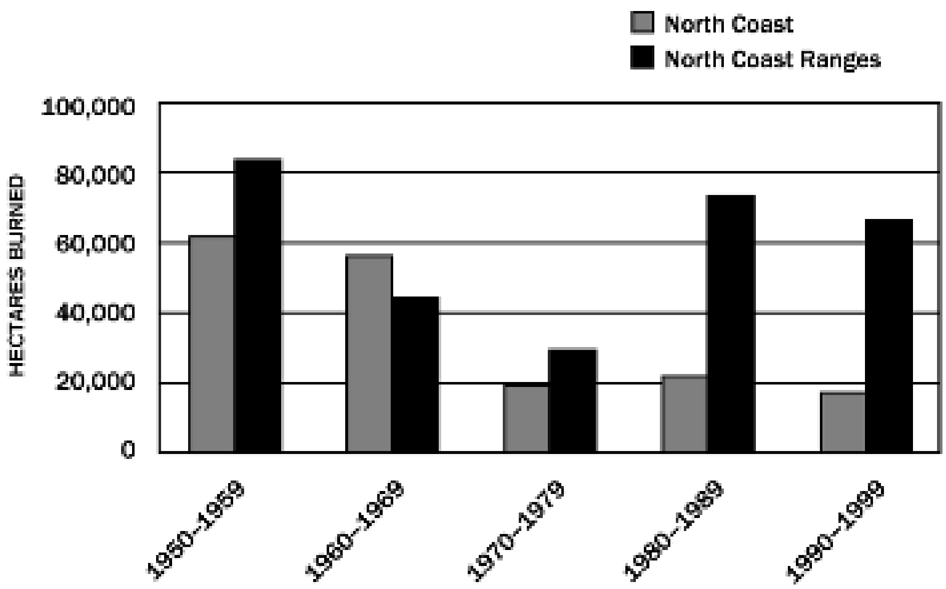


FIGURE 8.9. Number of hectares burned for fires larger than 120 ha (300 ac) by decade in the North Coast and North Coast Ranges Ecological Sections.

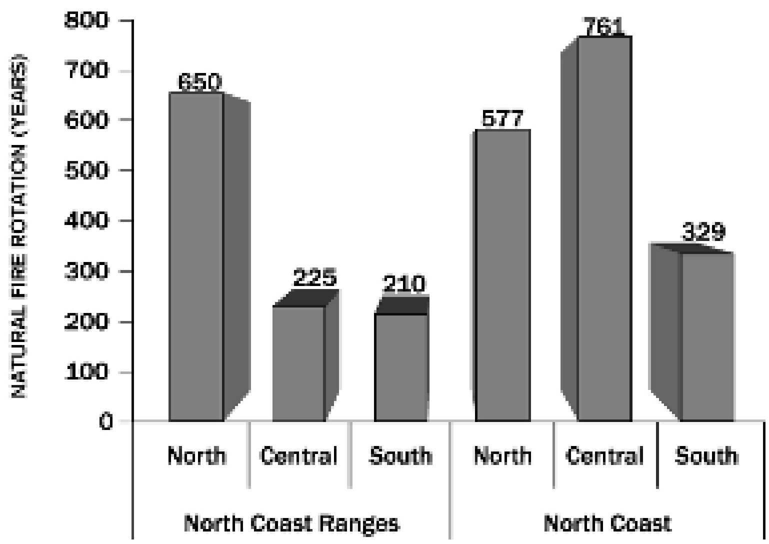


FIGURE 8.10. Natural fire rotation based on fires larger than 120 ha (300 ac) between 1950 and 1999 by latitude in the North Coast Ranges and the North Coast Ecological Sections. For the North Coast Ranges, North = Humboldt, Trinity, and Tehama Counties; Central = Glenn and Mendocino Counties; and South = Lake, Colusa, Sonoma, and Napa Counties. For the North Coast, North = Del Norte and Humboldt Counties; Central = Mendocino and Lake Counties; and South = Sonoma, Napa, Solano, and Marin Counties.

1993). A few accounts by early European travelers in coastal California mention fires and comment on lush grasslands on coastal terraces. Because lightning frequency is very low in north coastal California, fires were probably deliberately set by Native Americans to maintain grasslands with their rich sources of grain, bulbs, and tubers. Soil and phytolith evidence suggests that many coastal prairie sites have been grassland for thousands of years (Bicknell et al. 1992). In the absence of burning or grazing, many of these sites with high grass phytolith content in the soil have been invaded by shrubs and trees, suggesting that regular aboriginal burning was required to maintain the coastal prairie (Bicknell et al. 1993, Evett 2000). Following displacement of the native population, many ranchers practiced deliberate burning to maintain the prairie and promote understory forage in forested areas (Bicknell et al. 1993). For the past 150 years, continuous livestock grazing has replaced frequent burning as the most important change agent throughout the coastal prairie. During this time, non-native mediterranean annuals have largely replaced native perennial grasses. Whether this

TABLE 8.2

Fire response types for important species in the North Coast bioregion

	Type of Fire Response			
	Sprouting	Seeding	Individual	*Species*
Tree	None	Neutral	Killed	Beach pine, Sitka spruce, western hemlock, western redcedar
	None	Neutral	Survive	Grand fir, Port Orford-cedar
	None	Stimulated (establishment)	Survive	Douglas-fir
	None	Stimulated (release)	Killed	Bishop pine, Bolander pine, pygmy cypress
	Stimulated	Neutral	Survive/ Top-killed	Bigleaf maple, California bay, canyon live oak, golden chinquapin, tanoak
	Stimulated	Stimulated (establishment)	Survive/ Top-killed	Redwood, California black oak, Oregon white oak, Pacific madrone
Shrub	Stimulated	Neutral	Survive/ Top-killed	Evergreen huckleberry, salal
	Stimulated	Stimulated (establishment)	Survive/ Top-killed	Evergreen blackberry, coyotebrush, salmonberry, thimbleberry
Grass	Stimulated	Stimulated (establishment)	Survive/ Top-killed	California oatgrass, Idaho fescue, purple needle-grass, tufted hairgrass

replacement would have been as extensive under continued frequent burning is unknown.

There is little data on mean fire return intervals in coastal prairie. Greenlee and Langenheim (1990) estimated pre-European settlement fire return intervals near Monterey Bay were 1–2 years; post-European settlement intervals, confounded by the simultaneous introduction of livestock grazing, were 20–30 years. Aboriginal fires were probably small and of low intensity due to the discontinuous nature of the coastal prairie and lack of fuel accumulation under a high-frequency regime. Seasonality of aboriginal fires is unknown; fires were probably more likely in the summer or early fall dry season (Table 8.3).

The removal of fire and livestock grazing from the coastal prairie has profound effects on the plant community composition. Sites at The Sea Ranch in northern Sonoma County, where livestock grazing was removed in the late 1960s and fires have been excluded, show a shift from mixed annual and perennial grasses to overwhelming dominance of non-native perennial grasses, a decline in biodiversity indices, and dangerously increased fuel loads (Foin and Hektner 1986, Evett 2002).

Small-scale attempts to reintroduce fire to coastal prairie sites to reduce non-native species and restore native species dominance have met with mixed success. Burning at The Sea Ranch sites reduced cover of the non-native grasses, velvetgrass and sweet vernalgrass, but increased cover of another non-native grass, hairy wallaby grass *(Rytedosperma pilosum)* (Evett 2002). Biological diversity increased because of increased cover of non-native forbs and annual grasses. Native grass species were mostly unaffected by burning; this was also true in a study in coastal San Mateo County (Hatch et al. 1999).

North Coastal Pine Forests Zone

Bishop, beach, and Bolander pine forests are sporadically arranged along coastal bluffs and marine terraces from the Oregon border to the Bay Area. Bishop pine occurs in disjunct populations in coastal California from Humboldt County to Santa

TABLE 8.3
Fire regime classification for the north coastal scrub and prairie zone

Temporal	
Seasonality	Summer–fall
Fire-return interval	Long
Spatial	
Size	Small
Complexity	Low
Magnitude	
Intensity	Multiple
Severity	High
Fire type	Passive-active crown

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

TABLE 8.4
Fire regime classification for the north coastal pine forest zone

Temporal	
Seasonality	Summer–fall
Fire-return interval	Truncated medium
Spatial	
Size	Medium
Complexity	Low
Magnitude	
Intensity	High
Severity	Very high
Fire type	Passive-active crown

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

Barbara County. It is also found on Santa Cruz and Santa Rosa Islands as well as in Baja California, Mexico (Metcalf 1921, Critchfield and Little 1966, Little 1979). Beach pine is much more widely distributed than Bolander pine and is found along the Pacific Coast from Yakutat Bay, Alaska, to Mendocino County (Little 1971, Critchfield 1980, Bivin 1986, Oliphant 1992). Bolander pine is endemic to the pygmy forests of western Mendocino County and is associated with pygmy cypress.

FIRE ECOLOGY

Bishop pine is a fire-dependent, obligate seeder (Table 8.2). Regeneration is dependent on a crown-stored seed bank. Cones can remain closed for years and only open after fire or on hot, low-humidity days (Van Dersal 1938). Fire is a critical process in the establishment and maintenance of Bishop pine ecosystems (Vogl et al. 1977). Older trees have thick bark that enables them to survive multiple surface fires (McCune 1988). Many Bishop pine stands, however, are very dense and stand-replacing crown fires are common. Cone serotiny is somewhat variable, with northern populations less serotinous than southern populations (Zedler 1986). Morphological differences in cones have been observed, but this does not result in a significant difference in cone-opening temperatures (Ostoja and Klinger 1999). Mycorrhizal colonization of Bishop pine is rapid after stand-replacement fires, and the source of the inoculum is probably heat-resistant propagules in the soil (Barr et al. 1999).

Beach pine is a fire-neutral, obligate seeder, whereas Bolander pine and pygmy cypress are fire-dependent, obligate seeders (Table 8.2). Beach pines are non-serotinous; Bolander pines and pygmy cypresses are variably so (Lotan and Critchfield 1990). Beach pine, Bolander pine, and pygmy cypress all have persistent cones and begin to produce cones within 10 years (Krugman and Jenkinson 1974). Bolander pine and pygmy cypress cones will open after fire or by desiccation (Johnson 1974, Vogl et al. 1977). Detached cones commonly open, but this rarely results in seedling establishment because of the need for bare mineral seedbeds and high amounts of sunlight.

FIRE REGIME– PLANT COMMUNITY INTERACTIONS

Bishop pine is adapted to stand-replacement high-severity fires (Table 8.4). Pre-historically, the majority of these fires probably occurred in the late summer and fall when fuel moisture contents were low. High-severity fires were probably mostly associated with warm, dry east winds. The spatial scale of fires is difficult to estimate. No fire history data exists to estimate the spatial extent of the fires, but in areas where the trees were in isolated groves surrounded by shrublands the fires were probably of moderate or large size (hundreds of ha or larger). Some high-frequency, low-intensity surface fires were ignited by Native Americans and ranchers in Bishop pine forests (B. Baxter, personal communication). Lightning-ignited fires are unusual (Keeley 1981), so anthropogenic ignitions were probably the main source of fires. The majority of Bishop pine forests have not burned in the last 40 to 70 years because of fire suppression. The lack of fire could threaten the long-term existence of Bishop pine because it relies on high-severity crown fires that prepare seed beds, enable the release of large quantities of seed, and remove the canopy thereby increasing the light reaching the forest floor. Conversely, fire at high frequency could extirpate Bishop pine because there would be insufficient time for the trees to produce viable seed between successive fires. Introduction of non-native grasses into recently burned areas would increase the risk of extirpation because the grasses could produce a highly continuous fuel bed in 1 to 2 years.

Little is known about the role of fire in Bolander pine and pygmy cypress forests. Wind, rather than fire, appears to be the primary significant source of change in beach pine stands (Green 1999).

Sitka Spruce Forest Zone

Sitka spruce forests are variously dominated by Sitka spruce, western hemlock *(Tsuga heterophylla)*, Douglas-fir, western redcedar *(Thuja plicata)*, Port Orford-cedar *(Chamaecyparis lawsoniana)*, grand fir *(Abies grandis)*, or red alder *(Alnus rubra)*.

FIRE ECOLOGY

In general, Douglas-fir and red alder regenerate well following fire, timber harvest, floods, or windthrow, whereas Sitka spruce, western hemlock, grand fir, western redcedar, and Port Orford-cedar regenerate well in either undisturbed or disturbed forests. Douglas-fir is a fire-enhanced obligate seeder, and red alder is a fire-neutral facultative sprouter (Table 8.2). Both species require full sunlight and mineral soil to regenerate. Young red alder trees sprout vigorously, but older trees rarely sprout (Harrington 1990). Sitka spruce, western hemlock, grand fir, western redcedar, and Port Orford-cedar are all fire-inhibited obligate seeders and regenerate well on organic seedbeds in shade or partial shade (Foiles et al. 1990, Harrington 1990, Harris 1990, Hermann and Lavender 1990, Packee 1990, Zobel 1990). Sitka spruce, western hemlock, western redcedar, and Port Orford-cedar are capable of reproducing by layering (Harris 1990, Packee 1990, Zobel 1990), although Port Orford-cedar layers only occasionally.

With the exception of Douglas-fir and larger Port Orford-cedar (Zobel et al. 1985), other potential canopy dominants and co-dominants in these forests are not fire resistant. Western hemlock, Sitka spruce, western redcedar, and red alder are shallow rooted and have thin bark (Uchytil 1989, Packee 1990, Griffith 1992). Furthermore, western hemlock has flammable foliage and a low branching habit (Tesky 1992). Grand fir is fire sensitive when small, but can develop bark thick enough to resist light surface fires (Howard and Aleksoff 2000).

FIRE REGIME–PLANT COMMUNITY INTERACTION

Fires were generally uncommon in Sitka spruce forests. Lightning ignitions were scarce and Native Americans either ignited the few fires that did burn significant areas or fires spread from inland areas and were most likely accompanied by warm, east winds. Fuel moisture is almost always too wet to support fire in these coastal forests with the exception of late summer and early fall after summer fog has run its course. Even then, temperature and humidity are usually not conducive to burning so close to the Pacific Ocean. With the exception of Native American ignitions in prairies or near villages, fire intervals were long to very long. When fires did burn, however, they were surface fires or with warm, dry east winds they developed into passive/active crown fires. Fires were small to moderate in size, with moderate spatial complexity and intensity, and had multiple severity levels (Table 8.5).

TABLE 8.5
Fire regime classification for the Sitka spruce forest zone

Temporal	
Seasonality	Summer–fall
Fire-return interval	Truncated long
Spatial	
Size	Small–Medium
Complexity	Moderate
Magnitude	
Intensity	Moderate
Severity	Multiple
Fire type	Passive-active crown

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

Fire history in Sitka spruce forests is not well documented. Inferences can be made from fire histories from the cool, moist redwood forests in Del Norte County and from similar forest types along the coast of Oregon and Washington. Veirs (1982) found that redwood forests in coastal Del Norte County had fire intervals between 250 and 500 years. Impara (1997) found similar patterns in Sitka spruce forests in the central Oregon Coast Range with pre-settlement (1478–1845) fire intervals averaging around 300 years. Agee (1993) reported fire intervals of around 200 years for the southern Oregon coast, 400 years for the northern Oregon coast, and 1,146 years in Sitka spruce forests of western Washington (Fahnestock and Agee 1983). Wind is the more frequent cause of change in these coastal forests (Agee 1993, Green 1999).

Red alder is known as an early seral species that aggressively colonizes moist, mineral soils in full sunlight. Early growth is rapid and it usually dominates competitors for the first 25 years or so until it is overtopped by other conifers (Uchytil 1989). If Douglas-fir is present, it may eventually overtop red alder and potentially dominate in the overstory for centuries. If Douglas-fir is not present, then Sitka spruce, western hemlock, grand fir, or Port Orford-cedar (Hayes 1958) may develop into canopy dominants. Port Orford-cedar and western hemlock can regenerate in the shade of a canopy (Franklin and Dyrness 1973), whereas Sitka spruce and grand fir, though not as shade tolerant as Port Orford-cedar or western hemlock, can self-perpetuate following windthrow or pockets of overstory mortality (Franklin and Dyrness 1973).

There has been little change in fire regime from pre-European time to the current time period. The 60 to 70 years of effective fire suppression is much shorter than the pre-European fire intervals. Even though many coastal stands were logged and presented different stand structures than old growth, a benign climatic regime, rapid plant recolonization, rapid plant growth, and rapid fuel decomposition have allowed many stands to approximate fire environments seen in old growth stands. Effective fire suppression should continue to minimize the probability of wildfire in these forests into the future.

Redwood Forest Zone

FIRE ECOLOGY

Redwood is a fire-enhanced facultative sprouter (Table 8.2). Seedling establishment is problematic in the absence of fire, windthrow, or flooding because of low seed viability (Olson et al. 1990) and unsuitable seedbeds. It is rare to find redwood seedlings that have become established on their own litter because of the combination of damping-off fungi (Davidson 1971) and low light intensities commonly found beneath redwood canopies (Jacobs 1987). However, exposure of mineral soil following fire, windthrow, or flooding often results in successful redwood seedling establishment. Redwood is also capable of establishing from seed on duff (Olson et al. 1990), logs (Bingham 1984), debris (Olson et al. 1990), and litter from other species (Jacobs 1987). Seedling establishment is better under high light intensities (Jacobs 1987), and juvenile growth is best in full sunlight (Olson et al. 1990).

Sprouting in redwood can occur from lignotubers at the root crown, induced lignotubers on layered branches, trunk burls, and from adventitious buds on tree trunks (Del Tredici 1998). Sufficiently intense surface fires can stimulate basal lignotubers to sprout, whereas crown fires often result in redwood "fire columns" (Jepson 1910, Fritz 1931) whose denuded trunks sprout new leaves and eventually develop new branches. The development of redwood lignotubers and axillary meristems are a normal part of seedling development (Del Tredici 1998) and may represent an evolutionary response to fire, windthrow, or flooding.

Redwood bark serves as either a resister or enabler of fire damage to the cambium layer depending on its thickness and the water content of its loosely packed, sponge-like fibers. Bark, 15 to 30 cm (6 to 12 in.) thick (Fritz 1931), protects the cambium from heat damage, especially when moist. Thin-barked trees, however, are susceptible to fire damage and are readily top-killed (Fritz 1931, Finney and Martin 1989, 1993) as are large trees that have had their once-thick bark reduced by recurring fires. Dead cambium acts as an infection court for sapwood and heartwood rots. Surface fires burn into the rotten sapwood or heartwood hollowing out tree bases *(goosepens)*. Subsequent fires in goosepens continue to expand the cavity with the result that many trees are consumed standing (Fritz 1931). Fire scars have been recorded to be as tall as 70 m (Sawyer et al. 2000). Such tall scars were initiated by dry bark burning in long strips. The burned strips are enlarged by ensuing fires and can further develop into scars up to a meter wide.

Redwood stands are among the most productive in the world (Fritz 1945, Fujimori 1977) and consequently produce impressive fuel loads. Rapid litter decomposition helps to keep the litter loads relatively low. Pillers and Stuart (1993) found that the time to decompose 95% of the weight of oven-dried litter ranged from approximately 7 to 11 years on four sites in Humboldt County.

Litterfall is episodic and varies by site and by species. In general, most litter falls in a few weeks to a few months. Redwood litter is particularly flammable after it falls. Its leaves have had several weeks to air dry on the tree and, because leaves do not abscise individually but as sprays of leaves, the resultant fuel bed is made up of loosely compacted fuel enabling the litter to quickly respond to moisture changes

TABLE 8.6

Fire regime classification for the redwood forest zone

Temporal	
Seasonality	Summer–fall
Fire-return interval	Short–long
Spatial	
Size	Small–medium
Complexity	Moderate
Magnitude	
Intensity	Moderate
Severity	Low
Fire type	Surface

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

and to increased oxygen supply during combustion (Pyne et al. 1996).

Accretion rates for larger fuels such as branches and logs are episodic and may not be dependent on significant wind events. Although fuels less than 25 cm (10 in.) in diameter accrete every year, large branches and trees may take centuries to fall. In addition to wind, snow and wildfire can cause stem breakage or mortality that eventually augments the large forest floor dead fuels.

Decomposition of Douglas-fir, western hemlock, and Sitka spruce logs in redwood forests can take hundreds of years (Harmon et al. 1986). Redwood's renowned decay resistance (Agee 1993) suggests even slower decomposition rates.

Understory plants can either inhibit or intensify fire behavior. Coastal redwood forests in Del Norte County, for example, include many plants (Mahony 1999) with moisture high enough to retard fire spread. Inland redwood forests, in contrast, have a higher proportion of sclerophyllous understory trees and shrubs that can exacerbate fire behavior. Stuart (1986) found that during prescribed burns in Humboldt County, flame lengths on redwood litter and duff were 10 to 90 cm (4 to 35 in.) long, yet beneath evergreen huckleberry the flames were 300 to 500 cm (9 to 16 ft) long.

FIRE REGIME–PLANT COMMUNITY INTERACTIONS

Redwood forests typically burned in the summer and early fall with variable fire intervals. The wettest sites had long fire intervals and drier sites had short fire intervals. Many fires ignited by Native Americans in vegetation adjacent to redwood forests were likely extinguished as they spread into cool, moist fuels usually associated with forest floors in old-growth redwood stands. Occasionally, though, fires larger than 10 ha (25 ac), and some larger than 1,000 ha (2,400 ac), would occur, especially during droughts and under the influence of warm, dry east winds.

Redwood forests generally experienced moderate-intensity surface fires that consumed irregular patches of surface fuel and understory vegetation (Table 8.6). Occasional passive

TABLE 8.7
Fire intervals in redwood forests

	Fire Interval (years)	*Composite Area (ha)*	*Source*
Del Norte and northern Humboldt Counties	50–500	1	(Veirs 1982)
East of Prairie Creek Redwoods State Park	8	0.25–3	(Brown and Swetnam 1994)
Humboldt Redwoods State Park	11–44	7	(Stuart 1987)
Southern Humboldt County	25	12	(Fritz 1931)
Jackson State Forest	6–20	4–20	(Brown and Baxter 2003)
Salt Point State Park	6–9	~200	(Finney and Martin 1989)
Annadel State Park	6–23	14 trees[a]	(Finney and Martin 1992)
Near Muir Woods National Monument	22–27	75	(Jacobs et al. 1985)
Western Marin County	8–13	5–10; 10 trees in 1 stand	(Finney 1990) (Brown et al. 1999)
Jasper Ridge Preserve, Santa Clara County	9–16	1–3	(Stephens and Fry 2005)
Big Basin Redwoods State Park	~50	Variable, dependent on estimated fire area	(Greenlee 1983)

[a]Point data.

crown fires occurred, especially along the southern and eastern edges of the range. On average, fire severities were lowest in the coolest, wettest regions and highest in the warmer, drier areas.

Redwood forests have a complex fire history. In general, pre-suppression fire intervals correspond to the three predominant climatic gradients described earlier where the longest fire intervals are found in moist, cool coastal sites in the north, and the shortest fire intervals are found in the drier, warmer interior and southern sites. Fire intervals from 125 to 500 years have been reported for coastal forests in Del Norte County where redwood grows in association with Sitka spruce, western hemlock, and western redcedar (Veirs 1982, Mahony and Stuart 2001). Drier, warmer redwood forests in eastern Del Norte County with higher proportions of Douglas-fir, tanoak, and Pacific madrone have pre-suppression fire intervals of approximately 50 years (Veirs 1982). Fire intervals to the south generally range between 6 and 44 years (Table 8.7). Some redwood stands had fire intervals of 1 or 2 years due to regular burning by Native Americans of prairies surrounded by redwood forest, near villages, and along travel corridors (Fritz 1931, Gilligan 1966, Lewis 1993). Other redwood stands had intervals in excess of 50 years because of their remoteness from Native American ignitions (Fritz 1931, Lewis 1993), fire-inhospitable microclimates, or fuel anomalies.

Few studies have attempted to estimate fire size in redwood forests. Stuart (1987) estimated fire sizes in old-growth redwood stands in Humboldt Redwoods State Park to be approximately 786 ha (1,940 ac) for the pre-settlement period, 1,097 ha (2,710 ac) for the settlement period, and 918 ha (2,270 ac) for the post-settlement period. California Department of Forestry fire records for Humboldt Redwoods State Park and nearby areas for the period 1940 through 1993 indicate that 30 fires larger than 120 ha (300 ac) burned, averaging 505 ha (1,250 ac) and ranging in size from 100 to 1,787 ha (250 to 4,400 ac) (Stuart and Fox 1993). Most of these fires were not located in old-growth redwood forests. Several fires were ignited in other vegetation types and burned into the redwood forest but were not sustained. One fire, however, that began on logged land outside of the park, did burn approximately 300 ha (740 ac) of old-growth redwood forest. Settlers during this period adopted the burning practices of the Sinkyone Indians and regularly burned the prairies in the upper basin to increase the production of livestock feed. Most fires burned into the old-growth Douglas-fir, "burning the vegetation and debris of the forest floor without destruction of the forest stands" (Gilligan 1966).

Succession and the climax status of redwood forests have been discussed since the early 1900s. Some authors contend that redwood is a seral species that, in the absence of fire, windthrow, or flooding, would eventually be succeeded by more understory-tolerant species as individual redwoods die (Cooper 1965, Osburn and Lowell 1972). Most ecologists, however, have argued that redwood is self-perpetuating and should be considered climax or as a fire sub-climax (Fisher et al. 1903, Weaver and Clements 1929, Fritz 1938, Whittaker 1960, Roy 1966, Becking 1967, Stone and Vasey 1968, Daubenmire and Daubenmire 1975, Veirs 1982, Olson et al. 1990, Agee 1993). It is difficult to imagine a scenario where redwood is unable to maintain itself in forests. Redwood's survival is ensured because of its great height, longevity, and resistance to fire by thick-barked individuals, ability to sprout, and capacity to establish seedlings on disturbed seedbeds.

Whether redwood is dependent on fire is an open question and should be answered on a case-by-case basis with each redwood community assigned a place on a fire-dependency continuum. A Redwood-Western Hemlock/Salmonberry association (Mahony and Stuart 2001) in coastal Del Norte County, for example, is fire tolerant but not fire dependent (Veirs 1982). Low to moderate surface fires kill fire-susceptible species such as western hemlock, western redcedar, and Sitka spruce. These moisture-loving understory-tolerant species quickly regenerate, grow, and have the capacity to develop into important ecosystem structural elements. A Redwood-Tanoak/Round Fruited Carex-Douglas Iris association (Borchert et al. 1988) near the droughty southern limits of the range, in contrast, could be thought of as fire dependent (Veirs 1982). In these areas, redwoods primarily regenerate from sprouts following recurring fires (Noss 2000). Reproduction from seed is difficult because of the inability of these relatively dry sites to meet redwood's soil moisture requirements (Olson et al. 1990, Noss 2000). The vast majority of redwood's range is found on sites intermediate to those described above with individual stands occupying intermediate positions on the fire-dependency continuum. Although the redwood species may not be dependent on fire to perpetuate in these forests, its ecosystem structures and functions may well be. Fire in redwood forests can determine size and spacing of dominant and co-dominant trees, snags, dead limbs, and logs. These features could provide critical habitat for a variety of wildlife species. Additionally, fire can increase the availability and cycling of soil nutrients, influence the establishment and perpetuation of understory species, and create natural edges (Hanson 2002).

Fire regime changes are evident in the drier portions of redwood's range, but not necessarily so in the wet north. Post-World War II (1950–2003) natural fire rotations for the northern, central, and southern redwood zones for fires larger than 134 ha were 1,083, 717, and 551 years, respectively (Oneal et al. 2004). The current fire interval in the north is probably not beyond the natural range of variability. However, the current fire intervals in the central and southern redwoods zones greatly exceed the 6- to 44-year pre-suppression intervals (Table 8.7).

It is possible, however, that a fire regime change in the north will eventually become evident because of modifications in fuel loading and structure following logging and land clearing. Only about 10% of the range of redwood is currently old-growth forest (Fox 1988). The other 90% of redwood's range is composed of young growth—some of which is more than 100 years old and dominated by large redwoods with fuel complexes not dissimilar to old growth, but much of the young growth is composed of small-diameter, dense complexes of conifers intermixed with broadleaved trees and shrubs. Other fuel complex alterations include the presence of large, persistent redwood stumps and logging slash, as well as greater shrub and herbaceous plant cover. In general, available fuel and horizontal and vertical fuel continuity have increased. Eventually, fire size, intensity, and severity may increase, whereas fire complexity may change to multiple and the fire type may become passive-active crown fire. The above speculation assumes that the current successes the redwood forest has benefited from in fire management and suppression will not be sustained. It is likely, however, that aggressive fire suppression on land that is largely the responsibility of the state of California will continue and that less-frequent, small fires may remain the norm in the redwood forests for the foreseeable future.

Douglas-Fir–Tanoak Forest Zone

Douglas-fir–tanoak forests are widely distributed in the bioregion in areas inland from the redwood belt. Both tanoak and Douglas-fir are major components of northern mixed evergreen forests and Douglas-fir–hardwood forests (Sawyer et al. 1988). Douglas-fir dominates the overstory, while tanoak dominates a lower, secondary canopy. Other important tree associates may be Pacific madrone, golden chinquapin *(Chrysolepis chrysophylla)*, bigleaf maple *(Acer macrophyllum)*, California bay *(Umbellularia californica)*, canyon live oak *(Quercus chrysolepis)*, ponderosa pine, sugar pine *(Pinus lambertiana)*, incense-cedar *(Calocedrus decurrens)*, California black oak, and Oregon white oak.

FIRE ECOLOGY

Douglas-fir regeneration is often episodic in part due to irregular seed crops (Strothmann and Roy 1984). Douglas-fir establishment is enhanced if a good seed crop follows a low to moderate surface fire. If, however, there was a poor seed crop, other species would become established and inhibit Douglas-fir seedlings in ensuing years. Seedlings are most likely to become established on moist mineral soil, whereas relatively few seedlings are found on thick organic seedbeds (Hermann and Lavender 1990). Douglas-fir is considered moderately shade tolerant in northwestern California (Sawyer et al. 1988) and relatively shade intolerant in western Oregon and Washington (Hermann and Lavender 1990). Young seedlings are better able to tolerate shade than older seedlings, although Douglas-fir seedlings growing on dry sites need more shade. In northwestern California, optimum seedling survival occurs with about 50% shade, but optimum seedling growth occurs with 75% full sunlight (Sawyer et al. 1988).

Mature Douglas-fir has thick corky bark and is fire resistant. Other fire adaptations include great height with branches on tall trees over 30 m (100 ft) above the ground, rapid growth, longevity (up to 700 to 1,000 years old), and the ability to form adventitious roots (Hermann and Lavender 1990).

Douglas-fir and tanoak litter decomposes to 5% of original dry weight in 7 and 9 years, respectively (Pillers 1989). Because of this, fuel beds are typically thin. Douglas-fir leaves are short and fall individually, resulting in compact litter. Dry tanoak litter, however, is deeper and more porous.

Tanoak, Pacific madrone, chinquapin, canyon live oak, bigleaf maple, and California bay are all fire-neutral facultative sprouters (Table 8.2). Tanoak generally dominates its associated broadleaved trees and reproduces from seed under most light conditions, but fares best in full sunlight (Sawyer et al. 1988). Although tanoak is very tolerant of shade, regeneration from seed in dense shade is limited. Tanoak can be easily top-killed by fire but vigorously sprouts from dormant buds located on burls or lignotubers (Plumb and McDonald 1981). Stored carbohydrates and an extensive root system aid in a rapid and aggressive post-fire recovery (McDonald and Tappeiner 1987). Resistance to low-intensity surface fires increases with size because of increased bark thickness (Roy 1957, Plumb and McDonald 1981). Dried tanoak leaves are very flammable in comparison to other mixed evergreen forest species. Dried tanoak leaves in a dead crown can enable long flames and torching fire behavior. Many older tanoak trees may initially survive low-intensity fires, but bole wounds facilitate the entry of insects and disease that may eventually kill the tree (Roy 1957). Wind and infrequent heavy snow loads in tanoak canopies can cause branch and stem breakage resulting in heavy, hazardous surface fuels (Tappeiner et al. 1990). Tanoak mortality from sudden oak disease may produce hazardous wildfire conditions, and areas with high infection rates may find increases in fire intensity, severity, and the potential for crown fires (McPherson et al. 2000).

FIRE REGIME–PLANT COMMUNITY INTERACTIONS

Pre-European settlement fires were relatively frequent in Douglas-fir–tanoak forests due to their warmer, drier, inland locations and increased lightning activity at higher elevations (Keeley 1981). In the North Fork of the Eel River, for example, an average of about 25 lightning strikes occur per year (Keter 1995). Native American ignitions were the primary ignition source in the North Coast Ranges, though, as they regularly burned to culture tanoak, true oaks, and basketry materials (Keter 1995). As with other regional forest types, fires are most likely to occur during the months of July through September (Keeley 1981, Lewis 1993) (Table 8.8).

There is scant literature describing pre-European settlement fire size, intensity, and severity. Ethnographic data on indigenous populations and fire history data suggest that fire sizes, intensities, and severities were highly variable. In areas subject to frequent Native American burning, fire intensities and severities were low (Lewis 1993, Adams and Sawyer). Other areas experienced fire intensities and severities that varied spatially and temporally across the landscape resulting in a complex mosaic of mostly multi-aged stands of varying sizes (Rice 1985, Lewis 1993, Wills and Stuart 1994). Fires in interior sites spread more extensively than those closer to redwood forests. Surface fires were common and were intermixed with areas that supported passive/active crown fires (Table 8.8).

TABLE 8.8
Fire regime classification for the Douglas-fir–tanoak forest zone

Temporal	
Seasonality	Summer–fall
Fire-return interval	Short
Spatial	
Size	Medium
Complexity	Moderate
Magnitude	
Intensity	Multiple
Severity	Low–moderate
Fire type	Surface

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

The few fire history studies of Douglas-fir–tanoak forests indicate that average pre-suppression fire intervals varied from 10 to 16 years (Rice 1985, Wills and Stuart 1994, Adams and Sawyer n.d.). Pre-suppression fire sizes were undoubtedly variable. Rice (1985) reported fires in the hundreds of hectares.

In addition to environmental factors such as soil type, aspect, and so forth, successional trajectories depend on fire severity, seed availability, and sprout density. The climax forest is characterized by an overstory of Douglas-fir with tanoak dominating the lower, secondary canopy. Surface fires appear to be the norm in all-aged and all-sized old-growth Douglas-fir–tanoak forests in the Six Rivers National Forest (Adams and Sawyer). Fire suppression has increased the density of shade-tolerant tanoak in many Douglas-fir–tanoak forests (Tappeiner et al. 1990, Talbert 1996, Hunter 1997, Hunter et al. 1999). Douglas-fir, though, is able to maintain its dominance because of its large size and longevity. Sawyer and others (1988) described several successional pathways for Douglas-fir–tanoak forests. Following a severe, extensive stand-replacing fire, seed-producing Douglas-firs are killed leaving the sprouting tanoak or other sprouting hardwoods to dominate during early succession. Salvage logging and broadcast burning can enhance sprouting hardwood dominance, while not-salvage logging will ensure that shrubs in combination with sprouting hardwoods will dominate during early succession (Stuart et al. 1993). Eventually, Douglas-fir will reinvade as growing space is created by maturing, self-thinning hardwoods. A moderate- to low-severity surface fire, in contrast, would not kill potential seed-producing overstory Douglas-fir, but would kill Douglas-fir seedlings and saplings (Rice 1985). Douglas-fir seedling establishment would then occur in the partial shade beneath the surviving mixed canopies of Douglas-fir and tanoak (or other hardwoods). Douglas-fir will continue to dominate the overstory and tanoak will continue to perpetuate in the understory and secondary canopy. A third scenario in more open mixed stands would allow both Douglas-fir and tanoak to persevere.

There isn't enough evidence to deduce whether the current fire regime in old-growth Douglas-fir–tanoak forests has changed since European contact. Fire regimes in young stands, though, have been modified. The most significant change in old growth is the greater density of understory shrubs and trees creating greater vertical fuel continuity, increasing the probability that a surface fire could burn into the crown. Many Douglas-fir–tanoak forests, however, have been logged or have experienced stand-altering wildfire. The current regime in these forests can be characterized as having longer fire return intervals due to effective and aggressive fire suppression, greater intensity because of increased fuel loadings from slash and from increased densities of understory shrubs and trees, and greater severity because of the accumulated ladder fuels and increased loading of large, dead surface fuels. Fine fuels decompose too rapidly to have increased beyond that of pre-European conditions. Seasonality of fire occurrence complexity is probably unchanged. The current fire regime probably accounts for a higher proportion of forest area burned in passive crown fires. Because pre-European fire size is not known with any certainty, we can't speculate whether there have been any changes.

Oregon White Oak Woodland Zone

Oregon white oak is distributed from southwestern British Columbia through western Washington and Oregon into California in the North Coast Ranges and Sierra Nevada (Little 1971). Oregon white oak woodlands often occur in the margin between conifer forest and prairies in the North Coast Ranges. Oregon white oak can also be found in open savannas, closed-canopy stands, mixed stands with conifers, or with other broadleaved trees (Burns and Honkala 1990).

FIRE ECOLOGY

Oregon white oak and California black oak are fire-enhanced, facultative sprouters (Table 8.2). Oregon white oak is frequently top-killed by fire but vigorously sprouts from the bole, root crown, and roots (Griffin 1980, McDonald et al. 1983, Sugihara et al. 1987). Sprouting has been reported to decrease with age (Sugihara and Reed 1987). As in most oak species, sprouts grow more rapidly than seedlings because of stored carbohydrates and an extensive root system. Seedling establishment is enhanced by the removal of the litter layer (Arno and Hammerly 1977).

FIRE REGIME–PLANT COMMUNITY INTERACTIONS

Pre-historically, Oregon white oak woodlands experienced frequent, low-intensity surface fires, many of which were ignited by Native Americans. Mean fire return intervals varied from 7 to 13 years in Oregon white oak woodlands in Humboldt County (Reed and Sugihara 1987). Fires probably spread in cured herbaceous fuels. There is no information on fire sizes in this vegetation type, but they probably were diverse. Fires ignited by Native Americans under moister conditions probably would not have spread far into adjoining conifer forests (Gilligan 1966), whereas those ignited in the summer and fall could have been extensive because of continuous dry herbaceous fuels. Frequent surface fires produced open savannas in the Bald Hills in Humboldt County (Sugihara et al. 1987) (Table 8.9).

TABLE 8.9
Fire regime classification for the Oregon white oak woodland zone

Temporal	
Seasonality	Summer–fall
Fire-return interval	Truncated short
Spatial	
Size	Medium
Complexity	Low
Magnitude	
Intensity	Low
Severity	Low
Fire type	Surface

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

Fire suppression has dramatically affected this plant community. Frequent surface fires once inhibited seedling establishment and reduced the density of Douglas-fir and other competing conifers (Barnhardt et al. 1996). In the absence of fire, conifers can over-top, suppress, and eventually produce enough shade to kill Oregon white oak. Management-ignited prescribed fires have been ineffective in reducing the density of competing conifers when they are over 3 m (10 ft) in height (Sugihara and Reed 1987). Hand removal of small Douglas-fir has been used in some areas and larger trees can be girdled to increase the dominance of the oak (Hastings et al. 1997). To maintain oak dominance, a minimum fire frequency of 3 to 5 years has been recommended (Sugihara and Reed 1987).

Management Issues

The management challenges in the ecosystems of the North Coast bioregion are diverse. In general, fire once occurred frequently in grasslands and oak woodlands, with decreasing fire frequencies in chaparral, mixed evergreen, and montane-mixed conifer. Some redwood forests also experienced very frequent fires, particularly the populations that are on relatively xeric sites. Fire was less frequent in moist, coastal conifer forests.

Native American ignitions presumably accounted for the most fire starts in this area, as lightning is infrequent during the summer months. Indian burning was interrupted in the mid 1860s largely because of the impacts of introduced diseases. Managers in this region must answer an important question: Should restoration and management objectives include the influence of past Native American ignitions? Because Native Americans were an integral component of this region for thousands of years it is logical that current plans should include their influences.

Removal of fire from coastal grasslands and Oregon white oak woodlands has dramatically changed these ecosystems. In the absence of fire, conifers can over-top, suppress, and eventually produce enough shade to kill Oregon white oak. Frequent surface fires also produced open savannas in the Bald Hills in Humboldt County. The use of fall-ignited prescribed fires should be used to enhance and maintain these ecosystems.

The majority of Bishop pine forests have not burned in the last 40 to 70 years because of fire suppression. The lack of fire could threaten the long-term existence of Bishop pine because it relies on high- and mixed-severity fires to prepare seed beds, enable the release of large quantities of seed, and remove the canopy thereby increasing the light reaching the forest floor. Conversely, fire at high frequency could extirpate this species because there would be insufficient time for the trees to produce viable seed between successive fires.

Redwood forests once experienced fire at different intervals depending on their geographic location. The wettest sites had long fire intervals, and drier sites had short fire intervals. Redwood sites that are in relatively dry areas should use fall-ignited prescribed fires to reintroduce fire as an ecosystem process. Some prescribed fire is presently occurring in parks in this area but this should be expanded. Although the redwood species may not be dependent on fire to perpetuate in these forests, its ecosystem structures and functions may well be.

Pre-European settlement fires were relatively frequent in Douglas-fir–tanoak forests due to their warmer, drier, inland locations and increased lightning activity at higher elevations. Fire suppression has reduced fire frequency, particularly in young-growth forests. The most significant change in old growth is the greater density of understory shrubs and trees that has increased vertical fuel continuity. This increase in vertical fuel continuity has increased the probability of high-severity crown fires. Past forest harvesting operations may have had the most influence on forest structure in this forest zone.

Fire has been an integral part of coastal prairie ecology and fire exclusion has led to undesirable consequences. Livestock grazing can mitigate some of these consequences (Hayes 2002), but effective management should include prescribed burning. The sparse published data on burning of coastal prairie in California combined with anecdotal evidence and evidence from outside the region suggest regular burning on a 3- to 5-year rotation will slow the invasion of some non-native species without reducing cover of existing native species. If the seed bank contains viable seeds of displaced native species, burning may stimulate increased cover of these species. To achieve satisfactory restoration on most sites, extensive reseeding of desirable native species is required, followed by a regular prescribed burning and/or grazing program (Evett 2002).

Scientific information on the influences of fire on the ecosystems of the North Coast bioregion should be expanded through adaptive management and experimentation. This area includes significant amounts of federal and state land along with the state's largest amount of industrial forests. Site-specific questions on fire's role in North Coast ecosystems need to be addressed on the full spectrum of private and public lands. Most fire-related research has been on public land and relatively little has been done on the extensive private lands found in this bioregion. More general ecologiclandscape questions such as species viability will have to be answered on a regional basis.

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