

FIRE EFFECTS ON CALIFORNIA CHAPARRAL SYSTEMS: AN OVERVIEW

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Chaparral is a shrubby, sclerophyllous vegetation type that is common in middle elevations throughout much of California. It occupies 3.4 Mha throughout the state in some of the steepest terrain and adjacent to some of the most populated urban areas. Although chaparral has little direct commodity value, it does have great value in slope stabilization, watershed cover, wildlife habitat, and nutrient cycling. Combined effects of the summer-dry climate and the high flammability of chaparral vegetation render it extremely susceptible to periodic crown fires. Fires in the urban interface not only impact the chaparral ecosystem, but may burn homes, and also can affect regional air and water quality. Wildfires remove plant crown cover and may alter vegetation composition. Many chaparral plant species are well adapted to regenerate after fire, either through the ability to sprout vegetatively, or through fire-related cues that enhance germination. Fire also alters animal habitat and affects species composition and population levels. Perhaps most dramatic are the postfire effects on water and sediment movement. Flooding and debris flows which are common in years after fires may cause substantial loss of soil and nutrients and major damage to homes and other structures.

INTRODUCTION

California chaparral is a shrubby vegetation type (Fig. 1) that occurs in one of the five mediterranean climate areas in the world. These areas are characterized by hot, dry summers and mild, wet winters. Chaparral is common in middle elevations (300-1500 m) (Cooper 1922) throughout much of California, and covers about 3.4 Mha (8.5% of the state) (Barbour and Major 1977). Because of the hot, dry summers and the flammable nature of the vegetation, fire is a common occurrence in chaparral. The typical chaparral crown fire burns with very high intensity.

Fire in chaparral impacts a wide range of ecosystem processes, from dynamics of biological populations to nutrient cycling and hydrologic processes. Because much of California's chaparral occurs in proximity to urban and residential communities, fire also has tremendous impacts on human populations as a result of debris flows, effects on water supply, smoke production and its impact on air quality, and combustion of structures. Our primary focus in this paper is the effects of fire on the ecosystem.

The most obvious immediate effect of fire is the removal of vegetation. Fire in chaparral typically burns as a crown fire, killing aboveground parts of



Fig. 1. A mature stand of chaparral as seen from the road. Stands of chaparral are typically 1-2 m tall at maturity and are nearly impenetrable. The ground beneath the shrubs is nearly devoid of herbaceous vegetation.

most plants. Chaparral vegetation is generally well adapted to regenerating after fires, by seed or basal sprouting (Horton and Kraebel 1955). Regeneration of most species typical of mature chaparral occurs in the immediate postfire years. After an initial surge of regeneration, most changes result from mortality and change in species dominance over time. Hanes (1971) refers to this type of succession where the chaparral species present immediately after fire continue to dominate over time, as "autosuccession". Fire is the "pulse" that restarts the successional cycle. But timing, intensity, and frequency of fire can critically influence vegetation recovery, leading to potentially long-term changes in vegetation and flammability (Zedler et al. 1983). Fire also releases and cycles high levels of critical nutrients, and fire emissions can temporarily degrade regional air quality.

Some of the most dramatic effects of these fires are the downstream flooding and debris flows that can occur with winter rains (Anderson and Trobitz

1949). Much of this sediment originates on hillslopes, and moves through the system as dry ravel during or shortly after the fire, or as waterborne sediment carried off slopes through extensive rill networks (Wells 1987). Current research is increasing our understanding of many aspects of ecosystem processes in chaparral.

THE FIRE ENVIRONMENT

Many of the characteristics of chaparral species which enable them to succeed in a fire-prone environment (sclerophyllous leaves, deep root systems, crown sprouting) may have evolved in response to factors such as nutrient limitation or drought-stress (Axelrod 1989; Zedler and Zammitt 1989). Through these and other adaptations a unique set of species was able to survive even as the summer-dry mediterranean climate developed over the area. The increasing presence of fire (beginning in the Neogene) probably favored speciation in genera such as *Arctostaphylos*

and *Ceanothus* (Axelrod 1989) and development of fire-related germination mechanisms, such as stimulation of germination by charred wood, in species with long-lived seed (Zedler and Zammitt 1989).

There is little consensus on what the "natural" fire cycle is for chaparral. Byrne et al. (1977) analyzed charcoal in layered sediments off the California coast. They estimated that over a 775-y period the average interval between large fire events was every 65 y for coastal drainages and every 30 to 35 y further inland. Because not all of the contributing area would have burned in every major fire event, fire interval on individual sites would probably have been much longer. Keeley (1982) suggests (based on frequency of lightning ignition) that the natural fire cycle may have been much longer than what we observe today. Other estimates of natural fire cycles range anywhere from 10 to 50 y for chamise-dominated chaparral (Hanes 1971; Biswell 1974; Philpot 1977; Keeley and Zedler 1978; Minnich 1983). Chamise has needle-like leaves and very fine branches. Natural fire intervals are probably longer for broadleaf hard chaparral types.

Fire intervals are influenced by aspect, marine influence, and dominant shrub type (Hanes 1971) as well as factors such as weather patterns and ignition events. Minnich (1989) suggests that, at least for San Diego County, current fire intervals may not be much different from historic ones. He has analyzed 50 y of fire data for chaparral sites in San Diego County and estimated a mean fire recurrence interval of about 70 y. While current fire frequencies may be similar to those in the past, replacement of lightning by anthropogenic causes as the major source of ignitions has probably resulted in a shift of seasonality of chaparral fires from the summer (July-August) period toward the fall (September-December) period, when fires are typically driven by warm, dry Santa Ana winds (Keeley 1982; Minnich 1989).

In the current environment, a high percentage of the area burned annually is accounted for by a small number of large fires. Over a 15-y period in northern California (which includes both chaparral and timber types of vegetation), the largest fires (1% of the fires) burned 96% of the area (Strauss et al. 1989). It may well be that large fires are even more important in southern California, where fires in excess of 3000 ha occur nearly every year. The relative importance of human-caused fires increases dramatically, both in terms of numbers of ignitions and area burned, from northern California (timber vegetation types, low populations) to southern California (chaparral vegetation, high populations). Human-caused fires also

tend to be larger than lightning fires. For example, in the 1970s on the four southern California national forests, man accounted for about 80% of the ignitions, and about 90% of the burned area (Keeley 1982). Currently, on the four national forests in southern California, only 15% of fires are started by natural causes (Mees 1990). The frequency of fires may thus be greatly increased due to the proximity of wildlands to urban areas.

Under extreme weather conditions, chaparral may burn even more frequently than every 20 y. For example, in a study of large (over 400 ha) fires in San Diego County between 1940 and 1985, 11.6% of fires included areas of at least 400 ha of reburns in fuels less than or equal to 20 y old. However, only 2 of the 147 fires studied had started in young fuels (Dunn 1989). This suggests that while young fuels will burn under high fire hazard conditions, they are not as easily ignited as older fuels. On the other hand, very recently-burned sites with large amounts of herbaceous vegetation, whether native or artificially seeded, may ignite readily in the late summer to fall period after fuels have cured (Zedler et al. 1983).

Many chaparral shrubs contain high concentrations of ether extractives (waxes, oils, terpenes, fats). The proportion of smaller fuels (less than 0.5" or 2.5 cm diameter) which also influences flammability, is greater than 60% in *Adenostoma fasciculatum* (chamise—a dominant in many California stands) (Countryman and Philpot 1970). The needlelike leaves of chamise make up 67% of the surface area but only 16% of the volume and 10% of the weight. Thus the form of the plant is conducive to rapid burning (Philpot 1969). In addition, the leaves have a high volatile content which may fluctuate with season (Rundel 1981). Responses of fuel moisture to climatic conditions also greatly influence flammability, especially under extreme conditions (Green 1981). A low packing ratio and a high surface to volume ratio make chamise a particularly good fuel bed. Some chaparral types (such as those dominated by *Ceanothus* or oak species) will burn only under conditions of very low fuel moisture or high winds (Dougherty and Riggan 1982). It is not unusual to find stands over 100 y old in these types.

Ever since Indian times, man has played a role in wildland fire starts. Indians are thought to have intentionally burned chaparral in both the fall and the spring for the purpose of stimulating new plant growth (Lewis 1973). Changes in the size, seasonality, and frequency of fires have undoubtedly come about due to the more recent intervention of man. However, interpretations of the types of changes that have oc-

curred and their impacts on the structure and composition of chaparral fuels vary widely. Some authors have suggested that after years of a strict fire prevention policy, chaparral managers are now faced with large expanses of overage brush (Hanes 1971). These large expanses are more likely to burn in major conflagrations than in the past since they have been artificially maintained in an unburned state (Minnich 1983). In contrast, other sources (Byrne et al. 1977; Minnich 1989) suggest that the current fire interval may be considerably shorter than that before human influences largely due to increased ignitions. Partially in recognition of the ecological need for fire, the California legislature authorized the use of prescribed burning in chaparral in 1945 (Biswell 1974).

Although chaparral systems now appear quite resilient to a wide range of fire frequencies, chaparral vegetation in some areas has been degraded due to greatly increased frequency of human-caused fires

(Radtke 1981; Zedler et al. 1983). Perhaps more critical than debate over how natural fire patterns have been altered, is the question of how chaparral can be managed to achieve a fire regime that is ecologically sound. Due to the high percentage of anthropogenic ignitions in chaparral, return to a "natural" fire regime (even if it could be defined) appears unlikely.

FIRE EFFECTS ON VEGETATION

Many chaparral species are well adapted to regenerating after fires. Keeley (1977a) identifies three major modes of reproduction/regeneration for chaparral shrub species after fire: obligate seeders, sprouter/seeders, and sprouters with low (or no) seedling production. Shrubs that depend on seed reproduction after fires tend to have seeds that require a fire stimulus (either heat or charred wood) to germi-



Fig. 2 Fire removes aboveground vegetative cover. One mechanism for shrub regeneration is sprouting from underground storage organs (lignotubers). Chamise (*Adenostoma fasciculatum*) sprouts are pictured.

nate. Few new species establish after the initial flush (although in some mesic chaparral types, oaks and conifers may regenerate in mature chaparral given a long enough fire interval). Herbaceous annuals and perennials (Fig. 2) are also important components of the postfire flora (Sweeney 1956). They attain maximum cover values one or two years after the fire and decline as the shrub canopy develops (Sampson 1944; Horton and Kraebel 1955; Keeley and Keeley 1988). Herbaceous species also fall into several categories: herbaceous perennials, annuals with no fire-related germination requirements, and annuals with fire-dependent germination (Keeley and Keeley 1988). Because the species typical of mature chaparral generally regenerate immediately following fire, vegetation development in chaparral is characterized by a gradual decrease in number and density of species over the inter-fire periods.

Many chaparral shrub species sprout from underground storage organs (lignotubers) (Fig. 2). When their tops are removed by fire, below-ground buds are stimulated to begin growth. Sprouts of some species are visible within 10 days to 2 months after a fire (Plumb 1961; Radosevich and Conard 1980; Keeley and Soderstrom 1986). Under ideal conditions, sprouts have been observed to reach a height of 2.1 m within the first 10 y after fire (Horton and Kraebel 1955). Not all sprouting species survive fire equally well, however. Survival appears related to reproductive strategies, with species that have low mortality during fires typically being sprouters that have little or no seedling reproduction following fires (Keeley 1986). Survival of broadleaf evergreen sclerophylls such as *Rhus* spp. and *Heteromeles arbutifolia* is generally high (70-100%) even in severe fires (Plumb 1961; Zedler et al. 1983). These species tend to have low levels of seedling establishment following fire, and are highly dependent on sprouting for maintaining population levels. *Adenostoma fasciculatum* (chamise), on the other hand, has extremely variable survival, ranging from about 15-85% (Keeley and Zedler 1978; Plumb 1961; Zedler et al. 1983; Rundel 1984). Apparently timing and intensity of the fire, site characteristics, and shrub size are important factors in determining shrub survival. Chamise frequently produces large numbers of seedlings after fire. Several authors (Keeley and Keeley 1981; Plumb 1961; Keeley and Soderstrom 1986; Zedler et al. 1983), have noted that rates of sprouting for various species vary with elevation and aspect, with some species apparently sprouting better on more mesic sites and others on more xeric sites.

In addition to vegetative reproduction after fire, most chaparral shrubs (once they reach reproductive maturity at age 3 to 5 y) produce seeds annually. Seeds of many chaparral shrub and herb species accumulate in the soil in the years between fires, remaining dormant in the soil until stimulated to germinate by fire (Fig. 3). Keeley (1987) investigated germination characteristics of 45 woody chaparral species (shrubs, subshrubs, trees, and lianas). About one third of the species had seeds that germinated readily without treatment. Heat-stimulation enhanced germination for about 25% and treatment with charred wood for another 25%. In general, the species that germinated readily with no stimulus were sprouters that establish few seedlings after fire. For the woody species that had enhanced germination with exposure to heat or charate, seedling establishment is limited to the postfire environment. Stone and Juhren (1953) discovered that chamise produces polymorphic seeds with some seeds requiring fire-related cues to germinate, while others germinate freely. Mechanisms for fire-induced germination may be either physiological (embryo stimulation) or physical (increased seed coat permeability). Keeley (1987) speculates that heat stimulation may serve to increase seed coat permeability, while charate may have a biochemical role in induction of germination. The mechanism for fire-induced germination in *Ceanothus velutinus* was found to be a heat-induced cracking of the hylar fissure in the seed coat which allowed water to enter the seed and physiological processes to begin (Gratkowski 1962).

Depending on the timing and intensity of the fire, and the position in the soil, seeds may be stimulated to germinate, others may be killed, and some may receive inadequate stimulation and remain dormant in the soil. Soil moisture also impacts germination after fires, particularly in seeds of species that do not require fire cues to stimulate imbibition. In chamise, soil moisture contents of 15% or greater resulted in almost complete seed mortality with heating (Rogers et al. 1989). It follows, then, that factors such as fire intensity and season of burning can have a great impact on germination success of chaparral species. Following early spring (low intensity) fires, *Ceanothus*, chamise, and manzanita establishment may be poor compared to more intense summer season fires (Horton and Kraebel 1955; Parker 1989; Kelly et al. 1989). Regeneration of *Ceanothus megacarpus* seedlings following experimental high-intensity fires in crushed chaparral has been much higher than in areas where brush was burned standing. Crushing is now being experimented with op-



Fig. 3. Shrubs may also regenerate after fire through germination of soil stored seeds. Seedlings of *Ceanothus crassifolius* and *Adenostoma fasciculatum* are shown.

erationally as a method for enhancing *Ceanothus* regeneration (Riggan et al. 1986).

Climatic conditions in the critical first year after fire may also significantly influence later species composition in chaparral stands. Jacks (1984) found that *Ceanothus crassifolius* seedlings appeared to be more drought tolerant than *Adenostoma fasciculatum* by comparing seedling populations after two fires in the same location but separated in time. *C. crassifolius* seedling establishment was higher relative to that of *A. fasciculatum* when the fire was followed by a dry year. Differences between the two species were further substantiated through water stress experiments with the two species in the greenhouse, which demonstrated that *C. crassifolius* seedlings were deeper rooted and survived drought better than *A. fasciculatum* seedlings. In the Santa Monica Mountains, postfire seedlings of *Ceanothus megacarpus* had consistently lower mortality than seedlings of *Rhus laurina* even though late summer and fall water po-

tentials of *Ceanothus* were comparable to or even lower than those of *Rhus* (Davis 1989). Davis suggests that the *Rhus* has shallower rooting patterns and lower overall drought tolerance than the *Ceanothus*. On the other hand, Hastings et al. (1989) found no significant differences in water potential among seedlings of *Quercus dumosa*, *Adenostoma fasciculatum*, and *Ceanothus greggii* following a fire.

Large numbers of herbaceous annuals and perennials become established from seed after chaparral fires (Horton and Kraebel 1955; Sampson 1944), lending great beauty to the postfire landscape and helping to stabilize erosion-prone soils. Some of the seeds stored in the soil may be stimulated to germinate by heat, others by chemical compounds released from charred wood (Keeley 1984). In northern California, Sampson (1944) noted grass species were the most abundant herbaceous plants both before and after fires but their numbers decreased significantly after the second postfire year. Grasses are not nearly as

common a component in southern California chaparral. Keeley and Keeley (1987) tested seeds of 57 species of herbs and suffrutescent species common in chaparral after fire. The 42% of the species that required charred wood to stimulate germination tended to be species that are restricted to the postfire environment and are probably present in the soil seed bank at the time of fire. Only one of the species in this study was stimulated to germinate by heat, while heat reduced germination for many species.

The cover of postfire herbs may vary greatly from site to site and can fluctuate widely from one year to the next in early postfire succession (Sampson 1944; Horton and Kraebel 1955; Sweeney 1956; Keeley 1977b). Based on 4 y of postfire data from three sites in San Diego County, Keeley (1977b) postulates that much of this year-to-year variation in herbaceous cover is directly related to patterns in seasonal precipitation. Keeley proposes a model of relationships between rainfall and early postfire herbaceous cover. The initial herb density and composition in the first postfire year can be critical in providing seed sources for future years. The effect of rainfall throughout this early successional period has potential to affect the stored seed populations and thus the composition of the herbaceous flora following fire (Keeley et al. 1981).

Although chaparral is well adapted to regenerating after fire, extremely long or short fire intervals may cause major shifts in vegetation. Fire (frequently in conjunction with seeding of non-native grasses) has been used successfully in California for many years to convert chaparral areas to grassland. There is some evidence that frequent fires can degrade chaparral and convert chaparral sites to more flammable soft chaparral types (Hedrick 1951; Radtke 1981; Zedler et al. 1983). Furthermore, the timing of prescribed fire in chaparral may be critical in terms of ensuring adequate regeneration of desired species. With the diversity of reproductive strategies in chaparral, it is not surprising that factors such as fire frequency, fire intensity and timing, and postfire weather conditions can have a profound effect on relative regeneration success of chaparral species, and may cause major shifts in species dominance (or—in extreme cases—composition) to occur from one fire to the next.

FIRE EFFECTS ON FAUNA

Chaparral serves as a home to many animal species. The impact of fire on chaparral animal populations is felt in two ways. Impacts that occur during the fire include increased soil temperatures, smoke, and changes in vapor pressure within the soil. Postfire

impacts include reduced cover and changes in food availability (James 1983). The vertebrates most greatly effected by fire in chaparral are the reptiles, small mammals and birds. Although there may be an influx of large mammals into a burned area after fire due to the increased availability of food, they are more free to roam beyond the boundaries of the burned area, are better able to escape fire by fleeing, and thus overall are less impacted.

Lizards can survive during a fire by retreating to burrows or seeking shelter under rocks. Kahn (1960) found fires had little effect on food preference of lizards as determined by examining the stomach contents of reptiles collected on burned and unburned areas. Lillywhite (1977) noted that peak lizard populations occurred in recently burned areas where brush was sparsest. He hypothesized that this was due to the increased number of burned stems which are used as perches.

The small mammals that seem to fare best during fires are the burrowing rodents. Lawrence (1966) measured temperatures at increasing depth using thermocouples. He found that four inches (10 cm) of soil could insulate against temperatures as high as 1000°F (538°C). Pocket gopher (*Thomomys* sp.) burrows in the Sierra Nevada, where his study was conducted, were typically 9-36 in (0.2-0.9 m) deep. Vapor pressure appears to be a better indicator than temperature of survival of animals in burrows, since animals cool by evaporating water vapor from the surface of their lungs. Lawrence (1966) concluded from his observations that animals can survive fire as long as vapor pressure in the burrow stays below 40 mm Hg.

Another response small mammals have to the occurrence of fire is to flee. Two species commonly observed fleeing chaparral fires are the Dusky footed woodrat (*Neotoma fuscipes*) and the brush rabbit (*Sylvilagus bachmanni*) (Quinn 1979). Brush rabbits may become extremely disoriented by fire, and firefighters have observed these animals racing about with their fur aflame. The woodrat is especially reluctant to leave his burrow during the fire. When he does finally leave, he often moves to a cleared area such as a road where he may succumb to asphyxiation or be run over. Quinn (1979) observed 44 dead woodrats along a 1.8 km stretch of road immediately after a chaparral fire. None had been singed; all had been run over.

The typical chaparral rodent species such as woodrat, brush mouse (*Peromyscus boylii*), and California mouse (*Peromyscus californicus*) require brush for cover and food, are severely affected by fire, and can be

slow to re-invade (Wirtz 1977; 1984; 1988). Cook (1959) believes lack of cover is more critical than food availability in determining rate of recovery. Some species such as the kangaroo rat (*Dipodomys agilis*) and Californian pocket mouse (*Perognathus californicus*) survive fire in their burrows and return quickly. Finally there are species not normally found in mature chaparral that come into burned areas, such as the deer mouse (*Peromyscus maniculatus*), the harvest mouse (*Reithrodontomys megalotis*) and the California vole (*Microtus californicus*) (Wirtz 1977; 1984). Early postfire chaparral sites are characterized by grassland rather than chaparral species (Lawrence 1966). The overall trend is that species richness (the number of species present) does not change with the occurrence of fire but species composition and population levels of individual species do change (Wirtz 1977).

The major impact of fires on birds is change in habitat due to fire, as they can easily flee an oncoming fire. Komarek (1969) noted that increased numbers of insect-feeding birds appeared during and soon after a fire. Examining an area after a prescribed fire, Lawrence (1966) noted that the number of breeding pairs increased postfire—probably due to greater seed availability and insect numbers. Wirtz (1977; 1984) found that the diversity of breeding birds was greater in 1-y- than in 17-y-old chaparral. This was not due to a change in the number of species but to an increase in the number of individuals. When he looked at utilization of burned chaparral areas according to feeding guilds (rather than species) he found that omnivores were less abundant on burned plots, while granivores and insect and seed eaters were more abundant. Of the raptors, only ravens (*Corvus corax*) increased after fire. Ravens are scavengers/predators of invertebrates and small vertebrates, so the postfire environment may provide greater food availability (Wirtz 1979). Red-tailed hawks (*Buteo jamaicensis*) and great horned owl (*Bubo virginianus*) densities are high after fire but reproductive success decreases later, possibly because destruction of habitat concentrates birds into a smaller area and leads to increased competition (Wirtz 1979).

The postfire flush of nutrient rich herbaceous vegetation and young, moist shrub sprouts provide increased browse for several mammal species. Tabor and Dasmann (1957) looked at black-tailed deer populations in mature chaparral and after recent burns. They found deer could escape mortality from the fire by fleeing ahead of the flames. Deer populations were low on newly burned sites. However, when shrubs began to sprout in October or November pop-

ulations increased. Pre-burn deer populations were 30/mi² (12/km²). The first year after fire, populations increased to 120/mi² (46/km²) and gradually decreased with each passing year. Thornton (1982) studied black-tailed deer populations under various management treatments and found populations increased by over 300% after prescribed burning. Elevated nutrient levels in the forage may last up to three years. Thornton (1982) found that deer feeding on this forage were in general larger and healthier.

FIRE EFFECTS ON NUTRIENT CYCLING

Soils under mature chaparral stands are greatly limited in nitrogen (N) and phosphorous (P) concentrations. Nitrogen is the nutrient most likely to limit plant growth in chaparral (Hellmers et al. 1955). As a stand ages, available forms of N and P are tied up in plant biomass. Chaparral shrubs reabsorb much of the N and P back into the plant before leaf drop (Gray 1983). Marion and Black (1988) found that soil N availability in chaparral stands increased up to age 50 to 60 y and decreased thereafter. The decline was due to decreases in both the quantity as well as the quality (ratio of potentially mineralizable nitrogen to total nitrogen) of N on site. In a 54-y-old stand they found that nutrients in plant biomass exceeded nutrients potentially available in the soil. Schlesinger (1985) showed the litter layer in *Ceanothus megacarpus* chaparral lost little N, P, or lignin over the 3-y period of his study, indicating these nutrients are immobilized in the litter layer.

The primary effects of fire on nutrient cycling are ash deposition and volatilization of nutrients (Woodmansee and Wallach 1980). Fire temperature influences not only the combustion of plant material but also the degree of volatilization (Rundel 1983). Volatilization begins when temperatures exceed 200°C, and soil temperatures of 700°C have been recorded during chaparral fires (DeBano et al. 1977). DeBano and Conrad (1976; 1978) did pre- and postfire measurements on soil nutrients (N, P, K, Mg, Ca, Na) in an area that was burned under prescription. Postfire measurements indicated 146 kg/ha N were lost from plants, litter, and soil by volatilization during the fire. Another 15 kg/ha N were lost through postfire erosion for a total nitrogen loss that amounted to ~11% of that present in the plants, litter, and upper 10 cm of soil. Riggan (in Black 1987) estimates nitrogen losses as high as 572 kg/ha due to fire. Although the pool of total nitrogen decreases with each fire, the concentration of available nitrogen (ammonium and nitrate) increases after fire (DeBano

et al. 1979). The quantity of available nutrients depends on how much and how thoroughly the organic matter burned. Available nutrients are more susceptible to losses by leaching. Riggan et al. (1985) noted increases in nitrate concentrations in streamwater leaving burned chaparral watersheds for up to two years after a fire. Erosion also takes its toll. Most of this loss occurs when debris flows carry organic matter off the slopes.

How the available nitrogen is conserved on the site the first year after fire and how replacement occurs later on in the successional cycle are mechanisms not well understood. Rundel and Parsons (1984) propose that postfire ephemeral herbs play an important role in conserving nitrogen on the site during the first postfire year. By taking up as much as 12% of the total nitrogen content of the ash and incorporating it into their biomass they secure it on the site until they themselves die and are decomposed. How nitrogen replacement occurs in chaparral ecosystems is also not completely clear. Likely contributors to the pool include the short-lived perennial *Lotus scoparius*; and the shrubs of the genera *Ceanothus* and *Cercocarpus* through their association with symbiotic nitrogen fixing bacteria. Williams et al. (1986) measured the contribution of *C. crassifolius* to the chaparral nitrogen budget during a postfire chronosequence and found nodule biomass (where fixation occurs) increased to age 26 y, when 100% of the shrubs were nodulated. Only 35% of the 67-y-old shrubs were nodulated. Delwiche et al. (1965) and Poth et al. (1986) measured the nitrogen fixing capacity of excised nodules. Given the observed rates it appears the shrub-bacteria symbiotic association could lead to ecologically significant nitrogen fixation levels. Ellis and Kummerow (1988) have measured significant nitrogen fixation rates in the field by *C. crassifolius* seedlings.

In areas near or downwind from major NO_x sources such as large population centers, high levels of pollution-derived nitrogen compounds are deposited in chaparral ecosystems. These compounds accumulate in the ecosystem during the intervals between fires and may affect the nitrogen balance of the system (Riggan et al. 1985).

FIRE EFFECTS ON AIR AND WATER QUALITY

With the occurrence of fire comes the mobilization of compounds either by release in smoke emissions during combustion or by movement into streamwater through leaching or overland flow. Chaparral fires frequently occur near urban areas, recreational areas and defense installations, where air quality and visi-

bility are important concerns. The smoke from chaparral fires can severely degrade air quality over large areas, above and beyond the poor air quality that already exists on any given summer or fall day in the south coast air basin in southern California. This area already has some of the highest recorded levels of NO_x emissions in the United States (Riggan et al. 1985). Following experimental prescribed fires in 1984, nitrate, ammonium, and sulphate yield increased dramatically in burned watersheds. The magnitude of the increases was strongly correlated with fire severity (Riggan 1985).

NO_x emission factors have been calculated for fires in southern California as well as fires in other vegetation types. The emission factor is a ratio of the concentration of the emission in a smoke plume to the amount of fuel (in kg) burned. Smoke from three chaparral fires in southern California had NO_x emission factors averaging 6.5 g/kg, as compared with an average of 1.9 g/kg for fires in other types of vegetation more removed from urban areas (Hegg et al. 1989). High levels of aerosol nitrate, sulfate, and phosphate have also been measured in smoke from chaparral fires (Cofer et al. 1988; Hegg et al. 1987). While the contribution of fire-derived NO_x emissions is only a small part (probably less than 1%) of the total NO_x emissions in urbanized areas such as the Los Angeles basin, the episodic nature of fire emissions can lead to substantial impacts on regional air quality (Hegg et al. 1989). In addition to production of nitrogen oxides during combustion, fire in chaparral also apparently greatly stimulates biogenic production of nitric oxide and nitrous oxide from the soil, an effect that can persist for at least six months after a fire (Anderson et al. 1988).

On a global basis, fire is an important contributor to emissions of greenhouse gases, such as CO_2 , methane, ammonium, and chloro-fluorocarbons. Although the ecosystem impacts are probably minor, the production of particulate matter in smoke from chaparral fires is of great concern to managers who must minimize impacts of fire on airborne particulates and on visibility (Franklin and Riggan 1989). The only available data on particulate emission characteristics derive from prescribed fires in southern California in December 1986 (Ward and Hardy 1989; Einfield et al. 1989; Cofer et al. 1988). Emission factors and particle-size distributions from these fires were comparable to those for flaming combustion of other wood fuels (Einfield et al. 1989; Ward and Hardy 1989).

FIRE EFFECTS ON EROSION/STREAMFLOW

Much of California chaparral occurs on extremely steep terrain, where slopes in excess of 100% (45°) are not uncommon. The already existing conditions of very steep, tectonically active slopes combine with the fire-induced removal of vegetation and litter, and the reduction in soil water storage capacity to produce erosion rates which may be several orders of magnitude greater than in unburned chaparral (Anderson and Trobitz 1949; Rowe et al. 1954; Wells 1981; Wells 1987).

In unburned chaparral the steep slopes are stabilized by the presence of vegetation whose canopies shield the slopes from wind and rain and whose roots anchor the soil and provide pathways for deeper water penetration. Dry ravel, unconsolidated material that moves down slope from the action of gravity, is common in unburned chaparral (Anderson et al. 1959). In fact dry ravel is only second in importance to landslides in moving material, according to a sediment budget constructed by Rice (1974). It can account for half of all erosion in some areas of southern California (Anderson and Trobitz 1949). This process is greatly accelerated by fire. Krammes (1960) noted postfire dry season erosion had increased 8 to 34 times the prefire levels. Accelerated movement of dry material during and immediately after fire has been witnessed by many observers. In one instance, the formation of debris cones, so large as to block the road, was noted within a week of the passage of a fire through the area (Krammes 1960).

Wells (1985) conducted artificial rainfall experiments in conjunction with a prescribed burn to determine the timing and magnitude of postfire erosion. His experiments confirmed the tremendous impact fire had on postfire wet and dry erosion. Dry erosion occurring during the fire was nearly two orders of magnitude greater than that which occurred during a preburn rainfall event. A postburn sprinkle led to daily debris production over 180 times greater than the preburn sprinkle.

The mechanism of this accelerated movement is not entirely clear. The removal of physical barriers such as stems and litter through combustion contributes in part. DeBano et al. (1979) note that destruction of organic matter by combustion may begin at temperatures above 100°C with subsequent decreases in soil cohesiveness. Duriscoe and Wells (1982) noted shifts in soil particle size occurring at soil temperatures above 400°C. Apparently the shift is from clay to sand and silt. They suggest that this shift could lead to more erodible surface soils since the cohesive nature of the clay fraction has been eliminated. Burned

slopes are also more vulnerable to rainsplash erosion from the impact of raindrops on unprotected soil (Brock and DeBano 1982).

Heating of the soil by fire can also lead to the formation of a water repellant soil layer. The presence of organic matter, soil texture, and fire intensity are all important factors in determining the severity of water repellancy. The substances causing water repellancy were found to be aliphatic hydrocarbons derived from the partial decomposition of plant material (DeBano 1981). The effect of fire on the formation of the water repellant layer is dependent on the duration and the intensity of the heat pulse. If soil containing organic matter is heated to between 204°C and 260°C for 15 min, water repellancy is intensified (DeBano and Krammes 1966). At temperatures above 370°C and duration of 15 min or longer, the water repellant layer is destroyed. As heating duration is increased, intensity needed to destroy the water repellant layer is reduced (DeBano 1981). However, even if surface temperatures exceed those needed to destroy the layer, if volatilized material is moving through the soil, it will eventually come to a cooler layer where it will condense. This leads to a surface layer that is wettable and a lower layer (location determined by fire intensity) that is water repellant.

With the occurrence of rainfall, the effect of the water repellant layer is observed. The presence of this water-repellant layer can reduce the effective storage capacity of the soil by 20 times or more (Rice 1974; Wells 1981). This makes the slopes much more susceptible to sheet and rill erosion. The formation of a rill network on a burned slope is an especially interesting process as described by Wells (1981). With the reduced storage capacity of the soil, as rain begins to fall, pore space between soil particles quickly fills with water. This leads to a build-up of pore pressure and a reduction in shear strength. When the shear strength of the soil is ultimately reduced below that of the shear stress of gravity, a failure occurs and the soil begins to slide. This is the beginning of a domino-like effect of successive failures downslope, eventually developing into a miniature debris flow. These small channels lined with water-repellant soil speed the movement of water and debris downslope (Fig. 4). Eventually the flow cuts below this layer to wettable soil and the flow is diminished.

The debris flows that occur in the early storms after a fire are on a larger scale. These flows of mud, rock, and debris may wreak havoc on communities and structures below. One of the first reported flows of this type occurred over 50 y ago when a New Year's Eve rain storm produced a wall of mud and



Fig. 4. With the formation of a water repellent layer in the soil, reduced soil water holding capacity leads to small onslope debris flows and the formation of rill-networks as pictured above.

boulders that roared through four foothill communities, killing 34 people and destroying 200 houses (Kraebel 1934). The disastrous flow originated on slopes that had burned in a 2000-ha fire in the previous November. Since that time many such flows have been recorded. According to Wells (1987) debris flows are caused by the combined effects of two erosion processes that are greatly accelerated by fire: dry ravel and extensive rill networks. Dry ravel serves to load stream channels with sediment and rill networks move water off the slopes more rapidly. With enough water the sediment in the channels is mobilized. Weirich (1989) measured debris flows that reached sediment concentrations of 60% by weight and speeds of 4-8 m/s. Wells (1987) reports that in February 1978 a debris flow 5-6 m deep descended on the town of Hidden Springs, destroying the town and killing 12 people. This occurred after a 12 km² fire intensely burned a 99-y-old watershed the previous autumn.

Little is known about the effects of fire intensity on the magnitude of postfire erosion and streamflow. Prescribed fires conducted on the San Dimas Experimental Forest in the San Gabriel Mountains in southern California in 1984 provided an opportunity to explore the effects of different fire intensities on postfire erosion and streamflow. Areas were burned under moderate and high intensity conditions. High intensity fires were created by cutting brush and allowing it to dry out before fires were conducted. Riggan (1985) noted water yield doubled from unburned to moderately burned watersheds and was nine times greater on intensely burned watersheds. Sediment production nearly tripled from moderately burned to intensely burned watersheds. Sediment production from unburned watersheds was near zero. These results suggest that prescribed fire may be used effectively to manage sediment and water production from chaparral watersheds.

SUMMARY

Fires are a common occurrence in chaparral and a given area may burn as often as every 20 y under extreme conditions. Chaparral shrubs are able to recover from recurrent fires and return to a site either through their ability to sprout from underground lignotubers or through germination of soil stored seeds. In addition, many herbaceous species (either fire-stimulated or opportunistic) dominate the first few postfire years. Although species composition may be greatly affected by fire intensity and postfire conditions, chaparral systems appear resilient to a wide range of fire frequencies.

Animals that exist in mature chaparral may be eliminated by fire but slowly re-invade as the canopy closes and environmental conditions become favorable for their existence. Other more typically grassland type rodents may thrive in the postburn chaparral environment until the canopy begins to close. Burrowing rodents may survive fire by retreating to their burrows, while reptiles are minimally affected by fire. Birds are affected through reduction in their habitat while large mammals can flee the fire and roam the postburn site with its abundance of herbs, seedlings and young sprouts.

Fire also causes changes that greatly increase erosion rates from chaparral watersheds. In addition to removal of small organic debris dams formed by the stems of shrubs and ground litter, fire causes changes in soil structure. These changes lead to acceleration of movement of soil and debris from the slopes to the channels in both the dry and wet season. Even small rainfall events in the first year after fire can lead to

movement of large quantities of material that can impact downstream residences and other structures.

Fire causes loss of nutrients from the site through volatilization and erosion. The replacement mechanisms for these limiting nutrients, especially nitrogen, are not well understood. Since many chaparral sites exist adjacent to large urban areas, deposition of pollutants into the ecosystem continues during the intervals between fires. The mobilization of these pollutants in smoke during the fire, and streamwater in the winter after the fire, can have negative impacts on local air and water quality.

Although there is debate over natural fire intervals in chaparral, some evidence suggests that intervals in southern California may have been longer than the current interval. In addition the season of fire is believed to have moved to later in the year from the summer to fall. The impacts of the shortened fire cycle and the change in season are not known. To complicate the matter, management practices may have led to changes in size and intensity of fires. Some believe the fire suppression policy that has been in effect for many years has served to decrease the number of fires but increase the size. Perhaps more important than the debate over how natural fire patterns have been altered, is the question of how chaparral can be managed in the most ecologically sound manner, given the present circumstances.

With the encroachment of urban areas into the wildlands, problems of balancing protection of the ecosystem with protection of society have become more complex and more expensive. A 1981 survey (Hunter 1981) stated annual losses and suppression costs from chaparral fires amounted to over \$50 million/y. Proximity to urban areas has greatly increased the incidence of arson. Man's increasing interaction with the chaparral ecosystem points to the need for research to increase our understanding of the processes taking place in the system and the adaptations which make the existence of the system possible. Researchers are continuing their efforts to understand the chaparral ecosystem. Studies are continuing on the impacts of fire on air quality, erosion processes, nutrient cycling, animal and plant ecology, and the urban/wildland interface. Through further investigations, we hope not only to gain more basic knowledge of the system but also to provide managers with better information on which to base their decisions.

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