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The Influence of Insect Pests and Pathogens on Sierra Forests

ABSTRACT

Currently, Sierra Nevada forests have high levels of mortality caused by bark beetles infesting trees stressed by drought, fire, overly dense stands, and pathogens. Fuel loads and fire hazard are high. Past logging and fire exclusion practices are partially responsible for this situation. Mitigative restoration requires thinning overly dense stands, primarily by controlled burning in parks and wilderness areas, combined with mechanical thinning and other selective tree-cutting practices elsewhere. Care will have to be taken to avoid creating more pest problems than are remedied, and some insect and disease activity should be tolerated as part of the restorative process. Failure to act may lead to continuation and perhaps worsening of present conditions. Widespread restoration should lead to sustenance of the biodiversity and productivity of these forests.

INTRODUCTION

Over the last decade, Sierra Nevada forests have sustained widespread, severe levels of tree mortality associated with a protracted drought. Most of the common conifer species and forest types were affected on both the western and eastern slopes of the range. Outbreaks of bark beetles were the proximate cause of tree mortality, affecting trees already stressed by drought and chronically weakened by pathogens and other agents (U.S. Forest Service [USFS] 1994). In California's Mediterranean climate, such outbreaks are not rare. Forest pest condition reports indicate that they have occurred somewhere in the Sierra Nevada and contiguous ranges in nearly every decade of this century (USFS 1917–49; California Forest Pest Council 1951–93). Climatological and tree-ring studies have established that recurrent droughts have been a long-standing feature of the Sierra Nevada climate (Fritts and Gordon 1980; Fritts et al. 1979; Graumlich 1993).

Large and diverse communities of insects and microbes influence the structure, composition, and function of Sierra Nevada forests. Most of these insects and microbes are indigenous, and their effects are considered beneficial and necessary for forest health (e.g., pollination, nutrient cycling). A few, however, are considered key pest species because they can cause widespread and severe injury or mortality to the conifer species that are major components of Sierra Nevada forests and thus can adversely affect management goals. Several alien species are also considered key pests, either currently or potentially, based on the same criteria. Taken together, these key pest species are omnipresent in the Sierra Nevada, affecting virtually every major tree species in every forest type (Furniss and Carolin 1977; Scharpf 1993). Their effects have commonly been perceived as negative, and mitigation methods have been developed and applied. Mitigation has sometimes not been successful or cost-effective, depending to some degree on whether it was undertaken before (preventive) or during (remedial) a pest outbreak. As our understanding of forest ecosystem functioning increases, however, we are reassessing the roles of key pest species in forest health. Some of their effects may be viewed in the future as positive and even necessary for forest sustainability over the long term. Indeed, because many insects and pathogens can seriously injure only those trees and forests already under some form of environmental stress, epidemics of these agents are increasingly recognized as symptoms, rather than causes, of poor forest health (Wickman 1992).

Although bark beetle outbreaks in the Sierra Nevada are

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commonly viewed as primarily drought-related, the severity of recent tree mortality has raised the question of whether there might be other important contributing factors. Attention has focused on whether the health of Sierra Nevada forests has declined as a result of human influences in the present century. In particular, it is believed that fire suppression and past logging practices have resulted in overly dense understories of the more shade-tolerant conifers, such as incense cedar, and the drought-susceptible white fir. In such stands, even species that are normally more drought-resistant, such as ponderosa pine, may suffer water stress and become susceptible to bark beetles during droughts. With their heavy complement of dead and dying trees and "fuel ladders" of highly flammable foliage, such stands are also highly susceptible to stand-destroying wildfires. Other factors may be contributing as well to this environmental stress and decline in forest health. Air pollution, urbanization, past logging practices, and invasion of alien pests (including insects and pathogens) are prominent among the factors being examined in this context. Nor has the possibility been ruled out that natural or anthropogenic (human-related) climatic shifts are causing changes in forest composition and structure.

Widespread concerns over the perceived decline in the health of Sierra Nevada forests have led to informal proposals of practices to mitigate and reverse current trends. Most of these proposals have the stated or unstated goal of restoring forest composition and structure to approximate those before settlement of the country by people of European origin. Inherent in this is the belief that restoration and maintenance of presettlement forests provide the best chance of sustaining these forests and their biodiversity in a reasonably intact and healthy state. It has been hypothesized that presettlement forests contained more old-growth (late-seral-stage) stands and that under extant fire regimes these stands were not choked with understory but rather more open and parklike. Unfortunately, because of the paucity of historical descriptions there is considerable uncertainty over just what these forests were like. There is also concern that some restoration and maintenance practices, if not judiciously applied, may have unforeseen side effects and cause more problems, especially with insects and pathogens, than they solve.

This chapter focuses on key insect pests and pathogens, both indigenous and alien, affecting major conifer components of Sierra Nevada forests. This focus was selected because conifers are the dominant vegetation in Sierran forests and therefore have the largest influence on the composition and functioning of these ecosystems. Moreover, many of the conifers are commercially valuable. Consequently, much more is known about the insects and pathogens affecting them than about pests with nonconifer hosts. Within this focus, the chapter describes current and past effects of key insects and pathogens on forest composition, structure, and functioning, as well as interactions with other environmental factors such as weather, fire, logging, urbanization, and air pollution. Critical knowledge gaps and research opportunities are identified. Finally, mitigation methods are described and evaluated in light of known or potential effects, and the potential results of taking no action or continuing present practices are evaluated. Particular attention is paid to potential effects on development and maintenance of old-growth (late-seral-stage) stands.

KEY QUESTIONS

1. What are the current conditions and trends in Sierra Nevada forests? It is necessary to describe current patterns and trends in forest conditions and effects of insects and pathogens as the starting point for assessing the effects of any changes in biotic and environmental factors, including human impacts, that may occur in the future.

2. What are the key insect pests and pathogens affecting Sierra Nevada forests? To understand the role of these agents in Sierra Nevada forests it is necessary first to identify which species have historically had major impacts and why (host tree species attacked, potential for spread, effects on the forest, history of outbreaks).

3. What are the interactions of key insect pests and pathogens with other biotic and environmental factors known to be important influences on these forests? Drought, fire, logging, air pollution, and urbanization have current or potential major influences on Sierra Nevada forests. Existing and potential interactions with these factors thus must be described in the context of the historical record in order to understand and predict the role of these agents.

4. What are the effects of key insect pests and pathogens on the composition and structure of these forests? To understand the role of these agents in influencing current conditions and to predict their effects in the future it is necessary to describe their effects in the past. Because Sierra forests fall into distinct and diverse forest types, it is necessary to describe the effects of these agents by forest type.

5. What mitigation methods are available? To explore how to mitigate current and future effects of key insect pests and pathogens it is necessary to examine mitigation methods currently available and assess their efficacy in the past.

6. What major knowledge gaps exist? It is necessary to identify major knowledge gaps in order to understand the uncertainties inherent in present assessments and predictions and to indicate the kinds of research and monitoring needed to fill these gaps.

7. How will key insect pests and pathogens respond to various management scenarios? Because past, current, and future environmental, biotic, and human conditions will constrain future management, certain management scenarios are more likely to be implemented in the future. It is therefore useful to explore probable responses of key insect pests and pathogens to these scenarios.

METHODS

The scientific and forest management literature, published and unpublished reports on pest conditions and on control projects compiled by federal and state agencies, and national forest management plans were used to identify key insects and diseases, their effects and interactions with other environmental factors, and their past and present effects on forest conditions. Key issues and relevant references were identified by means of a workshop convened in Davis, California, January 19–20, 1995, in which approximately twenty scientists offered their research findings and expert opinions on the subject. The same sources were consulted to identify mitigation methods and to assess their efficacy. Primary emphasis was given to reports from the Sierra Nevada, with reports from the contiguous southern Cascades and Modoc Plateau playing a supplementary role. All of this information was collated to develop models predicting the response of these agents to various environmental factors and management scenarios and the resulting impact on the effects of the agents. It was at this stage that major data and knowledge gaps became fully apparent. Except for a few research projects, quantitative data on trees killed by insects and pathogens were limited in time and space to outbreaks, while pest populations and tree mortality in other situations were reported merely as “endemic,” “normal,” or “balanced.” Formal quantitative modeling was therefore abandoned, and primary reliance had to be placed on the development of informal conceptual models.

Assumptions inherent in these methods are all subsidiary to the main one that past interactions among insect populations, pathogen populations, and natural and human-caused environmental factors, and their past effects on forest attributes, are applicable to understanding the future. Observations, however, are limited to the present century. If future trends and ranges of variability in any of these components exceed those of the present century, future forest responses may well be unpredictable. As it was, particular care had to be taken to ensure that qualitative terms used in the past such as endemic or normal were comparable with current definitions. Also, it was necessary to be mindful of biases in the information from earlier decades of the century when forest conditions, management, and utilization differed from those of today. For example, previously only the larger and more commercially valuable conifers (pines) received much detailed attention, while smaller or less commercially valuable species (firs, cedars) were largely ignored.

Sierra Nevada forests and their associated insect pests and pathogens are highly variable because of the variety in their growing sites and histories. It was difficult if not impossible to present this wealth of variety in a report of reasonable length. To achieve this and also provide focus, much variation is covered only briefly, and emphasis is placed on key insect pests and pathogens affecting the important conifers of the major forest types. Key pests were those that have had continuing, widespread, major impacts on Sierra Nevada forests. In general discussions and summaries, the mixed conifer forest type, because of its wide areal extent and because it exemplifies the major problems perceived to be facing Sierra Nevada forests, was emphasized. To be optimally effective, however, management prescriptions must be site-specific and take into account the full range of variation both in these forests and in the insect pests and pathogens affecting them.

CURRENT CONDITIONS AND TRENDS

Currently, Sierra Nevada forests are in the aftermath of the 1987–92 drought. Over the last few years, these forests have sustained catastrophic levels of tree mortality due to drought, fire, disease, and bark beetles. In Sierra Nevada national forests alone, this mortality totaled over two billion board feet of timber by 1993 (California Forest Pest Council 1951–93, for the years 1990 and 1993). Although these losses have occurred throughout the Sierra Nevada, they have been particularly high on the east side of the range, where mortality, mainly of pines and firs, has exceeded 80% of the standing volume in some stands (U.S. Forest Service [USFS] 1994). Mortality has been greatest in overly dense stands, especially those where past logging and/or fire-exclusion practices have promoted tree species susceptible to insects, pathogens, fire, and drought. Wildfires also occurred during the drought, leaving many scorched trees susceptible to insects. Exacerbating these losses are the extreme fire hazards resulting from the dead and dying trees. Although levels of insect-caused tree mortality are expected to subside with the cessation of the drought, the accumulation of fuel in the dead trees and overly dense stands will cause the fire hazard to remain critical for some years. Adding to this threat are potential negative impacts from increased logging, inappropriate management practices, urbanization, air pollution, and invasion of alien insects and pathogens.

KEY INSECT PESTS AND PATHOGENS

Among the large and diverse communities of insects and microbes occurring in Sierra Nevada forests, relatively few are considered key pests and pathogens that have had major impacts on current as well as past forest conditions (USFS 1994). Virtually all of the key insect pests and pathogens are indigenous, but the threat from alien species is increasing, and some of these are considered potential key pests.

Indigenous Species

Insect pests and pathogens currently and historically having major impacts on Sierra Nevada forests are listed by host tree and forest type in table 45.1. All of these agents are indigenous except for white pine blister rust.

Bark beetles have the largest impacts, with sporadic outbreaks causing widespread tree mortality in virtually all major conifers and forest types. These beetles are a continuing source of mortality, but at lower levels, during nonoutbreak periods. Western pine beetles and mountain pine beetles are the major killers of ponderosa pine, and the latter are the major killer of sugar, lodgepole, and most other pines in the Sierra Nevada except for Jeffrey pine, whose major killer is the Jeffrey pine beetle. To a lesser extent, several species of pine engraver beetles also damage pines, but mortality is usually limited to smaller trees or tops of larger trees. The fir engraver beetle is the major killer of white fir and red fir, as the Douglas fir beetle is of Douglas fir, although outbreaks of the latter are rare in the Sierra. Trees killed by bark beetles are also often infested with other bark and timber beetles, but these are usually not considered the primary cause of death.

Having lesser impacts are defoliator insects, outbreaks of which can reduce tree growth and sometimes cause tree mortality if they are persistent or if the defoliated trees are rendered susceptible to bark beetles; noteworthy in this regard are Douglas fir tussock moth (Orygia pseudotsugata), pandora moth (Coloradia pandora), white fir needle-miner (Epinotia meritana), and lodgepole needle-miner (Coletechnites milleri). Effects of these defoliators have been more limited temporally and spatially than those of the key insect pests as defined here, and none of these defoliators is currently reported to be in outbreak status in the Sierra Nevada. Thus they were not considered key insect pests for the purposes of this report. However, their effects on Sierra Nevada forests will require reassessment should their outbreaks become more widespread and protracted, as they have in forests of eastern Oregon and Washington (Wickman 1992). Similarly, a variety of insects infest regeneration (seedlings and saplings) but do not usually cause serious impacts except in limited situations, such as plantations. If more large plantations are established in the aftermath of large forest fires, however, these insects may become key pests as defined in this report.

Pathogens having major impacts by killing trees on their own and by predisposing them to bark beetles are the root disease fungi, mistletoes, and white pine blister rust. Of the fungus-caused root diseases, the most important are annosus root disease, armillaria root disease, and black-stain root disease. Taken together, these root disease fungi infect most of the major conifers in Sierra Nevada forests. Spread is by aerial spores, subterranean root contacts, or, in the case of black-stain, bark beetle vectors. Other major pathogens are the dwarf and true or leafy mistletoes, various species of which weaken and sometimes kill, either by themselves or in concert with bark beetles, most of the conifer species of the Sierra Nevada. The sticky seeds are spread either by hydraulic bursting of fruits (dwarf mistletoes) or by birds (true mistletoes).

Alien Species

One introduced pathogen, white pine blister rust, is having a major impact on sugar pine throughout most of its range in the Sierra Nevada and is now spreading to other white pines (western white and whitebark pines) in the subalpine forests

TABLE 45.1

Key insect pests and pathogens and major conifer hosts in Sierra Nevada forests (USFS 1994).

Species	Host Trees	Forest Types
Western pine beetle *(Dendroctonus brevicomis)*	Ponderosa pine	Ponderosa pine, mixed conifer
Mountain pine beetle *(Dendroctonus ponderosae)*	Sugar pine, lodgepole pine, ponderosa pine, western white pine	Ponderosa pine, mixed conifer, red fir, subalpine conifer
Jeffrey pine beetle *(Dendroctonus jeffreyi)*	Jeffrey pine	Jeffrey pine, mixed conifer, red fir
Douglas fir beetle *(Dendroctonus pseudotsugae)*	Douglas fir	Mixed conifer
Pine engravers (*Ips* species)	All pines	All
Fir engraver beetle *(Scolytus ventralis)*	White fir, red fir	Mixed conifer, red fir
Annosus root disease *(Heterobasidion annosum)*	All conifers	All
Armillaria root disease *(Armillaria ostoyae)*	All conifers	All
Black-stain root disease *(Leptographium wageneri)*	Ponderosa pine, Jeffrey pine, Douglas fir, single-leaf piñon pine	Mixed conifer, Jeffrey pine, piñon-juniper
White pine blister rust *(Cronartium ribicola)*	Sugar pine, western white pine	Mixed conifer, red fir, subalpine conifer
Dwarf mistletoes (*Arceuthobium* species)	All conifers	All
True mistletoes (*Phoradendron* species)	White fir, incense cedar, western juniper	Mixed conifer, piñon-juniper

of the Sierra. First reported in California in 1929, this rust fungus infects stems of hosts, weakening them and predisposing them to bark beetles. Damaging infections of sugar pine are now so common and widespread that there is concern that sugar pine might not survive as a significant component of Sierra Nevada forests in the future.

Other alien species have been identified as major potential pests should they become established in the Sierra Nevada. Pine pitch canker, caused by an introduced pathogenic fungus (Fusarium subglutinans f. sp. pini), infects Monterey and bishop pines on the California coast. It kills twigs, branches, and tops, weakening trees and making them susceptible to bark beetles. Spread is primarily by bark and cone beetles. Except for pruning and disposing of infected material, methods of mitigation have not yet been developed. In coastal California, this disease has been found in ponderosa pine, a major component of Sierra Nevada forests. Although it has not yet been reported in the Sierra Nevada, there is concern that the disease may spread inland by transport of infected Christmas trees, firewood, or logs.

Originally from Europe, the gypsy moth (Porthetria dispar) is an introduced defoliator of oaks and other hardwoods in the northeastern United States, where outbreaks have caused widespread defoliation. Established infestations have not yet been reported in the Sierra Nevada, but several newly established infestations have been eradicated by insecticidal spraying elsewhere in California. Transcontinental spread is mostly by cocoons and egg masses adhering to vehicles or cargo. Feeding trials indicate that oaks and other hardwoods indigenous to the Sierra Nevada are suitable hosts for the gypsy moth caterpillar. Introduction of the Asian form of this moth, not yet reported as established in North America, might be particularly damaging to Sierra Nevada forests, as the female moths fly (the European females are flightless) and feed on some conifers as well as hardwoods. Assessments have indicated that the risk of introducing the Asian form is particularly high if proposed large-scale importations of Siberian logs occur (USFS 1991). Forests of western North America, including those of the Sierra Nevada, are considered potentially susceptible to a number of serious forest pest insects and pathogens from eastern Siberia because the Bering land bridge connection was recent in geological time, and this suggests close affinities with Siberian forests. All such risk assessments are hampered, however, by the impossibility of assessing all potential pests, and historically it has often been an unsuspected agent, such as chestnut blight devastating indigenous chestnuts in eastern North America, that has proved most destructive. This is particularly sobering in light of contemplated increased importations of raw logs and wood into the United States from other parts of the world.

PEST INTERACTIONS WITH BIOTIC AND OTHER ENVIRONMENTAL FACTORS

Biotic Complexes

The key insect pests and pathogens affecting Sierra Nevada forests usually function as members of biotic complexes in which the members are highly interactive (USFS 1994). Frequently, but not always, infection by one or more pathogens weakens the host tree, making it susceptible to bark beetles. Common complexes are root disease / bark beetles, mistletoe / bark beetles, and root disease / mistletoe / bark beetles. Membership in the complexes varies with changing environmental conditions. In years during and immediately after drought, increasing percentages of trees are killed by insects (primarily bark beetles) only, while percentages of trees killed by insects and pathogens are initially high and fall steadily (table 45.2). This indicates that trees already weakened by pathogens tend to be killed early in the drought, whereas later in the drought most trees are killed by bark beetles only. Populations of all of these insects and pathogens are primarily controlled by the number of susceptible host trees. Any factor that increases the latter will usually produce population increases or even epidemics of the former. In California's Mediterranean climate, drought is probably the most important predisposing factor (Ferrell and Hall 1975; Ferrell et al. 1994; Miller and Keen 1960). But overly dense stands, fire, logging, urbanization, air pollution, snow breakage, windthrow, and flooding can also weaken trees and cause them to become susceptible to pathogens and insects (Furniss and Carolin 1977; Scharpf 1993). Like biotic complexes, environmental factors can be highly interactive. Fire, for example, can exacerbate the effects of drought in increasing susceptibility of trees to insects and pathogens.

Site and Stand Factors

Overly dense forest stands are an important cause of tree susceptibility to insects and pathogens (Ferrell et al. 1994; Oliver

TABLE 45.2

Agents causing tree mortality during and after the 1975–77 drought in twelve northern California national forests (USFS 1994).[a]

	Annual Percentage of Trees with Agents			
Agents	1976	1977	1978	1979
Insects only	24	43	59	82
Pathogens only	1	2	1	1
Insects and pathogens	69	53	40	14
Other	6	2	0	3

[a]The national forests studied include those in the Klamath Province as well as those in the Sierra Nevada.

1995; Slaughter and Parmeter 1989; Scharpf and Parmeter 1976). Intense tree-to-tree competition in overly dense stands tends to slow growth and decrease resistance of trees. Spread of insects, disease, and fire is also enhanced in dense stands. Overly dense stands are a major cause of tree mortality in Sierra Nevada forests during both drought and nondrought periods. This is evident if average annual mortality over a decade or more is expressed as a percentage either of levels of growing stock (total stem volume) or of growth. Expressed either way, tree mortality tends to be higher in forests with higher levels of growing stock (stand densities), especially if growth, expressed as a percentage of growing stock, is also low (table 45.3).

Stand composition and quality of the growing site interact with stand density in their effects on forest susceptibility to insects and pathogens. Sites have specific capabilities for the amount of forest biomass they can grow, and, when that level is exceeded, mortality of the trees will eventually occur, especially during periods of drought. There is not an absolute level for any site, but general ranges do exist for a particular quality of site. Poorer sites are usually drought-prone, because they occupy steep slopes with hot, dry exposures and thin, rocky or coarse-textured soil. Typical examples of such sites are steep canyon walls and ridgetops. Over the long term, these sites are able to support only sparse forest stands and have a higher risk of tree mortality, especially from mistletoe/root disease/bark beetle complexes, during both drought and nondrought periods. These effects are particularly pronounced in lower-to-middle-elevation forests on both the western and (especially) the eastern slopes of the Sierra, which tend to be hot and dry (Ferrell 1986; USFS 1994). Effects of stand density and site quality are compounded by the influence of stand composition. For example, during the recent (1987–92) drought, mortality was particularly high in mixed conifer and east-side pine stands that had been invaded by drought-sensitive white firs (Ferrell et al. 1994; USFS 1994).

Drought

Recurrent droughts are characteristic of the Sierra Nevada climate. Summers are usually hot and dry, with the bulk of the precipitation occurring in winter, much of it as snow. But in addition to the dry summers, there have been droughts of one or more years' duration in nearly every decade of this century (Graumlich 1993). Tree-ring studies have established that, compared to weather over the previous two centuries, however, weather during the present century has been relatively moist, without the decades-long droughts that occurred earlier (Fritts and Gordon 1980; Graumlich 1993). Records in this century indicate that increases in tree mortality caused by bark beetles are often triggered by droughts (table 45.4). Increased tree mortality may continue for one to several years after the return of normal precipitation (table 45.5). Increased mortality usually occurs first at the lower and middle elevations on both western and eastern slopes of the range and spreads to the upper elevations only if the drought is protracted (California Forest Pest Council 1951–93). During droughts, lack of spring precipitation has a particularly large influence, not only by increasing the susceptibility of the trees, as indicated by their rates of growth and beetle-caused mortality (figures 45.1–45.3), but also probably by aiding dispersal of and host selection by the flying beetles.

Fire

Recurrent fires, particularly during droughts, are also characteristic of the Sierra Nevada (Swetnam 1993), although their frequency and effects have varied temporally and spatially (Martin 1982; Pitcher 1987; Parsons and DeBenedetti 1979; Taylor and Halpern 1991). Trees with scorched trunks or crowns can die directly from the injury (Wagener 1961), or they can become susceptible to tree-killing bark beetles and suitable for beetle reproduction, but this is highly dependent on the severity and pattern of scorching (table 45.6). Trees badly scorched are readily infested by bark beetles but may not be optimal for bark beetle reproduction, and those only lightly scorched may not be rendered susceptible to beetle attack. If the fire is not during a drought, usually only a sharp spike of tree mortality, confined largely to scorched trees, occurs, and no protracted bark beetle outbreak ensues (Miller and Keen 1960). During a drought, however, beetles emerging from scorched trees can spread to surrounding stands and

TABLE 45.3

Endemic levels of tree mortality in relation to growing stock and growth in six national forests in the Sierra Nevada (Bolsinger 1980).[a]

National Forest	Growing Stock (ft^3/acre)	Annual Growth as a Percentage of Growing Stock	Annual Mortality: As a Percentage of Growing Stock	Annual Mortality: As a Percentage of Growth
Eldorado	3,670	2.2	0.1	4.8
Inyo	1,830	1.4	0.1	7.6
Plumas	3,690	1.6	0.2	10.2
Sequoia	3,860	1.1	0.2	14.3
Stanislaus	4,460	2.0	0.2	7.4
Tahoe	4,380	1.7	0.2	12.2

[a]The Sierra National Forest is excluded because it was inventoried during the 1975–77 drought, when epidemic mortality occurred.

TABLE 45.4

Increased tree mortality in relation to subaverage annual precipitation in seven national forests in the Sierra Nevada, 1917–49 (USFS 1917–49).

		Increased Tree Mortality (More Than 0.2 Trees/Acre Killed) by National Forest[b]						
Year	Subaverage Precipitation[a]	Eldorado	Inyo	Plumas	Sequoia	Sierra	Stanislaus	Tahoe
1917	√			√				
1918	√			√				
1919	√	√	√		√	√	√	√
1920	√	√	√		√		√	√
1921				√				
1922	√		√	√		√	√	
1923	√	√	√	√		√	√	√
1924	√			√	√			√
1925	√	√			√	√	√	
1926	√		√			√	√	√
1927	√		√					
1928	√							
1929								
1930	√							
1931								
1932	√	√				√		√
1933	√	√	√			√		√
1934	√	√				√		√
1935	√	√						√
1936	√	√						
1937	√	√		√				
1938	√			√				
1939								
1940								
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1945								
1946								
1947								
1948								
1949								

[a]From the statewide precipitation index by Fritts and Gordon (1980). A blank indicates that precipitation was at or above average that year.
[b]A blank indicates that mortality was at endemic levels that year.

contribute to the developing beetle outbreak. The beetle aftermath of forest fires, then, tends to be highly variable, depending on the intensity and pattern of the fire and the local levels of bark beetle populations. There is concern, however, that bark beetles, especially the red turpentine beetle, which is attracted to and readily reproduces in scorched pines, may become more of a problem if prescribed burning becomes widely used. This beetle usually does not kill trees on its own but rather weakens them and renders them more susceptible to other, tree-killing, bark beetles. Bark beetle infestations may be a serious problem especially following the initial reintroduction of fire into stands with high fuel levels due to long-term fire exclusion. In such stands, the number of fire-scorched, beetle-susceptible trees is expected to be greatest. Some damage to trees may be avoided by reducing fuel, for example, by pruning fuel ladders before the prescribed burning is started. Then scorching of trees should be lessened, and less beetle-susceptible host material will be produced.

Logging

Logging operations have been conducted in the Sierra Nevada ever since settlement began in the mid-nineteenth century. Levels and patterns of logging have, however, changed greatly over time with changing methods, technology, markets, and forest management (Laudenslayer and Darr 1990). Early logging concentrated mainly on the largest trees of the most commercially valuable species (a procedure called high-

TABLE 45.5

Tree mortality in relation to precipitation during and after the 1975–77 drought in twelve northern California national forests (USFS 1994; U.S. Weather Bureau 1977–80).

	1977	1978	1979	1980
Number of dead trees (millions)	4.5	5.8	1.1	0.9
Trees per acre killed	.71	.92	.17	.06
Percentage of normal precipitation	20–38	93–205	79–138	90–148

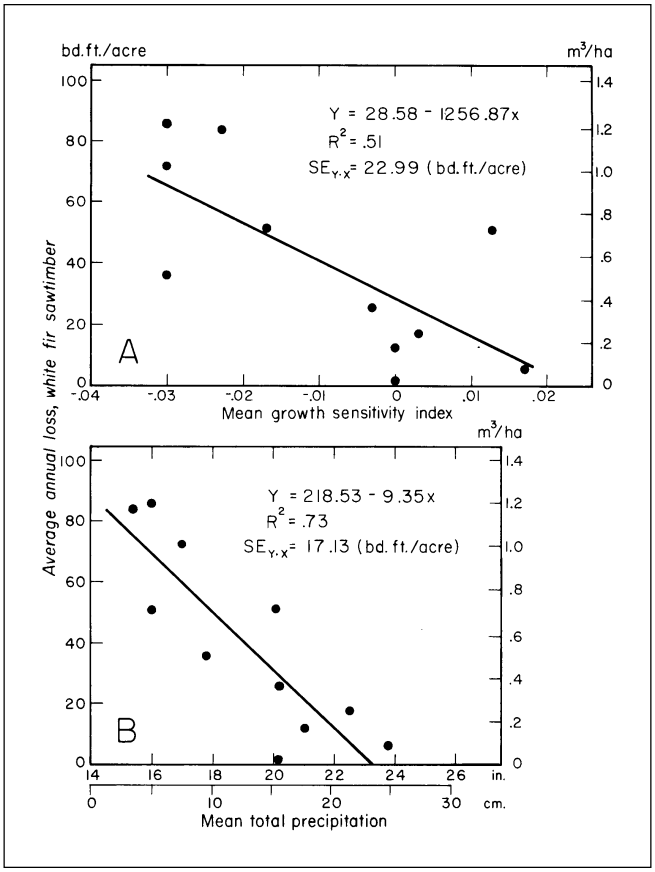


FIGURE 45.1

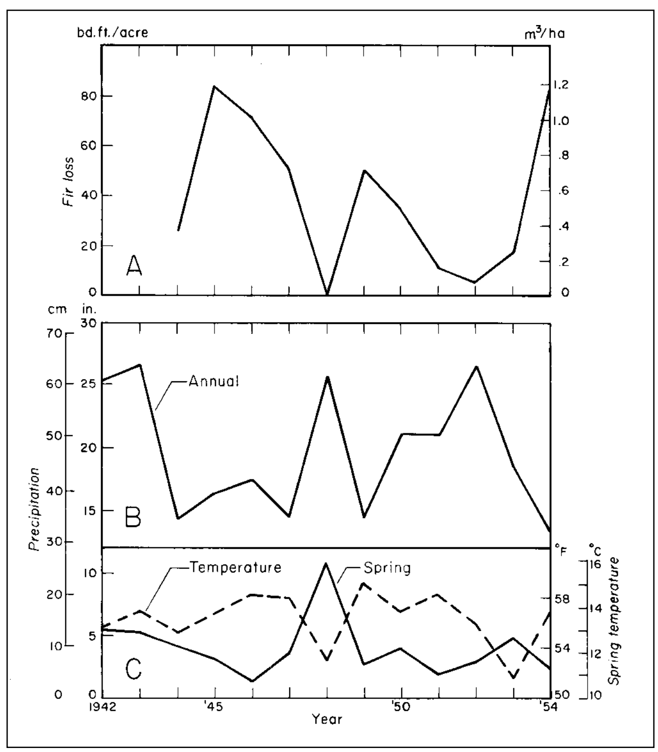
Relationship between white fir mortality in California caused by the fir engraver beetle and *a*, tree growth sensitivity index, which measures acceleration (>0) or deceleration (<0) of tree growth over the past two years; and *b*, average annual precipitation for the years 1944–54 (Ferrell and Hall 1975). The curve is the average of the levels shown.

grading). As readily accessible stocks of the most desirable trees became less available, foresters began to look toward husbanding this resource. They perceived, however, that this was not possible under prevailing mortality rates of the highest-value trees because many were old, diseased, and highly susceptible to bark beetles. To try to harvest these trees before they were killed by beetles, forest entomologists developed risk-rating systems for identifying the trees most likely to die soon (Keen 1936; Salman and Bongberg 1942; Ferrell 1989). The object was to cover the forest quickly with a light cut, removing the high-risk trees before they could be killed by beetles and thereby reducing tree mortality rates and maybe lowering beetle population levels as well. This risk-cutting was successful, particularly in east-side pine stands. Harvesting trees before they became infested by bark beetles reduced tree mortality rates for periods up to twenty-two years (Wickman and Eaton 1962), but it did not produce large volumes of timber for the market. With the increased market demand and improved harvesting and replanting technology of the 1950s, foresters began to implement intensive or high-yield management, based on heavier overstory removal cuts or clear-cuts to convert the old growth to younger, even-aged stands capable of producing higher yields of timber.

Each phase of logging had both positive and negative effects on forest health as influenced by insects and pathogens. High-grading, being essentially a single-tree selective cut, tended to favor shade-tolerant species such as firs and cedars at the expense of the more shade-intolerant and drought-resistant pines. Many of the high-graded trees were high-risk trees but others were still vigorous and among the best seed trees. Risk-cutting, also being a single-tree selection system, also tended to favor the drought-sensitive species, but to a lesser extent than high-grading, because the high-risk trees that were cut were not usually the best seed trees. Both of these single-tree selective cutting practices tended to lower the mortality rates of large, valuable pines. They may also have lowered the rates at which understory trees became infected by dwarf mistletoes by reducing the number of infected overstory trees, which are an important infection source (Hawksworth 1961). However, the promotion of a dense, drought-sensitive understory has increased the susceptibil-

FIGURE 45.2

The annual level of *a*, fir mortality caused by the fir engraver and round-headed fir borer, varied inversely with *b*, the levels of total precipitation, and *c*, the levels of spring precipitation and mean air temperature (Ferrell and Hall 1975).



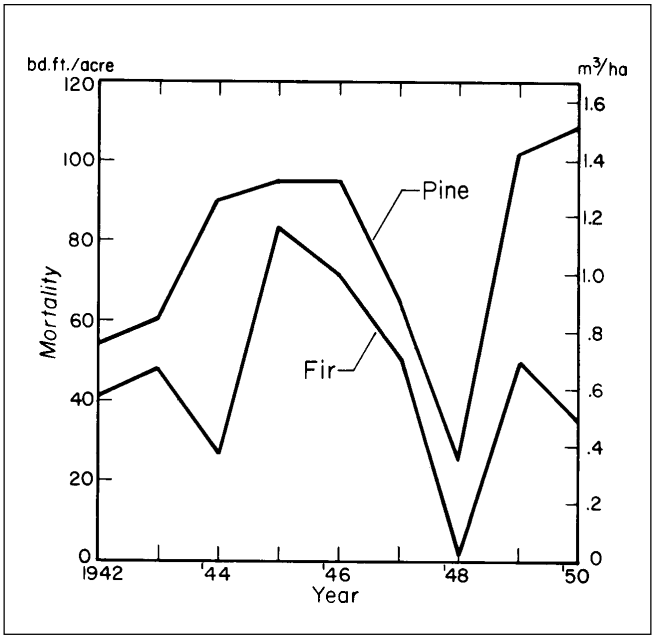


FIGURE 45.3

Mean annual mortality caused by subcortical insects was similar for white fir and pine during the years 1942 to 1950 (Ferrell and Hall 1975).

ity of these stands to bark beetles during droughts (Ferrell et al. 1994). Moreover, repeated logging of stands by these two selective methods, if not carefully done to avoid damage to the residual trees, led to increased levels of root disease by repeatedly providing stumps and trunk or root wounds, which are infection sites for root pathogens (Gast et al. 1991). Potentially, intensive forestry, involving conversion of old-growth to younger, even-aged stands, should mitigate most of these problems, but in practice this has not always been the case. Too often in the past the valuable overstory was removed, leaving a battered, pest-prone understory, which was left unthinned and unsanitized. Even if intensive forestry is well planned and executed, some critics are concerned that the resulting young, even-aged stands may be more pest-prone in the future. At present the evidence for this is at best unclear.

Urbanization

Urban development is increasing in the Sierra Nevada, although it is regulated by public ownership of lands and by the effects of the county land-use planning process on private lands (USFS 1995). Despite these constraints, urbanization, with attendant traffic and infrastructure development, is increasingly affecting Sierra Nevada forests and their management. Commonly occurring problems are construction, trenching, paving, sewage effluent disposal, insecticidal spraying of trees for mosquito abatement, and applications of highway deicing salt. All of these can injure trees or alter their environments and render them susceptible to insects and pathogens, with root diseases and bark beetles again the most serious. Transport and improper storage of bark-beetle-infested firewood and failure to thin overly dense stands of trees, or improper disposal of the thinnings, can cause problems at times. Fire risk is also increased at the urban / forest interface. Many of these problems can be avoided or mitigated by good planning, regulation, and education, and by adequate public and private expenditures for infrastructure.

Air Pollution

Forest injury from air pollution has been found in some parts of the Sierra Nevada (Cahill et al. 1996; Urban and Miller 1996; Miller and Millecan 1971; Peterson et al. 1992; Pronos and Vogler 1981). This pollution is generated by urban and agricultural sources in the San Joaquin and Sacramento valleys and transported to the Sierra Nevada by the prevailing winds, with the west-side forests thus receiving the highest concentrations. Towns, highways, and major resort areas such as Lake Tahoe can be sources of considerable locally produced air pollution at times. The effects of air pollution are now monitored closely in those parts of the Sierra forests suspected to be at highest risk for damage. Effects of air pollution on forests very similar to those in the Sierra Nevada have been studied intensively in the mountains surrounding Los Angeles. Tree species differ somewhat in their sensitivity, but affected trees display chlorotic, sparse foliage, reduced exudation of defensive resin in response to bark beetle attack, and therefore increased susceptibility to bark beetles (Miller et al. 1963; Stark et al. 1968). Ozone is known to be an important source of the damage because it destroys chlorophyll in conifer foliage. Incipient symptoms have been noticed in west-side forests of the southern Sierra Nevada, but, as yet, no pronounced increases in tree mortality or bark beetle populations have been clearly attributable to this source, probably because air pollution levels have not yet been high enough for long enough periods. Indeed, recent monitoring in the western slope of the Sierra Nevada indicates that levels of injury from

TABLE 45.6

Trees killed by bark beetles in relation to fire injury to crown and cambium (Salman 1934).[a]

	Percentage of Trees Killed	
Percentage of Crown Defoliation	Slight Cambium Injury	Moderate–Severe Cambium Injury
0–25	8.7	10.0
25–50	3.6	13.3
50–75	18.2	37.5
75–100	19.2	72.2

[a]Data are from the Sugar Hill fire, Modoc National Forest.

air pollution are not increasing as expected. In the future, however, rising levels of air pollution could interact with effects of fire and drought to produce widespread outbreaks of tree-killing bark beetles.

EFFECTS ON FOREST COMPOSITION AND STRUCTURE

Insects and pathogens, working in concert with other environmental factors such as drought and fire, strongly influence the composition and structure of Sierra Nevada forests. Specific effects, however, differ by forest type.

Ponderosa Pine Forests

Lying at the lower elevational edge of the commercial forest zone, the ponderosa pine forest type intergrades at its lower elevational limit with chaparral and at its upper elevational limit with the mixed conifer forest type. Ponderosa pine is the primary tree species on most sites, with an admixture of scattered California black oak. Because of the relatively low elevation, water availability, not temperature, is the strongest factor limiting forest growth. Primary insects and pathogens of concern here are complexes of bark beetles, fungal root diseases, and dwarf mistletoe killing ponderosa pines (table 45.1). Western pine beetle kills mainly mature pines weakened by root disease, dwarf mistletoe, or drought, while pine engravers kill mainly pole-size pines in overly dense stands, especially during droughts. Logging slash is also readily infested. Red turpentine beetle acts as a predisposing agent for the other pine bark beetles and may become even more important if controlled burning is reintroduced. Pines are usually killed singly or in small clumps during nondrought periods. But during droughts both mature and pole-size pines may be killed in large groups, and the openings thus created, as well as larger openings created by intense fires, are strongly invaded by manzanita and ceanothus shrubs. These shrubs may dominate such openings for many years, retarding reforestation. Oaks, too, are favored by fire, because they are able to sprout from stumps. Unless mitigated, logging increases the incidence of root disease by providing freshly cut stumps, which serve as entrance points for fungal infection. Because of the accessibility and relatively moderate climate of ponderosa pine forest, it has been greatly affected by previous logging, widespread urbanization, and fire exclusion. Many of the large pines have been logged; current stands are thus younger and denser, with a higher shrub component, than presettlement stands. Continued intense disturbances could cause more of this type to revert to brush fields, especially at the lower elevations.

Mixed Conifer Forests

In area, mixed conifer is the largest forest type in the Sierra Nevada, occupying the middle elevations below the red fir forest. The diverse conifer type is a variable admixture of ponderosa, sugar, Jeffrey, and lodgepole pines, white fir and Douglas fir, and incense cedar. At higher elevations and on the east side of the mountain range, Jeffrey and lodgepole pines largely replace ponderosa pine in this type. On the west slope of the Sierra, giant sequoia is found in a number of scattered, localized groves within this forest type. Previously, mixed conifer forests probably had greater complements of large pines, but logging and fire exclusion have led to increased components of shade-tolerant firs and incense cedar, especially in the understory. Bark beetles, dwarf mistletoes, root diseases, and white pine blister rust are the primary insects and pathogens affecting this forest type. The bark beetles kill trees predisposed by pathogens, fire, drought, or, more rarely, defoliator insects (table 45.1). Trees in overly dense stands and drier sites, such as ridgetops or steep canyon walls, are particularly affected. Windthrows, snow breakage, and logging slash also provide readily infested host materials. Western pine beetle and pine engraver are the primary insects affecting ponderosa pine, while mountain pine beetle is most important in killing sugar pine. The fir engraver is the most serious killer of white fir, the Douglas fir beetle is for Douglas fir, and the Jeffrey pine beetle is for Jeffrey pine. Major predisposing root diseases, caused by somewhat host-specific strains of fungi, are annosus root disease, black-stain root disease, and armillaria root disease. Host-specific dwarf and true mistletoes are also important predisposing agents. White pine blister rust, caused by an introduced stem rust fungus, has spread to sugar pine throughout this forest type, weakening and killing trees and predisposing them to bark beetles. Red turpentine beetle may become a more important predisposing agent for pines if controlled burning is reintroduced in this forest because the beetle readily infests fire-scorched trees. Neither incense cedar nor giant sequoia is host to any serious insect pests, but both are afflicted to some degree by annosus root disease.

Along with climatic fluctuations and fire, insects and pathogens have been postulated to contribute to maintaining the mix of conifer species in this forest type. In this view, when some combination of these agents increases densities and competitional stress in some of the component conifer species, host-specific bark beetles and predisposing pathogens combine to kill those species, reducing their proportion in the stand composition. Ecologists term such a process, in which the organisms with the highest population densities suffer the highest mortality rates, density-dependent mortality. Later on, when some other combination of environmental factors increases the density of another component and thus predisposes it to bark beetles, that species in turn is reduced, so that, although the stand composition fluctuates like a pendulum, the mixed composition is maintained over time. Such a process, involving pathogens and bark beetles, appears to have played a role in maintaining a mixed forest of Jeffrey pine and white fir near South Lake Tahoe in the Sierra Nevada (Ferrell et al. 1994; Scharpf and Bega 1981). There are indications that postsettlement human influences have led to an increase in the amplitude of these compositional variations and thus are a destabilizing influence. A key question for future management of mixed conifer forests is how to use natural processes, including the effects of insects and pathogens, to increase rather than decrease the stability of the composition and structure of the forests.

Red Fir Forests

Composed mainly of red fir, this forest type also includes other conifer species such as white fir, mountain hemlock, and western white, lodgepole, and Jeffrey pines as lesser components. The forests lie at the upper elevations in the Sierra Nevada, where winter snowpacks are usually deep and persist well into summer. Tree growth is thus normally limited by low temperatures; in fact, growth may increase during droughts, with their lesser snowpacks and longer growing seasons, provided the drought is not protracted. Development and dynamics of insects and pathogens are also temperatrue-controlled and usually slower at higher elevations. During nondrought periods, bark beetles kill scattered trees weakened by root diseases and dwarf mistletoes (table 45.1). Trees damaged by avalanches, windthrows, and snow breakage are also readily infested, as is logging slash. But fire damage is seldom a major source of beetle-breeding material, because large, intense fires are less common than at lower elevations. Not only is the fire season shorter, but also the rockiness of the subalpine terrain causes a disjunct distribution or patchiness of this forest. Increased mortality of trees occurs in response to droughts, but usually not in large groups and only if the drought lasts longer than two or three years. Because of their shallow root systems, lodgepole pines that have invaded wet meadows may be particularly susceptible to mountain pine beetle when water table levels change. The fir engraver is responsible for most of the mortality of red fir and white fir, killing both mature and pole-size trees; mountain pine beetle plays a similar role in lodgepole and western white pines. Jeffrey pine beetle is the primary bark beetle infesting Jeffrey pine. Important root diseases are annosus and armillaria root diseases, both of which are especially abundant in dense stands having red fir or white fir as the major component. Red fir in some stands is heavily infected by dwarf mistletoe, which weakens the trees and renders them susceptible to the fir engraver. Insects and pathogens normally kill individual trees or small clumps, rather than large groups of trees, in this forest type and thus normally cause few major shifts in the composition and structure of the forest.

Subalpine Conifer Forests

At the upper limit of tree growth in the Sierra Nevada occurs a variable mixture of several pine species (western white, whitebark, limber, foxtail, and lodgepole) and mountain hemlock, red fir, and Sierra juniper. Mountain pine beetle is the primary bark beetle infesting all of these pines, but outbreaks are rare because of low temperatures and the sparsity and disjunction of the stands due to the extreme rockiness of the growing sites. Usually only single trees or small clumps are killed by the beetle. All of the pines except lodgepole are, however, susceptible to white pine blister rust, and there is currently concern that this virulent pathogen may spread more widely into this forest type in the future. As susceptible pines are virtually the only trees in some high-elevation forests, they could be considered keystone species, because many animals at that elevation are almost totally dependent on them.

Jeffrey Pine Forests

Located at middle elevations on the steep eastern slope of the Sierra Nevada, Jeffrey pine forests are found on somewhat dry sites. They are composed almost wholly of Jeffrey pine with an understory of bitterbrush, sagebrush, and scattered mountain mahogany. Key insect pests and pathogens are Jeffrey pine beetle, annosus root disease, and dwarf mistletoe, operating in pest complexes as described for the other forest types (table 45.1). Located in the rain shadow of the Sierra Nevada, this forest type is well adapted to dry conditions, but, during droughts, outbreaks of Jeffrey pine beetle cause widespread mortality of trees, especially those weakened by root disease or mistletoe.

Piñon-Juniper Forests

Found at the lowest, driest elevations on the east flank of the Sierra Nevada, the piñon-juniper forest type is composed almost wholly of single-leaf piñon pine and western juniper, growing singly or in combination, with a mainly sagebrush shrub layer. Key insects and pathogens are pine engravers killing piñon pines, often those weakened by black-stain root disease or annosus root disease, with the latter also infecting western juniper. Usually single trees or small groups are killed, but where stands are dense, large clumps can be killed.

MITIGATION METHODS

Mitigation methods exist for most of the key insects and pathogens affecting Sierra Nevada forests, but their efficacy is highly dependent on the underlying condition of the forest, which is influenced by environmental and human factors (Furniss and Carolin 1977; Parmeter 1978; Otrosina and Cobb 1989; Kinloch in press). Consequently, the efficacy of past mitigation has been highly variable. Mitigation falls into two categories, based on the approach or strategy employed. Remedial or suppressive methods, sometimes termed direct control, are intended to remedy existing situations by directly suppressing pest populations and thus mitigating the damage they cause. Examples are pesticide applications and removal of infested trees from the forest. Experience has shown that beneficial results tend to be only temporary, and retreatments may be needed unless the forest, environmental, or human conditions that provoked the situation in the first place are altered.

In contrast, preventive methods aim to avert the development of future pest problems. These are usually the most effective methods, in terms of both cost and long-term efficacy, because their beneficial results tend to last, barring changes in the conditions governing stand susceptibility. In forest pest management they usually involve what is termed indirect control, in that they seek to decrease pest damage by decreasing the susceptibility of the forest rather than attacking the pests and thus are usually silvicultural in nature. Because patterns of forest susceptibility can change over time, and endemic populations of insects and pathogens are virtually omnipresent, however, even the mitigation provided by silvicultural treatments may not be lasting, and retreatment may still be required. In situations where the key insects and pathogens tend to operate as biotic complexes, direct and indirect control may not be strictly separable in practice, because direct control of, say, a pathogen may have its greatest effect as an indirect control of an insect because it reduces the susceptibility of the host tree to the insect.

As preventive methods, particularly those that decrease stand susceptibility to pests, are potentially the most efficacious and cost-effective in the long run, the following discussion focuses on them as the preferred approach to management of the disturbances caused by insects and pathogens in Sierra Nevada forests, although suppressive methods are mentioned where appropriate.

Mistletoes

Mitigation methods developed for the mistletoes infecting Sierra Nevada conifers usually include either direct reduction of sources of infection or increasing the growth and vigor of target trees so that they can outgrow the infection or tolerate it better or both (Parmeter 1978). Reduction of infection sources usually involves removal of infected overstory trees so that mistletoe seeds cannot drop from them and infect the understory. Source reduction can also entail thinning dense stands to reduce competition among residual trees and increase their height growth, thereby slowing upward spread of mistletoe in tree crowns. These approaches have the added benefit of reducing competition within the stand, thus increasing the growth and vigor of residual trees and increasing their ability to outgrow or tolerate the mistletoe. Pruning of infected branches is sometimes used to achieve the same results; it often increases tree growth but, of course, does not suffice if the trunk is also infected. Since mistletoes are host-specific, selective cutting can be used to alter the species composition of stands in the direction of increased resistance to a particularly prevalent and damaging form of mistletoe. Genetic resistance to mistletoes is known, and programs to develop resistant trees may in future provide resistant planting stock. Such stock may be needed if uneven-aged management (single tree or group selection) is used in stands with one major tree species in both the understory and the overstory. In such stands, unless all infected overstory is removed, it will seriously infect the understory, including naturally regenerated seedlings (Parmeter 1978; Scharpf and Parmeter 1976). Prevention or merely reduction of mistletoe infection by any of these methods often leads to increased resistance of the stand to bark beetles.

Blister Rust

Mitigation methods available and effective for white pine blister rust are few (Kinloch in press). Several approaches, including eradication of wild currant or gooseberry (Ribes species), the rust's required alternate host, have been tried and found to be costly and insufficiently effective. Infected branches of the pines can be pruned away and disposed of, but this is, of course, not effective if the infection has already spread to the stem. Maintenance of a mixed species stand composition may help slow buildup of the rust. More promising, perhaps, is the development of rust-resistant host trees. Genetically resistant sugar pines have been found, but there is evidence that even resistant trees might become infected under certain environmental conditions (Kinloch and Byler 1981). The current effort is to speed the development of resistance through selection and breeding, but, over the long term, resistance is also expected to develop in natural host tree populations. Meanwhile, cutting practices should avoid large reductions in host inventories so as to maintain sufficiently diverse gene pools to ensure host adaptability in the future.

Root Diseases

Effective mitigation methods for root diseases are mostly preventive (Otrosina and Cobb 1989). Reliable remedial treatments for established infection centers have not yet been developed for any of the major root diseases afflicting Sierra Nevada conifers despite much effort to do so. The difficulty arises from the ability of the root pathogens to spread to surrounding trees through root-to-root contacts and to survive for decades in infected or dead root systems. The only approach currently effective is to keep infections from occurring in the first place. Methods to do so involve borate treatment of freshly cut stumps to prevent their infection by annosus root disease. Additionally, care is taken during logging to avoid creating basal trunk wounds or open root wounds, which could serve as entry points for fungal infections. White fir is particularly susceptible to annosus infection through basal stem wounds. Avoiding such injuries has been difficult, given the heavy logging equipment used in the past, but lighter, more maneuverable equipment is rapidly coming into use. Greater understanding of the host-specific strains of root disease fungi is providing insights about how to manipulate stand composition silviculturally so as to reduce future infections.

Bark Beetles

For bark beetles, both suppressive and preventive methods are available, although lasting beneficial effects of the former are infrequent if the underlying susceptibility of the stand remains undiminished (Furniss and Carolin 1977). Suppressive methods include insecticidal sprays or "fell, peel, and burn" applied to infested trees or logs. Fell, peel, and burn involves felling the infested tree, peeling the bark, and burning, or otherwise disposing of, the bark, so no beetles can emerge from it to attack other trees. The trap-tree method, in which trees are felled to induce attack and, once infested, are destroyed or removed from the forest, also can be used. Prompt salvage logging, in which recently dead and perhaps still infested trees are removed from the woods, is another way to reduce bark beetle populations. Experience has shown, however, that unless virtually all infested trees are located and removed from the woods before the beetles have emerged, tree mortality rates are not greatly affected (Miller and Keen 1960). Preventive methods, most of which aim at reducing the number of susceptible trees in the forest, are far more likely to result in a lasting reduction in tree mortality rates. Sanitation logging, in which diseased or otherwise weakened (high-risk) trees are removed from the forest, has historically been efficacious, particularly in east-side pine stands (Wickman and Eaton 1962). A similar risk-cutting approach is currently being tested for sanitation logging of red fir and white fir in both west- and east-side forests (Ferrell 1989).

Thinning of overly dense stands is also a very important preventive method for bark beetles, although site-specific goals must be established, specifying the density of trees to leave. There have been insufficient studies to establish site-specific goals for the Sierra Nevada, but results so far (Oliver 1995) indicate that, at the least, "catastrophic" (extremely high) tree mortality from bark beetles can be prevented by reducing stand densities below about 14 m^2 (150 ft^2) per acre in basal area. Basal area is a frequently used measure of stand density. It is the cross-sectional area of all tree trunks, usually at 1.4 m (4.5 ft) above ground, and thus expresses total tree occupancy of the site. Developed only in young ponderosa pine stands, this 14 m^2 standard appears to apply to such stands on sites varying considerably in quality on both the west and the east side of the Sierra, but the standard has not yet been validated for other forest types (Oliver 1995).

With any of these preventive silvicultural treatments, opportunity exists to alter the species composition of the forest from one that is susceptible to one that is less so. However, care must be taken in any treatment involving logging to avoid leaving untreated stumps and injured trees susceptible to bark beetles and pathogens. All logging slash must be promptly treated or disposed of to prevent it from being infested by the beetles. Such considerations are particularly important in old-growth (late-seral-stage) stands, which can be maintained only if much care is taken to avoid injury to the residual stand following any forest treatments.

KNOWLEDGE GAPS

Critical gaps in knowledge about insect pests and pathogens in Sierra Nevada forests include the following:

- Insufficient understanding of conifer resistance to insects and pathogens and of the population levels of these agents that are required to kill trees under various conditions of stress (the so-called threshold of susceptibility of trees). Thresholds vary with changing forest and environmental conditions, and inability to specify them has been a major barrier in developing models predicting the forest damage that will be caused by these agents.
- Inadequate knowledge of how, and to what extent, various sources of stress, such as drought, air pollution, and fire, interact to determine tree and stand susceptibility. Air pollution and fire increase during droughts but their interactive effect on forest stress and susceptibility to insects and pathogens is not well understood.
- Paucity of systems for rating the risk of trees or stands to damage from insects and pathogens during both outbreak and nonoutbreak periods. Risk and hazard rating systems exist, but not for all major tree species and forest types in the Sierra Nevada.
- Dearth of site-specific guidelines to determine the reserve or residual stand densities to maintain after logging or thinning so as to maintain forest resistance during both drought and nondrought periods. Rough guidelines are used, but most of these were derived from a limited range of stands and forest types.
- Inadequate knowledge and ability to predict interactions between fire and insects or pathogens. Present knowledge derives largely from case studies of the aftermath of relatively few wildfires, with little characterization of affected trees and stands and their susceptibility to these agents.

- Unavailability of predictive models linking population levels of these agents to environmental factors, mitigative treatments, and forest dynamics. Population models are available for only some of these agents, and the models have not been linked to environmental variables and stand dynamics models, largely because thresholds of susceptibility are not known. Existing population models usually do not have a spatial component able to predict the spatial population patterns produced by these contagiously spreading agents.
- Insufficient ability to predict results of mitigative treatments for these agents, especially results for new methods, such as bark beetle attractants and repellents, on levels of forest damage. These results are needed both to judge whether mitigation is worthwhile and to add to predictive models.
- Unavailability of stand dynamics models that adequately predict spatial patterns of forest growth and survival in quantitative terms suitable for multiple-resource planning. Spatial patterns are critically relevant for contagiously spreading agents such as insects and pathogens, and quantitative predictions of forest dynamics must include nontimber as well as timber resources to facilitate the planning process. Most existing models have no spatial component and some do not produce outputs in units relevant to nontimber, as well as timber, resource planning.
- Inadequate knowledge of the role played by insects and pathogens in forest ecosystem function, especially those functions necessary for the long-term sustenance of forest biodiversity and productivity.

PEST RESPONSES TO FUTURE MANAGEMENT SCENARIOS

If present trends and management practices continue, Sierra Nevada forests will experience outbreaks of bark beetles and wildfires in response to the recurrent droughts characteristic of the California climate. It is not possible to predict the extent of the damage produced by these outbreaks, because they will depend partly on the intensity and duration of the droughts. But, because highly susceptible stands have developed in some forest types, in part as a result of past management practices and the synergistic effects of drought, pests, and fire, it is likely that the high levels of forest damage caused by these agents will increase in the future over much of the Sierra Nevada. Under such conditions, experience has shown that mitigation will not be adequate. Even previously treated stands and young plantations may suffer damage, because they will be surrounded by a large backlog of untreated stands with high fuel loads and populations of insects and pathogens. Moreover, the mortality of desirable remnant old-growth trees will increase due to their age-related higher susceptibility to insects and pathogens. Compounding these losses will be those arising from likely increased disturbances, such as frequent salvage logging, urbanization, and its many side effects, including air pollution and construction. Under these conditions, endemic or nonoutbreak populations of insects and pathogens may well increase, leading to quicker outbreaks at the onset of droughts, and the health of Sierra Nevada forests is likely to continue to decline.

If, on the other hand, management strategies are altered in the direction of restoring presettlement forest composition and structure, current forest conditions, including damage from insects and pathogens, would probably be mitigated. Likely scenarios include thinning the overly dense understory of firs and cedars to reduce its susceptibility to fire, insects, and pathogens. Reduction of this understory not only reduces fuel loads and the spread of insects and pathogens from tree to tree but also reduces competitive stress on the overstory and thus lowers its susceptibility to insects and pathogens. Controlled burning may be an ecologically sound method of thinning this understory, but mechanical thinning may have to be used, at least initially, in commercial forests where present fuel loads are too high to use burning. Fire alone may have to be used in parks and wilderness areas or other areas where logging is not an option.

Although understory reduction may reduce mortality rates of the remaining large overstory trees, mortality of the overstory trees may still be too high to meet the inventory goals of ecosystem management. Important among these goals is maintaining sufficient numbers of large trees to meet wildlife needs. For example, some owl species prefer to roost in such trees; some cavity-nesters such as woodpeckers prefer to excavate nest holes and to forage in such trees after they become snags. Snags do not remain standing forever, however. Survival and replacement of large trees must therefore provide adequate numbers of standing snags in future decades. Removal of competing smaller trees around large trees may prolong survival of the latter. The same treatment around rapidly growing midsize trees may speed their replacement of larger old trees as the latter die.

After wildlife and other ecosystem needs are met, there may be sufficient inventories of large trees to permit some selective logging. If so, this should be done on a sanitation basis. Removing diseased or otherwise high-risk trees decreases endemic populations of bark beetles and pathogens, thereby protecting the remaining stand and retarding outbreaks during droughts. This sanitation logging could be done on both a single-tree and a group basis, depending on the spatial distribution of high-risk trees. Indeed, this distribution is usually clumped because of the contagious distribution of root diseases and mistletoes. Group selection or patch-cutting should therefore be used to ensure that entire clumps of pathogen-infected trees are removed.

All restoration management has to be done carefully, especially because it may require repeated reentry into the stand,

and with every entry there is a risk of injuring the residual stand. In particular, scorching and mechanical injury to the residual stand should be minimized. Appropriate equipment and methods should be used to minimize soil compaction and root damage. Large stumps should be treated to avoid initiating root disease infection centers. Treatments should prevent not only root diseases but also entrance of heart-rot and other decay fungi, which can structurally weaken other tree trunks, leading to wind and snow breakage. Sufficient slash should be left for wildlife but treated to prevent bark beetle infestation. If, because of wildlife requirements, logging slash cannot be piled and burned or scattered and dried in full sunlight (proven beetle prevention methods), it should be lightly burned without piling, to dry it and render it unsuitable for bark beetles. Unless such precautions are taken, forest susceptibility to fire, insects, and pathogens may be higher after treatment than before.

A variety of thinnings, overstory sanitation cuttings, controlled burns, and other treatments will have to be used, with the specific combination dependent on the particular site and the goals for managing it.

If this program is undertaken, losses caused by insects and pathogens will still occur, at least initially, but as treatments become more widespread, the damage caused by these agents should decline over the long term.

The guiding strategy should be to restore the presettlement composition and structure of the forests by using the natural processes (or reasonable substitutes) under which these forests evolved. In this way chances of inadvertent extinctions are minimized, and chances of keeping the entire biota reasonably intact are maximized. Some treatments, such as mechanical thinning and sanitation logging, are largely precluded in forests within established parks and wilderness areas, where human influences are minimized. Instead, natural or prescribed fires will have to be relied upon largely to restore presettlement conditions. In stands with unnaturally high fuel loads due to previous fire suppression, fire injury to the forest overstory may, at times, occur, and insect- and pathogen-caused damage may also be extensive. If viewed as natural processes, however, the effects of these agents can be considered beneficial and necessary to restore presettlement conditions.

Accomplishing this restoration will not be quick and inexpensive. The current situation took many decades to develop, and due to its scope and magnitude it will require many decades to rectify. With widespread implementation of mitigative restoration, however, these forests can be sustained reasonably intact for future generations.

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