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15

Silviculture in the Sierra

ABSTRACT

This chapter summarizes for general readers the state of silvicultural knowledge of Sierra Nevadan forests. It has sections covering presettlement conditions, a historical overview of silvicultural and harvesting practices over the past 100 years, and discussions of silviculture and silvicultural systems. Summaries of current silvicultural practices and their effects on forest systems are based on especially commissioned reviews (attached as appendixes) by specialists in each field, including sections covering silvicultural aspects of forest soils, stand density, regeneration, vegetation management, and the current status of Forest Service plantations. A particularly important section summarizes what has been learned from three long-term studies of silvicultural treatments in the Sierra Nevada. The most significant of these is the thirty-year database from the University of California's Blodgett Forest Research Station. Additional short sections deal with silvicultural prescriptions on federal, state, and private lands. The chapter concludes with discussions of major factors and issues affecting silviculture, management, and policy analysis of Sierran forests, and identification of gaps in our current knowledge.

INTRODUCTION

This chapter summarizes the state of knowledge of Sierra Nevada silviculture for general readers. This knowledge is used by silviculturalists (1) for the science-based development of silvicultural prescriptions designed to meet a diverse array of specific management objectives within a landscape, and (2) as a basis for policy analysis and development.

Because of their mixed species composition, range of age classes, and spatial diversity, the forests of the Sierra Nevada provide broad opportunities for sustaining a wide variety of values for society and landowners. The forests of the Sierra Nevada are much more variable than the more uniform forests in the Pacific Northwest and have experienced many more harvesting and management strategies. Consequently, after nearly 150 years of use, the Sierran forests remain remarkable for their current diversity of structure and composition.

Sierran forests change in elevation from oak woodland in the foothills, to foothill pine and ponderosa pine at intermediate elevations to mixed conifer forests (consisting primarily of ponderosa pine, Douglas fir, sugar pine, California white fir, incense cedar, tan oak, and California black oak), true fir forests (red and California white fir), and lodgepole pine forests and finally to subalpine forests (whitebark, foxtail, and limber pines) at timberline (figure 15.1). The elevations at which one forest type makes a transition to another are lower in the northern Sierra than in the south.

Due to their characteristic diversity in vegetative cover, topography, and climate, Sierran forests provide a remarkable diversity of values and uses for society. They are sources of water, wildlife, timber, and aesthetic beauty, and they provide society with sites for urban communities, with jobs, and with recreation. But on a broad scale, landscape-level management and policy development are made extremely difficult by a complex mix of ownership and jurisdictional boundaries that includes federal, industrial, and small, private, nonindustrial landowners.

All forest stands are dynamic—they are continually changing in age, size, structure, and species composition due to natural and human-induced factors. Silviculture is the mixture of art and science that is concerned with the regeneration of forest stands and the development of composition and structure to provide goods, services, and values for society. Although the basic ecological requirements for the various combinations of plants, animals, insects, and diseases remain relatively stable, stands are dynamic and, as landowner and societal needs change, silvicultural practices must be tailored to meet existing stand conditions and changing management

Sierra Nevada Ecosystem Project: Final report to Congress, vol. II, Assessments and scientific basis for management options. Davis: University of California, Centers for Water and Wildland Resources, 1996.

Back to CD-ROM Table of Contents

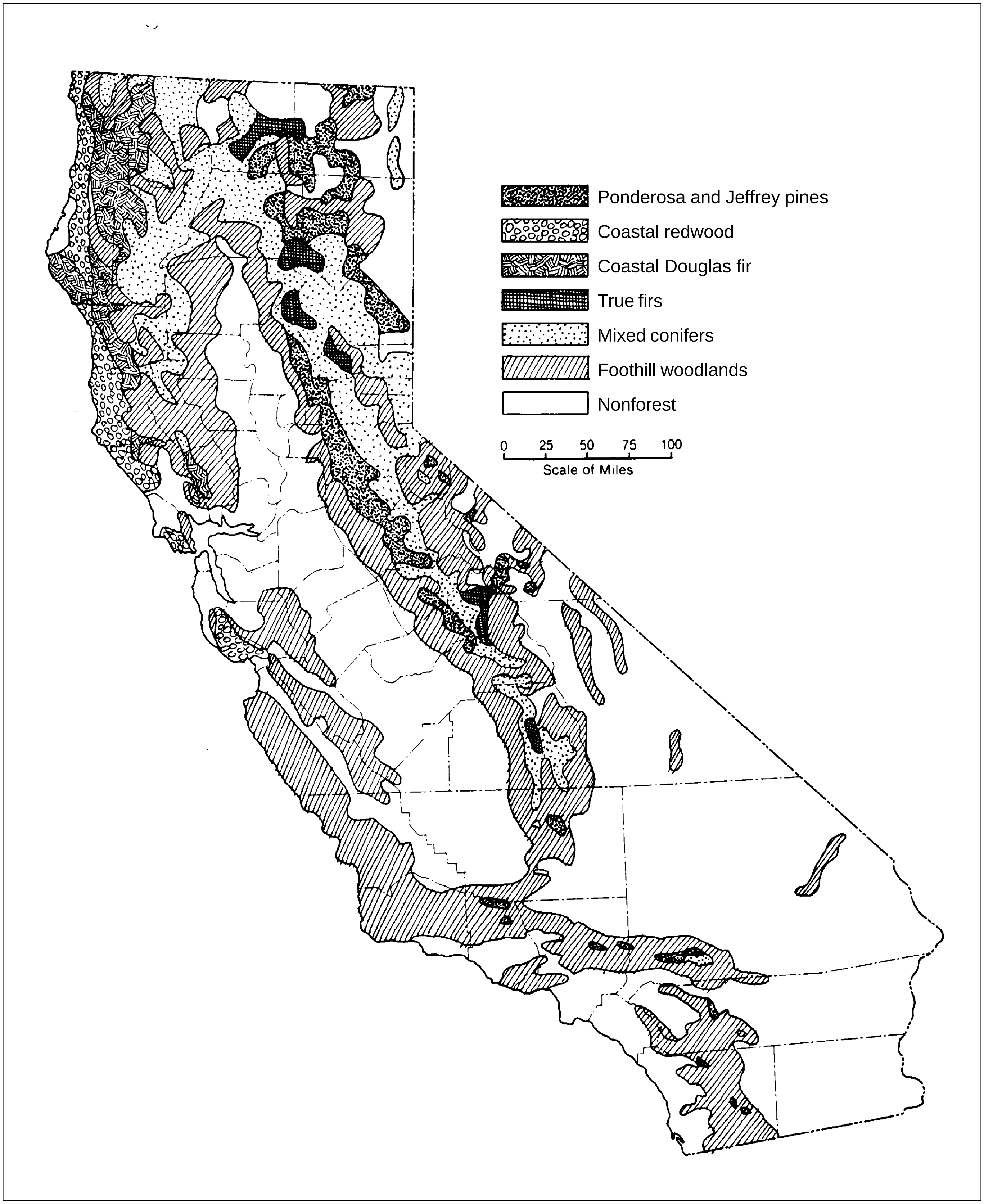


FIGURE 15.1

Distribution of forest types in California (adapted from Bolsinger 1980).

objectives. The effects of those silvicultural practices occur rapidly on sites of moderate to high productivity but take a longer time to become evident on sites of lower productivity.

There are numerous ecological problems confronting management and policy makers in the Sierra Nevada for which silviculture can offer some solutions. These include forest health; the development of a higher proportion of shade-tolerant species such as California white fir and incense cedar; the effects of wildfire suppression, including a buildup of fuels; and the sustainability of current forests and their capacity to meet the present and future needs of California and the nation.

This chapter provides historical background, presents what is known silviculturally about various forest types in the Sierra, and comments on the important current and emerging silvicultural issues. Emphasis is placed on the mixed conifer forest because of its relative importance and because of the greater abundance of knowledge regarding this forest type.

PRESETTLEMENT CONDITION OF SIERRAN FORESTS

The earliest and best-known descriptions of the mixed conifer forest were written by John Muir ([1895] 1977) who described the "inviting openness of the Sierra woods" and noted that their "park-like" condition enables one to have "little difficulty in riding on horseback through successive belts" to the peaks. The first quantitative descriptions were provided by Sudworth (1900, 1901), who measured fifty-three 0.10 ha (0.25 acre) plots in various parts of the Sierra (McKelvey and Johnston 1992). Seventeen of Sudworth's plots were located in the mixed conifer forests, and these probably provide the best description of "presettlement old-growth" forests, even though some had been subjected to partial cutting, fire, and grazing and were probably not representative of average conditions. An analysis of these plots shows that basal area (the total cross-sectional area of all trees per unit of land area) in the more southern group was considerably higher and tree size was larger (267 trees per hectare [108 trees per acre], 264 m^2/ha [1,148 ft^2/acre]), quadratic mean diameter 114.3 cm [45.0 in]) than in the more northern group in the mid-Sierra (250 trees per hectare [101 trees per acre], 165 m^2/ha [719 ft^2/acre]), ranging between 93 and 230 m^2/ha [406 and 1,004 ft^2/acre], and quadratic mean diameter 98.8 cm [38.9 in]). In both areas, the proportion of basal area in pines was 40% to 50%, with about 30% in either Douglas fir or California white fir and the remaining 20% in incense cedar. Additional evidence of open and parklike conditions is available in photographic records of Collins Almanor Forest taken in 1924 (Ford 1991) and from a comparison of photographs taken in the late 1800s with those taken recently (Gruell 1994). It appears from Sudworth's and Muir's descriptions and from early photographs that the original Sierran mixed conifer forests at the turn of the century, at least in some locations, were very dense and were composed of many large, old trees. These largest trees were not only pines but also Douglas fir, California white fir, and incense cedar.

The presettlement red fir forests were essentially dense monocultures of even-sized (although not necessarily even-aged) trees and were nearly devoid of understory. Because these stands were relatively inaccessible and were regarded as having lower value for wood products, they were largely ignored and unexploited. Due to their location at high elevation, the cold temperature and long periods of snow cover prevented downed woody material from decomposing as rapidly as in the lower-elevation forests. Consequently, original red fir stands were, and still are, characterized by heavy loads of dead and down fuel.

EVOLUTION OF CALIFORNIA SILVICULTURE IN THE SIERRA OVER THE PAST 150 YEARS

1850 to 1925

The first effects European settlers had on Sierran forests were associated with mining, logging, and grazing. Forests were regarded as inexhaustible, and cleared land had more value than forested land. Silviculture and forest management were irrelevant. Initially, the trees harvested were those that were most valuable, that were near rivers, or that were accessible by oxen. Later, with the advent of railroads and ground-skidding with cables, more distant stands could be harvested. Forests removed by logging or fire were replaced by either conifer regeneration or brush fields. Increasing populations of settlers greatly reduced the amount of old growth and changed the character of remaining stands through extensive "high-grade" logging (i.e., logging in which only the best trees of the most valuable species are cut), fire, and grazing.

1925 to 1979

One of the first silviculturists in California was Duncan Dunning, who was employed by the U.S. Forest Service (USFS) and had the responsibility of determining how to manage the mixed conifer forests in order to enhance their health and productivity. In 1923, Dunning reported that

> the situation confronting the forester was a very difficult one. As a result of early fires, insect attacks, and grazing, the forests were usually under-stocked with a preponderance of mature and decadent timber, a deficiency of intermediate-age classes from which to select thrifty reserves, younger trees poorly distributed or stagnating in groups, and reproduction frequently absent or

> composed of undesirable species. The stands were often invaded by brush and "bear clover" . . . With these conditions prevailing, the forester faced the problem of improving the health of the stand, increasing the rate of growth, and securing more pine reproduction.

A major force shaping timber harvesting and regeneration on private lands in California was section 12¾ of the state constitution. This section enabled landowners who harvested at least 70% of the volume of trees on a unit of land to pay taxes only on the land, rather than on the land and timber, for forty years or until another harvest was made. This form of tax relief on private land resulted in heavy selective cutting and discouraged more modest thinnings. Section 12¾ was repealed in 1973, when the existing Forest Practice Act, which had been in place since 1943, was replaced with new legislation (described later in this chapter).

Just before World War II, technology changed with the advent of chain saws, trucks, and tractors. Changing merchantability standards increasingly permitted the removal of smaller, lower-quality trees and more species. Silviculture was centered primarily on cutting high-risk trees susceptible to insect attack or "sanitation-salvage" trees killed by frequent wildfires and outbreaks of insects and disease. Early silvicultural procedures focused on the development of risk rating systems such as those by Dunning (1928), Keen (1936), and Salman and Bongberg (1942), that identified trees for harvesting that were likely to die within a fifteen- to twenty-year period. Most harvesting in this period on both public and private lands was selective cutting in which large, old trees—particularly sugar pine, ponderosa pine, Jeffrey pine, and, to a lesser extent Douglas fir, California white fir, and red fir—were preferentially removed in order to raise stand vigor and net growth. In addition, some cutting was done to replace existing old stands with regeneration, but this activity was at a low level relative to selective cutting. It was a common practice for timber-holding companies to high-grade the pine timber from their forest lands and exchange the cut-over land with the Forest Service for trees from federal forests. Large wildfires required substantial reforestation efforts.

An early priority in forest management was to clear brush fields that had resulted from natural and human-caused forest fires and early logging, and to plant them to pine. This program required the development of a system of forest tree nurseries capable of producing seedlings that could survive the rain-free summer periods typical of the Sierra. In the 1950s, the Forest Service recognized that mixed conifer forests consisted of mosaics of age classes and structure, each requiring different silvicultural treatment. This led to a concept called unit area control, a new approach to silviculture in the Sierra that focused on prescribing treatments based on an assessment of the condition of small stands or groups rather than on individual trees.

As chair of an important committee, F. S. Baker reported to the State Board of Forestry on California's regeneration problems (Baker 1955). Faced with increasing harvesting and loss of forests due to wildfire, the committee recognized four distinct problem areas: (1) determining the most desirable regeneration density in different forest types and sites; (2) developing seedbed preparation practices that would enable conifer seedlings to survive summer drought and competition from hardwoods, grasses, and forbs; (3) combating rodent predation on conifer seed; and (4) controlling tree species composition by understanding seed producing patterns, nature of germination, and seedling establishment.

During this period, some silvicultural practices were also applied in the management of national parks. Aerial insecticides were used to control lodgepole needle miner in Tuolumne Meadows, Yosemite National Park. Extensive logging was done in Yosemite Valley to remove diseased and insect-killed high-risk trees and to restore historic vistas that were being blocked by the increased density of trees. Prescribed burning was also used extensively in giant sequoia groves in Yosemite Valley and along Highway 120 and Tioga Pass. This was done to reduce undesirable understory vegetation and to decrease fuels.

An increased desire by landowners for prompt reforestation and less reliance on the vagaries of natural regeneration led to greater use of planting, control of competing vegetation by herbicides, and control of stocking and species composition. In 1973, the old forest practice rules that had existed since 1943 were replaced by the current Forest Practice Act and its associated regulations. The old rules had no provision for enforcement of regulations, relied on natural regeneration from residual trees, and identified the seed-tree harvesting and regeneration method (table 15.1) as the preferred silvicultural practice. The new rules established minimum standards for silviculture based on methods that produce both even- and uneven-aged stands and introduced mechanisms for inspection and enforcement.

1979 to 1995

Harvesting in the late 1970s and early 1980s continued to emphasize clear-cutting on national forest lands and on some private lands. Silviculture in this period changed from relying primarily on tractors to the use of modern aerial cable logging, particularly on steeper ground. Increased harvesting in the true fir forests led to the development of a risk rating system (Ferrell 1980) that was useful not only for predicting susceptibility to insects and disease but also for characterizing trees that could provide snags or dead wood for wildlife habitat. Although reforestation often relied on natural seeding, planting was done where prompt regeneration was required. In addition, thinning the overstory to encourage the growth of young trees in the understory, known as release of advance regeneration, was used wherever possible.

Environmental concerns restricted the use of herbicides on public lands and led to hand weeding and hand cutting of

TABLE 15.1

Regeneration methods (abridged from Society of American Foresters 1995).

Even-Aged Methods
Methods used to regenerate a forest stand with a single age class.

Clear-Cutting
A method of regenerating an even-aged stand in which a new age class develops in a fully exposed microclimate after removal, in a single cutting, of all trees in the previous stand. Regeneration is from natural seeding, direct seeding, planted seedlings, and/or advance regeneration.

Seed Tree
An even-aged regeneration method in which a new age class develops from seeds that germinate in a fully exposed microenvironment after removal of all trees in the previous stand, except for a small number that are left to provide seed.

Shelterwood
A method of regenerating an even-aged stand in which a new age class develops beneath the moderated microenvironment provided by the residual trees.

Uneven-Aged Methods
Methods of regenerating a forest stand, and of maintaining an uneven-aged structure, by removing some trees in all size classes either singly, in small groups, or in strips.

Group Selection
A method of regenerating uneven-aged stands in which trees are removed, and new age classes are established, in small groups.

Single-Tree Selection
A method of creating new age classes in uneven-aged stands in which individual trees of all size classes are removed more or less uniformly throughout the stand to achieve desired stand structural characteristics.

shrubs too large to weed. In some cases, control of competing vegetation through the use of cattle was successful; sheep and goats were found to be too difficult to control to reduce vegetation successfully. Biomass harvesting to provide fuel for electric power generation permitted, for the first time, the economic thinning of dense stands of small trees. This technique the potential not only to enhance stand growth and to promote forest health but also to effectively reduce fuel loads. During this period, the effects of the wildfire suppression policy, plus preferential harvesting of pines of the preceding fifty years became evident. Sierran mixed conifer forests had changed from a mosaic with some large trees with wide spacing dominated by pines to stands with a much higher proportion of shade-tolerant California white fir and incense cedar, higher densities of young trees, and “fuel ladders” with a continuity of branches and foliage that reached from the ground to upper canopy.

In the period 1988 to 1995, two important issues have arisen. First, conservation and wildlife habitat concerns have resulted in a two-thirds reduction in the harvest of timber on public lands in California. Clear-cutting has been eliminated on public forestlands, and harvesting methods on both public and private lands have moved toward variants of single-tree and group selection. Clear-cutting on public lands has been replaced by cutting methods that include the retention of live trees. Second, public concern has led to efforts to withdraw the remaining old-growth stands from the commercial timber base. As reported in Franklin and Fites-Kaufmann (1996), 8.2% of the Sierran landscape has forests with late-seral-stage or old-growth structural characteristics. Concern about the declining amount of old-growth forest has led to interest in increasing the amount of late-seral-stage stands on federal lands.

Over the past 150 years, therefore, silviculture in the Sierra Nevada has evolved in response to changes in technology, merchantability standards, human needs for wood products, and societal concerns for the environment. This evolution is reflected in changes on both public and private forestlands from high-grading to selective cutting to regeneration cutting with an emphasis on upgrading forest conditions to the use of even- and uneven-aged silvicultural systems. Management of forests on federal lands for sustained yield of timber has been replaced by an approach focused on sustaining values, managing ecosystems, and forming strategies for protecting the spotted owl and other wildlife species. Dominating all silviculture is economics and the recognition of Sierran forest characteristics of drought, fire, insects, and disease.

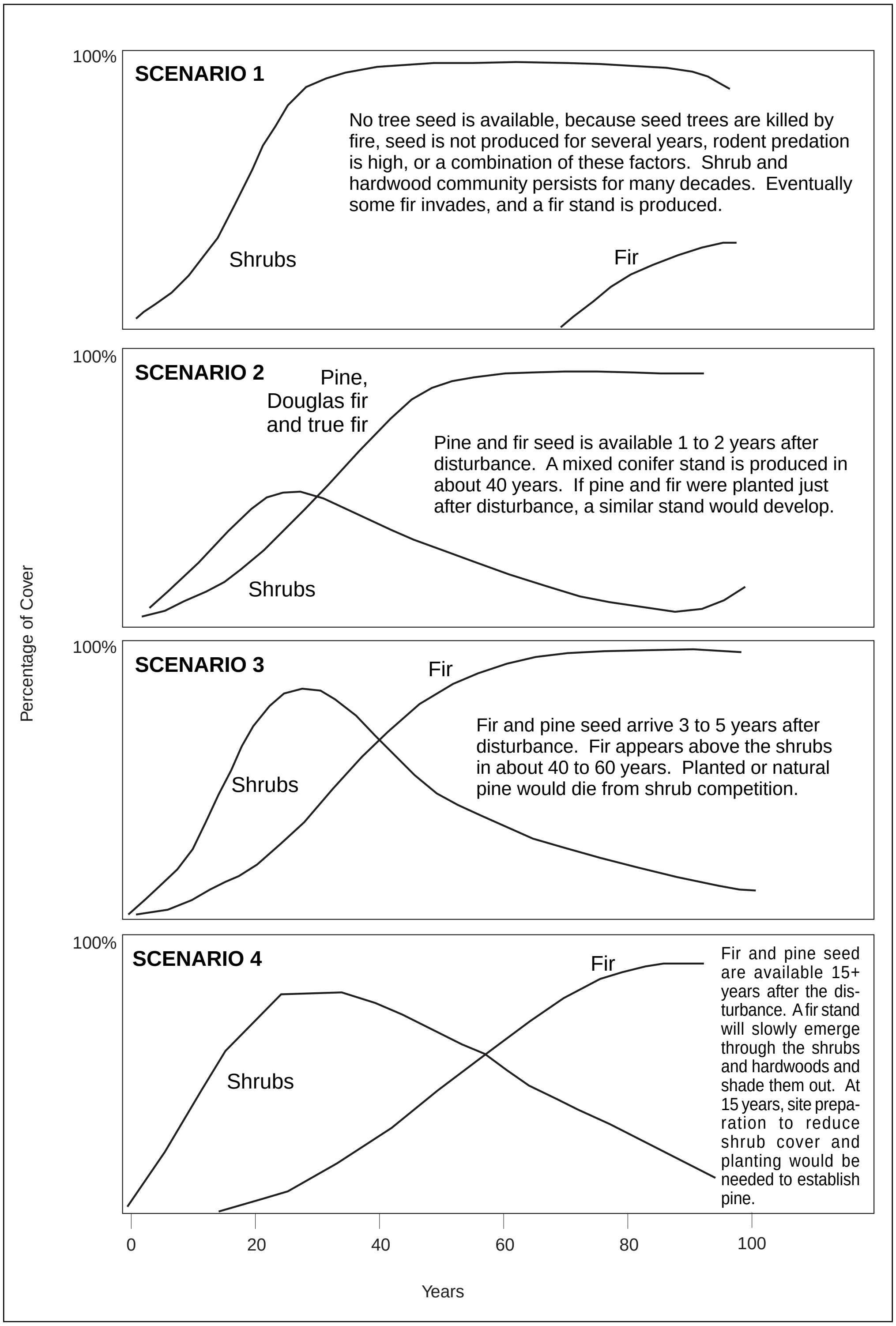
WHAT IS SILVICULTURE?

Silviculture is the art and science of controlling the establishment, growth, composition, health, and quality of forests and woodlands to meet the diverse needs and values of landowners and society on a sustainable basis (Society of American Foresters 1995). A silviculturist, therefore, is an applied ecologist who has sufficient knowledge of plant growth and environmental interactions to maintain or develop forest stands or landscapes of the desired composition and structure. Stand composition is the presence and abundance of trees, shrubs, herbs, and grasses. Stand structure is the vertical and horizontal arrangement of live and dead trees, including downed woody material, and the understory species composition of shrubs, hardwoods, and grasses. Thus, silviculturists can develop forests that, like some stands in nature, are basically a single species with high density and no understory, or that consist of complex mixtures at lower density with abundant understory. To do this, silviculturists assess variables such as stand density and productivity, seed source and presence of pathogens, and environmental conditions and constraints, and prescribe various treatments, including thinning, harvesting, regeneration, weed control, prescribed burning, animal pest control, and brush-field management designed to enhance stand structure to meet society’s needs.

Silviculturists use their knowledge of natural succession and stand development, as well as treatments such as planting and thinning, to achieve the desired stand conditions. For example, after a fire in a Sierran mixed conifer forest, several different stand types may result (figure 15.2) developing on

FIGURE 15.2

Four scenarios of stand development following a stand-replacement fire or other disturbance and no management or further disturbance. Species composition and structure of the future stand depend upon the species and amount of conifer seed present the first few years following the disturbance. Shrub seed (stored in the forest floor) and sprouting shrubs and hardwoods are nearly always present and will produce a dense stand after a disturbance.



different locations within the same burned-over area. If no source of conifer seed is available, the site will remain a brush field for many years, and true fir establishment may take many decades (scenario 1). However, if seed of different species of both pine and fir seed is available shortly after a disturbance, a mixed conifer forest will likely develop within about forty years (scenario 2). If seed is available after three or more years, it is likely that the next stand will slowly become stocked with fir, since pine competes poorly with established shrubs or hardwoods (scenarios 3 and 4). Assuming that no pine or fir seed is likely to be available soon after disturbance (scenarios 1, 3, and 4) and that a mixed conifer stand is the objective, a silviculturist would likely prescribe the planting of pine and fir as well as some shrub control to ensure that scenario 2 will occur. The land manager may decide that a brush field or a slowly developing fir stand would best meet management objectives, in which case no planting or shrub control would be done.

WHAT IS A SILVICULTURAL SYSTEM?

A silvicultural system is a planned sequence of operations that enables the forester to project the transition from an existing stand or landscape condition to a desired condition that conforms to a particular management objective. The process requires the articulation of management goals, the assessment of stand composition and dynamics, the capacity to modify stand treatments as conditions change, and the deliberate maintenance of options for changed objectives.

Control of Structure and Species Composition

All silvicultural treatments, in effect, influence the microenvironment, modify species composition, and thereby affect the relative capacity of grass, shrubs, and trees to grow and develop alternative stand structures. Such treatments help stands and landscapes develop structural diversity in both the horizontal and vertical dimensions, and these structures change over time as the vegetation grows and dies. Control of stand structure and species composition is effected by silvicultural prescriptions that control the interaction between species composition and the environment (temperature, water availability, light, etc.). This interaction controls the relative growth of specific forest vegetation, which, in turn, results in stands of a specific structure and composition.

Classical Systems

The traditional or classical systems of silviculture originated in Europe and were designed to upgrade stands that had been high-graded over past centuries with little regard for species mix or tree vigor. The systems result in stands having a distinctive structure representative of the range in structures in nature. The first systems developed were even-aged systems and included clear-cutting, seed tree, and shelterwood (table 15.1). Later systems developed were uneven-aged or selection systems that included single-tree and group selection. The range of techniques within both even- and uneven-aged systems facilitates the establishment and growth of both shade-intolerant and shade-tolerant tree species. The names of the systems are taken from the names of regeneration (harvest) methods. Each system represents a theoretical model of a distinctive set of stand conditions positioned along a continuum that ranges from systems suited to the regeneration and maintenance of stands of primarily shade-intolerant species (clear-cutting, seed-tree, and group selection) to those designed primarily for the management of the most shade-tolerant species (shelterwood and single-tree selection) (Troup 1959; Daniel et al. 1979; Smith 1986; State of California 1988; USFS 1995). The choice among systems is based on their ability to create and perpetuate stands having those characteristics that best meet specific land-management and societal objectives. Overriding all technical issues in the choice and implementation of systems are the particular managerial, ecological, and societal constraints that pertain to the management area in question.

Modern Variants of Systems

In modern silviculture, management goals tend to be very complex and therefore require diverse stand structures. It is often not desirable to manage stands according to one of the five conceptually simple silvicultural systems. This is because management objectives, on both public and private lands, usually have multiple values and because the implementation of a particular system may be modified due to peculiarities of the structure and composition of the existing stand and the quality, aspect, and topography of the specific site. Diversity and complexity of stands and landscapes can best be achieved by examining the structure and composition of each stand and determining what treatments are necessary to achieve the stand structure needed to meet management objectives. It is commonly desirable to use a range of systems or approaches within one landscape or large watershed. Treatment areas may have irregular boundaries that merge into neighboring stands, and both live and dead trees might be retained in even-aged systems and group selection to provide needed structural components. In many situations, it is important that the silvicultural system chosen be aesthetically pleasing as well as ecologically sound. Consequently, in any one location, much skill is needed to develop the system used.

CURRENT SILVICULTURAL PRACTICE

Silvicultural practice must be based on a firm scientific foundation. Although much remains to be understood, substantial knowledge has been accumulated to support stand treatments designed to control species composition and stand structure. This scientific knowledge is summarized in the sections that follow.

Understanding the Forest System

Forest Soils (Based on Poff 1996)

All terrestrial forest species are dependent upon soil, which supports the health and productivity of Sierra Nevada ecosystems. Consequently, it is imperative that soil characteristics and processes and the effects of forest treatments on soils be understood.

Three important indicators of forest soil productivity are soil volume, soil porosity, and organic matter, as well as their interactions. Soil depth controls rooting depth, available water, total nutrients, and buffering capacity. Soil porosity influences rootable soil volume, water infiltration, and biological activity. Organic matter is a storehouse of plant nutrients, especially nitrogen (N), phosphorus (P), and sulfur (S), and provides a habitat for a diverse biota that carries out energy transformations and cycles nutrients. In addition, organic matter on the forest floor protects soils from erosion and retards water evaporation, and large woody material provides a water reservoir and habitat for many organisms, as well as shelter and habitat for small and medium-sized mammals (Maser and Trappe 1984; Harmon et al. 1986).

Three important processes that tend to reduce soil productivity are erosion, displacement, and mass wasting. Under a forest canopy, soil erosion is negligible (McColl and Powers 1984), but, with removal of trees, soils may erode through sheet erosion, overland flow, rill formation, gully erosion, or dry ravel. The amount of erosion depends on the extent of the disturbance, the slope, and the soil type. In the Sierra Nevada, soils developed from granitic bedrock are the most erodible, whereas soils developed from metasedimentary bedrock are the most stable.

Mass wasting results from landslides and improper road building and is more common on steep slopes (Atzet et al. 1989). Although localized mass wasting can occur in the Sierra Nevada, it is not as widespread as in northwestern California or the Pacific Northwest, because about 70% of the forested land in the Sierra Nevada is on slopes of less than 32% (Rice 1979). Soil movement might be minimized by ensuring that ground cover is maintained. Leaving large residual trees or patches of trees, as in the current practice of green tree retention, provides better protection for the soil by reducing solar insolation and slowing the rate of decomposition of forest litter. In particular, because most erosion is associated with roads, special care needs to be taken in road design, placement, construction, and maintenance.

Distribution and Cycling of Mineral Nutrients. Globally, forest soils are enormous sinks for carbon and N, with the carbon in soil equaling that of vegetation and the atmosphere combined (Powers and Van Cleve 1991, Johnson 1994). This is because as much as three-fourths of net primary production can be associated with the development of fine roots and mycorrhizae (Grier et al. 1981), especially in true fir stands (Powers and Edmonds 1992). Most nutrients are taken up by a forest stand before crown closure, after which as much as 30% to 50% of N needs and 20% to 80% of P needs may be met by internal translocation (Powers 1979; Prescott et al. 1989; Powers and Van Cleve 1991). As a stand reaches maturity, the return of nutrients to the soil in litter fall approaches the rate of nutrient uptake (Powers 1979). Of all plant nutrients in forest ecosystems in the Sierra Nevada, N is often the most limiting (Powers and Edmonds 1991). In general, mature mixed conifer stands have about 10% of N in the forest floor, 80% in the soil, and the remaining 10% in standing biomass (Powers 1992). In true fir forests, due to colder temperatures and a slower rate of litter decomposition, the distribution of N is 40% in the forest floor, 47% in the soil, and 13% in standing biomass (Powers and Edmonds 1992).

To maintain nutrient status in forest soils, losses from leaching, biomass removal, volatilization, and soil loss must not exceed inputs from atmospheric deposition, decomposition of organic matter, and mineralization. Because the soil and forest floor on productive sites contain the vast majority of nutrients, management practices should be oriented toward maintaining their integrity and structure by minimizing compaction, erosion, and loss of soil organic matter.

Compaction. Soil compaction is a major cause of reduction in productivity. It occurs when a force is applied to a soil, particularly when it is moist (Baver 1930, Froehlich 1974, Alexander and Poff 1985), by harvesting and site preparation equipment that causes a reduction in macroporosity and an increase in density (Hatchell et al. 1970; Alexander and Poff 1985). Poor aeration, oxygen deficiency, and increased density reduce root penetration, lower water migration, and reduce mycorrhizal activity (Harmon et al. 1986).

The effects of compaction on individual tree growth are well documented (Froehlich 1978; Wert and Thomas 1981; Froehlich and McNabb 1984; Helms and Hipkin 1986a). This is because most studies have been designed to compare the growth of individual trees on compacted versus noncompacted soils on landings and skid trails. In general, the decrease in height growth of trees is directly proportional to the increase in soil density (Froehlich and McNabb 1984). Seedling height growth is commonly reduced by 20% to 40% in compacted soil (Minore et al. 1969; Murphy 1983; Froehlich and McNabb 1984). On the Foresthill divide, sixteen-year-old ponderosa pines associated with skid trails and landings having the highest amounts of compaction had a height reduction of 43% at the age of one year and 15% at fifteen years (Helms and Hipkin 1986a). In the same Foresthill study, individual tree volume growth on landings, on skid trails, and in areas adjacent to skid trails was reduced due to compaction by 22%, 29%, and 13%, respectively (Helms and Hipkin 1986b). In general, both the degree and depth of compaction are reduced by the presence of litter and various sizes of rock, and compaction increases with successive trips by machinery over a skid trail (Mace 1970; Froehlich 1978; Miles 1978; Boyer 1979; McColl and Powers 1984). Once soils are compacted, they may take up to fifty years to return to natural levels of porosity; the length of time for recovery depends on soil type, occurrence of subfreezing temperatures, and degree of compaction (Hatchell et al. 1970; Froehlich 1979; Wert and Thomas 1981; McColl and Powers 1984; Morris and Miller 1994). If compaction is deep, soils may never return to their natural state without major physical disturbance (McColl and Powers 1984).

The effects of soil compaction on the growth of an entire stand, however, are not well understood, because they are much more difficult to address. The study of the Foresthill pine plantation mentioned earlier, found that, because compaction caused substantial mortality, the reduction in stand volume per acre on landings increased from 22% due to compaction alone to a total of 69% when additional volume loss due to compaction-induced mortality, resulting in lower stocking, was considered; similarly, on skid trails, the reduction in volume increased from 29% to 55% (Helms and Hipkin 1986b). Stand growth on areas adjacent to main skid trails was reduced by 13% with no increase in mortality. Stand volume in the bulk of the stand between skid trails was not reduced. Consequently, it must be remembered that in managed stands, landings and skid trails are part of the permanent road/access system that will be used in each thinning entry and are not intended for tree growing. A reasonable approach for dealing with this issue, therefore, is to minimize that portion of the stands needed for access and harvesting, where compaction is not necessarily a potential problem, and to minimize the likelihood of causing compaction on the 90% of land devoted to tree growing.

Management strategies that can be used to limit soil compaction include using equipment that exerts a low pressure on the ground using aerial yarding systems, using winches to haul logs to the tractor on the skid trail rather than moving the tractor to each log, operating over snow or a cushion of slash or brush, avoiding operating when soils are moist, and minimizing the proportion of land area committed to skid trails.

Effects of Fire on Soils. The physical effects of fire on soils include loss of organic matter, loss of soil structure, hydrophobicity (DeBano 1979), and erosion and loss of nutrients (McNabb and Cromack 1990; Palazzi et al. 1992). The chemical effects include increase in pH, loss of the capacity to exchange cations, and loss of nutrients by volatilization, fly ash, and leaching. The biological effects include the direct mortality of soil organisms.

The effects of fire on soil productivity can be either beneficial or detrimental, depending on fire intensity, soil type, and site history (Atzet et al. 1989; Morris and Miller 1994). Adverse effects on soils increase as burn intensity increases, and the negative effects are proportional to the amount of surface duff and soil organic matter consumed (DeBano 1979; Sandberg 1980; Boyer and Dell 1980). Total N loss is almost linearly related to litter consumption and little N loss occurs until litter consumption, exceeds 25% (Dunn and DeBano 1977; Powers 1979, Clayton and Kennedy 1985). Cations such as calcium, magnesium, sodium, and potassium released in the ash bed are susceptible to leaching, but revegetation and exchange sites in the soil usually absorb them quickly (McNabb and Cromack 1990). This generalization may not be true of coarse-textured granitic soils that are low in organic matter. Relatively cool prescribed broadcast burning that does not entirely consume the forest duff and does not totally remove effective ground cover has little effect on nutrient status except on soils of low nutrient capacity. On the other hand, the piling and burning of slash concentrates nutrients, and the high intensities can damage the soil under the piles.

Effects of Silvicultural Treatments on Soils. The effects of silviculture on soils are primarily associated with the type of treatment and the frequency and extent of disturbance. Site preparation methods used in the 1950s and 1960s, such as scalping and windrowing of topsoil aimed at reducing competition by removing sprouting species and dormant weed seeds, have now been shown to greatly reduce long-term productivity (Kittredge 1952; Morris et al. 1983; McColl and Powers 1984; Dyck and Beets 1987; Powers et al. 1988; Powers 1991; Morris and Miller 1994). Currently, site preparation treatments are designed to keep as much soil in place as possible and to retain as much cover as possible consistent with securing regeneration.

Timber harvest can potentially affect soil productivity through erosion, displacement, compaction, nutrient removal, and leaching. The percentage of bare soil following logging can range from 2% for transporting logs to the landing by helicopter to more than 75% for tractor logging (Rice 1979). In partial cutting or thinning, the disturbance is less, but the total effects depend on the proportion of biomass removed and the frequency of entry. Surface erosion from yarding is typically quite low (McColl and Powers 1984). The potential erosion from skid trails can be high but is largely eliminated by forest practice regulations that require the placement of tractor- or hand-constructed mounds of soil (water bars) across skid trails. Most erosion during timber harvest is related to roads (McColl and Powers 1984).

The amount of nutrients exported through timber harvest depends on nutrient distribution in the ecosystem, utilization standards, and rotation length. The stemwood of conifers contains about 20% of the total tree carbon (C) and about 10% of the N. Even in the most intensive harvests, less than 10% of ecosystem N would be removed (Powers and Edmonds 1992). The actual amounts of nutrients exported would be considerably less under current practices, since the amount of clear-cutting in California has been drastically reduced, and green trees, unmerchantable material, snags, and small patches of trees are typically left on the landscape. Generally, stem-only harvests of middle-aged stands have little impact on nutrient export (Powers et al. 1990), and atmospheric inputs of N, P, and probably S probably exceed harvest export

(Morris and Miller 1994). During the 1960s there was concern about nutrient loss from leaching following clear-cutting (Likens et al. 1969), but the general consensus now is that, except in very extreme cases where vegetation is absent or intentionally suppressed, nutrient losses by leaching are negligible (McColl and Powers 1984; Johnson 1994).

Stand Density (Based on Oliver et al. 1996)

Stand density is a major controller of stand growth and development. It affects the abundance and composition of ground cover, shrub development, tree growth and vigor, species composition, cover and food for wildlife, fuels and fire hazard, and the dynamics of insect and disease populations (Assmann 1970; Smith 1986; Daniel et al. 1979).

Measures of Stand Density. Stand density is measured in absolute or relative terms, depending on the purpose for which the measure is used. Absolute measures include number of trees per unit area, basal area, volume, or cover. Relative measures include comparative assessments of "normal" or "full stocking" (Dunning and Reineke 1933; Schumacher 1928; Meyer 1938). In addition, various stand density indices are used (Reineke 1933; Curtis 1970). Stand density indices have the advantage of being relatively independent of age and site quality and, as a result, are used in the development of computer simulations of stand development (Reukema and Bruce 1977; Wensel et al. 1986; Ritchie and Powers 1993). These computer models are used extensively in forest management and permit one to predict how density affects such stand characteristics as tree mortality, growth rate, crown size, and other stand and tree parameters.

Effects of Thinning on Tree and Stand Growth. As trees grow and stand density increases, trees become more crowded, and fewer resources (water, light, and nutrients) are available for maintaining individual tree growth and stand vigor. The longest time-series analysis of stand development in the Sierra Nevada (Oliver 1979; Oliver and Dolph 1992; Oliver in press) has demonstrated that, through thinning, stands can be developed that have larger, more vigorous trees with longer live crowns and that also have a vigorous understory of saplings, shrubs, and grass. The unthinned, more dense stands, in contrast, had smaller, less vigorous trees, had no understory, were a poorer habitat for large mammals, and constituted a much greater fire hazard due to the presence of dead and dying small trees with low dead branches. For example, dense forty-year-old ponderosa pine stands at Foresthill had stem diameters averaging 34.3 cm (13.5 in) and had live crown ratios of 54% of their total height. Thinned stands, on the other hand, had stem diameters averaging 53.8 cm (21.2 in) and live crown ratios of 70%, and had developed a vigorous understory (Oliver 1979; Oliver and Dolph 1992; Oliver in press).

Past studies have also quantified the extent to which thinning influences the subsequent development of stand density in Sierran stands. In ponderosa pine, the increase in stand density tends to be slower as stands increase in age and in stands on less productive sites (Oliver 1979, 1988, in press). This information is fundamentally important in determining the effects of different levels of thinning on the capacity of stands to develop the desired types of structures. For example, red and California white fir stands differ from ponderosa pine stands in that, at the age of 100 years, the fir stands reach the much higher densities of 74 to 114 m^2/ha (320 to 498 ft^2/acre). The effects of greater shade tolerance and vigor at these higher stocking levels are that, after thinning, trees in these old, dense, true fir stands rapidly increase their growth rate. After about ten to fifteen years, these stands grow back to their previous densities (Oliver 1988). In mixed conifer stands, the relation between density growth following thinning depends primarily on the proportion of shade-tolerant and species to shade-intolerant species in the mixture and the overall stand vigor at the time of thinning. The relationships among stand density, tree size, and stand vigor developed for the Sierra Nevada are corroborated by many other studies in temperate forests (Assmann 1970; Daniel et al. 1979).

Ponderosa pine forests maintain a relatively constant rate of biomass production over a wide range of stand densities. In mixed conifer and true fir stands, however, net productivity tends to increase as stand density increases (Daniel et al. 1979; Oliver 1988, in press). This difference in productivity/density relationships has an important bearing on prescriptions for silvicultural manipulation. In shade-intolerant pine stands, it is very important to thin to maintain stand vigor, reduce susceptibility to insect and disease attack, and reduce the potential for drought-induced mortality. In the more shade-tolerant mixed conifer and true fir stands, however, it is not as imperative to thin to maintain stand vigor, but thinning is still desirable to reduce fuel loading, increase stand value for wood products, create variability in density suitable for a variety of wildlife species, create openings for ponderosa and sugar pine seedlings as well as understory plants, and accelerate stand development toward the late seral stage.

Effect of Understory on Stand Development. In the early stages of stand development, the growth of pines on sites of low productivity (17 m [55 ft] at the age of fifty) is restricted more by shrub density than by tree density (Oliver 1984). The effect of competition is very large, as, after twenty years, trees growing without shrubs had about 40% more volume than those on plots in which shrubs were not controlled. In general, it was found that as shrub cover increased from 0% to 30%, tree growth declined rapidly. Additional shrub cover from 30% to 100% had little further effect on tree growth on these lower-quality sites (Oliver 1984). On sites of higher productivity, intertree competition may be more important than tree-shrub competition.

These findings are important not only for timber management but also, for example, in deciding the tradeoff between providing dense layers of shrubs for wildlife cover versus the potential loss in wood production. Competing brush can substantially lengthen the time to first commercial thinning, regardless of tree spacing or site productivity, especially on lower-quality sites (Oliver 1979, 1984; Fiske 1982).

An additional issue concerns the contribution of shrubs to maintaining nutrient stability within forest systems. In the Sierra, Ceanothus species on poorer sites are commonly believed to contribute as much as 75 kg of nitrogen to the site per hectare per year (67 lbs nitrogen/acre/year). The proportion of this amount that is available to associated trees is questionable. However, the presence of nodulating shrubs is undoubtedly of value in adding nitrogen to the system and in cycling nutrients.

Shrubs affect the nutrient cycle in forest stands by increasing the concentrations and amount of nutrients, particularly cations, in the annual litter fall and by increasing nutrient turnover rates (Tappeiner and Alm 1975; Fried et al. 1989). In these studies, the increased annual input to the forest floor did not result in additional nutrients in the soil organic layers or the upper layer of soil. Compared to our knowledge of conifers, our understanding of the effects of shrubs or hardwoods on soil properties and long-term site productivity are not well understood. We know of no studies on the effects of understory shrubs on nutrient cycling and soil properties in Sierra Nevada forests.

Stand Density, Insects, and Disease. Considerable evidence exists that the susceptibility of stands to attack by a variety of insects is related to the decline in stand vigor with increasing density (Ferrell 1974; Ferrell and Smith 1976; Berryman and Ferrell 1988; Waring and Pitman 1985). Also, as stands become more dense they become more susceptible to root diseases, storm damage, and drought (Oliver 1985; Powers and Oliver 1970). A prime example occurred during the major drought in the late 1980s when Ferrell and colleagues (1994) showed that 98% of the variation in mortality in true fir could be explained by stand density and that individual tree characteristics were unimportant. This close relationship between density and insect attack has been observed in the Sierra, where ponderosa and Jeffrey pine stands that had been thinned had very low levels of insect attack, whereas about half of the trees in the unthinned stands were killed by bark beetles. On the other hand, there are some examples of apparently vigorous trees being killed by bark beetles. Insect populations can readily become epidemic because, once insects commence breeding, they are likely to spread to adjacent stands, even though these stands may be more vigorous.

The principal insect pests in Sierran forests are the tussock moth, western spruce budworm, and bark beetles which attack Douglas fir, and the fir engraver beetle and roundheaded fir borer which attack true firs. The insects most damaging to pines are the western pine beetle, the mountain pine beetle, the red turpentine beetle, and the California five-spined ips, which breeds in downed logs and slash. Diseases of particular concern include dwarf mistletoe (which is very prevalent but species-specific, so that the mistletoe associated with one tree species cannot infect another) and several root diseases, especially the annosus root disease, black stain root disease, and shoestring fungus (Burns and Honkala 1990; Scharpf 1993).

Of particular importance is a recognition of the interaction among bark beetles, fungi, and host trees that results in the death of pine trees. Wood 1993 provides three examples resulting from long-term collaborative research among forest entomologists and pathologists in the Sierra:

- As the symptoms of needle injury due to oxidant air pollution (ozone) increase, the incidence of infestation of ponderosa pine by the western pine beetle and mountain pine beetle increases.
- Attacks of black stain root fungus and the annosus root rot predispose ponderosa pine to infestation by pine beetles and white fir to infestation by the fir engraver beetle, particularly at low beetle populations:
- Tunneling by bark beetles, especially the red turpentine beetle, into ponderosa pine has been shown to introduce pathogenic fungi that cause the death of pines by interrupting water conduction in the xylem.

Sugar pine is a particularly noteworthy tree species of the Sierra Nevada. It is well known for its beauty, large-diameter stems, spreading crowns, large cones, and wood quality. It also has a remarkable capacity to continue rapid growth well into maturity (150 years or more). Unfortunately, it has been severely affected by white pine blister rust, which was introduced into North America from Asia at the turn of the century and extended into California in about 1930. This disease, which depends on an alternate host (*Ribes* spp.) for development, severely damages and kills smaller sugar pines in the cooler, moister northern Sierra. Although larger trees are less affected by the disease, the future of sugar pine as a component of northern Sierran forests is uncertain. Forest Service geneticists and pathologists at the Pacific Southwest Station are working on a program to produce rust-resistant stock for planting. Three different types of resistance to white pine blister rust have been identified, all of which are strongly inherited. One form of resistance appears to be controlled by a dominant gene that occurs with low frequency, another is a race of trees having slower rates of infection, and a third is a type of age-dependent resistance (Kinloch and Scheuner 1990).

Currently, some landowners in the Sierra are collecting cones from particular sugar pine trees and, by exposing seedlings to the rust, determining whether or not the parent trees are potentially resistant to the rust. Seed from sugar pine trees identified as being potentially rust resistant are collected and used for reforestation. In addition, normal silvicultural practices might also help retain sugar pine in Sierran stands. When groups of seed-bearing sugar pine trees with no (or slight) infection are found, thinning to favor the best sugar pines would reduce their risk of being destroyed by fire and possibly increase seed production. Soil scarification during thinning would prepare a seedbed and encourage natural regeneration. Thus, cohorts of new seedlings with potential rust resistance might be established throughout the Sierra, augmenting the rust resistance being developed by research.

In 1995, issues related to mortality caused by drought, insects, and disease reached major biological and political proportions due to the extremely high rate of mortality stimulated by a sustained drought in the Sierra since 1987. Most mortality occurred on relatively dry sites in stands having relatively high stocking levels, and consisted of the more shade-tolerant California white fir species. It appears that the trees initially lost vigor due to the drought and were finally killed by the fir engraver beetle. In portions of the Tahoe Basin, for example, 50% of the trees within certain stands died, raising complex issues regarding the extent to which these dead and dying trees should be salvaged for wood products or left to provide wildlife habitat and to be replaced by natural succession. The issue is made more complex by considerations of the extent to which dead trees contribute to fire hazard.

Management of Stand Density. In order to maintain diverse uses and values from Sierran forests it is generally necessary to provide a mosaic of stands of varying age and density throughout the landscape. In addition, mixed conifer stands have diverse species composition, whereas stands of lodgepole pine, true fir, and east-side pine are more pure. As individual stands develop within a landscape, the location of stands having particular characteristics changes over time. From past studies we know that, in general, stands with relatively high density have

Higher levels of:
Biomass production
Tree mortality
Slowed tree growth, with smaller branches
Susceptibility to insect attack
Storm damage
Insectivorous birds
Fuel loading and ladder fuels
Susceptibility to drought
Shade-tolerant species

Lower levels of:
Tree and stand vigor
Tree size
Rapid tree growth and larger branches
Understory cover and regeneration
Wildlife dependent on open space and large trees
Shade-intolerant species
Stand diversity

Consequently, to attain diverse land-management objectives, particularly on public lands, a mosaic of stands of varying density should be maintained, particularly if they are associated with a continuum of conditions from early to late seral successional stages.

Stand Growth Models. Several computer growth simulators are being used to project the growth of conifer forest vegetation types in the Sierra Nevada:

- CACTOS (University of California, Berkeley, Agricultural Experiment Station), the California Conifer Timber Output Simulator, is an interactive, FORTRAN 77–based computer program designed to simulate the growth and partial harvest of conifer forest stands in northern California. It is a distance-independent, individual-tree model. It predicts uninterrupted growth or the effects of various silvicultural prescriptions. Of particular value is the "free" harvest subroutine, which gives the user considerable flexibility in harvesting by diameter classes of varying width or species groups. The heaviness of cutting can be set by basal area limits or by a fraction of the trees present. Cutting limits can be set to prevent overharvesting.
- SYSTUM-1 (U.S. Forest Service, Pacific Southwest Research Station, Redding, California) is a computer program designed to simulate the growth of very young conifer stands in inland northern California and southern Oregon from three years after planting until the trees reach a diameter compatible with entry into CACTOS, ORGANON (from Oregon), and other models. The simulator is a distance-independent, individual-tree model. Trees are grown on a plot-by-plot basis to allow for varying densities. The growth reduction effects of different levels of up to six species of competing vegetation can be simulated. Precommercial thinning can be introduced.
- PROGNOSIS (U.S. Forest Service, Intermountain Research Station, Missoula, Montana) is a generic computer program that has two variants, SORNEC and WESSIN (U.S. Forest Service, WO-TM Service Center, Fort Collins, Colorado), that are used in northeastern California and in the western Sierra Nevada. These variants are designed to simulate the development of forest stands and silvicultural treatments that include stocking control, regeneration methods, site preparation, and thinning. The simulators can be linked to other models that predict the effects of pest outbreaks on forest stands and the production of other forest on. The combined outputs provide a basis for multiresource planning.

Each of these simulators has been used extensively in the Sierra to predict the likely outcome of alternative silvicultural prescriptions and management strategies. They do not predict the establishment of understory or the effects of fire, but they do model the growth of established stands.

Management goals for Sierran forests are commonly complex and diverse. Of greatest importance is the maintenance of forest health and the reduction of potentially destructive stand-replacement wildfires. Also, depending on specific goals, there is a need to regulate species composition, maintain tree growth and vigor, enhance wood production, and maintain wildlife habitat (Assmann 1970; Smith 1986; Daniel et al. 1979). Diverse stand conditions associated with different management goals can be obtained by controlling stand density and species composition through thinning combined with underburning. The absence of these two silvicultural treatments is evident today in Sierran forests, which are generally overly dense and unhealthy. Controlling density is also important to provide wildlife habitat. In general, populations of California spotted owl are associated with a mixture of denser, older stands for nesting and roosting and more open, younger stands for hunting prey. In terms of wood production, even though biomass production may be similar for stands growing at a wide range of densities, merchantable yields of wood are much higher in thinned stands composed of fewer, larger trees than in unthinned stands composed of many smaller trees. Further, greater financial efficiencies, from the standpoint of wood production, are generally obtained in stands maintained at relatively lower stocking levels.

It should be apparent that managing stand density by thinning requires considerable technical knowledge of the effects of thinning on growth and yield and on diverse wildlife species, as well as knowledge of fire behavior in stands of varying density. Knowledge is also needed regarding how to treat slash to avoid unacceptable fire hazard and insect buildup and regarding the potential for soil compaction and nutrient depletion. Trade-offs need to be made between the frequency and heaviness of thinning as well as among timing, tree size, choice of equipment, markets for products, and cost-effectiveness. Managing stand density is therefore a complex issue requiring the combined talents of silviculturists and specialists in other natural resource disciplines.

Regeneration (Based on McDonald and Tappeiner 1996)

The ability to regenerate stands after disturbances such as fire and timber harvest, as well as within the urban/wildland interface is an important part of forest management in the Sierra Nevada. Methods of regeneration include natural seedling establishment, planting, release of advance regeneration, and coppicing of hardwoods. Aerial seeding is not now being used in the Sierra, because (1) the hot, dry summers preclude the spring application of stratified seed; (2) fall seeding is not successful due to excessive losses of seed over the winter; (3) distribution of untreated seed results in most seed being consumed by rodents and birds, and coating seeds with repellents to avoid predation is no longer environmentally acceptable; (4) seed is now very expensive, so aerial seeding is not economically feasible. All regeneration methods (except aerial seeding) are appropriate in specific circumstances, and their use is determined by an evaluation of management objectives and such variables as availability of a seed source, microclimate, soil characteristics, potential competition from shrubs and grass, vigor and distribution of advance growth, and the desired species composition and structure of the future stand. In practice, combinations of methods are commonly used.

On many sites, federal and state regulations set standards for regeneration. Generally, they require that sites be stocked with 250 to 741 seedlings/ha (100 to 300/acre)within three to five years after any harvest that removes most of the trees, depending on tree species and site quality.

The need to develop reliable methods to regenerate Sierran forests was recognized well over half a century ago (Dunning 1923). Large fires from lightning, mining, logging, and railroads had resulted in hundreds of thousands of acres of brush fields. Because it would commonly take at least sixty years before these brush fields returned to forests—and these would consist of shade-tolerant fir and cedar— foresters embarked on a large program of brush-field clearing and planting of ponderosa pine, which was a dominant species of the presettlement forest. In 1955, Baker began a concerted effort to develop regeneration practices based on an evaluation of the interaction among the physiological condition of seedlings, genetic considerations of seed source, and the microclimate of the site to be regenerated (Baker 1955). This work resulted, in 1961, in improved seed zone maps in which the State is divided into eighty-three seed zones (Buck et al. 1970), supplanting the older maps developed by Fowells in 1946 that had only twelve zones. These new seed zones provide a mechanism by which seedlings can be planted in the same zones from which the seed was collected. The work also resulted in guidelines for seed collection and handling, nursery stock production, site preparation, planting techniques, and vegetation control (Schubert and Adams 1971; Jenkinson 1980).

Natural Regeneration. Sierran forests are, of course, generally capable of being established naturally from seed. In some stands, such as those consisting of east-side ponderosa pine, this might not be the case, as reported by Show (1926):

> In the virgin forest, particularly in pure yellow pine, when a good crop of seed is produced (and this only occurs at intervals of from five to eight years), the chances are slight that an equally good crop of seedlings will result. The long dry season and the severe frosts typical of the region will destroy the vast majority of the young seedlings during the first years of their lives. Only once in every 10 to 25 years, on the average, does a satisfactory stand of seedlings become established.

In nature, the timing and success of regeneration depends on the coincidence of favorable factors that include the availability of seed, presence of a suitable seedbed, limited predation (insects, rodents, birds, and disease), favorable microclimate (limited frost, moderate temperature, and low evaporative stress), adequate precipitation, and limited competing vegetation (Baker 1952; Tevis 1953; Schubert 1956; Beetham 1963; Stark 1963,; Tappeiner and Helms 1971; Ustin et al. 1984; Laacke and Tomascheski 1986). The success of regeneration under specific conditions is also influenced by the relative shade tolerance of the species in question. Another factor adding to the uncertainty of natural regeneration is that conifers typically do not produce a good crop of seeds every year. The interval between good seed crops varies throughout the Sierra but in true firs is generally about one to four years, whereas the interval in ponderosa pines and Douglas fir is about two to eight years (Fowells and Schubert 1956; Tappeiner 1966; Gordon 1986; Burns and Honkala 1990; McDonald 1992). California black oak has a periodicity of heavy acorn crops every eight years (McDonald 1992). Recognizing all these uncertainties, the silviculturist attempts to create microclimates suitable for natural regeneration by choosing the most appropriate harvesting and site preparation methods (Gordon 1970, 1979; Laacke and Tomascheski 1986; McDonald 1976, 1983; Dunlap and Helms 1983).

Release of Advance Regeneration. In the understory of both natural and managed stands, there is commonly advance regeneration—particularly of California white fir, red fir, and incense cedar, as well as California black oak and tan oak—which develops in openings in the canopy that are caused by thinning or by natural events. This advance growth grows slowly and may persist for decades in the understory. When the canopy is opened up through treatment or natural gaps, this advance growth is often released and becomes an important component of the stand structure (Dunning 1923; Von Althen 1959; Gordon 1973; Oliver 1985; Tesch and Korpella 1993). The rate of growth of advance regeneration after release can be predicted from measurement of the prerelease live crown ratio and annual height growth (Helms and Standiford 1983). Under partial harvesting, the capacity of understory seedlings to respond to increasing levels of light is in accordance with generally accepted shade-tolerance rankings (Minore 1979), in which California white fir is the most tolerant and shows the most rapid growth of all species with increasing light; Douglas fir, incense cedar, and sugar pine are similar and somewhat less tolerant than California white fir; and ponderosa pine is the least tolerant and exhibits the least growth—half that of other species—under all partial light conditions (Oliver and Dolph 1992).

A survey of literature and personal experience with natural regeneration indicates that

- Shade-tolerant species such as California white fir, incense cedar, and red fir reproduce well in microsites ranging from exposed to shaded. The fir species will seed into shrub communities and eventually overtop them and produce pure stands of conifer.
- Ponderosa pine, Douglas fir, and sugar pine will not reproduce reliably in dense stands nor in brush fields. Well-timed disturbance to the forest floor, an open environment, and seed availability are necessary for their establishment. In addition, competition from shrubs and grasses must be low for at least the first year and often for several years.
- Light shade aids the survival and early establishment of all species. Too much shade retards growth. Once seedlings have become established, all species grow best in full sunlight, regardless of tolerance.
- Natural regeneration of Sierra Nevada conifers can be used to regenerate sites after logging, providing there is sufficient seed source and a favorable microenvironment. Foresters must be able to use appropriate site preparation treatments such as well-timed scarification of the forest floor or prescribed burning that coincides with a seed crop and controls grass and shrub competition.
- Advance regeneration is an important component of regeneration. Careful logging is needed, and it may be desirable to interplant with shade-intolerant species to ensure well-stocked mixed conifer stands.

Planting. In today's forests, where prompt regeneration is a prime concern, the likelihood that natural regeneration will be a failure in any one year is such that forest managers often prefer to supplement natural regeneration with planting. Planting ensures that the desired mix and density of species can be established before competing weeds dominate the site. This is particularly important when it is necessary to regenerate a site after a disturbance or when it is desired to keep shade-intolerant species such as ponderosa pine, sugar pine, and giant sequoia in mixed conifer forests.

In the early years of planting conifers in California, a high mortality rate was common, primarily because of the characteristic summer drought in the Sierra Nevada. It was realized that seedlings had to be physiologically capable of becoming established rapidly during the short period in the spring when the soil is fully charged with water. The prime need was to produce seedlings capable of producing new roots immediately after being planted.

Research on seedling physiology, nurseries, and planting procedures has provided a scientific basis for successfully establishing Sierra Nevada conifers. The several state, federal, and private nurseries in California that produce conifer planting stock have utilized this knowledge and now produce seedlings with a high capacity for survival. The original research on the physiology of pine seedlings showed that nursery practices, especially seed source, time of lifting, and method of seedling storage, greatly influence seedling capacity to produce new roots (Stone and Schubert 1959; Stone et al. 1963; Stone and Jenkinson 1970, 1971). Measures of root growth capacity as an index of seedling vigor were shown to be directly related to the survival of field-planted seedlings (Jenkinson 1976, 1980). Other factors affecting seedling vigor are sowing schedules in the nursery and infection with beneficial mycorrhizal-forming fungi (Jenkinson and McCain 1993; Jenkinson et al. 1993). However, even seedlings in the best physiological condition will have lower survival rates if they are planted when soils are less than approximately 10°C for pines and less than approximately 3° to 4°C for red and California white fir (J. L. Jenkinson, U.S. Forest Service, Pacific Southwest Research Station, conversation with the author, 1995) and if they are planted improperly by inexperienced or poorly supervised crews.

Genetic Considerations in Reforestation. The growth and development of trees depends on the interaction between their genetic makeup and environment for growth. In any reforestation program it is important to use seeds from trees having desirable phenotypic characteristics. In addition, genetic makeup varies from tree to tree, from stand to stand, and at larger geographic or provenance levels. Consequently, to ensure adaptation to the site, as well as high survival and productivity, it is safest to use seeds or seedlings from a local seed source. As was mentioned earlier, to assist land managers in obtaining seed or seedlings from known sources, California is divided into approximately eighty seed zones (Buck et al. 1970; Arvola 1978). All seed or seedlings that are used for reforestation purposes are identified as to the zone from which they originated.

Because of genetic diversity within tree populations, there is an opportunity to develop seed sources or planting material that will ensure that reforested areas have broad genetic variation that will buffer the stands from changes in the environment. Opportunities for tree improvement are available at many levels of management, including by leaving better phenotypes as seed trees and shelterwood for natural regeneration, and by upgrading stands through selective cutting. In addition, genetic improvements can be made in the manner in which seed is collected or through the development of seed orchards. The first formal tree improvement plan in California was developed by the USFS in 1963. Which it established goals for hybridization of pines, seed production areas, sugar pine resistance to blister rust, and superior tree selection and seed orchards (Fowler 1963). This program was broadened into a tree improvement cooperative in 1971 involving the California Division of Forestry, several major forest industries, and the University of California, Berkeley (Kitzmiller 1976). This cooperative developed six seed orchards and a number of progeny testing sites in the northern Sierra and in other forest regions. The tree improvement plan had two areas of focus: (1) a base-level program aimed at ensuring the maintenance of at least the status quo with respect to native populations on all forestland while striving for gains in volume growth of up to 10%, and (2) a high-level program aimed at achieving sustained high genetic gains in adaptability and volume growth in major species through repeated cycles of selection and breeding. The second, longer-term program involved delineating breeding zones for each of the four major species, selecting 200 superior trees from each zone, testing their progeny, and establishing seed orchards of parents propagated by seed or by grafting (Kitzmiller 1976). The long-term aim of this cooperative program is to produce genetically improved trees for regeneration of both federal and private forestland in California that will ensure adaptability, be less susceptible to insects and disease, and have higher productivity.

Vegetation Management

Throughout the Sierra Nevada, almost all disturbed sites rapidly become invaded by shrubs, herbs, grasses, or sprouting hardwoods. Characteristically, soil surface layers contain millions of seeds per acre of ceanothus, manzanita, and other shrubs and forbs, some of which can remain dormant but viable in the soil for a hundred years or more (Quick 1956). Dormancy is broken by fire or by abrasion from machines, and seed rapidly germinates. Other particularly aggressive plants are bear clover and bracken fern, which sprout dense networks of underground rhizomes that produce dense foliar cover.

Shrubs are an important component of forest stands because they provide habitat for various wildlife species, help cycle soil nutrients and prevent erosion and because some fix nitrogen. However, depending on density, they can be severe competitors that prevent the establishment of conifers, particularly shade-intolerant pines (Harrington et al. 1991; McDonald and Fiddler 1989). The effect of competition on reducing conifer growth is well understood (Bolsinger 1980; Radosevich et al. 1976; Conard and Radosevich 1982b; Lanini and Radosevich 1986; Walstad and Kuch 1987; Tappeiner et al. 1992; McDonald and Oliver 1984; Oliver 1984; Conard and Sparks 1993). In some cases, survival of pine seedlings has been reduced by 80% as shrub biomass increased to about 7,000 kg/ha (6,245 lb/acre) (Hughes et al. 1987; McDonald and Radosevich 1992). The effect of shrub removal can be long lasting. Conard and Sparks (1993) showed that California white fir saplings maintained a continued response eight years after treatment. In general, research has supported the common observation that shrub canopy in the Sierra must be reduced to below approximately 30% before detectable increases in growth in conifer saplings will occur (Conard and Radosevich 1982a; Conard and Sparks 1993; Oliver 1984).

Options for controlling competing vegetation in the Sierra can include mulching, manual methods (cutting or grubbing), grazing, and herbicides (McDonald and Fiddler 1993). A review of forty studies has produced the conclusion that all of these methods will release conifer seedlings; however, herbicides continue to be the most effective and least costly method of control. Use of this method, however, is often constrained by societal concerns. Cattle browsing is very effective in some areas (Allen 1987; Huntsinger 1988). Mulching is often expensive, and hand grubbing is effective only when applied to herbaceous plants and small shrubs that have germinated from seed. Several cuttings may be needed to control vigorous sprouters such as tan oak, manzanita, and Prunus spp.

The need to release conifers from weed competition must be considered in all regeneration methods. This is true for both even-aged and uneven-aged methods because in both, bare mineral soil must be provided to permit conifer seedlings or germinants to become established, and this also favors the rapid growth of shrubs and herbs. All release treatments should be prescribed at the minimum level needed to provide desired plants with a temporary advantage relative to competing plants. Once the desired plants are established, the desired proportion of ground cover vegetation can be maintained.

In summary, forest managers have several methods for regenerating Sierran stands that are based on research and have been successfully applied. Experienced silviculturists, with firsthand knowledge of their sites and the information outlined here, are a key part of any successful regeneration project. Application of this information varies throughout the Sierra and must be adapted differently to east-side and west-side forests, depending on specific stand conditions. The potential natural regeneration of both trees and shrubs, methods for shrub control if needed, and the operational aspects of tree planting and evaluating seedling survival and growth vary from site to site.

Productivity of Sierran Forests

Except for stands on serpentine soils or on east-side volcanics, Sierran forests are productive, with growth rates varying within each forest type. Very productive mixed conifer sites can produce 17.5 m^3/ha/year (250 ft^3/acre/year) (Oliver in press), with trees that are 42.6 m tall trees (140 ft) in 50 years (Biging and Wensel 1985). Red fir forests at high elevation are often pure, sometimes mixed with California white fir, and can be very dense and highly productive. They are capable of producing 15.0 to 16.4 m^3/ha/yr (214 to 235 ft^3/acre/year), with trees that are 36.6 m (120 ft) tall in fifty years (Schumacher 1928). They also can attain high basal area densities of 114 m^2/ha (498 ft^2/acre) (Oliver 1988). In the northeastern California and on the east side of the Sierran crest, site quality is much lower due to low precipitation and shallow soils. East-side ponderosa pine forests, for example, reach densities of 32 m^2/ha (140 ft^2/acre) but have a productive capacity of only 5.6 m^3/ha/year (80 ft^3/acre/year) (Oliver 1972).

Knowledge Gained from Research Forests

The University of California Blodgett Forest Research Station: Mixed Conifer (Based on Olson and Helms 1996)

Blodgett Forest Research Station is a 1,214 ha (3,000 acre) property in the mixed conifer forest type at an elevation of between 1,188 and 1,463 m (3,900 and 4,800 ft) near Georgetown, California. It was given as a gift to the University of California, Berkeley, in 1933 after it had been logged of most high-grade commercial timber. Over time, new conifers became established and young-growth stands and residual large trees grew in size until, in 1958, the university was able to begin annual timber sales. Blodgett Forest is dedicated to research and the demonstration of forestry. In order to provide diverse stand structures, a management plan was initiated that divided the 109 compartments among even-aged management, uneven-aged management, and unmanipulated reserves. Regeneration methods used in Blodgett Forest include even-aged methods (clear-cutting and shelterwood) and uneven-aged methods (single-tree selection and group selection). In addition a treatment called overstory removal was used; this involves removing large trees to release existing conifer regeneration. All forest operations are done within the context of a Timber Harvest Plan approved by the State Department of Forestry and Fire Protection and meet the requirements of the California Forest Practice Act. Regeneration is accomplished with a mixture of natural seeding and planting. Because of sequential forest inventories, the records at Blodgett Forest permit an analysis of sixty years of forest growth and thirty-six years of comparative silviculture. These records are the longest time-series data set in the mixed conifer forest and provide the most extensive information on the long-term outcome of alternative silvicultural practices in the Sierra Nevada. Details of inventories, growth and yield, and outcomes from the use of alternative silvicultural treatments are provided in Olson and Helms 1996.

Growth in the Forest from 1899 to 1994. As was mentioned in an earlier section, Sudworth (1900, 1901) measured one of his fifty-three 0.10 ha (0.25 acre) plots in the Sierra Nevada in what is now Blodgett Forest. This single plot had, in 1899, 108 trees per acre, the average height of which was 45.7 m (150 ft), with clear stems 9.1 to 10.6 m (30 to 35 ft). The average area was 214 m^2/ha (930 ft^2/acre), which is twice that shown as maximum in Dunning and Reineke's 1933 tables for young-growth mixed conifer stands at age 150 years. Of the total basal area, 49% was in California white fir, 19% was in ponderosa pine, 13% was in incense cedar, 10% was in sugar pine, and 9% was in Douglas fir. The largest eight trees per acre, those between 121.9 and 137.2 cm (48 to 54 in) diameter at breast height (dbh), were all California white fir and ponderosa pine, but all five species were represented in diameters greater than 111.7 cm (44 in). No trees reported were less than 40.6 cm (16 in) dbh, and all had fire scars, with the most recent having occurred fifteen years previously. There was abundant regeneration of all species, aged from one to twelve years old. With a historic ground fire cycle of between seven and twenty years, most regeneration would presumably be repeatedly destroyed, giving rise to the commonly described open, parklike stand conditions of the presettlement period. Over the first decade of the 1900s the forest was extensively logged by railroad. The first inventory of the forest was made in 1934, and subsequent forestwide inventories were made in 1955, 1973, and 1994 (table 15.2).

These data show that growth in Blodgett Forest from 1934 to 1994 was 265,700 m^3 (56.3 million board ft). From 1955 to 1994, total harvest in the forest was 318,100 m^3 (67.4 million

TABLE 15.2

Growth over the period 1934 to 1994.

Year	Forest Stocking (Million Board Ft)[a]	Stocking (Board Ft/Acre)[b]	Growth (Board Ft/Acre/Year)
1934	26.18	12,700	
1955	37.82	18,350	257
1973	63.94	22,680	918
1994	82.47	29,270	959

[a]1 board ft = 0.02832/6 m^3.
[b]1 board ft/acre = 0.06997/6 m^3/ha.

board ft). Total growth was therefore 583,400 m^3 (123.7 million board ft), and the accumulated harvest through 1994 (adjusted for changes in forest area over time) represents 68% of total growth. As Blodgett Forest became more fully stocked, growth acre/year increased from 3.0 m^3/ha/year (257 board ft/acre/year) in 1934 to 11.2 m^3/ha/year (959 board ft/acre/year) in 1994.

Finding 1: Mixed conifer forests on high-quality sites are capable of having an increased stocking and growth rate while at the same time sustaining a harvest equivalent to 68% of growth. Concurrently, the diameters of trees can increase by as much as 76.2 to 101.6 cm (30 to 40 in), and overall forest structure can become more diverse.

Effects of Silvicultural Treatments on Growth. Productivity in terms of growth per acre per year depends both on silvicultural treatment and on the unit of measure (table 15.3). Because of the absence of harvesting, growth in compartments left as reserves was among the highest of all treatments. The highest-volume growth (including harvest volume) occurred in group selection areas, but this was due to relatively high harvest levels in areas with that treatment. The highest growth in basal area occurred in the clear-cut and group selection areas, reflecting the high growth rates of pine regeneration, the fact that all trees in a young planted stand grow rapidly, and the fact that areas with other treatments contain suppressed and intermediate trees that grow relatively slowly. Growth in single-tree selection areas was very similar to that in areas managed under even-aged methods with thinning. Stands that were clear-cut and replanted had lower average growth than continually stocked uneven-aged stands, due to the period during which clear-cut stands are being regenerated.

Finding 2: The board foot productivity of areas with group selection, single-tree selection, and even-aged treatment was similar. In time, it is expected that clear-cut areas will also produce about 1,000 board ft/acre/year. Differences in productivity and individual tree growth are due to the residual stocking levels after harvest (or the heaviness of the cutting).

Effects of Silvicultural Treatments on Regeneration. Regeneration surveys done in all treatment areas in 1994 show that the total number and distribution by species of seedlings 0 to 1.2 m (0 to 4 ft) tall and saplings 0 to 10.1 cm (0 to 4 in) dbh is not markedly different among silvicultural methods of regeneration (tables 15.4 and 15.5). The data show that the most abundant species of conifer regeneration on all treatment areas are California white fir and incense cedar. Least abundant are the shade-intolerant pines (ponderosa pine and sugar pine, particularly in areas where cutting has been aimed at thinning as opposed to establishing regeneration. Douglas fir is intermediate in abundance. California black oak and other hardwoods are abundant in all areas. Other softwoods (Pacific yew and giant sequoia) occur in small numbers. Regeneration in all treatment areas (including those using clear-cutting and group selection) is adequate to maintain representative species composition and control of quality by precommercial thinning. Additionally, observations show that seedlings planted in areas on which the shelterwood, group selection, and clear-cutting treatments were used grow much more rapidly than natural regeneration in these treatments.

Finding 3: Natural regeneration of all species is adequate to provide well-stocked stands in all silvicultural methods, providing that bare mineral soil is available as a seedbed. Growth of regeneration is enhanced with exposed microsites, lower stocking levels, and control of competing vegetation. Planting ensures prompt conifer regeneration that can more readily compete with grass and shrubs.

Effects of Silvicultural Treatments on Understory Vegetation. Over the past thirty years of management of Blodgett Forest, the understory vegetation in many compartments has been manipulated to provide a temporary advantage to regenerating conifers. Treatments have included underburning, herbicide applications, grazing, and mixtures of treatments. For the past twenty years, records have been kept on the

TABLE 15.3

Growth by silvicultural treatment, 1980 to 1994.

Treatments and Reserves	Growth + Harvest (All Species): Volume (Ft^3/Acre/Year)[b]	Growth + Harvest (All Species): Volume (Board Ft/Acre/Year)	Growth + Harvest (All Species): Basal Area (Ft^2/Acre/Year)
Reserves[a]	194	1,510	3.9
Group selection	216	1,090	8.4
Single-tree selection	123	710	4.5
Even-aged thinning	136	890	3.8
Overstory removal	70	400	3.1
Clear-cutting (0 to 14 years)	77	190	9.6

[a]No harvesting occurred in reserves.
[b]1 ft^3/acre/year = 0.06997 m^3/ha/year.

TABLE 15.4

Number of seedlings per acre[a] by species and treatment in young-growth and old-growth reserve areas.

Treatment	Ponderosa Pine	Sugar Pine	Douglas Fir	White Fir	Incense Cedar	California Black Oak	Other Hardwoods	Other Softwoods	Total
Group selection	140	170	98	398	423	1,525	121	0	2,875
Single-tree selection	355	90	138	379	445	1,271	140	0	2,818
Overstory removal	139	43	166	334	546	1,456	123	0	2,807
Even-aged thinning	68	45	189	482	450	1,637	447	3	3,321
Young-growth reserve	6	36	53	369	142	272	478	25	1,381
Old-growth reserve	26	50	200	647	1,185	479	612	82	3,281

[a]1 seedling/acre = 2.471 seedlings/ha.

amount of ground cover vegetation present in the forest. Table 15.6 shows the average amount of ground cover, by silvicultural treatment and method of control of ground vegetation when remeasurements were taken in 1993-94. Table 15.6 shows that without any treatment, the amount of understory vegetation in managed compartments is approximately 16% to 30%. This amount of cover can be compared with the level of 30% that has often been cited (Oliver 1984 and others) as the threshold level above which growth of conifer saplings is markedly reduced. The relatively low level of 7.5% cover in untreated reserve compartments is due to their having high stocking levels of 67 to 83 m^2/ha (290 to 360 ft^2/acre). The effectiveness of herbicides is shown by the fact that compartments with this treatment have understory vegetation cover of between 5% and 10%. As might be expected, cattle grazing results in the most variable amount of control, with cover ranging from 4% to 52%. The use of a combination of grazing plus spot herbicide application kept understory cover to 7% to 9%. Underburning, with an average ground cover of 14%, was not as effective as other methods of control (except grazing) but was still satisfactory. It should be noted that, in all methods of shrub and herb control, substantial amounts of understory vegetation have been retained. The management goal in vegetation control is not to eliminate all ground cover but to reduce it below the 20% to 30% level.

Effects of Silvicultural Treatments on Fuels. Surveys show that the amount of fuels in any given treatment area depends primarily on the regeneration method (table 15.7). Clear-cutting, site preparation, and planting resulted in one-third less fuel than other treatments. The least fuels were removed in the single-tree selection method.

> Finding 4: Clear-cutting and planting removed the most fuels, and single-tree selection retained the most fuels. There was little difference among group selection, overstory removal, and thinned areas. Overstory removal and clear-cutting resulted in less accumulation of material greater than three inches in diameter. All treatments retained similar amounts of the nutrient-rich duff layer that is also critical to protect the soil from erosion.

Summary of Major Findings at Blodgett Forest. Records of 60 years of forest development have shown that mixed conifer forests respond well to diverse treatments:

- Various kinds of stand structures can be sustained without affecting stand growth.
- The amount of regeneration amount and the species composition are relatively insensitive to the cutting method used.

TABLE 15.5

Number of saplings per acre[a] by species and treatment in young-growth and old-growth reserve areas.

Treatment	Ponderosa Pine	Sugar Pine	Douglas Fir	White Fir	California Incense Cedar	Black Oak	Other Hardwoods	Softwoods	Total
Group selection	8	2	19	83	63	2	64	0	241
Single-tree selection	22	2	26	112	100	5	10	0	277
Overstory removal	7	10	10	49	44	10	23	2	155
Even-aged thinning	0	3	50	58	55	37	26	0	229
Young-growth reserve	8	3	19	108	53	3	47	6	247
Old-growth reserve	3	9	6	85	79	0	26	9	217

[a]1 sapling/acre = 2.471 saplings/ha.

TABLE 15.6

Control of understory vegetation under different silvicultural regimes (data from forty-four compartments).

	Understory Cover (%)		
	Shrubs	Herbs	Total
No Shrub Treatment			
Group selection	21.7	1.6	23.3
Single-tree selection	11.4	4.4	15.8
Thinning	23.3	6.3	29.6
Reserve	6.0	1.5	7.5
Herbicide			
Group selection	6.2	1.8	7.9
Single-tree selection	0.8	4.5	5.3
Overstory removal	4.9	5.4	10.3
Grazing			
Group selection	18.5	8.0	26.5
Single-tree selection	2.9	0.7	3.6
Overstory removal	33.0	18.5	51.5
Shelterwood	2.2	3.7	5.9
Grazing + Herbicide			
Group selection	7.7	1.9	9.2
Single-tree selection	4.9	1.7	6.6
Overstory removal	7.6	3.0	7.2
Underburning			
Overstory removal	11.8	2.0	13.8

- Growth and yield depend primarily on the number of trees per hectare.
- Clear-cutting and overstory removal had the least amount of fuels remaining after treatment; individual tree selection and reserves had the most.

Experience at Blodgett Forest suggests that in environments without stand-replacing fires, the mixed conifer forests of the Sierra are amenable to a wide variety of silvicultural treatments without a loss of productivity. All silvicultural treatments are applicable, ranging from those using even-aged through uneven-aged structures and those aimed at retaining few to many species. Stands and landscapes can be managed to provide a wide array of forest values and uses. This experience forms the basis of figures 15.3 and 15.4, which show the range of stand structures that can be attained from mixed conifer stands by silvicultural treatment. Both figures show stands that differ in the age and condition of existing trees, and the manner in which stand structure can change over time through the use of different even- and uneven-aged silvicultural systems. In both cases, it is important to recognize that a wide variety of stand conditions can be maintained and that, if desired, a similar long-term stand condition can be arrived at even though stands were harvested or regenerated using different treatments.

It must be recognized that Blodgett Forest is situated on a relatively level and very productive site. The management opportunities and rates of response to treatments are, therefore, wider and more rapid than those of forests on sites of lower productivity. In general, however, sites of all levels of productivity have a similar range of opportunities for stand development, the difference being that the rates of stand development are slower as site quality decreases. In addition, as site quality decreases, the silviculturist becomes increasingly concerned about the effect of treatments on the maintenance of soil nutrient status.

U.S. Forest Service Blacks Mountain Experimental Forest—East-Side Ponderosa Pine

The east-side pine type of northeastern, central, and southeastern California developed in the presence of relatively frequent fires that burned with variable intensities (Martin and Dell 1978; Weatherspoon 1983). These fires, coupled with heavy grazing by sheep, maintained surface fuels at low levels and kept understories relatively free from tree regeneration. Old-growth trees were two hundred to three hundred years old and approximately 76 cm (30 in) in diameter, and stands varied in density from being overstocked and having a high level of mortality due to beetle infestation to being more open, averaging about 12 trees/ha (5 trees/acre) (Dolph et al. 1995). With the cessation of extensive grazing and the

TABLE 15.7

Amount of fuels (tons per acre)[a] remaining after application of treatments.

Treatment	Duff[b]	Size Class[c] 0–1 in	1–3 in	>3 in	Total
Group selection	17.5	2.1	3.4	12.5	35.4
Single-tree selection	25.5	2.1	3.4	15.0	46.0
Even-aged overstory removal	15.0	3.9	3.4	7.9	30.2
Even-aged clear-cutting/regeneration	14.9	1.0	1.5	4.8	22.2
Even-aged—thinning from below	18.1	2.0	2.3	15.4	37.8
Old-growth reserve	26.9	3.1	2.4	14.6	47.0
Young-growth reserve	19.7	1.8	2.0	11.6	35.2

[a]1 ton/acre = 2.511 tonnes/ha.
[b]Decomposed leaves and branches.
[c]Undecomposed branches and stems.

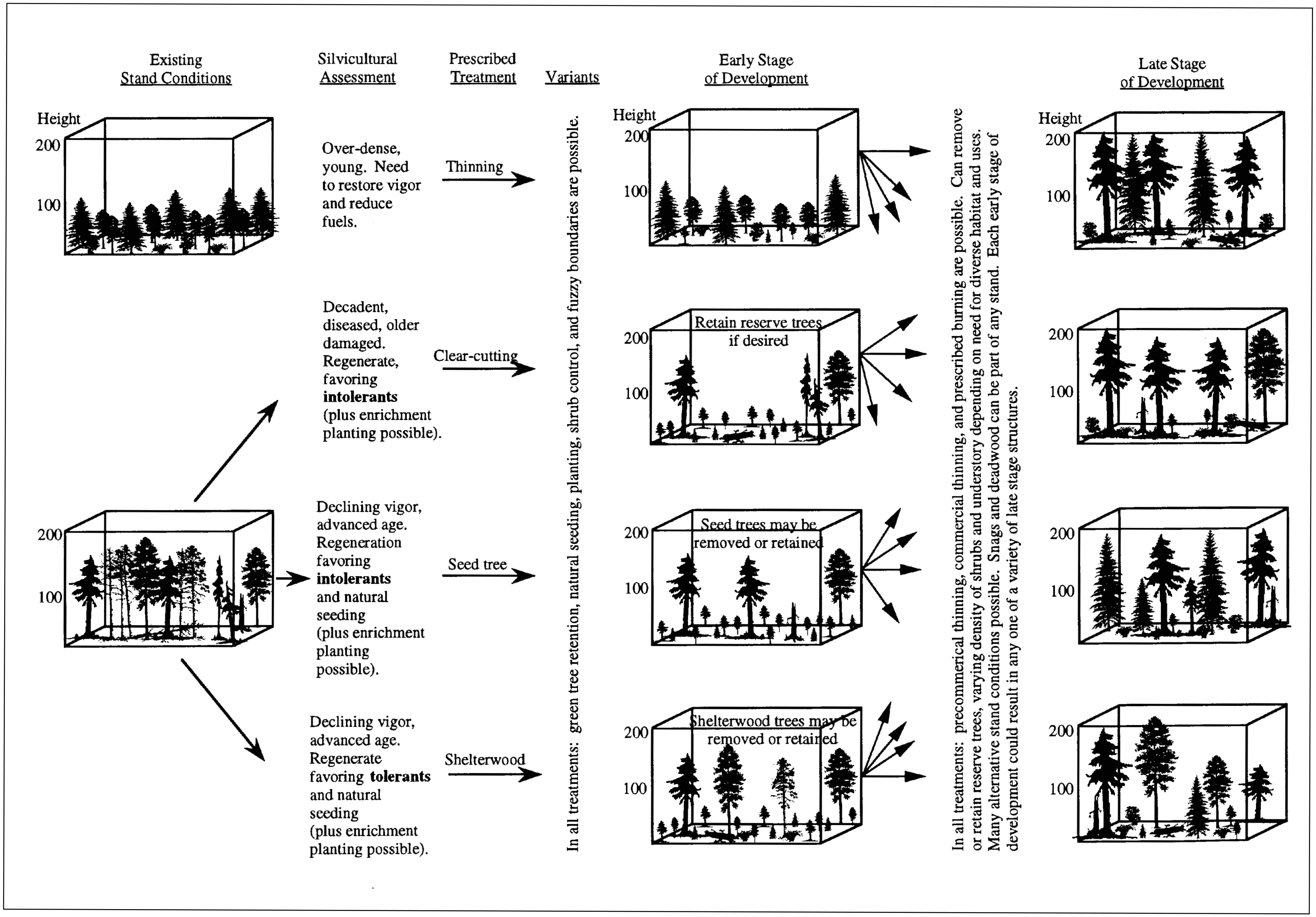


FIGURE 15.3

Hypothetical development of even-aged stand structures following differing silvicultural treatments in mixed conifer stands of differing initial condition.

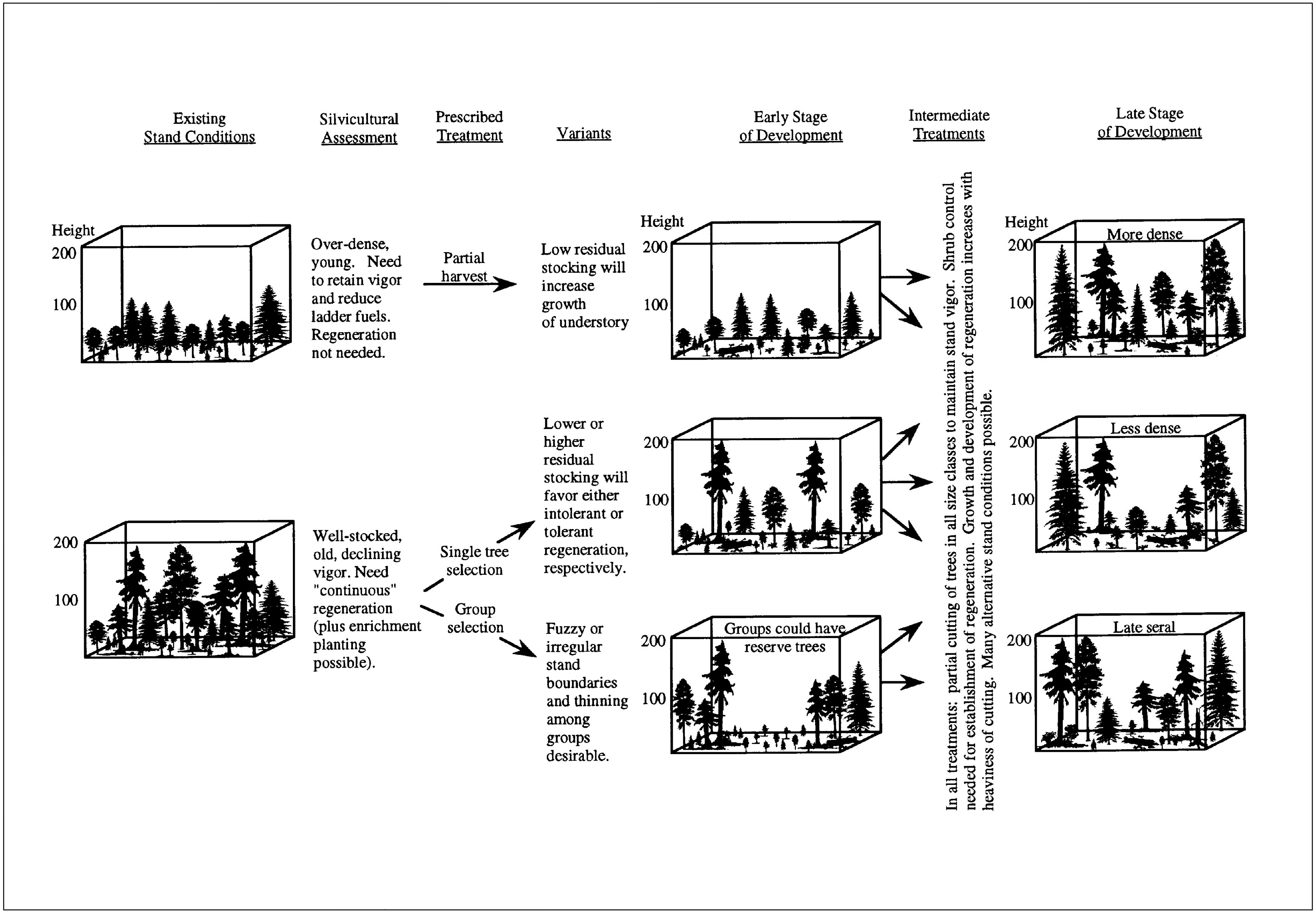


FIGURE 15.4

Hypothetical development of uneven-aged stand structures following differing silvicultural treatments in mixed conifer stands of differing initial conditions.

introduction of a fire-suppression policy, much of this forest type has developed abundant conifer saplings and poles.

In 1938 a study was begun on the Blacks Mountain Experimental Forest at an elevation of 1,706 to 2,103 m (5,600 to 6,900 ft) in northeastern California to test the effects of six levels of harvest on the growth and stand development of old-growth interior ponderosa pine. This forest type covers about 2.3 million acres, nearly 14% of the total available commercial forest area in California (Bolsinger 1983). The six treatments consisted of removing from 0% to 95% of existing volume. Forty-seven plots were established that covered, with their buffer strips, about 485.6 ha (1,200 acres). Because the plots were installed over a period of years, the database contains records ranging from forty-four to fifty-two years in length and consists of remeasurements of 13,274 trees on the plots (Dolph et al. 1995).

Diameter growth was lowest for pine and highest for California white fir, with actual rates being higher on stands with lowest residual stocking. Many large, old-growth pines showed zero or negative diameter growth due to the loss of bark. Initial volumes per acre ranged from 172.8 m^3/ha (16,010 board ft/acre) to 205.0 m^3/ha (18,480 board ft/acre). Growth ranged between 1.5 to 2.2 m^3/ha/year (22 and 32 ft^3/acre/year) with higher growth occurring on areas receiving heavier partial harvests. Growth responses in all plots were in proportion to the combined effects of different levels of cutting and competition from numerous small-sized trees. Also, ingrowth volume (the volume of trees that, since the previous inventory, have grown past the lower limit of measured diameter) increased, and mortality decreased with intensity of cutting. The loss of larger-diameter trees in all plots was probably due to increased stress brought about by competition from the large number of small trees. This stress resulted in reduced vigor and eventual mortality caused by bark beetles.

An evaluation of trends in plant succession found no evident relationships between changes in the percentage of the pine and California white fir portion of the pole component and intensity of cutting. Because the stands on the study plots developed under a Forest Service policy of wildfire suppression, the number of stems in the smaller size classes have increased dramatically since 1930.

The study results showed that if, as was the case in the 1930s, the objective is to maximize timber production, the best course is to convert slow-growing old-growth stands to young, faster-growing stands. Some old-growth characteristics have been lost in all plots, probably resulting from the wildfire-suppression policy. Perhaps the major lesson learned from this long-term study was a verification of the statement made by DeBell and Franklin (1987) that "characteristics and functions of old-growth stands cannot be guaranteed in perpetuity by simply preserving old-growth tracts." Like young-growth stands, old-growth stands must be managed for the desired attributes (Dolph et al. 1995).

U.S. Forest Service Swain Mountain Experimental Forest—Red Fir (Based on Laacke and Tappeiner 1996)

Red fir (Abies magnifica) and the varietal Shasta (Abies magnifica var. shastensis) occur in the higher elevations of the Sierra Nevada (Laacke 1990). Even though there are several associated species (California white fir, Jeffrey pine, incense cedar, sugar pine, western white pine, mountain hemlock, and lodgepole pine), much of the red fir forest is a natural monoculture. Red fir forests have an unusual capacity for sustaining high growth rates and developing stands having high density. Because of this, red fir forests commonly lack an understory and contain fewer and less diverse flora and fauna than more-diverse forests at lower elevations (Barbour and Woodward 1985; Gordon and Bowen 1978). The total numbers of vertebrate wildlife species in the red fir type, as indicated by the California Wildlife Habitat Relationships model (WHR) and database are slightly more than one-half of those predicted for the Douglas fir, ponderosa pine, and mixed conifer types (R. J. Laacke, U.S. Forest Service, Pacific Southwest Research Station, conversation with the author, 1995). Although wildfires of moderate to high severity do occur in the red fir type and can produce large patches of even-aged regeneration, the fire potential is low, and fires are characteristically of low to moderate intensity and result in small scattered groups of regeneration (Kilgore 1971, 1973; Agee 1990; Taylor 1993; Taylor and Halpern 1991). Red fir forests consist of stands of even-sized trees that appear to be of even age even though they were commonly regenerated over a long period and are thus actually of diverse ages.

With the exception of local impacts such as the narrow corridors harvested for fuelwood during the building of the railroads and the concentrations of livestock around new population centers (Leiberg 1902), incursion into the red fir forests was late in coming. Logging had begun in 1943 (Oosting and Billings 1943), but it wasn't until the mid 1950s that harvesting began to be significant. As recently as 1962, little was known about the silvical characteristics of red fir, and the type was regarded as too small, variable, and secondary in value to warrant management. Red fir forests continue to be, however, critically important from the standpoint of watersheds that produce much of California's water. Because of its inaccessibility, red fir has not been logged as heavily as other forest types and, after subalpine and lodgepole pine forests, is one of the least altered of the Sierra Nevada ecosystems.

Natural Regeneration. Natural regeneration is common in red fir forests (Barbour and Woodward 1985; Taylor and Halpern 1991), with good seed years occurring every one to four years (Laacke 1990). In a study of different regeneration methods, Gordon (1979) verified the importance of abundant seed and shade for adequate natural regeneration. Seedlings are most abundant in the most narrow clear-cuts, in small group selection cuttings, and under shelterwood stands having the largest number of trees in the overstory. The growth of seedlings is inversely related to the density of overtory (Laacke and Tomascheski 1986). Existing advance regeneration releases well following removal of the overstory (Gordon 1973), with the rate of release depending on the physiological condition of the regeneration (Gordon 1978; Oliver 1985). Initially, making large openings in stands resulted in little competition from grass and sedge. However, recent observations indicate that in later, adjacent openings the density of this vegetation increased due, probably, to an increased capacity for development of propagules. There is evidence that the increased cover of grasses, sedges, and herbaceous plants is providing opportunities for increased populations of gophers, which cause severe mortality to red fir regeneration. Although resistance to gopher damage increases with tree size, even large saplings can be killed when gopher populations are high (Gross and Laacke 1984).

Planting. Early reforestation efforts focused on planting cleared areas with Jeffrey pine, due to a high mortality rate among planted red fir. In many cases, natural red fir seedlings became established under the planted pines and became dominant before the pines reached maturity. However, on some sites, Jeffrey pine is now the dominant species. In the last two decades, studies of seed production (Gordon 1978); collection (Oliver 1974); and nursery production, storage, and handling (Jenkinson 1980) have provided the knowledge needed to raise vigorous seedlings with a high potential for survival after planting.

Silvicultural System. Past studies on Swain Mountain in the northern Sierra have demonstrated that red fir can be managed using either even- or uneven-aged systems. Harvested stands can be regenerated through natural seeding, providing the harvested areas do not exceed 61m (200 ft) in diameter. If the stands surrounding an area of this size are at least 45.7 m (150 ft) in height, they will offer sufficient shade and seed supply to provide regeneration. Larger blocks with a width of 106 m (350 ft) have about a ten-year delay in becoming fully stocked by natural seeding but, in time, develop into vigorous stands. With the current availability of high-quality seedling stock, it is expected that harvested blocks on favorable sites can readily be regenerated by planting. On more difficult sites, shelterwoods would enhance the survival of either natural or planted stock. A concern in even-aged management and group selection is the tendency for cut blocks to develop grasses and sedges that compete with seedlings and provide habitat for gophers. It has been demonstrated that red fir stands can readily be managed through the use of the shelterwood system. In stands of trees averaging 76 to 91 cm (30 to 36 in) in diameter, shelterwood cuttings left a range of cover represented by basal areas ranging from 12 to 48 m^2/ha (50 to 210 ft^2/acre). Most regeneration was obtained in the densest stands, but the highest growth rate was obtained in the least dense stands. Maximum growth of red fir, once established, occurred in fully exposed sites. Consequently, once seedlings have become established, the best growth is obtained by prompt removal of the overstory.

Because of the tolerant nature of the species and the response in its growth rate to partial cutting, there is considerable opportunity for the use of single-tree and group selection systems. This is indicated by abundant regeneration in natural gaps. The major constraint in uneven-aged approaches is the prevalence of dwarf mistletoe, which, where it occurs, makes it risky to regenerate stands using single-tree selection. The exception is on the most productive sites, where the growth rate of young trees will outpace the effects of the mistletoe. An additional difficulty with single-tree and group selection, particularly on steep ground, which requires the use of cable systems, is the potential for butt rot caused by logging damage. A risk rating system has been developed (Ferrell 1980) that provides quantitative guidelines based on crown characteristics for assessing the vigor of fir trees and their potential for mortality. These guidelines can be used to predict which trees are likely to die or produce snags and cavities and which have the potential to grow rapidly into larger size classes.

In all silvicultural treatments in true fir, it is necessary to avoid damage to trees, which often leads to infection by diseases (Aho et al. 1983, 1989). To ensure prompt natural regeneration, adequate soil disturbance produced by logging is needed to expose sufficient bare mineral soil as a suitable seedbed. Designated skid trails should be used to restrict soil compaction to permanent landings and access systems not used for growing trees. Red fir forests are noted for erodible soils and a high proportion of forest nutrient capital in the litter and down woody material on the forest floor (Powers and Edmonds 1992). Consequently, the use of practices such as broadcast burning of slash require more care in red fir forests than in other parts of the Sierra.

Even though red fir forests are dominated by one species, there is considerable silvicultural flexibility in their treatment, with many options available (Gordon 1970). Site-specific prescriptions will normally vary from the northern to the southern Sierra. For example, in the southern Sierra, lodgepole pine may regenerate with red fir. Providing the ground is not too steep, both even- and uneven-aged systems would work well, and variants of these methods that incorporate irregular-sized openings, thinnings, and the retention of groups of large trees, down logs, and snags would provide any structure needed for wildlife habitat, wood production, and watershed protection. Steep ground that requires the use of cable logging would limit treatment options.

U.S. Forest Service Challenge Experimental Forest—Mixed Conifer and Hardwood

The Forest Service Experimental Forest at Challenge, California, is the site of a long-term analysis of growth of natural regeneration under five different cutting methods (McDonald 1976). The site is highly productive, and the mixed conifer stands averaged 42.6 m (140 ft) tall. The study was installed

TABLE 15.8

Seedling density in study area, by cutting method.

Cutting Method	Seedling Density at Nine Years (per Acre)[a]						
	Ponderosa Pine	Sugar Pine	Douglas Fir	White Fir	Incense Cedar	Hardwoods	Shrubs
Single-tree selection	860	111	308	400	44	1,330	-
Group selection	1,500	185	134	565	16	807	-
Shelterwood	3,620	240	80	192	470	2,225	-
Seed tree	2,100	75	174	66	67	2,937	-
Clear-cutting	1,115	51	157	166	-	746	6,523

[a]1 seedling/acre = 2.471 seedlings/ha.

in the period 1960 to 1963, and either natural or artificial seeding was provided one to two years after cutting. Silvicultural methods tested were single-tree selection (20% of volume removed); group selection with 9.1, 18.2, and 27.4 m (30, 60, and 90 ft) diameter openings; shelterwood with 30 trees/ha (12 trees/acre), seed tree with 10 to 20 trees/ha (4 to 8 trees/acre), and clear-cutting. Table 15.8 shows the seedling density for each treatment at the end of the ninth growing season. These data show that pine was the most abundant conifer in all cutting methods, due to the predominance of pine seed sources in the overstory. In all cutting methods, the seedlings of all species were more than sufficiently abundant to develop into a mixed conifer forest, providing competing overstory was removed to allow seedling growth. Table 15.9 shows height growth for the site.

All species grew substantially faster in the clear-cut area; however the tallest species in all cutting methods were hardwoods and shrubs. Without exception, the height of every species increased as the availability of light and water increased, with growth being the least in single-tree selection.

Currently, approximately thirty years later (P.M. McDonald U.S. Forest Service, Pacific Southwest Station, conversation with the authors, 1995), reproduction in the group selection openings is about 4.6 m (15 ft) tall and constitutes releasable regeneration. The best growth is on trees in the center of the largest openings. Abundant conifers and hardwoods, especially those tolerant to shade, are present in all openings. All of the original species are present, but the growth of shrubs is limited.

Knowledge gained from the Challenge Experimental Forest includes the following:

- Each cutting method creates a specific microenvironment in terms of bare mineral soil, light, moisture, and soil surface temperature.
- The growth and development of species in these various microenvironments is directly related to their shade tolerance, with pine growing fastest and California white fir growing slowest as the amount of tree density and shade decreases.
- Hardwoods compete strongly with conifers and need to be controlled, initially, if conifer regeneration is to develop adequately.
- Tree growth is greatest in the centers of the largest openings.
- Densities of conifer seedlings and saplings densities need to be reduced if conifer regeneration is to develop adequately.

Silvicultural Prescriptions

Federal Lands

Silvicultural approaches in Sierran forests are based on policy, ownership, and existing stand conditions. Until the 1980s, decisions as to silvicultural treatments (such as harvesting, regeneration, and stand treatments) on federal lands were

TABLE 15.9

Seedling height in study area, by cutting method.

Cutting Method	Seedling Density at Nine Years (ft)[a]						
	Ponderosa Pine	Sugar Pine	Douglas Fir	White Fir	Incense Cedar	Hardwoods	Shrubs
Single-tree selection	0.5	1.0	0.7	1.4	0.9	2.4	2.1
Group selection	1.0	1.5	1.5	1.5	0.9	2.4	2.9
Shelterwood	2.7	2.6	2.1	2.9	1.9	2.9	3.1
Seed tree	3.7	3.4	3.1	3.7	2.7	4.3	3.7
Clear-cutting	6.2	5.5	4.2	4.0	-	12.6	7.8

[a]1 ft = 0.305 m.

based primarily on a goal of multiple use with an emphasis on timber management to support land-use plan goals. Assessments were made of stocking, health, and growth rate relative to equivalent well-stocked and healthy stands. Stands were then ranked in priority of need for treatment. Stands that were well-stocked, healthy, and growing well were bypassed, other stands were thinned, and the highest priority for treatment were those understocked, unhealthy, or slow-growing stands that could be made more productive by harvesting and regenerating. Culmination of mean annual volume increment (which indicates the maximum rate of biological productivity and commonly occurs in mixed conifer stands at the age of about 120 years when using merchantable measures of volume) was commonly used as an indicator of need to harvest and regenerate. In general, however, it was common for decisions regarding any one stand to be made incrementally, without a consideration of their implications —for example, a decision on regeneration might not be deliberately related to later needs for weed control or precommercial thinning.

Recognizing the need for better linkage between sequential decisions, the U.S. Forest Service in the mid-1970s instituted an advanced training program designed to teach silviculturists to develop an analytical and defensible approach to defining stand treatments. This approach centered on the development of a silvicultural prescription, which is a technical document supporting a recommendation on how to maintain or change existing stand conditions to meet desired conditions consistent with management objectives. It generally consists of (1) a description of stand location; (2) an assessment of current stand conditions (soil characteristics, site productivity, topography, climate, species, age, stocking, cover, structure, health, growth, understory composition, and cover); (3) a statement of management objectives; (4) a statement of ecological, managerial, and social constraints; (5) a list of proposed treatments; and (6) a description of the desired stand structure. The main objective of prescription writing is to formalize a procedure for assessing the ecological, managerial, and social characteristics of a particular situation, and to use this procedure to replace the more qualitative and subjective approaches used previously. Prescriptions vary in length and complexity, depending on the ecological and social sensitivity of the stand in question.

Stands that were diseased, poorly stocked, or slow growing due to past fires, harvesting, or insect and disease damage, were commonly clear-cut and planted with pines; the more shade-tolerant species native to the site were expected to seed in after the pines were established to re-form the mixed species composition. During the past decade, planting of mixtures of conifer species has become common. The sizes of clear-cut patches were small, averaging 2.0 to 8.1 ha (5 to 20 acres). If adequate advance regeneration was present and could be released, the treatment was called overstory removal. Other stands might be thinned (i.e., harvested selectively) to maintain health and to accelerate growth. This approach led to the maintenance of a mosaic of stand conditions on the landscape. Uneven-aged methods (single-tree selection and group selection) were seldom used in stands that are part of the "timber base" on federal lands.

Private Lands

On industrial private lands, with a goal of sustained timber production and consideration of other diverse land values, approaches similar to those used by the Forest Service were used to identify which stands were growing acceptably and which had a higher priority for harvesting or regeneration. Because existing stands had previously been salvage-cut or selectively cut, the diversity of size classes present provided a basis for more careful selective cutting (or thinning) designed to upgrade stand quality. Clear-cutting and planting was done in those stands that had a relatively uniform structure and where most trees were of economic size. In more structurally diverse stands, clear-cutting was not used, because of the need to dispose of the sometimes substantial amount of small-diameter, unmerchantable material and the probable need to plant. Approaches to regeneration varied considerably, depending on ownership and harvesting methods used. Natural regeneration was commonly relied on and, because of shaded conditions, the species that became established were primarily California white fir and incense cedar. This led to a change in species composition in the Sierra from the previously dominating pines to a preponderance of California white fir, incense cedar, and, in substantial areas, the dominance of released hardwoods. The past use of individual tree cutting on some private lands has led to an easy transition to adoption of the selection system.

Fire and Forest Management

There has been considerable experience with prescribed burning in the Sierra Nevada on park service and national forest lands. However, no comprehensive synthesis or summary of this experience has been undertaken to gain an understanding of the effects of the programmatic use of prescribed fires to limit wildfires, reduce fuels, or control the understory of established stands. Two important issues require research and application:

1. How to develop and maintain stand structures, densities and species composition that can be burned periodically to maintain fuelbreaks and forest health.
2. How can fire be introduced into stands that have not been underburned naturally or had prescribed fire for many years.

With regard to the first issue, there are currently no standard prescriptions. Perhaps a suitable goal would be to create wide spacing such that the crowns do not touch (about 40% crown closure). Maintaining this density in rapidly growing young stands (about thirty years of age) may require thinning every ten to fifteen years. Maintaining low levels of surface fuels (fallen trees, branches, shrubs, etc.) may require repeated prescribed burning at similar intervals. Pruning might be beneficial in these stands because it would limit the likelihood that wildfire and underburning will carry fire into the large crowns that develop at wide spacing and would also improve the quality of wood removed during thinning. If wood quality is not an issue, satisfactory reduction in crown length can be achieved through careful prescribed burning. Alternatively, maintaining a closed canopy might be beneficial on some sites, since this would encourage self-pruning, maintain a relatively cooler microclimate in the understory, and minimize the development of a shrub / hardwood / conifer understory. However, as trees age it may be necessary to encourage some conifer and hardwood regeneration to offset normal mortality. California black oak, tan oak, and Pacific madrone may be good fuel-break species, since they will sprout if their tops are damaged by prescribed fire.

The second issue involves several factors. First, on many sites where fire has not occurred for decades—especially productive sites—abundant fuel has accumulated from dying trees or limbs, growth of understory, and logging slash. To prevent controlled burns from doing unacceptable damage, these fuels should probably be reduced by either a combination of thinning from below and chipping followed by prescribed fire or if these treatments are not appropriate, a very careful initial burn followed by one or more reburns to consume the new fuels created by the initial burn. Second, fire commonly stimulates germination or sprouting of shrubs and hardwoods from seed banks and from buds on root crowns and rhizomes. Thus, controlled burning may produce more fuel than before the treatment. Reburning, herbicide applications, or mechanical treatments may therefore be needed. Burning in relatively dense stands can reduce sprouting vigor and kill most shrub seedlings. Third, areas that have not been burned for long periods commonly have deep accumulations of organic debris at the base of trees. Near the soil surface, the decomposing organic matter is generally rich in nutrients, holds considerable water, and therefore has abundant fine roots. Fire at the base of these trees tends to become very hot and, as well as killing or damaging the stem cambium, tends to completely remove this organic matter and associated fine roots. This is especially true for older ponderosa pine and sugar pine trees, since complete consumption of litter at the base of trees is likely, regardless of the season of burning. For California white fir, damage to the bases of the stems can be fairly easily controlled by burning in spring, when the lower duff is wet.

The important objective in fuels and fire management is, therefore, to design prescriptions to make the transition from the existing condition of wildfires that often burn all organic matter down to mineral soil to fires that are more frequent, cooler, and controlled. Considerable experimentation and research will be necessary before effective burning prescriptions can be developed that take into account the interrelationships among fire intensity, soil and nutrient characteristics, soil water availability, insect and disease dynamics, and forest growth. Important social issues are those associated with the risk of fires escaping, smoke management, and cost. The liability associated with escaped fires is a major issue limiting the use of prescribed fire. As a result the costs of burning associated the liability resulting from an escaped fire are prohibitive. Current regulations and air-quality standards have limited the number of days in which prescribed burning can be done to such an extent that prescribed burning probably cannot accomplish the required fuels reduction in all the areas.

Logging Systems

Future management of Sierra forests will require innovative logging systems because of the more complex stand structures needed to meet diverse management objectives. Use of cable systems and low-pressure ground systems (used in other western forest types) should become more common. Efficient, low-impact systems that remove small material can play an important part in reducing fuels in the understory of older stands, in thinning young stands to reduce fuel loading, and in lowering the potential for future insect outbreaks. New yarding systems can be quite efficient if planning is done prior to their use. In addition, they require less road building and cause less soil disturbance than many ground-based systems.

Role of Planted Stands

Planted stands have always been a part of Sierran silviculture. Initially, this activity focused on the clearing and planting of brush fields that had increased in extent due to the combined effects of lightning-caused wildfire and fires associated with mining, logging, and grazing. Initially, planting was restricted to pines because of the historic value and preference for this species and also because the exposed microclimatic conditions were suited to pine establishment. Currently, wildfires still consume thousands of acres in the Sierra Nevada annually. On private lands, which are mostly at lower elevations, these burns are commonly replanted to ponderosa pine. On federal lands, which are more commonly at higher elevations, mixed conifer species are commonly planted. Because wildfires will continue into the future, planted forests will continue to have an important role in the Sierra. The important question to address, then, is, what is the appropriate seed source and species composition, structure, and size and location of these planted forests on the landscape? Forest sites in the Sierra can grow productive stands in a wide variety of forms. Depending on land-management goals and ownership, planted stands can vary from dense, productive monocultures with high timber yields to mixed, uneven-aged, more open stands that could be virtually indistinguishable from natural stands. Similarly, planted stands can vary in age before harvest from short-rotation, biomass stands grown for pulpwood production to stands that can take 100 years or more to reach the stage at which they contain uneven-sized trees, contain dead and dying trees for habitat, and have many of the characteristics of late-seral-stage stands.

Performance of Young USFS Plantations (Based on Landram 1996)

The Forest Service has recently completed an analysis of plantation information to determine the programmatic success of artificial reforestation. New analytical techniques using the most current information were employed.

The USFS reports that forestland on national forests in the Sierra Nevada covers approximately 3.1 million ha (7.6 million acres). Four percent of this land, 123,000 ha (300,000 acres), consisted of plantations in 1991. Another 2% consisted on nonstocked areas not yet planted or scheduled for replanting, most of which resulted from the large fires on the Plumas and Stanislaus National Forests that occurred in 1987. There are about 9,400 plantations in the SNEP study area. About 500 of these were established after fire and the remainder after timber harvest. However, because of the large size of the burns, about half of the plantation area resulted from burns and half from timber harvest. The average size of plantations following timber harvest is 6 ha (15 acres), and the average size following a fire is 138 ha (340 acres).

Using site-specific automated stand records, the Forest Service has estimated that about 90% of the area where planting was done between 1988 and 1992 (inclusive) was stocked at more than 371 trees/ha (more than 150 trees/acre) at the time of the last survey. About 10% of the area had not been successfully regenerated, and work is continuing on these areas.

Recent inventories of older plantations (average age twenty-three years) to evaluate growth and species composition have shown that

- 65% of trees are either ponderosa or Jeffrey pine.
- 2% of trees are sugar pine.
- California white fir and incense cedar are becoming established underneath the planted pines in most forest types.
- Shrub cover averages about 50% and tree cover about 25%.
- Average stocking in 1991 was 680 trees/ha (277 trees/acre) and 10.8 m^2 basal area/ha (47 ft^2/acre). Thinning to reduce intertree competition and to maintain tree vigor will probably be desirable in about ten to fifteen years in many plantations.
- The volume at age fifty-five years (the probable time of first commercial thinning) was forecast to be 252 m^3/ha (3,600 ft^3/acre), which would meet timber management objectives in the current national forest plans.

In developing this assessment of plantation status, it is recognized that additional inventories of older mapped plantations will provide better estimates of species composition, stocking, and growth rates. Random spot checks of actual plantations have been done to verify the general characterizations. The new development of GIS-based maps for each national forest, showing the location of plantations and other forestlands provides a sound basis for monitoring the results of silviculture projects both in plantations and in other vegetation types.

SILVICULTURE OF OAK WOODLANDS

As described in McDonald 1995, California's indigenous hardwood resources can be divided into groups: foothill woodlands at lower elevations and forest-zone hardwoods at higher elevations.

The hardwood rangeland in the foothills throughout California covers about 4 million ha (10 million acres), 18% of which is publicly owned. Four percent is in reserves (Bolsinger 1988; Greenwood et al. 1993). Historically, these lands have been regarded as of limited value. Currently, however, they are recognized as being important for wildlife habitat, as a watershed, for rangeland, for conserving biological diversity, and for retaining open space (Standiford and Tinnin 1992; Helms 1994). A survey of county residents showed that the most important management issues are retaining oaks for shade, aesthetics, wildlife habitat, and fuelwood; improving oak regeneration; and offsetting the effects of land development (LeBlanc et al. 1989). It has been estimated that, from 1945 to 1985, oak woodlands were reduced by approximately 485,600 ha (1.2 million acres) (Bolsinger 1988). Earlier in this period, losses of oaks were due primarily to clearing for rangelands. In later decades, the primary causes of cutting were residential and commercial development and road and freeway construction. Since 1985, however, oaks have been valued much more than previously for wildlife habitat, soil protection, and enhanced property values (Standiford and Tinnin 1992). Consequently, there is less tendency for oaks to be cut and an increased interest in management and conservation (Standiford and Tinnin 1992).

Perhaps the most important silvicultural issue in the management of oak woodlands is lack of regeneration. In recent years, statewide studies have been conducted through the University of California's Integrated Hardwood Range Management Program (Standiford and Tinnin 1992) that have evaluated how various environmental and management factors affect oak regeneration. Studies have been made of site preparation, the use of augers to break up compacted soil, fertilizing to ensure adequate nutrient availability, top pruning to develop a more satisfactory shoot-to-root ratio to offset loss of water to evapotranspiration, weed control, methods of protecting seedlings from animal damage, and the role of introduced grasses and fire. These studies have shown that establishing oak seedlings is not as difficult as was once thought. Naturally regenerated oak seedlings tend to grow slowly, however, planted oaks will grow rapidly (0.6 m/year [2 ft/year]) if adequate soil moisture is available, especially if competing grasses are removed by clearing areas 1.2 to 1.8 m (4 to 6 ft) in diameter for each oak seedling (McCreary 1991; Standiford and Tinnin 1992). Where livestock browsing is a problem, tree shelters have been shown to be particularly effective—although somewhat expensive ($5 per shelter)—both in preventing browsing and in enhancing the microclimate for rapid growth (Standiford and Tinnin 1992).

Stocking control and thinning have received little attention in oak woodlands. A valuable contribution in this area is a report on the results of a five-year thinning study in ten stands of coast live oak (Pillsbury and Joseph 1991). The stands were sixty to eighty years old and averaged 25 to 27 cm (10 to 11 in) in diameter, 741 to 865 trees/ha (300 to 350 trees/acre), and 34 to 37 m^2/ha (150 to 160 ft^2/acre), and prior to thinning averaged about 4.9 m^3/ha/year (70 ft^3/acre/year). Stands were thinned to 23 and 12 m^2/ha (100 and 50 ft^2/acre). Five years after thinning, growth in the basal area of trees in the 23 and 12 m^2/ha (100 and 50 ft^2/acre) plots exceeded that of trees in control plots by ratios of 9:1 and 11:1, respectively. In terms of volume growth, trees in the 23 and 12 m^2/ha plots grew 74% and 128% more, respectively, than those in the controls. The authors suggest that landowners can conduct an economically viable thinning operation and enhance stand vigor while promoting sound land stewardship.

Hardwood types in the forest zone occur at elevations from about 180 m (600 ft) in the north to about 2,400 m (7,800 ft) in the southern Sierra (McDonald and Huber 1995). Almost all the hardwoods are of sprout origin following fire or cutting. They include tan oak, California black oak, giant chinquapin, Pacific madrone, canyon live oak, and red alder. They are commonly found as single trees or clumps and in association with Sierran conifers and shrubs such as manzanita, deer brush, coffeeberry, Prunus spp., chamise, and forbs and grasses. The important uses of this zone are for wildlife, aesthetics, wood products, and water. The role of silviculture in this zone is to maintain, create, and sustain the species composition, density, and structure of vegetation desired by society and landowners to meet their diverse needs (McDonald 1992). A particular issue in this zone is increasing urbanization, with its associated problems of fragmentation, increased wood use, and greater fire hazard.

CALIFORNIA STATE FOREST PRACTICE REGULATIONS

Silviculture on private forestland in the Sierra Nevada is largely constrained by policies and regulations contained in the state Forest Practice Act. California has had a Forest Practice Act since 1943. The original Act, which was in effect until 1973, identified the seed tree system as the basic harvesting method. It encouraged private landowners to use "due diligence" in avoiding damage and protecting other resource values, but it had no budgetary provisions to enable administration or inspection. This act was declared unconstitutional in 1973 on the basis that it was administered by a Board of Forestry that was dominated by the timber industry.

In 1973, the existing Z'berg-Nejedly Forest Practice Act was approved, which changed the membership of the Board of Forestry such that a majority now consists of members of the public and environmental groups. Requirements for submission of a timber harvest plan and minimum stocking standards are defined in the act, and detailed constraints on land management are defined in accompanying regulations. The stated intent of the act is to ensure that

> The goal of maximum sustained production of high-quality timber products is achieved while giving consideration to values relating to recreation, watershed, wildlife, range and forage, fisheries, regional economic vitality, employment, and aesthetic enjoyment.

The minimum stocking standards are defined in the act as follows:

> Within five years after completion of timber operations, the harvested area must be acceptably stocked by:
> a) having a point count of 741/ha (300/ac) where i) each countable tree that is not more than four inches in diameter at breast height counts as one; ii) each countable tree over 10.1 cm (4 in) and not more than 30.5 cm (12 in) in diameter at breast height counts as three; and iii) each countable tree over 30.5 cm (12 in) in diameter at breast height counts as six.
> b) The average residual basal area, measured in stems one inch or larger in diameter, is at least 20 m^2/ha (85 ft^2/ac) on Site I, or 12 m^2/ha (50 ft^2/ac) on Sites II or lower.

The rules pertaining to silviculture in the Sierra Nevada are defined in two districts, the Northern Forest District and the Southern Forest District. A registered professional forester is required to select silvicultural methods or alternatives that achieve maximum sustained production of high-quality timber products. The harvest plan must designate one or a combination of regeneration methods, prescriptions, or intermediate treatments defined in the rules, or a defensible alternate method. Detailed specifications are provided for all even- and uneven-aged regeneration methods. If clear-cutting is used, block size is limited to 8.1 ha (20 acres). Provisions are made for wildlife protection practices that cover nest sites for many species of birds and habitats for animals. Protection is provided for riparian areas and buffer strips bordering streams. Timber harvest plans are reviewed by the

Department of Forestry and Fire Protection (CDF), the Department of Fish and Game, and other agencies before to CDF grants approval to harvest the designated trees.

SILVICULTURE AND FOREST POLICY ANALYSIS: PRESCRIPTIVE VERSUS GOAL-ORIENTED POLICIES

Recently, several major forest assessments and analyses have provided bases for major shifts in forest management. These include FEMAT (Forest Ecosystem Management Assessment Team) in the Pacific Northwest, the CASPO (California Spotted Owl) report and the U.S. Forest Service DEIS (draft environmental impact statement) for implementing CASPO and SNEP (Sierra Nevada Ecosystem Project).

In evaluating any policy report, it is important to determine whether the intent is actually to regulate what can be done on the ground or simply to provide general guidance to achieve the overall forest structure that will provide for multiple values and uses. Both FEMAT and the CASPO report contain quite prescriptive language that specifies silvicultural systems or practices and provide limited flexibility to respond to varying ecological conditions within and among stands. The DEIS is less prescriptive and provides limited ranges of opening sizes and canopy cover. The difficulty with this approach is that the more prescriptive the silvicultural policy the greater the difficulty in making it meet multiple resource objectives, because of the wide variability in existing stand conditions. Implementing overly prescriptive policy leads to a reduction in landscape diversity. For example, specifying a diameter limit on cutting, the amount of basal area to be retained, continuous cover, and the number of snags over broad ranges of stand types could benefit certain wildlife species but would drive stand composition to shade-tolerant species and would also likely lead to stand-replacement fires, loss in stand vigor, and increased susceptibility to insects. On the other hand, general, goal-oriented policy statements that specify the need for reduced fire potential and certain types of habitat on a certain percentage of the forest and that allow forest managers flexibility in choosing the methods to implement the policy are much more likely to attain the desired objectives. For example, the "green tree retention" (GTR) policy in the DEIS would provide for better habitat, stand productivity, and visual quality by suggesting a broad range of trees to be left. Similarly, the group selection method should encourage a variable opening size that enables the silviculturist to obtain regeneration of varying levels of shade tolerance, develop "fuzzy" or more natural, irregular boundaries, address fire and fuels issues, and use safe logging practices. There is no single, universal silvicultural method or prescription that will result in sound management practices in all situations. Given the wide variability in existing stands in Sierran forests, flexibility is needed in prescribing treatments that best meet management and policy objectives.

In the development and analysis of forest management policy, evaluations are made of the long-term implications of various management alternatives. This means that the effects of alternative treatments on variables such as forest structure, wildlife habitat, timber and water yields, and fire potential must be projected over time. These projections commonly assume that certain "standard" silvicultural prescriptions will be implemented throughout the forest and that the vegetation will respond predictably. The standardized prescriptions used for these projections may be reasonable for policy analysis but should be used only as general guidelines for policy implementation. Sierran forests are so diverse in species mix, site productivity, density, and vigor that it is impossible to attain desired goals using a prescriptive approach. Also, it must be recognized that over the last two decades, some goals have undergone radical change. The alternative is to define goals and intent and to charge professional silviculturists with the responsibility and accountability of meeting these goals using appropriate, site-specific treatments.

The use of a prescriptive or regulatory approach is probably motivated by lack of trust. Resource specialists, special interest groups, or policy makers may not trust an agency's ability or an industry's willingness to implement a policy in the manner intended. However, rather than include prescriptive language in policy statements, it is far better to state desired outcomes and mechanisms (including monitoring procedures) for ensuring that the desired end results are achieved. In that way, the agencies can best use their professional expertise to devise workable solutions to complex forest management and silvicultural issues, and policy makers can ensure that their intent is carried out.

MAJOR ISSUES AFFECTING SIERRAN SILVICULTURE: IMPLEMENTATION OF NEW POLICIES

The major issues affecting the silviculture of mixed conifer forests are as follows:

The enormous buildup of small-diameter understory trees and fuels. One hundred years of selective forest harvesting in the Sierra Nevada have, in contrast to the Pacific Northwest where clear-cutting was the predominant practice, retained a heterogeneous forest of mixed species that still includes substantial amounts of large-sized trees, particularly on federal lands. The major change in forest structure and composition is the growth of an enormous quantity of small-sized, shade-tolerant trees in the understory, which has resulted from a combination of sixty years of wildfire suppression, logging that stimulated new growth of trees and shrubs, and the lack of markets for small-sized material. Ten years ago, this problem began to be addressed by a rising market for biomass thinnings that were burned to generate electricity. This thinning operation has covered about 40,469 ha (100,000 acres) per year for the past ten years. However, the subsidy for fuel chips has been removed, and use of woody biomass for power generation is no longer economical. Accompanying the rise in log stumpage prices, several sawmills have been built in California that are designed specifically to harvest small-sized trees for the production of 5 by 10 cm (2 by 4 in) studs, lumber, and fencing material. These operations only begin to address the enormous supply of small-sized trees that have accumulated in the Sierra. More plants of this kind will be needed if the problem is to be adequately addressed and potential fuels removed in a significant way. Prices for pulp chips fluctuate markedly, but even when high, additional markets for small material are needed in order to make possible sustained thinnings of small-sized understory trees, particularly of shade-tolerant species.

The high probability of catastrophic fire in the Sierra Nevada makes the leaving of unmanaged reserves for parks or wildlife habitat silviculturally untenable. Experience in Yellowstone and elsewhere has demonstrated the critical need to manage fuels on a landscape basis. Fuels management has a large silvicultural component, including controlling stand densities where appropriate.

The fact that California is currently importing about 65% of the wood fiber it needs. Sierran forests are generally very productive. If policies are developed that aim at increasing the proportion of wood grown for industrial consumption, silvicultural knowledge is already available that could double the current average production of 5.2 m^3/ha/year (75 ft^3/acre/year). Some stands could be designated primarily for sustained production of wood. The structure and species composition of these could be quite simple and of relatively short rotation or quite complex, uneven-aged, long in rotation, and "natural-looking." Silvicultural knowledge is already available to develop and manage both types of planted forests.

The need for long-term sustainability of forests. Silvicultural knowledge is available, and is currently being applied, that ensures long-term sustainability of forest stands from the standpoints of soil stability and nutrient demands. What needs to be developed is a new approach to the application of silvicultural systems that preserves the integrity of forests at the landscape or watershed level and results in the desired spatial distribution of diverse stand structures. A critical issue is the buildup of stand densities, with the associated increase in risk from fire and insects. In addition, better collaboration is needed among landowners, logging engineers, and silviculturists to ensure that operations are conducted in an ecologically sensitive manner.

Forest health. Forest health is a complex subject that involves the interaction of many factors, including stand density, vigor, and susceptibility to forest pests. What makes the concept difficult is that forest health can be interpreted at various spatial scales that include individual trees, stands, watersheds, and landscapes. In addition, forest health has a temporal characteristic that necessarily changes as one views it in terms of a year, a decade, or a millennium—that is, on human or ecosystem time scales. It must be recognized that healthy forests must periodically experience and be able to withstand drought, fires, and epidemic levels of insects and disease. Thus, a healthy forest is characterized by having long-term resilience to disturbance. In this context it is reasonable to include within "disturbance" the effects of timber harvesting, including limited clear-cutting, where these disturbances are used within the goals of sustaining long-term forest productivity.

The need for wildlife habitat for threatened and endangered species, in the form of old-growth, late-seral-stage forests. Increased awareness of the need to address forest fragmentation and to enhance the proportion of late-seral-stage forests does not require new silvicultural knowledge but the application of existing knowledge in a new way. Experience gained by both publicly and privately employed silviculturists has demonstrated a capacity to control stand structure and composition. It is a small extrapolation of this knowledge to anticipate that silviculturists can manipulate stands to provide many of the characteristics of old-growth forests even though they may be of relatively young age. Stands having large, well-spaced trees with suitable understory and downed woody material and with snags and dead trees in the canopy layer can probably be produced on lands of high site quality within 120 years, starting with bare ground. Existing seventy-year-old stands could be transformed into ones having many of the late-seral-type characteristics in fifty years. These manipulations would depend on markets for small material and opportunities for operations such as prescribed burning and the use of herbicides. Because silvicultural prescriptions are increasingly needed to meet complex wildlife habitat requirements, a particular need is to link silvicultural expertise in manipulating stand composition and structure to wildlife habitat as defined by the Wildlife Habitat Relations (WHR) models, which are used to predict the species of wildlife that are likely to be present in a stand of given characteristics. The approach used in these models of defining stands in terms of classes of canopy closure and diameter is increasingly being used for land classification and management planning.

In addressing wildlife habitat needs in the Sierra Nevada, it is probably inappropriate to design silvicultural treatments across landscapes and watersheds aimed at solving the problems of an individual target species. In general, the best way to ensure desirable habitat for diverse species of wildlife is by sustaining a diversity of stand structures and habitat. This can be done only by retaining the capacity within watersheds to use a diversity of silvicultural treatments and regeneration methods; the feasibility of doing this has been demonstrated at Blodgett Forest. Past history in California has shown the detrimental effects of the overuse of clear-cutting that was intended to overcome problems created by the previous overuse of high-grade harvesting. Similarly, rather than focusing on solving wildlife problems by a pattern of unmanaged reserves interconnected with corridors, it would seem preferable to emphasize management of lands to provide diverse habitats and values.

The need to protect of riparian areas and improve stream habitats. The most sensitive areas in mixed conifer forests are the areas adjacent to streams and wet meadows. It is essential that streams and aquatic ecosystems be maintained or restored to provide high-quality habitat. Existing forest practice rules provide stringent restrictions on management practices within streamside buffer zones and riparian areas. These rules must continue to be used on private lands and at least equivalent practices must be used on public lands. However, to maintain and enhance these areas, it is necessary to permit appropriate manipulation designed to meet these objectives. Precluding all management may lead, as has been shown in Yellowstone National Park and other ecosystems, to an unstable system, due largely to the elimination of natural disturbances such as fire.

The need to ensure sustained production of high-quality water. Considerable work was done in earlier decades aimed at evaluating the effects of different harvesting methods on water yields in the Sierra (Kittredge 1953; Anderson and Gleason 1959; West 1962; Turner 1985, 1986). This area of research must receive continued attention, since water is the most valuable product from Sierran watersheds. Forests play an important role in watersheds in protecting the soil and in ensuring that water is incorporated into the soil and released slowly into streams. Evapotranspiration and interception of water by forests is largely influenced by leaf area and canopy architecture—both of which are readily manipulated by silvicultural treatment.

The increasing pressure on urban/wildland interface forests. The growing population in California, with its associated increase in societal demands and expectations for goods and services, is placing increasing strain on Sierran forests. In particular, the rapid increase in urban development in the mixed conifer forests is creating a new zone of land use in the Sierra (USFS 1995). Silvicultural treatments are needed in these areas to ensure the health of trees that are in close proximity to structures and paving. Regeneration is needed to provide replacements as trees mature and die. And special treatments are needed to reduce fire hazards and risks and to retain forest health.

Fragmented forests resulting from checkerboard patterns of forest ownership and differing land ownership objectives. Ecosystem, watershed, and regional approaches to land management are requiring a new type of silviculture that transcends traditional stand-level and independent ownership approaches. This can already be seen in USFS approaches to the management of land by watershed or other landscape-level analysis as opposed to the traditional approach in which a given watershed might have several independent plans based on separate federal ownerships. The situation is made much more complex where watersheds contain private landholdings, which introduces major issues of private property rights. Silviculture could be the common language in these complex situations where collaborative land-management planning is becoming increasingly necessary.

In addressing these issues, silviculturists are redefining their field in the context of new approaches to the management of public lands:

Ecosystem management. Ecosystem management is also a complex subject. As envisioned by the Chief of the Forest Service at its inception, it is "an ecosystem approach" to management rather than the management of ecosystems. Although defined in various ways, the U.S. Forest Service defines it as "the skillful, integrated use of ecological knowledge at various scales to produce desired resource values, products, services and conditions in ways that also sustain the diversity and productivity of ecosystems" (Hazelhurst et al. 1995). This approach adds an expanded dimension to standard silvicultural prescriptions that traditionally have been used at the stand level. Ecosystem management requires a broader responsibility from the silviculturist and requires landscape-level planning.

Watershed analysis. Federal agencies have adopted a new approach to land management and interagency cooperation in the Pacific Northwest. Because agencies such as the Forest Service and the Bureau of Land Management often share responsibilities in the same watershed, a new concept of watershed analysis has developed as an outcome of FEMAT (Reid et al. 1994). Although currently being tested in north coast California forests, this concept may have relevance to Sierran forests. Watersheds have been adopted as the geographic unit for evaluating habitat needs and physical and socioeconomic conditions. The objective of watershed analysis is to summarize existing information, to identify information gaps, and to describe large-scale and interdisciplinary relationships. The analysis is commonly expected to be completed within a two-month period. Following this analysis will come detailed site inventory, analyses, and project planning. Watershed analysis is expected to aid in the management of riparian areas and to be a means of understanding ecosystems and cumulative effects (Grant 1994; Reid et al. 1994). It may also result in reducing the frequency of silvicultural entry within a watershed.

Adaptive management. An adaptive management strategy strengthens and formalizes a concept used by the Forest Service that encourages feedback and adjustment in forest management. It consists of a series of steps structured to promote rapid learning and to modify management in responsive to changing societal objectives and evolving knowledge of ecosystems (USFS 1994). It is a strategy designed to increase the probability of attaining desired outcomes. It links actions through time and is seen as an important component of ecosystem management. The concept of adaptive management has traditionally been used by silviculturists, particularly those who have had the benefit of long-term association with a given land base. Adaptive management formalizes this approach which will be a positive influence in the development of sound silvicultural prescriptions on public lands.

CONCLUSIONS

A substantial amount of silvical and silvicultural knowledge is available to guide the management of Sierra Nevadan forests. Silviculturists have the knowledge and capacity to maintain or modify forest composition and structure to meet the diverse needs of society. All coniferous forest types in the Sierra—mixed conifer, true fir, and ponderosa pine—respond well to treatment and can be manipulated to provide both even- and uneven-aged structures having diverse mixtures of early, middle, and late seral stages. Both even- and uneven-aged assemblages of forest vegetation can be developed relatively quickly that have many of the characteristics of old-growth stands. Stands and watersheds can be managed for a variety of species mixes and vertical and horizontal structures. Thus, managers have considerable flexibility in meeting diverse management goals. Results from Blodgett Forest Research Station and elsewhere suggest that, given adequate time, the differences in productivity between even- and uneven-aged systems are likely to be small. Whether this is true across sites of varying quality remains to be determined. Differences may occur in stands on steep ground and on sites of lower quality, where there will be practical limitations on the choice of logging and silvicultural options. Also, experience in uneven-aged silviculture is very limited, and there might well be programmatic problems, such as economics, practicality of record keeping, contracting for work, and workforce organization and supervision, applying the system to large land areas. However, in the absence of particular biological, managerial, or societal constraints, all systems are potentially applicable and, over a landscape, can have the same range of density, size classes, frequency of entry, road density, and species mixes. Sites of higher quality will respond more rapidly and will be more amenable to a wider range of treatments than will sites of lower quality. Past history in California and elsewhere has shown that it is important to ensure that no one or two harvesting methods dominate the landscape. Silviculturists must learn to merge systems and take advantage of existing heterogeneity through the use of "fuzzy" variants that leave green and dead trees, develop understories, have vertical and horizontal structural diversity, and use irregular boundaries.

The critical silvicultural challenges are to keep forests healthy, to reduce the potential for catastrophic crown fires, and to keep soil in place on hillsides. The basic knowledge to do this is available; all that is required are the will and finances to do it. Two major deterrents are regulations, such as air-quality standards that limit use of prescribed burning, and policies and regulations that limit silvicultural choice of harvesting and regeneration methods. In a broader context, regulatory problems that affect silviculture and increase costs are more complex because they involve nonsilvicultural issues such as planning ordinances affecting residence construction in forested areas and road access in forest zones. Because of the diversity of conditions in the Sierra, it is preferable to define the desired outcome and require professional silviculturists to prescribe and use the most effective methods to achieve the desired forest composition and structure at the landscape and watershed levels. To encourage the long-term use of sound silvicultural practices, markets are needed for small-sized trees, and stability is needed in the policy and regulatory environments.

Research Needs

More knowledge is needed to support the development of new silviculture aimed at addressing current and emerging issues. The following areas are particularly important. Current research is addressing many of these, but sustained funding and greater effort are needed to ensure adequate knowledge covering the broad range of forest types and situations in the Sierra.

- Fire-risk rating systems need to be developed for stands and fuel profiles over landscapes.

- We need to know how to establish and maintain effective fuel breaks.
- We need to find ways in which to encourage the widespread use of low-impact logging systems to selectively remove fuels and small trees from the understory of older stands and to thin young stands.
- We need to know the relative regeneration and growth rates of conifers, hardwoods, shrubs, and grasses in the understory under varying levels of overstory density, as well as their relative capacities for release in uneven-aged systems and their relation to wildlife habitat.
- We need to understand the effects of fire and biomass removal on soils and nutrient status on sites of differing levels of productivity.
- Better information is needed on the interrelationships among site quality, species composition, stand structure, weather (climate), wildlife, and insects and pathogens.
- Improved site-specific, GPS-based, multiresource inventory information is needed.
- Models are needed that project the likely development of a variety of forest structures at the landscape level under alternative management scenarios.
- We need to know how to culture hardwood sprouts.
- An understanding is needed of the applicability of silviculture to enhance the development of late-seral-stage stands.
- An understanding is needed of the applicability of uneven-aged systems at large-scale levels, on sites of diverse productivity, to meet diverse societal needs.
- We need to know the likely dynamics of forest composition and structure in the context of possible climate change and increasing air pollution.

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Back to CD-ROM Table of Contents