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14

Silviculture-Ecology of Forest-Zone Hardwoods in the Sierra Nevada

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Back to CD-ROM Table of Contents

ABSTRACT

Although the principal hardwood species in the forest zone of the Sierra Nevada (California black oak, tanoak, Pacific madrone, and canyon live oak) are key components of many ecosystems, they have received comparatively little study. Currently they are underutilized and unmanaged. This paper brings together what is known on the silviculture-ecology of these species and weaves it into a framework that has value to the academician and the practitioner. With species amounts, utilization, adaptations, and ecology as background, seed production, regeneration, early seedling growth, root crown sprouts, growth of trees and stands, and epicormic branching are presented. Ten major points having management implications conclude the paper.

Key Words: Hardwoods, ecology, regeneration, vegetative propagation, growth

INTRODUCTION

Native hardwoods in the forest zone of California's Sierra Nevada constitute a major resource that currently has vast potential, but about which critical information is absent or fragmented. In old-growth stands, the hardwoods are decadent and dying, but little regeneration is present to replace them. Current artificial regeneration techniques are ineffective. In younger stands, tree density generally is too high, and tree growth is miniscule, but thinning guides by species and site quality are scarce. Oak acorns and Pacific madrone berries are recognized as being critical to wildlife, but the timing and magnitude of acorn and berry crops are poorly documented. The gain in water yield from deciduous hardwoods, relative to evergreen hardwoods and conifers, has been documented in northern and southeastern American stands, but no such studies are known for western hardwood stands.

Forest-zone hardwoods can be found throughout the Sierra Nevada and are an inherent part of many ecosystems. Until the hardwood component of these ecosystems is better understood, their management will be incomplete.

Research on the silviculture-ecology of forest-zone hardwoods in the Sierra Nevada of California has been scant. When knowledge from research in the Cascade Mountains of southwestern Oregon is included, several gaps are filled, but the overall research base remains small. Most of the work in both areas has been concentrated at a few locations where trials have been mostly case histories. If there is a strength, it is that most of the major components of hardwood silviculture have been examined, albeit not in depth. Another strength is that work in both California and Oregon, where replicated, has shown similar trends. Further, ecological and silvicultural findings on related species of *Quercus* in eastern North America show similarity to findings on western species of *Quercus* in several areas. The point is that the silvicultural concepts and principals presented here have support, but much more research is needed.

Because ecosystem management is likely to be the management paradigm for natural resources in the future, the material that follows needs to be put in perspective. Basically, the Sierra Nevada forest-zone hardwoods have never had a management philosophy because they were regarded as being largely uneconomical and something to be converted to pines and firs. McDonald and Huber (1994, 1995) have suggested that this is not realistic. The forest zone hardwoods have great worth when the total resource (wildlife, water, aesthetics, wood products) is assessed. Within the ecosystem management perspective, the role of silviculture and a viable hardwood timber processing industry is vital. Silviculturists will carry out the prescriptions needed to create, maintain, and even enhance desired assemblages of species, structures, and growth rates. The raw material derived from attaining these prescriptions will sustain a viable hardwood processing industry. Inherent to this vital role, however, is recognition that what is now known is not enough. New techniques must be tried, and new knowledge, particularly on a large area-long timeframe basis, must be developed. This paper presents what is known on the silviculture and ecology of forest-zone hardwoods in the Sierra Nevada.

SPECIES, OCCURRENCE, AND INVENTORY

Although California's indigenous hardwood resources can be divided into two basic groups: those that grow in the foothills and woodlands at lower elevations, and those that grow in the forest-zone at higher elevations, only those that grow in the forest zone are discussed here. And for them, only those that are the most abundant and have a fairly large natural range in the Sierra Nevada, are presented. These include tanoak (*Lithocarpus densiflorus* [Hook. & Arn.] Rehd.), California black oak (*Quercus kelloggii* Newb.), Pacific madrone (*Arbutus menziesii* Pursh), and canyon live oak (*Quercus chrysolepis* Liebm.). All of these species have an established history of utilization for wood products and other yields (Economic Development Administration 1968), and as food and raw material for human beings (Wolf 1945), especially Native Americans (Baumhoff 1963).

Seldom do these hardwood species, alone or together, occupy entire mountain sides. Most often they are found as single trees, in clumps or groves, or occupying a given aspect in areas of up to 100 acres. Exceptions can occur, however, where extensive cutting and burning of conifer associates has allowed hardwood species to dominate over much larger areas. Seldom do each of these species grow in pure stands; rarely are all of them found growing together. Only in the northern Sierra Nevada are tanoak, Pacific madrone, and California black oak associates, sometimes with scattered canyon live oak on poorer sites. In the southern Sierra Nevada, California black oak and canyon live oak may intermix occasionally, but usually grow alone. Canyon live oak is widespread throughout the Sierra Nevada, particularly on poor rocky sites and on south-facing walls of canyons where it often forms nearly pure stands. All of the hardwood species mentioned in this paper except Pacific madrone have a shrub form. In most instances, the shrub forms grow on poor or extremely poor sites and, in general, extend the specie's natural range to higher elevations. Shrub tanoak (*Lithocarpus densiflorus* var. *echinoides*) does this also, but is found on good sites, especially where moisture is plentiful.

Rarely are the hardwoods found without conifer associates. The most common are Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) and ponderosa pine (*Pinus ponderosa* Dougl. ex Laws var. *ponderosa*), with California white fir (*Abies concolor* var. *lowiana* [Gord.] Lemm.), incense-cedar (*Libocedrus decurrens* Torr.), and sugar pine (*Pinus lambertiana* Dougl.) less abundant.

Shrub species that associate with the hardwoods in the Sierra Nevada tend to be few and variable in number, primarily because of differences in tree density. Some common shrub genera include *Arctostaphylos*, *Ceanothus*, *Rhamnus*, *Prunus*, *Castanopsis*, and *Adenostoma*. Forbs and grasses, like the shrubs, vary tremendously beneath the hardwoods. They can be almost totally absent in the shade beneath dense stands, or quite diverse and abundant in more open stands.

The area in the Sierra Nevada clothed with forest-zone hardwoods totals 423,000 acres (Bolsinger 1988). Total growing stock volume of the principal forest-zone hardwood species in California in trees 5.0 inches in breast height diameter (dbh) and larger in 1985 was over 1.6 billion cubic feet with California black oak, canyon live oak, tanoak, and Pacific madrone constituting 92 percent of the total (table 1). This volume was split almost evenly between public and private land. Total sawtimber volume of the principal forest-zone hardwood species in the Sierra Nevada in trees 11.0 inches dbh and larger in 1985 was over 722 million cubic feet (table 1). Local volume tables for California black oak, Pacific madrone, and tanoak on a high site in northern California are available (McDonald 1978).

A major attribute of California hardwoods is that much of the sawtimber volume is in trees greater than 29 inches dbh. This is in strong contrast to hardwoods in the rest of the Nation where almost all trees in this size class have been harvested.

UTILIZATION

Although timber and wood products are generally thought to be a major use, a more detailed examination gives timber a low ranking. Currently, wildlife ranks first, followed by water, pleasing scenery, and wood products (McDonald and Huber 1995).

The hardwood forest environment, and especially its unique foodstuffs of acorns and berries has critical value for wildlife (McDonald and Huber 1994). At least 355 species in the western Sierra Nevada alone call this area “home” (Verner and Boss 1980). These include 26 species of amphibians, 27 reptiles, 208 birds, and 94 mammals.

Water is a major yield from the Sierra Nevada, and one that is now reaching critical status in California. Current use in California is about 42 million acre feet of water annually with a predicted increase of 3.5 million acre feet by the year 2010 (California Department of Forestry and Fire Protection 1988). Increases are primarily for domestic and industrial use and to satisfy in-stream flow requirements. Much of the increase will have to come from the Sierra Nevada. Currently, 41 percent of total runoff in the state or over 32 million acre feet originate in the Sacramento and San Joaquin River Basins (California Department of Forestry and Fire Protection 1988).

Pleasing scenery is a major “yield” from the land and the colorful hardwood forests give accent to spring and contrast and beauty to the fall (Heady and Zinke 1978, Litton and McDonald 1980, McDonald and Whiteley 1972). Californians currently spend more than 100 million days each year recreating on forest land administered by state and federal governments (California Department of Forestry and Fire Protection 1988). This is predicted to increase, and a significant portion of it is expected to be in the Sierra Nevada.

Utilization of Sierra Nevada hardwoods for lumber and wood products began with the gold rush of 1849 and has continued to the present. Tannic acid for curing leather, crude lumber, charcoal, and fuelwood were the first uses. By the late 1880’s high quality lumber for furniture, balconies, mantles, and flooring was being manufactured from California black oak. By the 1920’s, a wealth of products were being manufactured from Sierra Nevada hardwoods. In addition to lumber, flooring, barrels, charcoal, and fuelwood, hardwoods were utilized for industrial timbers, crossties, novelties, pipes, bobbins and shuttles, and handles for tools. More recently, pallets, odor-free food storage units, veneer, and chips for pulp have been manufactured (Economic Development Corporation 1968, Huber and McDonald 1992). By 1994, no fixed, large-scale manufacturing industry existed. The only uses for Sierra

Nevada hardwoods were for pulp chips and fuelwood. However, local “cottage” industries were springing up in the northern and central Sierra. They employed mini-mills and other modern machines to produce high-quality lumber for furniture, flooring, novelties, and other uses. Many new developments, among them the change in attitude on hardwoods from negative to positive, better estimates of the inventory base and resource value, cooperatives, better seasoning techniques, and a host of new marketing and promotional developments, suggest a revitalized hardwood industry with a solid future (McDonald and Huber 1994).

ADAPTATION AND ECOLOGY

Based on millions of years of adaptation through natural selection (Chaney 1925), the four major hardwood species in the Sierra Nevada are well adapted to changes in the environment. They ought to be--the fossil record reveals that they have lineage to the Mascall flora of the Miocene epoch of 12-26 million years ago. Consequently, they have survived such major geologic events as glaciation, volcanism, upthrusting, and subsidence. They also are well adapted to a broad range of more recent biotic agents and abiotic events (Cooper 1922, Keeley 1977, Kummerow 1973, Mooney and Dunn 1970). And the harsher the site, the better adapted they are. The adaptations are both morphological and physiological. Morphological features include special structures and coatings on leaves and stems to inhibit moisture loss, smooth upper-stem bark to facilitate the transport of water to the base of the tree via stemflow, an extensive deep-thrusting root system, capability to form a burl at an early age, and capacity to produce both an enormous amount of seed and large numbers of rapidly-growing root crown sprouts. The burl has at least two important functions: as a reproductive platform by virtue of its many dormant buds (from which sprouts arise), and as a food-storage organ. Physiological processes involve photosynthesis, transpiration, and respiration, which govern plant metabolism, energy intake, water losses, and eventually dominance potential (McDonald 1982).

The capability to internally monitor and control respiration is particularly worthwhile. Normally, plants respire excessively when internal moisture levels are low and internal temperatures become high. But these hardwoods have a built-in “fail-safe” mechanism that lowers respiration, even though temperatures may become quite high (Mooney and Dunn 1970). This keeps the plant from using all its energy reserves during the hot windy days of late summer. Equally important is that photosynthesis can take place at low internal moisture levels and that it can happen quickly after the onset of favorable conditions. Positive net photosynthesis for an hour, early in the morning of a hot summer day, or for an hour in the early afternoon of a warm day in midwinter, provide energy inputs at opportune times.

The advantages gained from the adaptations above combine to give the species a special competitive advantage that takes the form of water wasting. The hardwood species discourage competition by using all the water in the soil without paying the price of high internal moisture stress, high respiration, and eventual death. Species that lack these adaptations succumb, because no water is left to support life functions.

A major limitation, however, is tree height--Sierra Nevada hardwoods do not grow as tall as conifer associates. Because of their shorter stature, the hardwoods need periodic disturbance to dominate. As Atzet and Martin (1992) noted “Disturbance brings change that helps maintain compositional, structural, and functional diversity, helps to select adapted, resilient individuals, and helps to dampen the effects of minor environmental oscillations and extremes. Change is an essential ingredient of healthy ecosystems.” Sierra Nevada forest-zone hardwoods depend primarily on fire, logging, blow-down, insect devastation, or mass soil movement to provide the disturbed and temporarily vegetation-free ground needed for establishment (McDonald and others 1983). Continued absence of disturbance allows the conifers to overtop and eventually eliminate the hardwoods.

Fire is both a blessing and a curse for forest-zone hardwood species. On one hand, fire creates the necessary disturbance by killing the conifers. The hardwoods often are killed as well, but only aboveground. Belowground, they retain the capability to sprout and grow rapidly. 0n the other hand, the thin, poorly insulated bark provides little protection from heat. Just a little fire kills the trees to groundline. Once a hardwood stand is established, fire plainly is undesirable for scores of years.

SILVICULTURE

Seed Production

For the four primary hardwoods in the Sierra Nevada, the magnitude and periodicity of seed production are quite variable and dependent more on local conditions than on regional ones. For example, one study reported that abundant seed crops of California black oak were produced at 2- to 3- year intervals (Roy 1962). At the 2,500-foot elevation on the Challenge Experimental Forest in the northern Sierra Nevada, medium to bumper black oak seed crops were produced in 4 of 20 years. At the 2,800-foot elevation in south-central Shasta County, medium to bumper seed crops were borne on large trees in 4 of 8 years. At the 560-foot elevation in Shasta County, black oaks yielded sound acorns in 6 of 7 years. Of these, two each rated as bumper, medium, and light (McDonald 1990). Tanoak on the Challenge Experimental Forest produced 4 medium-heavy and 9 light-very light seed crops from 1958-1981. During the same period, Pacific madrone yielded 2 medium-heavy and 10 light-very light seed crops (McDonald (1992). Canyon live oak is reported to produce good seed crops every 2 to 4 years (Thornburgh 1990). The fecundity of the hardwood species, as noted by individual trees, is amazing. A 16-inch dbh. tanoak tree on the Challenge Experimental Forest had the equivalent of 1.1 million acorns per acre beneath it in a bumper seed year. The acorns were 79 percent sound (McDonald 1978). On the same site in a light seed year, a 15.7-inch dbh. Pacific madrone tree produced 107,640 berries or about 2.1 million seeds (McDonald 1978).

Regeneration

Exposure often is deadly to acorns on the ground, and only a few hours of sunlight slanting beneath a tree crown can kill the embryos. Freezing also kills the embryos in acorns that are not covered by leaves or other organic material. Deep duff and litter are ideal for germination and downward root penetration by young oak seedlings. However, any organic matter, which inevitably houses damping-off fungi and invertebrates such as slugs, is anathema to Pacific madrone seedlings. The best medium for this species is shaded, but bare mineral soil (McDonald and Tappeiner 1990, Pelton 1962).

Natural regeneration of the oaks (including tanoak) tends to be clumpy with large numbers beneath parent tree crowns and few elsewhere. After 6 to 12 years, tanoak seedlings tend to die back to the root crown, often for no obvious reason, and sprout from dormant buds on the burl (Tappeiner and McDonald 1984. Hence the seedlings become seedling-sprouts. Tanoak tends to accumulate more seedling-sprouts on the shady forest floor than other hardwood species. On a high site in the northern Sierra Nevada, young tanoaks reached a density of 6,000 per acre (McDonald 1978). Of the four major hardwood species, young Pacific madrone seedlings are the least abundant. They tend to be widely scattered with concentrations along the edges of dirt roads, at the base of overturned trees, and at other locations where the soil is both bare and shaded.

Artificial regeneration of the three oak species and Pacific madrone has shown them to be difficult to establish, and even harder to grow at an acceptable rate (McDonald 1978, Narog 1994). None of these species can be established in conventional sunlit plantations, even when fertilizer and water are provided the first year. Based on early results, McDonald (1990) noted the possibility that California black oak could be established in conventional plantations. However, when several of these plantations were revisited, tree form and development were not satisfactory. Consequently, direct seeding of germinated acorns or the planting of nursery-grown plugs gives adequate early survival, and perhaps even acceptable 10th-year survival, but growth is inconsistent and unreliable. Growth of black oak seedlings planted in the shade is unknown. The growth of planted and natural seedlings in shade has not been compared.

Early Seedling Growth

The mechanism and timing of very early seedling growth are a marvel of adaptation. Take California black oak as an example. The radicle is first to emerge from the acorn. Fueled by the abundant energy in the acorn, it grows downward for some time, often 10 to 20 days, before the epicotyl appears above ground (McDonald 1990). This process allows the seedling to get to and stay in a zone of available soil moisture, and in minimizing transpiration losses and herbivory. Black oak seedling roots commonly extend as deep as 30 inches the first growing season. Shoot length after one growing season is 6 to 8 inches, and probably does not begin to accelerate until root capacity is extensive enough to obtain adequate soil moisture. This may take years and in many instances, the seedling becomes overtopped by other vegetation. Continued overtopping almost always causes death.

The oak species and probably Pacific madrone form a rudimentary burl just below groundline and develop capability to produce sprouts at a young age. Dieback of the sprouts is common and the reproduction typically is made up of seedlings and seedling-sprouts. The seedling-sprouts, because of the burl, have higher odds for survival than the seedlings. Much information is available on age/height relationships of tanoak seedling-sprouts (Tappeiner and McDonald 1984) and on survival relationships of tanoak and madrone seedlings (Tappeiner and others 1986). The burl develops slowly and steadily with age, but height is indeterminate. At age 10, for example, tanoak seedling-sprouts in the northern Sierra Nevada might have a 0.5-inch diameter burl, four sprouts, and a sprout height of 20 inches. By age 40, the burl will be 2- to 3-inches in diameter, and be a clump of 4 to 6 stems, about 20 inches tall. Height of the seedlings and seedling-sprouts of the Sierra Nevada hardwoods noted here ranges up to 8 inches after the first growing season and up to 60 inches for older plants.

Root Crown Sprouts

All of the forest-zone hardwoods mentioned in this report produce both sprouts and seed. Species that have both reproductive modes have an obvious advantage over those that have only one. Sprouts, because of fast and robust growth, almost instantly reoccupy original sites. Seeds, through the action of disseminators, enable the species to occupy new areas. “It is not extravagance, but good investment for the oaks to provide subsistence for a continuing population of animal associates” (Grinnell 1936).

Root crown sprouts (as opposed to seedling-sprouts) are defined as those that originate from stumps larger than 2 inches in diameter. Such sprouts are the primary reproductive mode of the principal hardwoods. Examination of over 1,380 recently cut stumps in the northern Sierra Nevada revealed that almost all were of sprout origin. Plainly, most reproduction is by vegetative means (sprouts) with only one tree in hundreds originating from seed. This is consistent with the role of disturbance and the origin of stands.

Most root-crown sprouts develop from dormant buds on a burl that forms at or just below groundline. After cutting, burning, or other damage, sprouting is assured except for very old, moribund trees whose buds are occluded by thick bark. In fact, it is almost impossible to keep stumps of these hardwood species from sprouting. After the tree is killed above ground, the number of sprouts in the initial flush varies tremendously, but has been noted as being up to 1,400 on one large tanoak stump (Tappeiner and others 1990), and more than 300 on one 10-inch Pacific madrone stump (McDonald and Tappeiner 1990). Other sprouts originate from the top of the stump or on the vertical part of the stump between the top and the ground. These are called stool sprouts and are undesirable for several reasons. They are weakly attached to the stump, are peeled off by wind and snow, and are prone to heart rot at an early age. Leaving a low stump less than 8 inches tall promotes numerous, healthy, rot-free sprouts.

The size and vigor of the parent tree largely determines the number of sprouts and their height and crown spread. In general, stumps from larger trees produce a larger number of sprouts and more vigorous ones. Indeed, sprout height, clump width, clump area, leaf area, total above-ground biomass, and number of stems per clump 1 to 6 years after cutting, were statistically correlated with parent tree diameter at breast height before cutting or burning (Harrington and others 1984). Thus sprout clump size and total cover of sprout clumps can be predicted on a per acre basis and used to estimate competition, biomass, or other useful determinations.

Long ago, David Smith (1962) noted that “Vegetative reproduction obtained after clearcutting is usually superior to that resulting from partial cutting.” This has proved true for the species denoted here. In a study on the Challenge Experimental Forest with California black oak, tanoak, and Pacific madrone, sprout clump dynamics were quantified in both a clearcutting and in a shelterwood where 50 percent of the stand basal area was removed (McDonald 1990). For all three species, more and vigorous sprouts were found in the clearcutting. Even shade-tolerant tanoak grew best in the clearcutting, probably because no roots of parent trees were utilizing site resources, particularly water. After 10 years, sprout clumps of California black oak in the clearcutting averaged 20 feet tall and about 10 feet wide (table 2). Clumps of tanoak sprouts in the clearcutting were about equally tall and wide; those of Pacific madrone were slightly taller (22 feet) after 10 years and were of equal width.

Given that sprouts are numerous and many die quickly, thinning at an early age seemed a likely technique to stimulate growth of selected stems. This was done on the Challenge Experimental Forest for California black oak, tanoak, and Pacific madrone, always leaving 3 or 4 sprouts well dispersed around the stump. Thinning was performed at ages 1 and 4. It proved difficult and ineffective at age 1 and yielded no gain in growth relative to unthinned sprouts at age 4 (McDonald 1978). Thinning sprout clumps before age 10 is not recommended. Results from thinning between age 10 and 30 are unknown but could prove beneficial.

Growth of Trees and Stands

Because disturbance, chiefly fire, is commonplace throughout the range of Sierra Nevada forest-zone hardwoods, and stand establishment is by root crown sprouts, most stands consist of clumps of sprouts, although many clumps have become single trees. These stands tend to be even-aged and quite dense. On a good site in northern California, trees in a 60-year-old mixed hardwood stand that were 3.5 inches in breast height diameter or larger, numbered 659 per acre and contained about 200 ft^2 of basal area per acre. They were growing at a rate of about 15 rings per inch.

Would the typically dense hardwood stands respond to thinning, and what was the best thinning technique? After trial and error, the consensus of foresters was “yes” they will respond to thinning, but only a “crown” thinning was practical. Crown thinning is where crowns of individual trees are provided growing space. A more traditional thinning technique would be to leave an even spacing of trees on each acre. For 60-year-old trees in the northern Sierra Nevada, a crown thinning of 40 to 50 percent with 100 to 125 ft^2 per acre retained, doubled the diameter growth rate after 8 years (McDonald 1980). On a stand basis, this amounted to growth of about 85 ft^3 per acre per year over the 8-year period. California black oak trees responded best when thinned to about 100 ft^2 per acre, and tanoak and Pacific madrone to about 125 ft^2 per acre--the latter two species needing a more shady environment.

Other findings of interest to silviculturists were that individual trees in a clump of up to four stems grew as well as if they were single trees. Consequently, clumps of up to four members can be retained with no reduction in growth. And when diameter growth was averaged for two of the wettest and two of the driest years and compared, the response was similar between wet and dry over a wide range of stand densities.

Tanoak and Pacific madrone rarely produce sprouts (called epicormic branches) along the bole, but California black oak does. Canyon live oak sprouts readily from the bole and the crown, particularly if the crown has only been scorched by fire. After a conifer-killing fire, logging, or a heavy thinning, large amounts of nutrients and water become available. The typically slow-growing and thin-crowned hardwood trees that remain do not have enough crown to utilize the extra site resources provided by the roots. These extra resources must be utilized in some way, so extra "crown" in the form of epicormic branches develops. Epicormic branching creates a dilemma for the forester. Stands of California black oak, for example, require thinning to increase growth and the production of acorns, but epicormic branches, which yield no acorns and constitute a serious lumber degrade, often result.

The crown thinning in the 60-year-old hardwood stands on the Challenge Experimental Forest created basal areas that ranged from 85 to 141 ft^2 per acre. These, plus trees in an unthinned control and those bordering small openings, were studied to quantify epicormic branching and to determine causal factors. In 1976 or 6 to 9 years after thinning, 2069 living and dead epicormic branches on 189 California black oak trees were observed. Statistically significant predictors of epicormic branching were position of tree in stand, cardinal direction of bole face, and bole segment (McDonald and Ritchie 1994). Number of epicormic branches increased with decreasing stand density, proximity to openings, on south and east bole faces, and with increasing distance above the stump.

These findings, together with the silvical characteristics noted earlier suggest that a series of crown thinnings be applied, beginning when the stand is as young as 20 years. The goal is to achieve rapid crown development, and wide-crowned trees that will in turn maximize growth and acorn production. This means applying a series of thinnings that provides some room each time for crown and root expansion.

MANAGEMENT IMPLICATIONS

The idea that native California hardwoods needed to be managed was stated over 30 years ago. Edwards (1957) and Roy (1962) denoted some silvicultural possibilities and made a few tentative management recommendations. Based on new silvicultural/ecological information, McDonald (1978) suggested that many benefits could be realized if natural resource managers in different disciplines worked together. Later Tappeiner and McDonald (1980), Plumb and McDonald (1981), and McDonald and Tappeiner (1987) suggested more detailed management recommendations based on an increasing amount of new ecological and silvicultural information. In 1994, McDonald and Huber noted that the extensive and complex hardwood ecosystems had value far beyond timber and wood products. They noted that on public land, wildlife, water, and pleasing scenery outranked wood products in terms of current and near-term use, and suggested an ecosystem management perspective for managing the hardwood resource. Later McDonald and Huber 1995) noted that on both private and public land, it will be silviculturists who maintain, manipulate, and create the ecological types and habitats desired by society. The art of hardwood silviculture should enjoy its finest hour.

The best of all these recommendations, plus some new ones from the preceding material, are denoted below.

- The forest-zone hardwood ecosystems in the Sierra Nevada are unique and special and worthy of being managed as such.
- Implicit in the inventory data is the fact that forest-zone hardwoods constitute a large, variable, and complex resource. Of extreme importance is that this resource is largely intact. Unlike softwoods, every hardwood age and size class is present, including large numbers of big, old-growth trees. Tree density also ranges widely--from one or two per acre to over 700 per acre. The wide variety of sizes and densities gives managers virtually unlimited opportunities to maintain, create, or sustain every habitat or ecological type that they should need. And when the conifer-hardwood mixtures are included, and they too are numerous and varied, the total number of habitats is huge and their variety and potential for management is virtually unlimited.
- The worth of forest-zone hardwoods may be manifest more in wildlife, water, and pleasing scenery than in wood products, but the wood products provide the raw material for industry, which in turn provides jobs and stability to rural America.
- Natural regeneration of California black oak, tanoak, Pacific madrone, and canyon live oak in an undisturbed setting is characterized more by a slow steady accumulation of seedlings rather than by large pulses of them.
- Artificial regeneration in a conventional sunlit plantation is beset with problems, especially lack of consistent and reliable seedling growth. Partial shade appears to be mandatory, but how much and until when is unknown.
- Propagation of root crown sprouts is the major regeneration method and until artificial regeneration techniques are perfected, vegetative propagation remains the best way of renewing hardwood stands.
- Thinning of root crown sprouts is impractical through age 10, but after age 10 should stimulate growth on remaining sprouts. Retaining 3 to 4 of the most healthy sprouts evenly spaced around the circumference of the stump is necessary to maintain clump health.
- Traditionally too-dense hardwood stands respond well to thinning. Diameter growth, for example, can be doubled relative to an uncut control.
- Epicormic branches of California black oak are a major degrade under current log grading rules. These branches, although almost always present, can be minimized

by a thinning regime that begins early and occurs often. The key is to create space into which crowns and roots can grow without becoming out of balance with each other.

- Given that exposure promotes epicormic branching and that significantly more epicormics occur on trees at the edge of stands than on interior trees, the number of epicormic branches can be reduced by managing trees in larger aggregations.

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Table 1. Growing stock and sawtimber volume for California black oak, tanoak, Pacific madrone, and canyon live oak in the Sierra Nevada, 1985[1]

Location	Growing stock	Sawtimber
	million ft^3	
National Forest and other Public land	830	353
Outside National Forests and Parks	810	369
Total	1740	722

[1]Extracted from Bolsinger 1988.

Table 2. Density, height, and width of California black oak sprouts for 10 years after cutting, Challenge Experimental Forest

Year	Sprouts per stump		Height		Crown width	
	Clear cut	Shelter wood	Clear cut	Shelter wood	Clear cut	Shelter wood
	number		ft.		ft.	
0	55+	28	-	-	-	-
2	55+	23	4	3	4	2
4	35	17	8	4	6	3
6	23	15	12	5	8	4
8	18	13	16	6	9	5
10	15	12	20	7	10	7

Back to CD-ROM Table of Contents