United States
Department of
Agriculture

Forest Service

Pacific Southwest
Research Station

General Technical Report
PSW-GTR-204
July 2007

Growth of Thinned and Unthinned Hardwood Stands on a Good Site in Northern California

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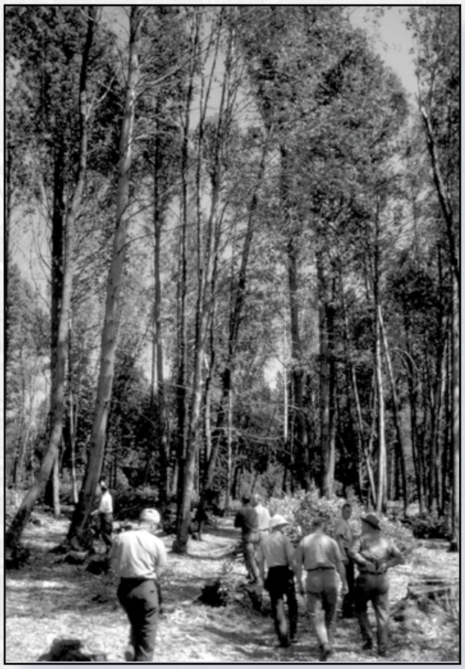

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Abstract

McDonald, Philip M.; Vaughn, Nicholas R. 2007. Growth of thinned and unthinned hardwood stands on a good site in northern California. Gen. Tech. Rep. PSW-GTR-204. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 23 p.

Pacific madrone (*Arbutus menziesii* Pursh), tanoak (*Lithocarpus densiflorus* (Hook. & Arn.) Rehd.), and California black oak (*Quercus kelloggii* Newb.) are three hardwood species commonly found in the Sierra Nevada of California, an area better known for its mixed-conifer forests. Hardwood stands in this region currently are unmanaged and underutilized for commodity production. However, some landowners are now asking "How fast do these hardwoods grow," and "Will thinning increase growth and yield?" Twelve young-growth, mixed-hardwood stands on the Challenge Experimental Forest in north-central California were thinned from an average basal area of 202 ft^2 per acre to different levels of residual basal area that ranged from 66 to 153 ft^2 per acre. An additional stand (control) provided information on development in an untreated condition. Tanoak trees grew faster in diameter in thinned plots and control than Pacific madrone, which grew faster than California black oak. In general, having two to four members per clump did not hinder diameter growth in the thinned plots. Tanoak also grew significantly faster both in diameter and volume in a very wet year, but for the other two species a very wet or very dry year did not make a difference. Both diameter and volume growth were best if stands were thinned to less than 75 ft^2 per acre, and net volume growth (gross growth minus mortality) compared favorably to eastern oak stands on good sites. A future thinning and management regime is suggested.

Keywords: California black oak, diameter growth, Pacific madrone, stand thinning, tanoak, volume growth, yield.

Summary

California's economically promising hardwoods–Pacific madrone (*Arbutus menziesii* Pursh), tanoak (*Lithocarpus densiflorus* (Hook. & Arn.) Rehd.), and California black oak (*Quercus kelloggii* Newb.)–occupy millions of acres of forest land and are an integral part of many ecosystems. These species provide important habitat for birds and other animals, visual diversity in the landscape, and many commercial wood products. They also are common in the rural-urban interface where management for fuel reduction has become a critical issue. But in spite of these attributes, these species are underutilized and virtually unmanaged.

Part of the reason for the lack of management is that little information is available about these species and specifically on their growth. How fast do trees of these species grow; do clumps of trees grow as well as single trees of the same size; and is growth sensitive to wet and dry years? What is the response of these stands to thinning, and if they do respond, how much basal area should be retained to maximize stand growth? What yield per acre can be attained? These questions, being asked by foresters and land managers, are addressed in this paper.

Thinning hardwoods is more involved than thinning conifers. The young-growth hardwoods in this study originate mostly by sprouting from the root crowns of stumps or clumps of stumps and thus clothe the landscape in clumps or single trees. Some trees lean into openings in the canopy and some grow straight and tall. A sudden opening of the stand, which often results in too much light, is detrimental to all three species. Thus, thinning needs to be done carefully to provide both shade and room for residual trees to enlarge their crowns. In some instances, "guard" trees need to be left to shade "save" trees. Consequently, a crown thinning is the most effective thinning technique.

Twelve ¼-acre circular plots and one uncut control plot were installed on the Challenge Experimental Forest in north-central California to study tree and stand growth. Data on species, diameter at breast height, clump density, mortality, ingrowth, and stem volume were recorded periodically over 10 to 15 years.

In the natural or unthinned control, tanoak trees grew faster in diameter than either Pacific madrone or California black oak. Mortality was confined mostly to black oak and specifically to smaller trees that found the unthinned control to be too dense and too shady. All three species combined increased their diameters by about 0.9 inch (in) per tree over 15 years, and stems in clumps of 2, 3, and 4 members grew slower than single stems.

In the thinned plots, tanoak also had the fastest diameter growth rate. The average diameter of combined species increased by 1.9 in per tree for the 15-year timespan. Mortality from suppression and unknown causes was distributed almost evenly over the three species, with root disease in tanoak and cankers on Pacific madrone as prime suspects. Stems in clumps of 2, 3, or 4 members grew about the same in diameter as single stems.

A mixed-model analysis showed that diameter growth of individual trees was statistically related to species, breast-height diameter, and residual basal area. More specifically, tanoak grew the most, trees with larger diameters had the highest growth rate, and residual basal areas of 66 to 75 ft^2 per acre indicated the highest growth rate per tree. Growth generally declined if thinning left more than 114 ft^2 per acre of basal area.

Results for volume growth were similar to those for diameter growth. In general, heavy thinning to a residual basal area of 66 to 75 ft^3 per acre provided the highest rate of volume growth per tree and thinning to 124 to 153 ft^2 per acre the lowest rate. Natural mortality reduced average annual growth from 0 to 22 percent per plot. After accounting for mortality, net cubic volume growth was highest in plots thinned to 114 and 113 ft^2 per acre, respectively. Their average over 10 years was 109 ft^3 per acre per year.

These three hardwood species are noted as being drought resistant, but are they? An analysis to determine the effect of very wet and very dry years showed that diameter and volume growth did not differ statistically between wet and dry years for Pacific madrone and California black oak, but did differ for tanoak, which grew significantly better during the wet year.

Contents

Introduction

In 1992, a series of publications on California's hardwood resource in the forest zone was begun. In the first publication, Huber and McDonald (1992) detailed the history of use for three species of economically promising hardwoods (California black oak (*Quercus kelloggii* Newb.) tanoak (*Lithocarpus densiflorus* (Hook. and Arn. (Rehd.)), and Pacific madrone (*Arbutus menziesii* Pursh),[1] especially for wood and wood products, and presented 22 reasons why the industry had not been sustained. In the second publication, they followed the progress of the industry and cautiously suggested that a viable wood processing industry was possible in the near future (McDonald and Huber 1994). By developing this industry, demand for products from the hardwood forest could be created, which could lead to active management of the resource. McDonald and Huber (1994) also recognized that wood products were just one of four major "yields" from the land and that wildlife, water, and pleasing scenery were more valuable than wood products. This led to an ecosystem management perspective that was followed a year later by a publication that described a philosophy and presented guidelines for managing for these four yields in the general forest zone, as well as in an agroforestry and urban interface setting (McDonald and Huber 1995).

Although these publications provided an overview and a management framework, they did not include specifics on the reproductive biology and silvicultural practices necessary for regenerating and managing forest stands. In the fourth publication, McDonald and Tappeiner (2002) brought together what is known about regeneration (seedlings, seedling sprouts, and root-crown sprouts) of these three species in both natural and artificial environments (plantations). In this fifth and last publication, the authors present the growth of trees and stands on the Challenge Experimental Forest in north-central California in both a natural and artificial (thinned) setting.

California black oak, tanoak, and Pacific madrone can be found southward from the Oregon-California state line almost to the Mexican border, and eastward from near the Pacific Ocean to the Nevada state line. These species are also extensive in southwest Oregon, but only Pacific madrone is found in Washington. Within California, they grow well to an elevation of about 7,500 ft and form many ecological types as pure hardwood stands, as components of mixed hardwood and conifer stands, and as occasional trees, clumps, and groves within the conifer forest (McDonald and Huber 1995).

[1] Common and scientific names are from Little 1979.

As a resource, the inventory of hardwood trees is large, contains every size class and structure possible, and even has a high proportion of old-growth trees. In California, Waddell and Barrett (2005) estimated that the Pacific madrone, tanoak, and California black oak forest types occupied more than 2.85 million acres; 2.5 million acres as timberland and 0.35 million acres as woodland. The total net growing-stock volume of these species that were at least 5.0 inches in diameter at breast height (d.b.h.) in the 1990s in California was almost 6.8 billion cubic feet. In addition to the timber resource, hardwood stands have high value for wildlife (Ohmann and Mayer 1987), for aesthetics (McDonald and Litton 1998), and possibly for increased water yield (McDonald and Huber 1994).

In spite of this large and extensive resource, little information is available on the growth of these three hardwood species and stands, especially after manipulation. McDonald (1980a) presented findings for seven of the plots in this study and found preliminary relationships between tree diameter growth and species, diameter class, and number of stems per clump.

Although the data and analyses presented in this study are intensive, findings are directly applicable only to specific species at a particular stand age on a high site. Hardwoods growing on poorer sites or at different ages may differ in their response to thinning.

This paper quantifies the response of three hardwood species in a wide range of residual basal areas over 10 to 15 years in terms of diameter growth, number of stems per clump, ingrowth, mortality, and average annual and net volume growth.

Methods

This study was located on the Challenge Experimental Forest in north-central California (Yuba County), T 19 N, R 7 E, MDM, sec. 29. The forest cover type in the vicinity of the research plots is Pacific ponderosa pine-Douglas-fir (SAF type 244) (McDonald 1980b). Several conifer and hardwood species characterize this type. In terms of ecological subregions of California, the area corresponds to section M261 E Sierra Nevada and the granitic and metamorphic hills subsection (USDA Forest Service 1997). Site quality is high, with dominant California black oaks averaging about 70 ft tall, for a site index of 60 at 50 years (Powers 1972).

Early logging (McDonald and Lahore 1984) and subsequent forest fires removed most of the conifers from part of the Challenge Experimental Forest and left a hardwood stand that had originated from sprouts and essentially was even aged. This was administratively designated as a hardwood compartment. The few conifers that were present were logged in spring 1966, leaving a 60-year-old pure hardwood stand. The slash was piled by hand and eventually burned.

Summers on the experimental forest are hot and dry; winters are cool and moist. The mean annual temperature is 55 °F. Precipitation was recorded each month and totaled each year. Average annual precipitation is more than 67 in with 94 percent falling between October and May. Soil moisture is the environmental factor that limits plant growth. The hardwood compartment where the study was located is quite homogeneous with an elevation of 2,750 ft, 15 percent slope, and southwest aspect.

To quantify the growth of individual species, as well as that of the mixed-hardwood stands, thirteen ¼-acre circular growth plots, plus buffer, were established in the hardwood compartment. Before logging, basal areas ranged from 165 to 244 ft^2 per acre and, after logging, from 66 to 153 ft^2 per acre. Desired basal area density levels ranged from 60 to 150 ft^2 per acre and were randomly assigned. One of the 13 plots was randomly selected as an unthinned control.

Marking young-growth hardwood stands for thinning is difficult and different from marking conifer stands. First of all, the stands are dense, and the trees tend to be slender with poorly developed crowns (fig. 1). The trees often are in clumps; their roots can occupy one area and their crowns can influence another. Second, the crowns of tanoak and Pacific madrone weaken and decline because of the high light levels created by sudden opening of the stand, and California black oak trees tend to form undesirable epicormic branches along the bole (fig. 2) (McDonald and Ritchie 1994). Thus, "guard" trees were left around selected "save" trees where

Figure 1—A typical young-growth stand of Pacific madrone, tanoak, and California black oak before thinning on the Challenge Experimental Forest.

Figure 2—After thinning, the narrow crown of this California black has been supplemented with a false crown of epicormic branches along the bole.

In terms of classical thinning regimes, this thinning closely resembled a crown thinning whereby residual trees were provided with some "sky area" into which their crowns could expand.

possible. For California black oak, the primary purpose of guard trees was to shade boles, and their secondary purpose was to partially shade crowns. In terms of classical thinning regimes, this thinning closely resembled a crown thinning whereby residual trees were provided with some "sky area" into which their crowns could expand. Save trees, or those that were to be retained after thinning, were straight and tall with a minimum of crook and sweep, no forks, no logging wounds, and no evidence of rot. Almost all guard trees also met these criteria.

Local fuelwood cutters thinned the stand in return for the wood (fig. 3 A, B, C). However, they were not available every year, and the initial cutting of individual growth plots took place from 1968 through 1979. Cutting rules required the removal of all unmarked trees, stumps no higher than 8 in above mean ground line, the piling of slash, and leaving no more than four stems per clump. Short stumps promote healthy, rot-free sprouts from the root crown, rather than weak sprouts from the top or sides of taller stumps (McDonald 1980a). Slash from thinning was piled well away from marked trees.

In each growth plot, all trees larger than 2 in d.b.h. were recorded and their diameters measured. These constituted the before-thinning sample. Every save tree was tagged (numbered) 2 in above breast height and measured at breast height. Untagged trees were removed. Species, diameter to the nearest 0.1 in, and clump density (1, 2, 3, or 4 members per clump) were recorded every year for the first 6 years and at ages 10 and 15. Unfortunately, data from five plots were not recorded after 10 years. Diameter growth was calculated on a per-tree basis with quadratic means for reporting on a per-stand basis. Total tree volumes were estimated from local volume tables applicable to each species on a high site (McDonald 1983).

These hardwood species can die in a single year or over several years. Trees of Pacific madrone usually die in 1 year, and those of all three species die in 1 or 2 years if diseased. As noted earlier, the crown of tanoak trees dies back, but rarely do trees die from suppression. The crowns and false crowns (epicormic branches) of suppressed black oaks die from the top down, and thus death was not recorded until the bole was dead at breast height. Rarely did the boles of any species expand in diameter after crown decline, and sometimes they actually shrank. For these reasons, diameter and volume growth were calculated only for trees that lived throughout the study period. Year of death and suspected cause were noted at each survey.

After thinning, root-crown sprouts quickly appeared at the base of most stumps. These sprouts form clumps of stems and tend to grow rapidly (McDonald and Tappeiner 2002). When they reached 3.5 in d.b.h. they were termed ingrowth, given a tag, and measured as part of the stand.

Statistical analysis was by analysis of variance, linear regression, mixed-model analysis (SAS 2001), and paired t-test (R Development Core Team 2004).

A

B

C

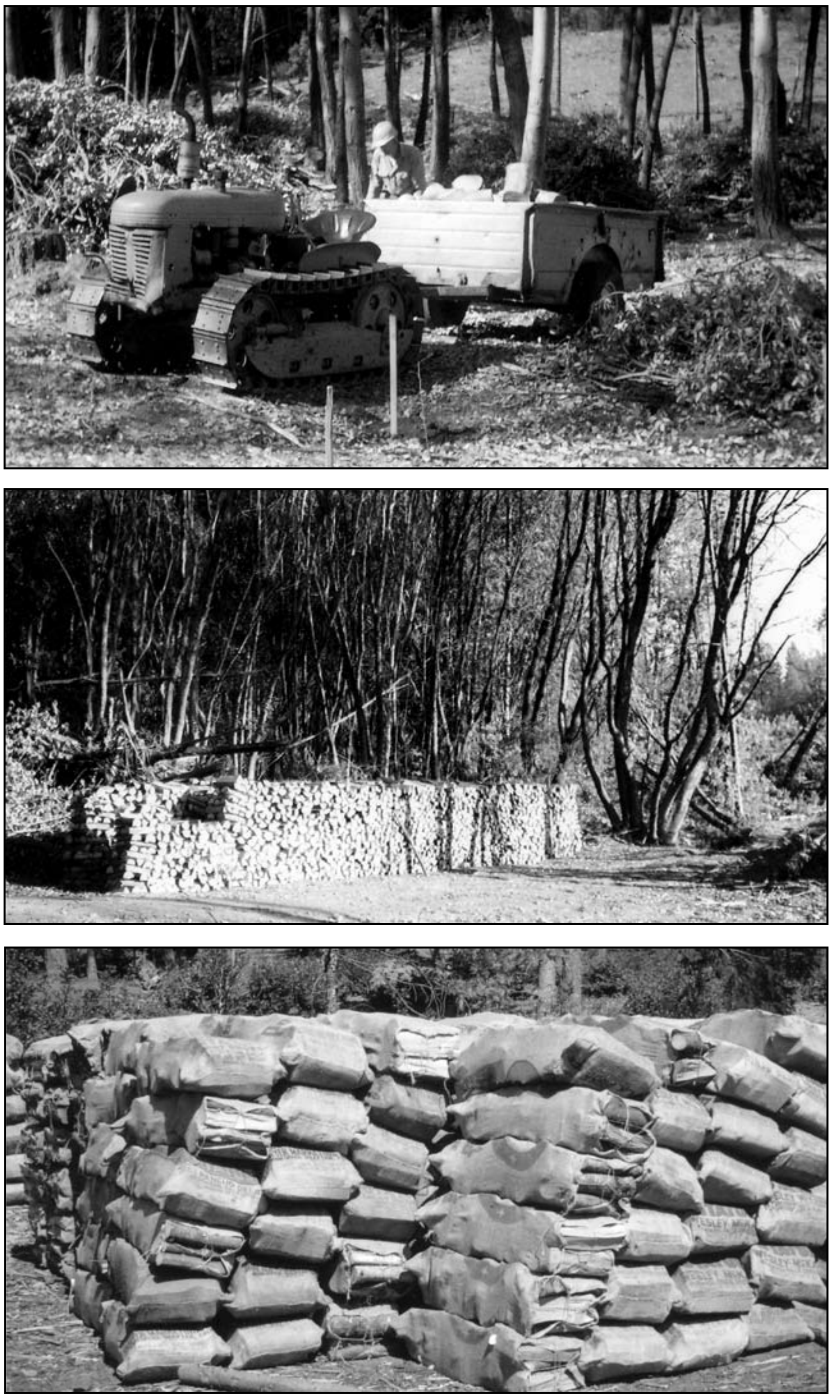

Figure 3—Thinning and harvesting the stand. (A) Gathering wood from the partially thinned stand, (B) stacked wood ready for shipment, and (C) smaller diameter wood sacked for sale to a local supermarket.

Results

The Thinning

After thinning, the desired basal area density levels, which ranged from 60 to 150 ft^2 per acre, were generally achieved, with an average variation of 2.5 ft^2 per density level (range 0 to 6.1 ft^2). Before thinning, the average stand contained more than 202 ft^2 per acre of basal area and 575 trees per acre. After thinning, the average stand contained 110 ft^2 per acre of basal area and 163 trees per acre. Thus, stand basal area was reduced by 45 percent and density by 71 percent (tables 1 and 2). Thinning removed all trees smaller than 4.1 inches d.b.h. and many trees smaller than 8.1 in d.b.h., thus favoring larger trees of all three species (table 2). Thinning also increased the average tree diameter of every species in every plot relative to the control (table 3). In terms of crown classification, all trees in the suppressed crown class and many in the intermediate class were removed. Examination of the cut stumps showed a slow and generally declining diameter growth rate, with no evidence of heart rot.

Table 1—Basal area of growth plots and control before and after thinning on the Challenge Experimental Forest, Yuba County, California

	Basal area		
Plot	**Before thinning**	**After thinning**	**Reduction**
	Square feet per acre		*Percent*
1	165.1	101.7	38.4
2	194.2	109.8	43.5
3	207.7	124.9	39.9
5	229.8	141.3	38.5
6	205.6	136.0	33.9
7	187.8	85.4	54.5
8	231.5	153.1	33.9
9	225.1	113.3	49.6
10	175.1	103.7	40.8
11	244.3	114.1	53.3
12	181.8	75.5	58.5
13	179.9	66.2	63.2
Average	202.3	110.4	45.6
4 (control)	202.3	202.3	–

– = no data.

Table 2—Stand density by species and diameter class before and after thinning on the Challenge Experimental Forest, Yuba County, California

	Diameter class (inches)											
	3.5–4.0		4.1–8.0		8.1–12.0		12.1–16.0		16.1–20.0		Total	
Species	*B*[a]	*A*[a]	*B*	*A*	*B*	*A*	*B*	*A*	*B*	*A*	*B*	*A*
	Number of trees per acre											
Pacific madrone	8	0	66	3	28	14	5	4	0	0	107	21
Tanoak	48	0	185	10	83	46	36	31	1	1	353	88
California black oak	12	0	63	20	35	30	5	4	0	0	115	54
Total	68	0	314	33	146	90	46	39	1	1	575	163

[a] B = before thinning; A = after thinning.

Table 3—Quadratic mean tree diameter by species in thinned plots and control at the Challenge Experimental Forest, Yuba County, California

Plot	Pacific madrone	Tanoak	California black oak
	Inches		
1	–	11.6	10.1
2	12.2	11.3	9.2
3	11.2	9.3	8.8
5	10.3	11.1	9.1
6	–	11.9	8.2
7	9	11.1	7.5
8	10.6	11.2	8.7
9	11.2	10.8	10.9
10	9.3	12.2	7.5
11	11.6	12	10.4
12	11.7	12.1	9
13	9.7	11	9.1
Average	10.7	11.3	9
4 (control)	8.7	7.6	6.6

– = no data.

More than 1,235 trees were removed for an average yield of 1,650 ft^3 per acre or 12.9 cords per acre. The average volume of trees retained on thinned plots was 2,515 ft^3 per acre or 19.7 cords per acre.

Thinning also modified the makeup of the stand by increasing the number of California black oaks at the expense of Pacific madrone and tanoak. Species composition as a percentage of average stand density before and after thinning was:

Species	Before	After
Pacific madrone	19	13
Tanoak	61	54
California black oak	20	33

The changes in species composition were entirely the result of the thinning prescription and not because of species preference.

Diameter Growth

To ascertain relationships among species and tree sizes, data were first analyzed by 4-in diameter classes (from 4 to 20 in) for each species, and then for all species combined. Only Pacific madrone trees in the largest diameter class (17 to 20 in) showed a period of strong early growth surge (0.20 to 0.47 in in diameter per tree per year at age 3), a phenomenon often termed "release." Tanoaks in the largest diameter class indicated a decline in early growth rate (0.37 to 0.22 in per tree per year at age 3). For all other species and diameter classes, increases and decreases in average diameter growth after thinning tended to be small, and no release was indicated.

For all species in all diameter size classes combined, the average growth rate of trees in thinned plots remained fairly constant through age 15, but in the control declined slightly (table 4). Relative to the control, thinning increased the cumulative average diameter growth per tree from 63 to 133 percent.

Table 4—Average annual diameter growth per tree at five measurements in thinned plots and control for all species combined and percentage increase of thinned plots over control, Challenge Experiental Forest, Yuba County, California

Years since treatment	Growth: Control	Growth: Thinned	Increase
	Inches/tree/year		*Percent*
1	0.08	0.13	63
3	.07	.14	100
5	.06	.14	133
10	.06	.14	133
15	.06	.13	117

The relationship of average breast-height diameter growth per tree to time since thinning in both the thinned plots and control (fig. 4 A, B, C) was analyzed with a weighted linear regression of the form:

$Y_{ij} = \beta_{0i} + \beta_{1i} \bullet \tau_{ij} + \varepsilon_{ij}$ in which:

Y_{ij} = d.b.h. growth of tree j of species i (three levels: Pacific madrone, tanoak, or California black oak),

β_{ni} = coefficients estimated by the linear regression procedure for species i,

τ_{ij} = number of years after thinning, and

ε_{ij} = random error.

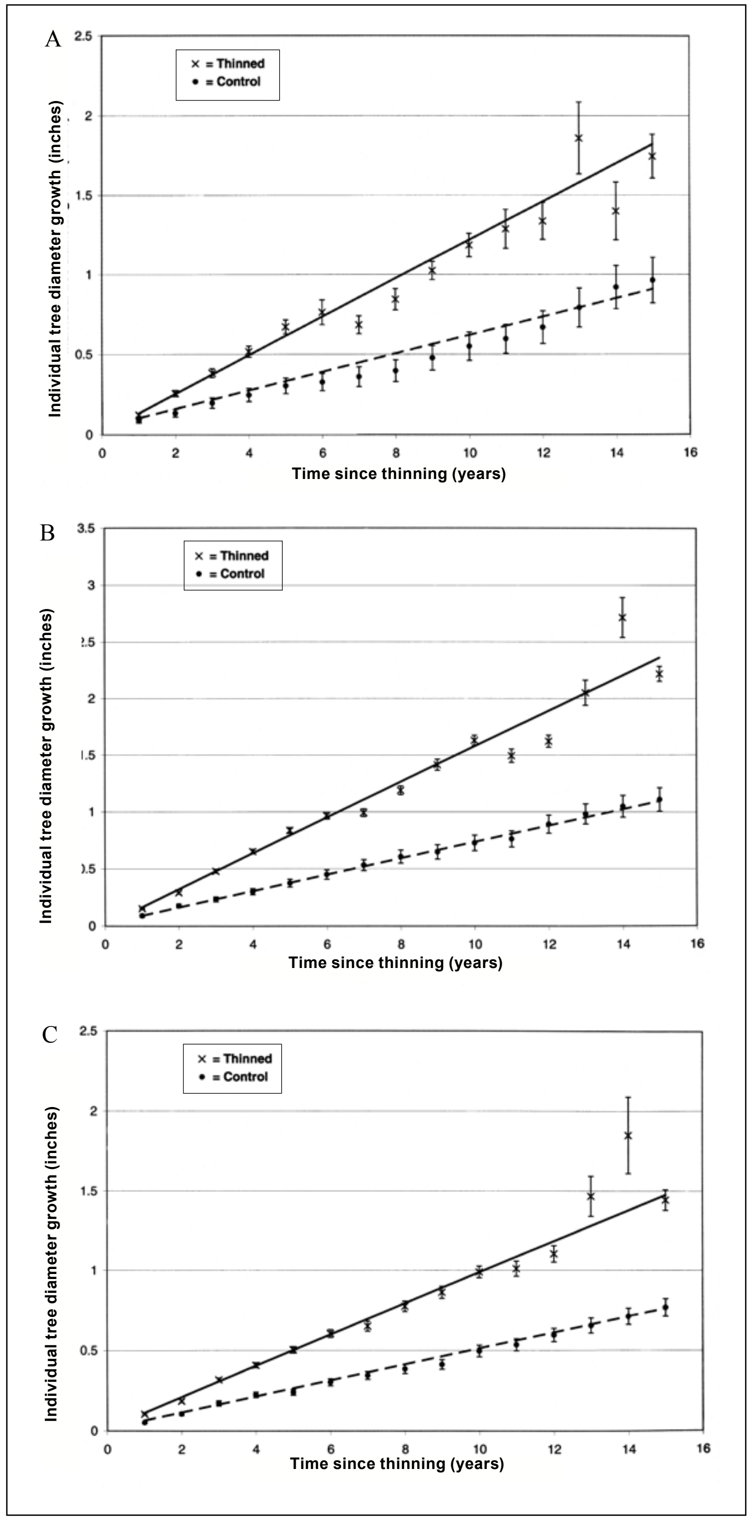

Figure 4—Relationship of individual tree diameter growth to time since thinning for Pacific madrone (A), tanoak (B), and California black oak (C) on the Challenge Experimental Forest, Yuba County, California. Bars around means depict standard errors.

We determined that the variance of diameter growth increased as time since thinning increased. Therefore, the regression was weighted with the square of time (years since thinning). Repeated measurements of the same plot were assumed to be independent of each other for this analysis. Given this assumption, the slope term for each species and treatment is an estimate of the annual growth rate per tree.

Tanoak grew faster than the other species in both the thinned plots and control during the study. Pacific madrone was intermediate in diameter growth rate, and California black oak had the lowest growth rate. Relevant statistics and regression procedures (SAS 2001) are noted (table 5).

Do trees in a clump of two, three, or four members grow faster or slower than single trees of the same diameter? The answer is important to foresters when determining which members to save when thinning a stand. Thus, diameter growth for clumps of up to four members was quantified for both thinned plots and control.

Table 5—Fitted parameters for the weighted linear regressions relating cumulative diameter growth per tree to years since treatment for Pacific madrone, tanoak, and California black oak

Species	Action	Intercept	Slope	*F*-value	Probability > *F*
Pacific madrone	Thinned	-0.0033	0.1264[a]	395.27	<0.0001
	Control	.0427[a]	.0580[a]	94.56	<.0001
	Thinned	-.0056	.1617[a]	2,327.76	<.0001
Tanoak	Control	.0187[b]	.0715[a]	243.52	<.0001
California black oak	Thinned	.0074	.1001[a]	1,302.18	<.0001
	Control	.0096	.0514[a]	368.63	<.0001

[a] Parameter is significantly different from 0 at $\alpha = 0.05$.

[b] Parameter is significantly different from 0 at $\alpha = 0.10$.

Table 6—*F*-tests (type III) of the parameter estimates for the relationship of clump density, species, and treatment to single-tree diameter growth

Factor	Representation	Estimate	Denominator degrees freedom	*F*-value	Probability > *F*
Intercept	β_0	1.12023	–	–	–
Species[a]	β_1	0.57890	1	138.73	<0.0001
Trees in clump X treatment	β_{21}–β_{20}	0.25369	2	59.03	<0.0001
Thinned	β_{21}	-0.06842	–	–	–
Control	β_{20}	-0.32211	–	–	–

[a] Pacific madrone and California black oak were compared with tanoak in this factor. The levels of species are 1 = tanoak and 0 = madrone or black oak.

– = no data.

Ten years after thinning was considered to be the time of most interest. Data were analyzed by species, and no significant difference was found between California black oak and Pacific madrone ($\alpha = 0.05$), so they were combined and compared to tanoak by an analysis of covariance (SAS 2001) with the form:

$$Y_{ijk} = \beta_{0j} + \beta_1 \bullet S_j + \beta_{2i} \bullet C_x T_{ijk} + \varepsilon_{ijk}$$

where:

Y_{ijk} = 10-year diameter growth for tree k of species j and treatment i,
$\beta_{n(i)}$ = coefficients estimated by the SAS GLM (General Linear Model) procedure,
S_j = species $j = 1$ for tanoak or 0 for Pacific madrone or California black oak,
$C_x T_{ijk}$ = interaction term, number of trees in the clump by treatment, and
ε_{ijk} = residual error.

For thinned plots, an increase in one member per clump caused only a 0.068-in decrease in average diameter (table 6). Consequently, the forester can leave clumps of up to four members, with only an insignificant loss in diameter growth. In the control, an increase in one member per clump caused a 0.32 in decrease in average stem diameter.

Diameter growth was then evaluated by species and residual basal area density level to evaluate the stand response to thinning. After 10 years, average diameter growth of Pacific madrone ranged from 0.83 to 1.9 in per tree, that of tanoak from 1.09 to 2.55 in, and that of California black oak from 0.77 to 1.6 in per tree. In general, each species alone or in a mixture grew best if heavily thinned (60 to 75 ft^2 of basal area per acre) and poorest if lightly thinned (124 to 153 ft^2 per acre) (fig. 5).

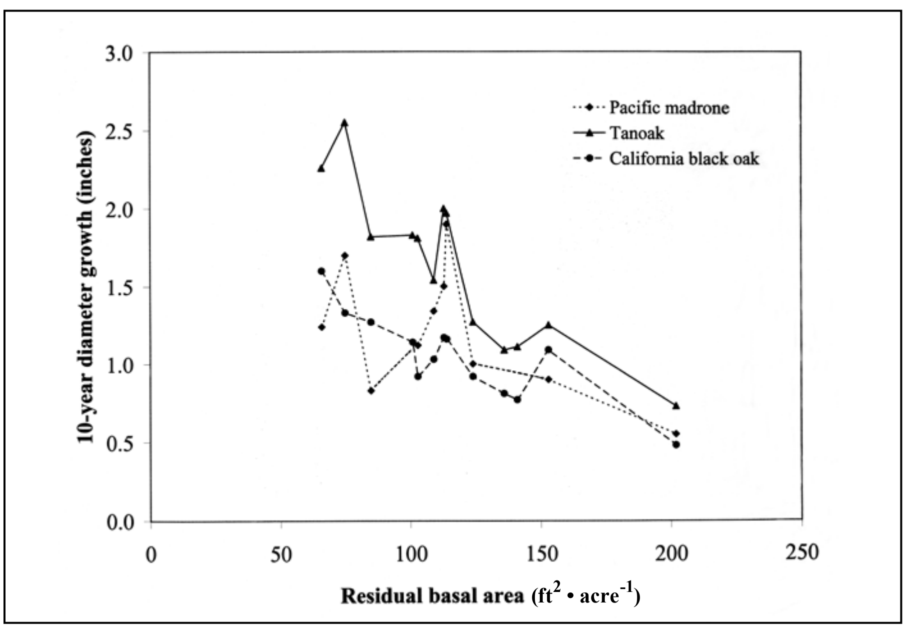

Figure 5—Effect of residual basal area on diameter growth per tree for Pacific madrone, tanoak, and California black oak.

To better portray diameter growth relative to beginning diameter, diameter growth was evaluated as a function of species, basal area density level, and d.b.h. of individual trees by a mixed-model analysis (SAS 2001) with the form:

$$Y_{ijk} = \beta_{0j} + \theta_i + \beta_{1j} \bullet \left(\frac{1}{Rba_i}\right) + \beta_2 \bullet Dbh_k + \varepsilon_{ijk}$$

where:

Y_{ijk} = 10-year diameter growth for plot i, species j (1 for tanoak, 0 otherwise), and tree k,

β_{nj} = coefficient estimated by mixed-model analysis,

θ_i = random plot effect i = 1 to 13 plots,

Rba_i = residual basal area for plot i,

Dbh_k = d.b.h. for tree k, and

ε_{ijk} = residual error.

This analysis showed that residual basal area, d.b.h., and species explained a significant amount of variation in the diameter growth of these hardwoods (table 7). More specifically, table 7 and some of the foregoing tables and figures show that results, significant at the 0.001 level, 10 years after thinning, were fivefold: (1) tanoak had a significantly higher growth rate per tree than Pacific madrone or California black oak, (2) the basal area density levels that promoted the highest growth rate were at the lower end of those studied (60 to 75 ft^2/acre), (3) larger diameter trees had better growth, (4) the species-diameter interaction was statistically significant, and (5) the species-basal area interaction was significant. The significant interactions mean that as diameter increases and basal area decreases,

Table 7—F-tests (type III) of the parameter estimates for the relationship of residual basal area, species, and beginning diameter to diameter growth

Factor	Representation	Estimate	Denominator degrees freedom	F-value	Probability > F
Intercept	β_{00}	-0.60250	–	–	–
Residual basal area (1/r.b.a.)	β_{10}	142.36	12	110.44	<0.0001
Diameter (d.b.h.)	β_{20}	.07148	666	161.6	<.0001
Species[a]	$\beta_{01} - \beta_{10}$	-.21280	666	1.46	.227
R.b.a. x species[a]	$\beta_{11} - \beta_{10}$	-93.20	12	34.55	<.0001
D.b.h. x species[a]	$\beta_{21} - \beta_{20}$	.06427	666	15.51	<.0001

[a] Other species were compared with tanoak in each of these factors. The levels of species are 0 = tanoak and 1 = other species. Therefore, these factors are the effect on the intercept and the residential basal area (r.b.a.) and diameter at breast height (d.b.h.) slopes that are caused by changing the species from tanoak to either of the other two species.

–= no data.

tanoak growth will increase faster than California black oak and Pacific madrone although the rate of increase in growth is not noticeable at smaller diameters or higher residual basal areas.

Volume Growth

Although volume growth was calculated from local volume tables, which are based on stem diameter (d.b.h.), the relationship of diameter growth to volume growth differs because volume is based on squared diameter values and the relationship is curvilinear. Also, foresters and land managers prefer volume estimates to arrive at yield values.

To better understand growth relationships, volume per tree and volume per stand also were examined. After 10 years, average volume growth for Pacific madrone in thinned stands ranged from 2.3 to 10.9 ft^3 per tree; for tanoak, from 3.3 to 9.8 ft^3 per tree; and for California black oak, from 2.1 to 5.0 ft^3 per tree. In general, volume growth was highest for heavily thinned stands (66 to 75 ft^2 per acre) and lowest for lightly thinned stands (124 to 153 ft^2 per acre) (fig. 6).

We then expanded the analysis of stand volume from a gross-growth to a net-growth basis. But first, mortality needed to be calculated (table 8). For thinned plots, mortality amounted to 19 trees and was about evenly divided among species. Pacific madrone lost the most volume (38.9 $ft^3 \bullet acre^{-1} \bullet year^{-1}$) and California black oak the least (17.8 $ft^3 \bullet acre^{-1} \bullet year^{-1}$). For the control, 26 trees were lost, with the majority of both trees and volume being California black oak.

After 10 years, average volume growth for Pacific madrone in thinned stands ranged from 2.3 to 10.9 ft^3 per tree; for tanoak, from 3.3 to 9.8 ft^3 per tree; and for California black oak, from 2.1 to 5.0 ft^3 per tree.

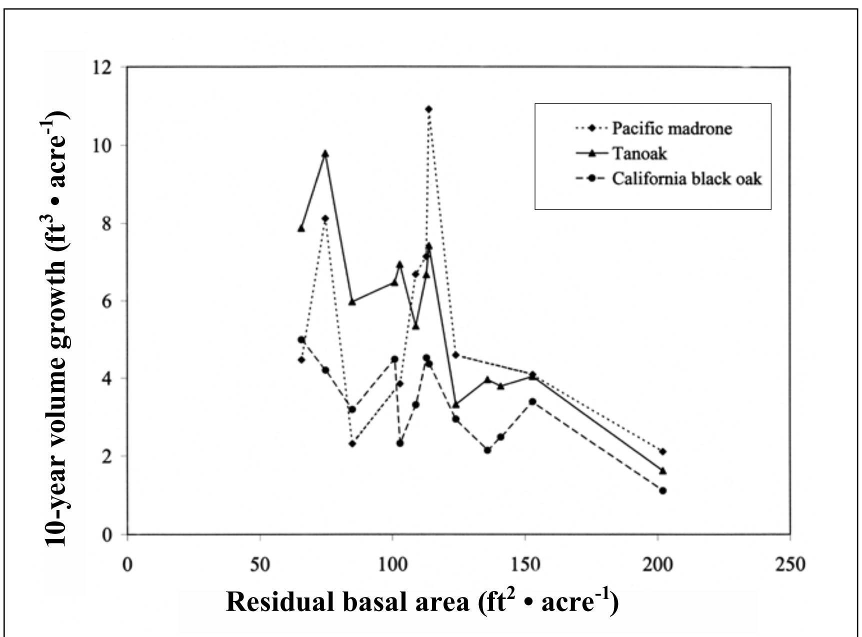

Figure 6—Effect of residual basal area on volume growth per tree for Pacific madrone, tanoak, and California black oak.

Table 8—Mortality by species during 10 years in the 12 thinned plots and the control plot on the Challenge Experimental Forest, Yuba County, California

Category	Species	Number of trees	Volume
			ft^3• $acre^{-1}$• $year^{-1}$
Thinned plots	Pacific madrone	6	38.9
	Tanoak	6	23.1
	California black oak	7	17.8
	Total	19	79.8
Control	Pacific madrone	4	3.5
	Tanoak	0	0.0
	California black oak	22	19.5
	Total	26	23.0

Ingrowth often is used as an offset to mortality if larger trees are present, but in this study all the trees that became ingrowth were very small and thus their volume was inconsequential. Ingrowth consisted of 49 saplings in five plots cut from 85 to 125 ft^2 per acre. More than 31 percent were Pacific madrone, 67 percent were tanoak, and slightly less than 2 percent were California black oak. Most became ingrowth at age 15.

Natural mortality reduced average annual (gross) volume growth from 0 to 22 percent per plot in thinned stands and 26 percent in the control. Plots with residual basal area density levels of 85 and 141 ft^2 per acre had the highest percentage losses. After subtracting mortality, net volume growth was greatest in plots thinned to 114 and 113 ft^2 per acre (fig. 7). These two plots had the highest gross volumes (114.5 and 104.2 ft^3 •$acre^{-1}$• $year^{-1}$, respectively) and no mortality.

Because Pacific madrone, tanoak, and California black oak are noted for tolerating drought (McDonald 1982, Morrow and Mooney 1974, Waring 1969), we compared average diameter and volume growth of each species and all species combined for the 2 wettest years (1974 and 1978) and the 2 driest years (1976 and 1977) to test this assumption. The analysis attempted to relate full-year growth to the amount of precipitation for both the time of active growth (April 1 through July 30) and the full year. Relative to the 50-year average taken at the Challenge Ranger Station less than 1 mile away, precipitation during the active growth period decreased 48 percent during the average driest year and increased 36 percent during the average wettest year. Similar comparisons for the full year were driest year, 60 percent decrease; wettest year, 42 percent increase:

Period	50-year average	Dry year	Wet year
	- - - - - - - - - - - - - *Inches of water*	- - - - - - - - - - - - -	
Active growth	7.97	4.18	10.86
Full year	67.31	26.84	95.38

To minimize thinning effects, plots had to have been thinned at least 4 years before the year could be selected as a wet or dry year. Values are for a calendar year, rather than a water year (July 1 to June 30).

A paired t-test (R Development Core Team 2004) showed that whereas average diameter growth for Pacific madrone, tanoak, and California black oak was greater during the average wet year, it was significantly greater (p = 0.047) only for tanoak (table 9). Similar results were obtained for volume growth as well (table 10).

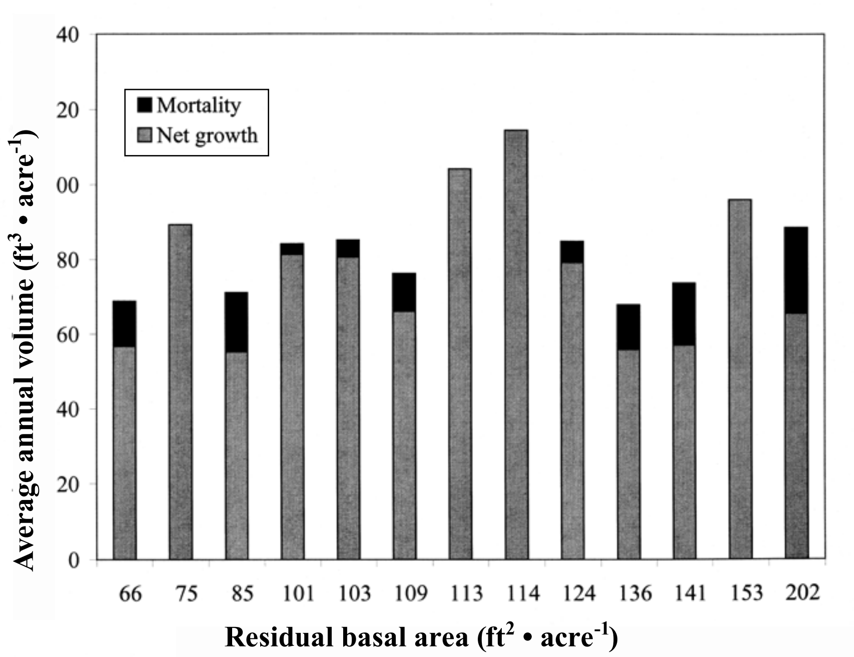

Figure 7—Relationship of average annual net volume growth and mortality to residual basal area density level.

Table 9—Diameter growth per tree by species for the average of 2 relatively dry years (1976 and 1977) and 2 wet years (1974 and 1978) at the Challenge Experimental Forest, Yuba County, California

Species	Dry years	Wet years	Difference	n	*T*-value	Prob > |*T*|
	Inches per tree					
Pacific madrone	0.060 (0.0075) [a]	0.065 (0.0097)	0.006 (0.0087)	42	0.68	0.49881
Tanoak	.090 (.0052)	.101 (.0049)	.010 (.0051)	172	2	.04687
California black oak	.067 (.0043)	.072 (.0040)	.006 (.0044)	184	1.28	.20124
All species	.076 (.0032)	.084 (.0031)	.008 (.0031)	398	2.44	.01514

[a] The value in parentheses is the standard error of the given mean estimate.

Table 10—Volume growth per tree by species for the average of two relatively dry years (1976 and 1977) and two wet years (1974 and 1978) at the Challenge Experimental Forest, Yuba County, California

Species	Dry years	Wet years	Difference	n	*T*-value	Prob > |*T*|
	- - - - - - - - - - - - - - - - *Cubic feet per tree*	- - - - - - - - - - - - - - -				
Pacific madrone	0.265 (0.0423)[a]	0.305 (0.0514)	0.039 (0.0404)	42	0.97	0.33532
Tanoak	.283 (.0191)	.340 (.0212)	.057 (.0170)	172	3.35	.00100
California black oak	.209 (.0173)	.233 (.0173)	.023 (.0146)	184	1.59	.11331
All species	.247 (.0124)	.286 (.0135)	.039 (.0108)	398	3.64	.00031

[a] The value in parentheses is the standard error of the given mean estimate.

Discussion and Conclusions

Thinning young-growth (60-year-old) mixed-hardwood stands requires special considerations.

Thinning young-growth (60-year-old) mixed-hardwood stands requires special considerations. Most hardwood trees in the Sierra Nevada of California originate as root-crown sprouts and hence form clumps of stems. At 60 years of age, natural mortality has reduced the number of stems per clump to fewer than 10, but almost all the clumps remain with one or more trees. This combination produces a dense stand of slender trees. These trees are striving to establish their canopies in sunlight and thus allocate most available resources to height growth rather than to crown development or bole width. Consequently, the typical young-growth hardwood stand consists of a variable number of slow-growing trees in a variable number of clumps. Usually, the tallest and straightest trees remain, but sometimes a tree will curve away from the clump, turn upward, and become part of the canopy. When several trees in a clump survive, one or more often develop a leaning or J-shaped lower bole. Multiple-stemmed clumps of tanoak and Pacific madrone tend to be more common than those of California black oak. Consequently, the silviculturist that prepares the thinning prescription must decide whether to leave whole clumps, parts of clumps, or single trees. Of paramount importance to this decision is whether trees in clumps grow as fast as single trees. In general, we found that for thinned stands, a tree of a given diameter in a clump of two to four members grew at about the same rate as a single tree of the same diameter. In the control, trees in clumps of up to four members grew slower than single trees.

Thinning hardwoods becomes even more complicated because the crowns of the various species have a different sensitivity to abrupt changes in light. Newly exposed crowns of tanoak become blighted, die back, and eventually die to that point on the bole where the branches are shaded. Crowns of Pacific madrone also become blighted and turn into a collection of branches with little tufts of leaves at the end. Crowns of California black oak withstand sudden exposure better than the other two species, but epicormic branches often proliferate along the bole. The tendency for epicormic branching is both genetically controlled and a function of tree and stand characteristics. Epicormic branching of California black oak on the Challenge Experimental Forest occurred on all but the most heavily shaded trees and increased significantly with decreasing stand density, proximity to openings, and location on south and east bole faces (McDonald and Ritchie 1994). These branches produced no acorns and degraded lumber quality. Thinning, then, necessitates opening up the stand carefully and removing a high percentage of small trees. It also necessitates leaving some trees as guard trees that normally would be removed.

Consequently, the most practical type of thinning was a crown thinning, whereby the crown of each save tree was provided space for expansion.

Periodic measurements of several hundred living trees in 12 growth plots and an uncut control provided insight into how trees and stands grow in a natural and thinned state. For all plots, before-thinning basal areas ranged from 165 to 244 ft^2 per acre and after thinning from 66 to 153 ft^2 per acre. Somewhere within this range should be a basal area that would balance the level of growing stock with the most efficient use of available site resources and therefore maximize tree and stand growth.

Tanoak grew reasonably well in the dense natural (unthinned) stand. Even small trees grew well, and mortality was negligible. Pacific madrone ranked second for diameter growth with some mortality, and California black oak was third. Mortality of California black oak was high because many small trees could not tolerate the deep shade and died from suppression. However, for larger, healthier black oaks, the deep shade of the unthinned control helped curtail the production of epicormic branches.

The timing and magnitude of the response to thinning for Pacific madrone, tanoak, and California black oak in this study differed by species and tree size. The growth of some trees of some species increased immediately after thinning, some responded later, and still others never responded to the increase in growing space. This variation was not surprising because factors such as prethinning tree vigor, clump density, development of epicormic branches, crown size, and crown position, as well as the interactions of all these variables, could lead to differences. In thinned stands, all three species of hardwoods had twice the diameter growth rate of trees in the control 3 years after thinning and maintained this superiority through age 15. However, the overall difference between thinned trees and trees in the control narrowed at 15 years, indicating that these stands could have been thinned a second time around age 10. Among species, tanoak grew faster than Pacific madrone, which in turn grew faster than California black oak. For all species, growth slowed if thinning left 124 to 153 ft^2 of basal area per acre.

Because forest managers are interested in yield, gross (average annual) volume growth was calculated, as was net volume growth after tree mortality was subtracted. Gross volume growth for trees in thinned stands ranged from 2.1 to 10.9 ft^3 per tree for the 10-year period. Mortality was about evenly divided among species in thinned plots and reduced gross volume growth from 0 to 22 percent per plot. In the control, mortality, mostly of small California black oaks, amounted to 26 percent.

Among thinned plots, results for volume growth were quite similar to those for diameter growth. In general, volume growth per tree was highest in stands thinned from 66 to 75 ft^2 per acre and lowest in stands thinned to 124 ft^2 per acre or more. After mortality was subtracted, the plot with about 114 ft^2 per acre had the highest net growth (114.5 $ft^3 \cdot acre^{-1} \cdot year^{-1}$). Net volume growth for trees in the control was 65.6 ft^3 per acre per year.

The volume growth of these three California hardwood species compared quite favorably with that of eastern hardwood species on sites of similar quality.

The volume growth of these three California hardwood species compared quite favorably with that of eastern hardwood species on sites of similar quality. For natural even-aged, young growth stands of the five principal upland oak species in the central United States, volume growth averaged 43 $ft^3 \cdot acre^{-1} \cdot year^{-1}$ (Schnur 1937). In the same general area, thinned stands of upland oaks added about 43 ft^3 per acre per year at a residual basal area of 94 ft^2 per acre (Dale 1972). For a mixed-hardwood stand on an excellent site in West Virginia, net volume growth for trees in the range of residual basal areas of 60 to 100 ft^2 per acre averaged about 94 $ft^3 \cdot acre^{-1} \cdot year^{-1}$ over a 10-year period (Trimble 1968).

The finding that a very wet year or a very dry year did not make much difference in the diameter or volume growth of Pacific madrone and California black oak was not surprising. All three species of hardwoods in this study have ancient progenitors in the Miocene epoch of 12 to 26 million years ago (Axelrod 1973), and all were part of the arborescent community then as now. Two species, tanoak and Pacific madrone, are classified as broad sclerophylls; California black oak is not, probably because it is deciduous. Broad sclerophylls are noted for having many morphological and physiological adaptations for tolerating drought (Cooper 1922). Although tanoak has many of these adaptations, its natural range is characterized by a cool, moist climate with high levels of either precipitation, fog, or relative humidity (Tappeiner and others 1990). Plainly, tanoak differs from the other two species in its tolerance of drought, and therefore it was not surprising that it grew significantly better in a wet year.

Purely in terms of wood production, volume (quantity) considerations are only half the decision for future management. The quality of the wood (bole) is the other half. Although speculative, a regime of careful thinning and pruning is suggested. A reasonable future thinning schedule would be to thin two more times at approximately 10-year intervals. A few guard trees would have to be kept at the second thinning, but none would be left at the third. After three thinnings, tree crowns should have become fully developed and be in better balance with the roots in terms of biomass and ability to capture site resources (fig. 8). More wood, acorns, and berries will result. Epicormic branching on California black oak also should become minimal because of this balance and because the well-developed crowns would be shading tree boles. Pruning at the time of first thinning or even earlier should be inexpensive because most trees in the characteristically dense stands prune naturally, and only a few branches would need to be removed.

In the longer term, the root-crown sprouts from the cut stumps will soon be ingrowth and then small trees. They, too, will need to be managed. Thus a cutting method resembling a two-stage shelterwood is suggested, with the thinned overstory being the first stage and the root-crown sprouts the second. The environment beneath the thinned stands should be favorable in terms of available light, and stem form should be straight and tall. After removal of the overstory, the crowns of the sprouts will be in a codominant position, which is best for these hardwoods. Eventually, they also will need to be thinned and management of the stands repeated.

Figure 8—After three thinnings, trees such as this California black oak with a straight bole, no epicormic branches, and a well-developed crown should be present.

Metric Equivalents

When you know:	Multiply by:	To find:
Inches (in)	2.54	Centimeters
Feet (ft)	.3048	Meters
Mile (mi)	1.609	Kilometers
Acre	.405	Hectares
Square feet (ft^2)	.0929	Square meters
Cubic feet (ft^3)	.0283	Cubic meters
Degrees Fahrenheit (°F)	$\frac{F-32}{1.8}$	Degrees Celsius

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