Long-term effects of tanoak competition on Douglas-fir stand development

Timothy B. Harrington and John C. Tappeiner II

Abstract: In 1- to 2-year-old Douglas-fir (*Pseudotsuga inenziesii* (Mirb.) Franco var. *menziesii)* plantations near Cave Junction and Glendale, Oregon, sprout clumps of tanoak *(Lithocarpus densiflorus* (Hook. & Arn.) Rehd.) and other hardwoods were removed with herbicides in April 1983 to leave relative covers of 0%, 25%, 50%, or 100% of the nontreated cover, which averaged 15%. In 1996 (Cave Junction) and 1998 (Glendale), precommercial thinning (PCT) of Douglas-fir and cutting of nonconifer woody species were operationally applied across the four densities of tanoak. In 2005, Douglas-fir in 0% relative cover of tanoak averaged 5-8 cm larger at breast height and 3-6 m taller, and had two to four times the net stand volume of those growing in 100% relative cover. From 1999 to 2005, Douglas-fir stand growth accelerated more rapidly in tanoak relative covers of 0% and 25% than in covers of 50% and 100%. Differential development of Douglas-fir and hardwoods in relative covers of 0%, 25%, and 100%, followed by selection of crop trees via PCT, resulted in three distinct stand structures: pure stands of Douglas-fir with a single canopy layer 12-16 m tall, mixed stands with overstory Douglas-fir (12 m) and midstory hardwoods (7 m), and mixed stands with a single canopy layer (8-9 m).

Resume: Dans des plantations de douglas de Menzies typique (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*, agees de 1 à 2 ans et établies pres de Cave Junction et de Glendale, en Oregon, des touffes de rejets de lithocarpe de Californie *(Lithocarpus densiflorus* (Hook. & Arn.) Rehd.) et d'autres feuillus ont ete éliminés à l'aide d'herbicides en avril 1983 pour laisser un couvert de 0, 25, 50 et 100 % relativement au couvert existant qui atteignait 15 % en moyenne. En 1996 (Cave Junction) et 1998 (Glendale), une éclaircie précornrnerciale (EPC) du douglas et une coupe des espèces ligneuses non résineuses ont ete appliquées de façon opérationnelle dans les quatre classes de densité de lithocarpe. En 2005, comparativement aux plants sous 100 % de couvert relatif de lithocarpe, les plants de douglas sous 0 % de couvert avaient, en moyenne, un DHP plus grand de 5 à 8 ern et une hauteur de 3 à 6 m plus élevée et le volume net du peuplement était deux à quatre fois plus élevé. De 1999 à 2005, la croissance du peuplement de douglas a augrnenté plus rapidement sous 0 et 25 % que sous 50 et 100 % de couvert relatif de lithocarpe. Les écarts de développement entre le douglas et les feuilIus sous 0, 25 et 100 % de couvert relatif de Iithocarpe, suivis d'une selection d'arbres d'avenir à l'aide de l'EPC, ont engendré trois structures distinctes de peuplement : des peuplements purs de douglas avec une strate unique d'une hauteur de 12 à 16 m, des peuplernents mixtes avec un couvert dominant de douglas (12 m) et une strate interrnediaire de feuillus (7 m), ainsi que des peuplements mixtes avec une strate unique d'une hauteur de 8 à 9 m.

[Traduit par la Redaction]

Introduction

In southwestern Oregon, competition from evergreen hardwoods, such as tanoak *(Lithocarpus densiflorus* Hook. & Arn. (Rehd.)) and Pacific madrone *(Arbutus menziesii* Pursh), limits the growth of planted conifers for 10 years or more (Wang et al. 1995; Harrington and Tappeiner 1997). Soon after timber harvest, stumps of these hardwoods sprout vigorously to reclaim their growing space. In the first several years after sprouting, their growth in height and crown width greatly exceeds that of newly planted conifer seedlings. The hardwoods compete with conifer seedlings by depleting soil water early in the growing season (Pabst et al. 1990; Zwieniecki and Newton 1996) and by limiting light availability to seedlings with their dense evergreen foliage (Hanington et al. 1994).

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Herbicides have been used successfully to control hardwood sprouts and establish conifer plantations in southwestern Oregon (Tesch et al. 1992). However, removal of hardwoods often stimulates germination of a vigorous population of shrub species, such as deerbrush *(Ceanothus integerrimus* H. & A.), snowbrush *(Ceanothus velutinus* Dougl.), and whiteleaf manzanita *(Arctostaphylos viscida* Parry) (Tappeiner et al. 1992), which also compete vigorously with conifer seedlings (White and Newton 1989; Monleon et al. 1999). Grasses and broadleaf herbaceous species usually occupy much of the remaining growing space.

The early effects of competing vegetation control on plantation development of coast Douglas-fir *(Pseudotsuga menziesii* var. *menziesii* (Mirb.) Franco) have been studied extensively (Newton and Preest 1988; Wagner and Radosevich 1991; Harrington et al. 1995; Rose et al. 2006). However, few studies have examined the long-term effects of controlling competing vegetation on Douglas-fir plantation development (e.g., Newton and Cole 2008) because of the challenge of protecting and maintaining experimental plots. In addition, little is known regarding the effects of subsequent silvicultural treatments, such as precommercial thinning (PCT), on stand development that was initially influenced by early control of competing vegetation.

As part of the Forestry Intensified Research program at Oregon State University, a study was initiated in March 1983 to determine the effects of various levels of tanoak competition, with or without control of understory herbs and shrubs, on Douglas-fir seedling development in two plantations in southwestern Oregon (Harrington and Tappeiner 1997). Eleven years after study initiation, Douglas-fir survival (96%-100%) did not vary significantly among tanoak levels. However, Douglas-fir trees averaged 4 cm greater in basal diameter and almost 2 m taller where tanoak was completely removed than where it was not treated. Control of understory vegetation resulted in additional increases in Douglas-fir growth, but only where the density of tanoak and other hardwoods had been reduced to relative covers of 0% or 25% of nontreated cover. This paper summarizes growth responses of Douglas-fir, tanoak and other hardwoods, and understory herbs and shrubs during 17-23 years after controlling competing vegetation to various levels. Of particular interest was whether operational PCT of Douglas-fir and cutting of nonconifer woody vegetation 14-16 years after the herbicide treatments had influenced the Douglas-fir growth responses to early vegetation control. In addition, black stain root disease (caused by *Leptographium wageneri* (Kendrick) var. *pseudotsugae* T.C. Harrington & F.W. Cobb) was identified as the cause of occasional Douglas-fir mortality following PCT at Cave Junction, and mortality rates were hypothesized to differ among relative covers of tanoak. To address these research questions, the following null hypotheses were tested:

H1: No change in treatment differences with time. Statistical differences among tanoak levels for growth of Douglas-fir and hardwoods did not change after PCT.

H2: No relationships to tanoak cover. Stand volume of Douglas-fir and cover of understory vegetation 23 years after the herbicide treatments were not related to initial tanoak cover 1 year after treatment.

H3: No site differences in relationships to tanoak cover. Relationships of Douglas-fir volume and understory vegetation cover in year 23 to initial tanoak cover did not differ between sites.

H4: No interaction with black stain root disease. Douglas-fir mortality rates due to black stain root disease did not differ among tanoak levels.

Methods

Study sites and treatments

Long-term effects of tanoak competition were studied in Douglas-fir plantations near Cave Junction (42.1635°N, 123.4144°W) and Glendale (42.7873°N, 123.4367°W), Oregon. The Cave Junction site has gravelly-loam soils of the Pollard and Beekman Series (Typic Palexerults and Typic Dystroxerepts, respectively), and the Glendale site has clay loam soils of the Josephine and Speaker Series (Typic Haploxerults and Ultic Haploxeralfs, respectively) (USDA NRCS 2008). Douglas-fir site index (100 year basis; McArdle et al. 1961) varies from 35 (Cave Junction) to 37 m (Glendale). Plant associations include tanoak - Douglas-fir – canyon live oak (*Quercus chrysolepis* Liebm.)/Oregon grape (*Mahonia nervosa* (Pursh) Nutt.) at Cave Junction and tanoak - Douglas-fir/salal (*Gaultheria shallon* Pursh) - Oregon grape at Glendale (Atzet et al. 1996). The previous old-growth Douglas-fir stand at each site was harvested in 1980, followed by a site preparation burn in spring 1981. Two-year-old bare-root seedlings of Douglas-fir were planted in spring 1981 at Cave Junction and in spring 1982 at Glendale.

In April 1983 cover of the 2-year-old hardwood sprout clumps averaged 15%, with values ranging from 10% to 20%. Within square 0.04 ha plots, triclopyr herbicide was applied to individual sprout clumps of tanoak and other hardwood species with a backpack sprayer. The goal of the treatment was to leave relative covers of 0%, 25%, 50%, or 100% of the nontreated hardwood cover in randomly assigned plots. A relative cover of 75% was not included as a treatment because we expected that the resulting conifer growth response would be very similar to that of the 100% relative cover treatment. The four relative covers, corresponding to actual cover values of 0%, 4%, 8%, and 10%-20%, respectively, were replicated six times at Cave Junction and three times at Glendale in randomized complete-block designs. Three of the replications at Cave Junction were also treated with a broadcast application of glyphosate herbicide in April 1983 to control herbs and shrubs (i.e., understory vegetation). Three additional replications of 0% relative cover installed at Glendale also received understory control. Control of understory vegetation was maintained in subsequent years by manual removal (1984) and installation of fabric mulch around individual Douglas-fir (1985). Additional site and study information is provided in Harrington et al. (1991).

In summer 1993 researchers thinned the Douglas-fir in the study plots at Glendale to leave 500 crop trees·ha^{-1} (Hanson 1997). Several years later, federal land managers contracted a PCT of Douglas-fir and cutting of nonconifer woody species across all treatments at Cave Junction (summer 1996) and Glendale (summer 1998). Contract specifications required thinning Douglas-fir to a 4.3 m x 4.3 m spacing (549 trees·ha^{-1}) with allowance for a 25% variation in spacing to enable retention of the best crop trees. All tanoaks, other hardwood species, and shrubs within 4.9 m of a crop Douglas-fir and at least 0.3 m tall were cut to a 0.15 m height. If a crop Douglas-fir was not available at the required spacing, a stem of tanoak or other hardwood species was left as a replacement. All debris from PCT were left in place. Table 1 provides a chronological listing of treatments and recent growth measurements by site. References to the chronology of treatments and vegetation responses are given in years since the herbicide treatments of April 1983.

Vegetation measurements

Early measurements of Douglas-fir growth (years 1-11 at Cave Junction and years 1-7 at Glendale) were based on 15 randomly selected trees per treatment plot - a sampling approach that did not permit direct calculation of per-hectare stand growth. To enable tracking of long-term stand-growth responses of Douglas-fir and hardwoods, a 0.03 ha circular

Table 1. Chronological history of treatments and recent measurements at each study site.

Treatment	Study site: Cave Junction	Study site: Glendale	Years since herbicide treatment
Tanoak and understory control	Spring 1983	Spring 1983	0
Douglas-fir PCT	—	Summer 1993	11
Stand growth–mortality measurement	Fall 1993	Fall 1993	11
Douglas-fir PCT; tanoak and shrub cutting	Summer 1996	Summer 1998	14, 16
Stand growth–mortality measurement	Fall 1999	Fall 1999	17
Stand growth–mortality measurement	Fall 2002	Fall 2002	20
Black stain root disease identified	Summer 2003	—	21
Stand growth–mortality measurement	Fall 2005	Fall 2005	23
Mortality measurement	Fall 2006	—	24

Note: PCT, precommercial thinning.

plot (r = 10 m) was centered over each square treatment plot in year 17 (1999), and all Douglas-fir trees rooted within the plot were tagged (n = 6-22 trees per plot). The circular plot design facilitated precise identification of measurement trees within an understory crowded with debris from PCT and resprouting woody vegetation. In years 17, 20, and 23, diameter at breast height (DBH, nearest millimetre at 1.37 m above ground) was measured on each tagged Douglas-fir, and 20% of the trees were systematically selected for height measurement (nearest 0.1 m). In addition, uncut tanoaks and other hardwoods with a DBH > 5 cm were tagged and measured similarly. For each species of understory vegetation (herbs, shrubs, and hardwoods <2.5 cm DBH) rooted within 3 m of the plot center, cover was visually estimated (nearest 5%) and average height was measured (nearest 0.1 m) in year 23. In years 20, 23, and 24, Douglas-fir mortality observed at Cave Junction was recorded for all trees rooted within each of the original 0.04 ha treatment plots. In year 21, the cause of mortality was identified as black stain root disease (Ellen Goheen, USDA Forest Service, personal communication). Only one Douglas-fir died at Glendale during years 20-24, and no cause of mortality was determined.

Statistical analysis

For years 11, 17, 20, and 23, plot means were calculated for DBH (expressed as quadratic mean diameter) and height of Douglas-fir and hardwood trees and for cover and height of understory herbs, shrubs, and hardwoods. Net stand basal areas for Douglas-fir and hardwoods (square metres per hectare) were calculated for years 17, 20, and 23 as the total cross-sectional area at breast height expressed on a per-hectare basis. Stepwise polynomial regression was used to develop models for predicting height of Douglas-fir, tanoak, and other hardwood species as functions of their DBH and age using combined individual-tree data from the three measurement years for each species. Individual-tree values of DBH, height, and predicted height of Douglas-fir for years 17, 20, and 23 were applied to the equations of Bruce and DeMars (1974) to calculate stem volume per tree, and these values were summed for each plot and expressed on a per-hectare basis to equal net stand volume (cubic metres per hectare). A similar approach was used to calculate net stand volume of hardwood trees using the equations of Pillsbury and Kirkley (1984). Cumulative mortality from black stain root disease at Cave Junction during years 20-24 was expressed as either stem density (trees per hectare) or basal area (square metres per hectare).

To test the significance (α = 0.05) of tanoak level, understory level, measurement year, and their interactions, a repeated-measures analysis of variance (ANOVA) was conducted in SAS PROC MIXED using combined data from years 17, 20, and 23 (SAS Institute Inc. 2005). To test the significance of treatment effects on Douglas-fir prior to PCT, ANOVAs of DBH and height were conducted using data from year 11 and adjusting for random effects of blocking. Data from Cave Junction were analyzed as a factorial design (four tanoak levels x two understory levels), while data from Glendale were analyzed as five treatments (four tanoak levels without understory control and 0% relative cover of tanoak with understory control). Douglas-fir stem density in year 17 did not differ among treatments at either site (P > 0.121), and therefore, it was used as a covariate in ANOVAs of Douglas-fir growth when significant (α = 0.05). Residuals for each response variable were plotted against predicted values to check for nonhomogeneous variance. Prior to ANOVA, a logarithmic transformation was applied to tree growth and mortality variables and an arcsine, square-root transformation was applied to cover variables to homogenize their residual variances (Sokal and Rohlf 1981, pp. 419–421, 427–428). If the interaction between tanoak level and measurement year was significant, multiple comparisons of least-squares (adjusted) tanoak-level means were conducted for a given measurement year using Bonferroni-adjusted probabilities (Quinn and Keough 2002). When only main effects were significant, multiple comparisons were used to compare adjusted treatment means among tanoak or understory levels.

Hypothesis 1 (i.e., no change in treatment differences with time) was rejected if interactions of tanoak level or understory level with measurement year were significant and multiple comparisons indicated that statistical differences among treatments were changing with time. Linear or nonlinear regression analyses were used to identify relationships of Douglas-fir stand volume and cover of herbs, shrubs, and tanoak in year 23 to initial tanoak cover in year 1, as well as to determine whether regression parameters differed between the two study sites (Sokal and Rohlf 1981, pp. 499-509).

Table 2. Analysis of variance results for cover and height of understory vegetation 23 years after removing sprout clumps of tanoak and other hardwoods to leave 0%, 25%, 50%. or 100% of nontreated cover, with or without control of understory vegetation.

				P >F					
				Cover (%)			Height (m)		
Site	Source of variation	dfn	dfd	Herbs	Shrubs	Hardwoods	Herbs	Shrubs	Hardwoods
Cave Junction	T	3	14	0.100	<0.001	<0.001	0.430	0.517	0.274
	U	1	14	0.143	0.926	0.480	0.128	0.988	0.112
	T × U	3	14	0.043	0.033	0.123	0.655	0.563	0.604
Glendale	T	4	8	0.916	0.072	<0.001	0.540	0.033	0.488

Note: T, tanoak level; U, understory level; dfn, degrees of freedom in the numerator; dfd, degrees of freedom in the denominator.

Hypothesis 2 (i.e., no relationship to tanoak cover) was rejected if any of the regression parameters for initial tanoak cover was significant. Hypothesis 3 (i.e., no site differences in relationships to tanoak cover) was rejected if any of the regression parameters differed between sites. Hypothesis 4 (i.e., no interaction with black stain root disease) was rejected if Douglas-fir mortality from black stain root disease differed among tanoak levels.

Results

Understory vegetation responses

Species of understory vegetation (herbs, shrubs, and hardwoods <2.5 cm DBH) at Cave Junction that had covers exceeding 3% in year 23 included tanoak (46% cover), Oregon grape (5%), bracken fern (*Pteridium aqulinum* (L.) Kuhn, 5%), and deer brush (4%). At Glendale, common understory species included tanoak (35% cover), beargrass (*Xerophyllum tenax* (Pursh) Nutt., 11%), whipplea (*Whipplea modesta* Torr., 7%), Oregon grape (4%), and whiteleaf manzanita (3%).

At Cave Junction, ANOVA detected a significant interaction between tanoak level and understory level for covers of herbs and shrubs ($P \leq 0.043$; Table 2). Multiple comparisons indicated that with understory control herb cover was greater in 0% than in 100% relative cover of tanoak, whereas without understory control, herb cover did not differ among tanoak levels (Table 3). With understory control, shrub cover was greater in 25% than in 50% or 100% relative covers of tanoak, whereas without understory control, shrub cover was greater in 0% than in 50% or 100% relative covers. At Cave Junction, only main effects of tanoak level were significant in the ANOVA for cover of understory hardwoods ($P < 0.001$). Cover of understory hardwoods averaged 25%, 47%, 57%, and 74% for tanoak relative covers of 0%, 25%, 50%, and 100%, respectively. Multiple comparisons indicated that understory hardwood cover was less in 0% than in 25%, 50%, or 100% relative covers of tanoak, and it was less in 25% than in 100% relative cover.

At Glendale, herb and shrub covers did not differ significantly among treatments ($P \geq 0.072$), averaging 14% and 7%, respectively, but cover of understory hardwoods did ($P < 0.001$; Table 2). For tanoak relative covers of 0%, 25%, 50%, and 100% (without understory control), cover of understory hardwoods averaged 7%, 44%, 69%, and 54%, respectively, whereas for 0% relative cover with understory control, cover of understory hardwoods averaged 5%. Multiple comparisons indicated that cover of understory hardwoods was less in 0% relative cover of tanoak (with or without understory control) than in 25%, 50%, or 100% relative covers.

Table 3. Mean cover of herbs and shrubs at Cave Junction 23 years after removing sprout clumps of tanoak and other hardwoods to leave 0%, 25%, 50%, or 100% of nontreated cover, with or without control of understory vegetation.

Species group	Tanoak relative cover (%)	Understory level: Controlled	Understory level: Not controlled
Herbs	0	24.0a	1.0a
	25	9.9ab	3.3a
	50	1.7ab	0.6a
	100	0.0b	3.7a
Shrubs	0	13.4ab	35.2a
	25	24.1a	11.4ab
	50	2.4b	2.0b
	100	2.9b	1.3b

Note: For each species group, row means do not differ significantly, and column means followed by the same letter do not differ significantly ($P > 0.05$).

With one exception, height of understory vegetation did not differ among treatments at either site ($P \geq 0.112$; Table 2), averaging 0.5, 0.7, and 2.6 m for herbs, shrubs, and understory hardwoods at Cave Junction, respectively, and 0.4 and 2.0 m for herbs and understory hardwoods at Glendale. At Glendale, treatment effects were significant for shrub height ($P = 0.033$); however, multiple comparisons failed to detect differences among relative covers of 0% (both with and without understory control), 50%, and 100%, where shrub height averaged 0.2, 1.6, 0.3, and 2.4 m, respectively. At Glendale, shrubs were absent in the understory vegetation measurement plots for each of the three replicates of 25% relative cover.

Douglas-fir responses

In year 17 at Cave Junction, 3 years after PCT, stem density of Douglas-fir (308 trees·ha^{-1}) averaged considerably lower than that required by PCT contract specifications (549 trees·ha^{-1}). Stem density of Douglas-fir at Glendale (480 trees·ha^{-1}) was close to that resulting from the initial PCT in year 11 (500 trees·ha^{-1}), indicating that few additional trees were cut in the study plots during the operational PCT in year 16. For years 17-23, stem density of Douglas-fir did not differ among treatments at either site ($P \geq 0.095$;

Table 4. Analysis of variance results for mean size and stand growth of Douglas-fir 17-23 years after removing sprout clumps of tanoak and other hardwoods to leave 0%, 25%, 50%, or 100% of nontreated cover, with or without control of understory vegetation.

			P >F				
Source of variation	dfn	dfd	DBH	Height	Stem density	BA	Volume
Cave Junction site							
T	3	15–16*	<0.001	<0.001	0.651	<0.001	<0.001
U	1	15–16	0.323	0.407	0.417	0.482	0.518
T × U	3	15–16	0.663	0.236	0.762	0.576	0.620
Y	2	31	<0.001	<0.001	0.007	<0.001	<0.001
Y × T	6	31	0.006	0.914	0.198	0.037	0.033
Y × U	2	31	0.516	0.065	0.819	0.547	0.501
Y × T × U	6	31	0.185	0.845	0.624	0.820	0.808
D17†	1	15	—	—	—	<0.007	0.004
Glendale site							
T	4	10	<0.001	0.009	0.095	0.001	<0.001
Y	2	20	<0.001	<0.001	0.386	<0.001	<0.001
Y × T	8	20	<0.001	0.518	0.466	0.002	0.009

Note: T, tanoak level; U, understory level; Y, year; D17, stem density in year 17; dfn, degrees of freedom in the numerator; dfd, degrees of freedom in the denominator.

*Denominator degrees of freedom =15 if the model included the covariate stem density in 17 years (D17, trees·ha^{-1}).

†Analyses for basal area (BA) and volume at Cave Junction have been adjusted for the covariate, Douglas-fir stem density in year 17 (D17, trees·ha^{-1}).

Table 4). At Cave Junction, Douglas-fir stem density decreased with time (P = 0.007) because of mortality from black stain root disease (described below), averaging 308, 298, and 294 trees·ha^{-1} in years 17, 20, and 23, respectively.

In years 17-23, DBH, height, stand basal area, and stand volume of Douglas-fir all differed significantly among treatments at the two sites (P < 0.009; Table 4). At Cave Junction, none of the Douglas-fir growth variables differed significantly between understory levels (P ≥ 0.323), and there were no significant interactions between tanoak level and understory level (P ≥ 0.236). In year 23, Douglas-fir averaged 5-8 cm larger in DBH and 3-6 m taller in 0% than in 100% relative cover of tanoak (Fig. 1). From year 11 to 17, some of the statistical differences in the average size of Douglas-fir among tanoak levels had changed (i.e., reject hypothesis 1). For example, beginning in year 17, Douglas-fir height at Cave Junction and DBH at Glendale were both less in 100% than in 50% relative cover of tanoak. Statistical differences among tanoak levels continued to change at Cave Junction from year 17 to 23: beginning in year 20, DBH in 25% tanoak relative cover no longer differed from that in 0% relative cover.

In year 23, Douglas-fir growing in 0% relative cover of tanoak had two to three times the stand basal area and two to four times the stand volume of those in 100% relative cover (Fig. 2). From year 17 to 23, statistical differences among tanoak levels for basal area and volume changed at Cave Junction (reject hypothesis 1) but not at Glendale (fail to reject hypothesis 1). Beginning in year 20 at Cave Junction, Douglas-fir basal area and volume in 50% relative cover no longer differed from those in 100% relative cover.

Responses of uncut hardwoods

Tanoak, Pacific madrone, and canyon live oak accounted for 64%, 34%, and 2% of the basal area of uncut hardwoods at Cave Junction, respectively, while tanoak, giant chinkapin (*Castanopsis chrysophylla* (Dougl.) A. DC), and Pacific madrone accounted for 38%, 32%, and 30% of the basal area of uncut hardwoods at Glendale. Hardwood stem density increased with time because of ingrowth of smaller trees (P < 0.002; Table 5), averaging 16, 33, and 33 trees·ha^{-1} at Cave Junction and 26, 34, and 34 trees·ha^{-1} at Glendale in years 17, 20, and 23, respectively. At Cave Junction, the interaction among tanoak level, understory level, and measurement year was significant for hardwood stem density; however, multiple comparisons failed to detect any significant differences. At Glendale, hardwood stem density in 0% relative cover of tanoak (0 and 3 trees·ha^{-1} with and without understory control, respectively) was less than in 25%, 50%, or 100% relative covers (81, 363, and 317 trees·ha^{-1}, respectively).

At Cave Junction, both the mean size and stand growth variables for hardwoods did not differ among tanoak levels, understory levels, or their interaction (P ≥ 0.129; Table 5). At Glendale, the interaction of treatment and year was significant for hardwood DBH, height, basal area, and volume (P < 0.020; Table 5). However, multiple comparisons for DBH and height failed to detect differences among treatments (Fig. 3). Statistical differences among tanoak levels for basal area and volume of hardwoods changed with time at Glendale (i.e., reject hypothesis 1). For example, beginning in year 20, hardwood basal area in 50% relative cover of tanoak was significantly greater than that in 25% relative cover, and hardwood volume in 50% relative cover no longer differed significantly from that in 100% relative cover (Fig. 4).

Mean sizes of hardwoods and Douglas-fir varied among tanoak levels in an inverse fashion (Figs. 1, 3). For example,

Fig. 1. Mean DBH and height of Douglas-fir (± standard error) 11-23 years after removing sprout clumps of tanoak and other hardwoods to leave 0%, 25%, 50%, or 100% of nontreated cover.. Means for a given year with the same letter do not differ significantly ($P > 0.05$). Main effects of tanoak level are shown for Cave Junction because understory effects were not significant..

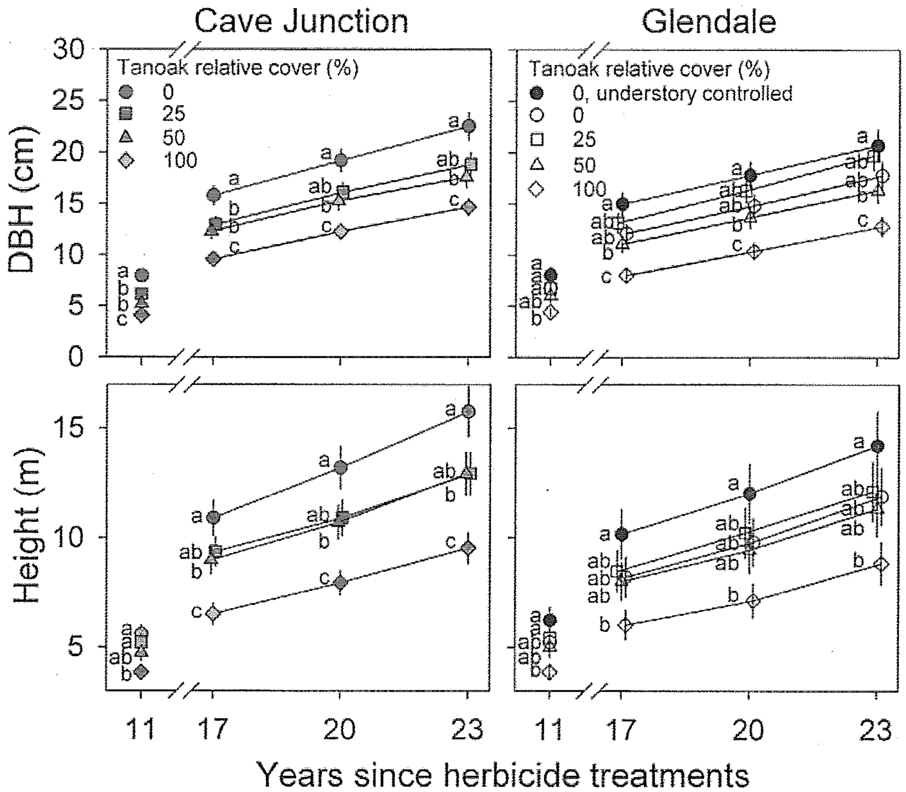


Fig. 2. Mean net stand basal area and volume of Douglas-fir (± standard error) 17-23 years after removing sprout clumps of tanoak and other hardwoods to leave 0%, 25%, 50%, or 100% of nontreated cover.. Means for a given year with the same letter do not differ significantly ($P > 0.05$). Main effects of tanoak level are shown for Cave Junction because understory effects were not significant..

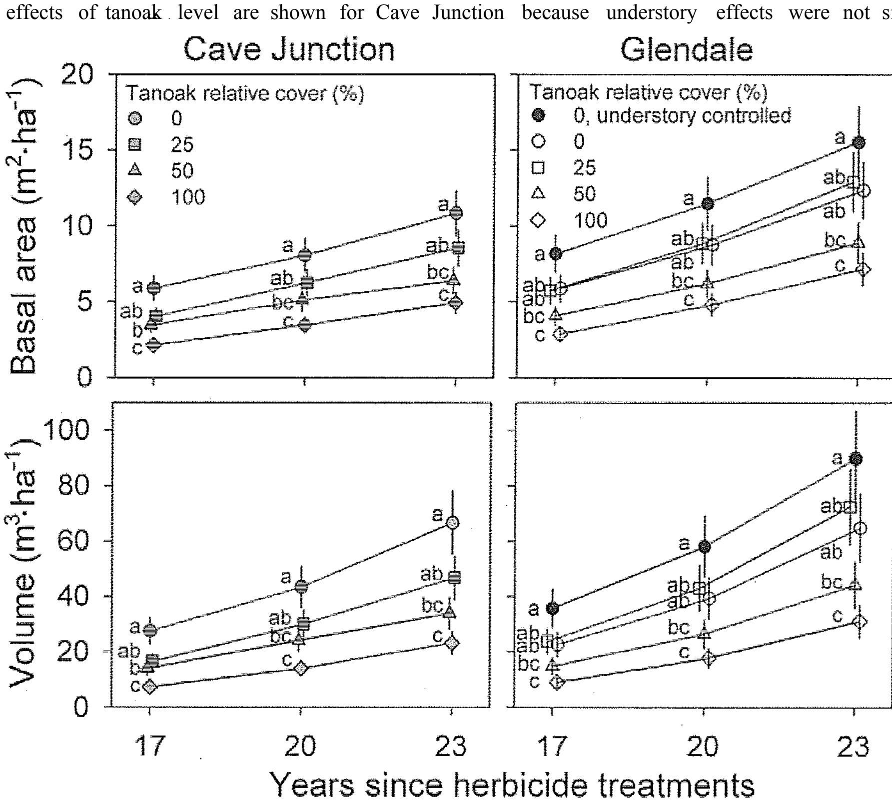
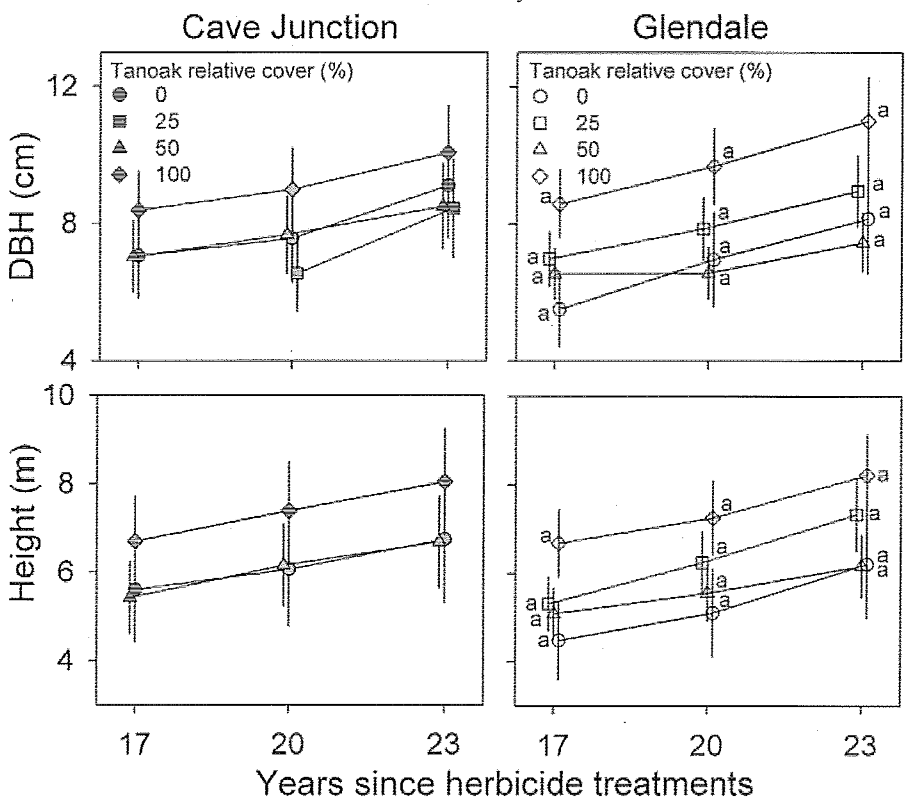


Table 5. Analysis of variance results for mean size and stand growth of uncut hardwoods 17-23 years after removing sprout clumps of tanoak and other hardwoods to leave 0%, 25%, 50%, or 100% of nontreated cover, with or without control of understory vegetation.

Source of variation	dfn	dfd	*P* >*F* DBH	Height	Stem density	BA	Volume
Cave Junction site							
T	3	16	0.407	0.570	0.660	0.330	0.399
U	1	16	0.892	0.129	0.472	0.683	0.856
T × U	3	16	0.277	0.540	0.217	0.179	0.189
Y	2	32	<0.001	<0.001	0.002	<0.001	<0.001
Y × T	6	32	0.132	0.882	0.609	0.600	0.988
Y × U	2	32	0.107	0.839	0.997	0.997	0.660
Y × T × U	6	32	0.040	0.314	0.048	0.131	0.092
Glendale site							
T	4	10	0.066	0.125	<0.001	<0.001	<0.001
Y	2	20	<0.001	<0.001	0.001	<0.001	<0.001
Y × T	8	20	0.020	0.010	0.093	<0.001	0.001

Note: T, tanoak level; U, understory level; Y, year; BA, basal area; dfn, degrees of freedom in the numerator; dfd, degrees of freedom in the denominator.

Fig. 3. Mean DBH and height of uncut hardwoods (± standard error) 17-23 years after removing sprout clumps of tanoak and other hardwoods to leave 0%, 25%, 50%, or 100% of nontreated cover. Means for a given year with the same letter do not differ significantly ($P > 0.05$). Means from Cave Junction did not differ among tanoak levels, and main effects are shown for comparison purposes. At Glendale, no hardwood stems were present in 0% relative cover of tanoak with understory control.



at 0% relative cover of tanoak, Douglas-fir DBH and height in year 23 were two to three times the values observed for hardwoods, respectively. However, at 100% relative cover of tanoak, Douglas-fir DBH and height were similar to values observed for hardwoods. Basal area and volume of Douglas-fir and hardwoods also varied inversely among tanoak levels, especially at Glendale (Figs. 2, 4).

Relationships to initial tanoak cover

Shrub cover, understory tanoak cover (DBH <2.5 cm), and Douglas-fir stand volume in year 23 all had significant regression relationships to initial tanoak cover in year 1 ($P < 0.001$; reject hypothesis 2; Fig. 5). Monomolecular and negative-exponential models were used to describe the relationships of understory tanoak cover and shrub cover to ini-

Fig. **4.** Mean net stand basal area and volume of uncut hardwoods (± standard error) 17-23 years after removing sprout clumps of tanoak and other hardwoods to leave 0%, 25%, 50%, or 1OO%of nontreated cover. Means for' a given year with the same letter do not differ significantly *(P>* 0.05). Means from Cave Junction did not differ among tanoak levels and main effects are shown for comparison purposes.

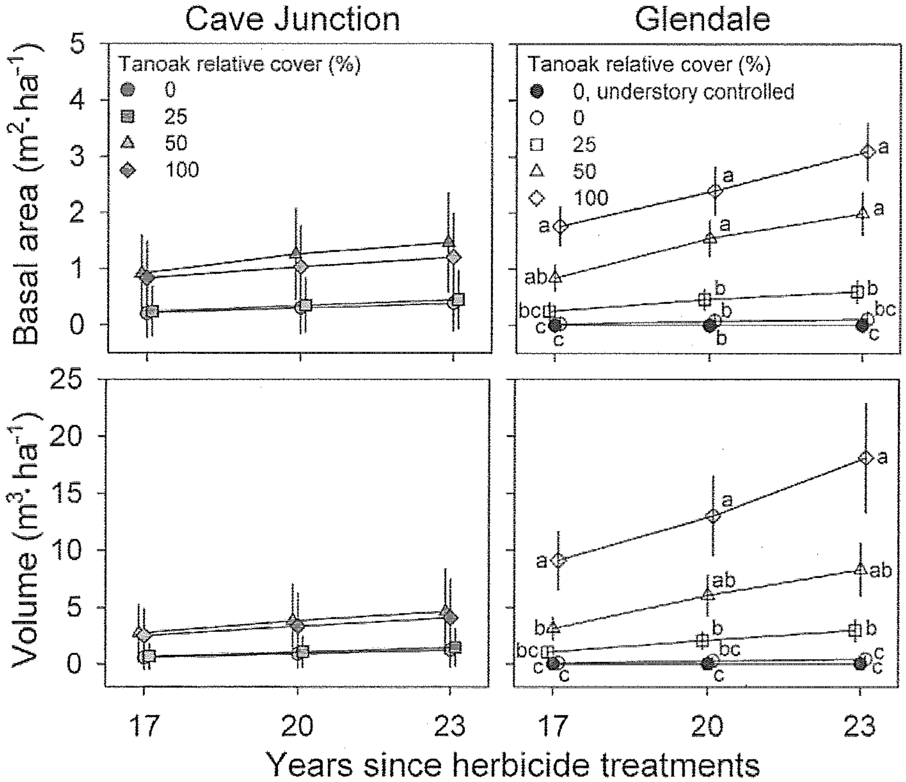
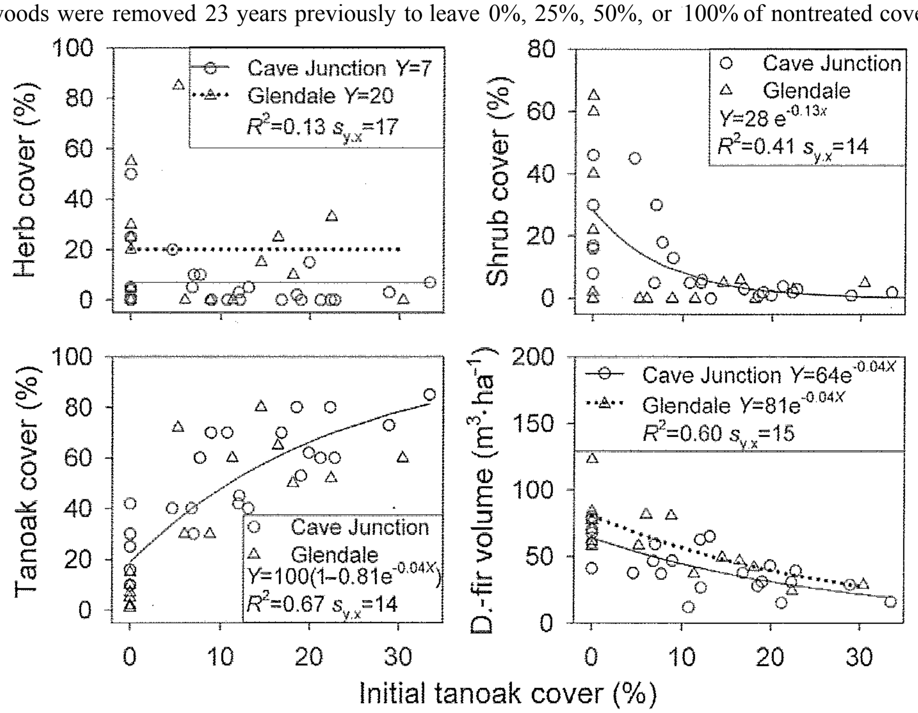


Fig. 5. Relationships of herb, shrub, and tanoak cover and Douglas-fir volume in year 23 to initial tanoak cover in year 1. Sprout clumps of tanoak and other hardwoods were removed 23 years previously to leave 0%, 25%, 50%, or 100% of nontreated cover.



tial tan oak cover, respectively. For the tanoak and shrub cover models, regression parameters did not differ between sites ($P \geq 0.096$; fail to reject hypothesis 3). The slope of the regression for herb cover did not differ significantly from zero ($P = 0.242$), but the regression intercept was greater at Glendale (20% cover) than at Cave Junction (7% cover) ($P = 0.025$; reject hypothesis 3). The higher mean cover of herbs observed at Glendale was attributed to two

Table 6. Analysis of variance results for mortality of Douglas-fir at Cave Junction from black stain root disease 20-24 years after removing sprout clumps of tanoak and other hardwoods to leave 0%, 25%, 50%, or 100% of nontreated cover, with or without control of understory vegetation.

			P >F	
			Mortality*	
Source of variation	dfn	dfd	Stem density	BA
T	3	13	0.087	0.006
U	1	13	0.054	0.082
T × U	3	13	0.623	0.902
D17[†]	1	13	0.010	0.008

Note: T, tanoak level; U, understory level; Y, year; D17, stem density in year 17; dfn, degrees of freedom in the numerator; dfd, degrees of freedom in the denominator.

*Mortality is expressed as stem density (trees·ha^{-1}) or basal area (m^2·ha^{-1}) of dead trees.

[†]Analyses for stem density and basal area mortality have been adjusted for the covariate, Douglas-fir stem density in year 17 (D17, trees·ha^{-1}).

shade-tolerant species, whipplea and beargrass, that were abundant in the understory.

Douglas-fir stand volume in year 23 had a negative-exponential relationship to initial tanoak cover ($P <$ 0.001; reject hypothesis 2; Fig. 5). The regression intercept differed between sites (P = 0.02; reject hypothesis 3), because Douglas-fir volume averaged 17 m^3·ha^{-1} greater at Glendale than at Cave Junction when initial tanoak cover was zero. To adjust the regression for site differences in stem density and plantation age, stand volume was converted to mean annual growth in volume per tree. In this adjusted regression, mean annual volume growth versus initial tanoak cover had a negative-exponential relationship (R^2 = 0.54) with an intercept parameter that differed between sites (P = 0.04; reject hypothesis 3; relationship not shown).

Douglas-fir mortality from black stain root disease

Black stain root disease was identified as the cause of Douglas-fir mortality at Cave Junction beginning in year 20, six years after PCT. The main effects of tanoak and understory levels were marginally significant for stem density mortality from black stain root disease during years 20-24 ($P \geq$ 0.054; Table 6). During this period, an average of 4 trees·ha^{-1} died from the disease. Basal area mortality from black stain was significantly greater in 0% relative cover of tanoak (1.0 m^2·ha^{-1}) than in 25% or 100% relative covers (0.04 and 0.1 m^2·ha^{-1}, respectively) (P = 0.006; reject hypothesis 4). The difference in basal area mortality between 0% and 50% relative covers was marginally significant (1.0 and 0.2 m^2·ha^{-1}, respectively; P = 0.053).

Discussion and conclusions

Early vegetation control clearly has had long-term effects on development of these Douglas-fir stands. Controlling sprout clumps of tanoak and other hardwoods in 1- to 2-year-old plantations resulted in a tripling of Douglas-fir stand volume after 23 years - a response similar to that observed by Newton and Cole (2008) for Douglas-fir competing with Pacific madrone. The increases in Douglas-fir growth resulting from understory control observed in year 11 (Harrington and Tappeiner 1997) were no longer statistically significant by year 17. Newton and Cole (2008) also saw diminishing gains in Douglas-fir growth over time as a result of understory control. Converging responses of Douglas-fir to the two levels of understory vegetation may have resulted from decreases in tree growth where understory control caused an earlier onset of intraspecific competition and increases in tree growth where understory vegetation was not controlled but its abundance declined with Douglas-fir crown closure.

Treatment effects on hardwood density were still detectable after 23 years: stem density of uncut hardwoods at Glendale was 0-3 trees·ha^{-1} in 0% relative cover of tanoak versus 81-363 trees·ha^{-1} in 25%-100% relative covers. Likewise, cover of understory hardwoods at both sites was 5%-25% for 0% relative cover of tanoak versus 44%-74% for 25%-100% relative covers. The effects of vegetation management also facilitated long-term shifts in species composition of understory plants. Where complete removal of hardwood cover was combined with control of understory vegetation, a plant community dominated by herbaceous species has developed. At Cave Junction, plots having 0% relative cover of tanoak with understory control were dominated after 23 years by herbs (24% herb cover versus 13% shrub cover), whereas plots having 0% relative cover without understory control were dominated by shrubs (35% shrub cover versus 1% herb cover). In contrast, herb cover at Glendale did not differ among tanoak levels because of successful colonization of the understory by two shade-tolerant species, whipplea and beargrass.

This study has provided the unique opportunity to determine whether an operational PCT of Douglas-fir and cutting of nonconifer woody vegetation influenced Douglas-fir growth responses to early vegetation control (hypothesis 1). Although experimentally controlled comparisons of presence and absence of PCT were not included as part of the study design, some inferences can be made about the additional effects of this treatment. Precommercial thinning is typically applied to Douglas-fir plantations to accelerate the development of merchantable volume by allocating stand growth to fewer trees, to homogenize their size distribution through selection of crop trees, and to improve stand vigor and maintain crown development (Reukema 1975). In general, higher residual density after PCT results in higher yield but smaller average stem diameter when conifer stands are commercially thinned at a later date (Pettersson 1993). Size distributions of planted Douglas-fir have lower variance and greater positive skewing where competing vegetation is retained versus where it is controlled (Harrington et al. 1991; Knowe et al. 1992). In this study, PCT removed over half of the originally planted Douglas-fir (1076 trees·ha^{-1} planted; 308-480 trees·ha^{-1} remaining after PCT). If it is assumed that cut trees were from the lower half of the size distribution (i.e., thinning from below), increases in average tree size from removal of smaller trees would be greater for stands having size distributions with higher variance and less positive skewing (e.g., those where competing vegetation was controlled). Thus, immediate effects of PCT would be to increase the differences in average tree size among tanoak levels, as was observed in year 17 for height at Cave Junction and for DBH at Glendale.

From year 17 to 23, the growth trajectories for Douglas-fir basal area and volume at both sites lagged for 50% and 100% relative covers of tanoak compared with those for 0% and 25% relative covers. Conversely, the growth trajectories for hardwood basal area and volume showed greater acceleration for 50% and 100% relative covers of tanoak than for 0% and 25% relative covers, especially at Glendale. Initial stand conditions after PCT and subsequent responses of Douglas-fir and hardwoods suggest that precommercial thinning caused this divergence in stand growth trajectories among treatments in two ways. First, PCT intensified the inverse relationships observed between Douglas-fir and uncut hardwoods for average tree size and stand growth. During PCT, hardwood trees were left where conifer crop trees were not available, and the frequency of this occurrence increased with relative cover of tanoak because plots with high relative covers had fewer conifer crop trees and more hardwood trees. Second, stand basal area and volume of hardwoods increased more rapidly in high relative covers than in low relative covers of tanoak during years 17-23, particularly at Glendale, resulting in greater competition with Douglas-fir. In 100% tanoak relative cover, average tree size differed little between Douglas-fir and hardwoods, indicating intense crown competition between the two species groups, whereas in 0% relative cover, the Douglas-fir were twice the height of the hardwood trees, indicating little or no crown competition.

The relationships of herb, shrub, and tanoak cover in year 23 to initial tanoak cover in year 1 (hypothesis 2) confirm that vegetation control early in stand development and subsequent development of tanoak cover were dominant forces that had a long-term impact on the abundance and species composition of understory vegetation. Where initial tanoak cover exceeded 10%, it averaged 49% by year 23. Initial tanoak covers of 10% or greater severely limited shrub cover to values less than 10% by year 23, suggesting a competition threshold whereby the greatest reductions in growth of subordinate vegetation with increasing competition occur at low abundances of a dominant competitor (Wagner 2000). Herb cover was not related to initial tanoak cover because two shade-tolerant species, whipplea and beargrass, successfully colonized the understory at Glendale.

Does Douglas-fir stand volume follow a similar threshold response to tanoak competition level? Based on the regression analysis, it can be concluded that Douglas-fir volume in year 23 had a negative exponential relationship to initial tanoak cover, indicating that proportionate reductions in Douglas-fir growth with increasing competition were greatest at low levels of tanoak cover. Such a threshold response is often observed for competition effects on young conifer stands (Wagner 2000; Newton and Cole 2008). In addition, ANOVA results indicated that Douglas-fir volume in year 23 did not differ between 0% and 25% tanoak relative covers, and values for these treatments greatly exceeded that observed in 100% relative cover. This finding suggests that with treatments such as PCT and commercial thinning that favor dominant crop trees, Douglas-fir growth in low relative covers of tanoak (≤ 25%) is not likely to differ strongly from growth in the complete absence of tanoak. However, at relative covers of 50% or greater, strong reductions in Douglas-fir growth from tanoak competition are likely to persist for decades, regardless of thinning treatments.

Some of the relationships of Douglas-fir growth and vegetation abundance to initial tanoak cover differed between sites (hypothesis 3). Although herb cover in year 23 was not significantly related to initial tanoak cover, it averaged greater at Glendale (20%) than at Cave Junction (7%) because of two shade-tolerant species, whipplea and beargrass. Relationships of both shrub cover and tanoak cover in year 23 to initial tanoak cover did not differ significantly between sites. However, the relationship of Douglas-fir growth to initial tanoak cover differed between sites despite adjustments for differences in stand age and stem density. Both stand volume and average annual volume growth per tree were greater at Glendale than at Cave Junction, especially when initial tanoak cover was zero. Two explanations could account for these site differences in Douglas-fir response to competition. First, Douglas-fir site index at Glendale (37 m, 100 year basis) exceeded that at Cave Junction (35 m), indicating inherent differences in site productivity. Second, the Douglas-fir plantation at Glendale was precommercially thinned earlier, more frequently, and more selectively (by researchers in year 11 and by operational contractors in year 16) than at Cave Junction (by operational contractors in year 14). Presumably, these differences in PCT timing, frequency, and selectivity combined to encourage growth of crop trees where conditions were most favorable (i.e., low initial cover of tanoak), resulting in greater growth responses at Glendale than at Cave Junction. Unfortunately, the study does not provide a direct way of separating effects of early vegetation control from those of PCT because of site differences in treatment specifications, as well as the absence of growth data in the years before and after thinning.

An important finding from this research that merits further study is the observed interaction between black stain root disease and tanoak level (hypothesis 4). At Cave Junction, a higher basal area of Douglas-fir died from black stain in 0% relative cover than in 25%, 50%, or 100% relative covers of tanoak. Stem density mortality, however, did not differ significantly among tanoak levels, and averaged 4 trees·ha^{-1} from year 20 to 24. This result suggests that Douglas-fir were more susceptible to the disease where tanoak cover was completely removed than where some of it was retained. Wounded Douglas-fir or fresh slash from PCT probably attracted the various bark beetles (e.g., *Hylastes nigrinus*) and root or crown weevils (e.g., *Pissodes fasciatus*) that are known vectors of black stain root disease (Harrington et al. 1983). Previous research indicates higher rates of colonization for insects known to spread black stain when thinning occurs during September to January than when it occurs during May to July (Witcosky et al. 1986), although the latter timing was used at the Cave Junction site. The disease can move in the soil between roots and along root grafts, spreading outward from centers of infection at a rate of 1 m·year^{-1} (Hansen and Lewis 1997). Once infected, Douglas-fir usually dies within 3 years. Two hypotheses could explain the patterns of mortality observed at Cave Junction. First, tan oak' had low abundance in the 0% relative cover treatment at the time of PCT, and this relative absence of a species immune to the disease created more continuity in the food source for the vector insects, allowing a larger population to build and spread the disease. Second, the larger Douglas-fir that developed in the absence of tanoak had root systems that explored greater soil volumes and, hence, were more likely to be inoculated with the disease.

Three distinct stand structures have resulted from the treatments in this study: (1) pure stands of Douglas-fir with a single canopy layer 12-16 m in height, (2) mixed stands having a two-layered canopy composed of overstory Douglas-fir (12 m height) and midstory hardwoods (7 m height), and (3) mixed stands of Douglas-fir and hardwoods with a single canopy layer 8-9 m in height. The three stand structures resulted from three levels of tan oak control early in stand development - 0%, 25%, and 100% relative covers, respectively - combined with PCT that retained hardwood crop trees where Douglas-fir crop trees were not available.

The three stand structures resulting from the treatments in this study support a broad range of silvicultural objectives for the mixed evergreen forest community of southwestern Oregon (Tappeiner et al. 2007). The first stand structure is indicative of the potential productivity of Douglas-fir when grown with little or no competing vegetation. Its yield of merchantable wood is likely to be somewhat greater than that of the second stand structure, but probably not statistically greater. The second stand structure represents a moderately productive Douglas-fir stand with limited amounts of midstory hardwoods. Depending on their vigor, the hardwoods may someday provide value to wildlife for cover and mast production. The third stand structure will have much lower productivity of Douglas-fir than the other two, but its density and vigor of hardwoods will be greater than those in the second stand structure, and thus, it is likely to provide higher quality habitat for wildlife (Hagar 2007). While it is unknown for how long these stand structures will persist given future competitive interactions, differences in Douglas-fir yield among them are likely to remain stable or even increase as the species continues to exert its dominance.

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