Influence of species proportion and timing of establishment on stem quality in mixed red alder – Douglas-fir plantations

Amy T. Grotta, Barbara L. Gartner, and Steven R. Radosevich

Abstract: The relationships among stand structure, Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) branch characteristics, and red alder (*Alnus rubra* (Bong.)) stem form attributes were explored for 10- to 15-year-old trees growing in mixed Douglas-fir – red alder plantations. Treatments included a range of species proportions, and red alder was either planted simultaneously with Douglas-fir or after 5 years. Both replacement effects (total stand density held constant) and additive effects (stand density doubled) of competition were considered. When the two species were planted simultaneously and red alder proportion was low, red alder trees had low crown bases and much stem defect (lean, sweep, and multiple stems). Douglas-fir grew slowly when the two species were planted simultaneously. When red alder planting was delayed, species proportion did not affect red alder stem form, and height to the base of the Douglas-fir live crown decreased with increasing red alder proportion. Doubling Douglas-fir density increased the height to the base of the Douglas-fir live crown; however, doubling stand density by adding red alder did not affect Douglas-fir crown height. Douglas-fir lumber coming from mixed stands may be inferior because of the changes in knot characteristics associated with these different patterns of crown recession. In stands with a low proportion of red alder, red alder product recovery may be compromised because of the stem defects described above.

Résumé : Les relations entre la structure du peuplement, les caractéristiques des branches du douglas de Menzies (*Pseudotsuga menziesii* (Mirb.) Franco) et les attributs de la forme de la tige de l'aulne rouge (*Alnus rubra* (Bong.)) ont été étudiées chez des arbres âgés de 10 à 15 ans qui croissaient dans des plantations mixtes de douglas de Menzies et d'aulne rouge. Les traitements incluaient différentes proportions de chaque espèce et l'aulne rouge avait été planté en même temps que le douglas de Menzies ou 5 ans plus tard. Tant les effets dus au remplacement (le fait de garder constante la densité totale du peuplement) que les effets additifs (le fait de doubler la densité du peuplement) dus à la compétition ont été considérés. Lorsque les deux espèces avaient été plantées en même temps et que la proportion d'aulne rouge était faible, les tiges d'aulne rouge avaient beaucoup de défauts au tronc (troncs penchés, courbés et multiples) et la base de leur houppier était basse. Le douglas de Menzies croissait lentement lorsque les deux espèces avaient été plantées simultanément. Lorsque la plantation de l'aulne rouge était retardée, la proportion de chaque espèce n'affectait pas la forme de la tige de l'aulne rouge et la hauteur de la base du houppier vivant du douglas de Menzies diminuait avec l'augmentation de la proportion d'aulne rouge. La hauteur de la base du houppier vivant du douglas de Menzies augmentait si on doublait la densité du douglas de Menzies. Par contre, la hauteur du houppier du douglas de Menzies n'était pas affectée si on doublait la densité du peuplement en ajoutant de l'aulne rouge. Le bois d'œuvre de douglas de Menzies provenant des peuplements mixtes pourrait être de qualité moindre à cause des changements dans les caractéristiques des nœuds associés à ces différents patrons de récession du houppier. Dans les peuplements avec une faible proportion d'aulne rouge, la récupération de produits provenant de l'aulne rouge pourrait être compromise à cause des défauts au tronc décrits plus haut.

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Introduction

In the Pacific Northwest, mixed Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) – red alder (*Alnus rubra* (Bong.)) forests often result when red alder regenerates naturally in a planted conifer stand or where both species regenerate naturally. Management of Douglas-fir – red alder mixtures has generated much interest over the last several decades, especially because red alder has expanded into cutover areas that it historically did not occupy (Puettmann and Hibbs 1996) and because of red alder's increased market value. Potential advantages of these species mixtures over monospecific stands include increased nitrogen availability (Tarrant 1961), greater nutrient cycling, greater abundance and diversity of wildlife, aesthetic appeal (Puettmann and Hibbs 1996), and depending on site characteristics and management decisions, increased overall productivity (Tarrant 1961; Miller and Murray 1978; Binkley 1983). Despite these potential benefits, management of Douglas-fir – red alder plantations on a commercial scale up to the present has been rare. Successful

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management will depend on research showing that such mixtures can produce wood of both high volume and quality.

Research from monocultures will not predict stem form or growth well in species mixtures. Both competition and facilitation are possible between Douglas-fir and red alder (Tarrant 1961; Cole and Newton 1986, 1987; Shainsky and Radosevich 1991, 1992; Comeau and Sachs 1992; Newton and Cole 1994; Miller et al. 1999; D'Amato 2002). Because these species differ in many of their phenological, physiological, and architectural characteristics, whether a tree has one species or the other as its neighbor could have a large effect on its growth and wood quality. For example, Douglas-fir growth is less sensitive to water stress than is red alder (Chan et al. 2003), and in contrast to Douglas-fir, red alder has a nitrogen-fixing root associate, it has faster early height growth, it is deciduous, and its foliage is more transparent. Therefore, the resources that are available to any given plant will depend in part on the species of the neighbors surrounding it.

In Douglas-fir, important characteristics for wood quality include stem form and knottiness and anatomical characteristics that affect pulping and physical properties. This paper considers knot size and frequency, which are two of the most important features determining Douglas-fir lumber and veneer grade (Fahey et al. 1991; WWPA 1998). Other research on these stands considers the effects of species interaction on earlywood and latewood production (Grotta 2002). Knot characteristics are influenced by the longevity of live branches and the persistence of dead branches. The more rapid rates of crown recession in denser stands causes branch diameter and knot size to decrease as stand density increases (Grah 1961; Carter et al. 1986; Ballard and Long 1988; Briggs and Turnblom 1999; Robbins 2000). By the same mechanism, thinning increases branch size on remaining crop trees (Maguire et al. 1991). Trees growing in species mixtures may exhibit different crown growth and recession patterns than trees in monocultures, depending on the variability of resource capture among species in the mixture (Menalled et al. 1998). For example, it is possible that Douglas-fir trees will have higher branch longevity and higher growth rates when grown with red alder rather than in monoculture, if they have more light penetration and enhanced soil fertility.

In red alder, important characteristics for wood quality include stem form and knottiness and anatomy related to pulp and paper; work on wood density has shown the wood to be very uniform (Harrington and DeBell 1980; Lei et al. 1997; Gartner et al. 1997). Red alder log quality is quite variable, but it often has stem defects due to branchiness, sweep, and lean. Red alder tends to grow into open areas (Newton and Cole 1994). In irregularly spaced natural stands, this tendency causes lean because of the uneven crown development in light and shaded areas (DeBell and Giordano 1994). Research in monoculture showed that straighter trees can be grown by controlling tree spacing in either plantations or managed natural stands (Bormann 1985). If open grown, red alder also has a tendency to produce multiple stems (Newton and Cole 1994), which may result in more lean and sweep and possibly less merchantable wood. In its highest value uses, red alder is sold for furniture, face veneer, and other applications where aesthetics are important; thus clear, knot-free wood commands a price premium (Oregon Department of Forestry 2003). Sweep does not cause much defect per se because most logs are cut short. However, trees with sweep may exceed critical values of lean necessary to produce tension wood (9°–26°, depending on the individual; Wilson and Gartner 1996). Tension wood is considered a defect because it machines poorly, can have excessive radial shrinkage (Lowell and Krahmer 1993), and produces poor fiber-to-fiber bonding in paper. Without studies in mixed stands, it is impossible to predict how the Douglas-fir neighbors will affect the red alders, but it is possible that the red alder will grow as if it is open-grown (with high incidence of multiple stems, high sweep, and high lean) in the early years of growing with the slower-growing Douglas-fir.

The objectives of this study were to (*i*) quantify stem quality attributes — branch size and distribution in Douglas-fir and lean, sweep, length of clear bole, and multiple stems in red alder and (*ii*) assess patterns of these attributes as a function of inter- and intra-specific competition. We utilized a replacement series experiment to separate the effects of the two types of competition. We hypothesized that (*i*) species proportion in a stand drives variation in stem quality, when total stand density is kept constant, (*ii*) multiple-stemmed red alder trees have a greater amount of stem defect (i.e., lean, sweep) than do single-stemmed trees, and (*iii*) the timing of red alder establishment relative to Douglas-fir affects stem quality of both species. Such information would be useful in predicting patterns in future sawlogs from similarly managed natural stands or plantations and in evaluating whether stem quality attributes associated with species mixture are significant enough to affect product quality.

Materials and methods

Site description

The study site is in the Oregon Coast Range in the Cascade Head Experimental Forest near Lincoln City, Oregon (45°02′N, 123°58′W), within 5 km of the Pacific Ocean and at 330 m elevation. The site was originally dominated by old-growth Sitka spruce (*Picea sitchensis* (Bong.) Carrière) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.). Mean annual precipitation is about 250 cm, with the majority occurring between November and April. Average minimum and maximum temperatures are 2.2 and 20.9 °C, respectively. Soils are well drained and deep (up to 1 m) and highly fertile (Rhoades and Binkley 1992).

The study was conducted on experimental plots established in 1985 as part of an ongoing study of Douglas-fir – red alder interactions and measured for the current study in 2001. The plots represent a replacement series of Douglas-fir and red alder (Table 1) in a randomized complete block experimental design. In 1985, the site was clear cut and the following year trees were planted at a square spacing of 3 m × 3 m (1109 trees/ha). Combinations of the two species ranged from 100% Douglas-fir (100:0) to 100% red alder (0:100), with intermediate ratios of 90:10, 75:25, 50:50, and 25:75. Each combination is represented by two series: one in which seedlings of both species were planted in year 1 (1986) and one in which red alder planting was delayed 5 years (1991). Additionally, monocultures of each species

Table 1. Replacement series treatment descriptions.

Proportion		
Douglas-fir	Red alder	Red alder planting†
100	0	—
90	10	Immediate
90	10	Delayed
75*	25	Immediate
75	25	Delayed
50*	50	Immediate
50	50	Delayed
25*	75	Immediate
25	75	Delayed
0	100	Immediate
0	100	Delayed
100‡	0	—
0	100‡	Immediate

*Douglas-fir not measured.
†Red alder planting date: immediate = year 1 (1986); delayed = year 6 (1991).
‡Planted at 4.2 m × 4.2 m spacing; all other treatments planted at 3 m × 3 m spacing.

were established at 4.2 m × 4.2 m spacing (555 trees/ha) to represent the same within-species density found in the 50:50 mixture, with the absence of the other species.

Each treatment was replicated in three blocks for a total of 45 plots. Each plot consisted of nine rows for a total of 81 trees, except in the monocultures planted at 4.2 m × 4.2 m, where only 41 trees were planted because of the wider spacing. Trees that died were replaced for the first three growing seasons. Volunteer trees and shrubs were hand-removed until year five. Survival of Douglas-fir in treatment with immediate red alder planting was quite low when red alder made up more than 10% of total stand density. By year 15 of the experiment, when the trees were measured for the current study, Douglas-fir trees in the treatments with immediate red alder planting were far smaller than Douglas-fir trees in the treatments with delayed alder planting. In the treatments where red alder planting was delayed, red alder trees were generally as tall or taller than the conifers, despite the 5-year difference in age (A. D'Amato, Universtiy of Massachusetts, unpublished data).

Douglas-fir branch measurement

Douglas-fir trees were measured in seven treatments (Table 1). Five trees were selected randomly from the inner 25 trees of each plot; forked trees and trees with missing neighbors were excluded. With three replicate plots per treatment, a total of 21 plots and 105 trees were studied. All live and dead branches greater than 0.5 cm in diameter (outside bark) were counted to a height of 5.2 m (the length of the first 16-ft log with a 1-ft stump allowance; 1 foot = 0.3048 m). A branch was categorized as alive if any current-year needles were present; otherwise, the branch was categorized as dead, even if green needles from previous years persisted. Douglas-fir branches in the lower crown may live for years without increasing in diameter before mortality occurs (Robbins 2000). Thus for this study, dead branches were all those that had presumably reached their maximum size.

Trees were visually divided into longitudinal quadrants, and the diameter of the largest branch in each quadrant was determined with a digital caliper. Two perpendicular measurements were taken just distal to the branch collar and were averaged. The four branch diameters were averaged to obtain BD_4, a common branch size index (Fahey et al. 1991; Maguire et al. 1991). The height to the lowest live branch in each quadrant was measured with a height pole, and the height to the base of the live crown (HLC_{PSME}) was defined as the second-highest of these four measurements, i.e., the lowest point below which three of the four quadrants of the tree had live branches. Finally, diameter at breast height (DBH) was measured.

Red alder stem form measurement

Red alder trees were measured in 11 treatments (Table 1). All red alder trees within the inner 25 trees of each plot were measured; thus, depending on the species proportion within the treatment, 6–25 trees per plot were measured. With three replicate blocks, a total of 31 plots and 391 trees were measured (for treatment 13, only one plot was measured).

The amount of sweep (deviation from a straight line) was measured for the lower 2.4-m segment of each stem (after leaving a 30-cm stump allowance). This length was chosen to reflect conventional milling lengths (8 ft) for red alder (Willits et al. 1990). A 2.4-m pole was positioned against the bole with the base 30 cm above ground level, and the widest perpendicular distance between the inner surface of the bole and the pole was measured. To calculate lean (deviation from vertical), we attached a plumb line to the top of the pole. The horizontal distance between the weight at the end of the plumb line and the base of the pole was measured. The angle produced by the base of the tree and the ground could thus be calculated and subsequently the lean angle in degrees determined. A tree was considered to have multiple stems if the multiple stems started anywhere between ground level and breast height. If multiple stems were present, then DBH, lean, and sweep were measured for each individual stem greater than 10 cm DBH. Finally, height to the base of the red alder live crown (HLC_{ALRU}) was measured using an Impulse laser sensor (Laser Technology, Inc., Englewood, Colo.). HLC_{ALRU} was measured at the lowest point below which there were live branches on three of the four quadrants of the tree.

Data analysis

Total number of branches, percentage of branches that were alive, BD_4, and HLC_{PSME} were determined for each sample Douglas-fir tree; lean, sweep, and HLC_{ALRU} were determined for each sample red alder tree. Data for each tree were averaged by plot to result in plot means for each of the above response variables.

The incidence of multiple stems was treated as a binomial response variable with a Bernoulli distribution (each tree was assigned a value of 0 for a single stem or 1 for more than one stem). A logit transformation of the data, whereby for each plot the sum of these values was divided by the total number of red alder trees in the plot, provided estimated probabilities of trees developing multiple stems for each treatment (Steel et al. 1997). This probability value became the response variable to describe multiple stem development.

Table 2. Branch characteristics of Douglas-fir trees in Douglas-fir – red alder mixtures at two spacings and with either simultaneous planting of both species (immediate) or a 5-year delay in alder planting (delayed).

Treatment (Douglas-fir:red alder)	No. of branches	Branches/m	BD_4 (cm)	HLC_{PSME} (m)	% live branches	DBH (cm)
100:0, 3 m × 3 m	70.7 (4.2)	14.5 (0.9)	2.6 (0.1)	3.6 (0.3)	33.2 (4.6)	16.6 (0.7)
100:0, 4.2 m × 4.2 m	71.7 (3.5)	14.7 (0.7)	3.1 (0.1)	2.1 (0.1)	73.0 (2.5)	17.5 (0.8)
90:10 immediate	51.7 (3.1)	10.6 (0.6)	2.1 (0.1)	3.5 (0.3)	45.0 (6.5)	11.0 (1.0)
90:10 delayed	72.6 (3.9)	14.9 (0.8)	2.5 (0.1)	3.2 (0.2)	40.5 (4.8)	14.5 (0.7)
75:25 delayed	61.1 (3.5)	12.5 (0.7)	2.6 (0.2)	3.6 (0.3)	33.5 (5.1)	15.2 (0.9)
50:50 delayed	73.4 (4.3)	15.0 (0.9)	2.8 (0.1)	2.5 (0.2)	54.7 (3.6)	15.0 (0.8)
25:75 delayed	63.2 (3.5)	13.0 (0.7)	2.5 (0.1)	2.6 (0.3)	58.8 (6.2)	13.9 (0.6)
Overall mean	66.4 (1.6)	13.6 (0.3)	2.6 (0.1)	2.9 (0.1)	48.4 (2.2)	14.8 (0.4)

Note: Trees were planted at 3 m × 3 m spacing unless noted otherwise. BD_4, average diameter of the four largest branches; HLC_{PSME}, height to base of the Douglas-fir live crown; DBH, diamter at breast height. Mean (±SE) is given for n = 15 trees per treatment.

A similar transformation was carried out to determine whether the presence of sweep (0 for no sweep, 1 for sweep > 0) was associated with treatment.

Replacement effects of competition on each response variable were analyzed using the SAS MIXED procedure (SAS Institute Inc., Cary, N.C.), where species proportion was treated as a continuous explanatory variable and block was considered a random effect. Separate analyses were carried out for the two series in which red alder was planted immediately or after 5 years. For analysis of Douglas-fir characteristics, percent Douglas-fir of total stand density (0–100) was the explanatory variable describing species proportion; for red alder characteristics, using log(percent red alder) resulted in the best-fitting models. Initial exploration revealed that most Douglas-fir characteristics correlated strongly with DBH; thus, DBH was initially tested as another continuous explanatory variable in all models for Douglas-fir characteristics and then dropped if found not to be significant. Explanatory variables were deemed statistically significant with an associated p = 0.05.

Other treatment comparisons of interest were evaluated with analysis of covariance (ANCOVA), again using the MIXED procedure. These contrasts included (*i*) the two Douglas-fir monocultures at different spacings to test the additive effect of Douglas-fir on Douglas-fir; (*ii*) the 50:50 (delayed) mixture vs. the widely spaced Douglas-fir monoculture to test the additive effect of red alder on Douglas-fir; and (*iii*) the 50:50 (immediate) mixture vs. the widely spaced red alder monoculture to test the additive effect of Douglas-fir on red alder. The Fisher procedure for multiple planned comparisons was used to correct confidence interval widths (Steel et al. 1997).

Results

Douglas-fir branch frequency and size

The total number of branches per Douglas-fir tree (basal 5.2-m stem length) ranged from 29 to 104 (5.9–21.3 branches/m of stem), with an overall mean among all experimental units of 66.4 (13.6 branches/m) (Table 2). Treatment means ranged from 61 to 73 branches per tree (10.6–15.0 branches/m). BD_4 ranged from 1.4 to 3.7 cm, with an overall mean of 2.6 cm (Table 2). The 100% Douglas-fir treatment at wide spacing had the highest mean BD_4 of all treatments, and the 90:10 mixture with immediately planted red alder had both the lowest branch frequency and the lowest mean BD_4.

Both branch frequency and BD_4 were strongly correlated with DBH (Fig. 1); smaller trees had fewer, smaller branches. However, after accounting for differences in tree size, regression and ANCOVA models showed that neither branch frequency nor BD_4 was affected by Douglas-fir proportion in mixed species treatments, tree density in the two pure Douglas-fir treatments, or between the treatments with Douglas-fir at 4.2 m × 4.2 m spacing.

Douglas-fir branch vitality

Among all trees, HLC_{PSME} ranged from 1.0 to 5.8 m, with a mean of 2.9 m (SE = 0.1 m). Treatment means ranged from 2.1 to 3.6 m (Table 2). DBH did not affect HLC_{PSME} (p = 0.20); thus, the DBH variable was dropped from models describing HLC_{PSME}.

HLC_{PSME} increased with Douglas-fir proportion in treatments where red alder planting was delayed (Table 3); our model estimated a 0.9-m difference in HLC_{PSME} between the treatments with 10% and 100% Douglas-fir (SE = 0.5 m). Block affected the intercept of the equation describing this relationship; however, the slope of the equation was not different among blocks. In one of the three experimental blocks, HLC_{PSME} was estimated to be more than 1 m lower than in the other two blocks. This could have been due to differences in slope and aspect among blocks (plots in the first block mentioned were on flat to gently south-facing slopes, whereas the other two blocks had moderate to steep slopes facing northeast).

As expected, HLC_{PSME} was greater in the narrowly spaced, pure Douglas-fir treatment than in the widely spaced treatment, indicating a significant additive effect of Douglas-fir density (Fig. 2*a*). However, there was no statistically significant difference in HLC_{PSME} between the 50:50 mixture and the pure, widely spaced Douglas-fir treatment, indicating that there was no additive effect of red alder density on HLC_{PSME} (Fig. 2*a*).

Among all trees, the percentage of live branches on the lowest 5.2 m of the bole ranged from 0% to 87.1%, with an overall mean of 48.4%. Treatment means ranged from 33.2% to 73.0% (Table 2). The percentage of branches that

Table 3. Regression coefficients (±SE) and summary statistics for analysis of Douglas-fir crown characteristics as a function of Douglas-fir proportion (DFprop) in treatments where red alder planting was delayed.

Dependent variable	β_0	$\beta_1 \times$ DFprop	*p*	df*	*F*	R^2
HLC_{PSME}†	2.05 (0.36)	0.01 (0.005)	0.002	3,11	9.7	0.73
Percent live branches	60.54 (7.63)	–0.21 (0.09)	0.004	3,11	8.3	0.69

*Degrees of freedom (numerator, denominator).
†Height to the base of the Douglas-fir live crown.

Fig. 1. (*a*) Number of branches and (*b*) mean diameter of the four largest branches (BD_4) per Douglas-fir tree as a function of diameter at breast height. Plotted points are plot means.

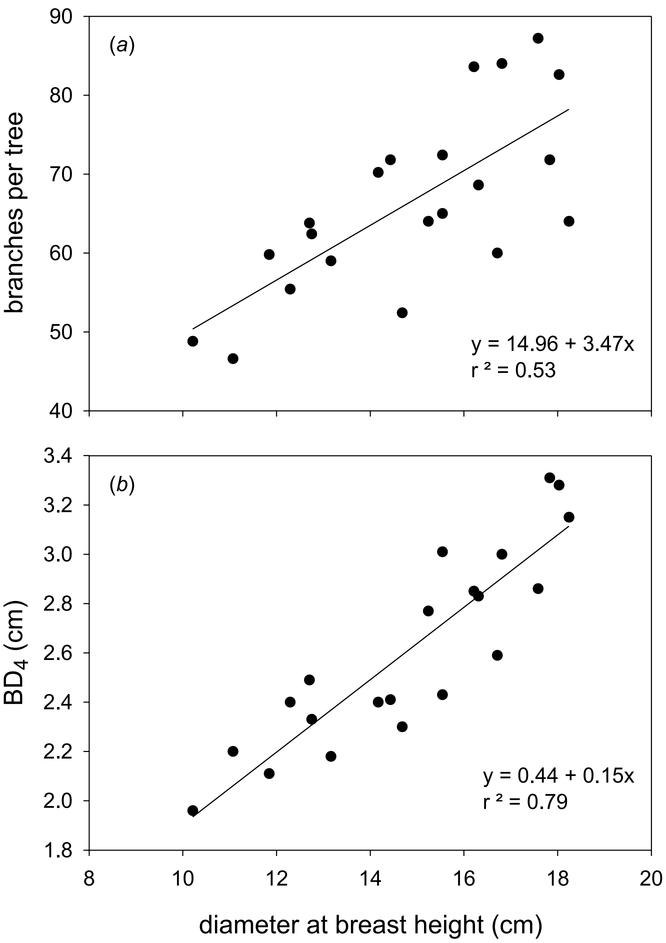
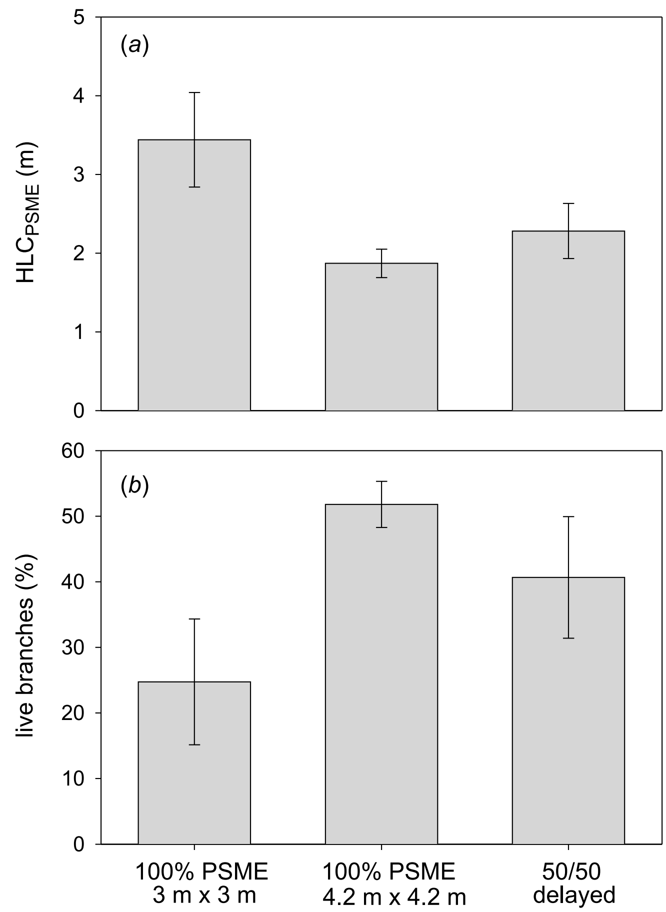


Fig. 2. (*a*) Height to the base of the Douglas-fir live crown (HLC_{PSME}) and (*b*) percent live branches for selected treatments (mean of three plots ± SE).



were alive decreased slightly with increased Douglas-fir proportion among the treatments where alder planting was delayed (Table 3). There was no difference in the percent live branches between the widely spaced pure stand and the 50:50 mixture, indicating that there was no additive effect of red alder density (Fig. 2*b*). However, the additive effect of Douglas-fir density was to decrease the proportion of live branches, because trees in the widely spaced, pure Douglas-fir stand had 27% more live branches than trees in the closely spaced pure stand (SE = 9%, Fig. 2*b*).

Red alder lean

Lean in individual red alder stems ranged from 0° to 43°, but the lean values were highly skewed, with most trees having between 0° and 8° of lean. All treatments had some trees with no lean, except for the 75% red alder, delayed-planted treatment, where the minimum lean angle was 2°. Treatment means ranged from 5° to 12° (Table 4).

Lean angle decreased as red alder proportion increased when alder was planted immediately (Fig. 3*a*). Our model estimated that the mean lean angle in stands with 10% red alder would be 11° (SE = 1°), whereas in a pure red alder stand it would drop to 6° (SE = 1°). No proportion effect was detected when red alder planting was delayed ($p = 0.30$, data not shown). ANCOVA showed no difference in lean angle as a function of timing of red alder planting at any level of species proportion ($p = 0.65$, data not shown).

Red alder sweep

Of the 489 stems measured (on a total of 391 trees), 143 stems had no measurable sweep. Of the 346 stems with mea-

Table 4. Summary statistics for red alder.

Treatment*	Trees (n)	Stems (n)	Lean angle (°)	Stems with sweep (%)	Sweep (cm)†	Sweep (cm)‡	Max. sweep (cm)	Trees with multiple stems (%)	HLC_{ALRU} (m)§
10; immediate	18	42	12 (2)	62 (4)	6.0 (1.3)	9.6 (2.0)	27.2	83.3 (0.0)	2.9 (0.1)
10; delayed	18	18	8 (1)	94 (6)	5.1 (0.7)	5.4 (1.0)	24.5	0.0 (0.0)	3.2 (0.2)
25; immediate	25	46	9 (1)	52 (8)	3.3 (0.5)	6.4 (0.1)	15.6	63.5 (19.5)	3.8 (0.9)
25; delayed	23	24	10 (3)	79 (12)	4.9 (1.2)	6.0 (0.6)	16.5	3.7 (3.7)	2.8 (0.1)
50; immediate	39	52	6 (1)	77 (3)	3.5 (0.3)	4.6 (0.4)	14.2	25.6 (5.1)	5.4 (0.6)
50; delayed	37	39	6 (1)	66 (10)	3.1 (0.6)	4.7 (0.9)	16.6	5.6 (2.8)	3.0 (0.4)
75; immediate	50	61	8 (2)	74 (1)	2.8 (0.3)	3.8 (0.5)	9.0	20.0 (1.8)	7.4 (0.5)
75; delayed	52	52	8 (2)	87 (6)	4.3 (0.8)	4.8 (0.5)	12.5	3.6 (1.8)	3.9 (0.6)
100; immediate	73	83	7 (1)	63 (10)	2.6 (0.4)	4.2 (0.2)	13.7	11.1 (7.3)	7.9 (0.5)
100; delayed	21	23	5 (—)	70 (—)	3.4 (—)	4.8 (—)	10.8	9.5 (—)	2.0 (—)
100; wide spacing	35	49	6 (1)	69 (2)	4.1 (0.7)	5.8 (0.9)	19.9	28.5 (2.5)	5.3 (1.0)
Total	391	489	8 (1)	72 (3)	3.9 (0.3)	5.5 (0.4)	27.2	24.0 (5.1)	4.5 (0.4)

Note: Means (and standard errors where indicated) are calculated from plot means.
*Numbers refer to percent red alder. Immediate–delayed refers to the time frame that red alder was planted.
†All stems.
‡Stems without sweep excluded.
§Height to the base of the red alder live crown.

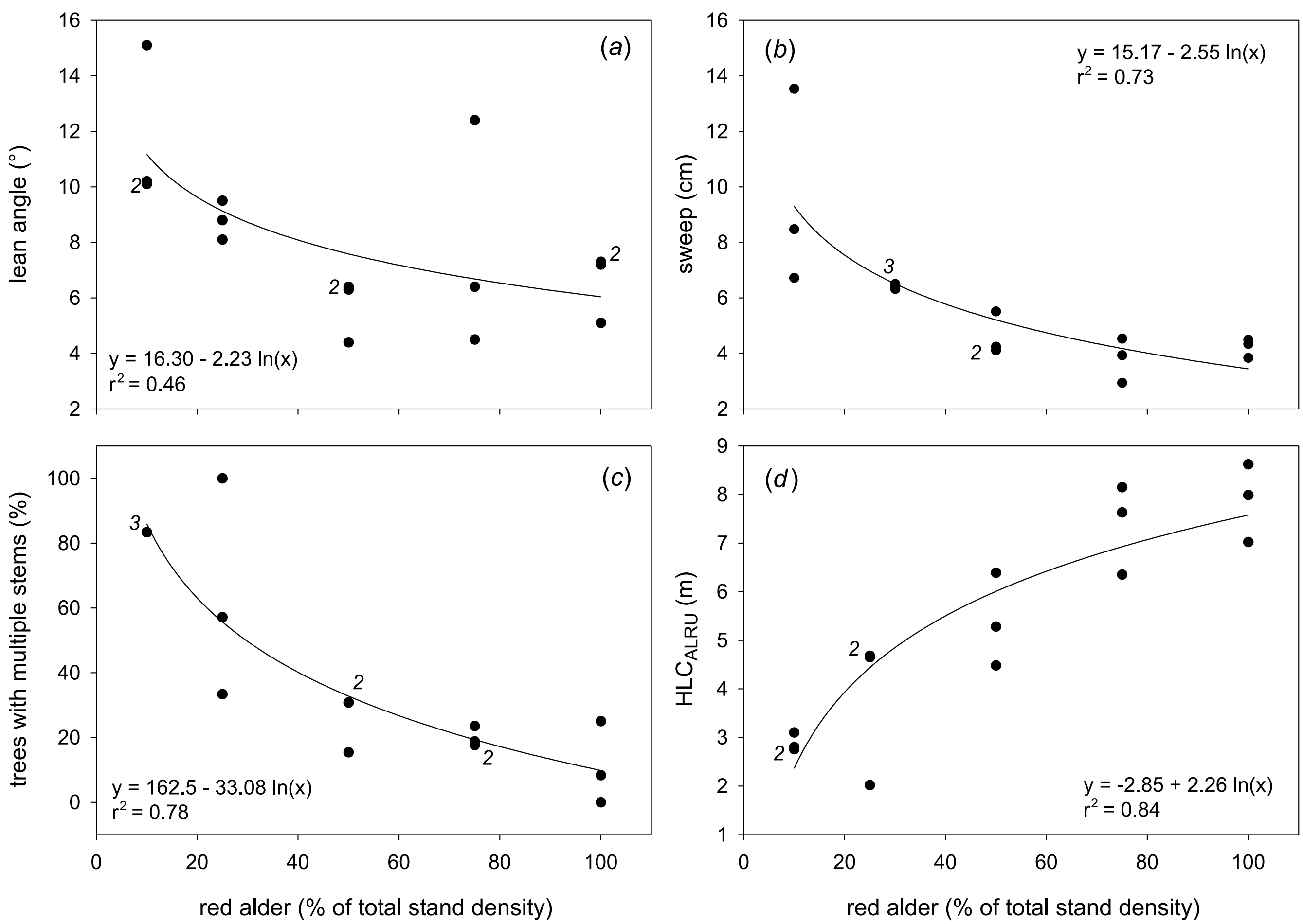


Fig. 3. Observed values and fitted regressions for (*a*) lean angle, (*b*) sweep, (*c*) likelihood of multiple stem development, and (*d*) height to the base of the red alder live crown (HLC_{ALRU}) as a function of red alder proportion when red alder planting was immediate. Plotted points are plot means. Numbers indicate multiple data points at the same location. All regression equations were significant at $p = 0.01$, df = 3,11.

surable sweep, mean sweep was 3.7 cm and the maximum sweep measured was 27.2 cm; treatment means ranged from 3.8 to 9.6 cm (Table 4). The frequency of stems without any sweep was unrelated to species proportion ($p = 0.4$). Though stems from immediately planted trees were less likely to have measurable sweep than stems from delayed-planted trees (generalized linear model; $F_{[1,27]} = 4.78$, $p = 0.04$), the magnitude of sweep was not different between the two timing treatments (*t* test; $p = 0.46$). Sweep was also positively correlated with lean angle (simple linear regression; $F_{[3,27]} = 11.1$, $p < 0.0001$, $R^2 = 0.55$).

In the immediately planted series, sweep decreased as red alder proportion increased, considering only stems that had measurable sweep (Fig. 3*b*). The mean sweep value for stems in the 10% red alder treatment was predicted to be 9.1 cm (SE = 0.8 cm), whereas in a 100% red alder stand, the predicted mean sweep value was only 3.4 cm (SE = 0.6 cm). However, when red alder planting was delayed, there was no relationship between red alder proportion and sweep ($p = 0.5$, data not shown). Additionally, no additive effect of Douglas-fir density influenced sweep (i.e., there was no difference in sweep between the 50:50, immediately planted and the 100% red alder, widely spaced treatments; $p > 0.1$, data not shown).

Multiple stems and associated effects

In the immediately planted treatments, the incidence of red alder trees with multiple stems increased as red alder proportion decreased (Fig. 3*c*). Our model predicted that in the 10% red alder treatment, 86% of trees would have multiple stems (SE = 8%), whereas only 10% of trees in the pure red alder stand would (SE = 6%). No significant effect of red alder proportion was detected where red alder planting was delayed ($p = 0.10$, data not shown). In this case, the probability of multiple stem development was estimated at less than 0.1 at all levels of red alder proportion. Finally, there was no difference in the probability of the occurrence of multiple stems between the wide-spaced, pure alder stand and the 50:50, immediately planted stand, indicating that there was no additive effect of Douglas-fir density ($p > 0.1$, data not shown).

When red alder was planted immediately, stems from multiple-stemmed trees had more lean and sweep than single-stemmed trees, but the difference varied with species proportion (ANCOVA; $F_{[5,20]} = 10.8$, $R^2 = 0.73$, $p < 0.001$, Figs. 4*a*–4*b*). In single-stemmed trees, lean angle and sweep increased with red alder proportion, whereas in multiple-stemmed trees, lean angle and sweep decreased with alder proportion. With 10% red alder, our model predicted 11.5° more lean and 6.4 cm more sweep in stems of multiple-stemmed trees (SE = 1.3° and 0.6 cm), but in a pure red alder stand, lean angle and sweep were the same in single- and multiple-stemmed trees. There was no such relationship in plots where red alder planting was delayed; however, because the incidence of trees with multiple stems in these treatments was quite low, such a comparison was difficult to make.

Individual stems on multiple-stemmed trees were smaller than single-stemmed trees in all treatments (ANCOVA; $F_{[5,20]} = 21.4$; $p < 0.0001$; Table 5, Fig. 4*c*). However, the sum of the cross-sectional area (at breast height) of all stems

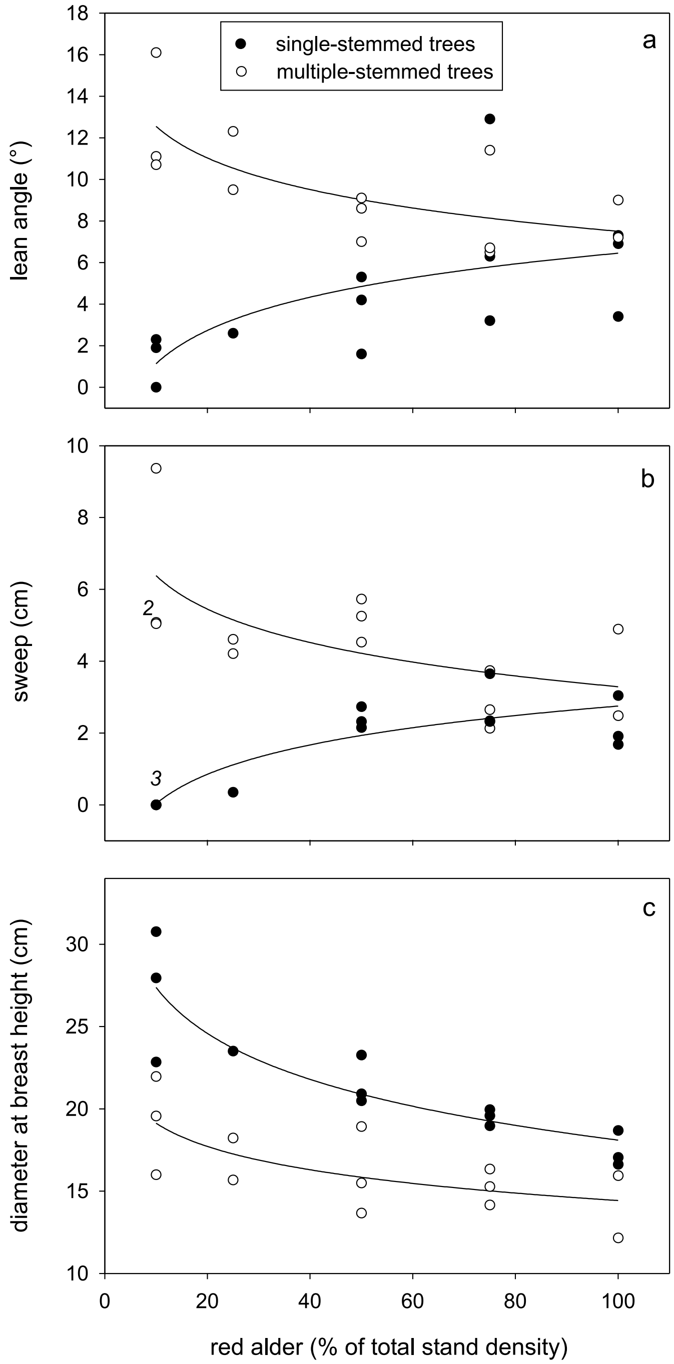


Fig. 4. (*a*) Lean angle, (*b*) sweep, and (*c*) diameter at breast height of single-stemmed (solid symbols) vs. multiple-stemmed (open symbols) red alder trees in plots where red alder was planted immediately. Plotted points are plot means for single- and multiple-stemmed trees. Numbers in panel *b* indicate multiple data points at the same location.

on multiple-stemmed trees was greater than that of single-stemmed trees (ANCOVA; $F_{[1,23]} = 16.9$; $p < 0.001$; Table 5). So, assuming that tree heights were similar between the two groups, multiple-stemmed trees produced a greater total volume of wood per tree, but the size of each stem on these trees was smaller than that of single-stemmed trees.

Table 5. Total cross-sectional area and quadratic mean diameter of all stems on multiple-stemmed trees compared with cross-sectional area and diameter of single-stemmed trees in treatments where red alder was planted immediately.

	Area (cm^2) per tree		Diameter (cm)	
Treatment*	Multiple-stemmed	Single-stemmed	Multiple-stemmed‡	Single-stemmed
10	761 (47)	620 (104)	19.5 (0.8)	27.9 (2.4)
25	613 (33)	444 (20)	18.5 (0.6)	24.1 (—)
50	475 (53)	387 (33)	15.9 (0.9)	21.9 (1.0)
75	408 (21)	321 (7)	15.5 (0.7)	19.9 (0.3)
100	341 (62)	253 (18)	13.1 (0.8)	17.8 (0.7)
100†	523 (53)	327 (69)	17.3 (1.3)	22.0 (1.4)

Note: Cross-sectional area was calculated from diameter at breast height values for individual stems. Means (±SE) are the average of three plots.
*Percent red alder.
†Wide spacing.
‡Quadratic mean diameter of all stems per tree.

Height to the base of the live crown

Among all trees, HLC_{ALRU} ranged from 0.8 to 13.8 m, with a grand mean of 5.0 m. Treatment means ranged from 2.0 to 7.9 m (Table 4). When red alder and Douglas-fir were planted at the same time, red alder live crowns were much higher where red alder proportion was greater (Fig. 3*d*). With red alder proportion at 10%, HLC_{ALRU} was predicted at 2.4 m (SE = 0.5 m), whereas in a pure stand it was predicted at 7.6 m (SE = 0.4 m). There was no effect of species proportion when red alder planting was delayed ($p = 0.6$, data not shown). Also, there was no difference in HLC_{ALRU} between trees in the widely spaced monoculture and the 50:50 immediately planted treatment, indicating that there was no additive effect of Douglas-fir density ($p > 0.1$, data not shown).

Discussion

Douglas-fir branch size, number, and vitality

Variation in the number of branches per tree and branch diameter was related mainly to tree diameter, whereas the responses of these variables to species proportion were insignificant. These associations are likely related to tree vigor. Larger, more vigorous trees have more photosynthate allocable for branch production, whereas suppressed trees must use more of their photosynthate for height growth and maintenance activities.

We found no relationship between branch count and stand density in Douglas-fir monocultures, consistent with previously reported results (Briggs and Turnblom 1999). It also appears that species proportion in red alder – Douglas-fir mixtures may be manipulated without affecting Douglas-fir knot abundance, at least on the butt log. However, the number of branches on a particular stem length can be attributed partially to the number of branch whorls on that section of stem, which is a direct result of a tree's annual height growth. Trees with greater height growth will have fewer branch whorls per meter (Maguire et al. 1991) and thus may be expected to have fewer total branches for a given stem length. Furthermore, the position of knots relative to one another affects lumber grade more than the total number of knots within a piece (WWPA 1998). Too many knots within a short linear distance can devalue the product. For this reason, the number of branches per whorl (e.g., Carter et al. 1986) is probably a better indicator of future lumber quality than the total number of branches on a log.

Because branch diameters were measured outside the bark, the branch sizes that we report overestimate knot sizes by about 10%. Accounting for this, a branch with an outside-bark diameter of 2.4 cm would yield a knot of approximately 2.2 cm diameter, the upper size limit for Select Structural grade 2 × 4 lumber (WWPA 1998). At 15 years of age, 83 of 105 trees had at least one branch larger than this size. No tree had branches that were larger than 5.1 cm in diameter, the maximum knot size allowed for No. 2 dimension 2 × 4 lumber (WWPA 1998). Slightly older Douglas-fir trees (19–21 years) at spacings comparable to those in this study had a similar range of largest-branch diameters (Robbins 2000). Middleton and Munro (1989) reported a mean BD_4 of 4.4 cm in intensively managed Douglas-fir trees ranging from about 45–65 years old and found that oversized knots caused almost 30% of lumber to be downgraded from Select Structural. Although inferences from data from other sites and experimental designs must be made cautiously, these data provide insight on what the future trajectory of the pure Douglas-fir stands described in this study might be. However, to predict future knot sizes in the mixed-species treatments, one needs to consider how interspecific competition affects crown recession.

Although few differences in Douglas-fir branch size were found among treatments at age 15, different rates of crown recession may cause differentiation in branch size as the stands age. With a greater proportion of red alder, Douglas-fir crown recession slowed, despite the fact that Douglas-fir trees across the delayed red alder treatments were similarly sized (in DBH). This relationship supports our hypothesis that Douglas-fir crown recession is affected differently by interspecific competition from red alder than by intraspecific competition. Crown recession occurs when insufficient light is available for lower branches to produce enough carbohydrates to be photosynthetically self-sufficient (Sprugel et al. 1991). Although the red alder trees were planted 5 years after the Douglas-fir, by stand age 15 the alder were as tall or taller than the Douglas-fir (T. D'Amato, unpublished data), resulting in a mixed canopy. More light is transmitted through red alder canopies than through denser Douglas-fir canopies (Grotta 2002; Parker et al. 2002); thus, with a greater proportion of red alder in the stand, more light was likely available at the level of the lower Douglas-fir crown than in a pure conifer stand. As a result, in stands with a high proportion of red alder (i.e., 50%–75%), Douglas-fir crowns were relatively deep at age 15. This combination of species could eventually result in Douglas-fir logs with a higher number of large knots over a greater proportion of the bole or in logs that would be less suitable for veneer because of a larger-diameter knotty core. However, verification of this assumption would require continued observation of these stands for a longer period of time. Also, the eventual effect, if any, on lumber grade cannot be predicted without future data.

Red alder stem form

With simultaneous planting of the two species, red alder stem form appeared to be controlled by a combination of two factors: the proportion of stand density that was red alder and the development of multiple stems. According to Newton and Cole (1994), there are several mechanisms that may drive the development of multiple stems. It is thought that widely spaced alders are more prone to antler rubbing in the first years of growth, resulting in top dieback. Open-grown trees also are more likely to develop basal suckers, which, given adequate light resources, eventually may develop into codominant boles. Both of these mechanisms can be supported with data from this study, because there was a clear trend of increased development of multiple stems with increased spacing between red alder trees.

Because red alder grew much more rapidly than Douglas-fir through age 15, red alder tree density was more important than competition from the understory conifers in determining resource availability to red alder trees. When there were few widely spaced red alder trees in the stand, abundant light and space enabled the development of wide crowns. The individual stems on multiple-stemmed trees leaned outward to fully occupy open canopy space rather than compete with one another. Thus, multiple-stemmed trees had high amounts of both lean and sweep; however, single-stemmed trees were near vertical and had very little to no sweep. Single-stemmed trees in these stands were significantly larger in diameter than stems of multiple-stemmed trees, since woody biomass was allocated to only one bole. It is possible that as these single-stemmed trees grew larger, any amount of lean and sweep originally present was reduced, because new wood was unevenly distributed around the circumference of the tree. Although documentation of the relationship among stem diameter, lean, and sweep in red alder is scarce, in a study of stem form in birch species, less sweep was found in stands with larger mean tree diameters (Viherä-Aarnio and Velling 1999).

When red alder trees were planted closer to one another (i.e., at high proportions of total stand density), there was no difference in lean or sweep between multiple- and single-stemmed trees. Additionally, there was a lower incidence of multiple stem development. Again, it appears that any competition from the few understory Douglas-fir trees was irrelevant, and with a more crowded canopy, red alder stem form took on characteristics similar to those of a dense monoculture (DeBell and Giordano 1994).

Although the total volume of wood produced by multiple-stemmed trees was likely greater on average than that of single-stemmed trees, the smaller-diameter individual boles from multiple-stemmed trees potentially could result in logs that do not meet the size minimum for sawlog grade at the time of harvest, if growth rates remain the same. Red alder sawlogs typically must have a minimum 8-inch (20-cm) top, so after accounting for taper, a sawlog needs a minimum basal diameter of about 10 inches (25 cm). At the time of measurement, 10% of stems from single-stemmed trees were ≥10 inches DBH, while only 2.6% of stems from multiple-stemmed trees were that size.

For a hardwood log to meet minimum sawlog specifications, sweep must not exceed half the diameter of the small end (Rast et al. 1973). Using a taper equation for red alder, we estimated diameter at the top of the 8-foot sections on which sweep was measured. Twenty-three percent of all stems had sweep greater than half of this estimated diameter; of these, about 50% came from multiple-stemmed trees. Of the stems with sweep less than half of top-end diameter, only about 30% came from multiple-stemmed trees, and they were larger in diameter than those that failed to meet the grading criteria. So in general, single-stemmed, large-diameter trees had little sweep, whereas the smaller-diameter stems from multiple-stemmed trees had more. But, whether the magnitude of sweep measured in this study could have a significant effect on product quality and value is unknown. At the time of measurement, only about 4% of stems were large enough to meet minimum sawlog size; of these, none had enough sweep to cause a log degrade. Hardwood log buyers in this region remark that in practicality, sweep is not a factor when determining log grade, but that size is more important (S. Sabalaske, Cascade Hardwood LLC, personal communication).

The range and distribution of lean angle in the trees measured in this study was comparable with that found in the literature for trees of similar size in natural stands (Wilson and Gartner 1996), though in older (>30 years), natural stands with larger trees, lean angles were lower than those found here (Bormann 1985). The mean lean angle in all treatments was below the threshold (26°) above which Wilson and Gartner (1996) found tension wood in all red alder trees, but they found elevated growth stresses in most trees leaning >9°. Thus, it is difficult to predict how the quantity of tension wood would change with either timing or proportion of red alder planting; however, one might expect greater growth stresses in multiple-stemmed trees and trees in treatments where red alder density was low.

When both species were planted simultaneously, HLC_{ALRU} was highest in stands with high proportions of red alder. Because Douglas-fir trees grew much more slowly than red alder (D'Amato 2002), canopy gaps formed between individual red alder trees above the Douglas-fir tree-planting sites. Lower branches thus have been able to persist longer in cases where a high proportion of Douglas-fir resulted in larger canopy gaps. The modeled difference in HLC_{ALRU} between the 50% red alder stand and the pure red alder stand was 2.9 m. This is more than the equivalent of one additional mill-length (8 ft) clear log from each tree in the pure stand, compared with the 50:50 mixture. Hardwood logs and lumber are graded according to the amount of surface area that is clear of knots (Rast et al. 1973; NHLA 2003); thus, assuming that log diameters are sufficient for sawlog grade and that crown recession follows current patterns, red alder log and lumber value could be greater from pure stands than from mixtures based on the length of the clear bole.

Delayed establishment of red alder

Delaying the establishment of red alder reduced many of the negative red alder stem form effects that were present when the two species were planted simultaneously. The incidence of multiple stem development was sharply reduced; consequently, although at the time of measurement there was no difference in the magnitude of lean or sweep between immediately planted and delayed-planted trees, the association of these attributes with multiple stems indicates that as the delayed-planted trees mature, lean and sweep may be lower overall than in immediately planted trees.

The effect of species proportion on lean, sweep, multiple stems, and HLC_{ALRU} that was detected in immediately planted trees was eliminated when red alder planting was delayed. These results indicate that in the delayed series, inter- and intra-specific competition were approximately equal in their effect on red alder stem form. Delaying the establishment of red alder elevated the competitive status of Douglas-fir neighbors, particularly in terms of reducing the availability of space and light to red alder trees.

There has been much speculation about the effect of delayed red alder establishment on total stand productivity (Stubblefield and Oliver 1978; Miller and Murray 1979; Comeau and Sachs 1992; Newton and Cole 1994). From our results, it appears that this management strategy has potential to improve red alder wood quality. However, red alder trees in the experiment described here are still quite small and the future trajectory of these stands is unclear, making it difficult to draw inferences from the present status to harvest age. Continued monitoring of the experiment would yield information on stand productivity, wood quality, and product recovery as a function of delayed alder planting.

At present, mixed Douglas-fir – red alder plantations are seldom managed commercially; most existing mixtures result from the natural regeneration of one or both species. In these situations, to optimize productivity and quality, one must decide how much alder should remain in the stand and (or) for how long alder regeneration should be controlled to reduce competition with Douglas-fir. Although this study was carried out in mixtures with highly controlled species densities and spacings, our results could be of use in managing natural mixtures as well.

Conclusions

When total tree spacing in mixed red alder – Douglas-fir plantations is 3 m × 3 m and both species are planted simultaneously, the probability of a red alder tree developing multiple stems and the magnitude of sweep and lean increase as red alder proportion decreases. Individual bole diameters of red alders are smaller if multiple stems develop. Also, the height to the base of the red alder live crown is lower at low red alder proportions. If the two species are established simultaneously, Douglas-fir height growth in the first 15 years of stand development is not sufficient to create the competitive environment needed to produce red alder trees with optimal stem form characteristics. These effects disappear when red alder planting is delayed. Thus, it appears that to optimize red alder wood quality, low proportions of red alder in mixed conifer–alder stands should be avoided, trees should be planted more densely, or red alder establishment should be delayed.

Douglas-fir branch characteristics are affected by species proportion in stands where red alder planting is delayed 5 years. Increasing the proportion of red alder does not significantly alter Douglas-fir branch frequency or size over the lower portion of the bole; however, the height to the Douglas-fir crown base is reduced, resulting in a larger proportion of live branches. Assuming that this trend continues as the stand ages, the size of the knotty core in Douglas-fir logs from stands with a high proportion of alder may be larger. When Douglas-fir density is held constant, the additive effect of red alder is to increase the height to the base of the Douglas-fir live crown and decrease the proportion of live branches on the lower bole. However, the effect is less pronounced than the additive effect of increased Douglas-fir density. These effects may be linked to the differences in light penetration through red alder and Douglas-fir crowns.

At stand age 15, few trees of either species are yet of merchantable size. However, the trends in stem quality described here may result in differences in lumber grade as the stands age. Because competition between red alder and Douglas-fir is dynamic through time, such predictions must be validated through monitoring and measurement of older stands.

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