Size of Douglas-fir trees in relation to distance from a mixed red alder – Douglas-fir stand

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Variation in diameter, height, and stem volume of 57-year-old Douglas-fir (*Pseudotsuga menziesii* var. *menziesii* (Mirb.) Franco) was related to distance of these trees from a 27 m wide strip in the same Douglas-fir plantation that had been interplanted with red alder (*Alnus rubra* Bong.). Within the interplanted strip and despite its greater total stand density, bole volume of dominant and codominant Douglas-fir averaged 1.27 m^3 compared with 0.55, 0.45, 0.46, or 0.49 m^3 in trees 15, 30, 45, or 60 m, respectively, from the edge of the mixed stand. Some positive influence of nitrogen-fixing red alder apparently extended about 15 m beyond the edge of the mixed stand at this poor quality site in southwest Washington. We infer that similar ribbonlike distributions of naturally regenerated red alder could be retained to improve growth of nearby conifers on nitrogen-deficient sites.

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La variation en diamètre, en hauteur et en volume de la tige des arbres dans une plantation de sapin de Douglas (*Pseudotsuga menziesii* var. *menziesii* (Mirb.) Franco) de 57 ans a été mise en relation avec la distance entre les arbres et la limite d'une bande de 27 m de largeur dans laquelle de l'aulne de l'Orégon (*Alnus rubra* Bong.) était planté à travers le sapin de Douglas. Malgré une densité totale du peuplement plus élevée dans la bande, le volume de la tige des sapins de Douglas atteignait en moyenne 1,27 m^3 comparativement à 0,55, 0,45, 0,46 ou 0,49 m^3 chez les arbres situés respectivement à 15, 30, 45 ou 60 m de la limite du peuplement mélangé. Une certaine influence positive de l'aulne de l'Orégon, une espèce fixatrice d'azote, s'est apparemment étendue jusqu'à 15 m au-delà de la limite du peuplement mélangé dans ce site de qualité pauvre situé dans le sud-ouest de l'État de Washington. Nous concluons que des bandes semblables de régénération naturelle d'aulne de l'Orégon pourrait être conservées pour améliorer la croissance des conifères situés à proximité sur des sites déficients en azote.
[Traduit par la rédaction]

Introduction

Insufficient available nitrogen (N) limits tree growth in many forest types. In coast Douglas-fir (*Pseudotsuga menziesii* var. *menziesii* (Mirb.) Franco), extensively distributed field trials show that volume growth of about 70% of stands in this type can be increased by N fertilization (Miller et al. 1986). At some locations (Miller and Murray 1978; Binkley 1983), Douglas-fir growth has been increased by admixing red alder (*Alnus rubra* Bong.), an N_2-fixing, commercial tree species. In young, equal-aged mixtures, however, the beneficial effects of N_2-fixation to Douglas-fir can be counteracted by the competitive effects of nearby rapidly growing alder. Delaying alder planting or maintaining adequate tree spacing by early thinning are means to reduce alder competition.

We describe the size of Douglas-fir crop trees at different distances from a strip in the same plantation that had been interplanted with red alder. Previous research at this N-deficient site in southwest Washington showed that both red alder (Tarrant 1961; Miller and Murray 1978) and ammonium nitrate fertilizer (Miller and Tarrant 1983) enhance Douglas-fir growth; a single application of 157 kg N/ha increased stand volume growth by about 50% in a 15-year period. Within the interplanted strip, Douglas-fir crop trees are clearly larger than those in the surrounding pure yet less dense plantation. By plantation age 30 years, N in the forest floor and soil of the mixed stand averaged at least 30% or 1120 kg/ha more than in the pure stand (Tarrant and Miller 1963). These rates are about average for mixtures of red alder and Douglas-fir (Binkley 1992). By tree age 48 years, Douglas-fir volume in the mixed stand averaged about 222 m^3/ha compared with 202 m^3 in the adjacent pure Douglas-fir stand (Miller and Murray 1978). The additional red alder volume in the mixed stand was about 167 m^3/ha.

The objective of our investigation at tree age 57 years was to determine if diameter, height, or cubic volume of Douglas-fir differed in relation to distance from the mixed stand.

Methods

Study area

The study area is located between 547 and 608 m in elevation near Carson, Wash. At the Wind River Ranger Station, about 204 m lower in elevation, annual precipitation averages 2540 mm with 10% falling during the frost-free growing season of about 130 days. The soil, a moderately deep, well-drained gravelly loam derived from pyroclastic rocks, contained about 3174 kg/ha total N to a 0.91-m depth in the pure plantation at age 30 years (Tarrant and Miller 1963).

Located at the northeast edge of the 119 070 ha Yacolt Burn, the study area was swept by wildfire in 1902 and 1927. After the Yacolt Fire of 1927 and the 1928 growing season, 2-year-old Douglas-fir from a nonlocal seed source were planted at 2.4 × 2.4 m spacing. Four years later, and with no additional site preparation, 2-year-old red alder were interplanted at 1.8 × 1.8 m spacing to create a 27 m wide strip as a firebreak; this mixed species strip straddled a north–south section line through the plantation (Fig. 1). The alder source

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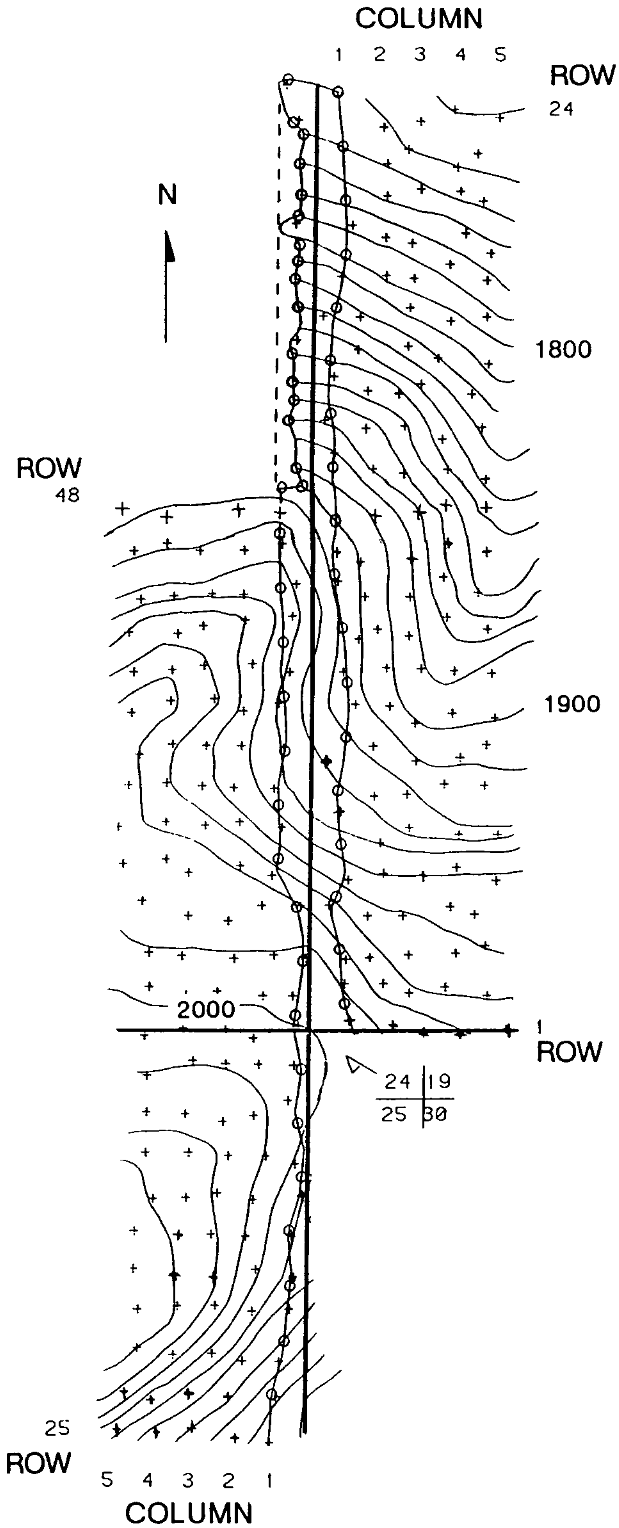

FIG. 1. Topography and tree location in the study area. Contours give elevation in feet (1 ft = 0.305 m). +, measured trees located on a 15 × 15 m grid; edge of mixed stand designated by small circles.

was also off site, because the seed was collected at a 15-m elevation near Olympia, Wash.

Sampling

We surveyed a 15 × 15 m grid east and west of the mixed stand and selected an undamaged dominant or strong codominant Douglas-fir closest to each grid point. We designated Douglas-fir nearest to and parallel to the outermost row of alder as column 1 (Fig. 1). These Douglas-fir were within the drip line of alder crowns and most were inside the mixed stand. Thus, trees in column 1 were influenced directly by red alder. Trees in columns 2–5 were 15, 30, 45, and 60 m, respectively, from the outer row of red alder (Fig. 1).

Tree measurement

In 1983, we measured diameter at breast height (DBH) of Douglas-fir sample trees to the nearest 2.5 mm and total height to the nearest 0.30 m. We computed cubic volume, including stump and tip, from general volume equations based on DBH and total height (Bruce and DeMars 1974).

Study design and data analysis

We based our statistical analysis on the way we selected experimental units (Douglas-fir trees). Accordingly, we divided the study area on each side of the mixed stand into columns based on distance from alder and into rows (east–west lines) based on slope position. There were 24 rows and 5 distances, or 120 trees on each side.

We analyzed data from east and west of the mixed stand separately because (*i*) alder influence and topography on the two sides probably differed and (*ii*) the two sides were fixed, not random locations. Using the model for a two-way analysis of variance (ANOVA), we treated the 24 slope positions on each side as one factor and distance from the mixed stand as the second factor. We recognized, however, that treatment combinations could not be assigned randomly. Distance from the mixed stand is a continuous variable, so we used the method of orthogonal polynomials to fit an approximate response function to distance (Snedecor and Cochran 1980). We specified an α-value of 0.10 to judge statistical significance of differences.

We analyzed tree DBH, total height, and total stem volume as individual response variables. We show the degrees of freedom breakdown in ANOVA for each side (Table 1). Our initial expectation of an interaction between slope position (P) and distance (D) from alder was tested by using Tukey's test for nonadditivity (Snedecor and Cochran 1980, pp. 283–285). This test indicates whether the experimental error term was inflated because a $P \times D$ interaction actually existed. Tukey's test was nonsignificant in four of six analyses. Rather than including possible $P \times D$ interaction as a source of variation in our error term, however, we followed Miller's (1986, pp. 125–128) suggestion and used the one degree of freedom and sum of squares associated with this test to remove most of the interaction effect from the error term, so it legitimately could be used to test the main effects in all statistical analyses.

Results

Diameter

Average DBH of sampled Douglas-fir in the mixed stand was about 50% larger than in the pure plantation on either side (Table 2). On both east and west sides, average DBH declined sharply within 15 m of the mixed stand. Although the quadratic expression of this decline in DBH with distance was significant, it was an inadequate fit as suggested by the significant lack of fit component (Table 1). When data from all distances were pooled, DBH averaged about 11% larger on the east side than the west side (Table 2).

Height

Dominant and codominant Douglas-fir in the mixed stand averaged 23 and 44% taller on the east and west sides, respectively, than in the pure stand. Average height declined sharply by 15 m and greater distances from the mixed stand (Table 2). The quadratic expression of this size–distance relation was significant and an adequate expression of the decline of alder influence with distance on the east but not the west side

TABLE 1. Degrees of freedom, *F*-ratios, and observed *P*-values from analysis of variance of DBH, height, and volume for both the east- and west-side experimental areas

Source	df	DBH		Height		Volume	
		F-ratio	*P*-value[a]	*F*-ratio	*P*-value[a]	*F*-ratio	*P*-value[a]
East side[b]							
Position	23	2.8	0.01	7.6	0.01	3.1	0.01
Distance	4	26.2	0.01	18.9	0.01	23.8	0.01
Linear	1	64.2	0.01	54.5	0.01	60.3	0.01
Quadratic	1	31.4	0.01	19.4	0.01	28.2	0.01
Lack of fit	2	4.6	0.01	0.8	0.45	3.4	0.04
Nonadditivity[c]	1	0.7	0.39	1.9	0.17	8.7	0.01
West side[b]							
Position	23	2.1	0.01	5.0	0.01	2.1	0.01
Distance	4	40.2	0.01	44.3	0.01	36.8	0.01
Linear	1	78.3	0.01	96.4	0.01	69.4	0.01
Quadratic	1	72.9	0.01	71.5	0.01	64.4	0.01
Lack of fit	2	4.9	0.01	4.6	0.01	6.7	0.01
Nonadditivity[c]	1	0.6	0.43	19.6	0.01	2.0	0.16

[a] *P*-values are less than or equal to the given values.
[b] Both east side and west side had 92 degrees of freedom for error. The error mean square for volume was 140.9 and 113.3 for east and west sides, respectively.
[c] Results for Tukey's test of nonadditivity.

TABLE 2. Mean tree size (with coefficient of variation (%) given in parentheses) for distances of 0–60 m on either side of a mixed stand of red alder and Douglas-fir

Side	Distance from red alder (m)				
	0	15	30	45	60
DBH (cm)					
East	38.9 (18)	28.7 (22)	26.4 (19)	27.4 (19)	26.4 (18)
West	37.3 (20)	24.9 (12)	23.1 (15)	22.9 (19)	24.9 (21)
Height (m)					
East	28.0 (13)	24.0 (18)	22.5 (18)	22.2 (19)	22.2 (16)
West	26.8 (12)	19.5 (14)	17.9 (19)	18.2 (23)	18.8 (23)
Volume (m^3)					
East	1.33 (44)	0.69 (57)	0.55 (52)	0.58 (54)	0.54 (53)
West	1.20 (46)	0.40 (38)	0.33 (62)	0.34 (68)	0.42 (79)

NOTE: Sample size on each side was 24 trees at each distance.

(Table 1). East-side heights averaged about 17% greater than those on the west side (Table 2).

Cubic volume

Tree volume also declined sharply with distance from the mixed stand. As with DBH, falloff of bole volume with distance from alder was described inadequately by a quadratic relation (Table 1). Within the interplanted strip, bole volume of dominant and codominant Douglas-fir averaged 1.27 m^3 compared to 0.55, 0.45, 0.46, or 0.49 m^3 in trees 15, 30, 45, or 60 m, respectively, from the edge of the mixed stand (Table 2). Tree volume on the east side averaged 37% more than on the west side (Table 2).

Tree volume differed by slope position (Table 1). To illustrate this relation, we combined the 24 rows (east–west lines of trees) into six elevational groups of four lines each. Average tree volume for the four trees in each combination of elevational group and distance from alder is shown in Fig. 2 (east side) and Fig. 3 (west side).

Patterns of response were more apparent on the east side, in part because the slope positions represented a general progression on a north slope (Fig. 1). Tree volume increased from top to bottom of this slope. Within slope positions on both sides, however, largest trees are within the mixed and more dense stand (Figs. 2 and 3).

Discussion

This plantation offered a unique opportunity for quantifying the effectiveness of red alder in enhancing Douglas-fir growth. First, a severe N deficiency clearly limits tree growth. Second, the interplanted swath of red alder through an otherwise pure, uniformly spaced Douglas-fir plantation enabled detection of an interaction between tree response to N and distance from this

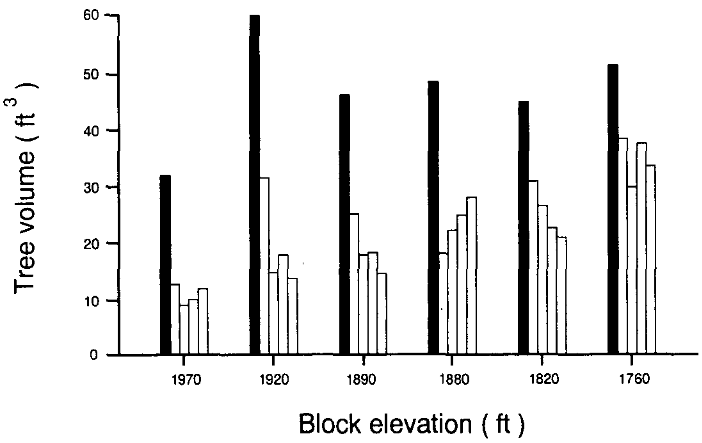

FIG. 2. Average bole volume of Douglas-fir trees at four distances at 15-m intervals (open bars) east of the mixed stand (solid bar). Each elevation block combines four slope positions (rows) (1 ft^3 = 0.0283 m^3).

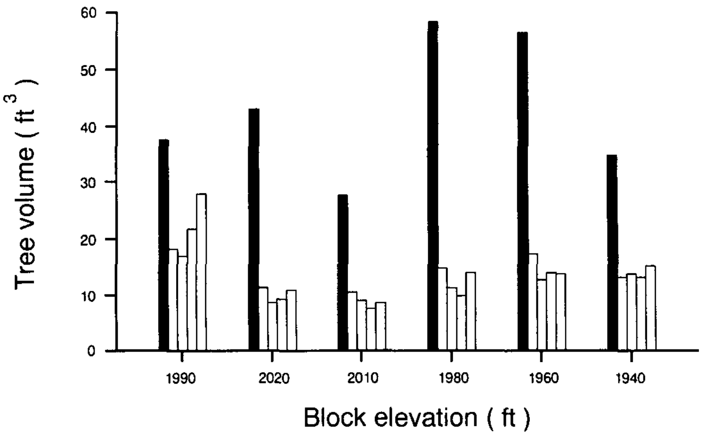

FIG. 3. Average bole volume of Douglas-fir trees at four distances at 15-m intervals (open bars) west of the mixed stand (solid bar). Each elevation block combines four slope positions (rows).

biological source of N. Third, a natural topographic gradient of site productivity exists east of the mixed stand; 50-year site index (King 1966) averages 21.0 m at the top of the slope and 29.5 m at the bottom of the slope (Miller and Murray 1978). Thus, trends of response to red alder could be compared over this downslope gradient of improved soil moisture, N, and microclimate. We expected that absolute and percentage response to red alder would diminish with increased site index, as is reported for N fertilizer trials in the Douglas-fir region (Miller et al. 1986).

The important treatment factor in the two-way ANOVA was distance from alder. The other factor was slope position, which was included to remove (statistically) the effect of slope position from the error term. Tukey's test for nonadditivity was used to check for presence and consistency of interaction between slope position and distance. The test indicated a significant interaction in two of six analyses. Thus, response of volume on the east side and of height on the west side was related to slope position. This inconsistency, and general lack of significance of Tukey's test, support our decision to remove most of the $P \times D$ interaction effect from the error term by removing the sums of squares associated with Tukey's tests. This procedure supported our primary objective of testing the main effects of distance from the mixed stand. Orthogonal polynomial response functions (linear and quadratic terms) were used to develop a simple model to assess response as a function of distance. We specifically avoided use of multiple comparison procedures, which are not recommended when treatment levels are quantitative. The statistical literature generally warns against using multiple comparison procedures for a quantitative factor (Warren 1986). We also believe that these data could not be reasonably analyzed via nonlinear regression. Our five distances provide only four degrees of freedom for the distance factor; therefore, any complicated yet reasonable, nonlinear regression model would easily use all the degrees of freedom, hence fit the mean values exactly. Finally, any simple, nonlinear model would not differ in any meaningful way from our simple quadratic model.

Effect of distance from the mixed stand

Interplanting red alder seedlings (2964/ha) reduced Douglas-fir survival. Initial planting density of 1680 Douglas-fir per hectare was reduced after 48 years to 638, compared with 949 trees in the adjacent pure stand (Table 3). Number of live red alder declined more rapidly, averaging 707/ha. In the next 9 years and before we established this crop-tree study after the 1983 growing season, mortality and growth were strongly affected by bear damage to many Douglas-fir in the mixed stand (spring 1976) and by severe crown breakage in many red alder (winter 1976–1977).

Our study confirmed enhanced growth of surviving Douglas-fir crop trees within the mixed stand despite its greater stand density (Table 3). Trees growing 30–60 m from the mixed stand appeared free of alder influence. On the east side, Douglas-fir within the strip averaged 45% larger DBH, 25% taller, and 137% greater volume than trees in columns 3–5. Corresponding gains for trees within the west side of the strip were 58% larger DBH, 46% taller, and 228% greater volume. The greater response to alder on the west side was predictable from its poorer site index (shorter heights).

Growth of Douglas-fir trees in column 2, located 15 m from the alder also may have been improved. East of the alder strip, trees in column 2 averaged 7% larger DBH, were 8% taller, and contained 24% greater volume than trees in columns 3–5. Corresponding gains on the west side of the strip were 5% larger DBH, 6% taller, and 9% greater volume. Response declined sharply within 15 m from the mixed stand. Although ANOVA showed that a quadratic equation approximated this decline, the significant lack of fit for most response variables indicated that this curve shape was not adequate to describe decline in response associated with distance from alder. The quadratic model does, however, indicate the trend over distance was not linear. We did not try to develop a more precise mathematical model by either transformation or nonlinear regression. Developing a prediction model for response was not the objective of this research because of its exploratory nature and the limited scope of the data (only one location). In addition, potential gain from more complex models is limited because most of the decline in response occurred between 0 and 15 m and data were taken only at 15-m increments. We do not propose a quadratic model be used as a predictive tool; hence, we do not present the equation.

A strong effect clearly exists in the mixed stand. It is not valid, however, to make strong statements about treatment

TABLE 3. Mean stand characteristics of the mixed and the pure plantation in 1974 and 1983

	Mixed stand[a]			Douglas-fir stand	
Year	DF	RA	All	DF	All
		Stems (no./ha)			
1974	638	707	1344	949	954
1983	529	489	1016	850	855
		Basal area (m^2/ha)			
1974	24.8	20.2	45.2	25.9	26.2
1983	28.5	17.2	45.7	30.5	30.8
		Volume (m^3/ha)			
1974	223	167	389	202	203
1963	286	159	445	272	272
		Height (m)[b]			
1974	25.7	19.6	—	21.1	—
1983	28.7	22.6	—	24.2	—

NOTE: Means are based on live trees measured in four matched pairs of 0.080-ha plots. These years correspond to 48- and 57-year-old Douglas-fir grown from seed.
[a] DF, Douglas-fir; RA, red alder.
[b] Mean height of the largest 100 trees/ha of the species.

effects at 15 m. The data provide some evidence of an effect at 15 m, although interpretation may differ among individuals. Clearly, at this site, response occurred mostly between 0 and 15 m, and these data are not adequate to characterize accurately this response–distance relationship. This, in itself, is valuable information. We recognize the restricted inferences from these data because they are from one site. Data from other sites are needed to see if response is typically less than 15 m. Our data suggest future researchers should focus on responses between 0 and 30 m, and with most sampling efforts concentrated at less than 15 m.

Our data indicate that growth-stimulating effects of red alder at this site extended farther on the east side than the west side. This inference is supported by recent aerial photos that show the red alder – Douglas-fir strip as a dark green band through the yellow-green Douglas-fir plantation. The west edge of this dark green strip has a sharp, narrow transition to the yellow-green of the pure Douglas-fir plantation. The east edge, however, has an irregular, wider transition. This may be caused by (*i*) prevailing wind from the southwest carrying N-rich alder leaves to the east of the strip and (*ii*) the topography having north to northeast aspect, so subsurface flow of N-rich gravitational water could be moving downslope and influencing tree growth east of the mixed stand. Nitrogen leaching below the 80-cm soil depth in the mixed stand is about 25.9 kg N/ha annually compared with 5.1 kg N/ha in the pure stand (Binkley et al. 1992). Additional leaching of both inorganic N (5.3 kg) and organic N (15.5 kg) contributes to the 5-fold greater leaching of N in the mixed stand at this location.

Effect of slope position

On both sides of the interplanted stand, tree size differed significantly with position on the slope (Table 1). This trend was especially apparent on the east side and for trees in columns 3–5; trees were larger near the bottom of the slope and progressively smaller with increasing elevation (Fig. 2). Trend in tree size was more apparent on the east side, probably because the slope was steeper and had a consistent northerly aspect (Fig. 2). On the west side, the southernmost block had a southeast aspect (Fig. 1), and trees there were much larger than other trees on the west side. This situation weakened our analyses and interpretations of the west-side data.

Interaction between slope position and distance from alder

Figure 2 (east side) shows that increase in tree volume with decreasing elevation is especially strong in columns 3–5. This trend is less apparent on the west side (Fig. 3). On a relative basis, effect of slope position on tree size seems much less for Douglas-fir within the alder strip than for those in columns 3–5. This implied interaction between slope position and distance from alder could be assessed only with Tukey's test for nonadditivity. This test indicated that response of volume, but not of DBH and height, on the east side was related to slope position (Table 1). Because volume is the product of diameter and height, it is the more sensitive measure of response. Among-tree variation in tree volume is also much more than that in DBH and height (Table 2). Unfortunately, Tukey's test provides only indirect confirmation of our expectation that beneficial effects of alder on the east side would decline within the gradient of increasing site quality.

Management implications

At this N-deficient location with poor site quality, Douglas-fir crop trees within the mixed stand averaged 2.4- and 3.3-fold more volume than those located 30 m or more from the mixed stand on the east and west side, respectively. Crop trees located 15 m from the nearest alder of the mixed stand averaged 1.2- and 1.1-fold more volume than non-alder-influenced trees of columns 3–5 on the east and west sides, respectively. A 10–20% increase in volume is still substantial, especially considering the increased value per unit volume as piece size increases. Positive benefits to Douglas-fir from N_2-fixing red alder, however, are less likely at high quality sites because N is less likely to limit Douglas-fir growth and because red alder is relatively more competitive (Newton et al. 1968).

These results should interest land managers with alder succession in abandoned skid roads, near streams, or in moist drainage. On N-deficient sites, ribbonlike distributions of this N_2-fixing species could be retained to improve yields. For example, skid trails typically average 10–25% of clearcut areas in western Washington and Oregon (Miller et al. 1989). Assuming (*i*) that these skid trails were 3 m wide, (*ii*) that alder formed much of the crown cover on these trails, and (*iii*) that the zone of N contribution by alder extended 15 m on either side of the skid trail, then, a 10% skid trail area could result in 100% alder influence, providing skid trails were uniformly spaced throughout the clearcut. Such uniform spacing and 10% skid trail coverage are most likely when skid trails are designated before yarding. Conventional ground skidding, however, creates more skid trail area but less uniform spacing; this will result in more gaps and overlaps of alder influence.

Tradeoffs between negative and positive influences of alder on associated Douglas-fir should be recognized. These opposing influences are both strong when the two species are in close proximity and decline sharply with increasing distance. In mixed stands of equal-aged alder and Douglas-fir, spacing in the first 20–25 years is critical to retain sufficient Douglas-fir crop trees (Miller and Murray 1978). Fast, early height growth of red alder makes this species a threatening competitor for Douglas-fir, especially on mesic, fertile sites (Newton et al. 1968; Brodie and Walstad 1987). Depending on stem numbers and spacing, some control of alder density may be necessary to ensure that positive benefits of N_2-fixation outweigh risk of overtopped and physically damaged Douglas-fir.

In this study area, 2964 alder per ha were intermixed with 1680 Douglas-fir. Some reduction in alder competition probably resulted from delaying interplanting 4 years after the Douglas-fir was planted; moreover, the planted alder were damaged by frost in the first and second years after planting (unpublished report, L.A. Isaac, Oct. 9, 1939, copy on file at the Forestry Sciences Laboratory, Olympia, Wash.). Local alder in the area, however, were not frost damaged, suggesting the off-site seed source of the planted alder could have been more susceptible. Yet, this suspicion was not supported at another study area near Enumclaw, Wash., where survival and growth of off-site alder was equal to that of a local source (Murray and Miller 1986).

In summary, the positive benefits of alder on this site clearly outweighed the negative. If early tree spacing had been attempted in the mixed stand, additional gains in volume production might have been achieved. Further development of a mixed-species option for supplying nitrogen requires (*i*) further quantification of the negative and positive effects of red alder when grown in admixture with Douglas-fir and (*ii*) comparisons of the cost-effectiveness of the red alder versus fertilizer option (Miller and Murray 1979).

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