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Comparative Effects of Urea Fertilizer and Red Alder in a Site III, Coast Douglas-Fir Plantation in the Washington Cascade Range

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Abstract

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Five randomly assigned treatments were used to quantify effects of adding varying numbers of red alder (*Alnus rubra* Bong.) or nitrogen (N) fertilization on growth of a 10-year-old conifer plantation at a medium-quality site in the western Washington Cascade Range. Zero, 20, 40, and 80 alder trees per acre were retained along with about 300 conifers per acre. Nearly all conifers were coast Douglas-fir (*Pseudotsuga menziesii* var. *menziesii* (Mirb.) Franco). A fifth treatment substituted N fertilizer for N-fixing alder. Changes in average tree height, and in numbers of trees, basal area, and volume per acre between plantation ages of 10 and 27 are compared. In pure conifer plots, gross volume growth averaged 26 percent greater on fertilized than nonfertilized plots, indicating measurable benefits of additional N. On both fertilized and nonfertilized plots, an average of 13 percent of the original conifers died. Retaining 20, 40, or 80 alder per acre (7, 13, and 27 percent of the associated conifer trees per acre, respectively) was associated with reduced numbers of Douglas-fir by about 19, 5, and 17 percent, respectively, in the next 17 years. Mortality and growth of Douglas-fir were not related to alder density, but losses of Douglas-fir were especially large on plots where relatively large red alder (20 per acre) were retained. Neither total stand nor conifer yields were changed by retaining alder. Additional comparisons are needed at other locations, especially those with known N deficiency.

Keywords: Mixed stands, competition (plant), Douglas-fir, *Pseudotsuga menziesii*, red alder, *Alnus rubra*, thinning, nitrogen fertilization, volume growth.

Summary

We compared 17-year survival and growth of Douglas-fir (*Pseudotsuga menziesii* var. *menziesii* (Mirb.) Franco) and other species after installing five silvicultural treatments in a 10-year-old, site III Douglas-fir plantation in western Washington. Conifer density was thinned to about 300 trees per acre (TPA); nearly all were planted Douglas-fir. Treatments 1 to 4 tested the effects of retaining 0, 20, 40, or 80 red alder (*Alnus rubra* Bong.) per acre, respectively. Treatment 5 retained 300 conifers but no alder, and substituted 200 lb nitrogen (N) per acre as urea fertilizer

for N biologically fixed by admixed alder. Our purpose was to quantify the effects of these treatments on size and yield of conifers and red alder. We installed two or three replicates of each treatment.

Nitrogen fertilization increased tree and stand growth in the 17 years of observation. Retaining red alder in the plantation had no effect on conifer or total stand yields. Retaining 20, 40, or 80 red alder per acre had no measurable positive but some negative effects on associated Douglas-fir. Admixed alder increased losses of Douglas-fir, especially where relatively large red alder were retained. Yield of the Douglas-fir component may have been reduced slightly. Combined yield of all species, however, was similar for admixtures of 0 through 80 red alder per acre.

During stand development, crowns of Douglas-fir can be mechanically damaged or suppressed by a neighboring alder, yet, conversely, individual red alder can be dominated by one or more Douglas-fir before contributing much N-rich organic matter to the soil. In our study, the 80-alder-per-acre treatment corresponds to an average spacing of about 23 ft between alder; 300 TPA of Douglas-fir equals an average spacing of 12 ft. Where these average spacings exist, each red alder neighbors four Douglas-fir. We assert that intensity and consequences of competition between the two species is site-specific and dynamic. Red alder was less competitive at this inland location than at the more moist, coastal site II location investigated earlier. To ensure timely control of alder in alder-Douglas-fir mixtures, foresters should periodically assess damage to conifer crowns. Controlling the stocking of either or both species is advisable. Moreover, we infer from our study that planting alder from an off-site source may be another way to reduce alder competition.

We suggest that retaining 80 red alder per acre with 300 Douglas-fir per acre at plantation age 10 is too many as an operational treatment. Moreover, future research should consider using a replacement design in which each red alder substitutes for or replaces one Douglas-fir. New testing should use large plots for both treatment areas and tree measurement plots. Application of our alder treatment to provide biologically fixed N was much more variable than our application of urea because sizes of individual alder differed greatly. Additional comparisons are needed at other locations, especially those with known N deficiency where the N-fixing capacity of associated red alder is more likely to enhance yield of Douglas-fir.

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Introduction

Additions of nitrogen (N) have special significance to coast Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) in the Pacific Northwest because growth frequently is limited by insufficient quantities of available N in the soil. Across the range of site qualities, about 70 percent of N-fertilization trials in western Oregon, Washington, and British Columbia show response to 150 to 200 lb N per acre (Chappell and others 1992, Miller and others 1986). Applying urea fertilizer (46-0-0) is the conventional way to supply N for increased stand growth. Using N-fixing plants has also been considered, especially red alder (*Alnus rubra* Bong.), an extensively distributed native hardwood with increasing commercial value (Hibbs and DeBell 1994). Published estimates of the amount of N fixed annually by red alder in pure and mixed stands range from 20 to 300 lb N per acre (Binkley 1992, Binkley and others 1994). Because of its rapid juvenile growth, red alder in mixed stands frequently threatens full and uniform distribution of associated, higher valued Douglas-fir (Newton and Cole 1994). This risk is generally greater on high-quality, mesic sites (where early height growth of red alder is more rapid than that of Douglas-fir) compared to lower quality, drier sites (where relative growth is slower) (Newton and others 1968). Thus, the silvicultural option of admixing red alder in Douglas-fir stands is more complicated than using fertilizer (Miller and Murray 1979).

We sought to determine the optimum density of nitrogen-fixing alder for improving growth of Douglas-fir and compared growth to that obtained by adding fertilizer.

Development of the red alder option for supplying N to Douglas-fir requires (1) quantification of both positive and negative effects of admixed red alder on yield and value of associated Douglas-fir at a wide range of site qualities and (2) comparison of the cost-effectiveness of retaining or planting alder vs. applying fertilizer. Thus, optimum density of alder admixture for Douglas-fir needs definition and comparison with optimum fertilizer dosage. Currently, this optimum fertilizer dosage seems to lie between 150 and 300 lb N per acre applied several times per rotation. For N-deficient sites, an economically optimum alder density in mixed stands could be about 40 trees per acre (TPA) maintained in a dominant/codominant position until about one-half of the red alder and associated Douglas-fir are removed at the first commercial thinning (Miller and Murray 1979).

We started such quantification about two decades ago on a good (site II) and a poorer (site III) quality site assuming that the balance between negative competitional effects of red alder and beneficial effects of its N-fixing capacity are likely to differ by site quality. Our controlled-treatment study was designed to test two working hypotheses about the consequences of red alder retained with Douglas-fir:

1. Benefits of soil improvement by red alder to Douglas-fir yield will be similar in magnitude to the benefits of N fertilization. We anticipated that fertilization with 200 lb N per acre would increase short-term volume growth less than 10 percent at our site II location and about 20 percent at our site III location.
2. With increasing alder stocking, negative competitive effects of red alder on associated Douglas-fir will gradually offset potentially positive effects of increased N and improved organic matter conditions in the soil. Thus, we speculated that yield of Douglas-fir on N-deficient sites would increase at lower densities of admixed alder, but progressively decline as increasing numbers of red alder damage or overtop more Douglas-fir.

Here we report results at our site III location and will compare these with results reported earlier for the better site (Miller and others 1999).

Materials and Methods

Location

The trial is located in a Douglas-fir plantation at 1,800 ft elevation about 4 mi east of Enumclaw, Washington. The current plantation was established in spring 1971 when 2+1 Douglas-fir seedlings were hand planted at an average density of 600 TPA. The preceding conifer stand had been clearcut, then yarded by tractor. Logging slash was piled, but not burned. The deep, well-drained soil at this site is mapped as Pitcher sandy loam, 8 to 30 percent slopes, which developed from a mixture of volcanic ash and andesitic rock (Goldin 1992). This soil is classified as loamy-skeletal, mixed frigid family of Typic Haplorthods. It has a spodic horizon but no underlying argillic horizon. We observed some rounded surficial gravel in the study area and suspect this originated from local alpine glaciation. Douglas-fir site index on the Pitcher soil averages 112 ft at 50-year breast-height age (site III).

Experimental Treatments

To test our two hypotheses, we compared tree and stand growth of conifers (practically all Douglas-fir) and red alder on plots representing varying densities of red alder with a constant nominal conifer density of 300 TPA (after precommercial thinning 10 years after planting). As shown in the following tabulation, the no-alder treatment (treatment 1) corresponds to a conventional regime that removes all red alder by herbicide or cutting. Admixtures of 20, 40, and 80 alder per acre straddle the assumed financially optimum number of alder to retain in Douglas-fir stands (Miller and Murray 1979). A code number for each treatment follows:

	Red alder retained (No. per acre)			
Urea (lb N per acre)	0	20	40	80
	Treatment number			
0	1	2	3	4
200	5	-	-	-

Treatments 1 to 4 define a red alder response surface; treatment 5 simulates a conventional regime that eliminates red alder and periodically uses urea fertilizer to increase stand growth.

Experimental Design

Our experimental design was treated in the analysis as a completely random assignment of five treatments, although plots of treatment 5 were installed beside and 4 years after plots of the other treatments. Treatments 1 and 5 (in pure conifer) have three replications, and treatments 2, 3, and 4 have two replications. Treatments were applied to twelve 0.20-acre areas. A 0.10-acre tree-measurement plot was centered in each treatment area, which left a 13-ft-wide treated buffer.

Treatment History

Our test included nine plots from an earlier investigation of interplanting local versus coastal sources of red alder. Those preliminary regimes were applied 3 and 7 years after Douglas-fir were planted; our test treatments were applied in year 10 after planting (table 1).

At age 3, the Douglas-fir plantation also contained volunteer trees of red alder, Douglas-fir, and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.). Three preliminary regimes (A, B, C) started at age 3. On three randomly selected plots, all volunteer alder were cut (regime A). Two years later, alder stump sprouts and new alder seedlings were cut and treated with Tordon[1] herbicide to maintain these three plots in an alder-free condition. Likewise in year 3 on six additional plots, all volunteer alder were cut, but two 2-year-old red alder wildlings were interplanted near each planted Douglas-fir, one at a distance of 2 ft from a Douglas-fir and the other at 4 ft. Density of the interplanted alder averaged about 1,200 TPA. Alder from a local

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[1] Use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

Table 1—Schedule of original and final treatment regimes in a Douglas-fir plantation

Item	Original regime			
	A	B	C	D
Years after planting:				
3 (1973)	All volunteer RA cut RA wildlings planted beside each planted DF	Same as regime A; 2 local RA wildlings planted beside each planted DF	Same as regime A; 2 nonlocal	No treatment
5 (1975)	RA sprouts and new seedlings cut; stumps treated with herbicide	No treatment	No treatment	No treatment
7 (1977)	RA sprouts and new seedlings cut	Most RA cut except 20, 40, or 80/acre retained	Same as regime B	All volunteer RA cut
10 (1980)	Conifer density reduced to 300/acre; RA sprouts and new seedlings cut	Same as regime A	Same as regime A 200 lb N/acre as urea applied	Same as regime A;
Final treatment No.	1	2, 3, 4	2, 3, 4	5
Years with RA:				
Volunteers	3	3	3	7
Planted	0	24	24	0
Years after thinning	17	17	17	17
Years after 200 lb N/acre	0	0	0	17

DF = Douglas-fir, RA = red alder.

source were planted on three of the six plots (regime B), and alder from a nonlocal source near sea level at Aberdeen, Washington, were planted on three other plots (regime C). The objective of this alder interplanting was to compare with no-alder (regime A) and to learn if one source of transplants grew faster, hence, was more competitive to associated Douglas-fir (regime A and B). Weyerhaeuser Company initiated this original investigation, which was expanded in 1977 to a cooperative study between Weyerhaeuser Co. and the USDA Forest Service, Pacific Northwest Research Station. The remaining untreated plantation constituted regime D.

In 1977 (plantation age 7, total age 10), three new plots sampling regime D were installed. On new and original plots, future crop trees were selected and tagged. Conifer density on all 12 plots was targeted at 300 Douglas-fir per acre. On three plots where suitable Douglas-fir were not available, a few western hemlock were substituted as crop trees. Alder were retained on plots and buffers of regimes B and C at randomly assigned densities of 20, 40, or 80 TPA within each alder source (to create treatments 2, 3, and 4). Surplus red alder were cut from all plots including regimes A and D (no-alder treatments).

Final thinning of conifers in 1980 occurred 10 years after planting (figs. 1a and 1b). Surplus conifers and alder seedlings missed earlier were cut as were recent stump sprouts. Average numbers of stems before and after cutting at ages 7 and 10 years are shown in table 2.

Fertilization

The three plots of treatment 5 were fertilized on February 27, 1981 (10 growing seasons after planting). Urea (46-0-0) was uniformly spread within string-bounded lanes to control distribution of the amount allocated to each lane and plot. Volatilization losses were unlikely because the surface soil was moisture-saturated when fertilized and weather remained cool with rain in the weeks after fertilization.

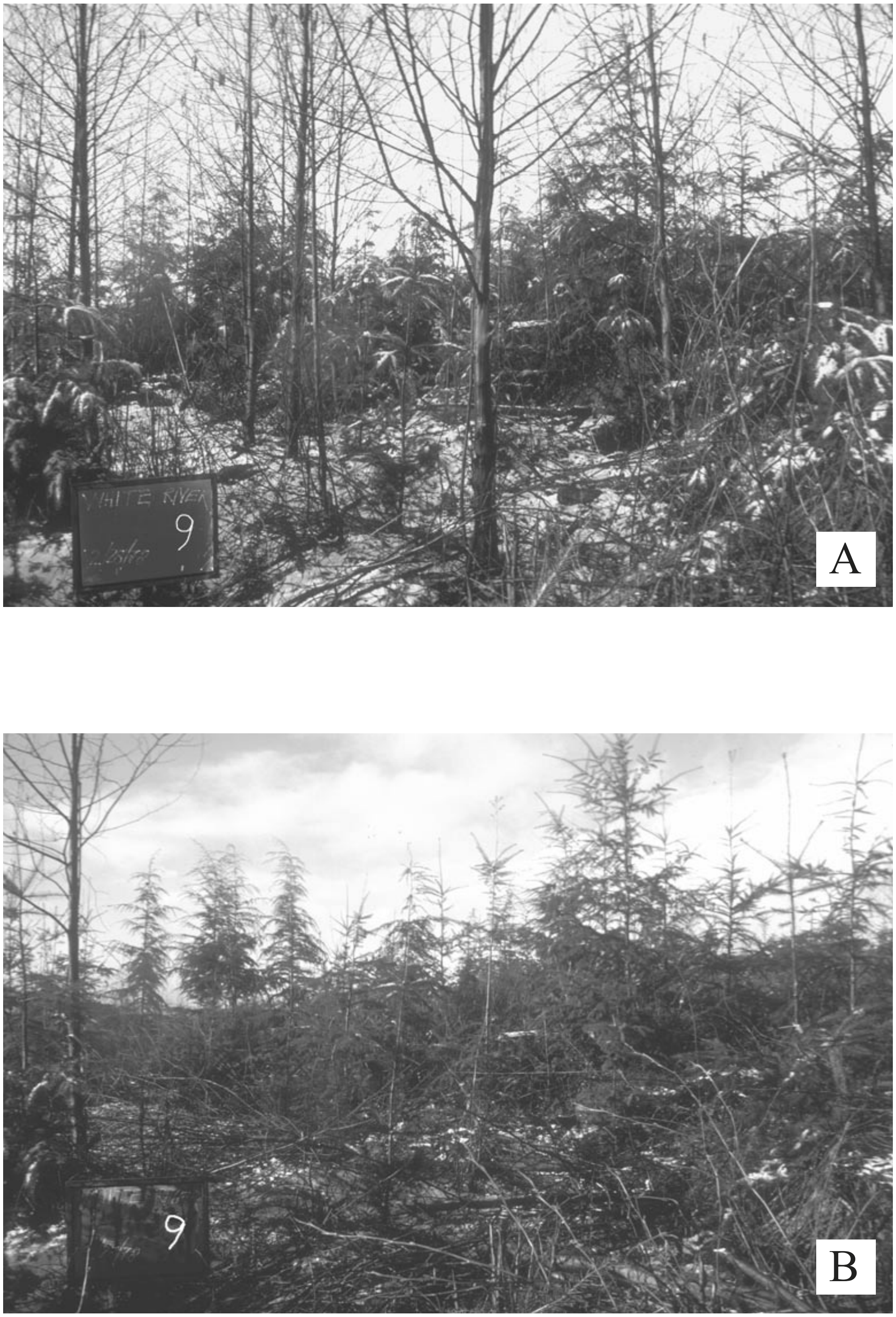

Figure 1—Stand on plot 9 (local alder source): (A) before and (B) after reduction of alder density at plantation age 7 (1977).

Table 2—Average number of stems per acre 0.1 inch d.b.h. and larger before and after cutting (in parentheses) of surplus alders and conifers at plantation ages 7 and 10 years

	Douglas-fir				Other conifers		Red alder		
	Planted		Volunteer		Volunteers		Planted	Volunteers	
Original regime	7 yr[a]	10 yr	7 yr	10 yr	7 yr	10 yr	7 yr	7 yr	10 yr
					Number per acre				
Volunteer alder:									
A. Alder cut at age 3	503	493 (307)	33 (0)	0	117 (37)	37 (10)	–	113 (0)	–
D. Alder cut at age 7	516	506 (313)	76 (0)	0	43 (17)	17 (4)	–	453 (0)	–
Planted alder:									
B. Local alder	443	433 (307)	50 (0)	0	97 (40)	40 (0)	723[b]	80 (0)	–
C. Nonlocal alder	476	473 (307)	30 (0)	0	13 (13)	13 (0)	894[b]	67 (0)	–

[a] No planted Douglas-fir were cut at age 7; difference between number of trees before cutting at 10 years and at 7 years is mortality.

[b] Alder were reduced to 20, 40, or 80 per acre on one plot each in both regimes B and C at year 7; these alder were retained at age 10.

Tree Measurement and Volume Computation

Tree diameters at breast hight (d.b.h.) were measured (to nearest 0.1 in) at 4.5 ft above ground. Heights of all trees exceeding 4.5 ft were measured to the nearest 0.5 ft by using graduated-height poles initially and either Abney-tape or Vertex hypsometer after tree heights exceeded about 35 ft. Diameters and heights were measured after the 1977, 1980, 1983, 1986, 1989, 1993, and 1997 growing seasons (plantation ages 7 through 27).

Total stem volume (inside bark), including tip and stump, was calculated for each tree from height-d.b.h. equations and regional volume equations for the appropriate species. Regional volume equations that were used included those for Douglas-fir (Bruce and DeMars 1974), western hemlock (Wiley and others 1978), and red alder (Browne 1962). Heights of a few nonmeasured trees were calculated from iteratively fitted height-diameter relations in metric units by using the equation form:

Est. ht. (in meters) = A*EXP(B*DBH**-1.0) + 1.37 m,
in FORTRAN language
(or mathematically, $y = ae^{b/x} + 1.37$, where x = d.b.h. in cm)

Height-diameter relations for Douglas-fir were fitted for individual plots, but those for red alder were fitted to pooled data from plots having the same treatment.

Data Summarization and Statistical Analysis

Individual tree data were summarized for each 3- to 4-year growth period after thinning and fertilization: 1981-83 (inclusive), 1984-86, 1987-89, 1990-93, 1994-97, and for the total 17-year period. Growth of conifers (mostly Douglas-fir) in basal area and volume per acre, as well as change in average height of Douglas-fir, were compared by covariance analysis, by using initial (at year 10, 1980) basal area, volume, or mean height, respectively, as covariates (SAS Institute, Inc. 1988). Height and volume growth of red alder and of all species were compared by ANOVA; covariance adjustment was inappropriate because the potential covariate (starting volume of red alder) was affected by treatment.

Because the number of red alder retained in the Douglas-fir plantation is a continuous variable, we used the method of polynomials to fit an approximate response function to the number of alder retained in treatments 1 through 4. In both covariance and ANOVA, we used nonorthogonal contrasts to separate the following treatments:

Contrast	Treatment numbers	Indicates the effects of
1	1 vs. 5	N fertilization
2	1 through 4	Increasing alder density, linear relation
3	1 through 4	Increasing alder density, lack of fit

By reusing treatment 1 in these contrasts, we affected to some unknown extent the probability levels at which we can ascribe statistical significance. Unadjusted means from ANOVA analysis of red alder and all-species volume growth were separated by Bonferroni multiple-comparison procedures (SAS Institute, Inc. 1988). All tests of statistical significance were made at $p \leq 0.10$.

Results

Trees Per Acre and Average Diameter

After thinning —Density of Douglas-fir among the five treatments ranged from 300 to 313 TPA after thinning at plantation age 10 (table 3). Inclusion of a few naturally regenerated hemlock as crop trees in treatments 1 and 5 increased the combined density of conifer crop trees to 317 TPA on these plots. Red alder density ranged from 0 to 80 TPA.

Quadratic mean d.b.h. (Dq) of residual Douglas-fir averaged 3.5 to 3.7 in among the five treatments. By chance, admixed alder in the 20 TPA treatment (treatment 2) averaged larger in both d.b.h. (table 3) and height (table 4) than those in the 80-TPA (treatment 4) and especially the 40-TPA (treatment 3) admixture.

Fewer Douglas-fir died where associated with 40 alder per acre than with 20 or 80 alder per acre.

Trends with time—Subsequent 17-year losses of planted Douglas-fir averaged from 0 to 140 TPA among the 12 plots (fig. 2). No hemlock crop trees died in treatments 1 and 5, where as many as 20 TPA hemlock were retained to provide uniform spacing of crop trees. Causes of mortality included disease (41 percent), suppression (25 percent), mountain beaver (*Aplodontia rufa*), or bear (*Ursus americanus altifrontalis*) (10 percent), windthrow (10 percent), and unspecified (14 percent). In treatment 1, which had no competing alder, an average of 50 TPA of Douglas-fir died (16 percent of the original 307 TPA of coniferous crop trees); however, losses among the three plots differed greatly (0 to 140 TPA) creating a standard error of 45 TPA. Mean d.b.h. of dead trees averaged less than that of live trees in each measurement period. An average of 50 (16 percent) of the original 313 TPA also died on fertilized plots in this 17-year period. Retention of 20, 40, or 80 alder per acre (representing 6, 13, and 27 percent, respectively, of the density of conifer crop trees) was related to reduction in numbers of associated Douglas-fir of about 22, 8, and 17 percent, respectively. The largest alder inadvertently were retained in the

Table 3—Average stand statistics after final thinning at plantation age 10, trees 0.1 inch d.b.h. and larger, by treatment and species

	Treatment	Stems			Quadratic d.b.h.				CVTS[b]		
Plantation	number	DF	RA	All	DF	RA	All	Site height[a]	DF	RA	All
		---- Number per acre ----			*---------- Inches ------------*			*Feet*	*----- Cubic feet per acre-----*		
Fertilizer:											
0 N	1	307	0	317	3.6	0	3.6	26.9	236	0	242
200 lb N per acre	5	313	0	317	3.5	0	3.6	25.8	210	0	210
Mixed (RA per acre):											
20	2	310	20	330	3.6	4.6	3.7	27.4	243	33	276
40	3	310	40	350	3.6	3.4	3.7	28.0	245	28	273
80	4	300	80	380	3.7	4.1	3.8	26.4	238	87	325

DF = Douglas-fir, RA = red alder, All = all species (includes other species beside DF and RA).

[a] Average height of the 80 largest (by diameter at breast height [d.b.h.]) Douglas-fir per acre.

[b] CVTS = cubic volume total stem, including tip and stump.

Table 4—Mean height and height ratio of live Douglas-fir (DF) and red alder (RA), by treatment, plantation age, and alder source

Alder retained	Treatment number	Age (years) and species									
		10		13		16		22		27	
		DF	RA	DF	RA	DF	RA	DF	RA	DF	RA
No. per acre		*Height in feet*									
0	1	22.4	–	32.7	–	40.4	–	60.0	–	73.7	
20	2	22.3	28.8	32.4	33.0	39.8	38.9	58.2	53.4	72.4	60.2
40	3	22.6	23.7	32.9	27.4	40.8	34.0	60.0	48.2	73.4	57.4
80	4	22.7	26.2	33.3	31.2	41.8	37.8	61.1	51.6	75.0	62.9
		Height ratio (DF/RA)									
20:	2	0.77		0.98		1.02		1.09		1.20	
Local			0.62		0.77		0.83		0.97		1.06
Coastal			.98		1.28		1.30		1.22		1.36
40:	3	.95		1.20		1.20		1.24		1.28	
Local			.94		1.17		1.12		1.17		1.18
Coastal			.96		1.24		1.29		1.33		1.39
80:	4	.87		1.06		1.10		1.18		1.19	
Local			.87		.98		1.03		1.08		1.15
Coastal			.87		1.17		1.20		1.31		1.24

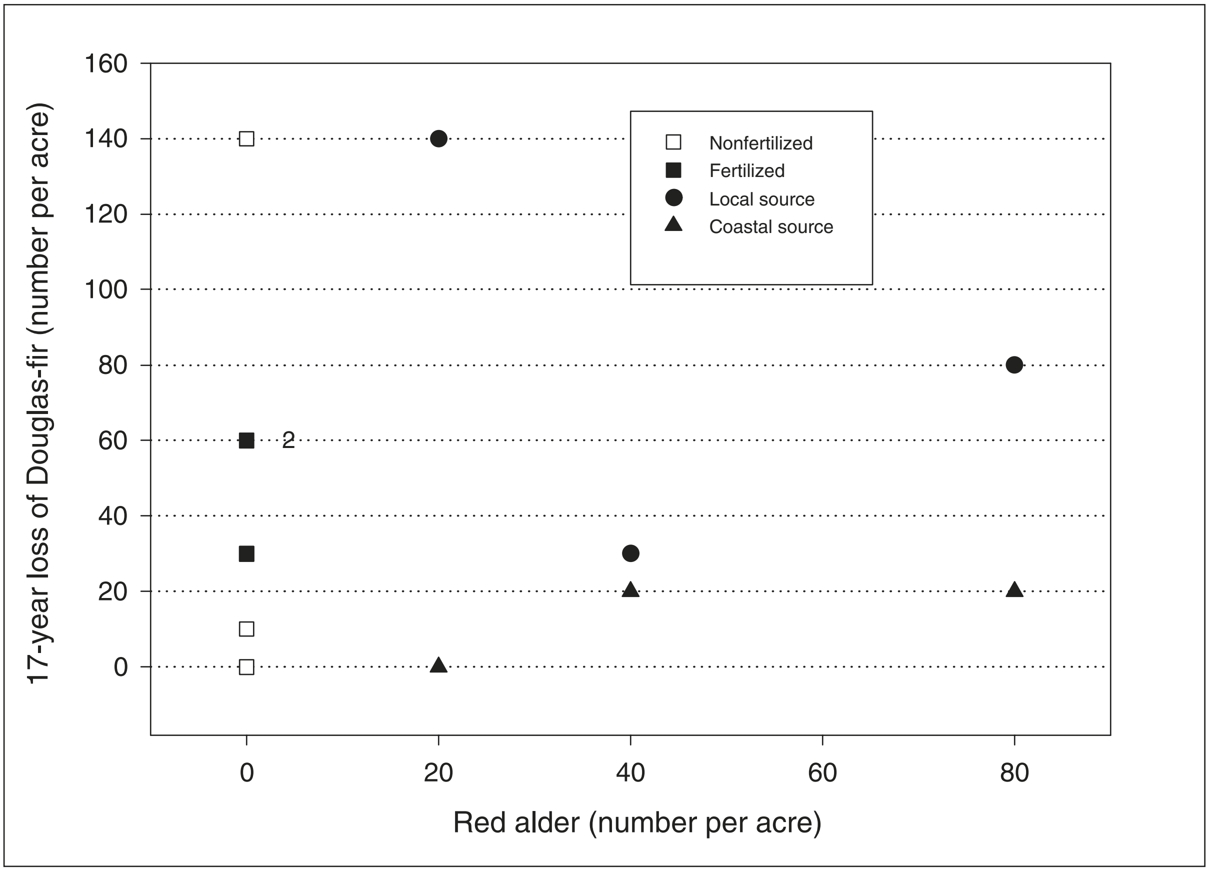

Figure 2—Number of Douglas-fir crop trees per acre that died (from the original of about 300 per acre) in the 17 years after thinning at plantation age 10 years, by alder density and source. Note the two overlapping plotting points indicated by "2."

20-TPA admixture; therefore, loss of 70 Douglas-fir TPA or about three Douglas-fir crop trees per retained alder is not surprising. Doubling the number of alder to 40 TPA, however, resulted in fewer losses of Douglas-fir (25 TPA vs. 70), probably because alder in treatment 3 averaged much smaller d.b.h. than those in the 20 TPA treatment (3.4 vs. 4.6 in; table 3). At each alder admixture, more Douglas-fir died where associated with the local source of alder transplants, especially in treatment 2 (fig. 1).

Loss of coniferous crop trees averaged the same for control plots (treatment 1) and fertilized plots, but increased with alder additions of 20 and 80 TPA (fig. 2).

Mean Height

After thinning —Ten years after planting, mean height of residual Douglas-fir was similar among the five treatments (22.3 to 22.7 ft; table 4). Alder in the 20-TPA alder treatment, however, averaged taller than those in the 40- and 80-TPA admixtures. Moreover, height of Douglas-fir in treatment 2 averaged only 0.77 that of associated red alder (height ratio: Douglas-fir/red alder = 0.77), compared to height ratios of 0.95 and 0.87 in treatments 3 and 4, respectively (table 4). This suggests that some suppression of Douglas-fir by the larger alder in treatment 2 might have occurred by year 10 after planting.

Trends with time—Mean height of both Douglas-fir and alder progressed in subsequent years (fig. 3). Douglas-fir initially averaged shorter than associated red alder. By plantation age 13, the Douglas-fir/red alder height ratio exceeded 1.0 with 40 and 80 alder per acre (table 4). This implied shift of Douglas-fir to dominance occurred later (year 16) in the 20-TPA alder treatment, probably because the ratio was only 0.77 at year 10. By year 27 after planting, Douglas-fir averaged about 20 percent taller than associated red alder in all admixtures. We infer from the DF/RA ratio of mean heights that the local source of red alder was more competitive with Douglas-fir than was the coastal source (table 4). Consequently, Douglas-fir associated with the local source required more years to exceed mean height of associated alder.

17-year change in mean height—Change in mean height represents (1) net height growth of individual trees and (2) change in the number and size of sample trees

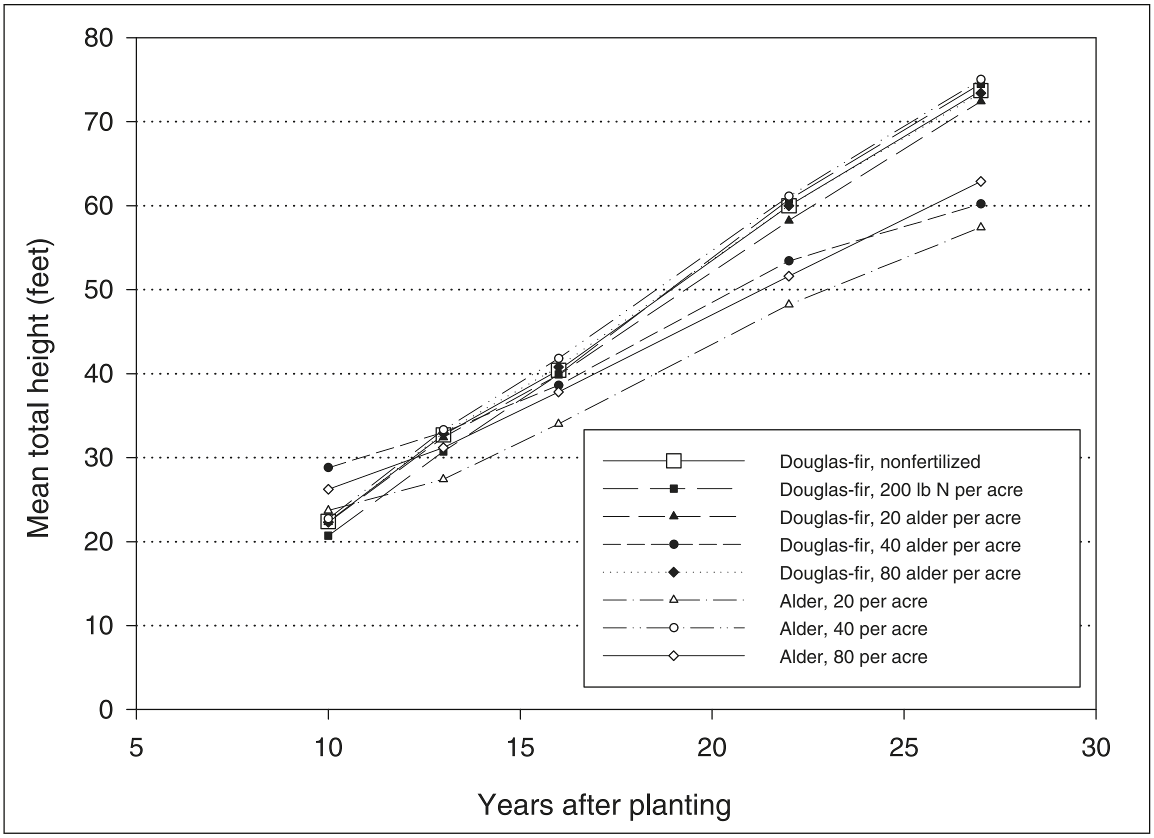

Figure 3—Trends of mean height of Douglas-fir (solid symbols) and red alder (open symbols) surviving each growth period, by treatment.

when some trees died. In this study, heights of all trees were measured, so no replacement of dead trees was possible. Tree losses in pure-conifer plots represented 13 percent of the original trees. Because Dq of dead trees averaged less than that for the entire stand, that loss of smaller trees arithmetically increased mean height and its 17-year change.

Observed annual change in mean height in the 17-year period after thinning, ranged from 2.94 to 3.17 ft per yr (table 5). To better isolate the effect of retaining red alder on height of associated Douglas-fir, treatment means of observed change in mean height were adjusted for initial differences in starting height among treatments. After covariance adjustment, Douglas-fir in fertilized plots (treatment 5) averaged 6 percent greater change in mean height than those on nonfertilized plots ($p = 0.07$; tables 5 and 6). A linear fit of adjusted means for the four treatments (0, 20, 40, and 80 alder/acre) was nonsignificant ($p = 0.35$) and unlikely to be improved by a curvilinear fit (table 6). We infer that mean height of Douglas-fir was not affected by increasing numbers of admixed alder (table 5). As in contrast 1, however, the arithmetic effect of mortality losses could have influenced these means.

Basal Area Per Acre

Adjusted gross basal area growth of fertilized crop trees in the 17-year period after thinning exceeded that of nonfertilized plots (table 5). The 29-percent greater basal area growth on fertilized plots, however, was statistically nonsignificant ($p = 0.12$; table 6). The pattern of basal area growth of Douglas-fir crop trees with increasing numbers of admixed alder was erratic and nonsignificant.

Volume Per Acre

To avoid misinterpretations, we define our terms as follows: (1) Net PAI is the estimated change in live stand volume between measurements plus the volume of small trees (in-growth) that attained minimum d.b.h. (0.1 in). This net volume growth, expressed on an annual basis, includes volume accumulated on trees that survived specified 3- or 4-year periods between measurements. (2) Periodic annual mortality (PAM) is the volume in trees that died in specific periods, also expressed on an annual basis. This mortality volume includes their volume at the start of the period and any growth added before death. (3) The sum of net PAI and PAM is the gross annual change in stand volume in specified periods.

Table 5—Mean annual change (years 10 to 27 after planting) in mean height, and stand basal area and volume on fertilized vs. nonfertilized plots, by species[a]

		Douglas-fir								All species	
		Height		Gross basal area		Gross volume		Net volume		Gross volume	
Stand and treatment[b]	Treatment	Observed	Adjusted[c]	Observed	Adjusted[c]	Observed	Adjusted[c]	Observed	Adjusted[c]	Observed	Adjusted[d]
	Number	------- *Feet* ------		*Square feet per acre*		----------------------------- *Cubic feet per acre*				--------------------------------	
Fertilizer:											
0 N	1	3.02	3.01 b	9.33	9.24	305	305	298	294	326	–
200 N	5	3.17	3.18 a	11.43	11.88	368	388	364	388	376	–
Difference		.15	.17	2.10	2.64	60	83	66	94	50	–
Fertilized trees (percentage of nonfertilized height)		(105)	(106)	(122)	(129)	(119)	(127)	(122)	(132)	(115)	–
Mixed (RA per acre):											
20	2	2.94	2.94	9.05	8.86	301	292	284	273	319	–
40	3	2.99	2.98	10.35	10.08	336	325	334	321	350	–
80	4	3.08	3.07	8.45	8.39	286	282	277	272	334	–

[a] Within columns, adjusted means with different letters are significantly different ($p \leq 0.10$); see table 6.

[b] Pounds of N per acre (in nearly pure Douglas-fir plots) or number of red alder per acre (in mixed-species plots).

[c] Adjusted means from covariance analysis, where covariate = postthinning mean height, basal area, or volume per acre, respectively. The linear relation was significant ($p \leq 0.10$) for each variable.

[d] Covariance adjustment of all species volume growth is inappropriate because the covariates were affected by treatment. ANOVA was used

Table 6—Degrees of freedom, mean squares, and p values from analyses of covariance of the mean annual changes (years 10 to 27 after planting) in mean height and stand basal area and volume of conifers

		Mean annual change, in years 10-27 after planting, conifers only							
						Volume			
		Mean height		Gross basal area		Gross		Net	
Source of variation	D.f.	MSE	p	MSE	p	MSE	p	MSE	p
Covariate[a]	1	0.0025	0.574	10.382	0.117	12,553	0.082	1,8256	0.081
Contrasts:[b]	4								
1 = Fertilizer	(1)	.0347	.068	10.025	.123	9,766	.116	12,421	.135
2 = Linear	(1)	.0073	.348	.515	.698	332	.746	196	.835
3 = Lack of fit	(2)	.0058	.484	1.319	.672	898	.744	1,509	.710
Error	6	.0071	–	3.108		2,891	–	4,160	–
Total	11								

[a] Covariate = postthinning height, basal area, or volume, respectively.

[b] Contrast 1 = fertilized vs. nonfertilized; contrast 2 = linear fit to adjusted means of treatments 1 through 4; contrast 3 = lack of fit (to linear) of treatments 1 through 4.

Trends of gross PAI—In both pure and mixed stands, mean gross PAI of conifer volume averaged greatest in years 23 through 27 after planting (table 7). In the first 3 years after fertilization, mean PAI of fertilized plots was similar to that of non-fertilized, but thereafter was consistently more than that of nonfertilized plots. We infer about a 3-year delay in response to fertilization. Within mixed stands, gross PAI of red alder volume was not proportional to number of retained alder; doubling alder density from 20 to 40 TPA had little effect on gross PAI, probably because alder were much smaller in the 40-TPA plots. Largely because of differences in tree size, doubling alder density from 40 to 80 increased PAI by a factor of 3 to 4 (table 7). Volume PAI of associated conifers increased over time and, not surprisingly, totaled most with 40 alders per acre, the treatment in which alders averaged the smallest mean size and the least growth (table 7).

Gross and net PAI in the 17-year period—In the 17-year period after thinning and fertilizing, adjusted gross and net volume PAI of Douglas-fir were both significantly related to initial volume of Douglas-fir ($p = 0.08$; table 6). We used covariance to adjust observed treatment means to a common (average) postthinning stand volume (table 5). Adjusted gross and net PAI of Douglas-fir on fertilized plots averaged greater than PAI on nonfertilized plots, but differences were statistically non-significant ($p = 0.12$ and 0.14, table 6). Adjusted gross volume growth was increased by 27 percent on fertilized plots (table 5). Gross and net volume growth of conifers was least where admixed with 80 TPA of red alder, but most with 40 alder per acre. A linear fit of adjusted means, however, was nonsignificant ($p = 0.75$ for gross PAI and 0.84 for net) as was a lack of fit (table 6). Thus, these current data provide no reliable evidence that alder admixture increased volume growth of associated conifers.

Periodic annual mortality (PAM)—Over the 17-year period, volume of dead Douglas-fir annually averaged 4 to 10 ft^3 per acre in the pure plantation (less than 4 percent of gross PAI) compared to 1 to 6 percent of gross PAI in the mixed stands. As expected, mortality of Douglas-fir averaged greater with 20 TPA of red alder than in the 40- and 80-TPA admixtures (table 7). Mortality of red alder was limited mostly to the highest density of alder admixture.

Table 7—Observed mean gross annual increment (PAI) and mortality (PAM) in stand bole volume, by treatment, age, and species

Stand and treatment[a]	Treatment number	PAI PAM	Plantation age (inclusive years) 11-13	14-16	17-22	23-27	11-27
			Cubic feet per acre				
Douglas-fir:							
Pure–							
0 N	1	PAI	188	219	355	376	308
		PAM	0	8	14	18	10
200 N	5	PAI	186	250	433	472	368
		PAM	2	8	3	4	4
Mixed–							
20	2	PAI	179	226	354	355	301
		PAM	1	8	8	42	17
40	3	PAI	182	250	396	410	336
		PAM	4	0	1	5	2
80	4	PAI	171	202	326	360	286
		PAM	2	11	8	15	10
Red alder:							
Mixed–							
20	2	PAI	15	16	17	9	17
		PAM	0	0	1	0	1
40	3	PAI	10	12	17	14	14
		PAM	0	0	0	0	0
80	4	PAI	42	49	56	41	48
		PAM	0	0	0	6	2

[a] Pounds N per acre (in pure-conifer plots) or number of red alder per acre (in mixed-species plots).

Yield at Plantation Age 27

Cumulative live-stand yield of Douglas-fir at age 27 after planting declined slightly with increasing density of admixed alder (fig. 4); the reduction was not significantly related to increasing numbers of retained alder (p = 0.84, table 6). Clearly, size of retained alder also contributed to the effects of alder on associated Douglas-fir (fig. 5). Decrease in Douglas-fir yield was offset by corresponding increase in alder volume, so that yield of combined species was similar across all densities of red alder admixture (fig. 6). Among the three mixed-stand treatments, yield of red alder was roughly proportional to alder density (fig. 4).

Yield of combined species was similar across all densities of red alder admixtue.

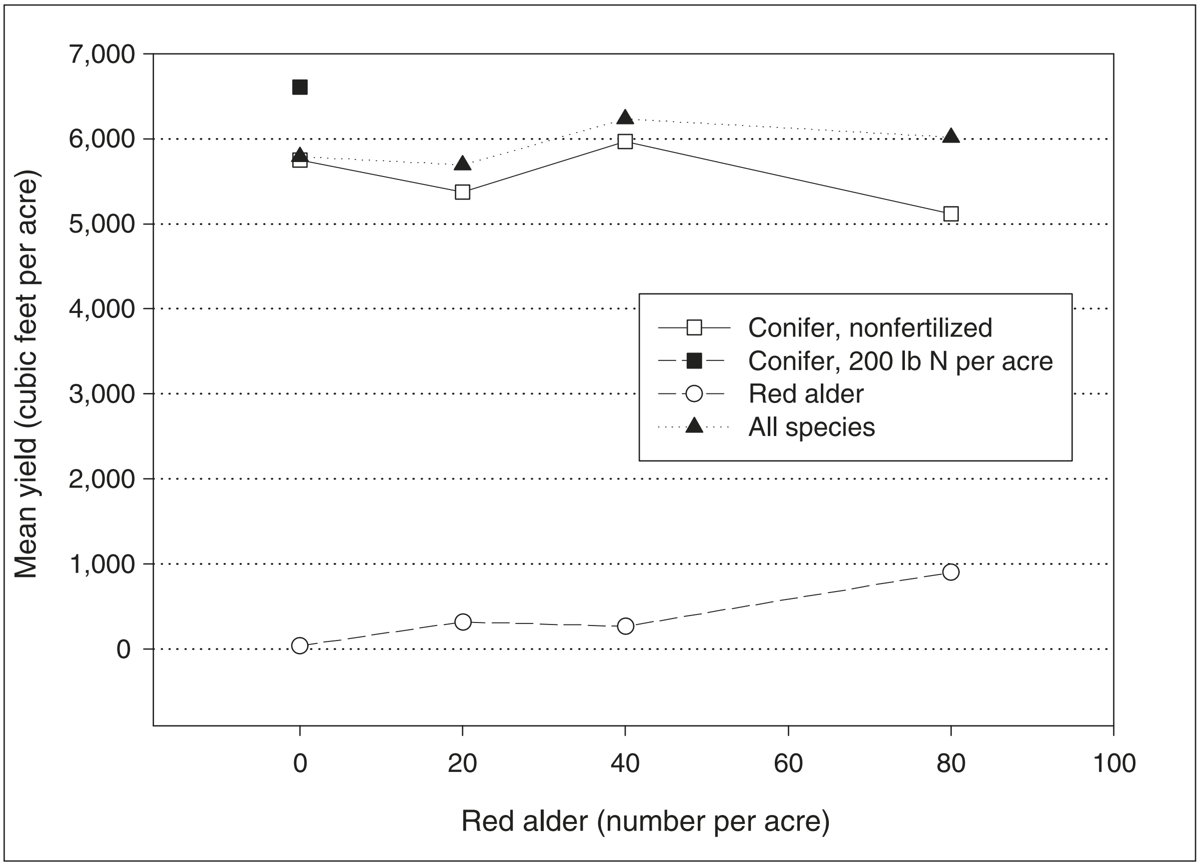

Figure 4—Mean live-stand volume at plantation age 27, by species and treatment.

Figure 5—Red alder transplanted from a local source proved more competitive than those from an off-site, coastal source. Note the relative size of the red alder (ribboned) of local source in 1994 (20 growing seasons after transplanting): (A) 20 alder per acre (treatment 2); (B) 40 alder per acre (treatment 3).

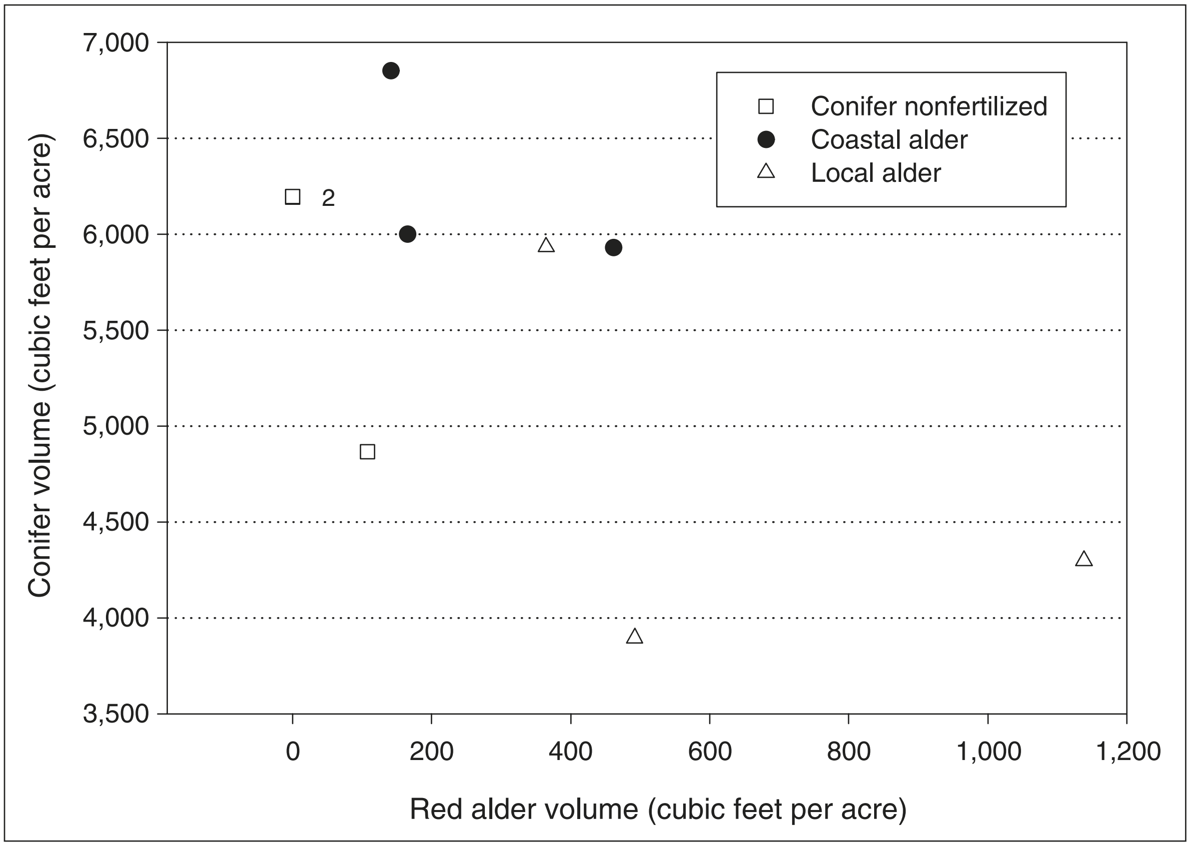

Figure 6—Conifer yield related to red alder yield at year 27, by alder source. Note the two overlapping plotting points indicated by "2."

Discussion

Effect of Fertilizing

Changes in mean height basal area, and volume of conifers on fertilized plots exceeded those on nonfertilized plots.

Changes in mean height, basal area, and volume of conifers on fertilized plots exceeded those on nonfertilized plots, although some differences were marginally significant (p = 0.07 to 0.14). For example, 17-year adjusted gross volume growth was increased by about 27 percent after 200 lb N per acre was applied. This surprisingly large response exceeded our expectation (20 percent) and totaled about 1,410 ft^3 per acre. Because volume of mortality was less on fertilized plots (smaller trees died), gain in net volume averaged 32 percent or 1,600 ft^3 per acre in the 17-year period after thinning and fertilization. Key statistics that summarize response of Douglas-fir after covariance adjustment (from tables 5 and 6) follow:

Adjusted annual change	Treatment Fertilized	 Nonfertilized	Difference Absolute	 Percent	 p
Mean height (ft)	3.18	3.01	0.17	5.5	0.07
Gross basal area (ft^2 per acre)	11.88	9.24	2.64	28.6	.12
Volume (ft^3 per acre):					
Gross	388	305	83	27.0	.12
Net	388	294	94	32.0	.14

In contrast to this strong response to N fertilization at this site III location, no response to the same 200 lb N per acre treatment occurred at our site II plantation near coastal Oregon (Miller and others 1999).

Douglas-fir mortality averaged 50 TPA (16 percent) on both nonfertilized plots and fertilized plots. The larger variation in crop tree losses among the three nonfertilized plots weakens any inference about the effect of fertilization on mortality. The general reliability of our mortality data is uncertain because our plots are small and replications few.

Effect of Increasing Numbers of Red Alder

In nearly pure Douglas-fir plots (treatments 1 and 5), 17-year mortality of Douglas-fir averaged 50 TPA; no hemlock died. The surprisingly large number of trees lost on one plot (140 TPA) clouds comparisons with Douglas-fir losses in mixed stands (fig. 2). The relatively large loss of Douglas-fir associated with 20 TPA of alder (70 TPA or 3 Douglas-fir per alder) compared to that with the doubled alder density of 40 TPA (25 TPA or 0.6 Douglas-fir per alder) is not surprising. Residual alder on the 20-TPA treatment initially averaged larger than those in the 40-TPA treatment (1.6 vs. 0.7 ft^3 per alder tree) and much taller than associated Douglas-fir (30 vs. 5 percent taller).

To comprehend spatial relations in our mixed-species stands, one should consider between-tree distances. With 300 TPA, Douglas-fir spacing averages about 13 ft. With 80 red alder per acre, alder spacing averages 23 ft. Where average spacing exists, each red alder adjoins four Douglas-fir. We suspect that Douglas-fir nearest vigorous red alder are most likely to be damaged or killed. At 80-tree alder retention, it is likely that individual Douglas-fir eventually will be competing with several red alder, especially if a rapid-growing source of red alder were used. At this study area, the local source of transplants grew faster and proved more competitive to associated Douglas-fir than did the coastal source. Because more Douglas-fir trees died when associated with increasing numbers of red alder, we infer that red alder densities of 80 TPA and greater reduced yield of Douglas-fir at this location.

Results in this Washington Cascade plantation contrast with those from a coastal Oregon plantation of similar age, but more fertile soil. At that site II coastal location, growth was not stimulated by N fertilization, but losses of associated Douglas-fir clearly increased as more red alder were admixed (Miller and others 1999). At that coastal location, our equation for predicting Douglas-fir losses in the 17-year period of observation was Y = 19 + ATPA (0.719), where ATPA is red alder TPA. Accordingly, an average of 76 Douglas-fir trees per acre could be expected to be lost in 17 years at that coastal site if 80 red alder were retained with 300 Douglas-fir per acre. Tree losses reduced stand yields (28 years after planting); average yield of Douglas-fir was greatest in pure stands and gradually declined as alder density increased. Results at that coastal location supported our second working hypothesis: by increasing alder density, negative effects of red alder on associated Douglas-fir will gradually offset the potentially positive effects of increased N and improved organic matter status.

Results at our Cascade site also contrast with those of an earlier investigation at a yet poorer (site V) location in the Cascade Range in southwest Washington. At that very N-deficient location, a 1929 Douglas-fir plantation grew taller and produced more bole volume in response to both N-fertilizer (Miller and Tarrant 1983) and a nearly 2:1 alder-fir planting mix (Miller and Murray 1978). This large complement of planted alder explained the 30-percent increase of N (about 1,000 lb N per acre) in the duff and mineral soil of the mixed stand compared to the adjacent pure Douglas-fir stand about 30 years after planting (Tarrant and Miller 1963). Not only were benefits to Douglas-fir of improved N status at that location clearly established, but competitive effects of alder were minimized because (1) alder was interplanted 4 years after the Douglas-fir were planted and (2) the newly planted alder (a nonlocal, low-elevation source) were severely frost damaged in the first year. Consequently, at plantation age 58, yield of Douglas-fir in the mixed plantation exceeded that in the pure Douglas-fir plantation, and combined yield of both species was nearly twice that of the pure stand (Miller and Murray 1978).

Survival and growth of associated Douglas-fir were reduced more by the locally derived admixed alder than by the nonlocal alder.

As a followup to that early study, Weyerhaeuser Co. scientists compared nonlocal vs. local sources at our site III location. Both sources were transplanted as 2-year-old volunteer seedlings into this 3-year-old Douglas-fir plantation. Through year 7, there was no apparent advantage in using nonlocal red alder to reduce competition with Douglas-fir at this location (Murray and Miller 1986). Our continued measurements through year 27, however, clearly show that trees from the local source eventually grew much more in height than those from the nonlocal source. Consequently, survival and growth of associated Douglas-fir were reduced more by the local source of admixed alder.

Implications for Silvicultural Researchers

Despite strong response to N fertilizer at our Cascade site, the benefits of red alder are not readily inferred. For several reasons, we have a less reliable test of our hypothesis at the Cascade site: smaller plots, two instead of three replications, and the varied size of admixed alder (in part related to delayed planting of two contrasting alder sources instead of retaining volunteer alder as at the site II study area.

The experimental design of both our trials does not permit separating the effects of increasing total stand density from increasing proportion of red alder. Our adding 20, 40, and 80 TPA of red alder to a constant 300 TPA of Douglas-fir changes both total stand density and proportion of red alder (7, 13, and 27 percent, respectively). This additive design limits understanding of competitive relations in mixed stands (Harper 1977, Hibbs and DeBell 1994, Peterson and others 1996). Two sets of more discriminating substitutive (replacement) designs have been installed in the Northwest to quantify competing relations within red alder/Douglas-fir mixtures. In one of these (Shainsky and others 1994), plots are small and not adequate for comparing stand yields beyond the sapling stage of development. The other set installed in the mid-1990s at six locations by the Hardwood Silviculture Cooperative at Oregon State University has suitably large plots[2], but results remain unpublished.

Further testing of our working hypotheses should (1) consider using a replacement design and (2) use much larger plots for both treatment areas and tree measurement plots. The 0.2-acre treatment areas and 0.1-acre measurement plots at our Cascade site were too small, especially with only two to three replications per treatment. Small plots are inadequate for characterizing stand dynamics occurring in mixed-species stands. “Treatment integrity” (Lipsey 1990) also proved difficult to attain because size of the retained alder differed greatly among the plots and treatments. For example, alder in the 20-TPA treatment averaged 4.6 in d.b.h. compared to 3.4 in d.b.h. in the 40-TPA treatment. Consequently, application of our alder treatment was much more variable than our application of urea. Installing larger plots is a likely solution to this potential problem, as well as to that caused by the large variation in mortality that we experienced among our control plots; this loss of “control group integrity” also complicated interpretation of our results.

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[2] Hibbs, D. 2001. Personal communication. Professor, Department of Forest Science, Oregon State University, Corvallis, OR, 97331-5752.

Implications for Land Managers

Numerous N-fertilization trials in coast Douglas-fir forests of the Pacific Northwest demonstrate where N fertilization is likely to increase tree growth. Similar areas could be candidates for using N-fixing species like red alder as an alternative source of N. Conversely, where a lack of response to N-fertilizer is predicted, we infer that N fixed by bacteria associated with alder roots also would be unlikely to stimulate growth of associated Douglas-fir. As noted by Binkley (1992), only on N-limited sites is growth of associated non-N-fixing trees in mixed stands generally greater than in pure stands.

We anticipate that growth of Douglas-fir on N-deficient soil would increase from either N-fertilizer or N fixed by red alder. To enhance N status, however, alder must survive in dominant or codominant positions so that photosynthesis can supply energy for both alder growth and associated N-fixing actinomycetes. Where moisture or temperature relations are less favorable to red alder (Cascades sites vs. coastal sites), we observed that red alder height and crown growth was less vigorous, hence, less likely to overtop or damage nearby Douglas-fir. The ratio of Douglas-fir to red alder heights is a useful measure of their relative development. Among plots at our site III, Cascade study area, Douglas-fir averaged 19 to 28 percent taller than associated alder (20 to 80 TPA) at plantation age 27 years. At 26 years on the coastal Oregon site, Douglas-fir averaged 0 to 14 percent taller, depending on alder density (Miller and others 1999).

Although we deliberately tested 80 red alder per acre retained with about 300 Douglas-fir per acre at plantation age 10, we suspect this is too many for an operational treatment designed to enhance Douglas-fir yields. Even at our lower quality Cascade site, which is less favorable to red alder growth, too many Douglas-fir were damaged or killed. With close spacing of admixed alder, individual Douglas-fir are likely to be mechanically damaged or suppressed by neighboring alder or, conversely, individual red alder are likely to be dominated by Douglas-fir before contributing N-rich organic matter to the stand. Delaying planting or using an off-site source of planted alder are other ways to reduce competition. Periodic assessment of crown damage in mixed stands is necessary to ensure timely reductions of stocking of red alder or Douglas-fir or both.

Conclusions

- Fertilization with 200 lb N per acre as urea at this site enhanced volume growth of Douglas-fir by about 30 percent.
- Alder size as well as numbers can affect survival and growth of associated Douglas-fir. Adding 80 red alder per acre likely reduced numbers, growth, and yield of associated Douglas-fir.
- Additional comparisons of fertilizer and red alder for enhancing growth of Douglas-fir are needed at other locations, especially those with known N deficiency.

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Metric Equivalents

1 inch (in) = 2.54 centimeters
1 foot (ft) = 0.3048 meter
1 mile (mi) = 1.609 kilometers
1 square foot (ft^2) = 0.0929 square meter
1 cubic foot (ft^3) = 0.0283 cubic meter
1 acre (ac) = 0.4047 hectare
1 square foot per acre = 0.2296 square meter per hectare
1 cubic foot per acre = 0.06993 cubic meter per hectare
1 pound (lb) = 453.59 grams
1 pound per acre (lb/acre) = 1.12 kilograms per hectare
1 tree per acre = 2.47 trees per hectare

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