Density and rectangularity of planting influence 20-year growth and development of red alder

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Abstract: Red alder (*Alnus rubra* Bong.) seedlings were planted in northwestern Oregon, U.S.A., at five initial spacings: 0.6 × 1.2 m, 1.2 × 1.2 m, 1.2 × 1.8 m, 1.8 × 1.8 m, and 2.5 × 2.5 m. Up to about age 10, tree and stand characteristics were correlated primarily with initial planting density in the expected manner; through age 20, however, tree growth and stand development in plots planted at rectangular spacings were substantially more rapid than in the two closest square spacings. Mean stand diameter ranged from 19.2 cm in the widest spacing to 14.0 cm in the closest square (1.2 × 1.2 m) spacing; mean tree height decreased from nearly 24 m in the widest (2.5 × 2.5 m) spacing to about 18 m in the closest square spacing. Diameter–density relationships in the widest spacing were consistent with existing density management guidelines, but very dense spacings and rectangular plantings began to experience substantial mortality at smaller diameters than assumed in the guidelines. We suggest that rectangular planting of red alder at dense spacing enhanced stand differentiation, accelerated competition-related mortality, and thus led to improved growth of surviving trees.

Résumé : Des semis d'aulne rouge (*Alnus rubra* Bong.) ont été plantés dans le Nord-Ouest de l'Oregon, aux États-Unis, avec un espacement initial de : 0,6 × 1,2 m, 1,2 × 1,2 m, 1,2 × 1,8 m, 1,8 × 1,8 m et 2,5 × 2,5 m. Jusqu'à l'âge de 10 ans, les caractéristiques des arbres et des peuplements étaient surtout corrélées avec la densité initiale tel que prévu; vers l'âge de 20 ans cependant, la croissance des arbres et le développement des peuplements dans les parcelles avec un espacement rectangulaire étaient substantiellement plus rapides que dans les parcelles avec les deux espacements carrés les plus près. Le diamètre moyen du peuplement allait de 19,2 cm avec l'espacement le plus grand à 14,0 cm avec l'espacement carré (1,2 × 1,2 m) le plus près. La hauteur moyenne des arbres allait de près de 24 m avec l'espacement le plus grand (2,5 × 2,5 m) à environ 18 m avec l'espacement carré le plus près. Les relations entre le diamètre et la densité avec l'espacement le plus grand étaient consistantes avec les directives d'aménagement existantes concernant la densité mais les espacements avec une forte densité et les plantations avec un espacement rectangulaire ont commencé à subir de la mortalité de façon importante alors qu'elles avaient un diamètre inférieur à celui qui est prévu dans les directives. Nous concluons que la plantation d'aulne rouge avec un espacement rectangulaire à forte densité favorise la différenciation du peuplement, accélère la mortalité due à la compétition et se traduit par conséquent par une meilleure croissance des arbres qui survivent.

[Traduit par la Rédaction]

Introduction

Red alder (*Alnus rubra* Bong.) is the most abundant commercial hardwood species on the Pacific Coast of North America. Its rapid juvenile growth, nitrogen-fixing ability, and desirable wood properties have kindled management interest during the past two decades that has centered on short-rotation production systems for pulpwood, bioenergy, and soil amelioration (control of soil-borne diseases or nitrogen and organic matter additions) and on somewhat longer rotations for sawtimber. Markets for short-fibered pulp, furniture stock, and other solid wood products have led to improved stumpage values. Present demands are being met with stands established naturally 40 or more years ago, before the widespread use of herbicides and other techniques used to control alder in stands managed for conifers. Young natural alder stands are less abundant, however, and considerable concern exists about the future availability of adequate supplies (Raettig et al. 1995).

Most foresters have had little management experience with the species, however, and applied silvicultural research has been much more limited than for conifer associates such as Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.). Information available for red alder has been summarized most recently in Hibbs et al. (1994) and Peterson et al. (1996). Normal yield tables (Worthington et al. 1960) and empirical yield, stand, and stock tables (Chambers 1974) have been developed for natural stands. Several reports have examined growth and productivity of red alder in unmanaged stands of various densities and ages (e.g., Smith 1968, 1978; Zavitkovski and Stevens 1972; Smith and DeBell 1974). Thinning trials in natural stands have demonstrated that thinning can be effective in stimulating diameter growth, especially if done before age 15–20 (Bormann 1985; Hibbs et al. 1989, 1995); thinning in dense, older stands can salvage mortality, but it is of questionable value for the purpose of

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enhancing increment on selected crop trees (Berntsen 1961, 1962; Harrington 1990; Harrington et al. 1994; Warrack 1964). Puettmann et al. (1993*a*) developed a guide to density management, using data from the above-mentioned sources and other unpublished data. Information on effects of initial spacing on growth and development of red alder is limited to a few papers reporting modelling efforts or very early growth based on data from seedling growth under greenhouse or lathhouse conditions (Smith and Hann 1984), 7-year-old Nelder plots (Knowe and Hibbs 1996), and 5- to 16-year-old small block plantings (Bormann and Gordon 1984; Puettmann et al. 1993*b*; DeBell and Giordano 1994; Knowe et al. 1997; Hurd and DeBell 2001).

Most alder spacing trials and commercial plantations have been established with square spacings (distance between trees within rows is equal to distance between rows). Rectangular spacings, however, are common in intensively cultured, short-rotation hybrid poplar plantations because space between rows must accommodate the use of mechanized equipment; rectangular spacings have also been used to establish forest plantations of other conifer and hardwood species. Commonly the plantings are either clear-cut or thinned to leave a square spacing prior to development of intense intertree competition. Square versus rectangular spacings have rarely, if at all, been compared quantitatively during a prolonged period of stand differentiation with substantial amounts of competition-related mortality.

This paper describes tree characteristics and stand structures of 20-year-old red alder stands planted at five spacings (two rectangular and three square) and traces their patterns of development in mortality, diameter, height, volume, and dry biomass. Implications regarding density and pattern of planting, precommercial thinning, and quantity and quality of yields are discussed.

Study area

The red alder spacing trial was located in the Coast Range of northwestern Oregon, U.S.A., (46°N, 123°W) at 300–350 m elevation. The site is very productive for conifers and was previously occupied by a stand of 45-year-old Douglas-fir with some western hemlock and red alder scattered throughout. The stand was fully stocked, except for numerous small openings caused by laminated root rot (*Phellinus* (*Poria*) *weirii* (Murr.) Gilb.). Site index for red alder (based on performance through age 20) was very high: 24 m at index age 20 years (Harrington and Curtis 1986). The spacing trial plots were located on gentle slopes (20% or less) facing north and east. Soils were deep, well-drained loams of the Hembre and Tolke series and were developed over volcanic and sedimentary parent material.

The original stand was logged in fall 1973, using rubber-tired skidders. Slash was broadcast burned in spring 1974, and the site was fenced to exclude elk and deer. Most of the area was used for a test of red alder as a biological control for laminated root rot (Hansen and Nelson 1975) and was planted in winter 1974–1975 in blocks (0.25 ha and larger) of Douglas-fir, red alder, or black cottonwood (*Populus trichocarpa* Torr. & Gray) at an approximate spacing of 2.5 × 2.5 m. The remaining area was used to conduct the spacing trial.

Methods

The study compared tree and stand characteristics at five spacings ranging from 0.6 × 1.2 m to 2.5 × 2.5 m. It was established in winter 1974–1975 with container-grown seedlings of local seed source. The four narrower spacing treatments (0.6 × 1.2 m, 1.2 × 1.2 m, 1.2 × 1.8 m, and 1.8 × 1.8 m) were planted in a completely random design on 0.04-ha plots at exact spacings and replicated twice. These spacings are quite dense and were selected because initial objectives of the trial assumed that trees would be coppiced on short cutting cycles; also, the dense plantings would provide an opportunity to assess the accumulation of nitrogen and organic acids, which were considered to be associated with the biological control of laminated root rot. With time, however, objectives of the trial were changed to focus on patterns of growth and stand development. One of the 1.8 × 1.8 m plots was abandoned after year 3 because of high mortality, possibly resulting from unseasonally low temperatures in a frost pocket. Data for the widest (nominal 2.5 × 2.5 m) spacing were obtained from two plots established in adjacent red alder blocks planted for the laminated root rot study; the planting stock was identical to that used in the narrower spacings of the spacing trial, but distances between planting spots were estimated by operational crews. Only one of the 2.5 × 2.5 m plots remained through age 20, the other was harvested in accord with objectives of the parent root rot study. Spots occupied by dead trees at the end of year 1 were replanted in winter 1975–1976. Assessments of mortality were made after years 2, 4, 7 through 12, 14, 16, and 20, but no replanting was done. Heights of 16 trees located near the centre of each treatment plot were measured after years 2, 4, 5, 6, and 7. The same trees were measured for stem diameter at 1.37 m after years 4 through 7. After year 7, measurement plots (0.02-ha) were established in each 0.04-ha treatment plot; also, 0.08-ha measurement plots were established in two adjacent blocks planted at 2.5 × 2.5 m for the laminated root rot study. All permanent measurement plots contained at least 60 trees at age 7 and were surrounded by two or more buffer rows planted at the same spacing. All living trees were tagged, and stem diameter at 1.37 m was measured annually at ages 7 through 12, and at ages 14, 16, and 20 years. Heights of 10 trees, two-thirds of which were larger than the tree of quadratic mean diameter, were measured in each plot at the same ages.

Characteristics of the stands at 7–20 years were summarized for each plot and spacing. Equations to predict height from diameter were developed for each spacing and used to generate heights for all trees on each plot. Bole volumes were calculated for each tree using the regression equation developed by Browne (1962), summed per plot, and expanded to per-hectare values.

Measurement plot data for years 7–20 were combined with data collected in earlier years on mortality from the entire treatment plot and on tree size from the 16-tree samples. Early year data for quadratic mean diameter and mean height were adjusted to reflect performance of the permanent measurement plot by calculating the ratio, (mean for measurement plot)/(mean for the 16-tree sample) for 7-year data, and multiplying the 2- to 6-year values for the 16-tree sample by that ratio. Adjustments ranged from –8 to 5% for quadratic mean diameter and –1 to 12% for mean height.

Table 1. Selected stand characteristics by spacing for red alder plantings at age 20.

Stand characteristics	0.6 × 1.2 m spacing *a**	*b*	1.2 × 1.2 m spacing *a*	*b*	1.2 × 1.8 m spacing *a*	*b*	1.8 × 1.8 m spacing	2.5 × 2.5 m spacing
Trees per hectare								
No. planted	12 515	11 288	6612	6723	4592	4360	2989	1570
No. surviving	1595	1534	2111	2111	1327	1454	1765	964
Mortality (%)	87	86	68	69	71	67	41	39
Quadratic mean diameter (cm)								
All trees	15.7	15.6	14.1	13.9	15.7	16.7	14.9	19.2
Largest 500 trees	19.7	18.7	17.6	18.6	19.7	20.0	18.6	21.8
Largest 200 trees	21.9	19.9	18.7	19.8	22.9	22.2	20.2	24.0
Height (m)								
All trees	21.6	21.6	18.1	17.6	21.6	22.1	20.3	23.5
Largest 500 trees	23.6	23.2	20.7	21.2	23.2	23.4	21.9	23.7
Largest 200 trees	24.4	23.7	21.3	21.9	24.2	24.2	22.5	23.9
Basal area ($m^2 \cdot ha^{-1}$)	30.9	29.4	33.2	33.2	25.8	31.9	30.7	28.0
Bole volume ($m^3 \cdot ha^{-1}$)	317	300	291	283	266	332	295	302

**a* and *b* are replicate plots for each of the three narrowest spacings.

Bole volumes at ages 4–6 were calculated for the tree of quadratic mean diameter in each spacing with the Browne (1962) equation; hectare yields were obtained by multiplying the mean-tree value by number of surviving trees per hectare. (Note that a comparison made with 7-year data of the summed individual tree versus the mean-tree approach revealed that yields estimated by the latter were reasonable and conservative (0 to –5%) approximations of those obtained with the complete stand data.)

Developmental patterns of trees and stands at the five spacings were examined from planting to age 20 by plotting tree and stand characteristics over stand age for each spacing and over each spacing for various ages. In addition, periodic measurements of quadratic mean diameter were plotted against corresponding density (number of surviving trees per hectare) on logarithmic scale. The diameter–density trajectories were compared with a current density management guide for red alder (Puettmann et al. 1993*a*).

Quadratic mean diameter and mean height were analyzed with analyses of variance at ages 8, 12, 16, and 20. Plot means were used in the analyses. The ANOVA model tested the effects of spacing treatments; *t* tests were used to contrast each rectangular spacing with the closest square spacing (always less dense than the rectangular spacing). Thus, for each age, for each variable, we tested the overall effect of spacing, whether the mean of the 0.6 × 1.2 m spacing differed from that of the 1.2 × 1.2 m spacing, and whether the mean of the 1.2 × 1.8 m spacing differed from the 1.8 × 1.8 m spacing. Although the data could have been analyzed as a repeated-measures analysis, we chose not to do so, because it would add unnecessary complexity to discussion. The results of the analyses at ages 8, 12, and 16 are provided primarily to demonstrate to readers that relationships among treatments changed over time. The primary test of rectangularity is at age 20.

Results

Stand characteristics at age 20

Because many of the following findings are unusual, Table 1 contains data on tree and stand characteristics at age 20 for all plots (both replicates for the three narrowest spacings) rather than treatment means. A remarkable consistency of trends among spacing treatments is evident, including those associated with pattern (rectangular vs. square planting). The number of trees planted varied from about 1600 trees/ha in the 2.5 × 2.5 m spacing to nearly 12 000 trees/ha in the 0.6 × 1.2 m spacing (Table 1). By age 20, cumulative mortality ranged from an average of 40% in the two widest spacings to 87% in the densest spacing. Differences in mortality patterns among initial spacings led to tree densities levels at age 20 that differ in ranking from those at time of planting, however. Fewer trees remained in rectangular plantings than in the next wider square plantings. Moreover, the 0.6 × 1.2 m planting had fewer trees at age 20 than the 1.8 × 1.8 m planting.

Quadratic mean diameter and height were significantly affected by initial spacing, and their rankings also showed some unexpected shifts that were associated with rectangularity (Table 2). Diameter of trees in the 0.6 × 1.2 m spacing was significantly greater than that in the 1.2 × 1.2 m spacing, and also in the 1.2 × 1.8 m spacing as compared with the 1.8 × 1.8 m spacing. Quadratic mean diameter at age 20 was nearly 40% larger in the widest spacing than in the 1.2 × 1.2 m spacing. Mean diameters of the 500 and 200 largest trees per hectare were also influenced by initial spacing and rectangularity, but absolute and relative differences among treatments tended to be less than for all trees (Table 1). The two rectangular spacings had diameters that were intermediate between the widest spacing and both of the closer square spacings in comparisons among all trees, the largest 500 trees, and the largest 200 trees per hectare.

Mean height of all trees averaged 21 m and was also affected significantly by initial spacing and rectangularity. Height at age 20 was greatest in the widest spacing and lowest in the closer two square spacings. Mean heights of all trees in the two rectangular spacings were in between mean heights in the 2.5 × 2.5 m spacing and the two exact square spacings and were significantly taller when compared with trees in the closest square spacing treatments. The same

Table 2. Probability of spacing effect (probability of greater F value), in analysis of variance of quadratic mean diameter and height, and probability of t value in pairwise comparisons.

	Quadratic mean diameter			Height		
Age (years)	Spacing	1 vs. 2	3 vs. 4	Spacing	1 vs. 2	3 vs. 4
8	<0.01	0.29	0.26	0.02	0.94	0.17
12	<0.01	0.47	0.79	0.05	0.13	0.26
16	0.02	0.43	0.36	<0.01	<0.01	0.75
20	0.01	0.03	0.08	<0.01	<0.01	0.02

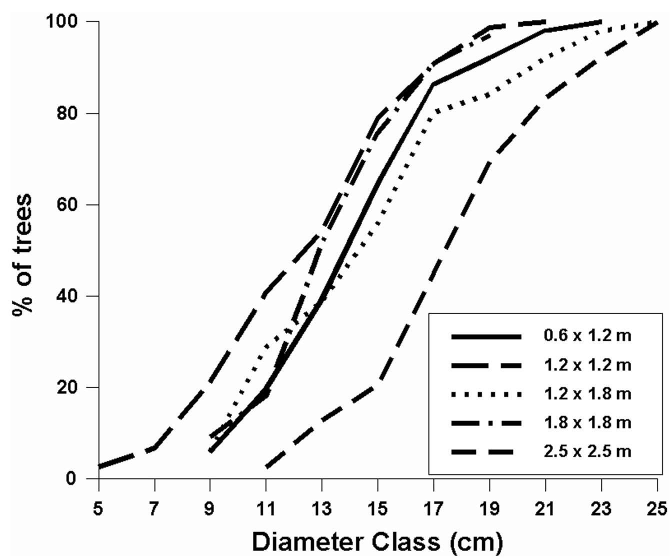
Note: The columns labeled "1 vs. 2" compare the rectangular 0.6 × 1.2 m and the square 1.2 × 1.2 m spacings; the columns labeled "3 vs. 4" compare the rectangular 1.2 × 1.8 m and the square 1.8 × 1.8 m spacings.

pattern in relative height by spacing and as influenced by rectangularity was evident for the 500 and 200 largest trees per hectare.

Basal area per hectare at age 20 averaged 30.1 $m^2 \cdot ha^{-1}$ and was rather similar among spacings. Because of differences in height and diameter distributions, however, the relative rankings among spacings in estimated bole volume differed from those for basal area. Volume yields for the two rectangular spacings and the widest (2.5 × 2.5 m) spacing ranged from 299 to 309 $m^3 \cdot ha^{-1}$, whereas those in the two closest square spacings were 287 and 295 $m^3 \cdot ha^{-1}$. Such yields averaging 298 $m^3 \cdot ha^{-1}$ represent mean annual increments of about 15 $m^3 \cdot ha^{-1} \cdot year^{-1}$.

Stand structure as reflected in diameter distributions also differed with spacing (Fig. 1). The widest spacing clearly differed from the four closer spacings in its diameter distribution. Interestingly, for trees >13 cm, the two rectangular spacings are further to the right on the graph than the two wider square spacings. That is, a greater percentage of the trees in the rectangular spacings were in the larger diameter classes. In the 2.5 × 2.5 m spacing, 841 trees had diameters 15 cm or larger; this is equivalent to 87% of the surviving trees. Of these, more than 42% were 20 cm and larger. A majority of the trees (61%) in each of the two rectangular spacings were 15 cm DBH and larger, whereas only 46 and 48% of the trees attained this size in the two closest square spacings.

Fig. 1. Cumulative diameter distribution at age 20 as related to initial spacing.



Patterns of tree growth and stand development

The consistency among replicate plots observed for tree and stand characteristics at age 20 was also apparent in developmental patterns over time, including the ages at which performance rankings among treatments change. Because this consistency has been documented in Table 1 and discussed in the previous section, however, the figures that illustrate growth and development over time were prepared from treatment means in order that trends be more readily seen.

Tree population trends indicate that the amount and timing of mortality differed considerably among initial spacings (Fig. 2*a*). Crown closure did not occur in the widest spacings until about age 5 years. At that time, cumulative mortality was highest (15%) in the densest spacing, totaled about 10% in the three intermediate spacings, and was negligible in the widest spacing. Competition became more intense over time, and mortality accelerated greatly, more so in the rectangular spacings than in the square spacings. Mortality in the densest spacing totaled 60% at age 10, 70% at age 12, and nearly 90% at age 20. Although mortality was also substantial (68% by age 20) in the next densest spacing (1.2 × 1.2 m), the decline in number of trees was much less abrupt; the net effect was that tree numbers were nearly identical in the two densest spacings at age 12, and at age 20, the square (1.2 × 1.2 m) spacing had 35% more surviving trees than the rectangular (0.6 × 1.2 m) spacing, which had been planted with twice as many trees. A similar pattern occurred with the 1.2 × 1.8 m and 1.8 × 1.8 m spacings where cumulative mortality resulted in very similar stands at age 12. These trends continued, and by age 20 even the densest rectangular (0.6 × 1.2 m) spacings had fewer trees than the square (1.8 × 1.8 m) spacing. In Fig. 2*a* the lines for each of the rectangular spacings crossed the lines corresponding to the square spacings planted with fewer trees. Thus, the rectangular spacings not only had greater mortality early on but their rates of mortality were greater even when a rectangular and square spacing had the same number of surviving trees. Competition intensified more slowly in the widest (2.5 × 2.5 m) spacing, but cumulative mortality at age 20 was nearly 40%.

Trends in quadratic mean diameter indicate that differences between the four closest spacings and the widest spacing widened up to about age 10 (Fig. 2*b*). Height measurements show that trees attained breast height during the second growing season, but diameter was not measured until year 4. At that time, mean diameters varied among

Fig. 2. Stand development as related to plantation age and initial spacing: (*a*) number of surviving trees and (*b*) quadratic mean diameter.

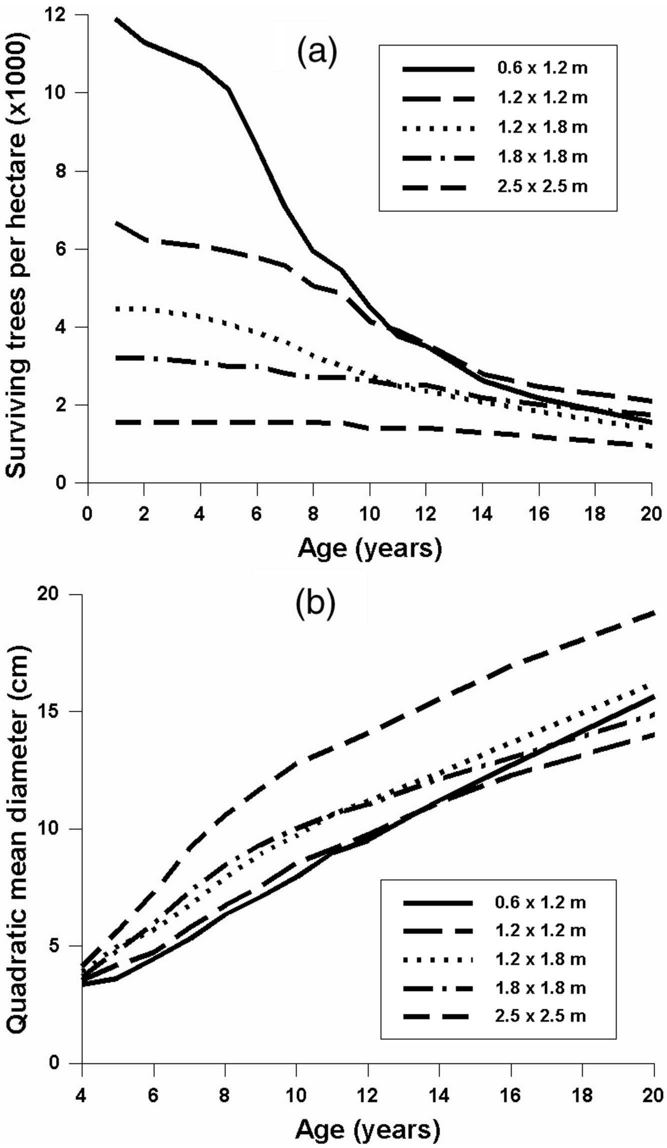
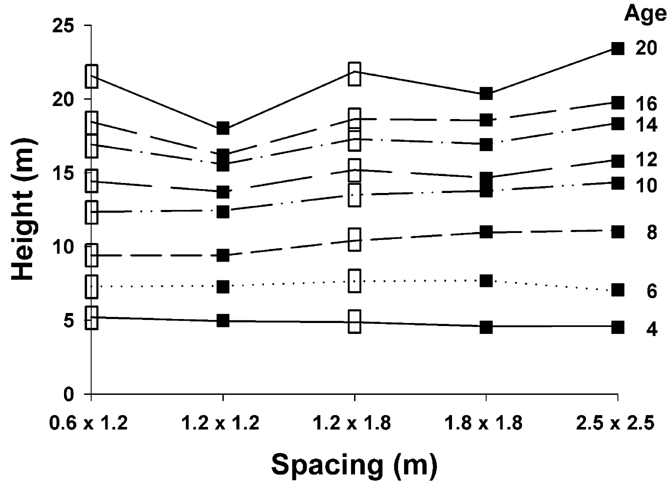


Fig. 3. Mean tree height as related to initial spacing and plantation age.



spacings by less than 1 cm. Over all spacings, the range in quadratic mean diameters increased to 5 cm at age 10, with diameters correlated with initial planting density as expected. Beyond age 10, however, trends among treatments in mean diameter began to parallel those previously mentioned with regard to competition-related mortality. Diameter growth slowed somewhat in most spacings between ages 10 and 12 and more so in the two closest square spacings than in the rectangular spacings and the widest spacing. As a result, quadratic mean diameters of trees in the 1.2 × 1.8 m spacing were similar to those in the 1.8 × 1.8 m spacing at age 11, when numbers of surviving trees were equal; mean diameter of the 1.2 × 1.8 m spacing surpassed that of the 1.8 × 1.8 m spacing at age 12, and differences between these two treatments continued to widen through age 20. Trees in the 0.6 × 1.2 m spacing were similar in size to those in the 1.2 × 1.2 m spacing at ages 11–14, after which differences between the two widened to 1.6 cm in favor of the rectangular spacing. Moreover, diameter of trees in the densest rectangular spacing surpassed that of trees in the square 1.8 × 1.8 m spacing between ages 16 and 20, despite the former spacing being initially four times more dense. By age 20, quadratic mean diameters in each rectangular spacing were significantly larger than those in the next wider square spacing (Table 2).

Although diameters beyond age 10 were not correlated with initial spacing in the manner expected, the relationship between current tree diameter and current number of trees per hectare remained similar over time (cf. Figs. 2*a* and 2*b*); that is, quadratic mean diameters were always larger in plots with fewer trees. The surprising shifts in relative performance of the initial spacings appear related to accelerated mortality in the rectangular spacings. Diameter growth patterns for the largest 500 and 200 trees per hectare paralleled the trends in quadratic mean diameter of all trees; moreover, diameter growth of the 500 largest trees per hectare in rectangular spacings slightly exceeded that in the widest (2.5 × 2.5 m) square planting during the 16- to 20-year period.

Patterns of height and height growth also varied with age, initial spacing, and rectangularity (Fig. 3, Table 2). At age 4, trees in the densest spacing averaged taller (0.3 m or more) than those in the wider spacings, and mean height generally decreased as spacing widened. Between ages 4 and 10 attained height generally increased with spacing. Beyond age 10, however, height growth in the two closest square spacings was on average less than that attained in the next denser rectangular spacing and in the widest spacing. And by age 20, mean height of trees of the two rectangular spacings was more or less equal and significantly taller than average tree height in the closest square spacings, but 2–3 m shorter than mean tree height in the widest (2.5 × 2.5 m) spacing. General trends for the largest 200 and 500 trees per hectare were similar to the above, except that at age 20, the largest 200 trees in the two rectangular spacings were equal to or taller than the largest 200 trees in the widest spacing.

Accumulation of stand basal area followed a pattern consistent with trends in mortality and diameter growth (Fig. 4*a*). Differences between the densest spacing and wid-

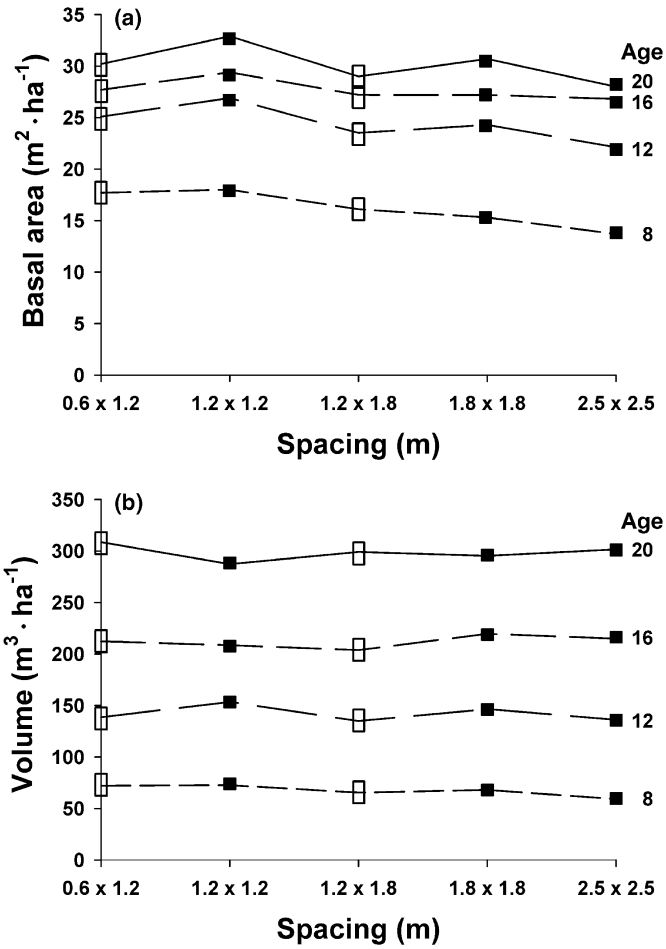


Fig. 4. Cumulative production per hectare as related to initial spacing and plantation age: (*a*) basal area and (*b*) cubic bole volume.

est spacing at age 4 were several-fold (not shown); at age 8, differences diminished substantially, but they remained strongly correlated with initial spacing. By age 12, basal area became less affected by initial spacing, ranging from 22.1 to 26.8 $m^2 \cdot ha^{-1}$. Mean annual basal area increment peaked at 2.4 $m^2 \cdot ha^{-1} \cdot year^{-1}$ in the two densest spacings, 2.1 $m^2 \cdot ha^{-1} \cdot year^{-1}$ in the 1.2 × 1.8 m and 1.8 × 1.8 m spacings, and 1.8 $m^2 \cdot ha^{-1} \cdot year^{-1}$ in the widest spacing. In all cases, mean annual basal area increment peaked when cumulative basal area attained 20–24 $m^2 \cdot ha^{-1}$. The plantings reached this level of cumulative basal area between the ages of 9 (at the closest spacing) and 12 (at the widest spacing). Between age 16 and 20, periodic annual increment in live basal area dropped off markedly, more so in the rectangular and widest spacings than in the square spacings. This pattern is associated with lower mortality in the two square spacings, not with greater growth on surviving trees (i.e., if one examines growth of the 200 largest trees per hectare, the rectangular spacings and the widest spacing have superior diameter growth).

Accumulation of bole volume per hectare also followed a pattern consistent with trends described for mortality and growth in diameter and height (Fig. 4*b*). At age 4, differences among spacings were about ninefold (not shown), but these large differences diminished substantially by age 8 when the difference between the widest spacing and the two densest spacings was only 23%. Bole volumes at age 20 averaged about 300 $m^3 \cdot ha^{-1}$, and the minor differences were more closely associated with rectangularity than with initial spacing. Mean annual increment had not peaked, and periodic increment did not appear to have peaked. From age 16 through age 20, increment in all spacings was equal or greater than that in the previous period. Periodic annual volume growth from age 16 to 20 in the rectangular plots and in the 2.5 × 2.5 m spacing was very similar and was considerably higher than in the two closest square spacings.

Discussion and implications

General

This spacing trial is unusual in a number of ways. It is the oldest spacing test for red alder; it contains a range of dense spacings, some of which were rectangular; and mortality and growth have been observed at relatively short time intervals over a rather long period of stand development. Nearly 90% of the trees in the densest planting have succumbed to competition-related mortality, and about 40% have died in the widest two spacings. Thus, our data provide an excellent opportunity to examine patterns of mortality and development in a rapid-growing, early successional species in relation to density and pattern of planting, including some marked changes in relative performance among spacings of different densities and rectangularity. In the succeeding paragraphs, we first compare the performance of the planted stands with characteristics of natural stands via normal yield tables at similar sizes and ages. Next we compare stand trajectories in relation to the self-thinning line (the line of mean maximum relative density) on which current preliminary stocking guidelines for red alder (Puettmann et al. 1993*a*) are based. Lastly, we examine the finding of growth benefits of rectangular spacings, consider its credibility and possible mechanisms, and discuss its practical implications.

Comparison with normal yield

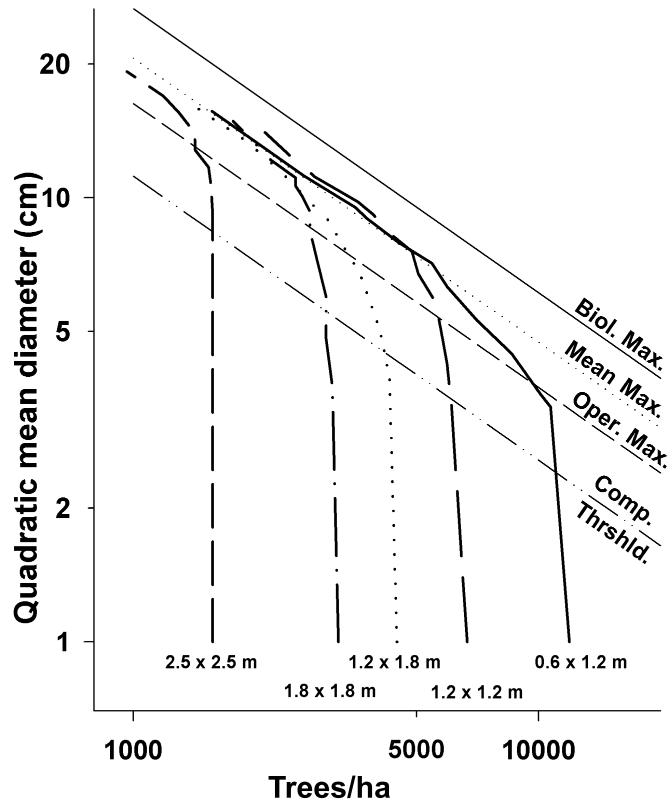
Older plantations of red alder are not common, and there are few published data on stand development of alder plantings beyond age 16. Comparison of the growth of trees in this 20-year-old trial with that of unmanaged natural stands on sites of similar quality can provide some indication of potential gains from planting.

To make such comparisons, we used the height of the largest 500 trees per hectare in the 2.5 × 2.5 m spacing (24 m) to compare with mean height of dominants and codominants listed for various site indices at age 20 in the normal yield table predictions (Worthington et al. 1960); this indicated that site index (50-year basis) of the spacing trial was equivalent to 33 m (or 120 feet) and, thus, was equivalent to the highest site class in the tables. On such sites, fully stocked, natural stands at age 20 contain about 930 trees/ha, averaging 18.3 cm in diameter, and yielding 24.6 $m^2 \cdot ha^{-1}$ of basal area. Trees in the widest planted spacing were slightly more numerous (964 trees/ha) and larger in diameter (19.2 cm). Basal area yields in the planted stand were about 14% greater than those in fully stocked, natural stands, and because individual trees were larger in diameter, gains in volume in the planted stand to any merchantable limit would be somewhat greater in magnitude.

The normal yield tables also permit estimates of time required for trees in unmanaged fully stocked natural stands to attain sizes or provide levels of stand basal area equivalent to those achieved in the planted stand. Thus, fully stocked, natural stands would attain mean diameters comparable with those of the widest spaced planting at age 21; at that time the natural stands would contain 8% fewer stems than the planted 2.5 × 2.5 m spacing (887 vs. 960 trees) had at age 20, and thus, basal area and volume of the natural stand would be correspondingly lower. Basal area of natural stands would not attain that achieved in the 20-year-old 2.5 × 2.5 m spacing until age 27.

It is clear from the above comparison that the widest spaced planting resulted in an alder stand that grew slightly faster in diameter and contained a few more trees than predicted for a fully stocked but unmanaged natural stand growing on a site of equal productivity (as estimated by site index). Such gains are probably conservative in that they are based on comparisons with fully stocked natural stands that do not represent the average unmanaged condition. Neither do they reflect the gains that may be possible with more intensive or refined cultural practices. Since this plantation was established, research has revealed several opportunities for further enhancing the quantity and quality of red alder wood production through genetic selection (Lester and DeBell 1989; DeBell and Wilson 1978; Ager et al. 1993; Ager and Stettler 1994), improved planting stock (Ahrens et al. 1992; Ahrens 1994; Radwan et al. 1992; Dobkowski et al. 1994), greater control of competition (Newton and Cole 1994; Dobkowski et al. 1994), and application of supplemental nutrients (Radwan and DeBell 1994).

Fig. 5. Stand trajectories (ln quadratic mean diameter vs. ln trees per hectare) for spacing treatments in relation to the density management diagram for red alder (Puettmann et al. 1993*a*).



Stand trajectories and the current stocking guide

The growth trajectories of all planted spacings, as indicated by log quadratic mean diameter versus log density (trees per hectare) plottings, were superimposed on the currently used density management guide (Puettmann et al. 1993*a*) in Fig. 5. The “ biological maximum” line shows the largest mean diameter attainable at given densities; it was defined by maximum values found in a survey of red alder plots and is the basis for relative density measures. The “mean maximum” line (immediately below the biological maximum line) shows the mean relative density that most stands approach as trees grow and mortality reduces their numbers; this line is also called the self-thinning asymptote. Alder stands generally have appreciable mortality before they reach the mean maximum line, however; therefore, the guide established an “operating maximum” at a level when most stands have lost 20% of the initial stocking. The lowest line defines the “competition threshold”, below which resources at the site are presumed to be not fully utilized. Recommended stocking levels lie between the competition threshold and operating maximum. The latter two lines were assumed to be parallel to the mean maximum because adequate data are unavailable for statistical determination of their slope and all of the relationships are presumed to be closely associated with crown size and leaf area.

Trajectories of all the planted spacings in our study closely approximated or were slightly above the mean maximum line, and those for the two widest spacings (1.8 × 1.8 m and 2.5 × 2.5 m) fit reasonably well with the operating maximum and competition threshold lines. Trajectories of the three closest spacings, however, showed that mortality was substantially greater than 20% when the stands reached the operating maximum and some mortality had occurred below the competition threshold; these trends were stronger in the two rectangular than in the 1.2 × 1.2 m spacing. Such a pattern of “premature” mortality (premature in the sense that substantial mortality occurred before the stand attained the mean diameters indicated by the competition threshold and operating maximum lines for the initial planting densities) in very dense square plantings was also noted in a loblolly pine (*Pinus taeda* L.) spacing trial (DeBell et al. 1989) and in a spacing–irrigation–fertilizer trial with red alder (Hurd and DeBell 2001). This suggests that the common assumption that slopes of the competition threshhold, operating maximum, and mean maximum lines are parallel is not valid, at least at very high initial stand densities. In most operations, however, plantations are established at much lower densities, i.e., spacings of 1.8 × 1.8 m and wider, and the trajectories for these spacings are consistent with, and should provide confidence in, the current density management guidelines.

Square versus rectangular spacings

The finding of important differences in tree survival and size associated with rectangularity was unexpected, and such trends were not obvious until after the 12th year. Differences in diameter growth (Fig. 2*b*) and height growth (Fig. 3) began between ages 10 and 12, however. Trend lines depicting numbers of surviving trees for various treatments crossed between ages 10 and 12 also, but rates of mortality expressed in various ways must have differed at even earlier ages. Had this topic been of interest initially, we would have planted identical numbers of trees per hectare in both square and rectangular plantings (cf. Niemistö 1995*a*). Although we did not set out to evaluate such differences, we place credence in these findings for several reasons: (*i*) early height measurements suggested uniformity among all plots, (*ii*) early patterns of diameter growth and mortality were "normal" in that they were correlated with initial planting density, (*iii*) the experimental design created a much higher hurdle to revealing differences because the square spacing being compared with the rectangular spacing was initially planted with fewer trees (i.e., 0.6 × 1.2 m vs. 1.2 × 1.2 m and 1.2 × 1.8 m vs. 1.8 × 1.8 m), and (*iv*) there was a consistency to the changing patterns (among plots in the rectangular or square spacing treatments and among the treatments). All four plots with rectangular spacing eventually surpassed the widest (1.8 × 1.8 m) exact square spacing in mean tree diameter and height and also contained fewer trees per hectare (despite the fact that the closest spaced rectangular plantings were initially four times as dense). Trees in the rectangular spacings were not larger at age 20 than those in the 2.5 × 2.5 m spacing, but mean diameter growth from 16 to 20 years was equal or better in the rectangular spacings and the largest 200 trees per hectare were equal in height to those in the 2.5 × 2.5 m spacing, despite the fact that the rectangular spacings still had about 50% more trees. In addition, it should be acknowledged that the 2.5 × 2.5 m spacing was planted by operational crews with distances between and within rows estimated; thus, it represented a nominal, non-exact spacing and lacked the extremely uniform spatial distribution of trees in the two closer square spacings.

If rectangularity of spacing can influence stand development, why have such findings not been reported previously? After all, forest researchers have long known that intertree competition influences tree growth and have developed distance-dependent growth models and competition indices to predict growth as a function of distance and size of competing trees. Since rectangular spacings are not common, however, such models have been developed and tested primarily with data from natural stands (with varying degrees of clumpiness) or plantations with square spacings. A number of studies of rectangularity have been undertaken, but none have been followed through stand development to the point where 40–60% of the planted trees have died. In our study, the unexpected shifts in ranking due to rectangularity were not evident until mortality in the rectangular spacings reached these levels, and stand trajectories were congruent with self-thinning or mean maximum density lines. The stands established for most other studies of rectangularity have been thinned or completely harvested prior to that stage because the rectangularity question has been adequately answered for most management situations (i.e., prior to high levels of competition-induced mortality). Thus, several studies in radiata pine and other species indicate that rectangularity ratios up to 4:1 had negligible effects on growth during the period observed (Lewis and Ferguson 1993; Savill et al. 1997).

Recent work with a related hardwood in Finland and with loblolly pine in the southeastern United States, however, has revealed the beginning of some growth differences between rectangular and square spacings in young stands at a rather early stage of development. The Finnish work showed that dominant (crop) trees in 19- to 20-year-old silver birch (*Betula pendula* Roth) plantings had improved diameter growth in rectangular plantings as compared with square spacings (Niemistö 1995*b*), yet branch thickness and stem eccentricity were unaffected (Niemistö 1995*a*). Increased density within the rows led to earlier natural thinning and faster differentiation into distinct canopy layers, hence, improved growth of dominants. Mortality in the rectangular plantings of this study was still below 30%. The loblolly pine work (Radtke and Burkhart 1999) examined relationships between the inflection point age for cumulative basal area (which is assumed to indicate a transition between relatively unhindered per-hectare growth and some level of stem growth reduction due to competition) and the extent of crown closure. Empirical models were developed using annual measurements from age 2 through age 13 on nearly 200 plots in the Piedmont and Atlantic Coastal Plain of Virginia and North Carolina. Although crown closure at the inflection age increased with stand density, it was reduced with degree of rectangularity, largely because of increased crown overlapping by trees within rows and larger uncovered areas in the wider, between row dimension (Radtke and Burkhart 1999).

With regard to our alder study, the loblolly pine findings suggest that within-row competition may become more intense in rectangular spacings (and thus with time enhance differentiation and accelerate mortality), while greater amounts of the stand (or plot) area remain open for crown expansion and resource exploitation by the more vigorous trees. The opposite situation, however, prevails for square spacings, i.e., more even competition among all trees and less area unoccupied by tree crowns. Somewhat related mechanisms and assumptions are inherent in the theoretical "honeycomb rippling model" of competition-related mortality developed to explain distribution of *Acacia reficiens* (Wowra Peyr.) trees in conjunction with bush encroachment and open savanna in southern Africa (K. Wiegand, D. Saltz, and D. Ward, unpublished data[2]). This model starts with trees of equal size distributed uniformly in a hexagonal pattern with crowns touching one another. If one tree becomes slightly larger or more vigorous than its immediate neighbors, the latter will have fewer resources and eventually die. This gives trees in the second circle around the subject tree more resources. Because distances between the subject tree and trees in the circle of surviving plants are not equal, every second seedling is at a disadvantage, leading over time to its death; the process continues, gradually leading to widely dispersed trees. Seemingly, the mechanisms leading

[2] K. Wiegand, D. Saltz, and D. Ward. A unifying patch dynamics approach to savanna dynamics and bush encroachment. In preparation. [Unpublished manuscript mailed to DeBell on 30 October 2000.]

to such dynamics in hexagonal spacing patterns would be even more strongly evidenced in rectangular plantings and would tend to maintain or reinforce the original spatial pattern, whether hexagonal, square, or rectangular.

Another mechanism of possible influence in our study is that the higher density planting in rectangular spacings is beneficial because (*i*) the probability is greater that any surviving tree will be of superior genetic makeup or occupy a better microsite and (*ii*) increased stand density may have a positive influence on tree growth at young ages. Although such benefits may eventually have some effect, we do not believe the higher density of rectangular spacings has influenced the shift in ranking between square and rectangular plots. First, within square spacings, tree size is strongly correlated with spacing and initial planting density; larger trees occur with wider spacing. The same is true among the rectangular spacings, albeit to a lesser degree. And second, although the positive effects of higher stand density on tree growth (primarily height) observed at early ages have been documented in red alder (Hurd and DeBell 2001) and other species (e.g., loblolly pine, Adams et al. 1973; poplars, DeBell et al. 1997; and Douglas-fir, Scott et al. 1998), such benefits appeared and waned in the spacing treatments of our study before the advantages of rectangularity developed. Clearly, some other mechanism must be operating. The idea that rectangularity enhances differentiation via the dual condition of earlier and increased crown overlap within row and increased unexploited area seems much more plausible; enhanced differentiation among trees would accelerate mortality in this shade-intolerant species, and the increased growing space would lead to increased growth of surviving trees.

Although the rectangular spacings evaluated in our study are far too dense to be considered in normal operations, the finding of beneficial effects of rectangular spacings may have some more general practical implications in planted forests. For example, rectangular planting might be considered for plantations unlikely to be thinned, for whatever reason, without serious concern for growth losses. It could eliminate or postpone the need for early or pre-commercial thinning in situations where trees may have been planted at higher density than normal to capture a site and prevent erosion. Rectangular spacings are commonly used in intensively cultured *Populus* plantations because space between rows must accommodate farm machinery, and there may be other situations where rectangular spacings would be operationally desirable (e.g., corridor thinning on steep ground) or would offer some advantage in simplicity or costs of operations (e.g., hand or machine planting). If our experience with rectangularity influences on red alder represents a general phenomenon, at least for shade-intolerant species, rectangular plantings may provide some benefits in terms of increased flexibility in the nature and timing of management operations. Growth may not be reduced and, more likely, may be increased.

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