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Relation of Initial Spacing and Relative Stand Density Indices to Stand Characteristics in a Douglas-fir Plantation Spacing Trial

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Cover: Young Douglas-fir stand next to older stand. Photo by U.S. Forest Service Pacific Northwest Region.

Abstract

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This report presents updated information on a 1981 Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*) plantation spacing trial at 33 years from planting. Stand statistics at the most recent measurement were compared for initial spacing of 1 through 6 meters and associated relative densities. There was no clear relationship of spacing to top height. Diameter, live crown ratio, and percent survival increased with spacing; basal area and relative density decreased with increase in spacing. Volume in trees ≥ 4 cm diameter was greatest at 2 m spacing, while utilizable volume (trees ≥20 cm dbh) was greatest at 4 m spacing. Live crown ratio decreased and total crown projectional area increased with increasing relative density indices. Total crown projectional area was more closely related to relative density than to basal area.

Keywords: plantation spacing, stand density, crown dimensions, yield, SDI, RD, *Pseudotsuga menziesii.*

Summary

This report presents updated information on a 1981 Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*) plantation spacing trial at 33 years from planting (35 from seed). Initial planting spacings were 1, 2, 3, 4, 5 and 6 m. Stand statistics by spacing and associated values of relative density at the most recent measurement (2013) were compared. There was no clear relationship of spacing to top height. Diameter, live crown ratio, and survival percentage increased with spacing; basal area and relative density decreased with increase in spacing. Volume in trees ≥ 4 cm diameter was greatest at 2 m spacing, while utilizable volume (trees ≥20 cm dbh) was greatest at 4 m spacing. Several common relative density indices have near-perfect correlations in these data and are essentially equivalent, except for proportionality constants. Live crown ratio decreased and total crown projectional area increased with increase in relative density. Total estimated crown projectional areas suggest that crown closure occurs at about 1/3 of maximum relative density. Total crown projectional area was more closely related to relative density than to basal area, suggesting that relative density may be a better predictor of shading.

Contents

Introduction

This report discusses developments in the "new" Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*) plantation spacing trial at the Wind River Experimental Forest. This trial is called "new" to distinguish it from the pioneering early trial (Reukema 1979) established at Wind River in 1925. The 1925 trial showed that wider spacing than was then in common use had considerable advantages both in reduced costs and superior tree development, a result that had a strong influence on planting practices in the Pacific Northwest. But, interpretation of results of the 1925 trial has been somewhat clouded by defects in the original experimental design (Miller et al. 2004), plus the fact that it represents only a single site of rather poor quality.

In the late 1950s and following decades, a number of organizations undertook additional plantation spacing trials with improved designs and including a wider range in geography and site quality.

The Study

We here present a progress report on one of these, the "new" Wind River spacing trial, established in 1981. The study differs from most previous trials in that it includes a wider range of initial spacings and more extensive replication of spacings within a single study area. Our objectives are to (1) update and supplement information given in a previous report by Harrington et al. (2009), and (2) provide some additional information on crown development in relation to initial spacing and stand density indices.

Study Area

The study area is in the Trout Creek Unit of the Wind River Experimental Forest (T4N R7E S18) on the Gifford Pinchot National Forest, near Carson, Washington. Elevation is 512 to 557 m, with slopes less than 10 percent and a southerly aspect. The soil is classified as a dark brown loam of the Stabler series, a medial, amorphic, mesic, Vitric Hapludand (Harrington et al. 2009). Preharvest vegetation was intermediate between the western hemlock (*Tsuga heterophylla* (Raf) Sarg.) and Pacific silver fir (*Abies amabalis* Dougl. Ex Forbes) zones (Franklin and Dyrness 1973, Harrington et al. 2009).

The area was clearcut in 1977, slash burned in 1978, and planted in spring 1981 with 2-0 stock. Herbicide was applied in summer 1981 to reduce vegetative competition with the planted seedlings. Naturally established seedlings were removed in 1986, 1990, and 1998.

Although the present stand is still too young for a precise site index estimate, it now appears to be a high site 3 (King 1966).

Study Design

Planting spacings were 1, 2, 3, 4, 5, and 6 m. Treatment plot size was 0.4 ha, with measurements taken on interior subplots of size varying with spacing (table 1).

We consider here only the 38 plots planted with pure Douglas-fir (some additional plots were mixed species). Assignment of treatments was randomized within the study area. There were four plots each in the 1 m spacing, ten plots in the 3 m spacing, and six plots each in the other spacings. Arrangement of plots is shown in figure 1.

Additional and more detailed information has been given by Harrington et al. (2009), including results from complete remeasurements in 1997, 2001, and 2005.

Table 1—Plot dimensions and initial number of trees, by spacing

Spacing		Measurement plot		Number of trees planted	
Meters	*Feet*	*Hectares*	*Acres*	*Per hectare*	*Per acre*
1	3.2	0.020	0.049	10,000	4,049
2	6.6	0.080	0.198	2,500	1,012
3	9.8	0.176	0.435	1,111	450
4	13.1	0.160	0.395	625	253
5	16.4	0.160	0.395	400	162
6	19.7	0.176	0.435	278	113

Methods and Results

The plots were most recently remeasured in fall 2013, 33 growing seasons after planting and 35 years from seed. This report presents results from the 2013 remeasurement, extending information given in the 2009 report. We also provide some comparisons of crown development in relation to spacing and relative density measures, additional to the information in the 2009 report.

Results are given in metric units for consistency with Harrington et al. (2009). We also give equivalent values in English units in parentheses, where this can be done conveniently. Table 7 in the appendix gives spacing means in English units.

Height

Heights and heights to live crown (HLC) were measured on all trees in the 5 m and 6 m spacings. Heights and HLC in other spacings were measured on a sample of trees, usually about 30 to 40 trees per plot distributed to cover the range of diameters, with about two thirds in the upper one-half of the diameter range. Height/diameter equations were fit to the data for each plot and these were used to supply estimated heights for those trees lacking measured heights. Stand height was expressed as top height (H100), defined as the mean height of those Douglas-fir included in the largest (by diameter) 100 trees per hectare (40/ac).

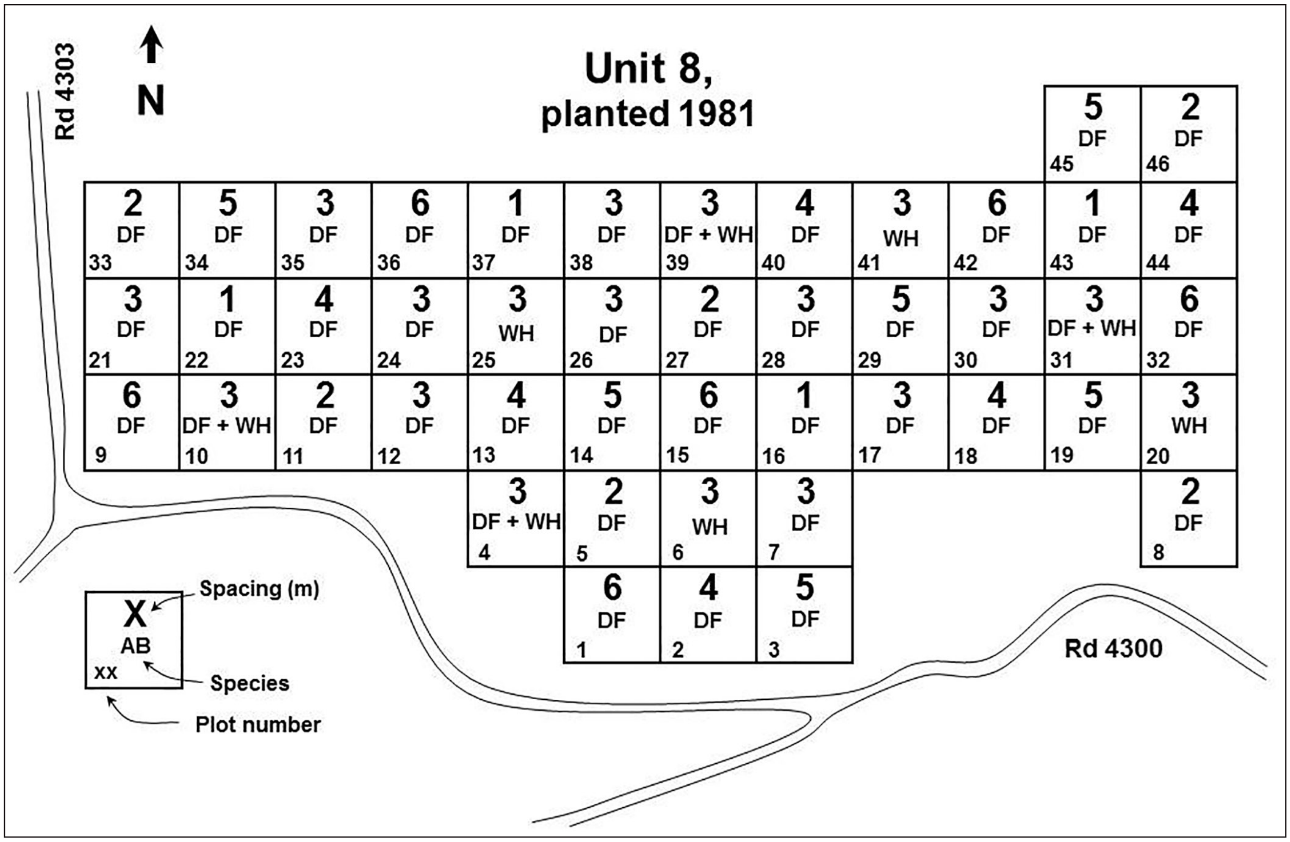

Figure 1—Physical arrangement of plots, with planting spacings.

Mean H100 in 2013 was 22.0 m (72 ft). Figure 2 compares spacing means of H100 and HLC in 2013, ± 1 standard error. Although figure 2 suggests that height growth may have been slightly reduced at the extremes of spacing, there is no clear evidence of an effect of spacing on top height. A regression of form H100 = a + b(spacing) + c(1/spacing) fit to the 38 plot values produced estimates in close agreement with the spacing means, but was not statistically significant ($p = 0.17$); a result consistent with Harrington et al. (2009).

Diameter (D)

Diameters were measured on all trees ≥ 4.0 cm diameter at breast height (dbh), and are here expressed in terms of two summary values. These are (1) D100, mean diameter of the 100 largest trees per hectare, and (2) QMD, the quadratic mean diameter of all live trees of diameter ≥ 4.0 cm (1.6 in). Values of D100 increased from 23.1 cm (9.1 in) in the 1 m spacing to 34.0 cm (13.4 in) in the 6 m spacing. Values of QMD increased from 11.3 cm (4.45 in) in the 1 m spacing to 28.55 cm (11.24 in) in the 6 m spacing. Spacing means ± 1 SE are shown in figure 3. D100 development over time is shown in figure 4, and QMD development over time in figure 5.

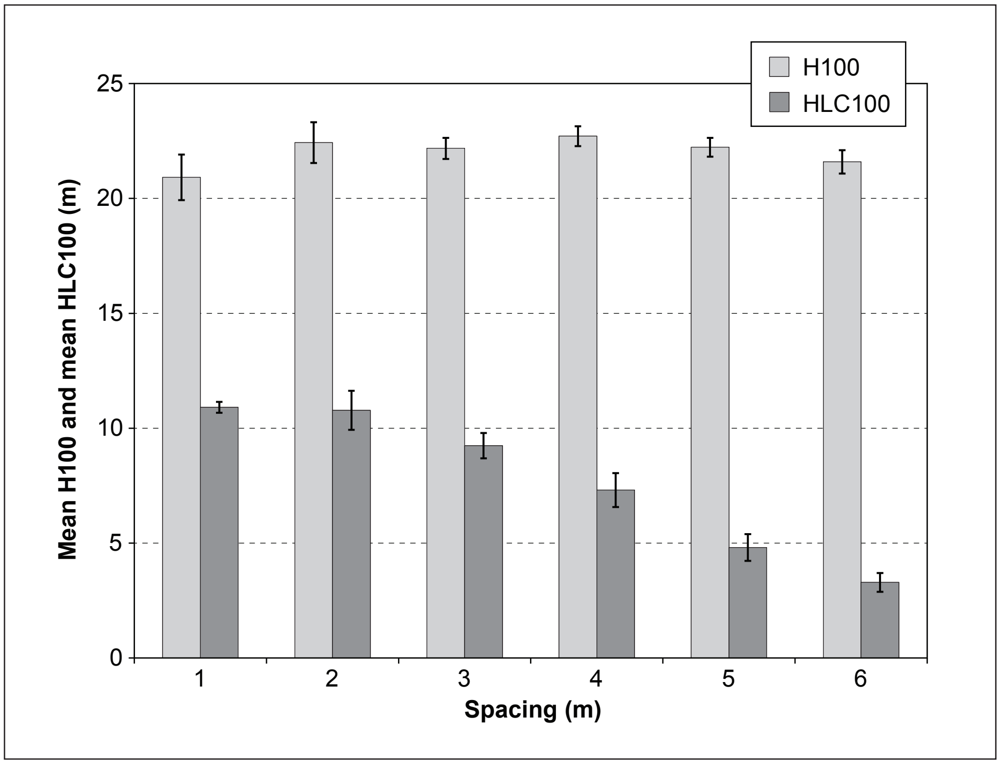

Figure 2—Spacing means of H100 and HLC100 at age 33 years from planting, 35 from seed, ± one standard error.

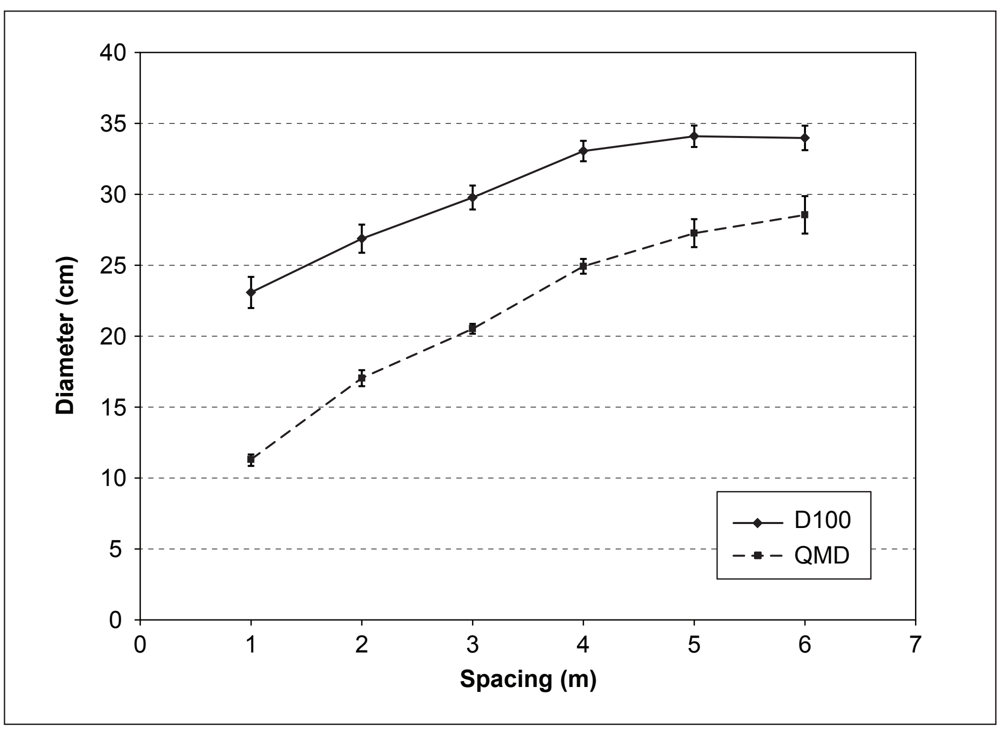

Figure 3—Spacing means of D100 and QMD at 33 years from planting, 35 from seed, ± one standard error.

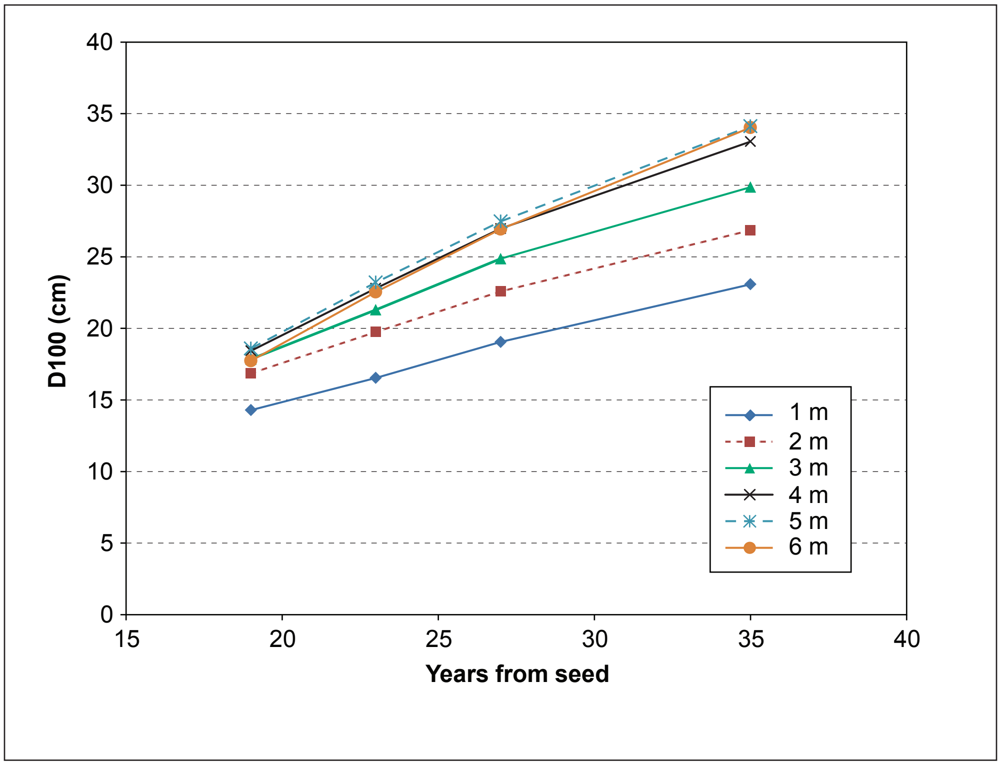

Figure 4—Time trends of D100 by spacing and age from seed.

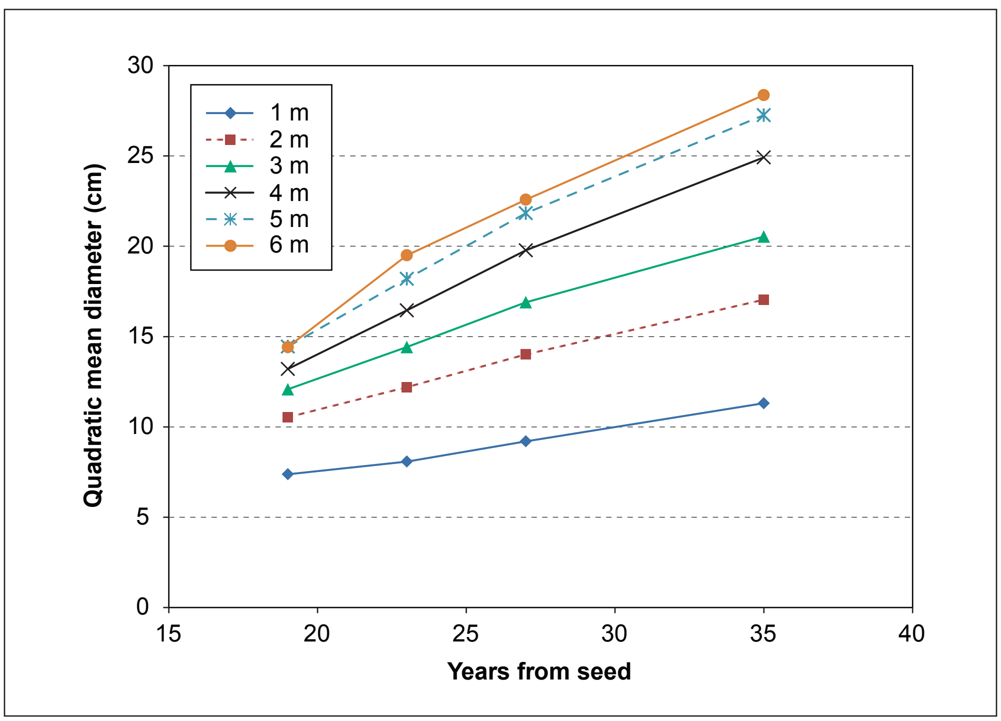

Figure 5—Time trends of QMD by spacing and age from seed.

Number of Trees

Figure 6 compares mean numbers of live trees of diameter 4.0 cm and larger at total age 35, by spacing. These ranged from 4387/ha (1,897/ac) in the 1 m spacing, to 279/ha (113/ac) in the 6 m spacing. Figure 7 shows trends over time in number of live trees. Figure 8 compares survival as a fraction of the number of trees originally planted. As would be expected, mortality has been extreme at the 1 × 1 m spacing, and decreased sharply as spacing increased.

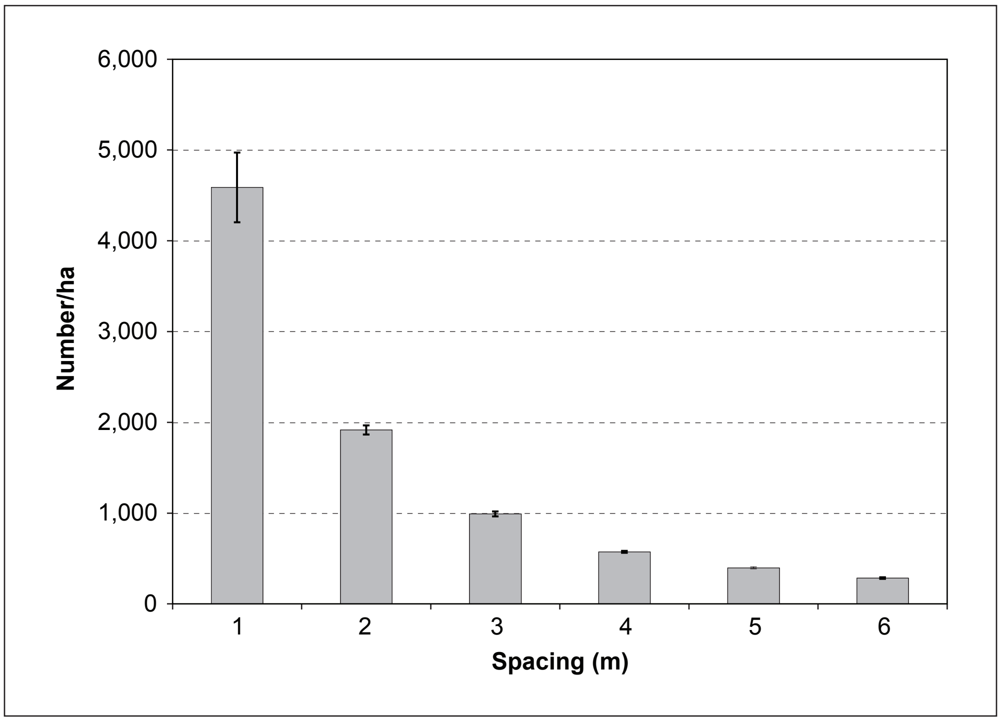

Figure 6—Spacing means of number of live trees ≥ 4 cm, at 33 years from planting, 35 from seed, ± one standard error.

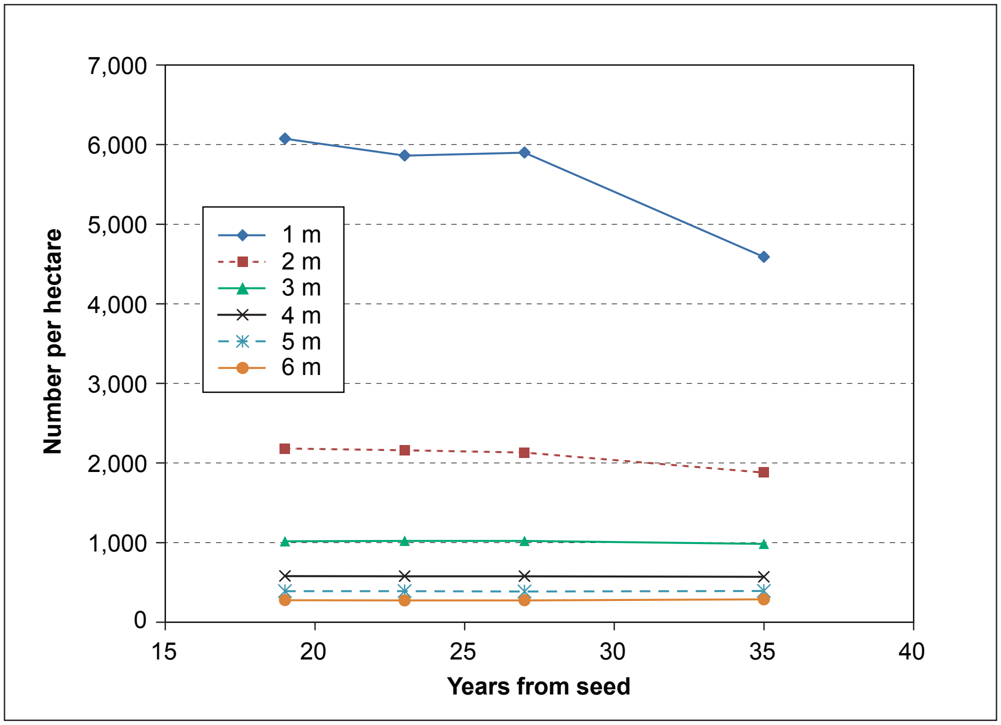

Figure 7—Time trends of number of live trees ≥ 4.0 cm, by spacing and age from seed.

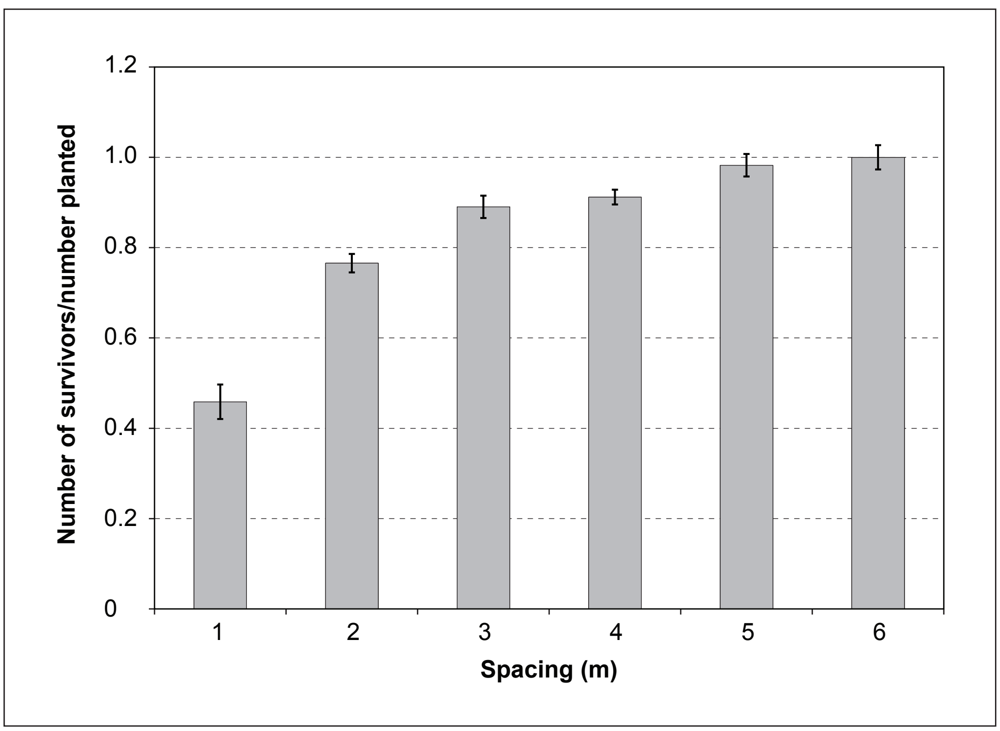

Figure 8—Number of live trees ≥ 4 cm at 33 years from planting, 35 from seed, expressed as a fraction of number planted. Error bars are ± one standard error.

Slenderness Ratio

The ratio Height/Diameter, in which both are in the same units, is related to competition and is sometimes used as an indicator of windfirmness and extent of crown abrasion (Wilson and Oliver 2000). The ratio decreased with increase in spacing as shown below for (1) the 100 largest trees per ha (40 per acre), and (2) all trees ≥ 4 cm.

Spacing	H100/D100	Hqmd/QMD
Meters	*Mean ± one standard error*	
1	90.6 ±2.5	121.9 ± 2.6
2	83.5 ± 2.2	105.7 ± 2.1
3	74.5 ± 0.8	91.0 ± 1.2
4	67.4 ± 1.0	79.0 ± 1.2
5	65.2 ± 0.4	72.8 ± 1.2
6	63.6 ± 0.7	67.4 ± 0.8

Basal Area

Basal area decreased with increased spacing, from 45.6 m^2/ha (199 ft^2/ac) in the 1 m spacing, through 19.2 m^2/ha (84 ft^2/ac) in the 6 m spacing. Means of plot basal areas by spacing at total age 35, ± 1 standard error, are shown in figure 9. Time trends of basal area, by spacing and age from seed, are shown in figure 10.

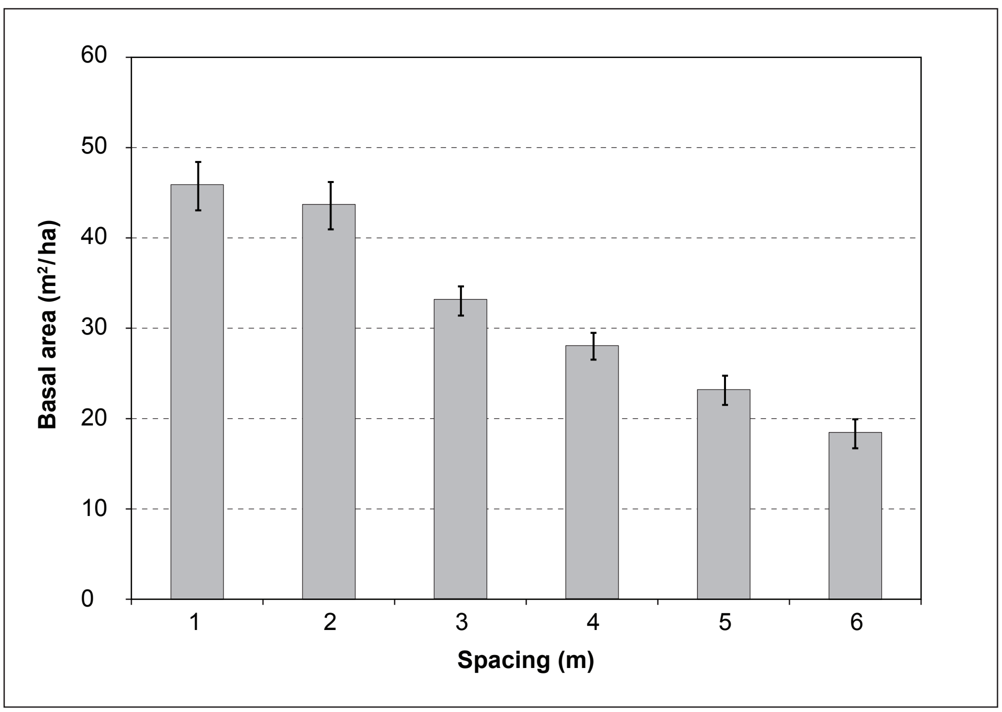

Figure 9—Spacing mean basal areas at age 33 from planting, 35 from seed, ± one standard error.

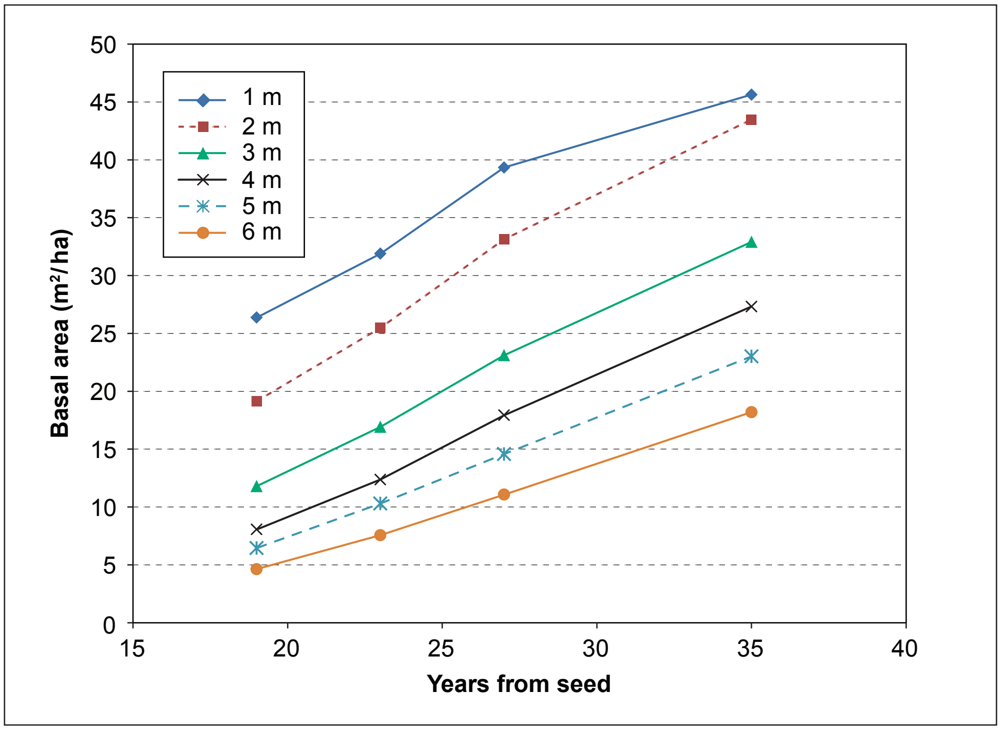

Figure 10—Time trends of spacing mean basal areas, by spacing and age from seed.

Volume

Volumes of stem wood in 2013 were calculated using the Bruce and DeMars (1974) volume equation. Measured heights were used when available; otherwise, heights were estimated using the H/D equations mentioned above. Two cubic volumes per hectare were calculated: (1) CV4, cubic volume of entire stem for trees of diameter ≥ 4.0 cm, and (2) CV20, the corresponding value for trees of diameter ≥ 20.0 cm (~8 in). The latter value was an arbitrary choice, as an approximation to trees that would likely be commercially utilizable. Values of CV4 at total age 35 peaked at 2 m spacing and decreased with increase in spacing, ranging from 301 m^3/ha (4,306 ft^3/ac) in the 1 m spacing, to 342 m^3/ha (4,896 ft^2/ac) in the 2 m spacing, to 140 m^3/ha (2,001 ft^3/ac) in the 6 m spacing (table 2). Maximum CV20 was 211.9 m^3 ha (3,030 ft^3/ac) in the 4 m spacing.

Figure 11 compares the means of the plot estimates of CV4 and CV20 at total age 35, by spacing, with their associated standard errors. Time trends of CV4 are shown in figure 12, by spacing and age from seed.

Table 2—Cubic volumes at 27 and 35 years from seed, in trees ≥ 4 cm

Spacing	Spacing	2005	2013	PAI[a]	PAI[a]
Meters	*Feet*	*Cubic meters/ hectare*	*Cubic meters/ hectare*	*Cubic meters/ hectare/year*	*Cubic feet/ acre/year*
1	3.28	215.4	301.1	10.71	153
2	6.56	215.1	342.4	15.91	228
3	9.84	148.6	265.1	14.56	286
4	13.12	113.3	228.6	14.41	206
5	16.40	92.4	182.9	11.31	162
6	19.68	62.0	139.9	9.74	139

[a] Periodic annual increment.

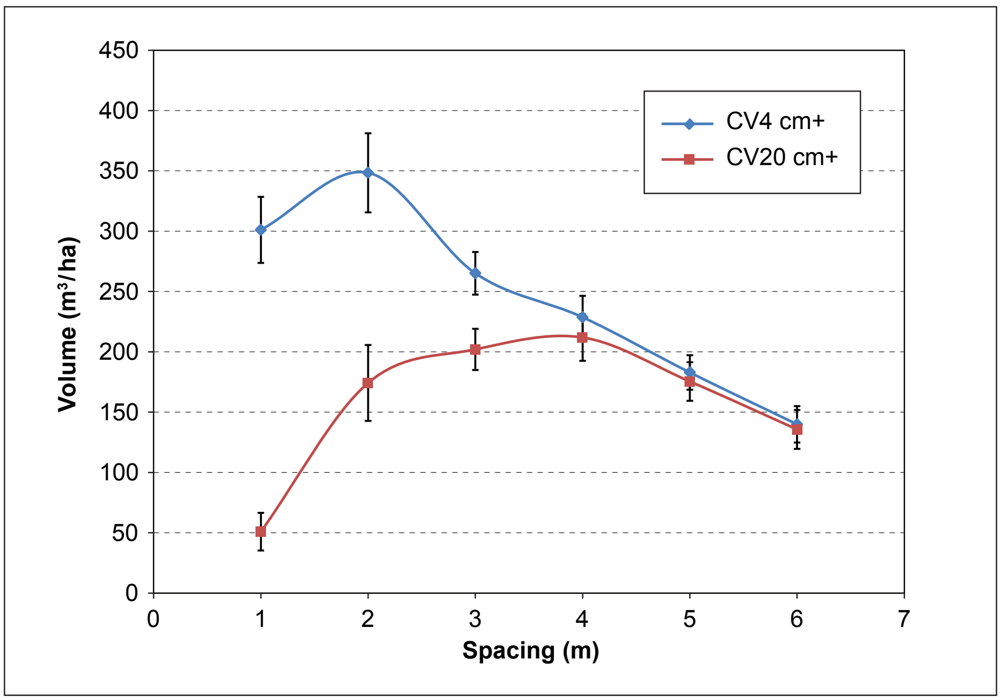

Figure 11—Means of cubic meters per hectare of trees with diameters ≥ 4cm (CV4) and ≥ 20 cm (CV20) at 33 years from planting, 35 from seed, by spacing. ± one standard error.

SDIsum

This variable, defined as SDIsum = $\sum(d_i/25.4)^{1.6}$/area, is the SDI* of Long and Daniel (1990) and SDIsum of Curtis (2010), converted to metric units. It is one of several expressions of relative stand density that are essentially the same except for scale factors.

Spacing mean values of SDIsum ± 1 standard error at total age 35 are shown in figure 13. As would be expected, they form a relatively smooth trend of SDIsum decreasing with increasing spacing.

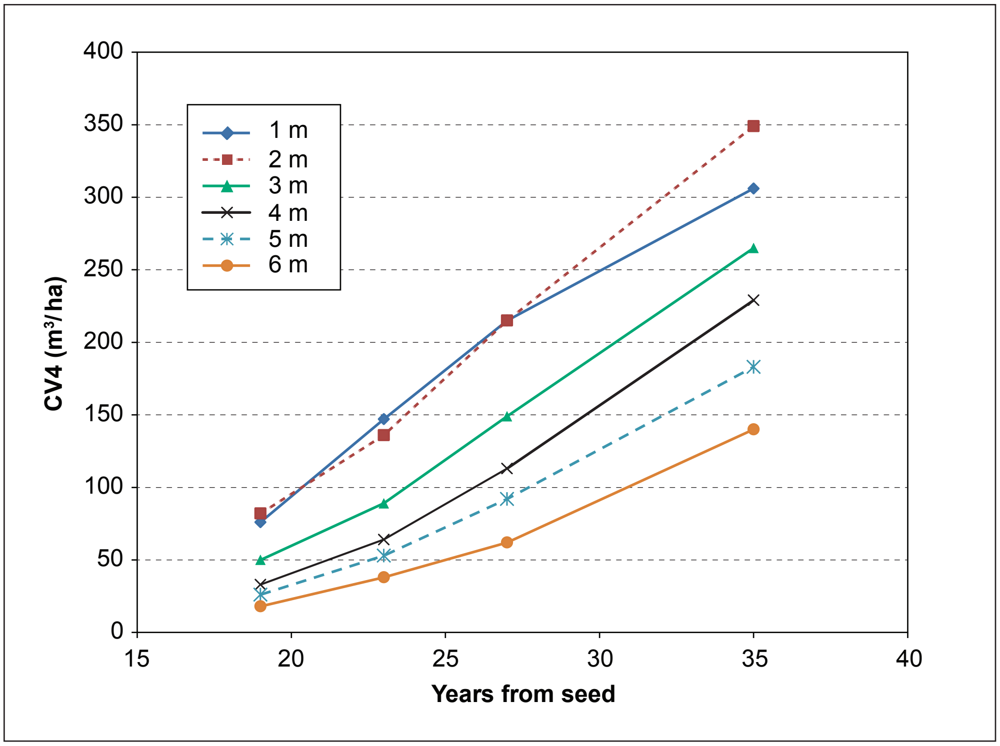

Figure 12—Time trends of cubic volume per hectare of trees with diameters ≥ 4 cm (CV4), by spacing and age from seed.

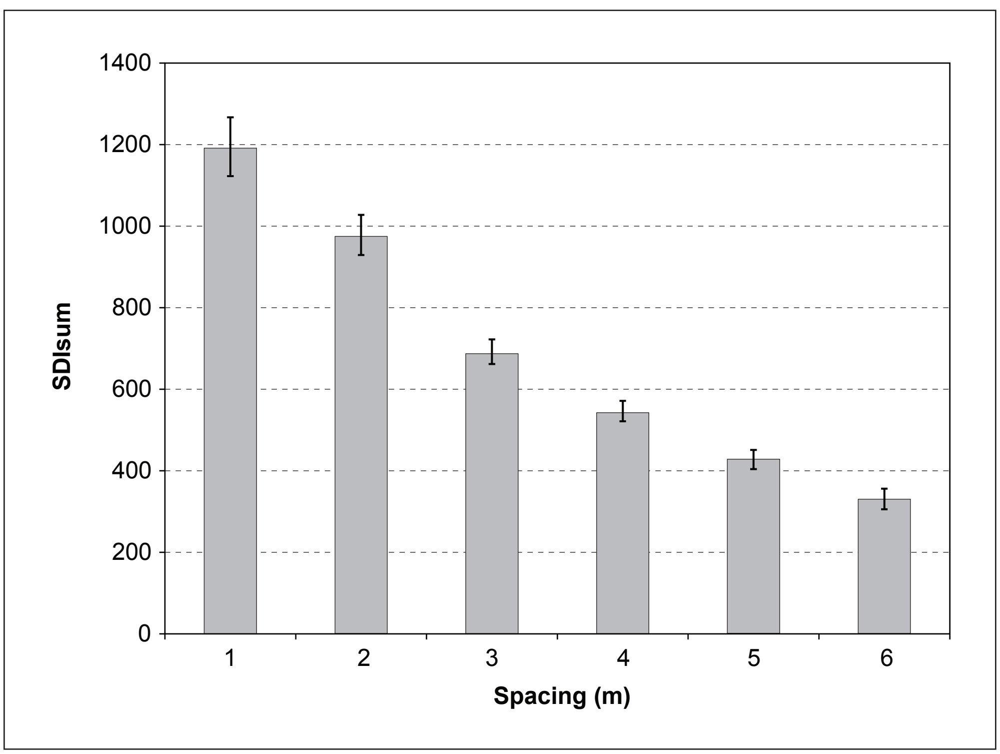

Figure 13—Spacing means of SDIsum at 33 years from planting, 35 from seed, ± one standard error.

Live Crown Ratio (LCR)

Height to live crown was measured on all trees measured for total height. Live crown ratio was calculated as:

$$LCR = (\text{tree height} - \text{height to live crown}) / \text{tree height}$$

Regressions $LCR = a + bD + cD^2 + d/D$ were fit, separately for each plot, retaining only significant terms. These regressions were then used to estimate two values used to characterize each plot, (1) LCR100, the live crown ratio corresponding to the value of D100, and (2) LCRqmd, the live crown ratio corresponding to the plot quadratic mean diameter. Figure 14 compares these values at total age 35, by spacing. As expected, the difference between LCR100 and LCRqmd decreases as spacing increases, and both increase as spacing increases. Figure 15 shows trends over time by spacing and age from seed. Figure 16 shows the trend of LCR100 in relation to SDIsum at the 2013 measurement.

Crown Width (CW)

Crown widths were measured on a much smaller subsample of trees, frequently 8 to 12 trees per plot but sometimes much less.

Crown width was calculated as the mean of two crown diameter measurements taken at right angles, to the outermost branch tip. Per plot sample sizes were often very small, particularly in the 1 m and 2 m spacings. Therefore, one regression of crown width on tree diameter was fit to pooled measurements from all plots at a given spacing, using the best subset from $CW = a + bD + cD^2 + d/D$. Similar computations were made for the 1997, 2001 and 2005 measurements. Estimated 2013 crown widths corresponding to the spacing quadratic mean diameter are shown in table 3.

Table 3—Estimated crown widths corresponding to quadratic mean diameter of trees ≥ 4.0 cm at 35 years from seed

Spacing	QMD	Estimated CW	QMD	Estimated CW
Meters	*Centimeters*	*Meters*	*Inches*	*Feet*
1	11.31	2.48	4.45	8.1
2	17.04	3.86	6.71	12.7
3	20.52	4.33	8.09	14.2
4	24.92	5.27	9.81	17.3
5	27.26	5.60	10.73	18.4
6	28.35	5.77	11.16	18.9

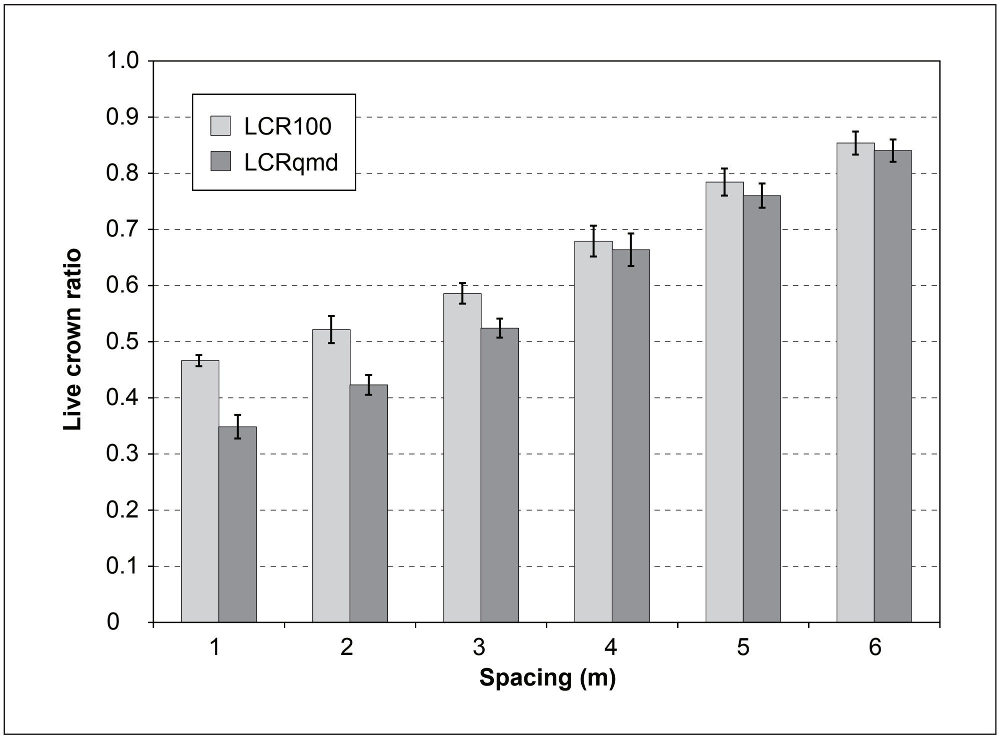

Figure 14—Spacing live crown ratios corresponding to (1) D100, and (2) QMD, at 33 years from planting, 35 from seed, ± one standard error.

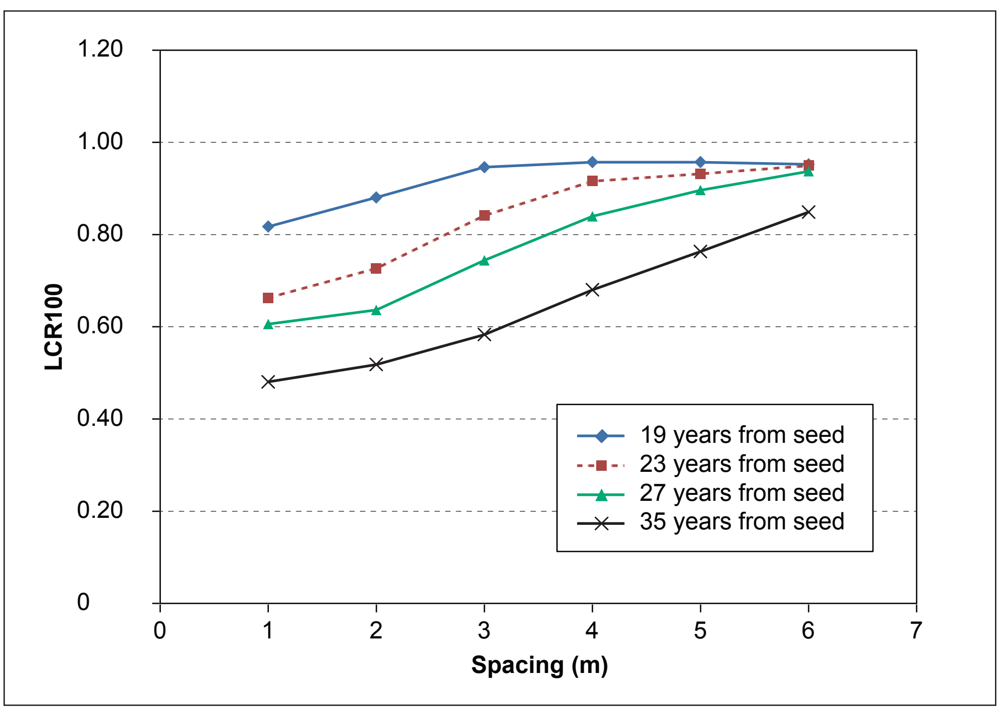

Figure 15—Time trends of LCR100 over spacing.

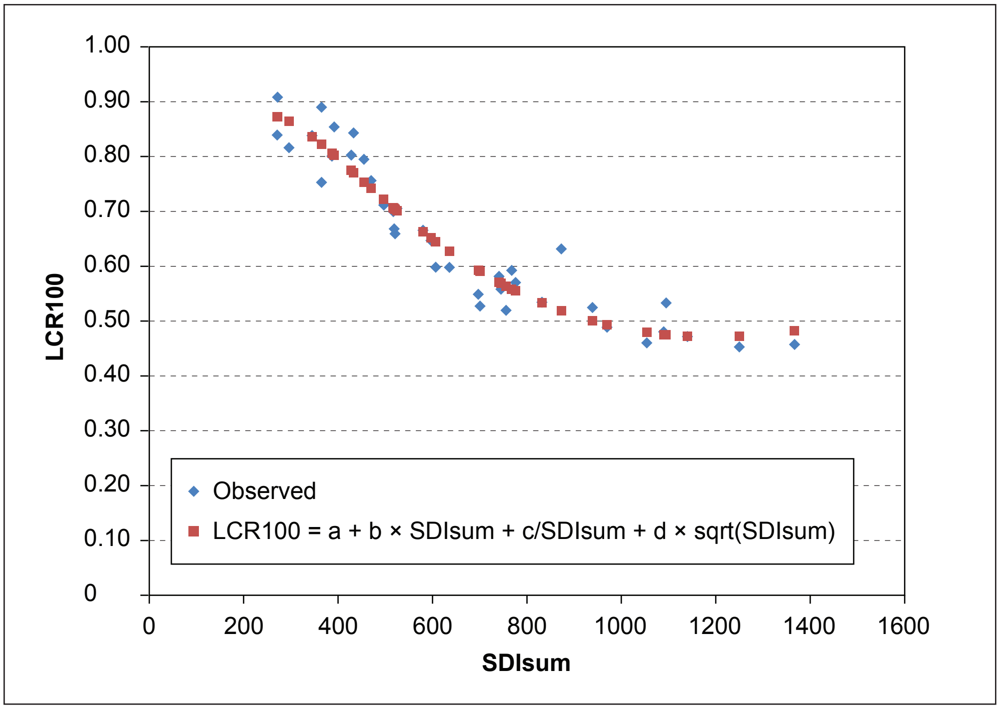

Figure 16—Trend of LCR100 in relation to SDIsum, at 33 years from planting, 35 from seed, with fitted regression curve.

Crown Area (CA)

Crown projectional area was calculated for each tree, as CA = 0.7854 $(CW)^2$, using measured CW when available, otherwise estimates from the CW = f(D) regressions. Estimated crown areas were summed over all trees on a plot and divided by ground area of the plot, to provide plot estimates of ∑CA/ha. Means of the resulting values are shown in table 4 for each spacing, together with the corresponding spacing means of SDIsum, RDsum, and number of trees ≥ 4 cm per ha.

Table 4—Spacing means at age 35 from seed, ± 1 SE

Spacing	∑CA/area	SDIsum[a]	RDsum[a]	RDqmd[a]	Trees[a]	DIsum[b]	RDsum[b]	RDqmd[b]	Trees[b]
Meters		*- - - - - - - - - - - - - Per hectare - - - - - - - - - - - - -*				*- - - - - - - - - - Per acre - - - - - - - - - -*			
1	2.15 ± 0.10	1191 ± 72	12.89 ± 0.79	13.6 ± 0.78	4588 ± 383	482	89.6	94.3	1857
2	2.10 ± 0.11	973 ± 49	10.10 ± 0.47	10.4 ± 0.50	1900 ± 51	394	70.1	73.2	769
3	1.33 ± 0.05	687 ± 30	7.01 ± 0.30	7.2 ± 0.37	983 ± 27	278	48.7	50.5	398
4	1.18 ± 0.04	543 ± 25	5.45 ± 0.24	5.6 ± 0.25	570 ± 10	220	37.9	38.8	231
5	0.92 ± 0.02	432 ± 24	4.19 ± 0.24	4.4 ± 0.23	393 ± 10	175	29.1	30.6	175
6	0.74 ± 0.05	336 ± 25	3.26 ± 0.24	3.3 ± 0.23	286 ± 9	136	22.7	23.2	136

[a] Metric units.
[b] English units

Discussion

Relative Stand Density

In this report, we have used SDIsum ($=\sum(d_i/25.4)^{1.6}/\text{ha}$) as the measure of relative stand density. This is the metric equivalent of the SDI* of Long and Daniel (1990) and the SDIsum of Curtis (2010), and was an arbitrary choice among several very similar measures.

Two relative density measures in common use in the Douglas-fir region are Reineke SDI (Reineke 1933) and Curtis RD ($=\text{basal area}/(\text{QMD})^{0.5}$; Curtis 1982), here symbolized as SDIqmd and RDqmd. Their computation involves QMD, which is strongly influenced by departures from the more or less symmetrical diameter distribution of truly even-aged stands, particularly skewed distributions arising from the presence of small trees of a younger age class. There are a number of closely related relative density measures that do not involve the calculation of QMD and are less influenced by skewed diameter distributions.

In the following discussion, we use the term “relative density” to denote a class of very closely related measures that do not use QMD and are nearly equivalent. These include SDIsum (used here), RDsum (Curtis 2010), and Tree-Area-Ratio (Curtis 1971). Algebraic manipulation of the basic formulas shows that all three of these can be expressed in the form “$a[\sum d^c/\text{area}]$”, where “a” is a factor specific to the relative density measure and measurement system (metric vs. English), and the exponent “c” has value 1.6 for SDIsum, 1.5 for RDsum, and 1.55 in Curtis TAR. Values of these measures are very highly correlated in these data (table 5). They are nearly proportional and aside from proportionality factors, differ only by small differences in the exponent of diameter. Any of these measures would have given results very similar to those shown here. We have included RDsum and RDqmd in table 5 because RDqmd is a widely used measure in the Douglas-fir region. RDsum = 0.01039 × SDIsum is a close approximation over the range of the present data.

Table 5— Correlation coefficients (r) among some relative density values calculated from the 2013 measurements

	SDIqmd	RDsum	RDqmd
SDIsum	0.9989	0.9987	0.9977
SDIqmd		0.9990	0.9984
RDsum			0.9996

In this even-aged plantation, SDIsum values were, as expected, close to those for Reineke SDI, being about 3 percent lower in 2013. Likewise, there is little difference at present between RDsum and RDqmd. However, the widest spacings are beginning to develop a naturally established understory, and they will soon contain many trees greater than the 4.0 cm lower measurement limit used here. Inclusion of these will in the near future materially affect the diameter distributions and QMD. Therefore, it seemed preferable to use one of the summation forms above rather than one that is dependent on QMD, even though there is little difference at this point in time.

Maximum Relative Density

It is generally considered that an upper limit of SDI (or other relative density measure) exists and is characteristic of a species. Reineke (1933) estimated maximum SDI as SDIqmd = 595 (1470 in metric units) for Douglas-fir.

In the 2013 data, the highest values observed on any individual plot (plot 37) were SDIsum = 1367 and SDIqmd = 1421. Among spacing means, maxima were SDIsum = 1191 and SDIqmd = 1245 in the 1 × 1 m spacing. Similarly, RD maxima among spacing means were RDsum = 12.89 and RDqmd = 13.58 in the 1 × 1 m spacing. These values (table 4) are broadly consistent with maximum density estimates from other sources.

Because the maximum is not a precisely determined value, we have preferred to use the calculated values of SDIsum in our comparisons, rather than expressing stocking as a percentage of a maximum which itself is only an approximation.

Volume

Figure 11 shows that in 2013, volume in trees ≥4.0 cm peaked at 2 m spacing, and that in trees ≥20 cm at about 4 m spacing. Harrington et al. (2009) concluded that the 10-ft spacing (~3 m) in common use is near optimal. This may change if stands are allowed to develop further without thinning. The CV20 curve is expected to approach the CV4 curve over time, and conclusions about the "optimal" spacing may well change with advancing age. If stands were allowed to grow for a substantial additional period without thinning, it seems likely that 4 m (~13 ft) or greater spacing would become superior.

Live Crown Ratio (LCR) and Height to Live Crown (HLC)

For each measurement on each plot, live crown ratio was regressed on D. The resulting equations were then entered with D100 and QMD to produce estimates of corresponding live crown ratios by spacing. Estimates for the 2013 measurement (total age 35) are compared in figure 14. Corresponding estimates of HLC100 [= H100 – (LCR × H100)] are shown in figure 2. As would be expected, values are strongly related to initial spacing. Differences between LCR100 and LCRqmd are greatest in the 1 × 1 m spacing, and decrease as spacing increases.

Figure 15 shows LCR100 trends over time and spacing.

There are strong relationships at the 2013 measurement between LCR100 and SDIsum (fig. 16), and between LCRqmd and SDIsum. There are similar relationships of LCR100 and LCRqmd with basal area. These can be described by regressions of the form:

$$LCR = a + bX + c/X + dX^{0.5}$$

Fit statistics for the above regression (table 6) suggest that SDIsum may be a slightly better predictor than basal area, although differences are small.

Table 6— Fit statistics for some alternative Live Crown Ratio equations, 2013 data

Equation form	RSME[a]	Adjusted RSQ
$LCR100 = a + bSDIsm + c/SDIsum + d(SDI)^{0.5}$	0.0413	0.9116
$LCR100 = a + bBA + c/BA + d(BA)^{0.5}$	0.0467	0.8866
$LCRqmd = a + bSDIsum + c/SDIsum + d(SDI)^{0.5}$	0.0397	0.9467
$LCRqmd = a + bBA + c/BA + d(BA)^{0.5}$	0.0544	0.9010

[a] Root mean square error.

Figure 17 shows trends of LCR100 in relation to time and SDIsum. The pattern for LCRqmd is similar. Values for the 1 m spacing are very different from the others, and those for the 2 m spacing somewhat so. These differences probably reflect difficulty in identifying and measuring height to sparse live crowns in very dense stands, in addition to density effects. If we consider only spacings of 3 m and greater, the time trends suggest that SDIsum (or equivalent relative density measure) should be a good predictor of live crown ratio.

Figure 18 is a similar plot of LCR100 in relation to time and basal area. Compared to figure 17, this appears to show a slight superiority of basal area over SDIsum as a predictor.

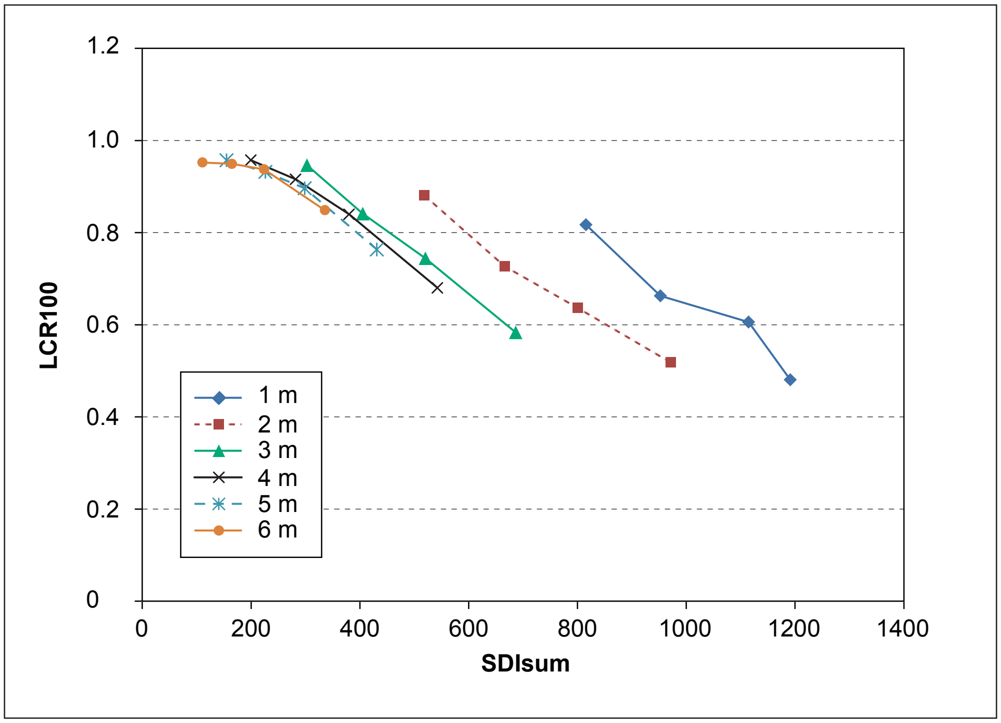

Figure 17—Time trends of LCR100 in relation to spacing and mean values of SDIsum at each measurement. Ages 17, 21, 27 and 35 years from seed.

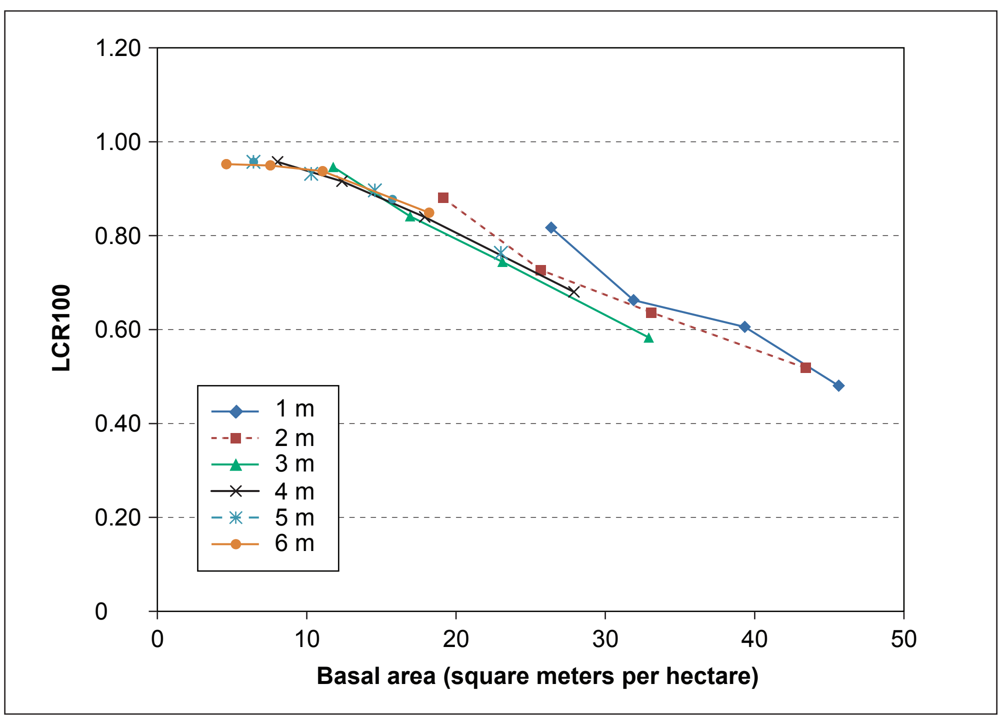

Figure 18—Time trends of LCR100 in relation to spacing and mean values of basal area at each measurement. Ages 17, 21, 27 and 35 years from seed.

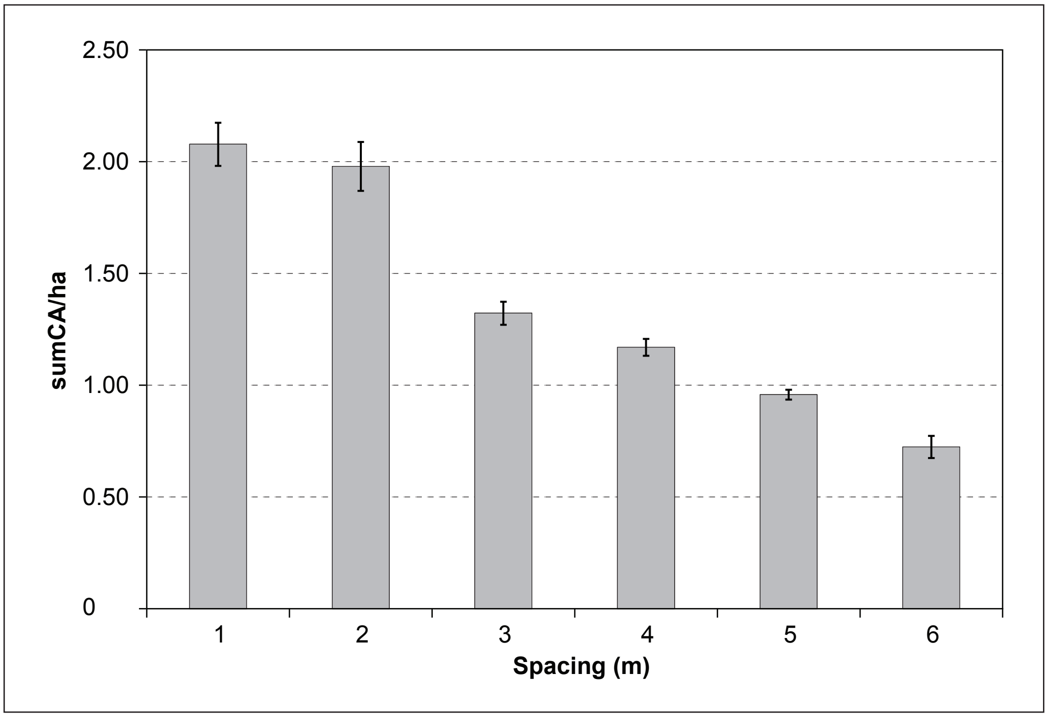

Figure 19—Spacing means of estimated ∑CA/ are, at 33 years from planting, 35 from seed, ± one standard error.

Crown Width and Crown Projectional Area

Table 4 and figure 19 show that variability in plot estimates of ∑CA/ha is greater in the 1 m and 2 m spacings than in other spacing. This reflects the greater mortality at these spacings as well as probable greater relative errors in measurement. They also show that the estimated spacing sums of crown projectional area are more than twice the corresponding ground areas for the 1 m and 2 m spacings. Such values are not plausible. We think these very high estimates are the combined result of several factors, including: (1) measurement of CW to the tip of the longest live branch, which probably overestimates effective CW and CA, (2) intermingling of branches at very close spacing, which makes it difficult to identify and measure to the margins of crowns, and (3) the fact that a given absolute error in determining crown width results in a relative error in estimated crown projectional area that is much larger for small narrow-crowned trees than for larger wide-crowned trees.

We note that Gill et al. (2000) used a somewhat similar summation of estimated crown areas procedure to obtain apparently reasonable crown cover estimates. However, their procedure differed in that they measured crown radii to the estimated intersection of adjacent overlapping crowns rather than to the tip of the longest branch. This difference would give substantially lower estimates of ∑CA.

We also note that Reukema and Smith (1987) found average crown widths considerably greater than the average distance between trees in plots planted to 0.9 m and 1.8 m spacing. Presumably this also can be attributed to a combination of actual crown overlap and error arising from the difficulty of defining and measuring crown margins in very dense stands of small-crowned trees.

Others have encountered similarly unreasonable estimates. Crookston and Stage (1999) provided a method for adjusting for crown overlap. Their equation is:

$$\% \text{ crown cover} = 100[1 - \exp(-0.01\ C')],$$

where C' is ∑(crown area calculated from crown width)/ground area. They assumed random spatial distribution, whereas our data had a uniform spatial distribution and would therefore be expected to have less crown overlap. We reasoned that there should be little overlap at the widest spacing (6 m), and therefore modified the coefficient in their equation from 0.01 to 0.018, which causes the estimate to coincide with the mean of the 6 m spacing. Figure 20 compares the result with values predicted by the unmodified equation; the modified estimates appear much more reasonable.

If the unmodified values for the 1 m and 2 m spacings are omitted, the other values fall in a well-defined line with relatively little scatter (fig. 21). These indicate that with near-uniform plantation spacing, full crown closure, 1.0, occurs at about SDIsum = 400, which is about one-third of maximum SDIsum. Similarly, closure is at about RDsum = 4, which again is about one-third of the possible maximum. The scatter of points is considerably less than in a plot of ∑CA/(plot area) over initial spacing.

Figure 22 is a plot of the time trends of means of ∑CA/(plot area), by spacing, over spacing means of SDIsum. Figure 23 is a similar plot over spacing means of basal area. (The 1 m spacing is omitted because of the very erratic trends associated with mortality and the difficulties with crown measurements noted above.) The figures suggest that SDIsum is a better predictor of ∑CA/plot area than is basal area in this unthinned plantation, contrary to the result of the comparison of LCR100 in figures 17 and 18. If we include all spacings, the simple correlation between spacing means of ∑CA/plot area and corresponding means of SDIsum is $r = 0.95$, vs. 0.85 for that with mean basal areas. If the 1 m spacing is excluded, these values become $r = 0.98$ vs. 0.94.

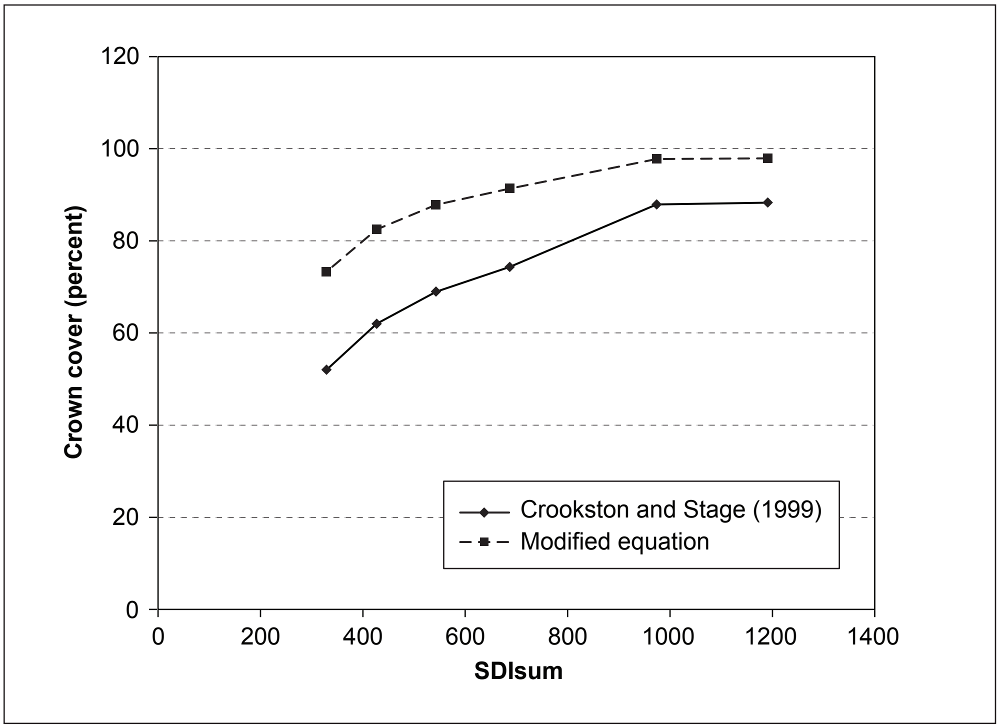

Figure 20—Crown cover estimates from (1) equation 2 in Crookston and Stage (1999) and (2) from equation modified to coincide with sum of calculated crown areas per unit area in the 6 m spacing, plotted over spacing means of SDIsum.

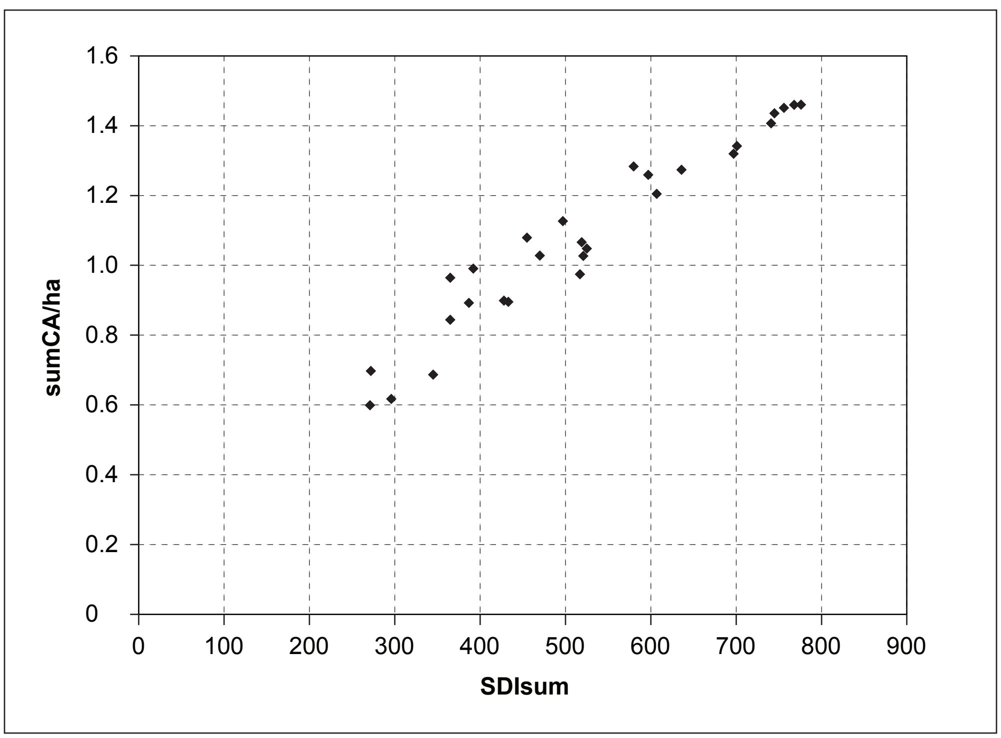

Figure 21—Individual plot estimates of ∑CA/ area, in relation to plot SDIsum, 33 years from planting, 35 from seed; 1 m and 2 m spacings omitted.

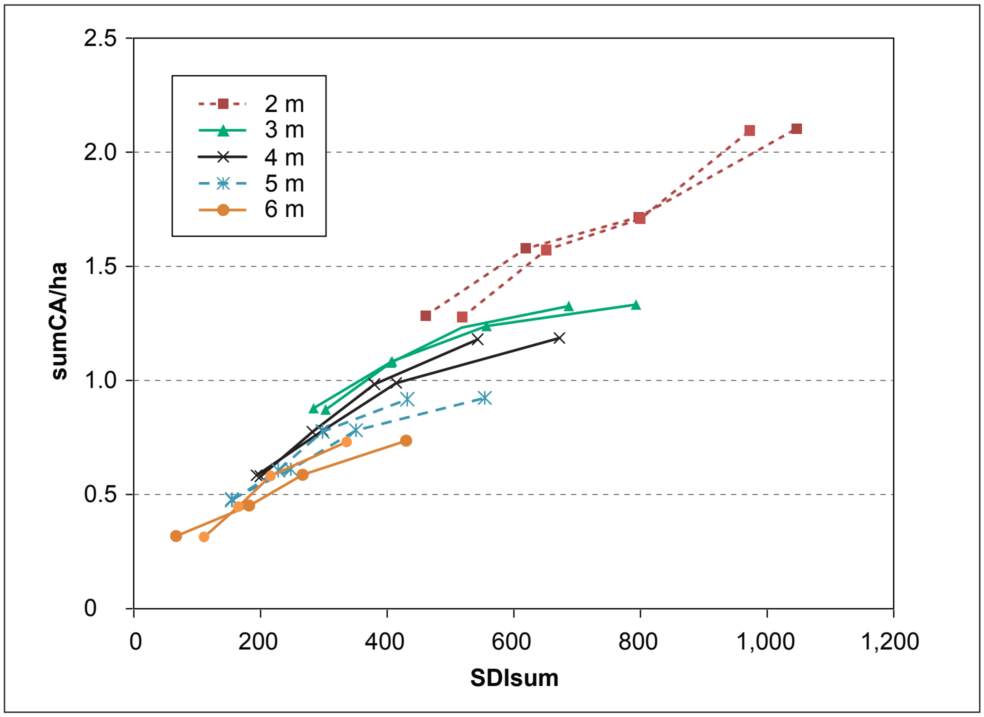

Figure 22—Time trends of spacing means of estimated ∑CA/ area in relation to corresponding means of SDIsum; 17, 21, 25, and 35 years from seed.

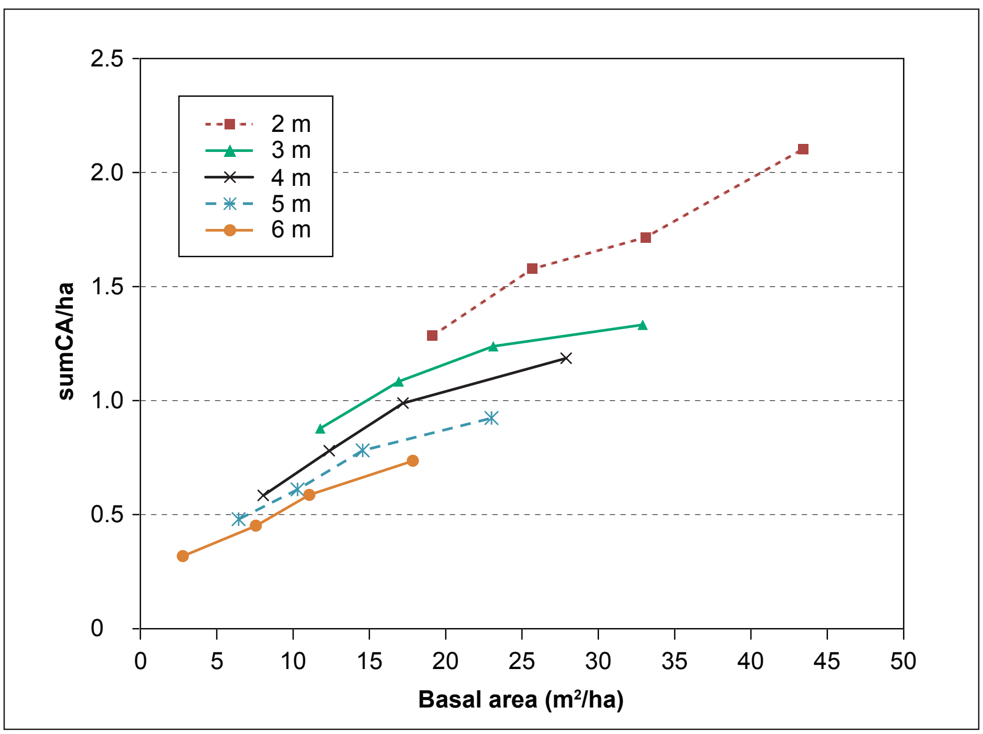

Figure 23—Time trends of spacing means of estimated ∑CA/ area in relation to corresponding mean basal areas; 19, 23, 27, and 35 years from seed.

Conclusion

Strong points of this study are excellent plot replication within the study area and reliable measurements, except that the crown width samples are undesirably small. Otherwise, the main limitation of the study is simply that it is confined to a single physical location, which limits generalization of results. The data should be very useful in future growth modelling efforts when combined with data from other past and ongoing spacing studies.

This report was motivated in part by the need to update the information given by Harrington et al. (2009), with the additional 8 years of observation. There are no surprises in the usual stand statistics, which follow trends that are generally consistent with observations from other spacing trials.

Motivation for analysis of the crown development data arose in part from interest in relative density measures as possible estimators of crown cover and shading, particularly in relation to forest practice rules governing treatment of stands in riparian zones. In Washington, Oregon, and Idaho, the existing rules specify acceptable stocking in terms of basal area.

It is here shown that for a range of initial planting spacing on the experimental area, live crown ratio is also related to SDIsum (and consequently, to the other closely related relative density measures), although differences from the corresponding and slightly closer relationship with basal area are small. Estimates of $\sum$CA are also related to relative density, and in these data have a somewhat closer relationship with SDsum than with basal area.

Relative density measures can be useful estimators of average crown characteristics and shading (e.g. Teply et al. 2014), and are more readily obtained than direct measurements of crown cover. They have a potential advantage over basal area in that—unlike basal area—they are not inherently related to average tree size or to site and age (Jack and Long 1996; Long 1985; Reineke 1933). Hence, their use would not require an estimate of site index or site class.

Differences in predictive ability of basal area vs. relative density in this study are small, because both are age-related and no site difference is present. Results in this study are suggestive, but the hypothesis that relative density measures can provide better estimates of crown cover than basal area cannot be confirmed or refuted on the basis of this study, because the data represent only one site and stand structure (pure plantation), and the same very limited range in age. It is highly desirable that the relationships discussed here be examined in other data including a range in site quality and age.

Crown width samples in any future work should be considerably larger than in the 2013 measurement in this study. Crown cover estimates from large-scale aerial photos or LiDAR imaging may be a better alternative, if these can be paired with concurrent ground-based basal area and relative density estimates at the same locations.

English Equivalents

1 centimeter = 0.3937 inch
1 meter = 3.2808 feet
1 square meter = 10.76 square feet
1 hectare = 2.47 acres
1 square meter per hectare = 4.36 square feet/acre
1 cubic meter per hectare = 14.3 cubic feet/acre
SDIsum in metric units = 2.47 × SDIsum in English units
RDqmd in metric units = RDqmd in English units/6.9487

References

Bruce, D.; DeMars, D.J. 1974. Volume equations for second-growth Douglas-fir. Res. Note PNW-239. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 5 p.

Crookston, N.L.; Stage, A.R. 1999. Percent canopy cover and stand structure statistics from the Forest Vegetation Simulator. Gen. Tech. Rep. RMRS-GTR-24. U. S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 11 p.

Curtis, R.O. 1971. A tree area power function and related stand density measures for Douglas-fir. Forest Science. 17(2): 146–159.

Curtis, R.O. 1982. A simple index of stand density for Douglas-fir. Forest Science. 28: 92–94.

Curtis, R.O. 2010. Effect of diameter limits and stand structure on relative density indices: a case study. Western Journal of Applied Forestry. 25(4): 169–175.

Franklin, J.F.; Dyrness, C.T. 1973. Natural vegetation of Oregon and Washington. Gen. Tech. Rep. PNW-8. Portland, OR: U. S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 417 p.

Gill, S.J.; Biging. G.S.; Murphy, E.C. 2000. Modeling conifer tree crown radius and estimating canopy cover. Forest Ecology and Management. 126: 405–416.

Harrington, T. B.; Harrington, C.A.; DeBell, D.S. 2009. Effects of planting spacing and site quality on 25-year growth and mortality relationships of Douglas-fir (*Pseudotsuga menziesii* var. *menziesii.* Forest Ecology and Management. 258(10): 18–25.

King, J.E. 1966. Site index curves for Douglas-fir in the Pacific Northwest. For. Pap. 8. Centralia, WA: Weyerhauser Forestry Research Center. 49 p.

Jack, S.B.; Long, J.N. 1996. Linkages between silviculture and ecology: an analysis of density management diagrams. Forest Ecology and Management. 86: 205–220.

Long, J.N. 1985. A practical approach to density management. Forestry Chronicle. 61(1): 23–27.

Long, J.N.; Daniel, T.W. 1990. Assessment of growing stock in uneven-aged stands. Western Journal of Applied Forestry. 5(3): 93–96.

Miller, R.E.; Reukema, D.L.; Anderson, H.W. 2004. Tree growth and soil relations at the 1925 Wind River spacing test in coast Douglas-fir. Res. Pap. PNW-RP-558. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 41 p.

Reineke, L.H. 1933. Perfecting a stand-density index for even-aged forests. Journal of Agricultural Research. 46: 627–638.

Reukema, D.L. 1978. Fifty-year development of Douglas-fir stands planted at various spacings. Res. Pap. PNW-253. Portland, OR: U. S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland. 21 p.

Reukema, D.L.; Smith, J.H.G. 1987. Development over 25 years of Douglas-fir, western hemlock, and western redcedar planted at various spacings on a very good site in British Columbia. Res. Pap. PNW-RP-381. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 46 p.

Teply, M.; McGreer, D.; Ceder, K. 2014. Using simulation models to develop riparian buffer strip prescriptions. Journal of Forestry 112(3): 302–311.

Wilson, J.S.: Oliver, C.D. 2000. Stability and density management in Douglas-fir plantations. Canadian Journal of Forest Research. 30: 910–920.

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Glossary of Symbols and Acronyms

CV4 = cubic volume in trees of D $\geq$ 4 cm.

CV20 = cubic volume in trees of D $\geq$ 20 cm.

D = dbh = diameter at breast height.

D100 = mean diameter of the 100 largest (by diameter) trees per hectare.

d_i = dbh of an individual tree “i”.

H100 = mean height of the 100 largest (by diameter) trees per hectare.

HLC = height to base of live crown.

Hqmd = height corresponding to quadratic mean diameter.

LCR = live crown ratio.

LCR100 = mean LCR of the 100 largest (by diameter) trees per hectare.

LCRqmd = LCR corresponding to the quadratic mean diameter.

N = number of trees per unit area.

QMD = quadratic mean diameter.

RDqmd = (Basal area)/sqrt(QMD).

RDsum (in metric units) = (0.00007854) × $\sum d_i^{3/2}$ / area.

SE = standard error of the mean.

SDIqmd = Reineke stand density index, calculated from QMD and number of trees.

SDIsum = $\sum(di/25.4)^{1.6}$ / area.

Appendix

Table 7—Spacing means at 2013 remeasurement, 33 years from planting, in English units

Spacing	H100	D100	QMD[a]	Number[a]	Basal area[a]	Volume CV4[a]	Volume CV20[b]
Meters (Feet)	*Feet*	*Inches*	*Inches*	*N/acre*	*Square feet/acre*	*Cubic feet/acre*	*Cubic feet/acre*
1 (3.3)	68.6	9.1	4.4	1,855	199	4,306	728
2 (6.6	73.6	10.6	6.7	775	190	4,982	2491
3 (9.8)	72.8	11.8	7.4	400	144	3,791	2,889
4 (13.1)	74.5	13.2	9.8	231	122	3,270	3,030
5 (16.4)	72.9	13.4	10.7	159	100	2,615	2,508
6 (19.7)	70.8	13.4	11.2	113	80	2,001	1,940

[a] Trees ≥ 1.6 in.
[b] Trees ≥ 7.9 in.

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