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ABSTRACT

Individual tree and stand characteristics were determined in a 27-year-old plantation of Sitka spruce (*Picea sitchensis* [Bong.] Carr.) near Terrace, B.C. Planting densities ranged from 478 to 2990 stems per hectare. Three stand components were examined: all stems per hectare, the largest 25% diameter at breast height outside bark (dbhob) stems per hectare, and the largest 250 dbhob stems per hectare. Wider espacements produced trees with larger diameters, crowns, and branches after 27 years. Total volume per hectare was greatest in the closest espacement when all trees were considered, although this relationship reversed when only the largest 250 stems per hectare were examined. The results of this experiment suggest there is considerable flexibility in choosing an optimum stocking level, and a range of 800 to 1400 stems per hectare is recommended.

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INTRODUCTION

Density control practices are highly desirable to foresters who wish to manipulate the physical characteristics of their stands and increase crop tree size at harvest. To date, nearly all research on stocking control in Sitka spruce (*Picea sitchensis* [Bong.] Carr.) has focused on thinning studies in which the stocking levels of existing plantations were reduced (Brazier 1970; Jack 1971; Lynch 1980; Hamilton 1981; Kilpatrick *et al*. 1981; Rollinson 1988). These studies, all conducted in the United Kingdom, demonstrate that early spacing control of Sitka spruce concentrates stand growth on the remaining crop trees.

Most of the studies, however, relied on stands that were originally planted at higher densities (i.e., 2500-3000 stems per hectare) than are commonly used in North America, and thinnings were used to lower stocking levels at 12 to 30 years of age. In contrast, this project examines the effects of initial differences among plantation densities that remain unthinned 27 years from seed, and that bracket the existing plantation targets of 1000-1100 stems per hectare now used in British Columbia. Such stands are typical of the less intensively managed forests common in North America.

METHODS

Study Area

The study area is located on the west side of Kitsumkalum Lake, 32 km northwest of Terrace, B.C. (54° 45' N. Lat., 128° 50' W. Long.) in Westar Timber Ltd. Tree Farm Licence 1 (Figure 1). The site lies at an elevation of 400-450 m in the northern drier maritime subzone of the Coastal Western Hemlock biogeoclimatic zone (Haeussler *et al*. 1984). Characteristic tree species in climax stands include western hemlock (*Tsuga heterophylla* [Raf.] Sarg.), amabilis fir (*Abies amabilis* [Dougl.] Forbes), Sitka spruce, and western redcedar (*Thuja plicata* Donn). The average pedon is a loamy-sand orthic humo-ferric podzol (CSSC 1978) over glacial till. The terrain is flat to slightly sloping with grades ranging from 3 to 10%, with an east to northeast aspect.

The climate for the subzone is suboceanic with a very wet fall, a cool winter with heavy to very heavy snowfall, and a warm, moist summer with significant dry spells. The mean total precipitation for the subzone is 154 cm and the mean total snowfall is 324 cm. The mean annual temperature is 6.2°C. There is an average frost-free period of 155 days and 1500 growing degree days per year (5° base temperature).

Study Establishment

The harvest of a mature forest of Sitka spruce, western hemlock, and amabilis fir was followed by an intensive wildfire in 1958. A randomized complete-block design with three replications of four espacements was laid out in 1960. The plots consist of 144 trees arranged in a 12 × 12 square. Within each plot, the inner 64 trees are permanently marked sample trees and the outer 80 trees in two rows serve as buffers. The installation was planted in May 1961 with 2+0 bareroot seedlings of local provenance, and a reserve of seedlings was established. Dead sample and buffer trees were replaced with reserve trees to ensure plots contained seedlings of identical age and provenance. Approximately 22% of the trees were replaced in this manner between 1961 and 1965.

Additional maintenance was performed as necessary to keep the plots intact. Hardwood species and coniferous wildlings were removed on three occasions. In 1967, the trees were sprayed with nicotine sulphate to control Cooley spruce gall aphid (*Adelges cooleyi* [Gill]). Some barking damage from porcupines was noted in one plot during the last assessment, yet sample trees were healthy, vigorous, and undamaged as of September 1987.

Assessments of sample trees, including measurements of height and dbhob at 1.37 m, were performed 7, 12, and 17 years from seed. The assessments at 23 and 27 years were more detailed. Height was measured

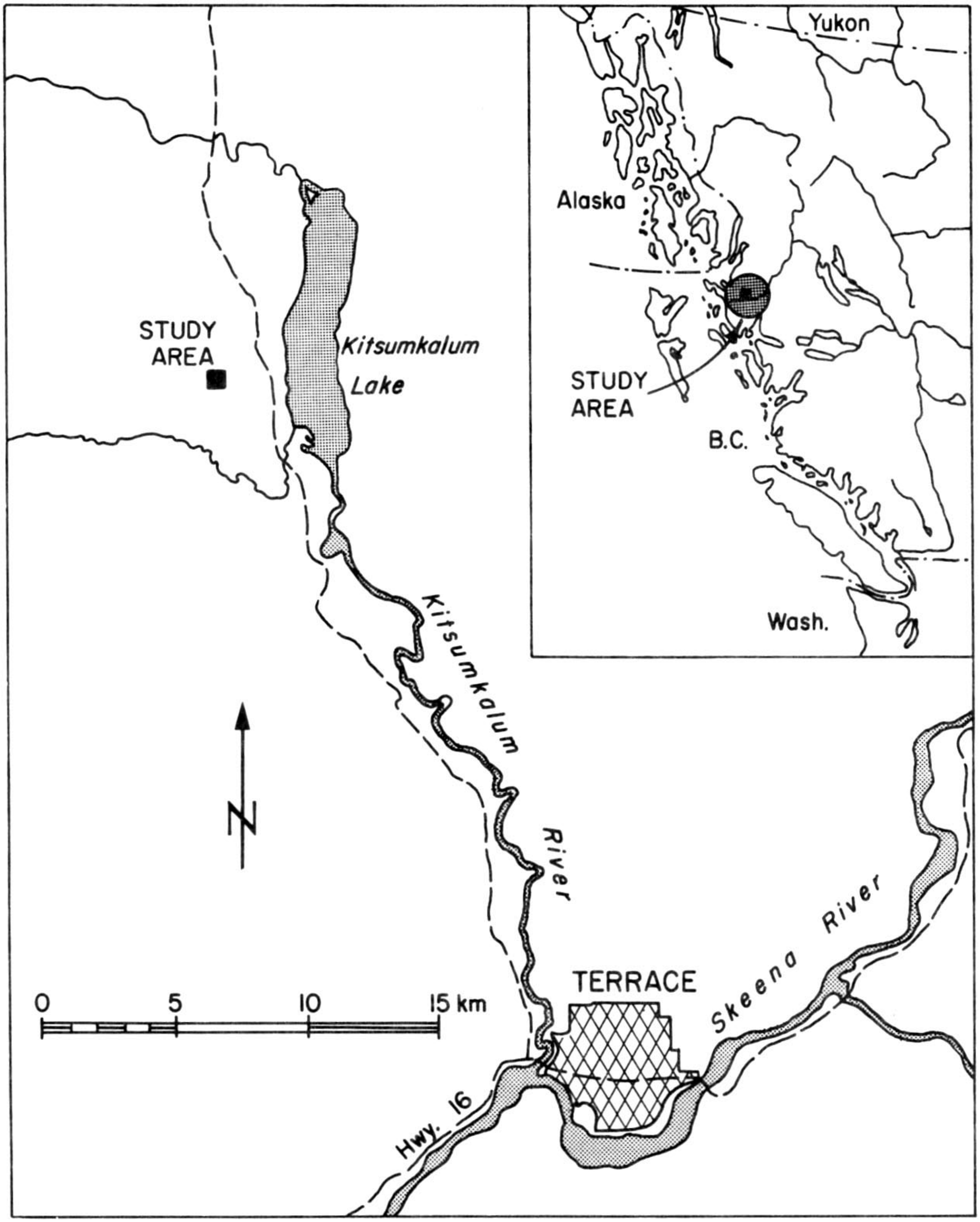

FIGURE 1. Location of study area.

to the nearest 10 cm with height poles, and dbhob at 1.30 m was measured to the nearest 0.1 cm with diameter tapes. The diameter of the largest branch in the whorl nearest breast height was measured to the nearest 0.01 cm, using dial calipers, at a point 2 cm from the bole. The height of the lowest living branch was determined to the nearest 5 cm, and two measurements of crown diameter were taken, at right angles, to the nearest 10 cm.

Data Analysis

Individual sample trees were examined during the 27-year assessment to determine if their history and surroundings were consistent with each treatment. A small number of trees adjacent to trees killed by man, and a number of multiple-stemmed trees, were excluded from the analysis.

In the detailed 27-year assessment, the data were sorted into three stand components (Table 1):

1. all sample trees;
2. the largest (dbhob) 25% of all sample trees; and
3. the equivalent of the largest (dbhob) 250 stems per hectare.

For each tree in each stand component, the mean crown diameter and circular projected area for the crown were calculated. Individual tree volumes were determined using a volume equation from Smith and Breadon (1964). Per-hectare basal area, volume, and increment values were evaluated as net values (i.e., excluding mortality, which was insignificant). These values were calculated by multiplying the mean value of sample trees in each plot times the planting densities given in Table 1. Crown closure for individual plots was determined as a percentage of the sum of all projected crown areas divided by the plot area. Statistical significance was determined by analyses of variance with linear and cubic contrasts for the all-tree, largest 25%, and largest 250 stems per hectare stand components at 27 years.

TABLE 1. Treatment plot characteristics and the number of sample trees analyzed for each level of growing stock

Plantation density (stems/ha)	Inter-tree distance (m)	Plot size (ha)	Stand component					
			All trees		Largest 25%		Largest 250/ha	
			No. of sample trees	Equivalent stand density (stems/ha)	No. of sample trees	Equivalent stand density (stems/ha)	No. of sample trees	Equivalent stand density (stems/ha)
478	4.57	0.301	64	478	16	120	33	250
747	3.66	0.193	64	747	16	187	21	250
1329	2.74	0.108	64	1329	16	332	12	250
2990	1.83	0.048	64	2990	16	747	5	250

For the remaining assessment dates, treatment means were determined for the all-tree stand component only. Mean stand height, quadratic mean dbhob, basal area per tree, volume per tree, and volume per hectare were calculated for 12, 17, and 23 years. Only mean stand height was determined for 7 years as many sample trees had not yet reached the 1.37-m height necessary for dbhob measurements. Stepwise multiple regression analyses were conducted using the plot means for mean stand height, quadratic mean dbhob, volume per tree, and volume per hectare, versus age.

RESULTS

Height

Height characteristics were not greatly affected by plantation density (Tables 2-4). However, a gradient was visible from age 12, with greater plantation densities producing shorter trees in the all-tree stand component (Figure 2). At age 27, mean height, mean top height, and mean periodic height growth (23-27 years) were not significantly affected by changes in espacement, although 478 stems per hectare produced 16% taller trees than did 2990 stems per hectare (Tables 4-5). A similar gradient was observed for mean top height, but it was not apparent for periodic height growth. Differences among espacements were least pronounced in the largest 250 stems per hectare component, as compared to the all-tree and largest 25% components.

A regression of height versus age produced an R^2 of 0.951 (Table 3).

TABLE 2. Means and standard errors for five variables in four espacements of Sitka spruce: ''all-tree'' stand component

Variable	Plantation density (stems/ha)	Total age (years)				
		7[a]	12	17	23	27
Mean height (m)	478	0.97±0.030	2.71±0.073	5.30±0.134	8.31±0.176	10.33±0.191
	747	0.89±0.030	2.58±0.082	5.09±0.161	7.90±0.223	9.83±0.242
	1329	0.76±0.025	2.17±0.057	4.43±0.115	7.23±0.157	9.33±0.175
	2990	0.89±0.030	2.11±0.053	4.14±0.094	7.03±0.139	8.93±0.155
Quadratic mean dbh (cm)	478	-	3.3±0.40	8.0±0.84	14.6±1.05	20.3±1.13
	747	-	3.3±0.52	7.8±1.30	13.7±1.69	18.6±1.75
	1329	-	2.3±0.27	6.2±0.71	11.4±0.92	15.2±1.05
	2990	-	2.2±0.19	5.9±0.34	9.9±0.39	12.4±0.55
Basal area/tree (cm^2)	478	-	9±0.8	51±3.1	169±7.8	322±13.1
	747	-	10±0.8	50±3.4	151±8.3	274±13.3
	1329	-	4±0.4	31±2.1	105±5.6	185±9.0
	2990	-	4±0.3	28±1.6	78±3.5	123±5.0
Total volume/tree (m^3)	478	-	0.008±0.0002	0.020±0.0012	0.075±0.0042	0.1632±0.0084
	747	-	0.008±0.0002	0.020±0.0011	0.067±0.0041	0.1381±0.0079
	1329	-	0.007±0.0001	0.014±0.0007	0.044±0.0027	0.0891±0.0053
	2990	-	0.007±0.0001	0.012±0.0004	0.033±0.0016	0.0581±0.0029
Total volume/ha (m^3/ha)	478	-	4±0.1	8±1.5	36±6.6	78±12.6
	747	-	6±0.3	13±3.0	51±13.2	104±24.0
	1329	-	9±0.1	15±2.0	58±11.2	117±22.2
	2990	-	20±0.2	32±2.3	97±8.3	172±17.5

[a] Few sample trees exceeded breast height at 7 years; therefore, dbh, basal area, and volume measures are not presented.

Diameter

For the all-tree stand component, quadratic mean diameter was reduced at greater plantation densities at age 12, and these differences increased with time to age 27 (Figure 3 and Table 4). A regression of quadratic mean diameter versus age and density produced an R^2 of 0.934 (Table 3). At age 27, the quadratic mean diameter at 478 stems per hectare was 64% larger than at 2990 stems per hectare (Table 5). A parallel relationship was observed in the largest 25% stand component. However, differences in both arithmetic and quadratic mean dbhob's were less pronounced in the largest 250 stems per hectare component. The quadratic mean diameter at 478 stems per hectare was only 27% larger than observed at 2990 stems per hectare in this component.

TABLE 3. Regression equations for mean height, quadratic mean diameter, volume per tree, and volume per hectare versus age, for the "all-tree" stand component

Equation	Model R^2	Partial r^2	
$Ht = -0.00492 + 0.01808\ Age^2 - 0.00000675\ Age^4$	0.951	Age^2 Age^4	0.942 0.009
$QDBH = 4.691 + 0.8974\ Age - 4.164\ Log\ (SPH)$	0.934	Age Log (SPH)	0.897 0.037
$VOL = 0.02222 + 0.00000018\ Age^4 + \frac{20.10}{SPH}$	0.733	Age^4 $(SPH)^{-1}$	0.642 0.091
$VOLH = -19.49 + 0.00018\ Age^4 + 0.01644\ SPH$	0.834	Age^4 SPH	0.696 0.138

where Ht = mean height (m) of all trees
QDBH = quadratic mean diameter (cm), outside bark
VOL = total volume per tree (m^3)
VOLH = total volume per hectare (m^3/ha)
Age = total age from seed
SPH = plantation density, in stems/hectare

TABLE 4. Effects of espacement on 27-year-old Sitka spruce

Variable	P value by stand component		
	All trees	Largest 25%	Largest 250/ ha
Mean height (age 27)	0.3204	0.1403	0.8407
Mean top height	0.4484	0.4484	0.4484
Periodic height growth (ages 23-27)	0.2543	0.8416	0.8175
Arithmetic mean dbhob	0.0068	0.0006	0.0751
Quadratic mean dbhob	0.0042	0.0006	0.0616
Periodic diameter increment (ages 23-27)	0.0001	0.0001	0.0015
Basal area/tree	0.0054	0.0005	0.0591
Basal area/ha	0.0044	0.0016	0.0591
Periodic basal area increment/ha (ages 23-27)	0.0187	0.0055	0.0061
Total volume/tree	0.0142	0.0024	0.1056
Total volume/ha	0.0128	0.0058	0.1056
Periodic total volume increment/ha (ages 23-27)	0.0450	0.0140	0.0254
Crown diameter	0.0013	0.0002	0.0017
Crown area	0.0018	0.0005	0.0025
Height to lowest living branch	0.0005	0.0001	0.0002
Percent live crown	0.0001	0.0001	0.0001
Percent crown closure	0.0003	-	-
Diameter of largest branch at breast height	0.0001	0.0016	0.0037

NOTE: Significance based on linear contrasts among treatments.

Diameter distribution curves for the all-tree component at age 27 showed a narrow range at 2990 stems per hectare versus wider ranges for the lower densities (Figure 4). Only 1.3% of all trees exceeded 20 cm dbhob in the 2990 stems per hectare density, whereas 65.6% of all trees exceeded this diameter at 474 stems per hectare.

Mean periodic diameter increment between ages 23 and 27 decreased as plantation density increased for all three stand components (Table 4). Differences were greatest for the all-tree and largest 25% components, with the 478 stems per hectare increments being 124 and 106% greater than the 2990 stems per hectare increments, respectively (Table 5). Differences among densities were reduced to 74% when only the largest 250 stems per hectare component was compared.

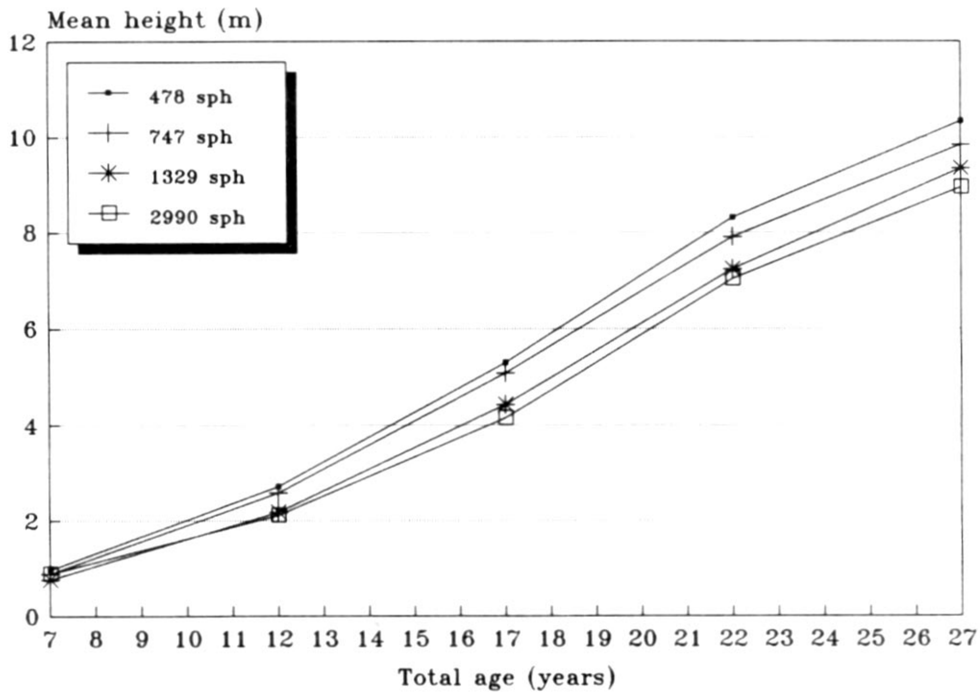

FIGURE 2. Mean height of Sitka spruce versus age for the all-tree stand component.

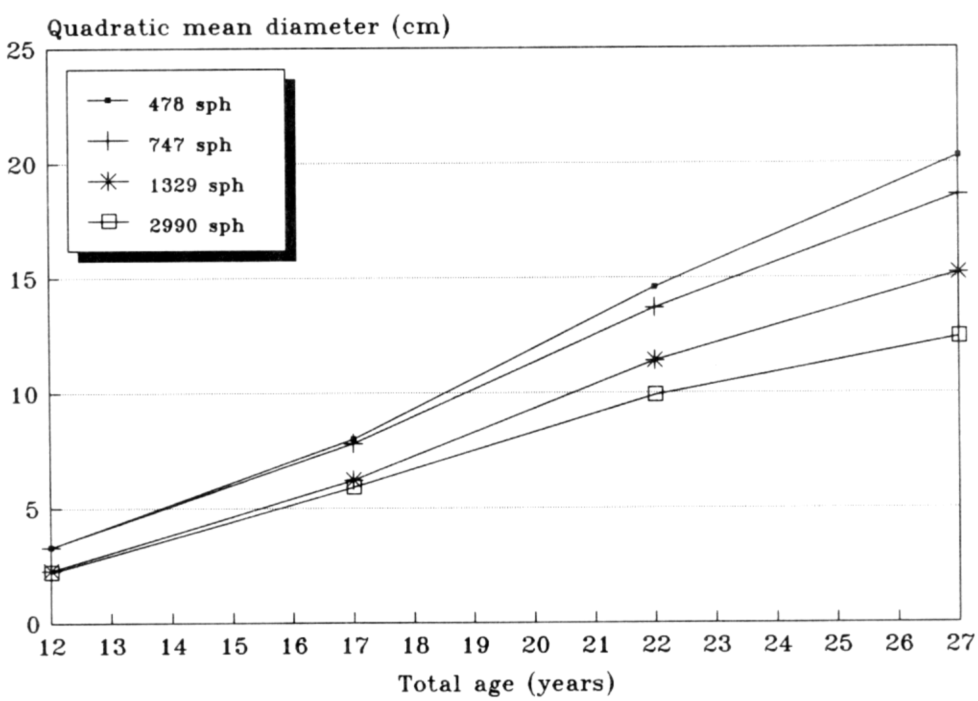

FIGURE 3. Quadratic mean diameter of Sitka spruce versus age for the all-tree stand component.

Basal Area

Differences in mean basal area per tree were pronounced in the all-tree component at age 12, and increased with time (Table 2). At age 27, the mean basal area per tree decreased with increased density, whereas mean basal area per hectare and periodic (ages 23-27) basal area increment per hectare increased for all three stand components (Table 4).

In the all-tree and largest 25% components, the mean basal areas of trees grown at 478 stems per hectare were 162 and 154% greater, respectively, than at 2990 stems per hectare (Table 5). This value dropped to 59% when only the largest 250 stems per hectare component was considered.

Mean basal area per hectare was greatest in the highest planting density. Plantations grown at 478 stems per hectare produced only 43% of the basal area of those grown at 2990 stems per hectare for the all-tree component. The largest 25% component was similar, yet the largest 250 stems per hectare component yielded 58% more basal area per hectare at 478 stems per hectare than at 2990 stems per hectare.

Periodic basal area increment per hectare (ages 23-27) displayed similar trends (Table 5). Plantations grown at 478 stems per hectare produced only 56 and 52% of the increment yielded by 2990 stems per hectare for both the all-tree and largest 25% stand components, respectively. However, 478 stems per hectare produced 109% more basal area increment per hectare than did 2990 stems per hectare in the largest 250 stems per hectare stand component.

Volume

Total volume per tree increased with wider espacement (Table 4). Trees at 478 stems per hectare were 181% larger than trees at 2990 stems per hectare. When total volume per hectare was considered, closer espacements produced more volume per hectare than wider espacements because of the greater number of smaller trees. Thus, at 27 years of age, a plantation of Sitka spruce grown at a density of 478 stems per hectare produced only 45% of the volume per unit area of a plantation, with a density of 2990 stems per hectare (Table 5).

While these relationships held for both the all-tree and the largest 25% stand components, they were not observed when only the largest 250 stems per hectare were considered (Table 4). Furthermore, although total volume per hectare and total volume per tree did decrease with increased stocking levels, these volumes were virtually identical for 478 and 747 stems per hectare in this stand component.

Regression equations for volume per tree and volume per hectare versus age produced R^2 values of 0.733 and 0.834, respectively (Table 3), with pronounced differences among espacements at all ages (Table 2; Figures 5 and 6).

Crown Characteristics

At age 27, all crown characteristics were significantly affected by density for all three stand components (Table 4). Trees grown at lower plantation densities displayed larger crown diameters, crown areas, percentages of live crown, and lower percentages of crown closure (Table 5). In the 478 stems per hectare density, mean crown area was 17.2 m^2 as compared to 6.9 m^2 for 2990 stems per hectare. Percent live crown was 97.4 and 84.2% for the corresponding plantation densities, and percent crown closure was 83 and 205%, respectively.

The mean diameter of the largest branch at breast height increased as plantation density decreased for all three stand components (Table 4). Wider espacements produced larger branches at this standard measurement position. In the all-tree stand component, 2990 stems per hectare produced branches 15.9 mm in diameter, which was 59% of the diameter of the branches produced at 478 stems per hectare. This relationship was similar when only the largest 25% of trees in the plantation were examined, but the differences among densities decreased when only the largest 250 stems per hectare trees were considered.

TABLE 5. Means and standard errors for 18 variables in four espacements of 27-year-old Sitka spruce

Variable	Plantation density (stems/ha)	Stand component mean ± S.E.		
		All trees	**Largest 25%**	**Largest 250/ha**
Mean height (m)	478	10.33±0.19	12.54±0.28	11.61±0.18
	747	9.83±0.24	11.84±0.26	11.52±0.25
	1329	9.33±0.18	11.53±0.22	11.55±0.25
	2990	8.93±0.16	10.88±0.17	11.39±0.29
Mean top height (m)[a]	478	12.66±0.26	Identical to "All trees"	Identical to "All trees"
	747	11.98±0.29		
	1329	12.48±0.35		
	2990	11.71±0.41		
Periodic height growth (m, ages 23-27)	478	2.02±0.054	2.04±0.109	2.10±0.066
	747	1.93±0.083	1.98±0.112	1.97±0.163
	1329	2.10±0.049	2.25±0.087	2.19±0.092
	2990	1.90±0.044	2.07±0.088	2.11±0.125
Arithmetic mean dbhob (cm)	478	19.5±0.42	26.1±0.42	22.7±0.37
	747	17.7±0.51	23.8±0.41	22.4±0.40
	1329	14.6±0.36	20.1±0.50	20.4±0.52
	2990	12.0±0.28	16.3±0.30	18.1±0.42
Quadratic mean dbhob (cm[a])	478	20.3±1.13	26.2±1.14	22.9±1.09
	747	18.6±1.75	24.0±1.22	22.6±1.47
	1329	15.2±1.05	20.3±1.43	20.6±1.47
	2990	12.4±0.55	16.4±0.61	18.1±1.00
Periodic diameter increment (cm, ages 23-27)	478	5.6±0.089	6.8±0.111	6.1±0.083
	747	4.8±0.138	5.9±0.102	5.9±0.207
	1329	3.7±0.078	4.7±0.104	4.8±0.106
	2990	2.5±0.074	3.3±0.084	3.5±0.163
Basal area/tree (cm^2)	478	322±13	539±17	414±14
	747	274±13	450±15	403±13
	1329	185± 9	326±17	335±18
	2990	123± 5	212± 8	260±13
Basal area/ha (m^2/ha)[a]	478	15.5±1.7	6.5±0.6	10.3±1.0
	747	20.7±3.7	8.5±0.9	10.1±1.3
	1329	24.3±3.4	10.8±1.5	8.4±1.2
	2990	36.4±3.2	15.7±1.2	6.5±0.7
Periodic basal area increment/ha (m^2/ha, ages 23-27)[a]	478	7.4±0.6	2.9±0.1	4.8±0.3
	747	9.3±1.1	3.6±0.2	4.5±0.3
	1329	10.5±1.3	4.4±0.5	3.4±0.4
	2990	13.3±1.4	5.6±0.5	2.3±0.3
Total volume/tree (m^3)	478	0.163±0.0084	0.300±0.0140	0.219±0.0096
	747	0.138±0.0079	0.238±0.0115	0.211±0.0095
	1329	0.089±0.0053	0.171±0.0112	0.176±0.0120
	2990	0.058±0.0029	0.106±0.0049	0.134±0.0082
Total volume/ha (m^3/ha)[a]	478	78±12.6	36± 4.8	55± 7.9
	747	104±24.0	45± 7.1	53±10.0
	1329	117±22.2	57±10.0	44± 8.1
	2990	172±17.5	79± 7.3	33± 4.3
Periodic total volume increment/ha (m^3/ha, ages 23-27)[a]	478	43± 6.0	19± 2.0	29± 3.5
	747	53±10.7	23± 2.8	27± 3.9
	1329	59±11.1	28± 4.5	22± 3.7
	2990	75± 9.2	35± 3.8	15± 2.1
Crown diameter (m)	478	4.60±0.092	5.63±0.140	5.06±0.744
	747	4.26±0.107	4.97±0.125	4.82±0.575
	1329	3.74±0.072	4.30±0.095	4.29±0.450
	2990	2.93±0.052	3.32±0.070	3.44±0.273
Crown area (m^2)	478	17.2±0.69	25.2±1.23	20.5±0.80
	747	14.9±0.68	19.6±0.98	18.5±0.73
	1329	11.3±0.42	14.6±0.63	14.6±0.70
	2990	6.9±0.24	8.8±0.35	9.3±0.43

TABLE 5. Continued

Variable	Plantation density (stems/ha)	Stand component mean ± S.E.		
		All trees	Largest 25%	Largest 250/ha
Height to lowest living branch (m)	478	0.25±0.012	0.22±0.024	0.23±0.014
	747	0.29±0.018	0.23±0.039	0.23±0.026
	1329	0.41±0.023	0.43±0.060	0.43±0.066
	2990	1.42±0.044	1.77±0.090	1.87±0.188
Percent live crown	478	97.4±0.15	98.3±0.19	98.0±0.13
	747	96.7±0.22	98.0±0.32	97.9±0.23
	1329	95.5±0.25	96.4±0.46	96.4±0.51
	2990	84.2±0.38	83.8±0.68	83.8±1.41
Percent crown closure	478	83±8.3	-	-
	747	113±15.3	-	-
	1329	149±12.6	-	-
	2990	205±12.0	-	-
Diameter of largest branch at breast height (mm)	478	26.8±0.45	31.1±0.75	28.9±0.52
	747	22.8±0.44	27.0±0.74	25.9±0.59
	1329	19.4±0.38	24.1±0.55	24.5±0.57
	2990	15.9±0.32	19.6±0.53	21.1±0.80

[a] Based on plot means (n = 3).

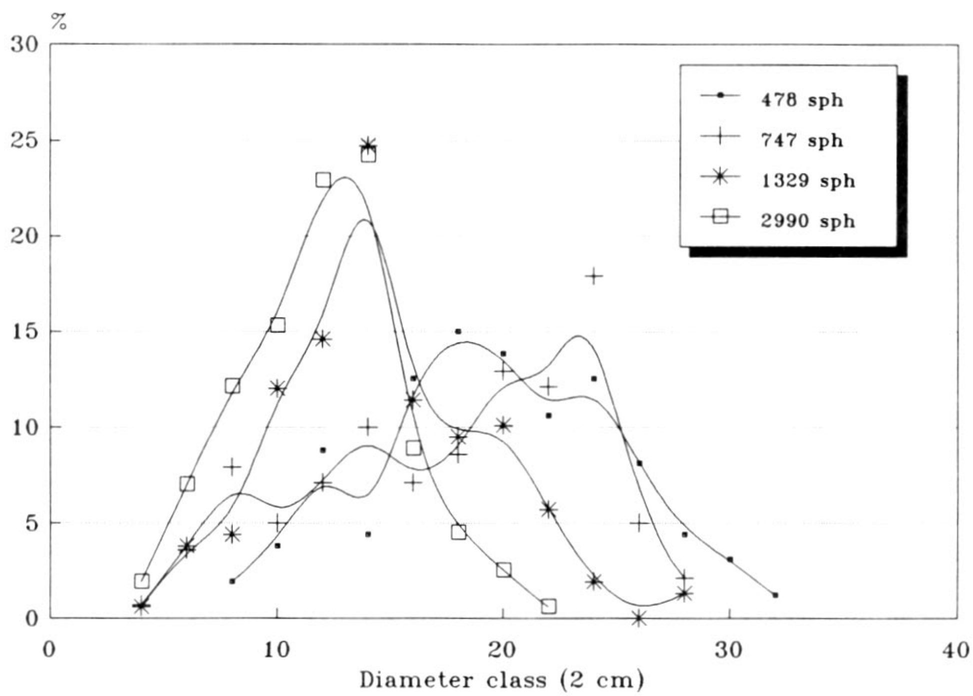

FIGURE 4. Diameter distribution of 27-year-old Sitka spruce for the all-tree stand component.

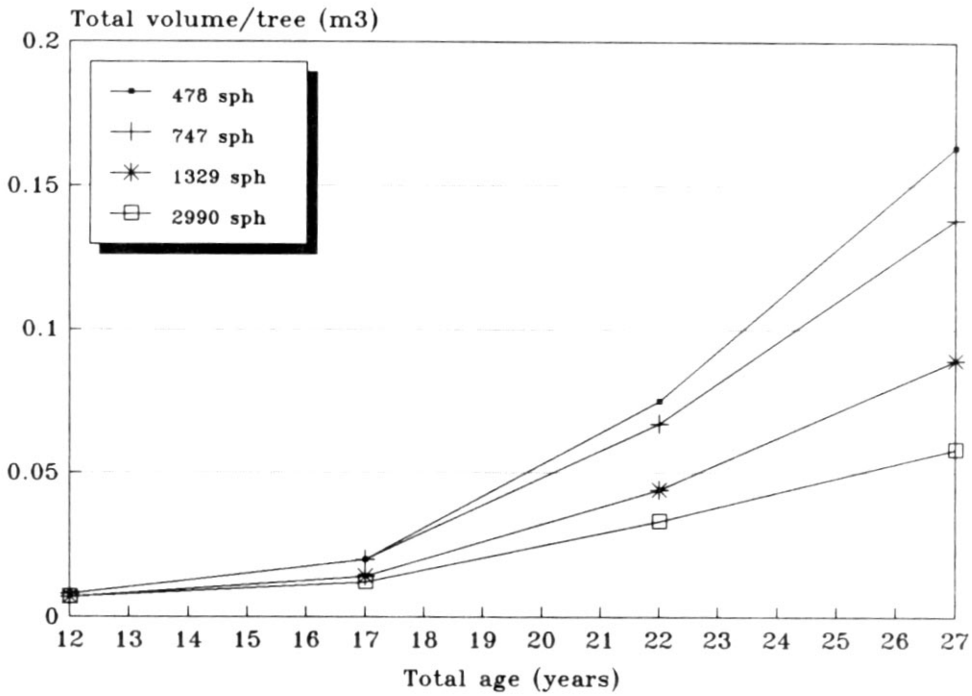

FIGURE 5. Volume/tree of Sitka spruce versus age for the all-tree stand component.

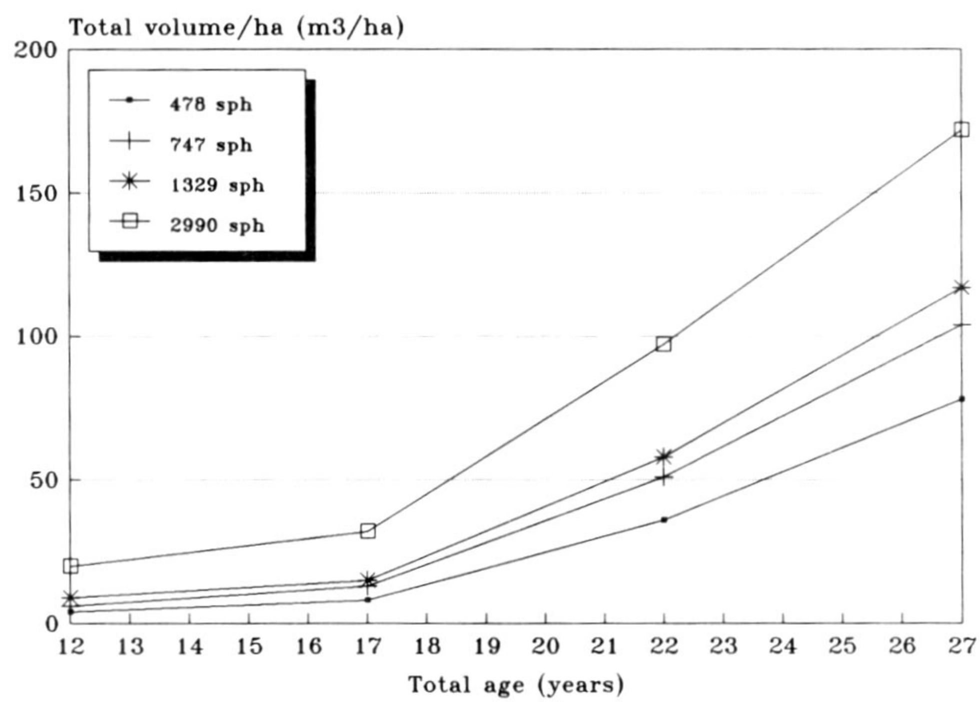

FIGURE 6. Volume/ha of Sitka spruce versus age for the all-tree stand component.

DISCUSSION AND CONCLUSIONS

In this experiment, individual trees were found to respond dramatically to lower planting densities. They displayed larger diameters, basal areas, crown widths, and branch diameters. These differences were most pronounced in the all-tree and largest 25% stand components. Although the mean diameters were smaller at close espacements, in these components the total volume per hectare was 120% greater at 2990 stems per hectare than at 478 stems per hectare. The consistently smaller branch diameters, more rapid initiation of crown lift, and higher expected wood density (Brazier 1970) are related factors that favor high plantation densities when only these stand components are examined. Conversely, at the highest density examined, 98.7% of this volume consisted of small diameter wood less than 20 cm dbhob.

Analysis of the largest 250 stems per hectare provided a somewhat different perspective. In this component, which represents the largest crop trees, many of the diameter and basal area differences were not pronounced at age 23. By age 27, however, these differences became significant. Lower densities produced somewhat larger trees (but not significantly so) with greater crown areas and branch diameters. The major difference between the 250 stems per hectare stand component and the others is the reversal of the trend for total volume per hectare production. The 478 and 747 stems per hectare densities produced 64% more volume per hectare than at 2990 stems per hectare.

Calculated from regional site index equations (B.C. Ministry of Forests and Lands 1987), the experimental area is of medium productivity with a site index of 28 m at 50 years reference age. The regression equations in this study indicate an average of 8.6 years from seed are required to reach breast height. Despite the moderate productivity of the site, 2990 and 478 stems per hectare stand densities produced periodic mean annual increments, over the last 4 years, of 18.8 and 10.8 m^3/ha per year. Using the Forestry Commission yield model in which thinnings are recovered, a culmination m.a.i. of 12.5 m^3/ha per year is predicted, with a 60-year rotation age. The B.C. Forest Service unadjusted model (without thinning) predicts a technical rotation of 70 years with a m.a.i. of 9.1 m^3/ha per year.

Although mean height and top height were not dramatically affected by plantation density, plot means did exhibit a gradient with shorter trees at higher densities. These findings are consistent with Kilpatrick *et al.* (1981) and Evert (1971), but do not support the work by Hamilton and Christie (1974) who noted that the height of Sitka spruce in Britain decreased with lower plantation densities.

Branch diameter and crown characteristics were strongly influenced by initial espacement. At age 23, the crown closure at 2990 stems per hectare was 137%, at which time crown lift was under way. By age 27, crown closure in this density reached 205% with an average height to live crown of 1.42 m. Crown lift at 1329 stems per hectare was apparent at a crown closure of 149%. It appears that crown lift begins at a closure of 130% in the density ranges studied. The authors of this study suggest that the same branch diameter, crown diameter, and crown closure relationships apply for the lower 2 or 3 m of bole among all espacements. In such a case, knot size at the time of crown lift is predicted to be 123% larger at 478 stems per hectare than at 2990 stems per hectare for the all-tree stand component. The result will be a 3.5 cm average knot size in the lower bole of Sitka spruce grown at 478 stems per hectare.

These data suggest the silviculturist has some flexibility when choosing plantation stocking levels over the first 20 years of growth. There were smaller differences among espacements, particularly in volume per tree and volume per hectare, when a standard number of crop trees per hectare are compared. In the more remote locations of North America, where only a few stand entries are economically feasible and a premium is placed on saw timber, the silviculturist may wish to minimize stand establishment and thinning costs by reducing the number of planted seedlings. This concentrates growth on crop trees, increases piece size, and reduces technical rotation length. In such situations, total volume production is always less at wider espacement, but the production of saw timber is higher.

Kilpatrick *et al.* (1981) noted that sawlog volume production in unthinned 31-year-old stands peaked at approximately 1450 stems per hectare when measured to a 14-cm top, and at 725 stems per hectare when measured to a 20-cm top. In this study, however, applying merchantability limits to crop trees with a projected culmination of m.a.i. at 60-70 years would be premature.

The lower practical limit to plantation density is influenced by both branch diameter and reduced wood density. This experiment indicates stands established at or below 500 stems per hectare will produce large branches. Thus, such low densities are justified only when pruning operations are feasible. The data also indicate that stand densities above 2000 stems per hectare needlessly accrue volume on non-crop trees that will be removed by precommercial thinning during the first 10-20 years.

After thinning, crop trees originally grown at excessively high densities will display smaller crown areas that require more time to occupy the site. The shift in individual tree characteristics, displayed between ages 23 and 27 in this study, clearly suggests a thinning window at age 15-20, prior to large reductions in crown area and diameter increment.

Given the equivalent volume per tree and volume per hectare responses of crop trees at 747 and 1329 stems per hectare, plantation densities in the 800-1400 stems per hectare range would allow for either precommercial thinning or no treatment, and the option for a commercial thinning is retained. These recommendations assume, however, that the production of saw timber remains the management objective.

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