Research Note

No.111 1992

ISSN 0226-9368

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Canadian Cataloguing in Publication Data
Main entry under title:
The Influence of initial espacement on the growth of a
32-year-old white spruce plantation

(Research note, ISSN 0226-9368 ; no. 111)

ISBN 0-7718-9247-0

1. White spruce - British Columbia - Houston Region - Growth. 2. White spruce - British Columbia - Houston Region - Spacing. I. Pollack, John C. (John Campbell), 1949- . II. British Columbia. Ministry of Forests. III. Series: Research note (British Columbia. Ministry of Forests) ; No. 111.

SD397.W47I53 1992 634.9'752 C92-092290-2

Published by the
Research Branch
Ministry of Forests
31 Bastion Square
Victoria, B.C. V8W 3E7

Copies of this and other Ministry of Forests titles are available from Crown Publications Inc., 546 Yates Street, Victoria, B.C. V8W 1K8.

The Influence of Initial Espacement on the Growth of a 32-year-old White spruce Plantation

by
John C. Pollack[1], Wayne Johnstone[2], K. David Coates[3] and Philip LePage[4]

[1] Forest Sciences
B.C. Ministry of Forests
518 Lake Street
Nelson, B.C.
V1L 4C6

[2] Kalamalka Research Station
B.C. Ministry of Forests
3401 Reservoir Road
Vernon, B.C.
V1B 2C7

[3,4] Forest Sciences
B.C. Ministry of Forests
3726 Alfred Street
Smithers, B.C.
V0J 2N0

November 1992

BC
Ministry of Forests

ABSTRACT

This 32-year-old experimental plantation, near Houston, B.C., is the oldest known espacement (or planting density) study of white spruce (*Picea glauca* [Moench] Voss) in western Canada. Individual tree and stand characteristics were periodically measured in permanent sample plots for espacements ranging from 420 to 6727 stems per hectare.

Pronounced growth differences among espacements were noted after 32 years. Wider espacements produced trees with larger diameters, crowns and branches. Basal area per hectare and total volume per hectare were greatest in the closest espacement.

Mean annual increment was estimated at 3.90–4.75 m^3/ha per year using the unadjusted Ministry of Forests' yield model for natural stands. TIPSY 2.0 Beta, the Ministry's managed stand yield model, forecast merchantable volume yields of 4.9–6.7 m^3/ha per year, depending on espacement. Mean annual increment and rotation age estimates were compared to those in other white spruce studies.

Of the four densities tested, the 1682 stems-per-hectare treatment provided the best compromise between individual stem growth and overall stand production. At the two lower planting densities, crown closure had not yet occurred and considerable variability in individual stem height existed. The 6727 stems-per-hectare planting density was impractically dense. The absence of planting densities between 1682 and 6727 stems-per-hectare in this study precluded direct comparisons for this density range. Based on present growth characteristics and TIPSY projections, an optimum plantation density range of between 1300–1600 stems per hectare is recommended.

Predictive equations for 19 tree and stand characteristics are presented for the complete density range of 420–6727 stems per hectare.

ACKNOWLEDGMENTS

This study was established by Keith Illingworth. Les Priest, Paul Chalifour and Tom Chatfield conducted the 28- and 32-year assessments. Emory Bella, Jim Goudie, Stephen Omule, Rob Brockley, Deborah DeLong, Ginny Garner and Ken Mitchell provided comments on earlier drafts. David Coopersmith kindly allowed us to use unpublished height-age data from EP 660, and Ken Mitchell supplied the latest unpublished version of TIPSY.

Special thanks go to Jim Goudie, who recognized the value of these old and neglected plots.

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INTRODUCTION

Despite the prominence of white spruce (*Picea glauca* [Moench] Voss) in reforestation, there are few Canadian growth and yield studies for the species (Rauscher 1984; Larocque and Marshall 1988; Coates *et al.*[1]). Height development of young white spruce plantations in British Columbia was first examined by Vyse (1981) near Williams Lake, and later by Pollack *et al.* (1985) near Smithers, using temporary plots and nondestructive techniques. Eis *et al.* (1982) examined height development of mature, natural stands on three common site types near Prince George, B.C.

Replicated growth and yield experiments in white spruce are rare. The most notable Canadian example is the series of spacing and espacement (i.e., planting density) trials, which date from 1922, at the Petawawa National Forestry Institute in Ontario (Stiell 1955, 1986; Stiell and Berry 1967, 1973; Berry 1978, 1987). A second Ontario study, established at Thunder Bay in 1951 (Ontario Ministry of Natural Resources 1989), was designed for demonstration purposes and has not been extensively reported or described. Studies in western Canada are much younger. Bella and De Franceschi (1980) and Bella (1986) reported the effects of initial spacing on 15- to 20-year-old jack pine (*Pinus banksiana* Lamb.), red pine (*Pinus resinosa* Ait.), and white spruce in southeastern Manitoba.

The oldest replicated white spruce stand density study in British Columbia — and the subject of this report — is Experimental Project (EP) 537. A similar study near Prince George (EP 660) involves white spruce, Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco var. *glauca*), and lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) at different espacements. Twenty-year results from EP 660 are expected to be published in the near future (D. Coopersmith, pers. comm. B.C. Ministry of Forests).

METHODS

Study Area

The site is located in north-central British Columbia (54° 47′ N. Lat., 126° 7′ W. Long), approximately 34 km northeast of the community of Houston. The site lies at an elevation of 760 m in the SBSdk (formerly the SBSd) subzone of the Sub-Boreal Spruce Zone (Pojar *et al.* 1984). Soils are loam to clay-loam textured Grey Luvisols with thin (5–8 cm) organic horizons. The dominant vegetation association is the Mesic rose-peavine-moss site series (SBSdk/01), with minor patches of Moist shrub-forb site series (SBSdk/08) also present (Pojar *et al.* 1984). Characteristic tree species found in the study area are white spruce, lodgepole pine, and trembling aspen (*Populus tremuloides* Michx.).

The study area was clearcut between 1949 and 1952, and burned by a wildfire in 1952. The area is flat to slightly sloping, with grades from 3 to 5% and south, north and east aspects in blocks 1, 2 and 3, respectively.

Study Establishment

A randomized complete-block design was used with three replications of four espacements. Each plot was 0.04 ha (0.1 acre) in area, with permanently tagged sample trees and a surround of buffer trees. The use of fixed-area plots created large differences in the total number of trees per plot (Table 1). For example, a 6727 stems-per-hectare plot originally contained 272 tagged sample trees, whereas a 420 stems-per-hectare plot contained only 17 tagged sample trees.

The plots were planted in May 1959, with 2+0 bareroot seedlings of local provenance. An on-site reserve plantation was established concurrently, and mortality in the plots was replaced annually with reserve trees. Mortality amounted to 42.4, 23.2, 29.8, 3.8, 2.8 and 2.2% for the first six growing seasons, respectively, after which seedlings were too large to transplant. Total sample tree replacement was 86.9%. The high level of mortality was ascribed to vegetation competition and small planting stock.

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[1] Coates, K.D., S. Haeussler, S. Lindeburgh, R. Pojar, and A. Stock. Unpublished report on the ecology and silviculture of interior spruce in British Columbia. For. Can., Pac. For. Cent., Victoria, B.C.

TABLE 1. Treatment plot characteristics and the number of sample trees measured

Plantation density (stems/ha)	Inter-tree distance (m)	Plot size (ha)	Original Sample trees per plot	Original Buffer trees per plot	1985–1988 Sample trees per plot[a]
420	4.88	0.0405	17	32	25
747	3.66	0.0405	30	34	36
1682	2.44	0.0405	68	88	64
6727	1.22	0.0405	272	257	64

[a] In 1985, the number of sample trees was reduced in the 6727 and 1329 stems/ha plots, and increased in the 747 and 420 stems/ha plots with the use of former buffer trees.

Competing vegetation included willow (*Salix* spp.), trembling aspen, black twinberry (*Lonicera involucrata*), prickly rose (*Rosa acicularis*), thimbleberry (*Rubus parviflorus*), currants (*Ribes* spp.), and fireweed (*Epilobium angustifolium*). Manual cutting treatments removed all brush within 60 cm of seedlings in 1960, and all woody vegetation over 1.4 m tall was removed in 1970 and 1985. Coniferous wildlings were removed as required.

Assessment of sample trees was confined to total height and survival at 8, 13, and 18 years from seed. At the 28- and 32-year assessments, height was measured to the nearest 10 cm using height poles, and diameter outside bark (DBHOB) at 1.30 m was measured to the nearest 0.1 cm. The diameter of the largest branch in the whorl nearest breast height was measured to the nearest 0.01 cm, with 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.

During the 28- and 32-year assessments, a number of buffer trees were measured in the lower density plots to increase sample size (Table 1). Additionally, a close examination of the 420 stems-per-hectare plot in block 3 revealed that this plot is located on a distinctly different ecosystem from the other plots, and that many sample trees were suppressed by vegetative competition. Data from this atypical plot were not included in the analyses.

Data Analysis

Means and standard errors were calculated for height at all measurement dates. In the detailed, 32-year assessment, means and standard errors were calculated for 19 growth variables. Total volumes (inside bark) for individual trees were calculated using small tree equations by Kovats (1977). Per-hectare basal area, volume, volume increment, and basal area increment were determined as net values. Diameter distribution curves were produced for each planting density.

Least-squares equations for mean stand height versus age, and for the 32-year variables versus plantation density, were developed using stepwise multiple regression techniques.

RESULTS

Height

Three height variables were examined (Table 2, Figures 1–3). At age 32, both top height (e.g., height of the 100 largest DBHOB trees per hectare) and mean periodic height growth (ages 28–32) were not influenced by espacement (Table 3). However, mean height varied with plantation density ($p=0.0009$), with an r^2 of 0.7248. Trees grown at 6727 stems per hectare were 16% shorter than trees at 420 stems per hectare (Table 3).

Regressions of mean height versus age were highly significant ($p=0.0001$), with r^2 values ranging from 0.9902 to 0.9976, depending on espacement (Table 4). The height versus age regression for 6727 stems per hectare displayed a visibly reduced slope compared to that for lower density treatments (Figure 3).

TABLE 2. Plot means, standard errors, and sample sizes for 19 variables in a 32-year-old white spruce espacement trial

	Plantation density (stems/ha)			
	420[a]	**747**	**1682**	**6727**
Top height (m)	7.12±0.18 (2)[b]	7.35±0.34 (3)	8.12±0.24 (3)	7.68±0.29 (3)
Mean height (m)	5.90±0.23 (41)	5.70±0.19 (80)	5.87±0.13 (143)	4.94±0.13 (157)
Mean height increment (m, ages 28–32)	1.15±0.066 (41)	1.18±0.045 (80)	1.22±0.033 (143)	1.00±0.046 (157)
Arithmetic DBHOB	10.14±0.54 (41)	9.49±0.41 (79)	8.86±0.27 (143)	6.10±0.22 (153) (cm)
Arithmetic DBHOB increment (cm, ages 28–32)	2.77±0.17 (41)	2.98±0.084 (76)	2.32±0.080 (142)	1.32±0.050 (150)
Quadratic mean DBHOB (cm)	10.65±0.74 (2)	10.15±0.24 (3)	9.40±0.17 (3)	6.68±0.28 (3)
Mean basal area per tree (cm^2)	89.9±8.02 (41)	81.1±5.86 (79)	70.0±3.90 (143)	34.9±2.23 (153)
Basal area increment per tree (cm^2, ages 28–32)	40.6±3.12 (41)	41.5±2.55 (76)	30.3±1.53 (142)	12.6±0.77 (150)
Basal area/hectare (m^2/ha)	3.76±0.52 (2)	4.93±0.47 (3)	10.15±1.07 (3)	20.93±1.38 (3)
Basal area/hectare increment (m^2/ha, ages 28–32)	1.70±0.12 (2)	2.53±0.22 (3)	4.41±0.27 (3)	7.59±0.45 (3)
Crown diameter (m)	2.65±0.110 (41)	2.48±0.081 (80)	2.39±0.055 (143)	1.67±0.041 (157)
Projected crown area (m^2)	5.90±0.45 (41)	5.25±0.30 (80)	4.82±0.22 (143)	2.39±0.11 (157)
Branch diameter (mm)	18.1±0.94 (41)	16.6±0.56 (77)	14.8±0.40 (142)	10.1±0.30 (149)
Height to lowest living branch (m)	0.38±0.022 (41)	0.49±0.021 (80)	0.51±0.014 (143)	0.84±0.020 (155)
Percent live crown	93.1±0.63 (41)	90.5±0.54 (80)	90.6±0.38 (143)	81.1±0.78 (155)
Mean volume/tree (m^3)	0.0270±0.0027 (41)	0.0245±0.0019 (79)	0.0218±0.0014 (143)	0.0106±0.00077 (153)
Volume/tree increment (m^3, ages 28–32)	0.0137±0.0012 (41)	0.0138±0.0010 (76)	0.0108±0.0006 (142)	0.0047±0.0003 (150)
Volume/hectare (m^3/ha)	11.3±1.44 (2)	14.9±0.99 (3)	31.6±3.17 (3)	63.7±4.77 (3)
Volume/hectare increment (m^3/ha, ages 28–32)	5.73±0.35 (2)	8.39±0.51 (3)	15.79±1.05 (3)	28.31±1.83 (3)

[a] Values for 420 stems/ha do not include the block 3, 420 stems/ha treatment plot, which suffered large height and volume reductions due to vegetation competition.

[b] Sample size.

Diameter

At age 32, the quadratic mean diameter at 420 stems per hectare was 60% larger than at 6727 stems per hectare (Table 2, Figure 4). A similar relationship was observed for mean periodic diameter increment between ages 28 and 32. Trees grown at the wider espacement exhibited a 110% greater diameter increment than trees at 6727 stems per hectare.

The diameter distribution curve for 6727 stems per hectare had a narrower range than did the other three lower densities (Figure 5). The distribution curves for the 420 and the 747 stems-per-hectare treatments were visibly similar.

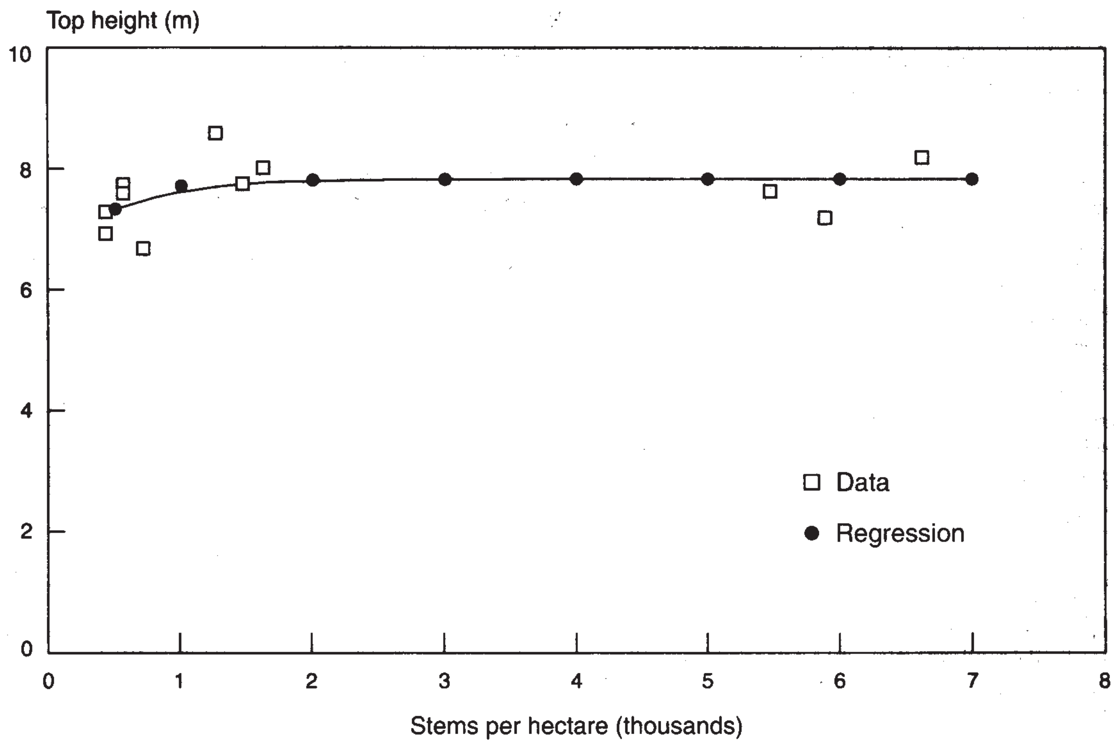

FIGURE 1. Top height vs density at age 32.

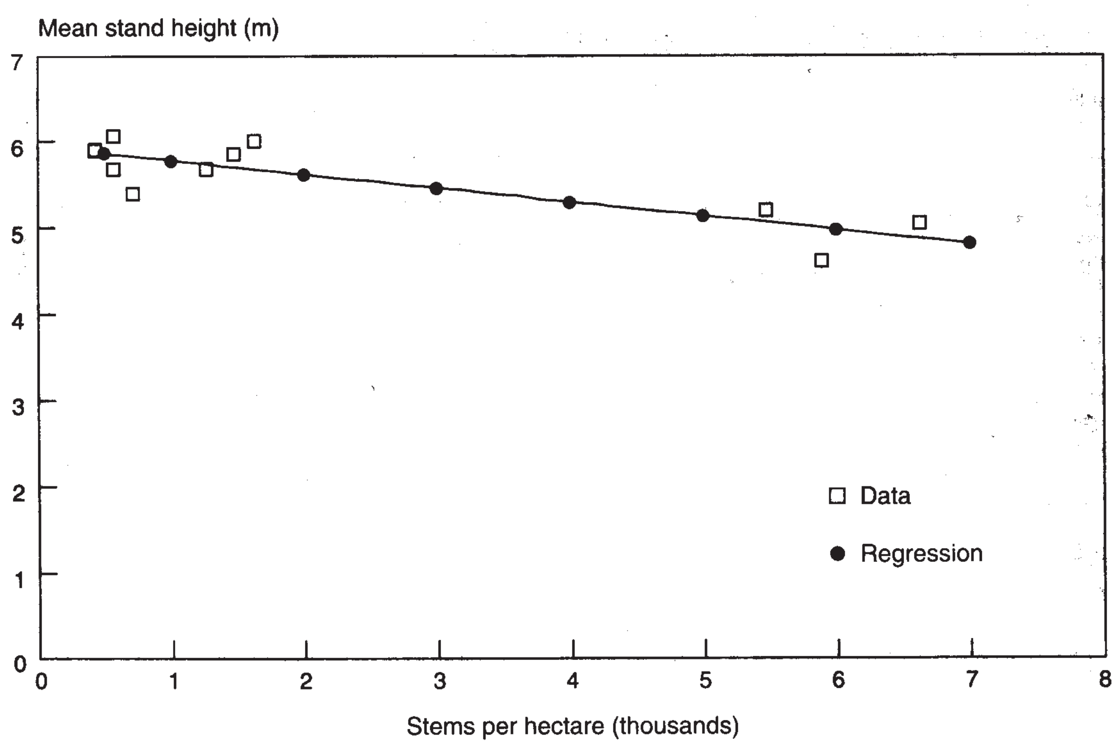

FIGURE 2. Mean stand height vs density at age 32.

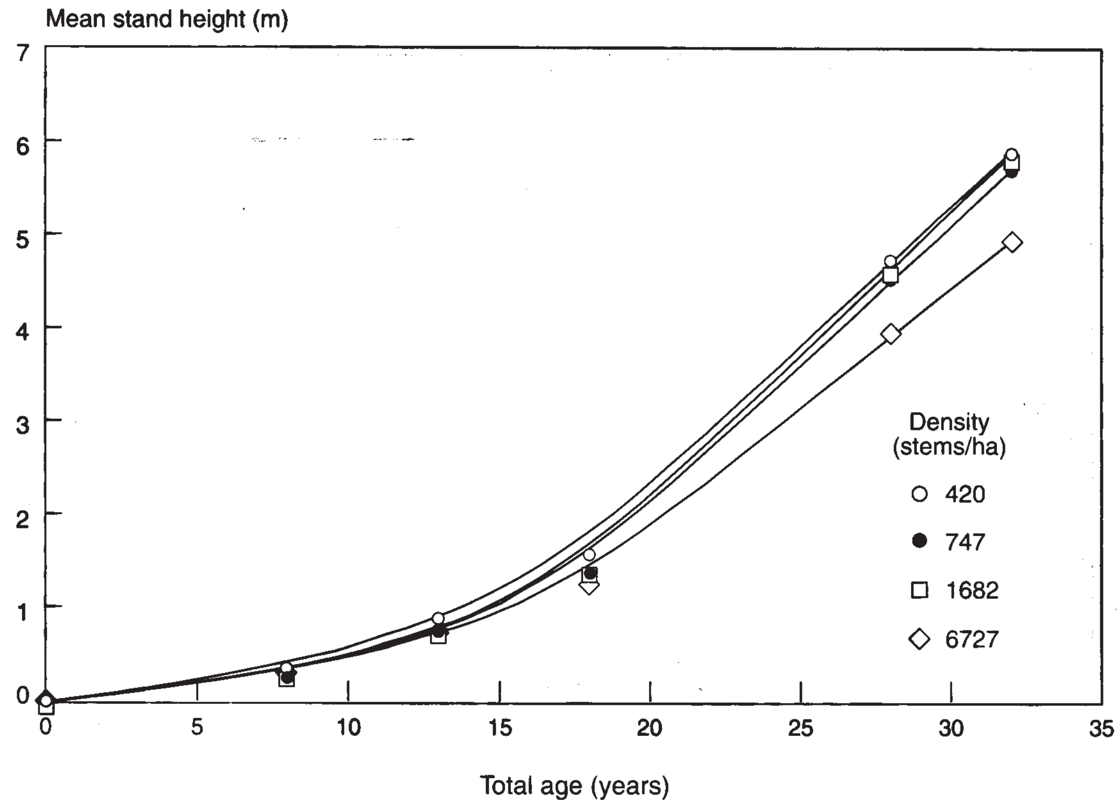

FIGURE 3. Mean stand height vs total age.

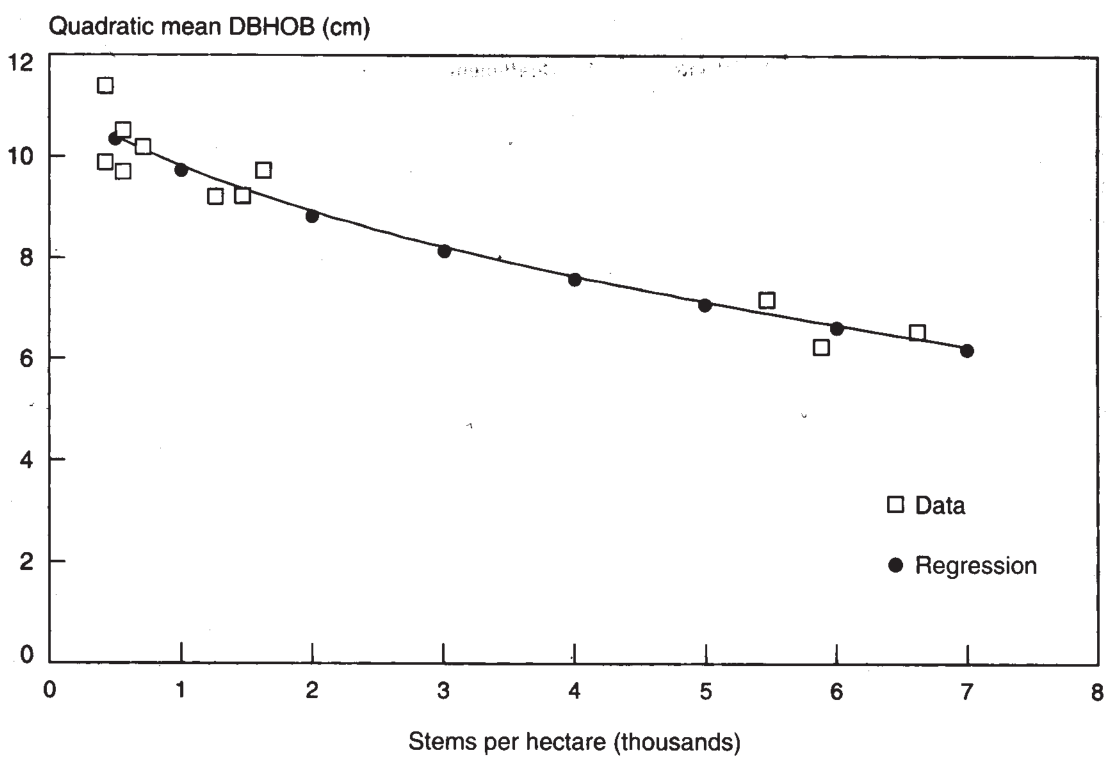

FIGURE 4. Quadratic mean DBHOB vs density at age 32.

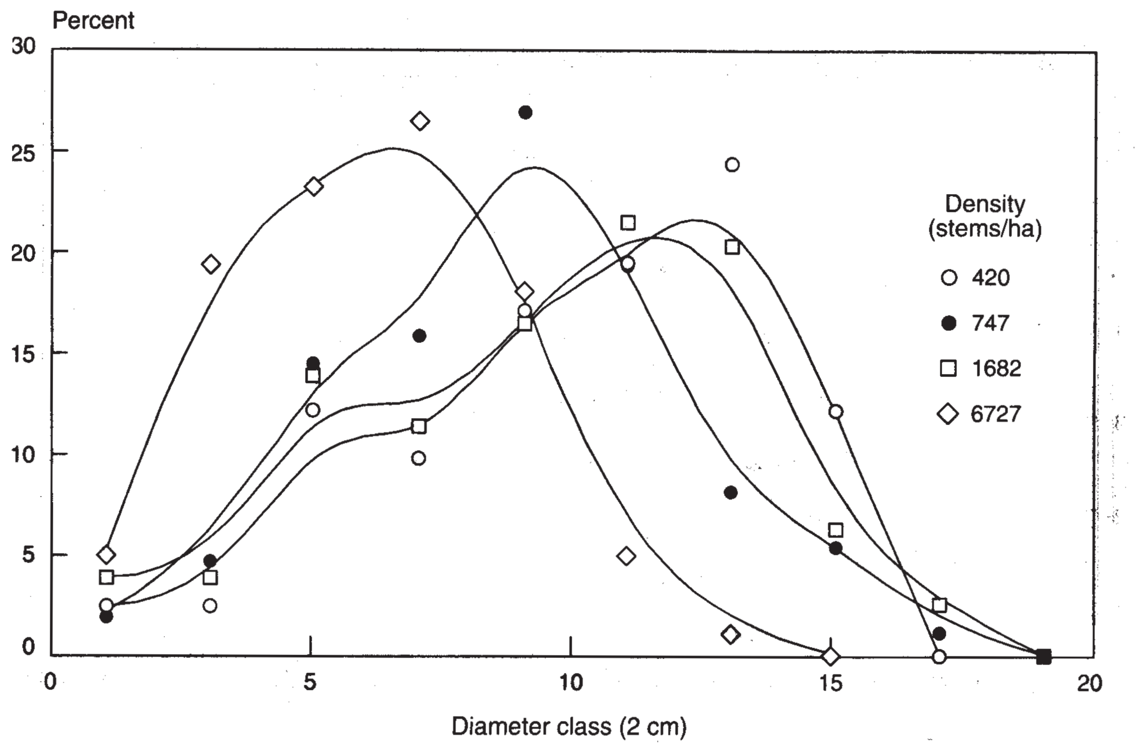

FIGURE 5. Diameter distributions at age 32.

TABLE 3. Regression statistics for 19 variables in a 32-year-old white spruce espacement trial[a]

Variable (y)	Intercept (a)	Coefficient (b)	Density (x)	r^2	P Value
Top height (m)	7.8554	–127392	SPH^{-2}	0.2542	0.1138
Mean height (m)	5.9408	-1.613×10^{-4}	SPH	0.7248	0.0009
Mean height increment (m, ages 28–32)	1.2205	-3.441×10^{-5}	SPH	0.3484	0.0559
Arithmetic DBHOB (cm)	11.3018	–0.06685	SQRT(SPH)	0.9172	0.0001
Arithmetic DBHOB increment (cm, ages 28–32)	3.5137	–0.02845	SQRT(SPH)	0.9411	0.0001
Quadratic mean DBHOB (cm)	11.922	–0.06754	SQRT(SPH)	0.9202	0.0001
Mean basal area per tree (cm^2)	104.72	–0.90191	SQRT(SPH)	0.8943	0.0001
Basal area increment per tree (cm^2, ages 28–32)	51.903	–0.51124	SQRT(SPH)	0.9635	0.0001
Basal area/hectare (m^2/ha)	–41.187	7.1255	LOG(SPH)	0.9660	0.0001
Basal area/hectare increment (m^2/ha, ages 28–32)	–11.580	2.2011	LOG(SPH)	0.9628	0.0001
Crown diameter (m)	2.9534	-1.641×10^{-2}	SQRT(SPH)	0.8762	0.0001
Projected crown area (m^2)	6.8908	–0.05768	SQRT(SPH)	0.8630	0.0001
Branch diameter (mm)	20.130	–0.12985	SQRT(SPH)	0.9085	0.0001
Height to lowest living branch (m)	0.4023	7.429×10^{-5}	SPH	0.8023	0.0002
Percent live crown	91.449	-2.9×10^{-7}	SPH^2	0.9165	0.0001
Mean volume/tree (m^3)	0.03184	-2.726×10^{-4}	SQRT(SPH)	0.9089	0.0001
Volume/tree increment (m^3, ages 28–32)	0.01740	-1.640×10^{-4}	SQRT(SPH)	0.9684	0.0001
Volume/hectare (m^3/ha)	–114.93	20.419	LOG(SPH)	0.9586	0.0001
Volume/hectare increment (m^3/ha, ages 28–32)	–46.177	8.5452	LOG(SPH)	0.9635	0.0001

[a] Equation form: $y=a+bx$.

Basal Area

All basal area variables were affected by plantation density, with individual tree values being inversely related to density (Tables 2 and 3). At age 32, mean basal area per tree was 158% larger at 420 stems per hectare than at 6727 stems per hectare. The corresponding increase in basal area increment per tree was 222% between the lowest and the highest plantation densities.

A direct relationship was observed between density and per-hectare basal area values (Table 3). Total basal area per hectare was 20.93 m^2 at 6727 stems per hectare versus 3.76 m^2 at 420 stems per hectare. A similar trend was observed for basal area per-hectare increment.

Volume

Total volume per tree increased with decreased plantation density (Tables 2 and 3, Figure 6). Individual trees at 420 stems per hectare had 155% greater volume than did trees at 6727 stems per hectare. A similar response was observed with volume increment per tree (Figure 7). When total volume per hectare considered, higher plantation densities produced more volume per hectare than did wider espacements because of the disproportionately greater number of smaller trees (Figure 8).

At 32 years of age, white spruce grown at 6727 stems per hectare produced 63.7 m^3/ha versus 11.3 m^3/ha for plots grown at 420 stems per hectare. This volume-per-hectare difference is a 464% increase as a result of increased planting density.

A similar relationship was noted in the periodic volume-per-hectare increment, whereby the closest espacements produced 28.3 m^3/ha over the last 4 years, and the widest espacements produced only 5.73 m^3/ha (Tables 2 and 3).

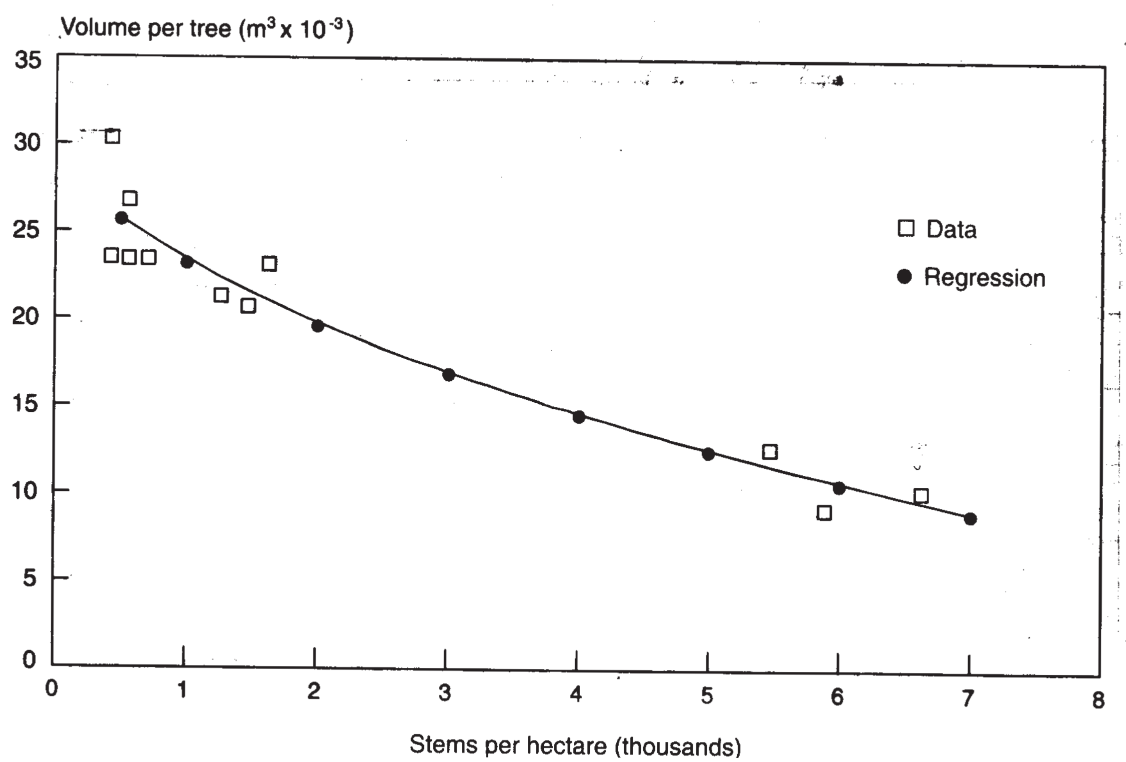

FIGURE 6. Total volume per tree vs density at age 32.

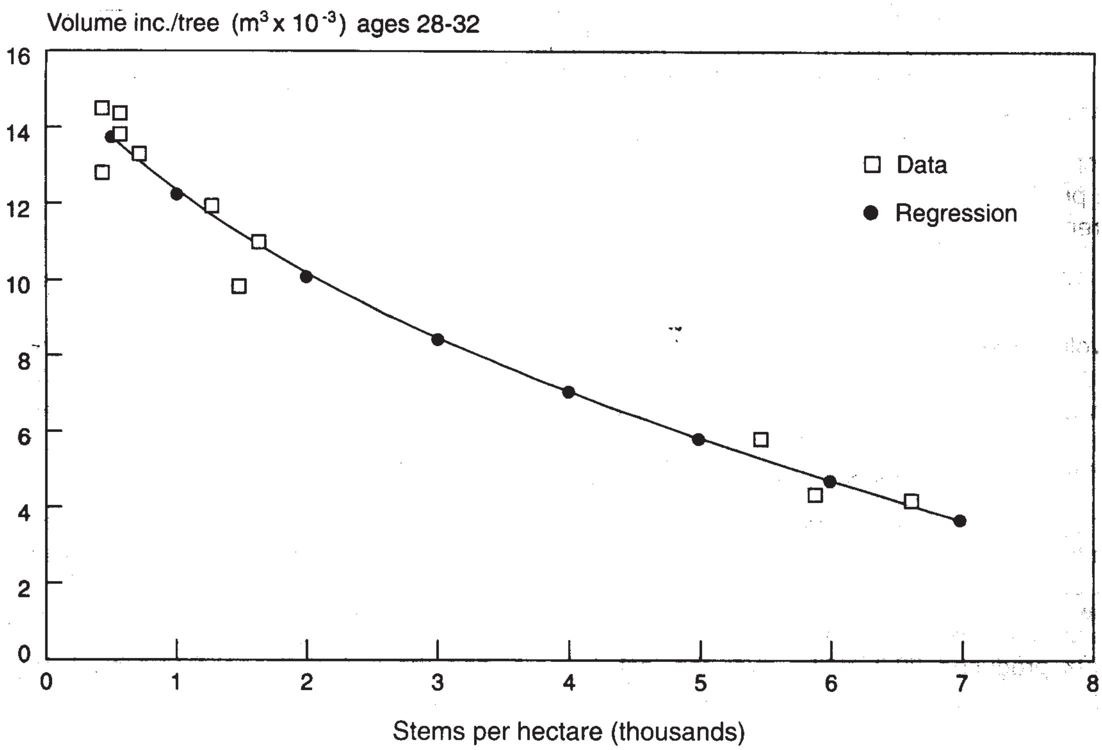

FIGURE 7. Total volume increment per tree vs density, ages 28–32.

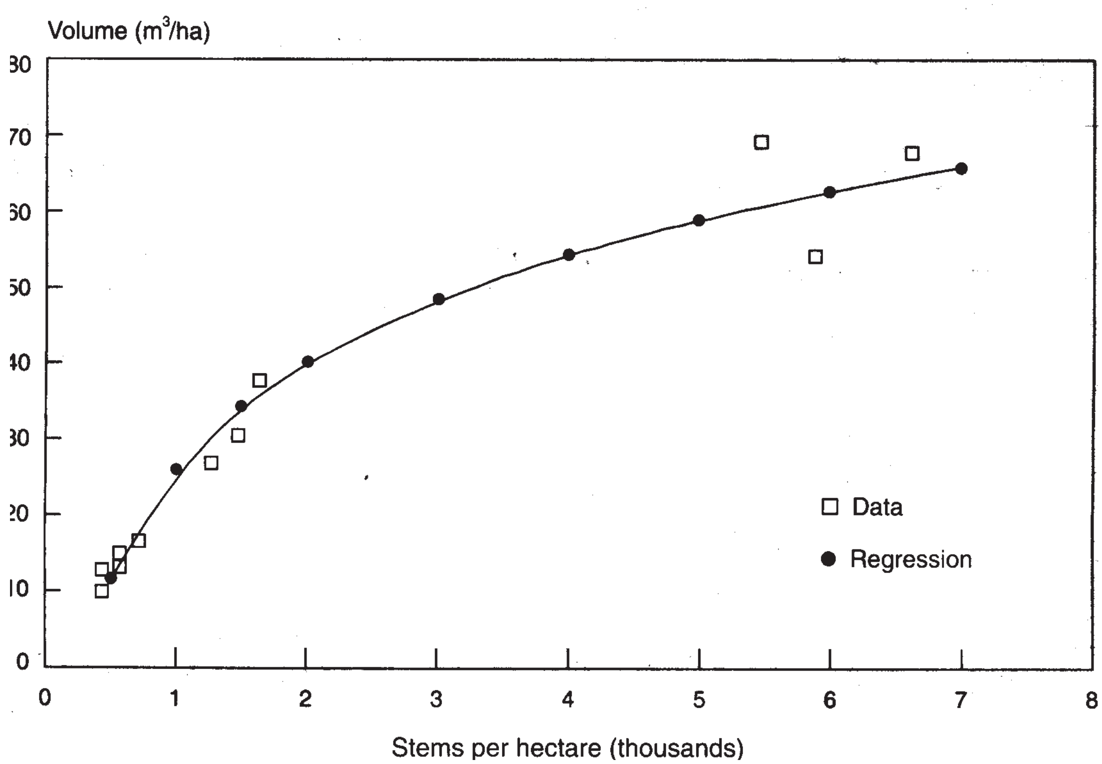

FIGURE 8. Total volume per hectare vs density at age 32.

Crown Characteristics

At age 32, all crown characteristics were significantly affected by density (Tables 2 and 3). Trees grown higher densities had smaller crown diameters and projected areas, smaller percent live crown, and greater heights to the lowest living branch. In the 420 stems-per-hectare density, mean crown area was 5.90 compared to 2.39 m^2 for 6727 stems per hectare. Percent live crown was 93 and 81% for the corresponding plantation densities.

The mean diameter of the largest branch at breast height increased as plantation density decreased (Tables 2 and 3, Figure 9). Trees grown at 420 stems per hectare had branches 18.1 mm in diameter versus the 10.1 mm at 6727 stems per hectare. The crowns had not yet lifted above breast height at 6727 stems per hectare at 32 years, and the average height to the lowest living branch was 0.84 m in this density (Table

Site Productivity

Site index curves by Thrower *et al.* (1991) indicate the study site has an average site index of 21.0 m at reference age of 50 years (breast height). Sample trees required an average of 15 years to reach breast height as compared with 9 years for the site index curves.

Mean annual increments (MAIs) and rotation ages were estimated with the use of two different yield models. The first estimate was obtained from the B.C. Ministry of Forests' unadjusted stand model for natural stands. For our site, the unadjusted model forecast a technical rotation of 84 years (total age) and a MAI 4.75 m^3/ha per year based on a diameter limit of 7.5 cm. A diameter limit of 12.5 cm raised the rotation age 92 years, with a reduction of MAI to 3.90 m^3/ha per year.

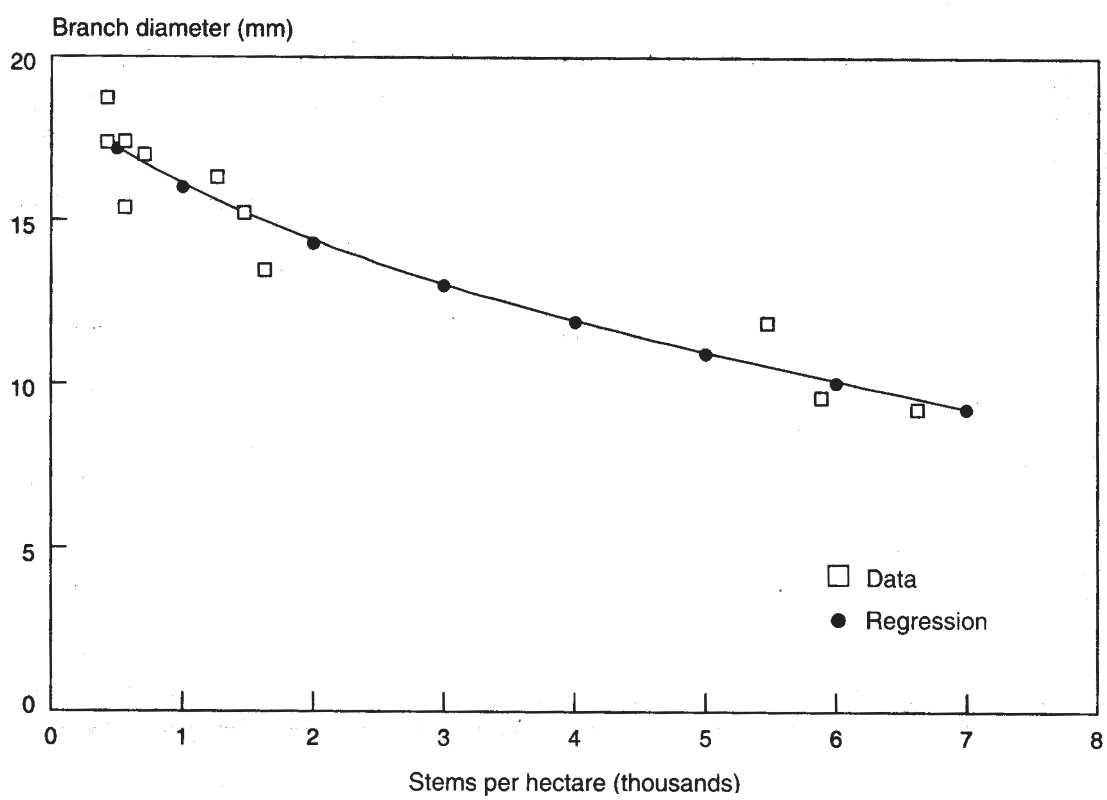

FIGURE 9. Branch diameter vs density at age 32.

TABLE 4. Mean height versus age regression statistics for the four espacements

Plantation density (stems/ha)	Mean height vs age equation	r^2	P Value
420	Height (m)=0.019754+0.005838(total age)^2	0.9976	0.0001
747	Height (m)=–0.05482+0.005677(total age)^2	0.9902	0.0001
1682	Height (m)=–0.05385+0.005806(total age)^2	0.9962	0.0001
6727	Height (m)=–0.01129+0.004888(total age)^2	0.9909	0.0001

NOTE: Based on three plot means per espacement at 7, 12, 17, 28 and 32 years total age.

TABLE 5. Mean annual increment and rotation age estimates for the four espacements[a]

Plantation density (stems/ha)	Mean annual increment[b] (m^3/ha per year)	Rotation age (years total age)
420	4.9	146
747	5.9	114
1682	6.7	84
4444[c]	5.9	100
6727	beyond model limits	beyond model limits

[a] These estimates were obtained using TIPSY 2.0 Beta and incorporated a 6-year regeneration delay to adjust for the 15 years required for EP 537 to reach breast height. No operational adjustment factor was used.

[b] Merchantible volume, 12.5 cm DBH limit.

[c] This density is the upper limit of TIPSY 2.0 Beta, and it is included for comparative purposes. A 4444 stems/ha treatment was not used in EP 537.

When this study's yield was estimated with the use of TIPSY 2.0 Beta, the Ministry of Forests' interim managed stand yield model for white spruce[2], MAIs and rotation ages varied with espacement as shown in Table 5. TIPSY predicted a maximum merchantable MAI of 6.7 m^3/ha per year, based on a 12.5 cm top and 84 year rotation age. A regeneration delay of six years was used to correct for the additional time required for EP 537 to reach breast height. No operational adjustment factor was used.

DISCUSSION

The selection of plantation density is a fundamental silvicultural decision that can greatly influence both future stand productivity and individual tree characteristics. Very low densities can produce large-branched "wolf-trees" and create understocked stands that do not capture the full productivity of the site. Very high densities can necessitate unplanned and costly juvenile spacing of plantations during the first 15–30 years of growth.

The long-term implications of plantation density, when combined with an annual nursery sowing program in British Columbia of more than 65 million white spruce seedlings, explain the need for existing plantation density standards to be critically examined using all available sources of data. Likewise, the scarcity of growth and yield data for white spruce in Canada, and the use of this study as a data source for calibrating the Ministry of Forests' white spruce managed stand yield tables, warrants a discussion of this study's limitations; and calls for a productivity comparison with the Petawawa and other studies, in addition to the usual discussion of stand and tree characteristics.

[2] Mitchell, K.J., S.E. Grout, R.N. Macdonald, and C.A. Watmough. 1992. User's guide for TIPSY. A table interpolation program for stand yields. B.C. Min. For., Res. Branch, Victoria, B.C. Unpublished report.

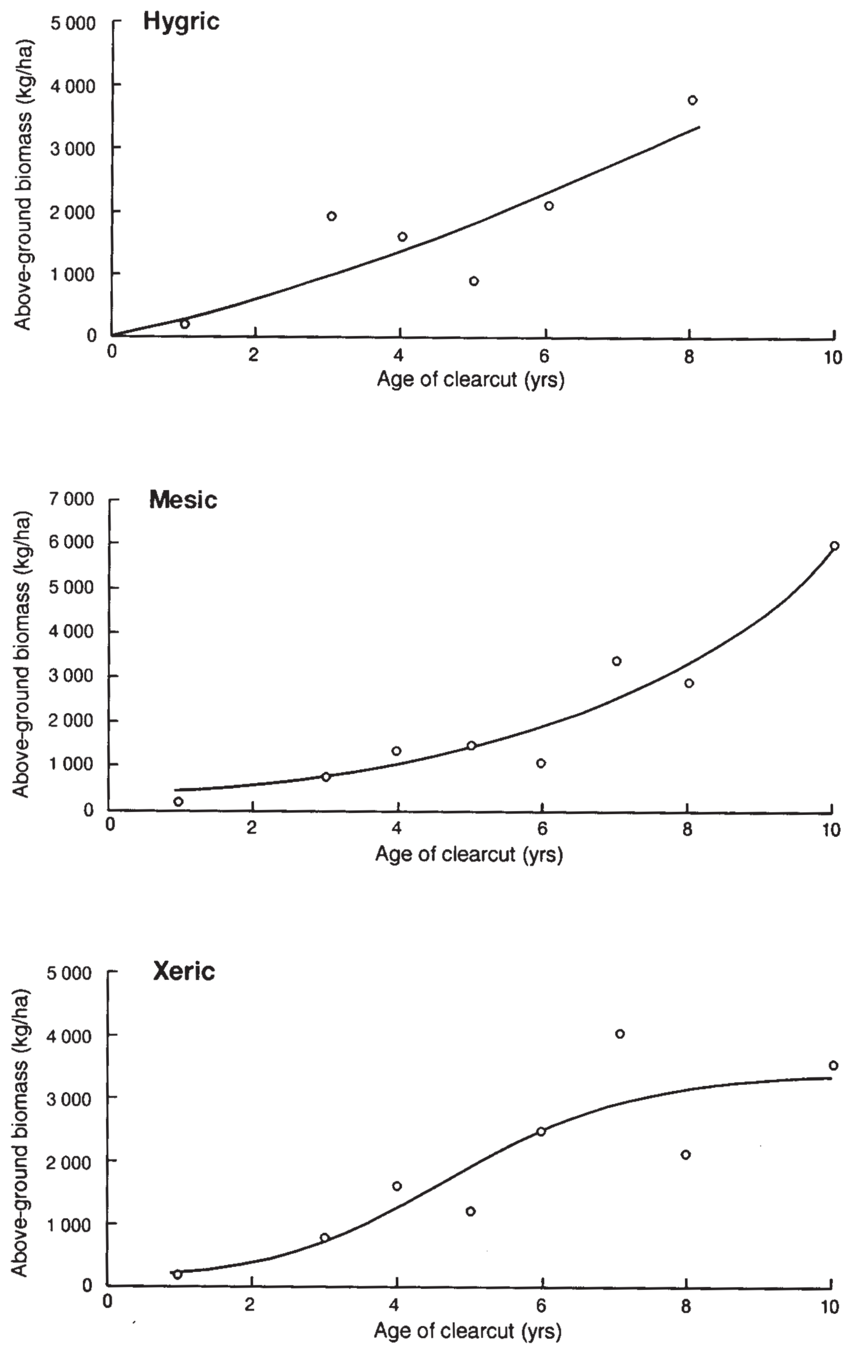

FIGURE 3. Trends in above-ground herb and shrub biomass ($kg{\cdot}ha^{-1}$) on the three slope positions (xeric, mesic, and hygric) on the series of clearcut ages. Curves were fitted using the equations:

xeric above-ground biomass ($kg{\cdot}ha^{-1}$) = 3453/(1 + exp [3.440 – 0.725 (age of clearcut)])
$r^2 = 0.76$, $P = 0.001$

mesic above-ground biomass ($kg{\cdot}ha^{-1}$) = 177105/(1 + exp [6.345 – 0.299 (age of clearcut)]
$r^2 = 0.94$, $P = 0.001$

hygric above-ground biomass ($kg{\cdot}ha^{-1}$) = exp [5.506 + 1.252 (*Ln* age of clearcut)]
$r^2 = 0.81$, $P = 0.015$

Tree and Stand Characteristics

With the design problems addressed, one can examine the relationships observed between individual tree and stand characteristics, and plantation density. These relationships are consistent with those found numerous other plantation density studies (Sjolte-Jorgensen 1967; Evert 1984). We found that individual trees responded dramatically to lower planting densities. Trees grown at 420 stems per hectare had 60% larger diameters, 158% larger basal areas, and 79.2% larger branch diameters. Density had no effect on individual tree height. Trees grown at the lowest densities were 192% larger in volume than those grown at the highest densities.

Although mean diameters and volumes were smallest at higher plantation densities, the total volume per hectare was greatest at higher densities owing to the larger number of stems per hectare. Total volume per hectare for 6727 stems per hectare was 463% greater than at 420 stems per hectare at age 32. Other per-hectare stand characteristics displayed similar differences.

Site Productivity

A review of other published white spruce growth and yield studies indicates that our site had the lowest height growth rate of any study, with the exception of Bella (1986). Examination of the mean stand height age curve (Figure 11) for Sub-boreal Spruce (SBS) sites in British Columbia, likewise indicates a relatively low site quality for the study site, when compared with the mean SBS curve (Pollack *et al.* 1985) and the EP660 data (D. Coopersmith, pers. comm., B.C. Ministry of Forests). The average SBS spruce plantation achieved mean stand height of 1.37 m after 12 years total age (Pollack *et al.* 1985), whereas saplings in this study required an average of 15 years to reach metric breast height, based on the equations from Table 4.

These low initial rates of height growth are surprising, given that the study site is an average SBS zonal site series, with typical soil, slope and vegetational characteristics, and a common silvicultural history

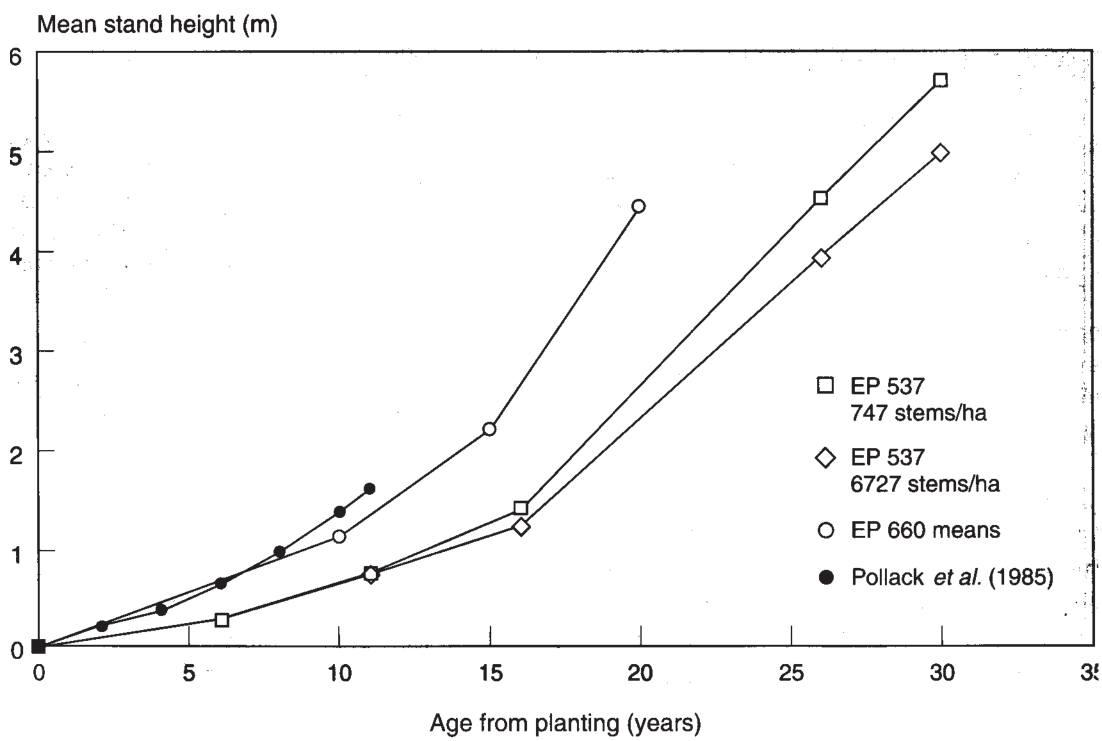

FIGURE 11. Mean stand height vs age for white spruce on SBS sites.

Likewise, the height increments between ages 28–32 indicate average performance. The poor initial height growth displayed on the study site is possibly the result of poor stock quality — a common problem in the 1950's — confounded by moderate levels of vegetation competition.

Mean Annual Increment and Rotation Age

Our managed stand MAI estimates at rotation age ranged from 4.9 to 6.7 m^3/ha per year, depending upon espacement; these values exceeded the Ministry of Forests' unadjusted model for unmanaged stands. Technical rotation age varied considerably according to espacement and, on the study site, ranged from 84 to 146 years.

Estimates for MAI in the literature were less than the predictions from TIPSY and approximately equivalent to the unadjusted Ministry of Forests' yield model for natural stands. Rotation age estimates were highly variable due in part to the wide range of utilization standards, methods of age determination, and stand origins used in these other studies. For stands of our site quality Berry (1987) predicts rotation ages of 50–55 years (total age) and an MAI of 4.3 m^3/ha per year based on merchantable volume to a 10 cm top. For natural stands, Eis *et al*. (1982) predicted a rotation age of 150 years and a culmination MAI of 4.0 m^3/ha per year (total volume) on Cornus-Moss sites with an average site index of 22.3 m.

Stand Establishment

Height growth increased dramatically after the 18-year assessment. At this age, trees in all treatment densities were open grown and crown closure had not occurred. By 32 years of total age, crown closure was well advanced in the 6727 stems-per-hectare density, and recently started in the 1682 stems-per-hectare density. Open canopies persisted in the 420 and 747 stems-per-hectare densities. Crown lift was beginning in the 6727 stems-per-hectare treatment, but is still less than 0.9 m. In this highest density, no suppression mortality was noted.

Observations of extremely slow height growth and crown closure are common in white spruce plantations (Vyse 1981; Pollack *et al*. 1985; Bella 1986). Slow height growth, delayed onset of release, and the open nature of spruce plantations may be typical of the SBS zone, and probably contribute to the high degree of within-stand variability often described by northern field foresters, and documented by Nienstaedt and Teich (1972), Vyse (1981), and Kiss and Yeh (1988).

In this study, large variations among individual trees were noted in total height and current leader growth in the 28- and 32-year assessments. The open nature of the lower density plots and the decrease in variation observed with increasing stand age suggest that the effect of espacement on height variation in white spruce cannot be adequately evaluated until crown closure is well advanced in all plots. Given their present open-grown nature, crown closure may not occur in the 420 and 747 stems-per-hectare plots for several decades.

Optimum Plantation Density

Despite our problems with the experimental design, and the considerable variability in height growth of individual trees within treatment plots, the influence of initial stand density on individual tree and stand characteristics, was clear.

Individual trees in the 420 and 747 stems-per-hectare treatments were often of poor form and the stands appeared unacceptably open after 32 years. The 6727 stems-per-hectare treatment was impractically dense. The 1682 stems-per-hectare treatment, however, given its recent crown closure, permits light-intensity juvenile spacing to deal with white spruce's height variability and creates full site occupancy at a reasonably early age.

The acceptability of the 1682 stems-per-hectare treatment should be tempered with an examination of projected yields using TIPSY 2.0 Beta. Figure 12 illustrates the stability of both MAIs and rotation ages between the densities of 331 and 4444 stems per hectare. MAI peaks from 1100–2000 stems per hectare, and rotation age is minimized between 1300–2500 stems per hectare. When combined with our data, these yield model estimates suggest an optimum planting density range of 1300–1600 stems per hectare.

CONCLUSIONS

This study has produced a considerable amount of useful information that is consistent with recent espacement studies on other species, and with the oldest white spruce espacement study in Canada Petawawa. Large growth differences among espacements were noted after 32 years. Wider espacements produced trees with larger diameters, crowns and branches. Total volume per hectare was greatest in the closest espacement. Mean height was less than for other British Columbia and the Ontario studies. However TIPSY predicted larger merchantable yields at culmination in this study, than those found in natural B.C. stands and the managed Ontario stands. Rotation ages for managed stands varied considerably. Given the delayed crown closure, height variability and MAI, our recommendation is for an optimum plantation density range of 1300–1600 stems per hectare.

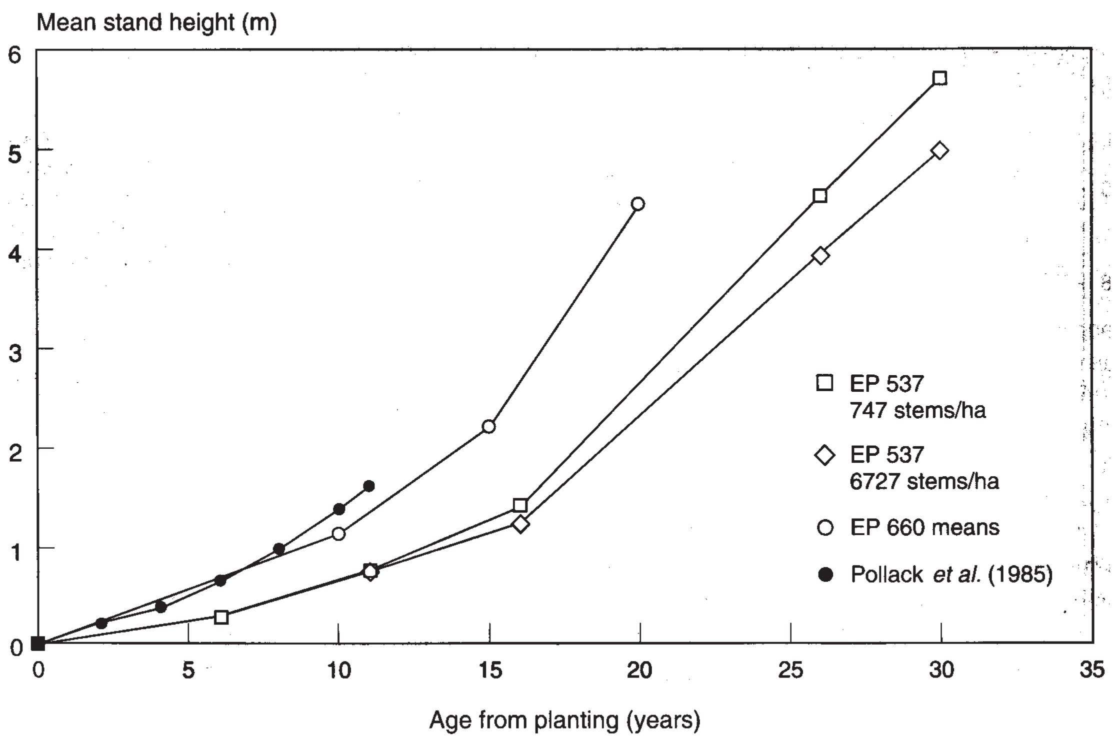

FIGURE 12. TIPSY 2.0 beta estimates of MAI and rotation age for EP 537.

REFERENCES

Bella, I.E. 1986. Spacing effects 20 years after planting three conifers in Manitoba. Environ. Can., Can. For. Serv., North. For. Res. Cent., Edmonton, Alta. For. Manage. Note 39.

Bella, I.E. and De Franceschi, J.P. 1980. Spacing effects 15 years after planting three conifers in Manitoba. Environ. Can., Can. For. Serv., North. For. Res. Cent., Edmonton, Alta. Inf. Rep. NOR-X-223.

Berry, A.B. 1978. Metric yield tables based on site class and spacing for white spruce plantations at the Petawawa Forest Experiment Station. Can. Dep. Environ., Can. For. Serv. Inf. Rep. PS-X-70F.

_________. 1987. Plantation white spruce variable density volume and biomass yield tables to age 60 at the Petawawa National Forestry Institute. Environ. Can., Can. For. Serv., Petawawa Nat. For. Inst., Petawawa, Ont. Inf. Rep. PI-X-71.

Eis, S., D. Craigdallie, and C. Simmons. 1982. Growth of lodgepole pine and white spruce in the central interior of British Columbia. Can. J. For. Res. 12:567-575.

Evert, F. 1984. An update (1970/71–1982) of the annotated bibliography on initial tree spacing. Environ. Can., Can. For. Serv. Petawawa Nat. For. Inst., Petawawa, Ont. Inf. Rep. PI-X-44.

Kiss, G. and F. Yeh. 1988. Heritability estimates for height for young interior spruce in British Columbia. Can. J. For. Res. 8:158–162.

Kovats, M. 1977. Estimating juvenile tree volumes for provenance and progeny testing. Can. J. For. Res. 7:335–342.

Larocque, G. and P.L. Marshall. 1988. Growth and yield of spruce in the inland mountain west: a literature review. In Proc. on Future Forests of the Mountain West: A Stand Culture Symp. U.S. Dep. Agric. For. Serv. Tech. Gen. Rep. INT-243, pp. 192–196.

Nienstaedt, H. and A. Teich. 1972. The genetics of white spruce. U.S. Dep. Agric. For. Serv. Res. Paper W0-15.

Ontario Ministry of Natural Resources. 1989. Forest research and management demonstration area: Thunder Bay spacing trial. Thunder Bay, Ont.

Pojar, J., R. Trowbridge, and D. Coates. 1984. Ecosystem classification and interpretation of the Sub-boreal spruce zone, Prince Rupert Forest Region, British Columbia. B.C. Min. For. Lands, Victoria, B.C. Land Manage. Rep. 17.

Pollack, J.C., F. van Thienen, and T. Nash. 1985. A plantation performance assessment guide for the Prince Rupert Forest Region. B.C. Min. For., Victoria, B.C. Land Manage. Rep. 35.

Rauscher, H.M. 1984. Growth and yield of white spruce plantations in the lake states. U.S. Dep. Agric. For. Serv. Res. Paper NC-253.

Sjolte-Jorgensen, J. 1967. The influence of spacing on the growth and development of coniferous plantations. Int. Rev. For. Res. 2:43–94.

Stiell, W.M. 1955. The Petawawa plantations. Can. Dep. North. Aff. Nat. Resour., For. Branch, For. Res. Div. Tech. Note 21. 46 p.

Stiell, W.M. 1986. Development of white spruce plantations at the Petawawa National Forestry Institute. Paper presented at 6th Internat. Workshop on Forest Regeneration at High Latitudes, Aug. 1984, Edmunston, N.B.

Stiell, W.M. and A.B. Berry. 1967. White spruce plantation growth and yield at the Petawawa Forest Experiment Station. Can. Min. For. Rural Development, For. Branch, Ottawa, Ont. Dep. Publ. 1200. 15 p.

_________. 1973. Development of unthinned white spruce plantations to age 50 at the Petawawa Forest Experiment Station. Can. Dep. Environ., Can. For. Serv., Ottawa, Ont. Publ. 1317. 18 p.

Thrower, J.S., A.F. Nussbaum, and M.M. Di Lucca. 1991. Site index curves and tables for British Columbia: interior species. B.C. Min. For., Victoria, B.C. Land Manage. Handbook Field Guide Insert 6.

Vyse, A. 1981. Growth of young spruce plantations in interior British Columbia. Forestry Chronicle 57:174–180.