RESPONSE OF UNEVEN-AGED INTERIOR DOUGLAS-FIR STANDS TO PRECOMMERCIAL THINNING IN CENTRAL INTERIOR, BRITISH COLUMBIA

by

TAEHEE LEE

B.Sc., Kyunghee Univ. Korea, 1998
M.Sc., Kookmin Univ. Korea, 2000

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

in

THE FACULTY OF GRADUATE STUDIES

(Forestry)

THE UNIVERSITY OF BRITISH COLUMBIA
(Vancouver)

April 2008

ABSTRACT

Proper management of uneven-aged interior Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) stands is important for British Columbia's central and southern interior. These stands constitute one of main components of the operable forest land in these areas, with easy access from main roads and towns. This study focused on the growth of uneven-aged Douglas-fir stands after pre-commercial thinning (spacing), with an impetus to improve upon current management practices. Data were collected from 24 permanent sample plots which were established near Williams Lake, British Columbia in 1989; thinning took place between 1990 and 1991. Three measurements have been made post-treatment: 1993, 1997 and 2004. The plot data were used to analyze different growth responses among three different spacing regimes (standard, 3 m clumped and 5 m clumped spacing) and a control. Analyses were performed at both the stand and tree level. The growth of basal area per ha, quadratic mean dbh, volume per ha and Lorey's height were used for stand level analyses. At the tree level, dbh, height, basal area and volume were the variables of interest.

At the stand level, mortality increased (7.1 to 107.1 stems/ha) and ingrowth decreased (2.4 to 8.6 stems/ha) for the second growth period (1997-2003), compared to the first growth period (5.8 to 107.1 stems/ha and 5.0 to 12.4 stems/ha, respectively). No significant differences in annual growth of quadratic mean dbh, basal area and volume per ha and Lorey's height were noted between the different spacing regimes and the control. At the individual tree level, the 5 m clumped spacing regime usually had the highest dbh, basal area and volume growth for both growth periods. The one exception was for height growth, when analyzed using mixed-effects modeling, where no significant differences were found. Trees on the other two spacing regimes also had higher growth in dbh, basal area, and volume than trees on the control plots.

The positive growth response to the spacing treatments at the single tree level was obtained without a reduction in growth at the stand level. This growth increase will result in the residual trees reaching larger sizes more quickly than they would have with no treatment, leading to improved mule deer winter range habitat and higher timber values.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGMENTS

The project on which this work is based was initiated by Dr. Peter Marshall.

I am grateful my supervisor, Dr. Peter Marshall and my committee members, Dr. Abdel-Azim Zumrawi, Dr Bruce Larson, and Mr. Ken Day for their recommendations and guidance throughout the course of my thesis. Many thanks to all of the people at the Alex Fraser Research Forest who helped with field work. I would also like to thank Dr Valerie Lemay for advice and help with statistical issues.

Finally I really thank my wife, Jin Lee and my mother, Wonsook Lee who supported and encouraged me throughout my thesis.

Taehee (Terry) Lee

April 2008

1. INTRODUCTION

1.1. THE INTERIOR DOUGLAS-FIR ZONE

Interior Douglas-fir (*Pseudotsuga menziesii* var. *glauca)* is an important tree species in the central interior of British Columbia because of its predominance in lower lying, easily accessible areas (Nigh 2004). Forests dominated by this species cover over 4 million ha of the BC interior (Bonnor 1990). In addition, forests in the interior Douglas-fir (IDF) zone provide grazing and recreation opportunities such as hiking and cross-country skiing to local residents. Since the central interior area is dry, interior Douglas-fir forests help to maintain sufficient water level in lakes for providing water to agriculture, cattle and residents (Hope *et al*. 1991). It also provides important winter habitat for the Rocky Mountain mule deer (*Odocoileus hemionus hemionus* Raf.).

The Knife Creek Block of the University of British Columbia's Alex Fraser Research Forest, where this study takes place, is managed for both timber and improving winter habitat for mule deer (Day 1998). Consequently, improving the growth of interior Douglas-fir without damage to the local environment is an important component of managing the forest.

Interior Douglas-fir is distributed throughout BC, the western United States, and Cordova, Mexico (Arno 1990). It is a moderately shade tolerant tree that grows to a maximum height of 35 m and 100 cm in dbh. It grows in climates that are dry and warm in the summer and mildly cold in the winter, with a range of precipitation from 300 mm to 600 mm (Vyse and Bonder 1990). The study area is located in the dry cool Interior

Douglas-fir subzone (IDFdk), which is one of seven IDF subzones included in the Biogeoclimatic Ecosystem Classification (BEC) of BC (Hope *et al*. 1991).

The IDF zone is distributed mainly in the former Cariboo Forest Region (approximately 16,860 km^2) in central BC and throughout the Kamloops and former Nelson Forest Regions in southern and southeastern BC, at elevations between 350 m and 1450 m (Hope *et al*. 1991). This zone has dry summers and long growing seasons; therefore, fire occurred frequently historically. Mean annual precipitation is normally between 300 and 750 mm, except for a few wetter areas. In most of this area, interior Douglas-fir is the dominant tree; however, Ponderosa pine (*Pinus ponderosa*) may be dominant on drier sites in the southern part of the region and interior spruce *(Picea glauca X englemanii*) may be dominant on wetter sites.

1.2. INDIVIDUAL TREE GROWTH

Sunlight and its interception for photosynthesis is the single most important factor in individual tree growth. However, water, ambient temperature, growing space and soil nutrients are also important (Oliver and Larson 1996). Tree growth for any species, irrespective of its shade-tolerance, increases with the intensity of sunlight until reaching a saturation point for the species (Botkin 1993). According to Botkin (1993) and Oliver and Larson (1996), growth rates vary with differing percentages of soil moisture and temperature under the same sunlight conditions. The availability of canopy space is the most important factor in crown growth and the ratio of live crown length. With a constant amount of sunlight, a larger crown resulting from an increase in canopy growing space provides more foliage surface area for photosynthesis. In other words, an increase in live crown length allows the tree to produce more energy and results in increased growth of the branches and the stem.

Tree height growth over age normally plots as a sigmoid curve. Tree height growth patterns are more constant relative to spacing than tree diameter growth (Oliver and Larson 1996). According to Wahlenberg (1946), the height growth of smaller trees is strongly correlated with tree vigor; more so than with spacing. Additionally, the height growth of larger trees has a stronger link with site productivity than with spacing, except for tremendously compact spacing (Hann and Ritchie 1988).

1.3. UNEVEN-AGED STAND DYNAMICS AND DENSITY CONTROL

Uneven-aged stands consist of many different sizes and ages of trees. Usually, these stands have an inverse J-shaped (negative exponential) dbh distribution (e.g., de Liocourt 1898, Leak 1964). Meyer (1952) found the average diminution quotient (q) of the number of trees in each dbh class that characterize balanced multi-aged diameter distributions based on de Liocourt's (1898) theories.

The density management of uneven-aged stands may be similar to that of even-aged stands except that dbh classes are usually explicitly considered. For example, Reineke's (1933) stand density index (SDI) has been widely used as an indicator of density in even-aged stands since the SDI equation only requires trees per ha and quadratic mean diameter (Dq). In uneven-aged stands, SDI may be calculated by dbh classes and summed to arrive at q-values (Long and Daniel 1990).

The growth rate of a tree depends mainly on the amount of photosynthesis which occurs and the amount of water and nutrients it receives (McWilliams and Thėrien 1996, Simpson 2000). The amount of photosynthesis which occurs depends on the percentage of crown area that is exposed to sunlight. Thinning allows residual trees to get more sunlight. However, if trees are spaced too widely, the total volume of trees on a site decreases despite the increase in the each volume of the residual trees. Appropriate spacing is also necessary for natural regeneration to occur (York *et al*. 2004).

There are many problems in determining the appropriate spacing for many tree species, including interior Douglas-fir. The structure of forests is variable; therefore, it is impractical to give all trees the same spacing treatment. Many other variables such as the size and width of individual tree crowns should be considered when deciding on suitable spacing. Dbh growth is definitely affected by growing space, but height growth, at least of the more dominant trees, is generally considered to be independent of spacing (Smith 1986, p. 69). Sometimes in the early stages of growth for an even-aged stand, there are different height growth rates between less dense and more dense stands; however, this difference is usually only temporary (Harrignton and Reukema 1983, and Hagglund 1981).

Selection cutting and thinning are based on the concept of growing spacing. Selection cutting may involve commercial harvesting and pre-commercial thinning at the same time. This is more efficient. The amount of thinning is often determined using the total basal area of the stand and the volume of trees present; therefore, the existing spacing among the trees is second priority.

Selection cutting is a useful approach in interior Douglas-fir forests for many reasons. It removes some trees that are merchantable and others that may never merchantable due to damage by insects or other disturbances or which may be too small to be merchantable. This often results in better dbh growth rates through increasing inter-tree spacing.

The purpose of thinning is to get better wood quality on average by removing defective trees and trees with higher DBH growth rates compared with untreated stands.

Thinning regimes are characterized by the quantity of trees removed (intensity), the length of time between thinnings (thinning cycle), and the type of thinning (Klinka and Carter, 1990). A number of researchers (e.g., Omule 1988; Marshall and Wang 1996; James 2001; York *et al*. 2004) have studied the optimal residual density of interior Douglas-fir. The BC Ministry of Forests has stocking guidelines covering thinning of interior Douglas-fir (Ministry of Forests 1992); however, the guidelines do not necessarily provide the best growth rates. The guidebook divides trees into four layers according to their dbh and Height: layer 1 trees are over 12.5 cm and layers 2, 3 and 4 are less than 12.5 cm. The guidebook also considers the horizontal structure of trees when spacing and indicates that the best spacing to keep between layers 2, 3, and 4 is a minimum of 2 m. One of the difficulties with using these four layers is that layer 1 is too wide to be of any practical use in prescribing treatment by dbh classes.

Barbour and Parry (2001) compared wood quality among thinned and unthinned interior Douglas-fir stands every 20 years. The wood from thinned stands was better than that from the unthinned stands in terms of log grade, visual lumber grades and machine stress-rated (MSR) lumber grades. In the same situation, unthinned stands had more volume than thinned stands (Omule, 1988); however, usually individual tree volume and quality are more important than total volume for timber production.

Information on mortality and ingrowth are important for spacing. Higher mortality rates and lower ingrowth rates than expected may not allow sufficient trees to be present to support stand growth at the expected level. Predicting accurate mortality and ingrowth rates help to ensure suitable space for the best growth rates of interior Douglas-fir. Van Hooser *et al*. (1990) found a 0.03% annual mortality rate and a 2% annual growth rate for the whole Interior Douglas-fir zone based on their analysis of the standing forest inventory. However, it is necessary to apply local mortality and ingrowth rates to specific areas to refine these averages. Uniformly thinned stands showed higher mortality rates and lower ingrowth rates than other types of thinning in uneven-aged interior Douglas-fir in this study area (Bugnot 1999). However, the difference between stands with different residual spatial structures was small.

1.4. MULE DEER

Mule deer (*Odocoileus hemionus*) are distributed across the western half of North America; from northern Mexico to southeast Alaska and southern Yukon, and from the Pacific coast to western Manitoba, Kansas, and northwest Texas (B. C. Ministry of Environment 2000).

The Knife Creek area is an important Mule deer winter range. Winter habitat for mule deer needs to provide food and shelter for warmth and protection from snow. Mule deer movements are limited when snow depth is over 30 cm and they cannot survive when there is more than 50 cm of snow (Simpson and Gyug 1991; Telfer and Kelsall 1979). As snowpack depth increases, the food source changes. For instance, the foliage of large interior Douglas-fir trees are consumed when the snow is deep; however, shrubs and small tree foliage are consumed when snow depth is shallow (Waterhouse *et al.*1993). During the summer, food quantity and variety is generally plentiful; however, during the winter, food is restricted to the foliage of big conifers (B. C. Ministry of Environment 2000). Mule deer prefer old growth interior-Douglas fir forests as winter habitat because the green foliage from large interior Douglas-fir trees provides food and shelter from snow.

1.5. OBJECTIVES AND ORGANIZATION OF THE THESIS

The purpose of this study is to determine the effect of different pre-commercial thinning (spacing) methods on the growth and development of interior Douglas-fir stands that were formerly diameter limit-logged. This experiment was analyzed by Bugnot (1999) using data obtained from the first re-measurement cycle following the thinning. This study will follow the general concepts and methods of Bugnot, but update the analysis to reflect a further seven years of growth. In addition, the height, dbh, basal area, and volume growth responses of individual trees within the treated stands will be assessed using a mixed-modeling approach.

The three null hypotheses used by Bugnot (1999) will be examined:

1. *Treatments do not affect stand growth in quadratic mean dbh, basal area per hectare, Lorey's height and volume per hectare.*
2. *Treatments do not affect individual tree growth in dbh, basal area, height and volume.*
3. *For each variable of interest examined at the individual-tree level, treatment response is not affected by initial dbh.*

The following chapter describes the methods followed. A summary of the data and the results of various analyses conducted are provided in Chapter 3. Chapter 4 contains a discussion of the results. Finally, the conclusion is found in Chapter 5.

2. METHODS

Parts of this chapter have been adapted from Marshall (1996) and Bugnot (1999).

2.1. STUDY AREA

The study area is found in the Knife Creek Block of the University of British Columbia's Alex Fraser Research Forest. The Knife Creek Block is located about 20 km southeast of Williams Lake, BC and lies in the Fraser Plateau physiographic subdivision (Figure 1). The Fraser Plateau is relatively flat with an elevation range between 900-1500 m; it covers the majority of the former Cariboo Region of the BC Ministry of Forests and Range. There are five tree species found on over the plots in the study: interior Douglas-fir, interior spruce (*Picea glauca* [Moench], *Picea engelmanni* Parry and their crosses), lodgepole pine (*Pinus contorta var. latifolia*), trembling aspen (*Populus tremnuloides* Michx) and white birch (*Betula papyrifera* Marsh). Interior Douglas-fir is the dominant tree species by basal area, followed by lodgepole pine and spruce (Bugnot 1999).

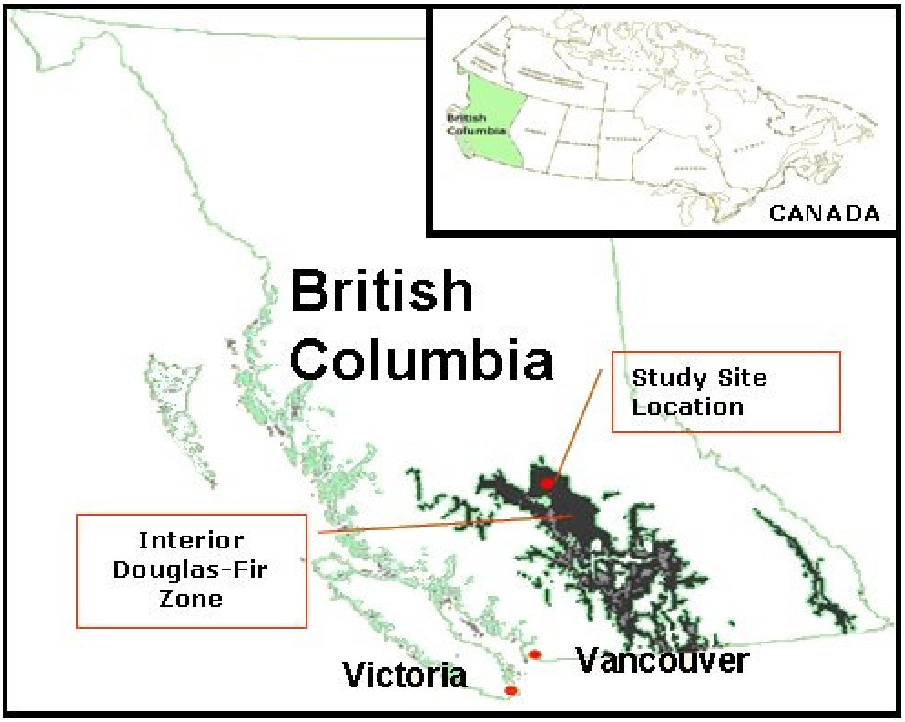


Figure 1. Study location.

2.2. STUDY DESIGN

Three blocks of approximately 40 hectares each were established: B, C and D (Figure 2). Block B is the driest site, Blocks C is moist, and Block D is the wettest site. Block B and C were dominated by interior Douglas-fir, while Block D was composed of mixtures of interior Douglas-fir, spruce and lodgepole pine on some plots, interior Douglas-fir was the secondary or tertiary species. These areas were logged in the 1950's and 1960's using a diameter limit which was assumed to be a minimum of 10 inches (25 cm). Therefore, stand structures today are dominated by small trees, with quite high densities in patches distributed over the stand. However, some larger trees remain.

Each block contains three treatments and a control, assigned randomly to each quarter. Two 500 m^2 sample plots were established in each treatment area; therefore, the total number of surveyed plots was 24 (2 plots × 4 treatments × 3 blocks; Figure 2). Each plot was located purposely in a dense portion of the area. Every plot had a 5 m buffer zone established around it, where all trees greater than 10 cm dbh were tagged and measured for dbh and height. Within the boundaries of the plots, all trees exceeding 1.3m in height were tagged and measured. The blocks are a few kilometres apart, along a west to east gradient; moisture levels increased from west to east. Each treatment area within a block had uniform environmental conditions.

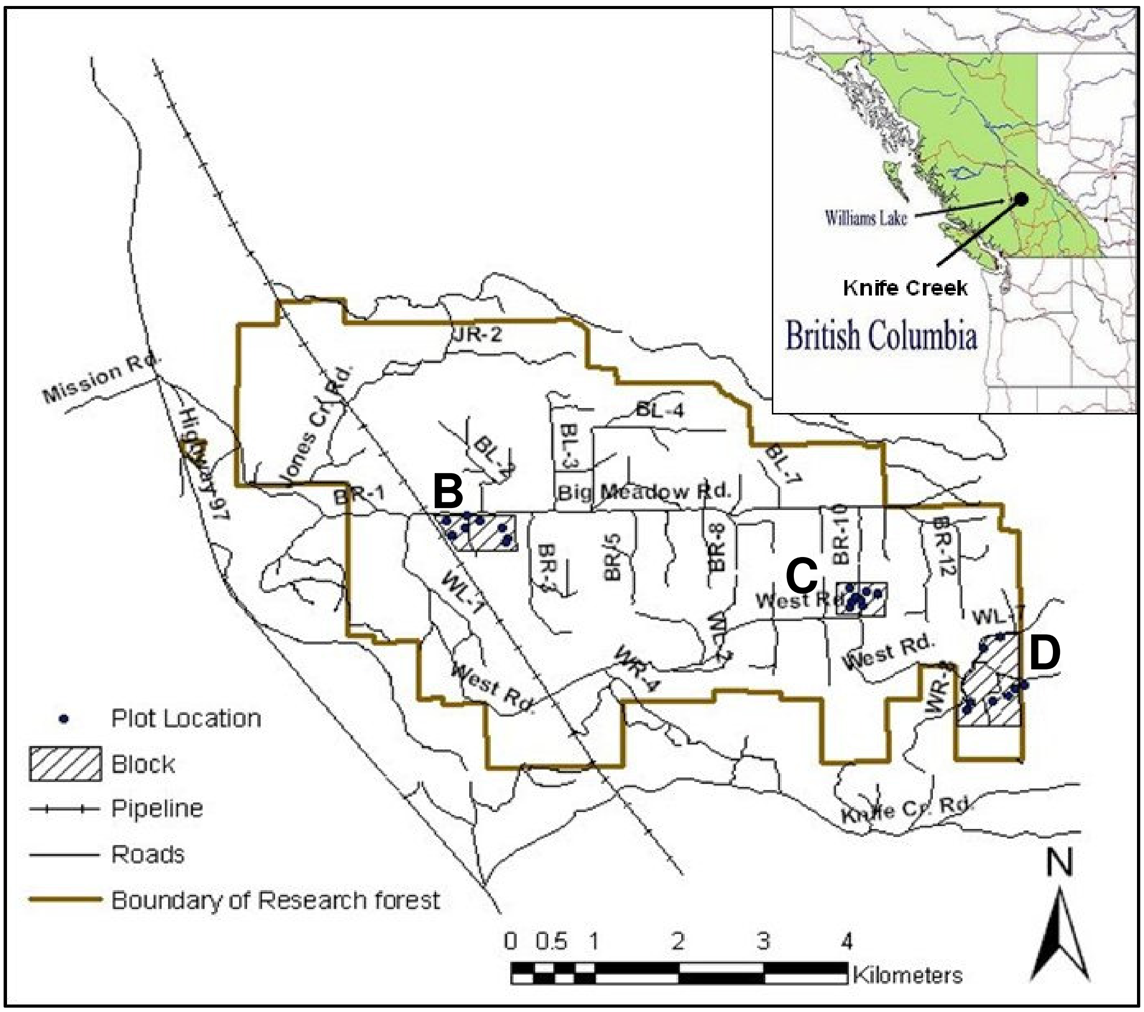


Figure 2. Block and plot locations at Knife Creek.

2.2.1.Treatments

The three pre-commercial thinning treatments were compared with a control. The thinnings were comprised of 3 m (C1) and 5 m (C2) clumped spacing and the standard (uniform) pre-commercial thinning regime prevalent in the early 1990s (S). The treatments were applied in the late fall and early winter of 1990/91. The pre-commercial thinning treatments are described in detail below (from Marshall, 1992).

i. ***Standard Spacing (S)*****:** This spacing followed the standards of the British Columbia Ministry of Forests in the early 1990s. At least 0.75 m was required between Douglas-fir and spruce trees less than 12.5 cm dbh, while 2.5 or 2.8 m was required for smaller trees of other species. In addition:

a. Any healthy Douglas-fir and spruce greater than 25 cm dbh was left standing in the treatment area.
b. Any Douglas-fir and spruce was left standing if it was between 12 and 25 cm dbh with at least 0.75 m spacing.
c. Trees less than 12 cm dbh were left standing if they had at least 0.75 m spacing and no crown competition.
d. Spacing for trees less than 12 cm dbh depended on species. For example, lodgepole pine was spaced to an optimum distance of 2.8 m with an allowed distance of 1.5 m to 4.0 m. Other species were spaced to an optimum distance of 2.5 m with a variation of 1.5 m to 3.5 m.
e. Spacing around the edges of openings with a diameter of 5 m or greater was reduced to the minimum spacing detailed in Rule d.
f. Douglas-fir and spruce less than 1.0 m in height and lodgepole pine less than 0.5 m in height were not cut.

ii. ***3m and 5m Clumped Spacings (C1 & C2)*****:** Each clump was intended to include three to nine trees of the same height class within a 3 m radius circle. The distance between each clump was either 3 m or 5 m. There were four categories of height considered: Class 1 – 1-3 m; Class 2 – 3-7 m; Class 3 – 7-15 m; and Class 4 – greater than 15 m. A total of 1113 trees per ha was estimated to be left in the 5 m clumped spacing and about 668 trees per ha were left in the 3 m clumped spacing. However, there were several exceptions such as:

a. The height class of the clump was chosen according to the height class of the healthiest trees present before spacing;
b. Douglas-fir, spruce and lodgepole pine that were shorter than 1.0 m within a clump were left standing, as were those trees larger than 25 cm dbh in any location;
c. In a clump, the optimum distance between trees was 2.1 m but a distance of 0.5 m to 2.5 m was allowed in order to include 7 trees on average in each clump;
d. As long as there was no crown competition, trees of a greater height class than the surrounding clump were left standing;
e. Any deciduous tree in crown completion with coniferous trees was cut or girdled;
f. Clumps with a height difference of at least 3 m could be left immediately adjacent to each other; and
g. Coniferous trees with a dbh over 25 cm and any deciduous trees outside of clumps did not affect the inter-clump distance.

iii. ***Control (C)*****:** No thinning was undertaken in these areas.

2.3. DATA

2.3.1.Site Characteristics

There are two BEC subzone variants in this study area: the interior Douglas-fir dry cool subzone (IDFdk3) and the sub-boreal pine-spruce moist cool subzone (SBPSmk) (Steen and Coupé 1997). According to Bugnot (1999), Blocks B and C are located in the IDFdk3 subzone variant and Block D is located in the SBPSmk subzone (Table 1).

Table 1. Site classification of blocks.

Block	Plots	Site series
B	1-8	IDFdk3/01 FdPl – Pinegrass - Feathermoss
C	17-24	IDFdk3/01 FdPl – Pinegrass - Feathermoss
D	9-16	SBPSmk/01 Pl – Pinegrass- Arnica

2.3.2.Measurements

The plots were established during the summers of 1989 and 1990 and treatments were applied in the fall and winter of 1990/1991. The most recent measurements took place from May through July 2004. Measurements were also made in 1993 and 1997. Each measurement was reflective of the tree size conditions as of the end of the previous growing season. The 1993 measurements involved re-establishing the plots following the thinning. The plots were originally located and trees recorded by dbh and species prior to the treatments. See Marshall (1996) for details on establishment, initial conditions, and the impact of the thinning treatments. Total height, dbh, crown diameter (in two directions), tree vigour, ingrowth and height to the live crown (in four quadrants) were measured on each tree. The 1997 and 2004 measurements of each tree are described in detail below.

i. ***Dbh*:**
Breast height was marked on each tree from prior measurements. For trees with a dbh of 5 cm or greater, a diameter tape was used and for trees less than 5 cm a small calipers were used. Dbh was recorded to the nearest 0.1 cm. Breast height was re-marked using blue spray paint.

ii. ***Total height*:**
A height pole was used for measuring the height of shorter trees (less than 8 m) and an Impulse laser dendrometer or an ultrasonic Vertex hypsometer was used measuring height on taller trees. The Vertex dendrometer was primarily used in dense areas. Heights were recorded to the nearest 0.1 m.

iii. ***Height to the base of the live crown*:**
This was measured on four sides of each tree starting at the tagged side and moving 90 degrees for each subsequent measurement in a clockwise direction. Height to the base of the live crown was recorded to the nearest 0.1 m.

iv. ***Crown diameter*:**
This was measured in two directions: parallel to the tagged side and at 90 degrees from the tagged side. Crown diameter was recorded to the nearest 0.5 m.

v. ***Tree vigour*:**
Tree vigour was divided into four categories using the quality and quantity of each tree's foliage and the shape of its crown using the system described in Marshall (1996) and Bugnot (1998): 0 indicated that the tree was dead; 1 indicated that the tree was alive, but had little potential for future development; 2 indicated moderate potential for development; and 3 indicated good potential for development.

vi. ***Ingrowth*:**
Any tree which had reached a height of at least 1.3 m since the last measurement was tagged, measured, its species recorded, and its location was mapped.

Missing tags were replaced and tags were added to the ingrowth trees during the field work. Along the 5 m boundaries for each plot, trees which had reached 10 cm dbh during the measurement period were measured, tagged, and marked with blue paint to facilitate re-location of the plots.

2.4. DERIVED ATTRIBUTES

Several attributes were derived for analysis from the data gathered in the field work:

i. ***Quadratic mean diameter (QMD)*:**

the dbh, measured in cm, of the tree of average basal area. It was calculated as:

$$D_q = (\sum_{i=1}^{N} dbh_i^2 / N)^{0.5}$$

where N is the number of trees in the plot.

ii. ***Basal Area (BA):***

the cross-sectional area of trees on a plot at breast height measured in m^2.

$$BA/ha = \sum_{i=1}^{N} (dbh_i / 200)^2 \times \pi \times 20$$

iii. ***Volume*****:**

The volumes of each species were estimated using the appropriate provincial volume equation (B.C. Forest Service 1976).

iv. ***Relative Density (RD)*****:**

Curtis' (1982) relative density was calculated for each plot as:

RD = (basal area per ha) / (square root of Dq)

v. ***Stand Density Index (SDI)*****:**

One of Reineke's (1933) standard density indices, given by Long (1985), was calculated:

$$\text{SDI} = (\text{stems per ha}) \times (\text{Dq}/25)^{1.6}$$

vi. ***Lorey's height*****:**

a mean height, with the individual trees weighted proportionally to basal area (Van Laar and Akca 1997, p. 146) (i.e., the height of the tree of average basal area)

$$\text{Lorey's height} = (\sum(H_i)(BA_i)) / (\sum(BA_i))$$

vii. ***Biomass*****:**

Biomass of Interior Douglas-fir was based on equations provided by Marshall and Wang (1996). Different equations were applied to small and large trees. Biomass of other species was calculated using equations from Standish *et al*. (1985). Biomass of each species was calculated for wood, bark, branches, foliage and all above-ground components together. The biomass equations used were developed for trees larger than 5 cm dbh; thus, some trees with a dbh less than 5 cm could have negative values. Negative values were set to zero.

These attributes were calculated using SAS® (Version 9.1) and summarized using MS Excel® (Version 2003).

2.5. ANALYSIS

2.5.1.Variables of Interest

Variables of interest in this study were divided into stand level variables and tree level variables. Change at the stand level was calculated using quadratic mean dbh, basal area per hectare, Lorey's height, volume per hectare and biomass per ha. Data from the two growth periods (1993 to 1996 and 1997 to 2003) were used and growth rates were compared by treatments.

The growth of individual trees was calculated using dbh, basal area, height and stem and volume. Tree measurements from 2004 (following the 2003 growing season) were linked with tree measurements from 1993 and 1996. Trees that were dead before the 2004 measurement were removed from the analysis for this study. However, pine trees recently killed by mountain pine beetle (MPB) were included in the stand level analysis; these pine trees were not killed by competition induced mortality and introduced considerable variability into the analysis, independent of the impact of the thinning treatments.

2.5.2.Statistical Methods

The second and third null hypotheses, which are related to individual tree growth, were initially tested the methods described by Bugnot (1999), by species and by dbh class. Bugnot (1999) used 5 cm dbh classes up to 15 cm; trees over 15 cm dbh were considered as a single group. In this study, trees were divided into three dbh groups (0 to 10 cm, 10 to 20 cm and over 20 cm). Species groups for testing the second and third null hypothesis were interior Douglas-fir alone, all other species, and all species together.

For testing for differences among treatments at the single tree level following the approach of Bugnot (1999), analysis of variance (ANOVA) was applied. This analysis used a randomized complete block design with three blocks, four treatments and two plots. The linear model with a number of observations per experimental unit was:

$$Y_{ijl} = \mu + \beta_i + \tau_j + \varepsilon_{ij} + \omega_{(ij)l} \qquad [2]$$

where Y_{ijl} = the observation on the tree *l* from the block *i* on treatment *j;* μ = the overall population mean; β_i = the effect of block *i;* τ_j = the effect of treatment *j*; ε_{ij} = the experimental error in treatment *j* on block *i; and* $\omega_{(ij)l}$ = the sampling error within block *i* and treatment *j.*

There are two main assumptions which should be met before ANOVA is applied to the results of this study. The first assumption is that variables in each treatment are normally distributed. The other assumption is that the variances are homogeneous; in other words, variances in each treatment should be similar. Bartlett's test (Snedecor and Cochran 1980, p .252) was used to test for homogeneity of variances. Scheffé's test (Hicks 1993, p.63) was used to perform multiple comparisons among the treatment means.

Also, an analysis of covariance (ANACOVA) was used to check whether differences in individual tree growth response to treatments were related to initial dbh (data measured in 1993). For multiple comparison tests of unequal sized samples, Scheffé's test (Hicks 1993, p.63) was used. Where data sets showed equal slopes of the regression line, adjusted means were used for comparison purpose.

Subsequently, a mixed effect model was fit to dbh, height, basal area and stem volume growth. The form of the model was:

$$y = X\beta + Z\gamma + \varepsilon \qquad [1]$$

where y = annual growth of dbh, height, basal area or stem volume during 11 year growing period or in each measurement period; β = fixed coefficients; X = initial dbh, height, basal area or stem volume at the beginning of the period which was treated as a fixed effect; γ = random effect coefficients; Z = block, block $\times$ treatment and plot within block $\times$ treatment used as random effects; and ε = model error.

For comparing the annual growth of the two measurement periods, the measurement periods (time) and the interaction between time and initial dbh or height were added as fixed effects to model [1]. Consequently, X became initial dbh or height, time, time $\times$ initial dbh or height, and treatment.

The mixed-effect model more appropriately incorporated the various factors that may influence tree growth. Separating fixed and random effects should provide a better overall explanation by the whole model (Littell *et al*. 2006). In this study, random effects were considered to be the block, the interaction between block and treatment, and the interaction between plots within the same treatment and block.

Increasingly restrictive subsets of trees were used in fitting this model. The least restrictive dataset consisted of all undamaged trees. The model was then refit using only the conifer species, and finally only with Douglas-fir. Then only the trees growing in the most prevalent size classes (between 2.5 cm and 17.5 cm) were considered. This range was divided into three 5-cm dbh classes and the “best X” Douglas-fir trees in each class in each plot were selected, with “best” defined as those trees growing the fastest. Subsets of up to 75, 50, 30, 25, 20, and 15 trees in each dbh class were considered. If a dbh class contained less than X trees, then all the undamaged Douglas-fir trees in that class were used.

All statistical analyses were performed using SAS 9 (version 9.1) with significance level (α) set to 0.05. MS Excel (version 2003) was used for performing basic calculations and cleaning data.

3. RESULTS

3.1.GENERAL FEATURES

3.1.1.Plot Conditions

Plot-level summaries for each measurement year (density, basal area, quadratic mean dbh (QMD), Curtis' (1982) relative density (RD), Lorey's height and volume) are shown in Tables 2, 3 and 4. The 1993 and 1997 plot summaries are adapted from Bugnot (1999). Not surprisingly, the control plots have higher densities than the spaced plots; the control plots were followed by the 3 m clumped spacing plots, the standard spacing plots and the 5 m clumped spacing plots in order of declining density. The patterns of basal area, QMD, RD and volume are identical through time; however, Lorey's height had a different pattern in the 3 m clumped and 5 m clumped plots. The average Lorey's height of the 3 m clumped spacing plots was lower than that of the 5 m clumped plots in 1993 and 1996; however, it was identical for these treatments in 2004.

The percentage composition of interior Douglas-fir by basal area increased with time, especially between 1997 and 2004. This recent increase is primarily due to some or the entire lodgepole pine component in some plots being killed by mountain pine beetle (MPB) attack. For instance, lodgepole pine contributed 26 percent of the basal area in plot 5 in 1997, but the plot was changed to essentially a pure interior Douglas-fir stand in 2003. The amount of living lodgepole pine was most reduced by MPB attack on plots 5, 8, 9, 15, 18, 23 and 24. This will affect the future growth on these plots since the mortality will reduce crown competition and provide more space for small tree development. Table

Table 2. Summary of plot conditions at the time of the1993 measurement (adapted from Bugnot 1999).

Treatment	Block	Plot	Density (tree/ha)	Basal Area (m^2/ha)	QMD (cm)	Relative Density	Lorey's Height (m)	Volume (m^3/ha)	Species Composition (% Basal Area)
Control	B	3	10,460	43.7	7.3	16.2	10.6	188.3	$Fd_{99}Pl_{1}$
(C)		4	8,240	39.8	7.8	14.2	10.4	166.9	$Fd_{96}Pl_{4}$
	D	15	5,500	36.2	9.1	12.0	12.0	179.0	$Fd_{65}Pl_{11}Sx_{4}At_{6}Ep_{14}$
		16	4,340	33.6	9.9	10.7	14.1	194.8	$Fd_{31}Sx_{59}At_{3}Ep_{7}$
	C	19	5,600	32.9	8.6	11.2	9.7	126.9	$Fd_{95}Sx_{3}Ep_{2}$
		20	5,480	32.4	8.7	11.0	10.0	131.0	$Fd_{78}Pl_{9}At_{6}Ep_{7}$
		Avg.	**6,603**	**36.4**	**8.4**	**12.6**	**11.1**	**164.5**	
3m	B	1	2,260	18.0	10.1	5.7	9.8	70.6	Fd_{100}
Clumped		2	1,960	26.7	13.2	7.4	13.0	135.2	Fd_{100}
spacing	D	11	3,100	36.8	12.3	10.5	15.3	230.0	$Fd_{44}Pl_{4}Sx_{43}At_{9}$
(C1)		12	2,300	27.2	12.3	7.8	12.4	138.7	$Fd_{61}Sx_{39}$
	C	21	2,440	24.7	11.3	7.3	13.2	129.8	$Fd_{59}Pl_{15}Sx_{5}At_{0}Ep_{21}$
		22	2,800	22.6	10.1	7.1	12.2	108.3	$Fd_{67}Pl_{13}Sx_{4}At_{4}Ep_{16}$
		Avg.	**2,477**	**26.0**	**11.6**	**7.6**	**12.7**	**135.4**	
5m	B	5	2,060	25.2	12.5	7.1	15.2	153.2	$Fd_{72}Pl_{28}At_{0}$
Clumped		6	1,400	22.4	14.3	5.9	16.1	126.1	Fd_{100}
spacing	D	13	1,500	18.9	12.7	5.3	11.8	89.5	$Fd_{80}Pl_{20}At_{0}$
(C2)		14	1,240	18.4	13.7	5.0	14.1	116.0	$Fd_{24}Pl_{67}Sx_{9}$
	C	17	1,140	14.8	12.9	4.2	11.0	63.0	$Fd_{72}Pl_{15}Sx_{5}Ep_{9}$
		18	1,280	14.7	12.1	4.2	10.5	61.0	$Fd_{701}Pl_{13}Sx_{8}At_{0}Ep_{9}$
		Avg.	**1,437**	**19.1**	**13.0**	**5.3**	**13.5**	**101.5**	
Standard	B	7	1,940	26.3	13.1	7.2	11.8	120.3	Fd_{100}
spacing		8	1,720	22.9	13.0	6.3	13.5	123.5	$Fd_{84}Pl_{16}$
(S)	D	9	2,300	25.7	11.9	7.4	14.1	149.4	$Fd_{77}Pl_{23}At_{0}$
		10	1,860	23.7	12.7	6.6	13.0	120.2	$Fd_{86}Pl_{14}Ep_{0}$
	C	23	1,720	27.5	14.3	7.3	18.0	193.6	$Fd_{76}Pl_{24}Sx_{0}At_{0}Ep_{0}$
		24	1,440	21.2	13.7	5.7	14.3	122.9	$Fd_{76}Pl_{24}$
		Avg.	**1,830**	**24.6**	**13.1**	**6.8**	**14.2**	**138.3**	

Table 3. Summary of plot conditions at the time of the 1997 measurement (adapted from Bugnot 1999).

Treatment	Block	Plot	Density (tree/ha)	Basal Area (m^2/ha)	QMD (cm)	Relative Density	Lorey's Height (m)	Volume (m^3/ha)	Species Composition (% Basal Area)
Control	B	3	9,780	45.7	7.7	16.5	11.1	206.0	$Fd_{99}Pl_{1}$
(C)		4	7,960	42.3	8.2	14.8	10.9	184.4	$Fd_{97}Pl_{3}$
	D	15	5,400	37.5	9.4	12.2	12.7	195.0	$Fd_{68}Pl_{12}Sx_{4}At_{3}Ep_{13}$
		16	4,000	35.2	10.6	10.8	14.8	213.3	$Fd_{32}Sx_{59}At_{3}Ep_{6}$
	C	19	5,440	36.6	9.3	12.0	10.6	152.4	$Fd_{95}Sx_{3}Ep_{2}$
		20	5,180	35.3	9.3	11.6	10.7	150.8	$Fd_{80}Pl_{9}At_{4}Ep_{7}$
		Avg.	**6,293**	**38.8**	**8.9**	**13.0**	**11.7**	**183.7**	
3m	B	1	2,260	22.9	11.4	6.8	10.8	98.3	Fd_{100}
Clumped		2	1,960	29.9	13.9	8.0	13.8	158.4	Fd_{100}
spacing	D	11	3,040	39.7	12.9	11.1	16.1	259.8	$Fd_{44}Pl_{4}Sx_{43}At_{9}$
(C1)		12	2,280	30.8	13.1	8.5	13.4	168.9	$Fd_{62}Sx_{38}$
	C	21	2,380	27.9	12.2	8.0	13.8	153.0	$Fd_{60}Pl_{15}Sx_{5}At_{0}Ep_{20}$
		22	2,720	25.9	11.0	7.8	13.1	132.5	$Fd_{67}Pl_{15}Sx_{4}Ep_{14}$
		Avg.	**2,440**	**29.5**	**12.4**	**8.4**	**13.5**	**161.8**	
5m	B	5	2,040	28.6	13.3	7.8	14.8	166.2	$Fd_{74}Pl_{26}At_{0}$
Clumped		6	1,400	25.4	15.2	6.5	16.3	145.2	Fd_{100}
spacing	D	13	1,420	22.3	14.1	5.9	12.8	113.3	$Fd_{80}Pl_{20}At_{0}$
(C2)		14	1,280	21.8	14.7	5.7	14.9	143.5	$Fd_{25}Pl_{65}Sx_{10}$
	C	17	1,200	18.6	14.0	5.0	11.9	85.1	$Fd_{72}Pl_{14}Sx_{6}Ep_{9}$
		18	1,440	18.5	12.8	5.2	11.2	80.9	$Fd_{72}Pl_{11}Sx_{8}At_{0}Ep_{9}$
		Avg.	**1,463**	**22.5**	**14.0**	**6.0**	**13.9**	**122.4**	
Standard	B	7	1,920	29.7	14.0	7.9	12.6	144.9	Fd_{100}
spacing		8	1,680	25.9	14.0	6.9	14.2	145.8	$Fd_{85}Pl_{15}$
(S)	D	9	2,400	28.4	12.3	8.1	14.7	170.8	$Fd_{77}Pl_{23}At_{0}$
		10	1,920	27.0	13.4	7.4	13.6	143.1	$Fd_{87}Pl_{13}Ep_{0}$
	C	23	1,740	30.3	14.9	7.8	18.2	213.3	$Fd_{77}Pl_{23}Sx_{0}At_{0}Ep_{0}$
		24	1,420	25.4	15.1	6.5	15.0	152.0	$Fd_{77}Pl_{23}$
		Avg.	**1,847**	**27.8**	**13.8**	**7.5**	**14.8**	**161.7**	

Table 4. Summary of plot conditions at the time of the 2004 measurement.

Treatment	Block	Plot	Density (tree/ha)	Basal Area (m^2/ha)	QMD (cm)	Relative Density	Lorey's Height (m)	Volume (m^3/ha)	Species Composition (% Basal Area)
Control	B	3	8,380	49.4	8.7	16.8	12.1	242.6	Fd_{100}
(C)		4	7,120	47.1	9.2	15.5	12.0	228.0	$Fd_{97}Pl_{3}$
	D	15	4,960	41.3	10.3	12.9	13.7	251.3	$Fd_{71}Pl_{11}Sx_{4}At_{3.1}Ep_{11}$
		16	3,220	36.3	12.0	10.5	16.3	250.7	$Fd_{34}Sx_{58}At_{3}Ep_{6}$
	C	19	4,960	41.3	10.3	12.9	12.6	207.2	$Fd_{97}Sx_{3}Ep_{1}$
		20	4,600	40.1	10.5	12.3	12.6	214.6	$Fd_{82}Pl_{9}At_{3}Ep_{6}$
		Avg.	**5,540**	**42.6**	**10.2**	**13.5**	**13.2**	**232.4**	
3m	B	1	2,260	28.7	12.7	8.0	12.6	142.1	Fd_{100}
Clumped		2	1,920	34.1	15.0	8.8	14.8	192.9	Fd_{100}
spacing	D	11	2,920	44.3	13.9	11.9	17.8	319.9	$Fd_{45}Pl_{4}Sx_{43}At_{9}$
(C1)		12	2,240	36.3	14.4	9.6	15.4	227.4	$Fd_{63}Sx_{37}$
	C	21	2,160	31.5	13.6	8.5	15.5	222.3	$Fd_{63}Pl_{15}Sx_{5}At_{0}Ep_{16}$
		22	2,660	31.3	12.2	8.9	15.0	203.6	$Fd_{68}Pl_{15}Sx_{4}Ep_{13}$
		Avg.	**2,360**	**34.4**	**13.6**	**9.3**	**15.2**	**218.0**	
5m	B	5	1,800	25.1	13.3	6.9	14.7	138.0	Fd_{100}
Clumped		6	1,400	29.3	16.3	7.3	17.9	185.6	Fd_{100}
spacing	D	13	1,400	27.6	15.8	6.9	14.7	162.4	$Fd_{82}Pl_{18}$
(C2)		14	1,240	26.4	16.5	6.5	16.6	201.1	$Fd_{28}Pl_{62}Sx_{10}$
	C	17	1,280	23.7	15.3	6.0	13.9	134.6	$Fd_{73}Pl_{14}Sx_{7}Ep_{7}$
		18	1,500	23.1	14.0	6.2	13.3	127.7	$Fd_{78}Pl_{7}Sx_{7}Ep_{9}$
		Avg.	**1,437**	**25.9**	**15.2**	**6.6**	**15.2**	**158.3**	
Standard	B	7	1,880	34.4	15.3	8.8	14.0	185.1	Fd_{100}
spacing		8	1,580	27.7	15.0	7.2	14.7	158.6	$Fd_{94}Pl_{6}$
(S)	D	9	2,020	29.2	13.6	7.9	14.9	176.9	$Fd_{86}Pl_{14}$
		10	1,860	32.2	14.8	8.4	14.9	188.9	$Fd_{88}Pl_{12}$
	C	23	1,720	27.9	14.4	7.4	18.6	191.0	$Fd_{99}Pl_{1}Sx_{1}$
		24	1,300	25.6	15.8	6.4	15.8	155.6	$Fd_{96}Pl_{5}$
		Avg.	**1,727**	**29.5**	**14.8**	**7.7**	**15.5**	**176.0**	

5 shows the adjusted 2004 plot summaries, including dead lodgepole pine trees to allow comparison among the treatments without the confounding effect of the MPB-induced lodgepole pine mortality.

The tree biomass (wood, bark, branches, foliage and total above ground biomass) on each plot in each measurement year is summarized in Tables 6, 7 and 8. From the onset of this study, they were highest on the control plots and the lowest on the 5 m clumped spacing plots. The 3 m clumped spacing plots and the standard spacing plots had similar values up to the 1997 measurement; however, the total biomass of the 3 m clumped spacing plots was larger than that of the standard spacing plots in 2004 as a result of lodgepole pine mortality caused by MPB attack. The 2004 measurement data, with the MPB-killed lodgepole pine added back in, is given in Table 9.

Table 10 shows Long's (1985) suggestions for self-thinning limits in pure even-aged stands by the percentage of Reineke's (1933) stand density index (SDI). Bugnot (1999) used this concept when comparing the three treated plots with the control. Table 11 provides the SDI of each treatment and the control by measurement year. There were gradually increasing SDI values in all treatments and the control over time. According to Long's (1985) values, the SDIs for all treatments were at least slightly over the lower limit of "full site occupancy" and below the lower limit of self-thinning in 1993 and 1997. The SDI for the control plots was always over the lower limit of self-thinning in any measurement year. The SDI of treatment C1 was just over the lower limit of the self-thinning level in 2004.

Table 5. Summary of plot conditions at the time of the 2004 measurement (including the lodgepole pine trees killed by the mountain pine beetle).

Treatment	Block	Plot	Density (tree/ha)	Basal Area (m^2/ha)	QMD (cm)	Relative Density	Lorey's Height (m)	Volume (m^3/ha)	Species Composition (% Basal Area)
Control	B	3	8,380	49.4	8.7	16.8	12.1	242.6	Fd_{100}
(C)		4	7,120	47.1	9.2	15.5	12.0	228.0	$Fd_{97}Pl_{3}$
	D	15	4,960	41.3	10.3	12.9	13.7	251.3	$Fd_{71}Pl_{11}Sx_{4}At_{3.1}Ep_{11}$
		16	3,220	36.3	12.0	10.5	16.3	250.7	$Fd_{34}Sx_{58}At_{3}Ep_{6}$
	C	19	4,960	41.3	10.3	12.9	12.6	207.2	$Fd_{97}Sx_{3}Ep_{1}$
		20	4,600	40.1	10.5	12.3	12.6	214.6	$Fd_{82}Pl_{9}At_{3}Ep_{6}$
		Avg.	**5,540**	**42.6**	**10.2**	**13.5**	**13.2**	**232.4**	
3m	B	1	2,260	28.7	12.7	8.0	12.6	142.1	Fd_{100}
Clumped		2	1,920	34.1	15.0	8.8	14.8	192.9	Fd_{100}
spacing	D	11	2,940	44.5	13.9	11.9	17.8	319.9	$Fd_{45}Pl_{4}Sx_{43}At_{9}$
(C1)		12	2,240	36.3	14.4	9.6	15.4	227.4	$Fd_{63}Sx_{37}$
	C	21	2,160	31.5	13.6	8.5	15.5	222.3	$Fd_{63}Pl_{15}Sx_{5}At_{0}Ep_{16}$
		22	2,660	31.3	12.2	8.9	15.0	203.6	$Fd_{68}Pl_{15}Sx_{4}Ep_{13}$
		Avg.	**2,363**	**34.4**	**13.6**	**9.3**	**15.2**	**218.2**	
5m	B	5	1,960	25.2	12.8	7.0	14.7	199.9	$Fd_{78}Pl_{22}$
Clumped		6	1,400	29.3	16.3	7.3	17.9	185.6	Fd_{100}
spacing	D	13	1,400	27.6	15.8	6.9	14.7	162.4	$Fd_{82}Pl_{18}$
(C2)		14	1,240	26.4	16.5	6.5	16.6	201.1	$Fd_{28}Pl_{62}Sx_{10}$
	C	17	1,280	23.7	15.3	6.0	13.9	134.6	$Fd_{73}Pl_{14}Sx_{7}Ep_{7}$
		18	1,520	24.0	14.2	6.4	13.3	133.1	$Fd_{75}Pl_{10}Sx_{7}Ep_{8}$
		Avg.	**1,467**	**27.2**	**15.4**	**6.9**	**15.3**	**169.5**	
Standard	B	7	1,880	34.4	15.3	8.8	14.0	185.1	Fd_{100}
spacing		8	1,620	30.3	15.4	7.7	16.3	200.0	$Fd_{86}Pl_{24}$
(S)	D	9	2,060	32.2	14.1	8.6	15.8	210.0	$Fd_{78}Pl_{22}$
		10	1,860	32.2	14.8	8.4	14.9	188.9	$Fd_{88}Pl_{12}$
	C	23	1,840	34.7	15.5	8.8	19.4	263.0	$Fd_{80}Pl_{20}$
		24	1,400	30.5	16.6	7.5	16.3	200.0	$Fd_{80}Pl_{20}$
		Avg.	**1,777**	**32.4**	**15.3**	**8.3**	**15.9**	**205.0**	

Table 6. Biomass of various tree components at the 1993 measurement (tonnes/ha) (adapted from Bugnot 1999).

Treatment	Block	Plot	Wood	Bark	Branches	Foliage	Total
Control	B	3	107.1	22.8	18.4	15.6	145.8
(C)		4	92.2	21.1	16.6	13.3	128.1
	D	15	96.0	18.4	17.1	11.2	129.1
		16	87.8	18.2	14.4	16.7	136.8
	C	19	69.2	17.9	12.5	10.1	96.7
		20	69.9	17.2	12.8	10.0	99.4
		Avg.	**87.0**	**19.3**	**15.3**	**12.8**	**122.7**
3m Clumped	B	1	41.9	9.9	7.4	5.0	57.1
spacing		2	75.8	17.5	9.0	8.7	104.3
(C1)	D	11	106.9	20.2	20.1	16.1	161.2
		12	66.8	14.2	16.4	11.3	104.4
	C	21	67.0	13.3	11.4	8.2	96.7
		22	53.1	12.0	8.3	7.7	77.8
		Avg.	**68.6**	**14.5**	**12.1**	**9.5**	**100.2**
5m Clumped	B	5	78.1	14.8	11.1	8.4	108.3
spacing		6	68.8	18.2	15.0	6.1	105.7
(C2)	D	13	48.0	11.3	8.2	5.6	68.1
		14	59.7	7.1	11.6	7.1	84.1
	C	17	31.9	8.7	7.4	4.8	50.2
		18	31.0	8.0	7.8	4.6	47.1
		Avg.	**52.9**	**11.4**	**10.2**	**6.1**	**77.3**
Standard	B	7	68.0	16.9	10.6	7.8	94.0
spacing		8	67.3	13.5	11.5	8.9	92.4
(S)	D	9	81.9	13.9	10.5	8.2	108.9
		10	65.8	14.4	11.9	7.0	92.8
	C	23	97.7	18.2	11.3	8.9	135.5
		24	67.0	12.1	10.9	7.0	92.2
		Avg.	**74.6**	**14.9**	**11.1**	**7.9**	**102.6**

Table 7. Biomass of various tree components at the 1997 measurement (tonnes/ha) (adapted from Bugnot 1999).

Treatment	Block	Plot	Wood	Bark	Branches	Foliage	Total
Control	B	3	118.6	24.7	20.1	16.5	161.2
(C)		4	102.9	23.1	17.6	13.8	141.4
	D	15	106.1	19.7	17.1	12.6	141.6
		16	96.4	19.3	18.8	17.6	151.2
	C	19	83.0	20.8	13.8	12.2	116.1
		20	81.5	19.4	15.2	11.4	114.6
		Avg.	**98.1**	**21.2**	**17.1**	**14.0**	**137.7**
3m Clumped	B	1	57.7	13.5	9.0	8.2	79.3
spacing		2	88.1	20.0	12.0	10.7	121.3
(C1)	D	11	120.2	22.2	23.2	18.0	179.7
		12	81.8	16.7	23.6	15.7	126.6
	C	21	80.1	15.8	15.0	9.5	117.0
		22	66.2	14.7	12.0	8.6	96.6
		Avg.	**82.3**	**17.2**	**15.8**	**11.8**	**120.1**
5m Clumped	B	5	87.3	17.3	18.2	11.4	123.4
spacing		6	78.7	20.8	17.7	8.0	120.7
(C2)	D	13	59.8	13.8	7.5	7.8	85.2
		14	73.0	8.7	14.3	8.3	102.5
	C	17	41.9	11.4	9.1	6.1	64.9
		18	40.0	10.7	9.5	6.3	60.5
		Avg.	**63.4**	**13.8**	**12.7**	**8.0**	**92.9**
Standard		7	81.3	19.6	12.1	10.2	112.7
spacing	B	8	79.1	15.8	15.3	10.5	108.9
(S)	D	9	93.1	16.0	11.9	10.0	124.2
		10	77.6	17.0	13.5	9.7	109.8
	C	23	108.5	21.0	15.3	10.2	151.1
		24	82.1	15.4	13.9	9.4	114.4
		Avg.	**86.9**	**17.5**	**13.7**	**10.0**	**120.1**

Table 8. Biomass of various tree components at the 2004 measurement (tonnes/ha).

Treatment	Block	Plot	Wood	Bark	Branches	Foliage	Total
Control (C)	B	3	141.3	27.5	50.2	24.0	230.4
		4	131.0	27.1	27.3	18.4	208.9
	D	15	144.8	25.7	34.2	15.7	214.1
		16	141.2	22.5	27.2	9.3	200.5
	C	19	117.7	25.3	22.2	15.9	178.2
		20	122.1	24.7	29.8	15.5	184.1
		Avg.	**133.0**	**25.5**	**31.8**	**16.5**	**202.7**
3m Clumped spacing (C1)	B	1	82.5	18.1	30.3	14.9	123.8
		2	106.2	23.9	29.0	16.2	154.6
	D	11	193.2	30.3	32.0	14.3	266.5
		12	131.4	21.7	22.8	13.1	182.4
	C	21	122.9	22.2	29.4	11.7	176.2
		22	111.4	22.0	23.1	11.0	161.3
		Avg.	**124.6**	**23.0**	**27.8**	**13.5**	**177.5**
5m Clumped spacing (C2)	B	5	74.8	18.4	23.3	11.8	113.0
		6	104.6	25.0	29.6	11.5	159.7
	D	13	89.0	18.2	15.1	10.2	122.2
		14	118.8	12.3	15.6	6.9	149.2
	C	17	70.9	16.4	16.4	8.3	102.8
		18	67.1	16.3	16.5	9.1	95.8
		Avg.	**87.5**	**17.8**	**19.4**	**9.6**	**123.8**
Standard spacing (S)	B	7	103.4	23.5	14.9	12.7	147.7
		8	88.5	18.9	21.9	12.5	127.4
	D	9	102.0	18.1	18.6	11.5	142.7
		10	106.0	21.5	23.2	13.0	150.8
	C	23	106.4	22.7	26.4	12.6	155.0
		24	87.7	18.1	24.9	12.4	124.2
		Avg.	**99.0**	**20.5**	**21.7**	**12.4**	**141.3**

Table 9. Biomass of various tree components at the 2004 measurement (tonnes/ha) (including the lodgepole pine trees killed by the mountain pine beetle).

Treatment	Block	Plot	Wood	Bark	Branches	Foliage	Total
Control	B	3	141.3	27.5	50.2	24.0	230.4
(C)		4	131.0	27.1	27.3	18.4	208.9
	D	15	144.8	25.7	34.2	15.7	214.1
		16	141.2	22.5	27.2	9.3	200.5
	C	19	117.7	25.3	22.2	15.9	178.2
		20	122.1	24.7	29.8	15.5	184.1
		Avg.	**133.0**	**25.5**	**31.8**	**16.5**	**202.7**
3m Clumped	B	1	82.5	18.1	30.3	14.9	123.8
spacing		2	106.2	23.9	29.0	16.2	154.6
(C1)	D	11	193.8	30.4	32.1	14.3	267.2
		12	131.4	21.7	22.8	13.1	182.4
	C	21	122.9	22.2	29.4	11.7	176.2
		22	111.4	22.0	23.1	11.0	161.3
		Avg.	**124.7**	**23.0**	**27.8**	**13.5**	**177.6**
5m Clumped	B	5	112.2	21.1	26.8	13.0	157.8
spacing		6	104.6	25.0	29.6	11.5	159.7
(C2)	D	13	89.0	18.2	15.1	10.2	122.2
		14	118.8	12.3	15.6	6.9	149.2
	C	17	70.9	16.4	16.4	8.3	102.8
		18	67.1	16.3	16.5	9.1	95.8
		Avg.	**94.3**	**18.2**	**20.0**	**9.8**	**131.2**
Standard	B	7	103.4	23.5	14.9	12.7	147.7
spacing		8	103.8	20.0	23.3	13.0	145.6
(S)	D	9	123.0	19.6	20.6	12.1	167.9
		10	106.0	21.5	23.2	13.0	150.8
	C	23	150.4	26.0	30.5	14.0	207.7
		24	114.6	20.1	27.4	13.3	156.4
		Avg.	**116.9**	**21.8**	**23.3**	**13.0**	**162.7**

Table 10. “Key” SDI values for interior Douglas-fir (adapted from Long 1985).

	Percentage of maximum SDI	SDI
Maximum	100	1450
Lower limit of self-thinning	60	870
Lower limit if “full site occupancy”	35	510
On-set of competition	25	360

Table 11. Reineke’s stand density index (SDI) by treatment in 1993, 1997 and 2004.

year	Treatment			
	3m Clumped (C1)	5m Clumped (C2)	Standard (S)	Control (C)
1993	721	505	648	1148
1997	796	578	717	1197
2003	893	644	742	1258

3.2.STAND LEVEL EFFECTS

3.2.1.Mortality and Ingrowth

Some tree mortality will inevitably occur in any sample plot followed through time. In this experiment, there were different mortality rates among the treatments and also across the different growth periods. The mortality rates for the two remeasurement periods are shown in Table 12. The annual mortality rate was slightly higher in the second period (1997 to 2003) compared to the first (1993 to 1996). This was especially true for the basal area and volume of the dead trees in the standard spacing plots in the second period as a result of the relatively large number of MPB-attacked lodgepole pine

Table 12. Summary of mortality for the two measurement periods.

Treatment	Block	Plot	Mortality 1993-1996 (trees/ha)	1993-1996 Basal Area (m^2/ha)	1993-1996 Volume (m^3/ha)	Mortality 1997-2003 (trees/ha)	1997-2003 Basal Area (m^2/ha)	1997-2003 Volume (m^3/ha)
3m Clumped spacing (C1)	B	1	0	0	0	0	0	0
		2	0	0	0	40	0.24	0.97
	D	11	60	0.1	0.4	120	0.44	2.38
		12	20	0	0	40	0.15	0.32
	C	21	140	0.3	1.4	280	1.45	6.96
		22	240	0.9	3.4	360	0.09	0.17
		Avg.	**77**	**0.22**	**0.85**	**140**	**0.4**	**1.8**
		Annual	**19**	**0.06**	**0.21**	**20**	**0.06**	**0.26**
5m Clumped spacing (C2)	B	5	20	0	0	240	7.3	61.89
		6	0	0	0	0	0	0
	D	13	80	0.1	0.2	60	0.01	0.01
		14	0	0	0	80	0.19	0.61
	C	17	20	0	0	20	0.01	0.01
		18	0	0	0	80	0.84	5.43
		Avg.	**20**	**0.01**	**0.02**	**80**	**1.39**	**11.33**
		Annual	**5**	**0**	**0.01**	**11**	**0.20**	**1.62**
Standard spacing (S)	B	7	20	0	0	60	0.01	0.01
		8	40	0.3	1.3	100	2.6	24.83
	D	9	100	0.6	2.6	420	3.83	37.19
		10	0	0	0	80	0	0
	C	23	100	0.3	1.3	200	6.82	72.06
		24	60	0	0.1	120	4.87	44.4
		Avg.	**53**	**0.2**	**0.82**	**163**	**3.02**	**29.75**
		Annual	**13**	**0.05**	**0.2**	**23**	**0.43**	**4.25**
Control (C)	B	3	680	1.1	4.3	1420	1.16	2.64
		4	280	0.3	0.6	840	0.54	0.97
	D	15	160	1.5	7.6	440	1.59	11.02
		16	340	0.8	3.5	840	2.45	10.07
	C	19	200	0.2	0.5	500	0.99	3.78
		20	320	1.1	5	580	1.1	4.64
		Avg.	**330**	**0.83**	**3.56**	**770**	**1.31**	**5.52**
		Annual	**83**	**0.2**	**0.89**	**110**	**0.19**	**0.79**

in some of those plots. The mortality of lodgepole pine was non-uniformly distributed across treatments (Table 13). The mortality of lodgepole pine between 1997 and 2003 is summarized in Table 13. The standard spacing and 5m clumped spacing plots had higher mortality than the other treatment plots because those plots had relatively more lodgepole pine than the other treatment plots.

Table 13. Summary of lodgepole pine mortality by plot between 1997 and 2003.

Treatment	Plot	Trees/ha	Basal area (m^2/ha)	Volume (m^3/ha)
3m Clumped spacing (C1)	11	20	0.15	1.18
	Total	**20**	**0.15**	**1.18**
5m Clumped spacing (C2)	5	160	7.29	61.86
	18	20	0.83	5.42
	Total	**180**	**8.12**	**67.28**
Standard spacing (S)	8	40	2.53	24.68
	9	40	2.98	33.13
	23	120	6.80	71.98
	24	100	4.87	44.40
	Total	**300**	**17.18**	**174.19**
Control (C)	15	20	0.29	1.96
	Total	**20**	**0.29**	**1.96**

The summary of ingrowth is given in Table 14 for the two measurement periods. The control plots had a smaller number of ingrowth trees than the thinned plots. Block C had a significantly higher ingrowth than the other blocks; Block B had little ingrowth except for Plot 3 in the second growth period. The ingrowth was primarily Douglas-fir and aspen.

Table 15 summarizes the yearly net growth in each measurement period after adjusting for lodgepole pine mortality. The first growing period shows better yearly basal area growth per ha than the second growing period on all treated and control plots. QMD growth had the same pattern as basal area in treated plots; however, it was higher in the second remeasurement period. There was more mortality and less ingrowth in the

Table 14. Summary of ingrowth for the two measurement periods.

Treatment	Block	Plot	Ingrowth (trees/ha) 1993-1996 Fd	Pl	At	Ep	Sx	All	1997-2003 Fd	Pl	At	Ep	Sx	All
3m	B	1						0						0
Clumped		2						0						0
spacing	D	11						0						0
(C1)		12						0						0
	C	21	40			40		80	60					60
		22	140			20		160	220			80		300
		Avg.	**30**			**10**		**40**	**47**			**13**		**60**
		Annual	**8**			**3**		**10**	**8**			**2**		**10**
5m	B	5						0						0
Clumped		6						0						0
spacing	D	13						0	20		20			40
(C2)		14			20	20		40				40		40
	C	17	20			60		80	20			80		100
		18	100	20		40		160	80	20		40		140
		Avg.	**20**	**3**	**3**	**20**		**47**	**20**	**3**	**3**	**27**		**53**
		Annual	**5**	**1**	**1**	**5**		**12**	**4**	**1**	**1**	**5**		**9**
Standard	B	7						0						0
spacing		8						0						0
	D	9			200			200			40			40
(S)		10			60			60	20					20
	C	23	60	40		20		120	160	20		20		200
		24				40		40						0
		Avg.	**10**	**7**	**43**	**10**		**70**	**30**	**3**	**7**	**3**		**43**
		Annual	**3**	**2**	**11**	**3**		**18**	**5**	**1**	**1**	**1**		**7**
Control	B	3						0	0		20			20
(C)		4						0	0					0
	D	15				60		60	60					60
		16						0	0			60		60
	C	19	20			20		40	40			20		60
		20	20					20	20					20
		Avg.	**7**			**13**		**20**	**20**		**3**	**13**		**37**
		Annual	**2**			**3**		**5**	**4**		**2**	**2**		**6**

second remeasurement period than in the first period except in the control. The average yearly volume growth per ha was higher in the second period than in the first period.

Table 15. Comparison of the average yearly net growth rates by treatment and growth period (after adjusting for lodgepole pine mortality).

Growth Period	Treatment	Average Yearly Change Ingrowth (Stems/Ha)	Mort. (Stems/Ha)	BA/ha (m^2/ha)	Volume (m^3/ha)	QMD (cm)	RD
1993-1996	3m Clumped spacing (C1)	10.0	19.2	0.88	6.72	0.22	0.19
1997-2003		8.6	19.6	0.70	8.04	0.17	0.14
Average		**9.1**	**19.5**	**0.77**	**7.56**	**0.19**	**0.16**
1993-1996	5m Clumped spacing (C2)	11.8	5.8	0.83	5.25	0.25	0.18
1997-2003		7.6	7.1	0.67	6.54	0.20	0.13
Average		**9.1**	**6.6**	**0.73**	**6.07**	**0.22**	**0.15**
1993-1996	Standard spacing (S)	12.5	15.0	0.90	5.80	0.23	0.19
1997-2003		6.1	16.1	0.66	6.20	0.19	0.12
Average		**8.4**	**15.7**	**0.75**	**6.05**	**0.20**	**0.15**
1993-1996	Control (C)	5.0	78.2	0.59	5.08	0.12	0.12
1997-2003		2.4	107.1	0.55	6.87	0.15	0.07
Average		**3.3**	**96.6**	**0.56**	**6.22**	**0.14**	**0.09**

3.2.2.DBH Distribution

Not surprisingly, the control plots had large numbers of small trees compared to the thinned plots (Figure 3). However, the shape of the dbh distribution for each thinning treatment and the control remained a reversed J-shaped curve. The number of dbh class 4 and 5 trees increased in all plots between 1997 and 2003 (Figure 4). Dbh class 1 in the control plots had a higher mortality rate than that of the spaced plots in this period (Figure 4).

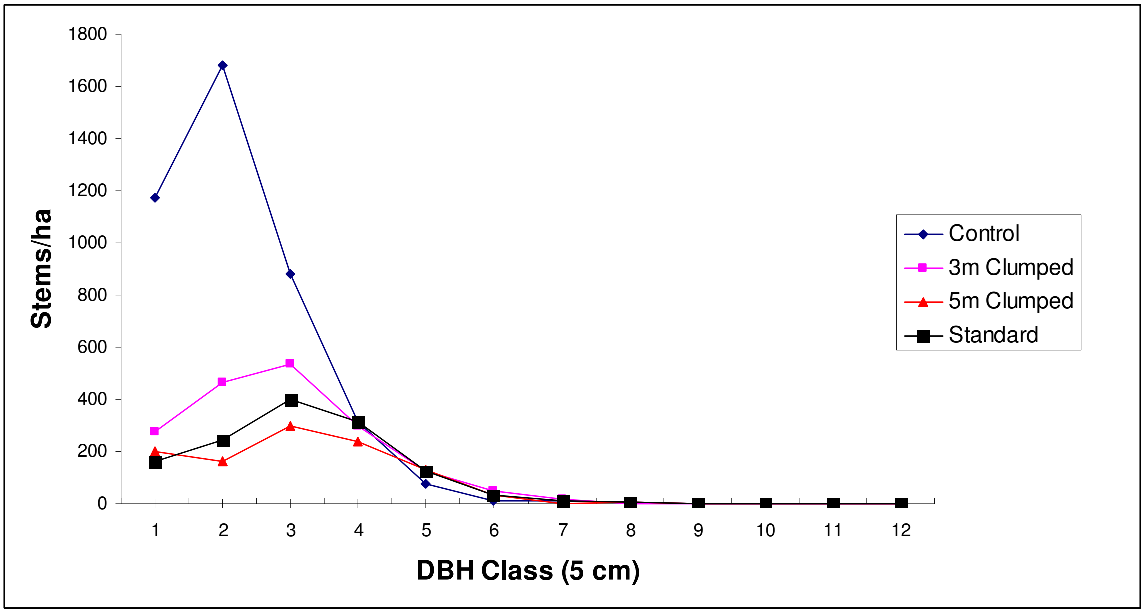


Figure 3. The number of stems per ha by size class in each treatment and control in 2004 (dbh class 1 =0 to 5 cm, dbh class 12 = 55 to 60 cm).

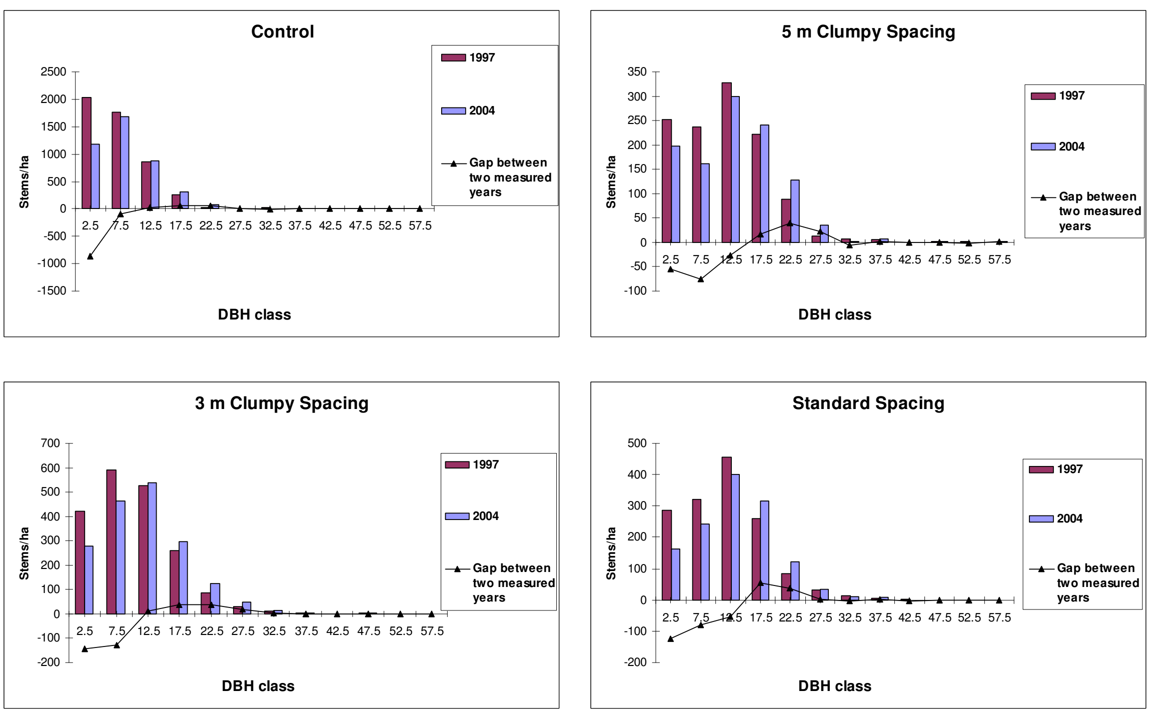


Figure 4. Distribution of the number of stems per ha and changes in the number of stems per ha by 5 cm DBH class in each treatment and control between 1997 and 2004.

3.2.3.Growth Response

The growth of QMD, basal area, Lorey's height, and volume were analyzed at the stand level using analysis of variance. Change in Lorey's height and volume were significantly different among the treatments. The control plots were lower than any of the spaced plots with the exception of C1 (Table 16).

QMD growth of the three spacing treatments was higher than that of control plots, but not significantly (Table 16). C2 had the highest growth. This was similar to the first growth period. As expected, there was decreased QMD growth as relative density increased (Figure 5).

Table 16. Mean of stand level growth and growth rates by treatment between 1997 and 2003.

	Variable	Treatment***							
		3m Clumped		5m Clumped		Standard		Control	
Absolute									
(Relative by 1997 (%))	QMD (cm)	1.21	(9.9)	1.40	(10.0)	1.33	(9.7)	1.08	(11.9)
		a	(a)*	a	(a)	a	(a)	a	(a)
	BA (m^2/ha)	4.89	(17.2)	4.71	(21.8)	4.59	(16.6)	3.87	(10.0)
		a	(a)	a	(a)	a	(a)	a	(b)
	Lorey's Height (m)	1.70	(12.8)	1.68	(12.8)	1.20	(8.3)	1.46	(12.8)
		a	(a)	a	(a)	b	(b)	ab	(a)
	Volume (m^3/ha)**	50.04	(31.5)	42.83	(37.0)	40.35	(24.9)	42.60	(23.5)
		a	(ab)	b	(a)	b	(b)	b	(b)

* The results of Duncan's multiple comparison tests, identical letters under the means indicate no statistical difference at the 0.05 probability level.
**Significant block/treatment interaction in the analysis of volume growth
***All variances among treatments are not significantly different at a 0.05 probability level.

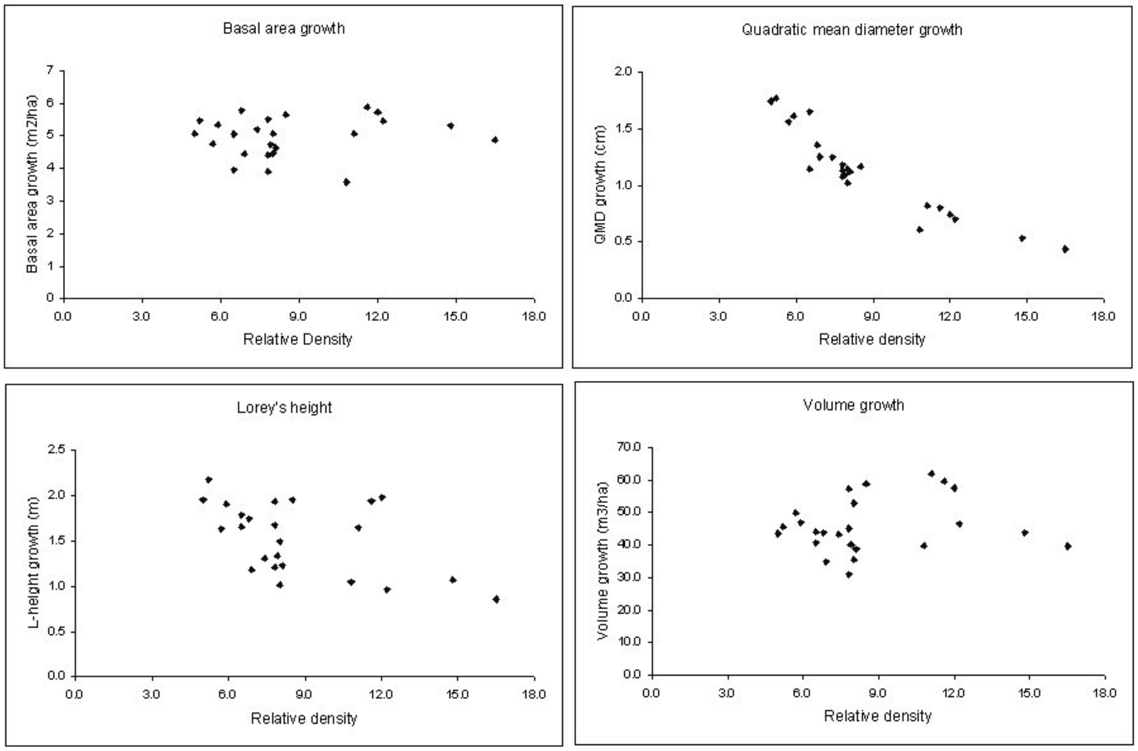


Figure 5. Relationship of Curtis' (1982) relative density in 1997 to the change in four stand-level variables' between 1997 and 2003.

Basal area growth showed a similar pattern to QMD growth since both are based on dbh and stems per ha (Table 16). The basal area growth rate of spaced plots was significantly different (higher) than the control plots. Over the seven year growth period between 1997 and 2003, the range of average annual growth was 0.66 to 0.70 m^2/ha for the treatments compared to 0.55 m^2/ha for the control plots.

Negative height growth occurred for a number of trees because of measurement error, broken tops and dead tops. Large trees were especially prone to negative height growth. This affected growth in Lorey's height and resulted in a different pattern than the other variables analyzed. The standard spacing had the lowest Lorey's height growth rate (Table 16). Among the blocks, Block B had significantly lower Lorey's height growth than Block C and D.

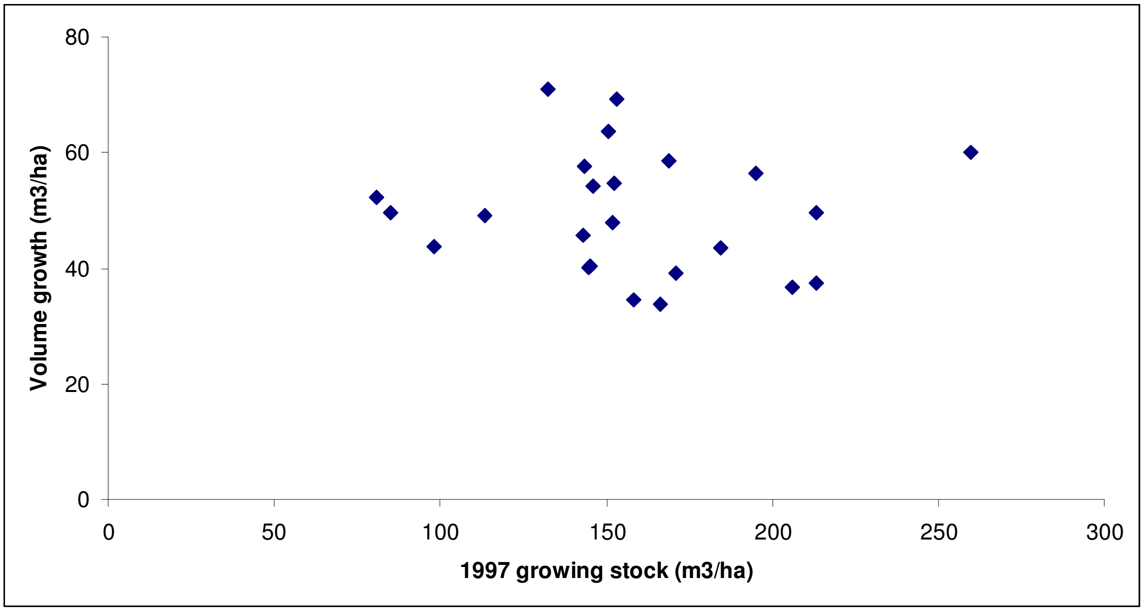


Figure 6. Net volume growth (m^3/ha) between 1997 and 2003 in relation to 1997 growing stock.

The volume growth varied widely among plots without a strong relationship with 1997 growing stock (Figure 6). The volume growth of the 3 m clumped spacing (C1) was significantly higher than other treatments and the control (Table 16). The control plots showed similar volume growth to the thinned plots despite lower average tree growth rates because it had many more trees than the spaced treatments. Block B had significantly lower volume growth than Blocks C and D.

There were different growth patterns among the various biomass components analyzed (Table 17). Bark, branch and foliage biomass showed no significant interaction between block and treatment. However, there was a significant interaction between block and treatment for stem wood and total biomass. For these biomass components, C1 was significantly different than the other treatments. The growth of branch biomass was much higher than the growth of the other biomass variables.

Table 17. Net biomass per ha growth (%) between 1997 and 2003.

Treatment	Block	Plot	Wood	Bark	Branch	Foliage	Total
3m Clumped Spacing (C1)	B	1	42.6	28.8	240.0	82.3	31.4
		2	20.5	18.5	147.1	53	20.0
	D	11	24.0	19.7	45.5	28.7	23.4
		12	35.9	24.7	26.1	20.6	32.9
	C	21	25.7	19.1	77.1	55.7	22.3
		22	40.9	27.8	73.1	63.5	36.6
	Average		**29.9**	**22.5**	**83.7**	**47.7**	**27.0**
5m Clumped Spacing (C2)	B	5	18.3	17.5	65.0	35.1	17.4
		6	33.2	18.8	68.4	44.6	27.0
	D	13	40.5	31.1	62.5	41.9	38.8
		14	32.8	34.8	65.2	57.5	30.2
	C	17	49.0	33.3	107.4	78.1	42.7
		18	50.2	38.8	99.0	92.1	46.3
	Average		**32.8**	**27.0**	**74.6**	**53.1**	**31.2**
Standard Spacing (S)	B	7	27.1	18.9	25.2	24.5	23.8
		8	22.4	22.4	61.7	32.3	21.4
	D	9	18.4	18.9	62.6	35.0	17.5
		10	29.1	22.5	86.1	44.2	26.3
	C	23	21.7	18.3	84.2	45.0	21.2
		24	27.6	26.6	119.7	59.8	27.1
	Average		**24.0**	**21.0**	**73.9**	**39.5**	**22.6**
Control (C)	B	3	19.0	10.2	150.3	45.9	12.9
		4	25.0	13.1	57.3	35.9	20.7
	D	15	17.6	15.2	73.6	42.5	15.6
		16	14.5	12.6	12.1	9.4	14.7
	C	19	37.2	14.9	55.2	40.3	29.1
		20	34.3	17.2	84.7	51.4	25.9
	Average		**23.4**	**13.8**	**70.7**	**39.0**	**19.1**

3.3.TREE-LEVEL GROWTH

Dbh classes were divided into three groups for statistical analysis. Table 18 provides the number of stems by treatment and dbh class. A total of 36 data groupings (three dbh classes × three groups of species × four variables) were used in analyses of variance. Eighteen of the groupings showed significantly different average growth among treatments at an α of 0.05. Twenty-six of the datasets had significantly different variances among the treatments. Another 48 data sets (three dbh classes × four treatment groups × four variables) were used for analyses of covariance. The covariate (initial dbh) was significant in 40 of these data sets. Adjusted means were used in 17 of the data sets because there was no significant interaction between the initial dbh and treatment. Only two data sets did not show significant differences among treatments.

Table 18. Number of stems per ha by treatment within three different dbh classes.

Treatment	DBH ≤ 10 cm All (Fd/Non-Fd)	10 cm<DBH≤20 cm All (Fd/Non-Fd)	DBH>20 cm All (Fd/Non-Fd)
Control	1203 (1108/95)	438 (334/104)	22 (20/2)
3m Clumped (C1)	346 (279/67)	310 (230/80)	53 (33/20)
5m Clumped (C2)	173 (146/27)	220 (176/44)	47 (25/22)
Standard (S)	193 (169/24)	284 (269/15)	56 (39/17)

There was a strong negative relationship between dbh growth and volume growth and Curtis' (1982) relative density in the middle and large tree classes (Figures 7, 8, and

9). Height growth was relatively independent of density. In the small tree class, dbh and basal area growth showed a strong relationship with Curtis' (1982) relative density.

For Douglas-fir, there were significant differences between treatments and controls for all variables except height growth. However, the order of ranking for the spacing treatments varied among the different variables examined. The results of the analyses of variance were variable for species other than Douglas-fir; this is perhaps a reflection of the small number of trees in certain plots and treatment combinations.

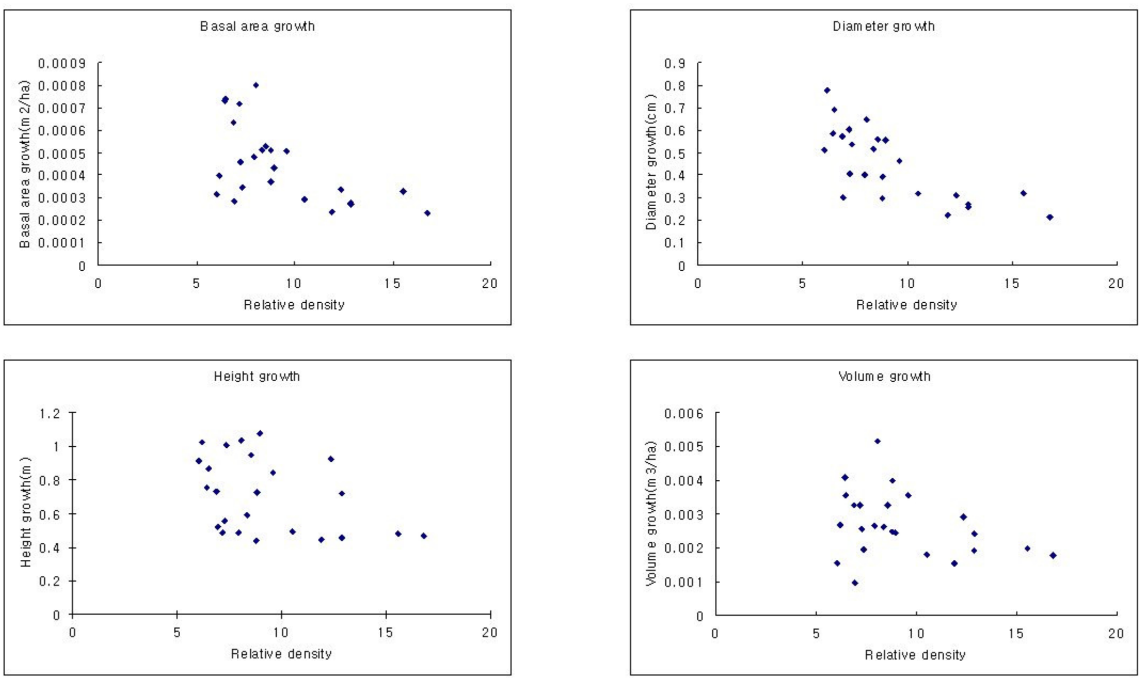


Figure 7. Mean of individual-tree growth response of trees less than 10 cm dbh in relation to Curtis'(1982) relative density between 1997 and 2003.

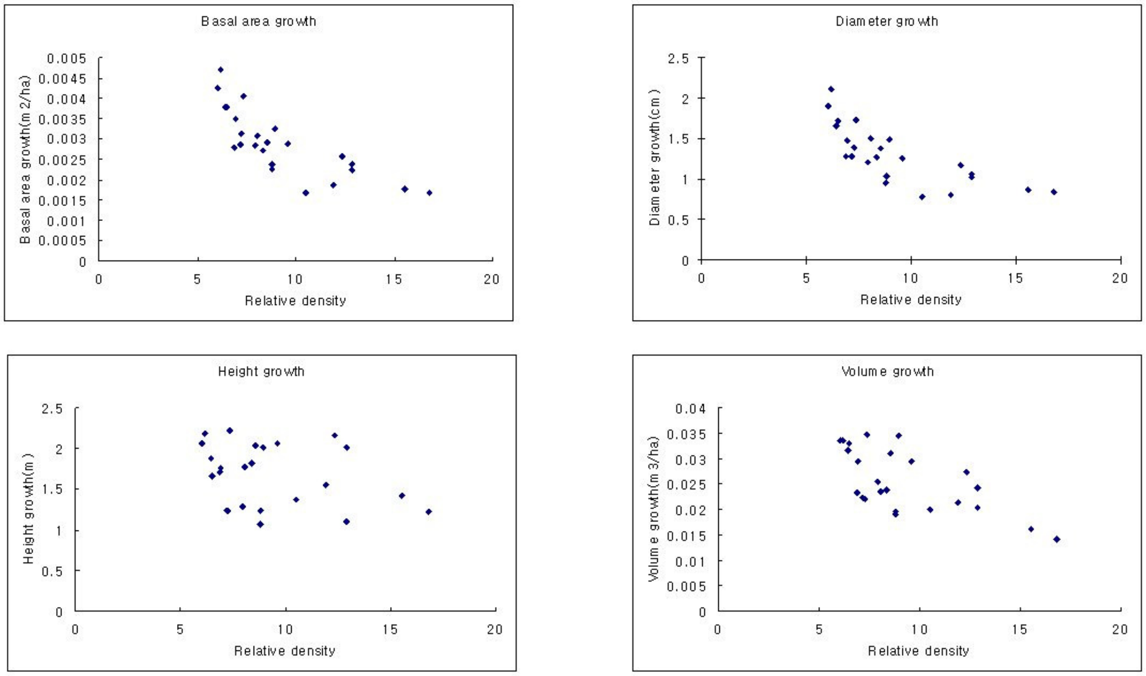


Figure 8. Mean of individual-tree growth response of trees between 10 cm and 20 cm dbh in relation to Curtis'(1982) relative density between 1997 and 2003.

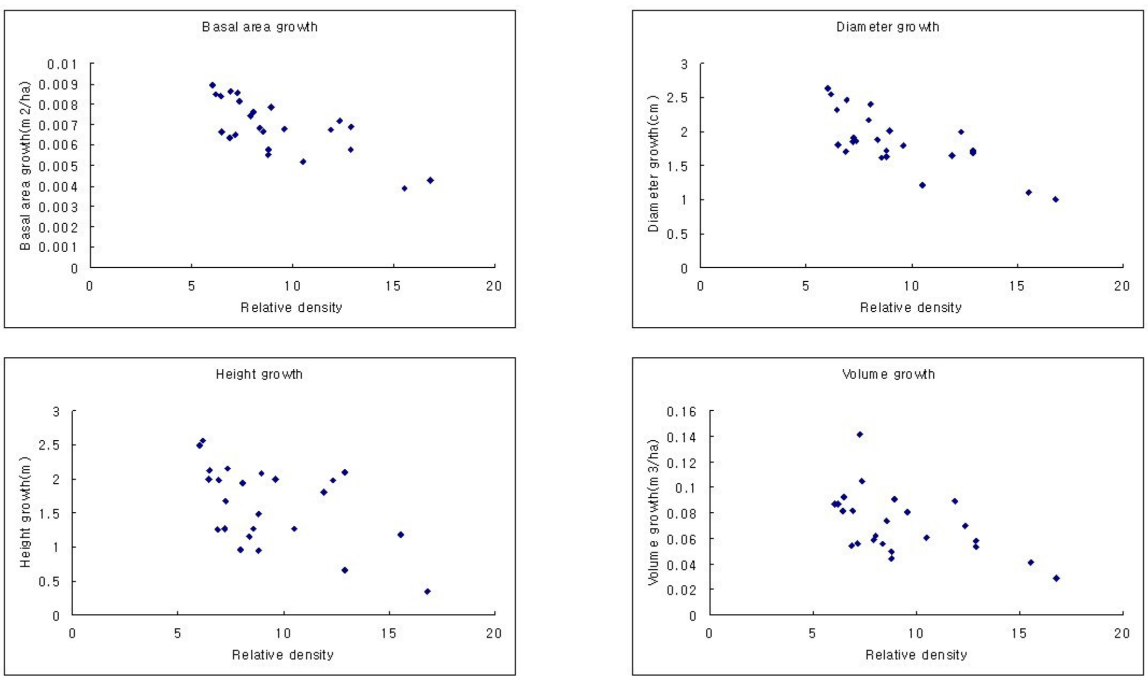


Figure 9. Mean of individual-tree growth response of trees larger than 20 cm dbh in relation to Curtis' (1982) relative density between 1997 and 2003.

3.3.1.Dbh

Dbh growth increased with increasing dbh class for all trees and the Douglas-fir alone, but not significantly in some treatments (Table 19).

In the smallest dbh class, all trees and Douglas-fir alone grew the fastest in the 5 m clumped spacing, followed by the 3 m clumped spacing and the standard spacing, which were similar, and then by the control (Table 20). Even though there was no significant difference among the treatments for the non-Douglas fir species group, average growth was higher on the treatments than on the control. There was a negative exponential relationship between diameter growth and Curtis' (1982) relative density (Figure 7).

For the middle dbh class, the growth on the 5 m clumped spacing was significantly higher than the other treatments in all species classes. However, the 3 m clumped spacing and the standard spacing were not significantly different from either the 5 m clumped spacing or the control. The relationship between dbh growth and Curtis' (1982) relative density was similar to the pattern shown by small trees (Figure 8).

There were not as many large trees as small and middle-sized trees. For the larger trees, the growth on the 5 m clumped spacing was significantly higher than on the other treatments for all trees and Douglas-fir alone. For the non-Douglas-fir species group, the 3 m spacing had the highest dbh growth. The control plots still had the lowest average growth (Table 20).

Table 19. Comparison of average dbh growth (cm) per tree among three dbh classes by treatment and species group.

Treatment	Species	DBH Class		
		DBH≤10 cm	10 cm<DBH ≤ 20cm	DBH>20 cm
3m Clumped Spacing(C1)	Fd	0.58 (c)*	1.43 (b)	1.83 (a)
	Non-Fd	0.36 (c)	1.06 (b)	1.49 (a)
	All	0.54 (c)	1.33 (b)	1.70 (a)
5m Clumped Spacing(C2)	Fd	0.76 (c)	1.82 (b)	2.22 (a)
	Non-Fd	0.56 (b)	1.32 (a)	1.43 (a)
	All	0.72 (b)	1.72 (a)	1.85 (a)
Standard Spacing(S)	Fd	0.62 (c)	1.42 (b)	1.94 (a)
	Non-Fd	0.31 (b)	1.18 (a)	0.18 (b)
	All	0.58 (b)	1.40 (a)	1.41 (a)
Control(C)	Fd	0.30 (c)	1.06 (b)	1.54 (a)
	Non-Fd	0.30 (a)	0.81 (a)	0.80 (a)
	All	0.30 (c)	1.00 (b)	1.47 (a)

* Means with different letters are significantly different at $\alpha = 0.05$ according to Scheffé's test. Only blocks C and D were used for Non-Fd analysis.

Table 20. Comparison of average dbh growth (cm) per tree among treatments by three dbh classes and species groups.

Dbh Class	Species	Dbh growth (cm) between 1997 and 2003			
		Treatment			
		3m Clumped	5m Clumped	Standard	Control
0-10 cm	Fd	0.58* (b)	0.76 (a)	0.62 (b)	0.30 (c)
	Non-Fd	0.36 (a)	0.56 (a)	0.31 (a)	0.30 (a)
	All	0.54 (b)	0.72 (a)	0.58 (b)	0.30 (c)
10-20 cm	Fd**	1.42 (b)	1.77 (a)	1.37 (b)	1.11 (c)
	Non-Fd**	1.08 (ab)	1.49 (a)	1.69 (ab)	0.88 (b)
	All	1.33 (b)	1.72 (a)	1.40 (b)	1.00 (c)
>20 cm	Fd	1.83 (ab)	2.22 (a)	1.94 (ab)	1.54 (b)
	Non-Fd**	1.49 (ab)	1.70 (a)	0.22(b)	Non-est
	All**	1.72 (a)	1.84 (a)	1.40 (a)	1.52 (a)

* Means with different letters are significantly different at $\alpha = 0.05$ according to Scheffé's test. ** Adjusted mean. Only blocks C and D were used for Non-Fd analysis.

3.3.2.Basal area

Basal area growth increased with an increase in dbh class for all species groups (Table 21). There was the same pattern for Douglas-fir alone in all dbh classes. Trees in the 5 m spacing had the highest basal area growth and trees on the control plots had the lowest growth (Table 22). This pattern was not present for the non-Douglas-fir species group. There was a negative correlation relationship between Curtis' (1982) relative density and basal area growth of trees in the smallest dbh class (Figure 7); however, it was a weaker relationship than with dbh growth. For the middle dbh class, growth in the 5 m spacing was highest, followed by the 3 m spacing, the standard spacing, and the control. For the largest dbh class, there was no significant difference in growth among the treatments. However, the average basal area growth of Douglas-fir on the 5 m spacing was still the highest. There was a stronger negative relationship between basal area growth and Curtis' (1982) relative density (Figure 9).

3.3.3.Height

Height growth behaved differently than dbh and basal area growth, with no consistent ordering of treatments or relationship with dbh class (Table 23). In the smallest and middle dbh classes for the Douglas-fir species group, height growth was higher in the two clumped spacing treatments than in the standard spacing and the control (Table 24). In the largest dbh class, there were no significant differences in height growth among treatments, nor were there strong relationships between Curtis' (1982) relative density and height growth of both the small (Figure 7) and middle dbh classes (Figure 8). However, there was a negative relationship between Curtis' (1982) relative density and the height growth of trees in the largest dbh class (Figure 9).

Table 21. Comparison of average basal area growth (m^2) per tree among three dbh classes by treatment and species.

Treatment	Species	DBH Class		
		DBH≤10 cm	10 cm<DBH ≤20 cm	DBH>20 cm
3m Clumped Spacing(C1)	Fd	0.00068 (c)*	0.00337 (b)	0.00757 (a)
	Non-Fd	0.00042 (c)	0.00264 (b)	0.00606 (a)
	All	0.00063 (c)	0.00318 (b)	0.00700 (a)
5m Clumped Spacing(C2)	Fd	0.00091 (c)	0.00445 (b)	0.00906 (a)
	Non-Fd	0.00032 (c)	0.00354 (b)	0.00534 (a)
	All	0.00082 (c)	0.00437 (b)	0.00732 (a)
Standard Spacing(S)	Fd	0.00074 (c)	0.00344 (b)	0.07850 (a)
	Non-Fd	0.00017 (b)	0.00334 (a)	0.00076 (b)
	All	0.00067 (c)	0.00343 (b)	0.00570 (a)
Control(C)	Fd	0.00034 (c)	0.00237 (b)	0.00678 (a)
	Non-Fd	0.00031 (b)	0.00199 (ab)	0.00278 (a)
	All	0.00033 (c)	0.00228 (b)	0.00642 (a)

* Means with different letters are significantly different at $\alpha = 0.05$ according to Scheffé's test. Only blocks C and D were used for Non-Fd analysis.

Table 22. Comparison of average basal area growth (m^2) per tree among treatments by three dbh classes and species.

Diameter Class	Species	Basal area growth (m^2) between 1997 and 2003 measurement			
		Treatment			
		3m Clumped	5m Clumped	Standard	Control
0-10 cm	Fd	0.00068* (b)	0.00091 (a)	0.00074 (b)	0.00034 (c)
	Non-Fd	0.00042 (a)	0.00035 (a)	0.00017 (a)	0.00031 (a)
	All	0.00063 (b)	0.00082 (a)	0.00067 (b)	0.00033 (c)
10-20 cm	Fd**	0.00336 (b)	0.00421 (a)	0.00322 (b)	0.00259 (c)
	Non-Fd**	0.00270 (a)	0.00337 (a)	0.00241 (a)	0.00214 (b)
	All	0.00318 (b)	0.00437 (a)	0.00343 (b)	0.00228 (c)
> 20 cm	Fd	0.00757(ab)	0.00906 (a)	0.00785(ab)	0.00678 (b)
	Non-Fd**	0.00579 (a)	0.00697 (a)	0.00115 (b)	Non-est
	All	0.00700 (a)	0.00732 (a)	0.00570 (a)	0.00642 (a)

* Means with different letters are significantly different at $\alpha = 0.05$ according to Scheffé's test. ** Adjusted mean. Only blocks C and D were used for Non-Fd analysis.

Table 23. Comparison of average height growth (m) per tree among three dbh classes by treatment and species.

Treatment	Species	DBH≤10 cm	10 cm<DBH ≤20 cm	DBH>20 cm
3m Clumped Spacing(C1)	Fd	0.92 (c)*	1.79 (a)	1.42 (b)
	Non-Fd	0.89 (b)	1.83 (a)	1.84 (a)
	All	0.92 (b)	1.80 (a)	1.58 (a)
5m Clumped Spacing(C2)	Fd	0.92 (b)	1.78 (a)	1.86 (a)
	Non-Fd	1.02 (b)	1.76 (a)	1.66 (ab)
	All	0.94 (b)	1.77 (a)	1.77 (a)
Standard Spacing(S)	Fd	0.79 (b)	1.59 (a)	1.42 (a)
	Non-Fd	0.90 (a)	1.23 (a)	0.12 (b)
	All	0.81 (b)	1.59 (a)	1.03 (b)
Control(C)	Fd	0.61 (c)	1.57 (a)	1.11 (b)
	Non-Fd	0.70 (a)	1.42 (a)	1.70 (a)
	All	0.62 (c)	1.54 (a)	1.16 (b)

* Means with different letters are significantly different at α = 0.05 according to Scheffé's test. Only blocks C and D were used for Non-Fd analysis.

Table 24. Comparison of average height growth (m) per tree among treatments by three diameter classes and species.

Diameter Class	Species	Height growth (m) between 1997 and 2003 measurement			
		Treatment			
		3m Clumped	5m Clumped	Standard	Control
0-10 cm	Fd	0.92 (a)*	0.92 (a)	0.79 (a)	0.61 (b)
	Non-Fd**	0.87 (a)	1.62 (a)	1.18 (a)	0.88 (a)
	All	0.92 (a)	0.94 (a)	0.81 (a)	0.62 (b)
10-20 cm	Fd**	1.79 (a)	1.77 (ab)	1.57 (ab)	1.61 (b)
	Non-Fd**	1.84 (a)	2.05 (a)	1.46 (a)	1.86 (a)
	All**	1.80 (a)	1.76 (ab)	1.56 (b)	1.55 (b)
> 20 cm	Fd**	1.38 (ab)	1.92 (a)	1.31 (a)	1.16 (b)
	Non-Fd**	1.84 (a)	2.02 (a)	0.15(b)	Non-est
	All**	1.58 (b)	1.77 (a)	1.02 (a)	1.31 (b)

* Means with different letters are significantly different at α = 0.05 according to Scheffé's test. ** Adjusted mean. Only blocks C and D were used for Non-Fd analysis.

3.3.4.Volume

For the smallest dbh class, the average growth of each treatment was significantly different than the control for all species groups (Table 25). The standard spacing had the lowest volume growth for the non-Douglas-fir species group (Table 26). The average growth by plot did not have a strong relationship with Curtis' (1982) relative density for either the smallest dbh class (Figure 7) nor the middle dbh class (Figure 8). The control showed the lowest average growth in any species group for the middle dbh class. The growth on the 5 m clumped spacing was higher than that of the other treatments, except for the non-Douglas-fir species group. For the largest dbh class, the 5 m clumped spacing also had the highest average volume growth except for the non-Douglas-fir species group. The rank order of the other treatments varied by block and species group. The average volume growth of the trees in the largest dbh class showed a weak negative relationship with Curtis' (1982) relative density (Figure 7).

3.3.5.Growth Using a Mixed –Effects Linear Model

A mixed-effects linear model was used to predict the growth of single tree dbh and height for the total 11 year measurement period, and the annual growth for the two intermediate periods (4 years and 7 years, respectively).

Average dbh growth for the total period differed significantly among treatments for all species groups at α=0.05 (Table 27). The probability value was reduced by decreasing the number of trees in the datasets which contained different number of trees in each plot. The dbh growth of the 5 m spacing was always higher than the other treatments and the control. However, there was no significant difference in periodic height growth among treatments, although the height growth of the control plot was

Table 25. Comparison of average volume growth (m^3) per tree among three dbh classes by treatment and species.

Treatment	Species	DBH≤10 cm	10 cm<DBH ≤20 cm	DBH >20 cm
3m Clumped Spacing(C1)	Fd	0.0042 (c)*	0.0288 (b)	0.0753 (a)
	Non-Fd	0.0047 (c)	0.0376 (b)	0.0940 (a)
	All	0.0043 (c)	0.0311 (b)	0.0824 (a)
5m Clumped Spacing(C2)	Fd	0.0050 (c)	0.0324 (b)	0.1028 (a)
	Non-Fd	0.0032 (c)	0.0463 (b)	0.0800 (a)
	All	0.0047 (c)	0.0352 (b)	0.0921 (a)
Standard Spacing(S)	Fd	0.0045 (c)	0.0289 (b)	0.0762 (a)
	Non-Fd	0.0013 (b)	0.0413 (a)	0.0099 (b)
	All	0.0041 (c)	0.0296 (b)	0.0560 (a)
Control(C)	Fd	0.0025 (c)	0.0213 (b)	0.0623 (a)
	Non-Fd	0.0031 (c)	0.0271 (b)	0.0519 (a)
	All	0.0025 (c)	0.0227 (b)	0.0614 (a)

* Means with different letters are significantly different at $\alpha = 0.05$ according to Scheffé's test. Only blocks C and D were used for Non-Fd analysis.

Table 26. Comparison of average volume growth (m^3) per tree among treatments by three dbh classes and species.

Diameter Class	Species	volume growth between the 1997 and 2003 measurements			
		Treatment			
		3m Clumped	5m Clumped	Standard	Control
0-10 cm	Fd	0.0042 (a)*	0.0050 (a)	0.0045 (a)	0.0025 (b)
	Non-Fd	0.0047(a)	0.0034 (ab)	0.0013(b)	0.0031(ab)
	All	0.0043 (a)	0.0047 (a)	0.0041 (a)	0.0025 (b)
10-20cm	Fd **	0.0287 (b)	0.0304 (a)	0.0268 (a)	0.0236 (b)
	Non-Fd**	0.0387(a)	0.0422(a)	0.0300(ab)	0.0293(b)
	All**	0.0310 (ab)	0.0323 (a)	0.0279 (b)	0.0247 (c)
> 20 cm	Fd	0.0754 (b)	0.1028 (a)	0.0763 (b)	0.0623 (b)
	Non-Fd	0.0940 (a)	0.1036(a)	0.0112 (a)	0.0621 (a)
	All	0.0824 (ab)	0.0921 (a)	0.0561 (b)	0.0614 (ab)

* Means with different letters are significantly different at $\alpha = 0.05$ according to Scheffé's test. ** Adjusted mean. Only blocks C and D were used for Non-Fd analysis.

lower for the all species groups' data sets. Reducing the Douglas-fir data to selected numbers in the three smallest 5 cm dbh classes (2.5 cm to 17.5 cm) removed the significant difference between the height growth of the trees in the control plot and those in the thinned plots.

The average annual growth of dbh and height in Period 1 (1993-1996) is shown in Table 28. There was significantly difference among the mean average annual dbh growth of the various treatments. The p-value increased until FD_30 and diminished after that in the average annual dbh. However, there was no significant difference for average annual height growth.

Table 29 illustrates the average annual growth of dbh and height in Period 2 (1997-2003). As was the case for the first growth period, there was a significant difference in the average annual dbh growth and no significant difference in average annual height growth among the treatments. The p-value increased with the restrictiveness of the dataset until FD_20 in average annual dbh growth.

Basal area and volume growth of individual trees for the entire measurement period (1993-2003) is presented in Table 30 and the annual basal area and volume growth of individual trees for the two measurement periods is shown in Tables 31 and 32. Periodic basal area and volume growth were significantly different among the treatments in all species groups (Table 30). Trees in the 5 m spacing had the highest growth for both measurement periods.

Table 27. Adjusted means of dbh (cm) and height (m) periodic growth by treatment during the total 11 year growth period (mixed model).

	Species	Control	3m Clumped	5m Clumped	Standard	Pr > F
DBH	All	1.07(c)*	1.72(b)	2.42(a)	1.83(b)	0.0070
	Conifer	1.08(c)	1.77(b)	2.46(a)	1.82(b)	0.0095
	FD_All	1.11(c)	1.76(b)	2.51(a)	1.77(b)	0.0089
	FD_75	1.33(b)	1.87(b)	2.61(a)	1.83(b)	0.0224
	FD_50	1.43(b)	1.94(b)	2.68(a)	1.89(b)	0.0206
	FD_30	1.54(b)	2.01(b)	2.75(a)	1.99(b)	0.0184
	FD_25	1.57(b)	2.07(b)	2.78(a)	2.06(b)	0.0148
	FD_20	1.63(b)	2.14(b)	2.83(a)	2.12(b)	0.0143
	FD_15	1.72(b)	2.30(b)	2.95(a)	2.17(b)	0.0123
Height	All	1.59(b)	2.10(a)	2.17(a)	1.81(ab)	0.0845
	Conifer	1.59(b)	2.13(a)	2.16(a)	1.80(ab)	0.0781
	FD_All	1.61(b)	2.10(a)	2.15(a)	1.73(ab)	0.0870
	FD_75	1.91(a)	2.27(a)	2.37(a)	1.91(a)	0.1509
	FD_50	2.05(a)	2.31(a)	2.41(a)	1.97(a)	0.2161
	FD_30	2.23(a)	2.37(a)	2.45(a)	2.06(a)	0.3458
	FD_25	2.29(a)	2.44(a)	2.49(a)	2.11(a)	0.3765
	FD_20	2.38(a)	2.51(a)	2.51(a)	2.16(a)	0.3750
	FD_15	2.54(a)	2.70(a)	2.68(a)	2.20(a)	0.2321

* Adjusted means with different letters are significantly different at $\alpha = 0.05$ according to Scheffe's test.

Table 28. Adjusted means of dbh (cm/yr) and height (m/yr) annual growth by treatment between 1993 and 1996 (mixed model).

	Species	Control	3m Clumped	5m Clumped	Standard	Pr > F
DBH	All	0.11(c)*	0.20(b)	0.28(a)	0.20(b)	0.0060
	Conifer	0.11(c)	0.20(b)	0.28(a)	0.20(b)	0.0077
	FD_All	0.11(c)	0.20(b)	0.28(a)	0.19(b)	0.0066
	FD_75	0.13(c)	0.21(ab)	0.29(a)	0.20(bc)	0.0165
	FD_50	0.14(b)	0.22(ab)	0.29(a)	0.21(b)	0.0156
	FD_30	0.15(b)	0.23(b)	0.30(a)	0.22(b)	0.0139
	FD_25	0.16(c)	0.23(b)	0.31(a)	0.23(b)	0.0110
	FD_20	0.16(b)	0.24(b)	0.31(a)	0.23(b)	0.0109
	FD_15	0.17(b)	0.26(b)	0.32(a)	0.24(b)	0.0106
Height	All	0.14(a)*	0.19(a)	0.19(a)	0.17(a)	0.1417
	Conifer	0.14(a)	0.20(a)	0.19(a)	0.17(a)	0.1251
	FD_All	0.15(a)	0.20(a)	0.18(a)	0.16(a)	0.1404
	FD_75	0.17(a)	0.21(a)	0.20(a)	0.18(a)	0.3159
	FD_50	0.18(a)	0.21(a)	0.20(a)	0.18(a)	0.4362
	FD_30	0.19(a)	0.22(a)	0.20(a)	0.19(a)	0.6742
	FD_25	0.20(a)	0.22(a)	0.21(a)	0.20(a)	0.6726
	FD_20	0.20(a)	0.23(a)	0.21(a)	0.20(a)	0.5375
	FD_15	0.21(a)	0.24(a)	0.22(a)	0.20(a)	0.2858

* Adjusted means with different letters are significantly different at $\alpha = 0.05$ according to Scheffe's test.

Table 29. Adjusted means of dbh (cm/yr) and height (m/yr) annual growth by treatment between 1997 and 2003 (mixed model).

	Species	Control	3m Clumped	5m Clumped	Standard	Pr > F
DBH	All	0.10(c)*	0.13(bc)	0.18(a)	0.14(ab)	0.0098
	Conifer	0.10(b)	0.14(b)	0.19(a)	0.14(ab)	0.0141
	FD_All	0.10(b)	0.13(b)	0.19(a)	0.14(b)	0.0156
	FD_75	0.12(b)	0.14(b)	0.20(a)	0.14(b)	0.0354
	FD_50	0.13(b)	0.15(b)	0.21(a)	0.15(b)	0.0312
	FD_30	0.14(b)	0.16(b)	0.21(a)	0.16(b)	0.0301
	FD_25	0.14(b)	0.16(b)	0.22(a)	0.17(b)	0.0261
	FD_20	0.15(b)	0.17(b)	0.22(a)	0.17(b)	0.0253
	FD_15	0.15(b)	0.18(b)	0.23(a)	0.17(b)	0.0195
Height	All	0.15(b)	0.19(ab)	0.20(a)	0.16(ab)	0.0973
	Conifer	0.15(a)	0.19(a)	0.20(a)	0.16(a)	0.0893
	FD_All	0.15(b)	0.18(ab)	0.20(a)	0.15(ab)	0.0932
	FD_75	0.18(ab)	0.20(ab)	0.22(a)	0.17(b)	0.1140
	FD_50	0.19(a)	0.21(a)	0.23(a)	0.17(a)	0.1548
	FD_30	0.21(a)	0.21(a)	0.23(a)	0.18(a)	0.1942
	FD_25	0.22(a)	0.22(a)	0.24(a)	0.19(a)	0.2122
	FD_20	0.23(a)	0.23(a)	0.24(a)	0.19(a)	0.2363
	FD_15	0.24(a)	0.25(a)	0.26(a)	0.20(a)	0.2321

* Adjusted means with different letters are significantly different at $\alpha = 0.05$ according to Scheffe's test.

Table 30. Adjusted means of basal area (m^2) and volume (m^3) periodic growth by treatment during the total 11 year growth period (mixed model).

	Species	Control	3m Clumped	5m Clumped	Standard	Pr > F
Basal	All	0.0022(b)*	0.0036(ab)	0.0055(a)	0.0041(ab)	0.0090
Area	Conifer	0.0022(b)	0.0037(ab)	0.0056(a)	0.0041(ab)	0.0110
	FD_All	0.0021(b)	0.0035(ab)	0.0054(a)	0.0039(ab)	0.0088
	FD_75	0.0025(b)	0.0035(b)	0.0051(a)	0.0034(b)	0.0325
	FD_50	0.0027(b)	0.0037(b)	0.0054(a)	0.0036(b)	0.0286
	FD_30	0.0030(b)	0.0039(b)	0.0056(a)	0.0039(b)	0.0268
	FD_25	0.0030(b)	0.0041(b)	0.0057(a)	0.0041(b)	0.0231
	FD_20	0.0032(c)	0.0042(b)	0.0057(a)	0.0042(a)	0.0175
	FD_15	0.0034(b)	0.0046(b)	0.0061(a)	0.0044(b)	0.0146
Volume	All	0.0190(b)	0.0311(ab)	0.0423(a)	0.0323(ab)	0.0048
	Conifer	0.0183(c)	0.0308(b)	0.042(a)	0.0319(b)	0.0045
	FD_All	0.0157(b)	0.0281(ab)	0.0360(a)	0.0307(a)	0.0024
	FD_75	0.0192(b)	0.0251(ab)	0.0334(a)	0.0236(ab)	0.0209
	FD_50	0.0210(b)	0.0267(b)	0.0350(a)	0.0252(b)	0.0207
	FD_30	0.0233(b)	0.0285(b)	0.0366(a)	0.0273(b)	0.0249
	FD_25	0.0243(b)	0.0298(b)	0.0375(a)	0.0290(b)	0.0283
	FD_20	0.0254(b)	0.0313(ab)	0.0375(a)	0.0299(b)	0.0340
	FD_15	0.0275(b)	0.0342(ab)	0.0411(a)	0.0317(b)	0.0310

*Adjusted means with different letters are significantly different at $\alpha = 0.05$ according to Scheffe's test.

Table 31. Adjusted means of basal area (m^2/yr) and volume (m^3/yr) annual growth by treatment between 1993 and 1996 (mixed model).

	Species	Control	3m Clumped	5m Clumped	Standard	Pr > F
Basal Area	All	0.00020(b)	0.00029(b)	0.00043(a)	0.00033(ab)	0.0132
	Conifer	0.00021(c)	0.00038(b)	0.00058(a)	0.00041(b)	0.0079
	FD_All	0.00020(c)	0.00037(b)	0.00055(a)	0.00040(ab)	0.0063
	FD_75	0.00024(b)	0.00037(ab)	0.00052(a)	0.00036(b)	0.0303
	FD_50	0.00026(b)	0.00039(ab)	0.00054(a)	0.00037(b)	0.0266
	FD_30	0.00028(b)	0.00041(ab)	0.00056(a)	0.00040(b)	0.0244
	FD_25	0.00029(b)	0.00043(ab)	0.00057(a)	0.00042(b)	0.0208
	FD_20	0.00030(c)	0.00044(ab)	0.00058(a)	0.00043(bc)	0.0173
	FD_15	0.00032(c)	0.00048(ab)	0.00061(a)	0.00045(bc)	0.0121
Volume	All	0.0016(c)	0.0028(b)	0.0038(a)	0.0028(b)	0.0038
	Conifer	0.0016(c)	0.0028(b)	0.0037(a)	0.0028(b)	0.0036
	FD_All	0.0014(b)	0.0025(a)	0.0031(a)	0.0027(a)	0.0022
	FD_75	0.0016(b)	0.0022(ab)	0.0028(a)	0.0.0021(b)	0.0203
	FD_50	0.0017 (c)	0.0024(ab)	0.0029(a)	0.0023(bc)	0.0202
	FD_30	0.0019(c)	0.0025(ab)	0.0031(a)	0.0024(bc)	0.0217
	FD_25	0.0019(b)	0.0026(a)	0.0031(a)	0.0025(ab)	0.0231
	FD_20	0.0020(b)	0.0028(a)	0.0031(a)	0.0026(ab)	0.0252
	FD_15	0.0022(b)	0.0030(a)	0.0034(a)	0.0028(ab)	0.0217

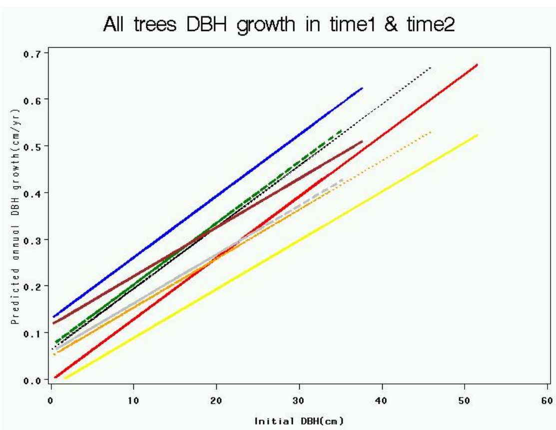
* Adjusted means with different letters are significantly different at $\alpha = 0.05$ according to Scheffe's test.

Table 32. Adjusted means of basal area (m^2/yr) and volume (m^3/yr) annual growth by treatment between 1997 and 2003 (mixed model).

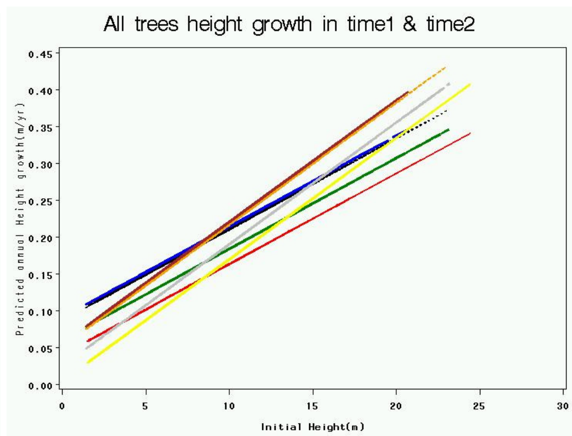
	Species	Control	3m Clumped	5m Clumped	Standard	Pr > F
Basal Area	All	0.00020(b)	0.00029(b)	0.00043(a)	0.00033(ab)	0.0132
	Conifer	0.00020(c)	0.00030(bc)	0.00044(a)	0.00033(ab)	0.0168
	FD_All	0.00020(b)	0.00029(ab)	0.00044(a)	0.00032(a)	0.0157
	FD_75	0.00023(b)	0.00028(b)	0.00041(a)	0.00028(b)	0.0390
	FD_50	0.00025(b)	0.00030(b)	0.00043(a)	0.00030(b)	0.0333
	FD_30	0.00028(b)	0.00032(b)	0.00045(a)	0.00032(b)	0.0331
	FD_25	0.00029(b)	0.00034(b)	0.00046(a)	0.00034(b)	0.0296
	FD_20	0.00030(b)	0.00035(b)	0.00047(a)	0.00036(b)	0.0224
	FD_15	0.00032(b)	0.00038(b)	0.00050(a)	0.00037(b)	0.0212
Volume	All	0.0019(c)	0.0028(b)	0.0037(a)	0.0029(ab)	0.0091
	Conifer	0.0018(c)	0.0028(b)	0.0037(a)	0.0029(ab)	0.0095
	FD_All	0.0016(b)	0.0025(a)	0.0033(a)	0.0028(a)	0.0084
	FD_75	0.0019(b)	0.0022(b)	0.0030(a)	0.0021(b)	0.0282
	FD_50	0.0021(b)	0.0024(b)	0.0032(a)	0.0023(b)	0.0278
	FD_30	0.0024(b)	0.0026(b)	0.0033(a)	0.0025(b)	0.0346
	FD_25	0.0025(b)	0.0027(b)	0.0034(a)	0.0026(b)	0.0408
	FD_20	0.0026(b)	0.0029(ab)	0.0035(a)	0.0027(b)	0.0525
	FD_15	0.0029(b)	0.0031(ab)	0.0038(a)	0.0030(b)	0.0539

* Adjusted means with different letters are significantly different at $\alpha = 0.05$ according to Scheffe's test.

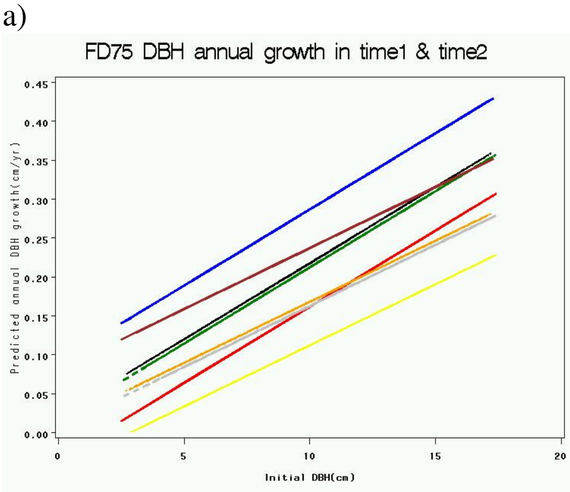
Figure 10 presents graphs of the linear model using only the fixed effect (initial measurement of dbh and height, time, time×initial measurement and treatment) for each treatment and the two measurement periods. The graphs for predicted dbh and height growth showed the same pattern within a measurement period for all the datasets examined; only the all species and FD_75 datasets are presented in Figure 10. Predicted dbh growth was higher in Period 1 than in Period 2 for a given initial dbh for all treatments and the control. The slope of the linear relationship in Period 1 was slightly steeper than in Period 2. For height growth, the slope of the linear relationship in Period 2 was much steeper than in Period .1 So, smaller trees were predicted to grow faster in period 1 compared to period 2 but trees over 7 or 8m were predicted to grow slower in period 1.



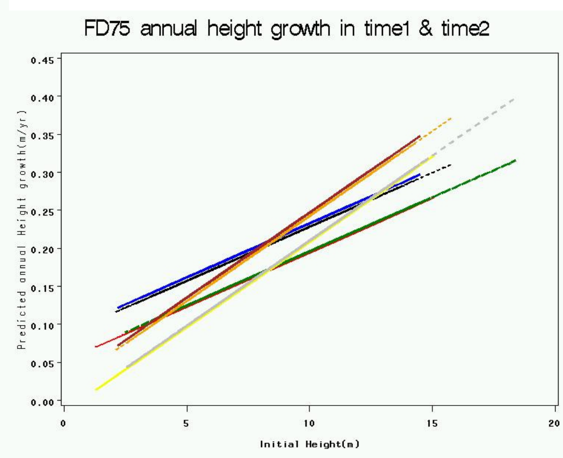
a)



b)



c)



d)

Figure 10. Predicted annual height and dbh growth versus initial height and dbh (1993) using a linear model with only fixed effects: a) and b)-- all trees; c) and d): -- Douglas-fir with 75 trees in each 5 cm diameter class. Period 1 (----C ---- C1 ---- C2 ----S) Period 2 (----C ----C1 ---- C2 ----S).

4. DISCUSSION

This study focused on growth at the stand and tree level for three different precommercial thinning regimes and a control over time. The first analysis on this experiment (Bugnot 1999) was done using data measured six years after the thinning. The data for this study were gathered 13 years after thinning. It is likely that the first analysis partially included the effect of thinning shock (Brockley 1983; Harrington and Reukema 1983). This analysis should illustrate the relatively longer term impact of each thinning regime.

4.1. GROWTH FOLLOWING THINNING

There are many environmental factors (e.g., light, water, nutrients, temperature and growing space) which affect tree growth (Oliver and Larson 1996). Biotic factors (e.g., damage by insects, and disease) also may impact on tree growth. In this section, only the effect of factors associated with stand density (growing space) on tree growth will be considered.

4.1.1. Stand-level Growth

4.1.1.1.Basal area and Lorey's height

The average number of stems per ha in the control plots was at least 2.5 times larger than in the treated plots in 1993. Even though many stems died in the control plots over the next 11 years, the number of stems in these plots was still about twice that of the treatment plots after the last measurement. The same trend is apparent for basal area per ha. The control plots had much higher basal area per hectare than the treatment plots in

1993 and, the control plots still had higher basal areas per hectare 11 years later. However, over this period, the average growth in basal area per hectare was significantly higher on the thinned plots than on the control plots: 3 m clumped thinning -- 8.4 m^2/ha; 5 m clumped thinning -- 8.1 m^2/ha; standard thinning -- 7.8 m^2/ha; and control -- 6.2 m^2/ha. It is likely that the differences in basal area between the control and the treated plots will continue to decrease with time.

Lorey's height (i.e., weighted-mean height) is a more stable variable than the simple arithmetic mean of height since it is less affected by high mortality in smaller trees (Loetsch *et al*. 1973). For both of the growth periods (1993-1996; 1997-2003), Lorey's height for the control plots was lower than that of the thinned plots. This was expected since the control plots had a lot more smaller trees than the thinned plots. However, changes in Lorey's height over the period were similar across treatments.

4.1.1.2.Volume and Biomass

Annual volume growth was similar among the thinned and control plots in the first growth period; however, in the second growth period, the 3 m clumped thinning had a higher value than the other treatments and the control. Growth in merchantable volume, measured from a 30 cm high stump to a 10 cm diameter inner bark top (Omule 1988), for each thinning treatment is expected to be significantly greater than the control over the next growth period because their diameter distributions contain more trees larger than 10 cm dbh at the time of the 2004 measurement. This trend should continue over time. Omule (1988) found that the adjusted cumulative merchantable volume of 86 year old trees in thinned areas was 11 percent higher than in unthinned areas.

At the time of the 2004 measurement, the total above-ground biomass (wood, bark, branches, foliage and total) on the control plots remained higher than that of the thinned plots (Table 9); however, the total above-ground biomass growth was larger on the thinned plots (Table 17). Biomass of branches and foliage increased by a higher percentage than the other biomass components between 1997 and 2003.

4.1.1.3.Mortality and Ingrowth

Generally, the annual mortality was slightly higher in the first measurement period than in the second measurement period, ignoring the lodgepole pine killed by the mountain pine beetle. Control plots had more dead trees than the thinned plots in either measurement period (Table 12). This is not surprising given the higher density in the control plots appears to be causing self-thinning. Certainly, the average density in these plots is above the self-thinning level identified by Long (1990).

Correspondingly, the annual ingrowth on the control plots was lower than in the thinned plots (Table 14). Control plots did not appear to have enough growing space to support ingrowth. The levels of ingrowth for the three thinning treatments were similar. Since the last measurement occurred only 13 years after the thinning took place, and regeneration needed to reach a height of 1.3 m before it was counted as ingrowth, it is possible that further ingrowth will occur on the thinned plots. A number of the broadleaf ingrowth (trembling aspen, white birch), present at the end of the first measurement period, were not included in the second measurement period because their tops were reduced below 1.3 m in height due to heavy browsing from moose and deer. Ingrowth of shade intolerant species (lodgepole pine, trembling aspen, and birch) was totally absent from the control plots due to the lack of sufficient light.

4.1.2.Tree-Level Growth

Two methods were used for comparing the growth of single tree variables across treatments: one was the same as Bugnot (1999) except with different dbh classes (standard ANOVA) and the other used a mixed effects linear model. The two analyses produced almost the same mean values; however, the degrees of freedom differed. Bugnot's (1999) analysis used individual tree values within treatments and blocks by dbh classes. The mixed modeling approach allowed consideration of individual tree values in each plot within treatment and block. This added interaction between plots within the same treatment and treatment and block was treated as a random effect.

4.1.2.1.Height and DBH

Many studies (e.g., Staebler 1956, Miller and Reukema and Bruce 1977, Crown *et al.* 1977, and Reukema 1979) showed that height growth is slow for a short period following precommercial thinning in coastal Douglas-fir plantations, but eventually increases. The results of this study reflected this pattern since the height growth in the first growth period did not differ among the treatments and the control according to Bugnot (1999). In the second growth period, height growth was significantly different for the smallest diameter class, but not for the larger classes. This is evidence of more photosynthesis taking place in these small trees following the increase in space (and light levels) provided on the thinned plots. Omule (1988) found that the height growth of top height trees was not affect by spacing. However, Reukema (1979) found a difference in height growth comparing with the 100 largest trees per acre in each treatment of a planted stand. Height growth response to treatment may be related to site quality since the speed of crown closure following a thinning is related to site quality (Reukema and Bruce 1977). Also, dominant trees which have enough growing space for photosynthesis are less impacted by thinning than smaller trees in uneven-aged stands (Aussenac and Granier 1987).

Annual dbh growth was higher in the first growth period than in the second growth period. However, the treatments were significantly greater than the control in both growth periods. It is possible that dbh growth was less affected by thinning shock effect than height growth. During the second growth period, many small trees died; this changed the distribution of trees by dbh classes from a reversed J-shape to a bell-shaped relationship (Figure 4).

During both growth periods and the total 11-year period, the growth of diameter was significantly different among the thinning plots and control plots using the mixed effects model (Tables 27, 28, and 29). The adjusted mean dbh growth on the control plots was usually two times lower than on the 5 m clumped plots. Even when the number of trees considered was reduced to a limited number of the best growing Douglas-fir trees in each dbh class, there were still significant differences in growth between trees on the thinned plots and those on the control plot.

4.1.2.2.Basal area and Volume

The basal area growth of Douglas-fir alone and all species together in two diameter classes (0 to 10 cm and 10 to 20 cm dbh) were significantly higher in the 5 m clumped thinning than in the other treatments or the control. Since this was the treatment with the lowest residual density, this result shows that basal area growth is positively correlated to the growing space available.

Individual tree volume is important for timber uses because trees with high volume usually have more value than smaller trees and consequently provide more return from harvesting for a given environmental condition. One of the main reasons for thinning is to provide higher individual tree volumes in a shorter period of time. The 5 m clumped spacing plots showed the highest yearly volume growth across the three different diameter classes for the Douglas-fir dataset (0.0050 m^3 – 0.1028 m^3), while the control plots showed the lowest rate of yearly volume growth (0.0025 m^3 – 0.0623 m^3). Trees with a dbh larger than 20 cm were few in number in all plots and they represented the dominant trees. It is not surprising that volume growth on these trees were not significantly affected by the thinning treatments; they generally had sufficient growing space irrespective of treatment.

4.2.LIMITATIONS

This study focused only on the differences in growth rate among three types of precommercial thinning and unthinned (control) conditions. However, there are other important factors which affect growth as I mentioned. Even if there were statistically significant differences between the thinned stands and the control, the differences may not be large enough to warrant the expense of the thinning. Economic analysis is necessary to evaluate the cost effectiveness of the thinnings in this experiment. Also, other factors such as wildlife habitat, landscapes, etc. may influence whether or not a stand is thinned.

The data used in this study came from the IDFdk3 subzone and the transition between the IDFdk3 and the SBPSmk subzones. It is expected that the results would apply to similar stands throughout the IDFdk3 subzone. While the magnitude of the response to pre-commercial thinning will likely vary in different IDF subzones, the same trends evident in this study should hold.

The last measurement occurred only 13 years after the thinning treatments in this study and it is likely that some response is still occurring. It will be necessary to follow the continued development of these stands through a number of future measurement periods to capture the entirety of their response to the thinning treatments.

During the 2004 measurement period, it was found that most of the lodgepole pine trees in the sample plots had been killed by mountain pine beetle. Such a mortality event will affect whole stand and individual tree growth since there is unplanned and unexpected space between trees not specified from the silvicultural prescription. As a result of this mortality, and the resulting increase in individual tree spacing, the dbh and volume growth of residual trees will be greater than in non-MPB affected plots in the same treatment area. For example, plots 5 and 23 lost 8 and 6 trees, respectively, with corresponding volume losses of 62 m^3/ha and 72 m^3/ha. This may mask (or confound) any treatment effect. During the next data collection and analysis interval, it will be very important to correctly interpret the impact of lodgepole pine mortality since there may be unexpected effects.

5. CONCLUSIONS

This study addressed responses from precommercial thinning in uneven-aged interior Douglas-fir stands over 11 years of measurements divided into two growth periods. The results of this study will help to inform future management of this forest type.

Growth of basal area per ha and volume per ha did not differ significantly among the thinning treatments nor between the treatments and the control (Hypothesis 1). Average eleven year growth in basal area ranged from 4.59 to 4.89 m^2/ha for the different types of thinning and was somewhat lower for the control plots (3.87 m^2/ha). For periodic volume growth, the average growth on the control plots (42.60 m^3/ha) fell within the range of average periodic growth for the thinning treatments (40.35 to 50.04 m^3/ha). The pattern of growth in the second period (1997 to 2003) was similar to the first growth period (1993 to 1996), although slightly lower.

Annual growth rates of Douglas-fir for dbh, basal area and volume on a per tree basis were highest on the 5 m clumped spacing regime (C2) from 1997 to 2003, and were significantly better than either of the other treatments or the control (Hypothesis 2). Annual height growth of Douglas-fir was highest on the 5 m clumped (C2) and the 3 m clumped (C1) thinning treatments, but was not significantly different than the standard thinning or the control (Hypothesis 2). When the dataset was reduced to include a smaller number of the best growing Douglas-fir trees on each plot, the differences in height growth among the treatments became even smaller.

The growth response of small trees (≤ 10 cm dbh) was significantly lower than middle-sized (10 to 20 cm dbh) and large trees (> 20 cm dbh) for dbh, basal area, height, and volume (Hypothesis 3). However, there results for middle-sized and large trees were variable.

Higher levels of mortality and variable growth rates among the smaller dbh trees reduced the number of smaller trees present in both the thinned stands and, especially, the control stands. Consequently, the dbh distribution appears to be changing from a reversed J-shape to more of a bell-shape. Higher levels of regeneration (ingrowth) would be required if a reversed J-shaped distribution is to be maintained. This is only likely to occur if disturbances (e.g., partial cutting) are introduced periodically.

As this permanent sample plot installation is maintained and remeasured over time, it is expected to continue to provide insight into the duration and magnitude of the response to precommercial thinning. Additional studies focusing on merchantable volume response at both the single tree and stand level, perhaps including economic projections, and on regeneration and small tree development would augment the results presented here.

According to the results of this study, the 5 m clumped spacing treatments had the highest individual tree dbh and volume growth, but the lowest stand volume of all spacing treatments. However, the 3 m clumped spacing may be the most appropriate silvicultural option for uneven-aged interior-Douglas stands when mule deer winter habitat, timber volume and timber value are all considered. The 5 m clumped spacing regimes have large canopy openings within the stands, and large crown areas around individual trees with low height to live crown ratios. The stand characteristics resulting from the 5 m clumped spacing may reduce timber value due to larger branches. As well, mule deer habitat might be limited due to the high snowpack that results from the large inter-tree canopy spacing. The dbh distribution of the standard spacing regimes is similar to that of the 3 m clumped spacing, except for dbh classes less than 15 cm. Since there are more small trees in the 3 m clumped spacing, there is more potential for future stand growth than with the standard spacing prescription. When making silvicultural decisions, it is important that actions are not taken that preclude further actions and choices in the future when different information may be available or different actions desired.

REFERENCES

Arno, S.F. 1990. Ecological relationships of interior Douglas-fir. P. 47-52 *in* Proc. of symposium on interior Douglas-fir: the species and its management. Baumgartner, D. M. and J.E. Lotan (eds.). Spokane, WA.

Aussenac, G. and A. Granier. 1987. Effects of thinning on water stress and growth in Douglas-fir. Can. J. For. Res. 18: 100-105.

Bonnor, G. M. 1990. A growth and yield study of interior Douglas-fir in British Columbia. P. 269-274 *in* Proc. of symposium on interior Douglas-fir: the species and its management. Baumgartner, D. M. and J.E. Lotan (eds.). Spokane, WA.

Blood D.A. 2000. Mule and black-tailed deer in British Columbia. B.C. Min. Environment.

British Columbia Forest Service. 1976. Whole stem cubic meter volume equations and tables. Forest Inventory Division, B.C. For. Serv., Victoria, B.C.

British Columbia Ministry of Forests. 1992. Correlated guidelines for management of uneven-aged drybelt Douglas-fir stands in British Columbia. Victoria, B.C. 59 p.

Botkin D.B. 1993. Forest dynamics: An ecological model. Oxford Unv. Press, New York. 309p.

Brockley, R.P. 1989. Response of thinned, immature lodgepole pine to nitrogen fertilization: three-year growth response. FRDA Rep. No. 36. Canada-B.C. Forest Resource Development Agreement, B.C. Min. of Forests. Victoria.

Bugnot, J.L. 1999. Effects of spacing on multi-aged interior Douglas-fir stands in central British Columbia. M.Sc. thesis, Univ. of British Columbia, Vancouver, BC, Canada. 96 p.

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

Crown, M., R.V. Quenet, and C. Layton. 1977. Fertilization and thinning effects on a Douglas-fir ecosystem at Shawnigan Lake: 3-year growth response. Can. For. Serv. Rep. BC-X-152. 36 p. Victoria. B.C.

Day, J.K. 1998. Selection management of interior Douglas-fir for mule deer winter range. Master's Thesis. Faculty of Forest. Univ. of British Columbia. Vancouver. B.C.

De Liocourt, F. 1898. De l'aménagement des sapinières. Bull. Soc. For. Franche-Comté Belfort, Besançon.

Barbour, R. J. and D. L. Parry. 2001. Log and Lumber Grades as Indicators of Wood Quality in 20- to 100-year-old Douglas-fir Trees from Thinned and Unthinned Stands. For. Serv., USDA. 21 p.

Hann, D.W. and M.W. Ritchie. 1988. Height growth rate of Douglas-fir: A comparison of model forms. For. Sci. 34:165-175.

Hagglund, B. 1981. Evaluation of forest site productivity. For. Abstr. 42(11):515-527.

Harrington, C.A. and D.L. Reukema. 1983. Initial shock and long-term stand development following thinning in a Douglas-fir plantation. For. Sci. 29(1):33-46.

Hicks, C.R. 1993. Fundamental concepts in the design of experiments (fourth edition). Saunders College Publishing. New York. 509 p.

Hope, G.D., W.R. Mitchell, D.A. Lloyd, W.R. Erickson, W.L. Harper, and B.M. Wikeem. 1991. Ecosystems of British Columbia. Special report series, B.C. Min. of Forests. 330 p.

Klinka, K. and Carter, R.E., 1990. Relationships between site index and synoptic environmental variables in immature coastal Douglas fir stands. *For. Sci.* **36**, pp. 815–830.

Leak, W.B. 1964. An expression of diameter distribution for unbalanced, uneven-aged stands and forests. For. Sci. 10:39-50.

Littell, R.C., Milliken, G.A., Stroup, W.W. & Wolfinger, R.D. (1996) SAS® for Mixed Models. SAS Institute, Cary, NC. 813 p.

Loetsch, F., Zöhrer, F., and Haller, K.E. 1973. Forest inventory. Vol. 2. BLV, Munich. Verlagsgesellschaft München, p. 48–58.

Long, J.N. 1985. A practical approach to density management. For. Chron. 23-27.

Long, J.N, and T.W. Daniel. 1990. Assessment of growing stock in uneven-aged stands. West. J. Appl. For. 5:93-96.

Marshall, P.L. 1996. Response of uneven-aged Douglas-fir to alternative spacing regimes: analysis of the initial impact of the spacing regimes. Canada-British Columbia partnership Agreement on Forest Resource Development: FRDA-2 Report 242. 27 p.

Marshall, P.L. and Y. Wang. 1996. Growth of uneven-aged interior Douglas-fir as influenced by different stand structures. Canada-British Columbia Partnership Agreement on Forest Resource Development:FRDA-2 Report 267. 20 p.

Miller, R.E. and D.L. Reukema. 1977. Urea fertilizer increase growth of a 20-year-old thinned Douglas-fir on a poor quality site. USDA For. Serv. Res. Note PNW-291. 8 p.

McWilliams, E.R.G., and Thérien, G., 1996. (revised 1997) Fertilization and thinning effects on a Douglas-fir ecosystem at Shawnigan Lake: 24-year growth response. FRDA Rep. No. 269. Canada – British Columbia Partnership Agreement on Forest Resource Development: FRDA II. B.C. Min. of Forests and Forestry Canada, Victoria, B.C.

Meyer, H.A. 1952. Structure, growth, and drain in balanced unevenaged forests. J. For. 50:85-92.

Meyer, H.A. 1963. Vertical distribution of annual increment in thinned Ponderosa Pine. For. Sci. 9, 394-404.

Nigh, G.D., C.C. Ying, and H. Qian. 2004. Climate and productivity of major conifer species in the interior of British Columbia, Canada. For. Sci. 50(5):659-671.

Oliver, C.D. and B.C. Lasrson. 1996. Forest stand dynamics (update edition). John Wiley & Sons, New York. 520 p.

Omule, S. A. Y., (1988). Growth and Yield 35 Years after Commercially Thinning 50-year-old Douglas-fir. B.C. Ministry of Forests and Lands Research Branch Canada. 15 p.

Reineke, L.H. 1933. Perfecting a stand density index for even-aged forests. J.Agric. Res. 46:627-638.

Reukema, D.L. and D. Bruce. 1977. Effect if thinning on yield of Douglas-fir: Concepts and some estimates obtained by simulation. USDA For. Serv. Gen. Tech. Rep. PNW-58, 36 p. Pac. Northwest For. and Range Exp. Stn., Portland, Oreg.

Reukema, D.L. 1979. Fifty-year development of Douglas-fir stands planted at various spacings. USDA For. Serv. Res. Pap. PNW-253, 21 p. Pac. Northwest For. and Range Exp. Stn., Portland, Oreg.

Simpson, D.G. 2000. Water use of interior Douglas-fir. Can. J. For. Res. 30:534–547.

Simpson, K., and L.W. Gyug. 1991. Part II. Movements, habitats and status of mule deer and moose populations influenced by the Okanagan Connector Freeway. Consultant's report prepared for Min. of Highways, Victoria, and Min. of Env., Penticton and Kamloops. 60pp.

Smith,D.M. 1986. The practice of silviculture (eight edition). John Wiley & Sons, New York. 527 p.

Snedecor, G.W. and W.G. Cochran. 1989. Satistical Methods. 8th ed. Iowa State Univ. Press. Ames, Iowa. USA. 503 p.

Standish, J.T., G.H. Manning and J.P. Demaerschalk. 1985. Development of biomass equations for British Columbia tree species. Can. For. Serv. Rep. Inform. Rep. BC-X-264.

Steen, O.A. and R.A. Coupé. 1997. A field guide to forest site identification and interpretation for the Cariboo Forest Region. B.C. Min. For., Victoria, B.C., Land Manage. Handb. No. 39.

Telfer, E.S. and J.P. Kelsall. 1979. Studies of morphological parameters affecting ungulate locomotion in snow. Can. J. Zool. 57(11):2153-2159.

Vyse A., R. A. Smith, and B. G. Bondar, (1990). Management of Interior Douglas-fir Stands in British Columbia: Past, Present and Future. P. 177-185 *in* Proc. of symposium on Interior Douglas-fir: The species and its management, Baumgartner, D. M. and J.E. Lotan (eds.). Spokane, WA.

York, R.A., R.C. Heald, J.J. Battles, & J.D. York. 2004. Group selection management in conifer forests: relationships between opening size and tree growth. Can. J. For. Res. 34: 630-641.

Van Hooser, D.D., K.L. Waddell, J.R. Mills and R.P. Tymcio. 1990. The interior Douglas-fir resource: current status and projections to the year 2040. P. 9-14 *in* Proc. of symposium on Interior Douglas-fir: The species and its management, Baumgartner, D. M. and J.E. Lotan (eds.). Spokane, WA.

Van Laar, A. and Akca, A. 1997. Forest Mensuration. Cuvillier Verlag, Goettingen.

Wahlenberg, W. G. 1948. Effect of forest shade and opening on loblolly pine seedings. J. For. 46:832-834.

Waterhouse, J. M., H. M. Armleder, and R. J. Dawson. 1991. Forage litterfall in Douglas-fir forests in the central interior of British Columbia. B.C. Min. For., Victoria, BC. Res. Note No. 108.