EP 770.55

DRAFT TECHNICAL REPORT

Effects of high plantation densities on the growth and yield of Lodgepole pine – 34-year results at Barnes Creek.

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Photo: July 2015

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Abstract

The effects of high plantation densities (espacement) on the growth and yield of lodgepole pine (*Pinus contorta* Dougl.) are reported over a period of 34 years. Seven densities ranging from 2,500 to 160,000 trees per hectare were established on plots found in the central interior of British Columbia. This study was designed to investigate height repression of lodgepole pine that has been observed with high densities established post wildfire. A variety of statistical tests provided strong evidence of general height reduction with increasing treatment and stand density. The stand level measures of top height and site height were found to be similar only when density > 10,000 sph with site heights > top heights when density < 10,000 sph. Nonlinear segmented regression estimates suggested threshold repression densities of around 11,000 and 8,000 sph respectively at age 15 for top height and site height. Treatment density trajectories indicated all plots were following known stand mortality dynamics. Total stand volumes were found to increase with increasing density with no indication of declining stand productivity at high treatment densities.

Acknowledgements

The Barnes Creek installation was established in 1984 by Michael Carlson, Wayne Johnstone and John Murphy from the Kalamalka Research Station located in Vernon, BC. Early data compilation and analysis was done by Jeff Stone, Research Branch between 1992 and 1995. In 2000, Wayne Johnstone compiled an unpublished summary and in 2005, Jim Goudie (Research Branch) reanalyzed the dataset to support TASS calibration. The MFLNRO Forest Analysis and Inventory Branch provided funds for the 34 year measurement in the fall of 2016. We gratefully acknowledge the assistance of Gordon Nigh and Peter Ott for providing comments and suggestions on the analysis.

Introduction

Lodgepole pine (*Pinus contorta* Dougl. Var. *latifolia* Engelm.) frequently regenerates to high densities following wildfire. Many regenerated stands have densities in excess of 50,000 stems per hectare (sph) and in some areas over 500,000 sph have established after fire (Mitchell and Goudie 1980, Worrall et al. 1985, Thrower 2013). In 2007, Newsome suggested there were over 130,000 ha of overstocked fire origin lodgepole pine in the Williams Lake, Quesnel and 100 Mile TSAs alone. These high density pine stands have resulted in characteristically slower than expected stand development where diameter, height and self-thinning trajectories have often been considered “stagnant” or “repressed” failing to meet timber management objectives (Goudie 1980). Much research has been published documenting pine response to juvenile spacing, thinning and plantation espacement (Johnstone and Pollack 1990, Farnden and Herring 2002, Johnstone 2002). For reviews see Reid (1983) and recently Stewart and Salvail (2017).

In 1984 the Barnes Creek pine espacement trial was established to emulate high density, fire-origin lodgepole pine stands to address questions of pine repression (Carlson and Johnstone 1985). Repeated measurements at the Barnes Creek site have resulted in a multiyear dataset spanning 34 years of growth. This dataset has been a valuable asset in the ongoing assessment and modelling of pine repression in BC. Early results from this study have been shown in several unpublished reports and presentations (Stone 1994 & 1995, Goudie 1996 & 2005, Johnstone 2000). The data has also been used in TASS model calibrations (Tree and Stand Simulator, BC MFLNRO 2015a) however; there is no formal publication of this information. This technical report documents the 34 years of repeated measurements and provides statistical evidence of density impacts to tree and stand level growth and yield.

A key objective of the Barnes Creek trial was originally stated as “describe temporal changes in growth and form parameters … that bracket the growth stagnation point” (Carlson and Johnstone 1985). Thirty years later interest in high density pine “repression” still continues to be a high priority (McWilliams et al. 2016). Operational foresters and managers are concerned over the site productivity impacts of high density, fire origin pine stands on timber supply. Questions continue to be asked such as, at what density, when and for how long does dominant height repression occur? More science-based evidence on height repression is needed to support policy decisions that set maximum density stocking standards for free growing stands (B.C. Ministry of Forests and Range 2007).

Methods

Site Description

The trial site (Experimental Project 770.55) was established within the Barnes Creek Reserve a large fenced area which is located on a well-prepared, gently sloping site, at an elevation of 730 m, approximately 30 km east of Enderby, B.C. (50°32'N, 118°59'W) (Figure 1). The area is found within the Interior Cedar Hemlock zone characterized by continental climate of cool and snowy winters with warm and moist summers (Lloyd et al. 1990). Soils at the site are a sandy loam with significant gravel content.

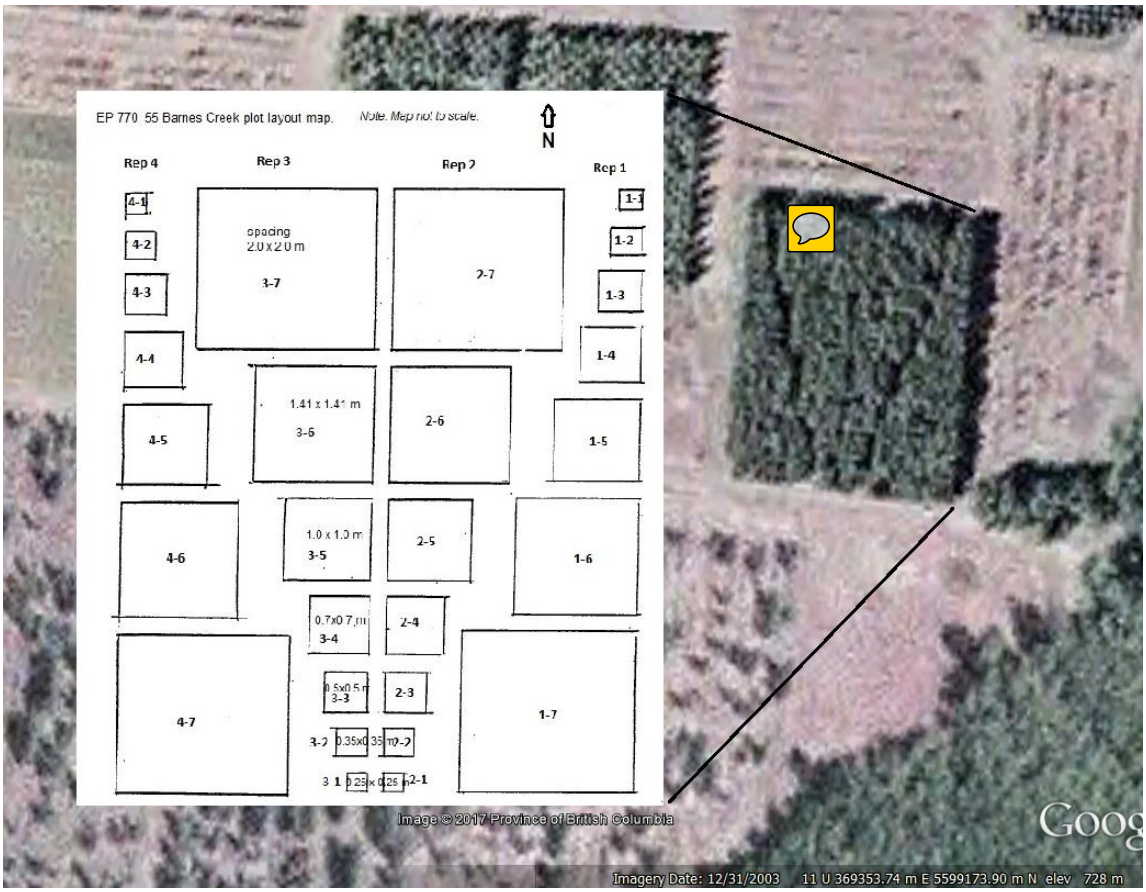


Figure 1. Plot layout map for EP 770.55 Barnes Creek installation superimposed on 2003 aerial imagery indicating the location of the four adjacent replications (Rep) of the seven density treatments (Table 1).

Study Design

The trial design consisted of four adjacent, complete blocks or replications systematically laid-out (Figure 1). Each block contained one 100-tree, square variable-area plot of the seven stand densities (Table 1). During the spring of 1984, a 10 x 10 grid was established on each plot, and a Lodgepole pine seedling (1+0 PSB 313) was planted at each grid intersection. Inter-tree spacing varied dependent upon the treatment plot density. Individual seedling locations were used as tree numbers following a common sequential numbering regime (Figure 2). Planting grid interval and plot sizes are found in Table 1. Total number of seedlings planted was 2800 (7 x 4 x 100).

Table 1. Planting density treatments and plot specifications.

Treatment no.	Stand density (trees/ha)	Inter-tree spacing (m)	Growing space (m^2/tree)	Plot size (ha)
1	160,000	0.250	0.0625	0.0005
2	80,000	0.354	0.1250	0.0010
3	40,000	0.500	0.2500	0.0020
4	20,000	0.707	0.5000	0.0040
5	10,000	1.000	1.000	0.0081
6	5,000	1.414	2.000	0.0162
7	2,500	2.000	4.000	0.0324

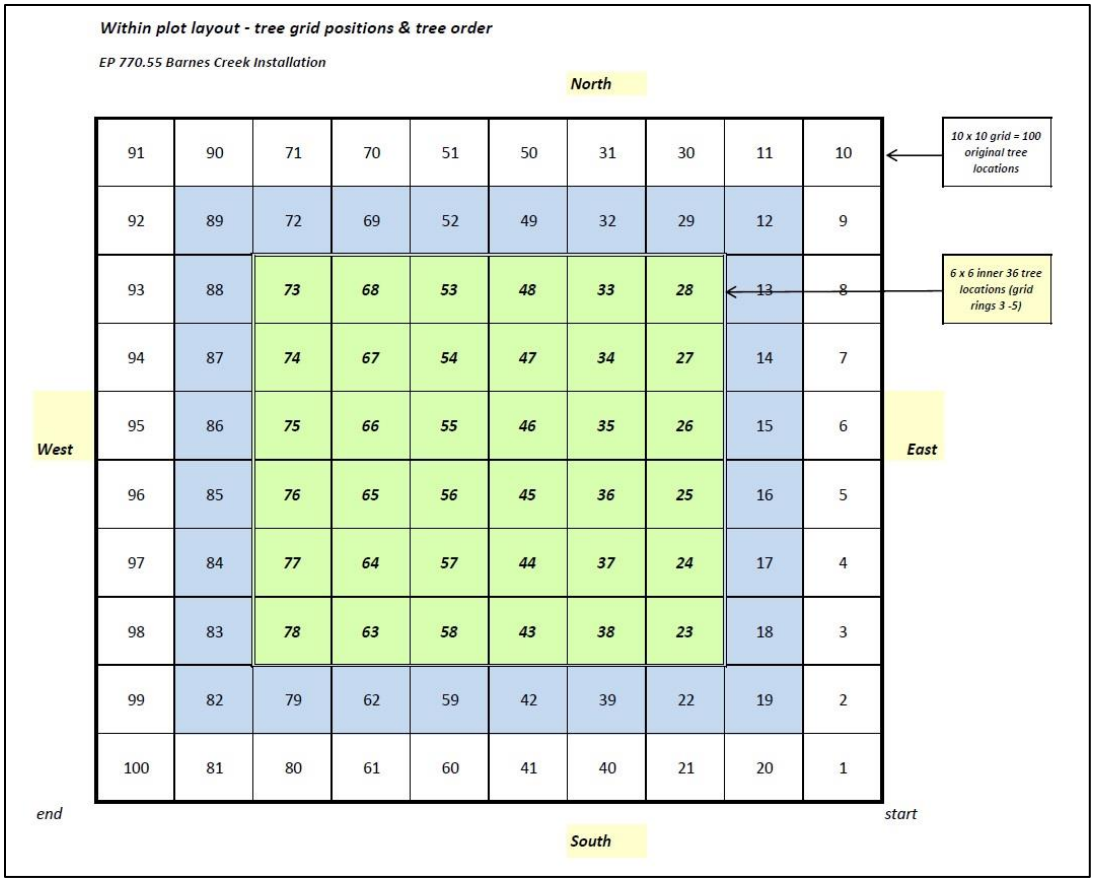


Figure 2. Example of within plot layout of tree grid positions and tree order for EP 770.55 Barnes Creek installation.

Tree Measurements and Compilation

First-year mortality (1984) was approximately six percent and was replaced in the spring of 1985 (Carlson and Johnstone 1985). All living seedlings were measured for height and basal diameter (3 cm above ground) after the third growing season (1986), and annually to the eleventh growing season (1993). Diameter at 1.3 m (DBH) replaced basal diameter measurements in the 15th growing season (1997) and subsequent measurements (fall of 1999, 2005 and 2016). Additional assessments included tree condition, damage and percent live crown (infrequent). During 2016, the largest branch diameter and number of branches on the first whorl above 1.3 m as well as the

total number of inter-nodal branches were recorded. Largest branch measurements were also assessed in 2005 although the location of the largest branch was not recorded.

All trees within the plots were identified by grid position. Data from trees located in the outer perimeter row of each plot were removed from the analyses. Only the inner 64 trees of each plot were compiled. Sample-tree and per-hectare values from each plot were combined to provide the treatment results presented. Unless otherwise noted arithmetic means are shown.

Analysis

Data analysis was completed using SAS version 9.3 (SAS Institute Inc. 2010). Statistical significance was based on $P < 0.05$. Stem volume was calculated using Kovats (1977) tree volume equations for juvenile Lodgepole pine in order to accommodate 3 cm (basal caliper) and 1.3 m (DBH) diameter heights. Previous work by Goudie (2005) was considered a baseline reference for the growth and yield compilations including previous SAS data files and programs (Stone 1994, Goudie 2005).

For analysis purposes the trial was treated as a completely randomized design with plots considered random and plantation treatment densities as fixed effects. Both a mixed effects model (Proc Mixed) and a general linear model (Proc GLM) were used to test replications as random effects and treatment densities as fixed effects using an alpha (α) = 0.05 to detect variable differences prior to using a Bonferroni adjustment with LSMEANS to determine densities differences. Linear and non-linear regression was used to predict key variables across density treatments.

In reality the assignment of treatments to the plots was not random. Field observations in 2016 clearly indicate several issues that need to be considered and documented

Plot size of the higher density treatments was too small to maintain sufficient sample size over the long term. In general, the greater mortality associated with high density stands will require large areas to maintain sufficient tree numbers for long term measurements (Pretzsch 2009). For example, treatments 1 – 3 (160,000 – 40,000 sph) lost a high percentage of inner measurement trees since age 17 (1999) due to stand mortality and concurrent deadfall and breakage into neighbours (Figure 3). The result has been the promotion of edge tree growth with poor representation of undamaged trees within the inner measurement grid. This can be seen in the data summaries for 2016 dependent upon the treatment and plot and to a lesser extent in the 2005 summaries. For example, only two of the four treatment 1 plots (160,000 sph) had live measurement trees in 2016.

Plot sizes were not designed with sufficiently large treed buffer zones to support long term measurements. To avoid edge effects, a treed buffer of at least 7.5 m is necessary that creates an area of at least one neighbouring tree outside the measurement plot (Pretzsch 2009). The higher density plots did not contain treed buffers of sufficient width to ensure both adequate numbers of measurement trees and protection from surrounding treatments and boundary edge effects.

Apparent site effects were related to the position of the block replications. The inner blocks (2 & 3) are surrounded by the outer blocks (1 & 4) on the east and west boundaries whereas the outer blocks are open on the east and west boundaries with prominent edge positions promoting open grown characteristics in the edge position trees. Blocks 2 & 3 due to their innermost position were void of open grown edge position trees in treatments 2 through 6. The outer edge position trees have likely benefited from lower competition influences.

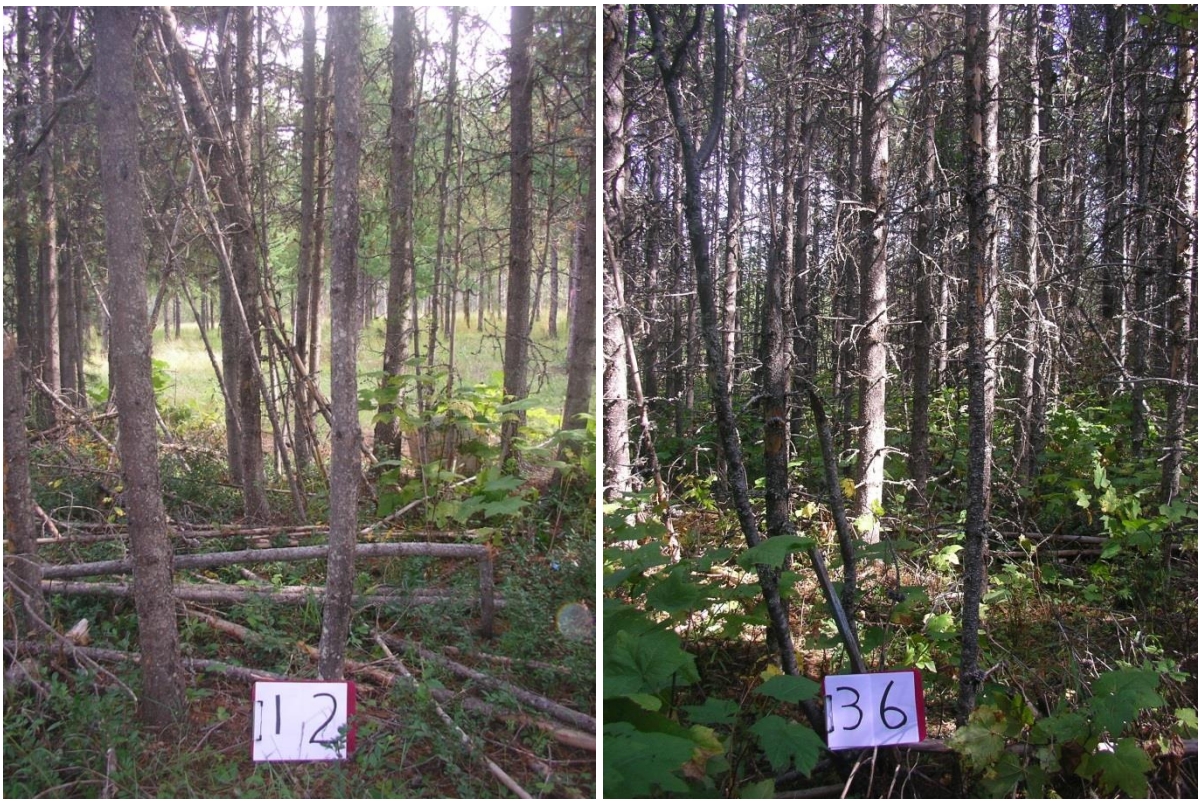


Figure 3. September 2016 photo comparison of plot 1 - 2 (replicate 1 of treatment 2 (80,000 sph)) showing the condition of the measurement tree grid and, plot 3 – 6 (5,000 sph). Note the lack of live inner grid trees at 80,000 sph, presence of deadfall and dominant edge trees.

Height Analysis

Plot and treatment level height statistics (site height, top height and mean height) are presented along with the results of linear and nonlinear regression which attempt to empirically describe changes in height growth patterns over time and density. The key objective of this trial, to describe changes with regard to repression density determination, was addressed by an analytical approach that attempted to systematically quantify the growth changes with density using simple statistics and, linear models progressing in complexity through nonlinear functions to segmented regression estimates (Proc NLMIXED).

Dominant Tree Selection

Dominant height tree selection was restricted to trees with no history of damage or disease as noted on the original field data sheets and / or condition codes recorded within the digital data files (Nigh 2017). As a result, by measurement age 34 the number of trees available for selection had declined substantially and in a few plots no live undamaged trees were available to sample. Two plots from the 160,000 sph treatment (rep #2 and #4) and one plot from the 40,000 sph treatment (rep # 3) did not have any sample trees and therefore no site and top height estimates were obtained.

At each measurement, top height trees (BC Ministry of Forests and Range 2009) were chosen in each plot from the largest diameter trees with no history of damage or disease. The number of trees selected for top height estimates, in each plot at each measurement date, was based on one tree per 0.01 hectare plot size. This resulted in only one tree per plot with the exception of the 2500 sph treatment where 3 trees per plot were required.

An additional dominant height statistic, site height was also estimated for each plot based on choosing the three tallest trees with no history of damage or disease at each measurement date, based on 5% of the initial total number of trees per plot (64). At measurement age 34, 3 trees were available for all plots except for 160,000 sph rep # 1, 80,000 sph rep # 1, 3 & 4 and, 40,000 sph rep # 4 where only one tree was available for sampling.

Results - Tree Level

Diameter

Figures 4a & 4b present treatment means for diameter over age and top height respectively. Average diameter was found to increase with declining treatment density across all measurement ages (see Appendix for tabular results, p-values and means comparisons, Table A1). Early results (age 4 -6) indicated pine found in density treatments > 40,000 sph had significantly smaller basal diameter than those from < 20,000 sph treatments. By age 7 treatment differences were evident between: 160,000 and 40,000; 20,000 and < 10,000 sph. Increasingly finer distinctions between treatment mean diameters continue through to age 17 where mean diameter differences exist between all treatment densities < 80,000 sph.

An indication of diameter growth response to changing treatment density can be obtained by comparing the treatment diameter trajectories in Figure 4a. It can be extrapolated that to reach a given similar diameter it will take additional growing seasons as the density increases. For example, it was observed that it took the 2500 sph treatment approximately 16 years to reach a mean diameter of 8 cm DBH while through extrapolation it took the 5000 sph treatment an additional 3 years, the 10,000 sph an additional 8 – 11 years, 20,000 sph 11 – 15 years and the 80,000 sph an additional 17 years to achieve a similar mean diameter of 8 cm (age 23).

Figure 5a provides a clear visual indication of diameter decrease with increasing treatment density. The incremental increase in diameter at densities < 80,000 sph visually develops into an apparent exponential increase in size with time (Figure 5b).

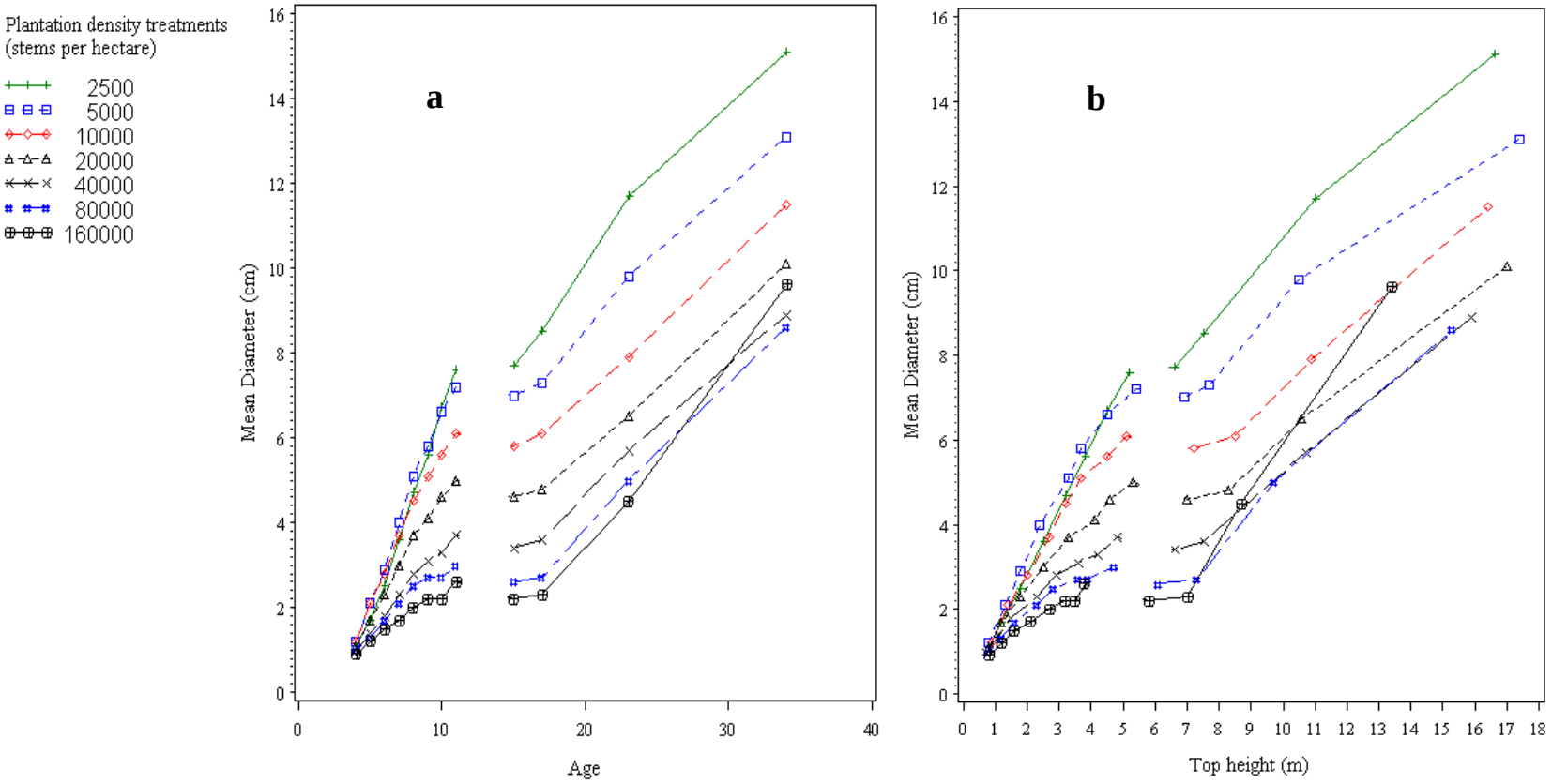


Figure 4. Treatment means over the 34 years after planting for tree diameter (cm) over age (a) or top height (b). Note basal caliper is presented until after age 11 where diameter measures were replaced with DBH.

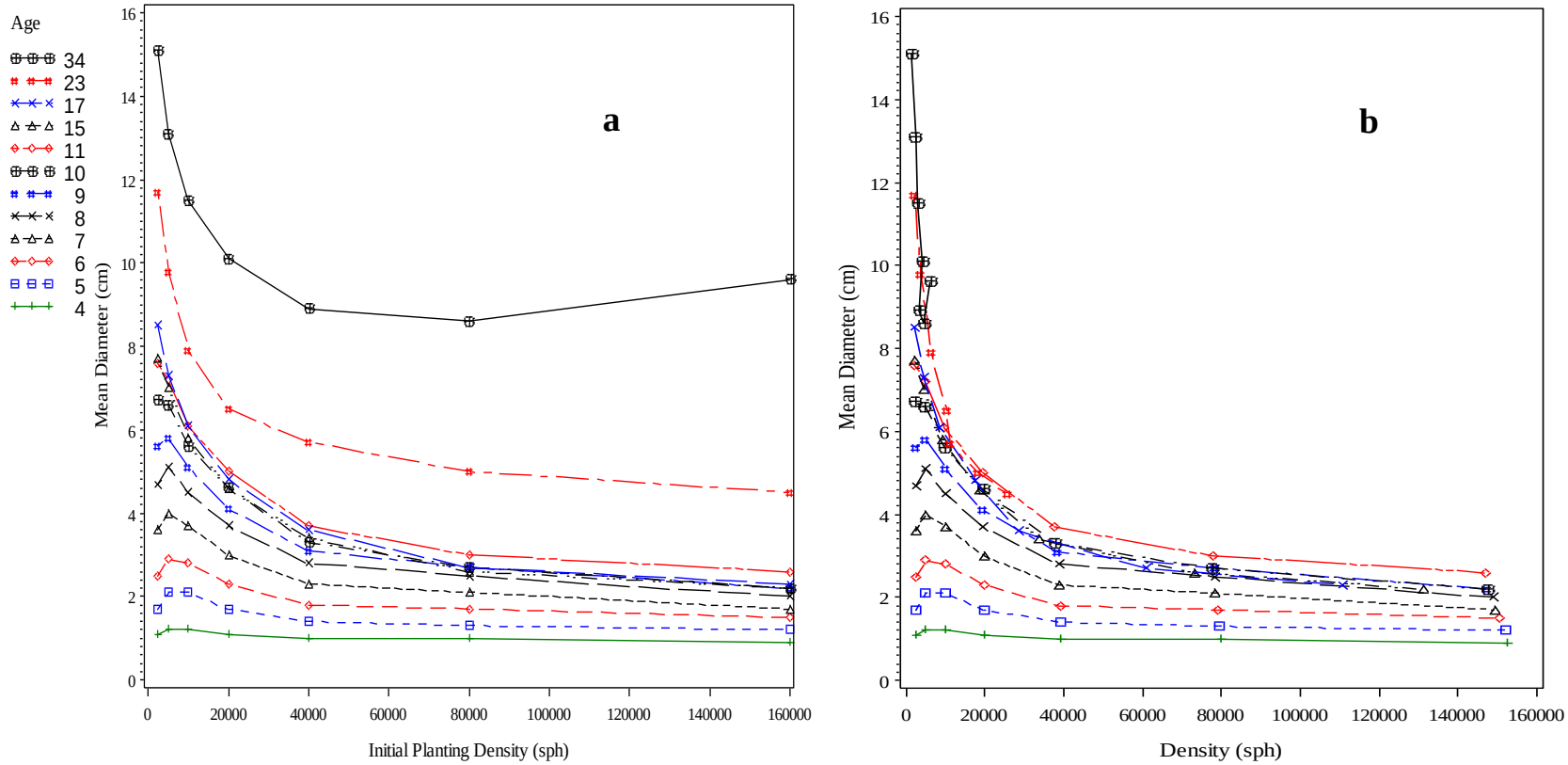


Figure 5. Treatment means for diameter development over initial planting density (**a**) and, real-time stand density (**b**) for the various measurement ages. Note basal caliper is presented until after age 11 where diameter measures were replaced with DBH.

Height

Mean Height over Age

Figure 6a presents treatment means for height over age. Treatment means comparison test results (Table A2) indicated mean height declined with increasing treatment density with initial evidence appearing at age 7 with treatment density 160,000 sph significantly shorter than 10,000 sph (this test result remained unchanged through until age 34). At age 8 and 9 both the 5,000 and 10,000 sph treatments were found to have the tallest mean heights of all treatments which were significantly taller than any treatments > 20,000 sph. During the next 14 years of measurements, a similar reoccurring pattern was evident where the group of treatment densities 2500 to 20,000 sph were statistically undifferentiated in mean height. All the treatments in this group were found to have taller mean heights than treatment densities > 40,000 sph from age 10 through 23. The 160,000 sph treatment consistently had the shortest mean heights, significantly shorter than all other treatments (< 160,000).

Top Height over Age

Figure 6b presents the top height treatment means over age. The earliest test results suggest treatment mean differences occurred at age 9. In general, there was a notable decline in mean top height with increasing treatment density however, the means tests only indicated significant differences between the 160,000 sph treatment and the treatment densities < 40,000 sph at ages 10 through 15. At older ages the increased plot to plot variation failed to provide meaningful statistically valid evidence of treatment mean top height differences (Table A3).

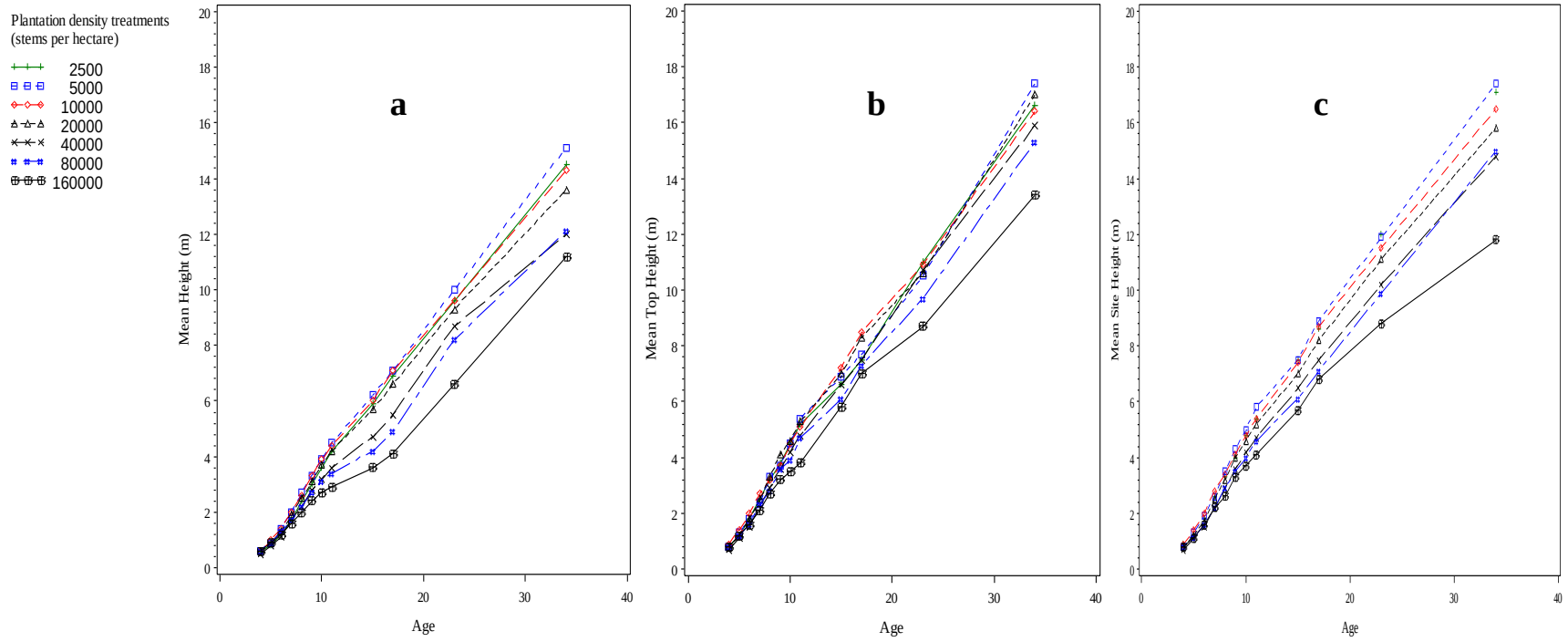


Figure 6. Mean height (a), top height (b) and c) site height development over age for the various plantation density treatments where top height is calculated as the average height of the 100 largest diameter trees per hectare.

Figure 7 provides an expanded graphic of top height development by density treatment up to age 17. Comparing the individual treatment trajectories over the 13 year period (age 4 – 17) highlighted the expanding differences in mean top height between treatment densities with time. A series of horizontal lines (blue) have been superimposed to provide a visual reference for assessment. The difference in treatment mean top height can be interpreted as a difference in years to obtain a similar mean top height development (α). For example, at age 6 the 40,000 sph treatment took an additional year of height growth to achieve a similar top height of 1.5 m that the 10,000 sph treatment achieved at age 5 (Figure 7 – α). By age 8, the 160,000 sph treatment dropped behind the leading top height densities (< 20,000 sph) by approximately 2 years (α_2 ~ 1.4 years), by age 17 this age difference has increased to approximately 3 years (α_3 ~ 2.5 years) and by age 34 the difference was 7 years (~ 6.3 years). The results suggest the number of years to a similar top height increases with age and varies by treatment density over 20,000 sph.

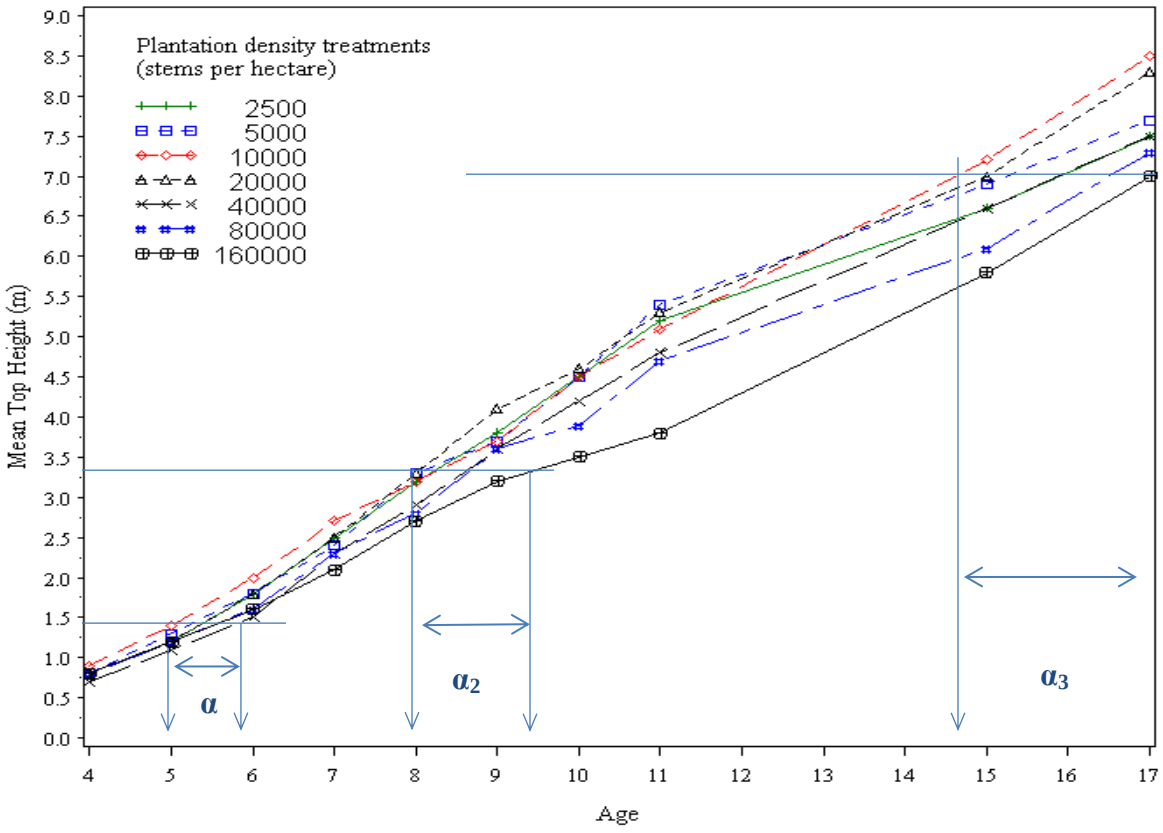


Figure 7. Early years of mean top height development from age 4 to 17 for the various plantation density treatments.

Site Height *over Age*

Site height results (Table A4, Figure 6c) were found to be much more consistent and less variable across time than top height. The earliest evidence of treatment differences occurred at age 5 continuing through to the last measurement at age 34. From age 8 onwards, mean site height for treatment densities < 20,000 sph were significantly taller than the 160,000 sph treatment and by age 9 significantly taller than the 80,000 sph (except age 34). From age 11 to 23, treatment mean site height differences had differentiated such that those treatments < 20,000 sph were found taller than treatments > 20,000 sph. Site height means comparison tests found no differences between any treatment densities between 2500 and 20,000 over the entire 34 year measurement period.

Height over Density

Figures 8 and 9 present the top height and site height treatment means over density, initial treatment planting density (a), real-time stand density (b) and the natural log transformed stand density (c) by measurement age. These figures provide a reference to the various age – treatment density trajectories of Figures 6 and 7 and are further compiled as 3 dimensional surface plots (Figures 10 & 11). The notable decline in height with increases in initial and stand density was used in formulating linear and non-linear models to describe the height – density trajectories. Treatment means and test results are found in the Appendix tables (Tables A2 - A4).

Simple linear models indicated a significant decline in treatment height (mean, top and site height) with increasing density (treatment and real time stand density). Top height and site height linear models (see Tables A5 & A6) suggested the slope of this decline (coefficient b) increased with age and was significantly different from zero only at ages > 6. The linear fit statistics were very good with R^2_{adj} describing 47 to 95 % of the top height and site height treatment variation (mean height results not shown).

Subsequent nonlinear models explorations resulted in the use of the natural log transformation (*ln*) of stand density to fit quadratic equations to the top height mean treatment plot data (Table 2, Figure 8c) (mean height and site height results not shown). The fitted quadratic functions allowed for three model coefficients to describe the parabolic trajectory shape (Sit and Poulin-Costello 1994). Through viewing the transformed density data (Figures 8c and 9c) one can gain an appreciation of how the parabolic model coefficients change to fit the very minor to major concavity (coefficient a) increase with age. The quadratic model was significant at ages 8 to 23

in describing between 19 to 62 % of the top height plot level variation. Age 6 and 7 analysis was marginally significant at P = 0.0827 and P = 0.0589 respectively.

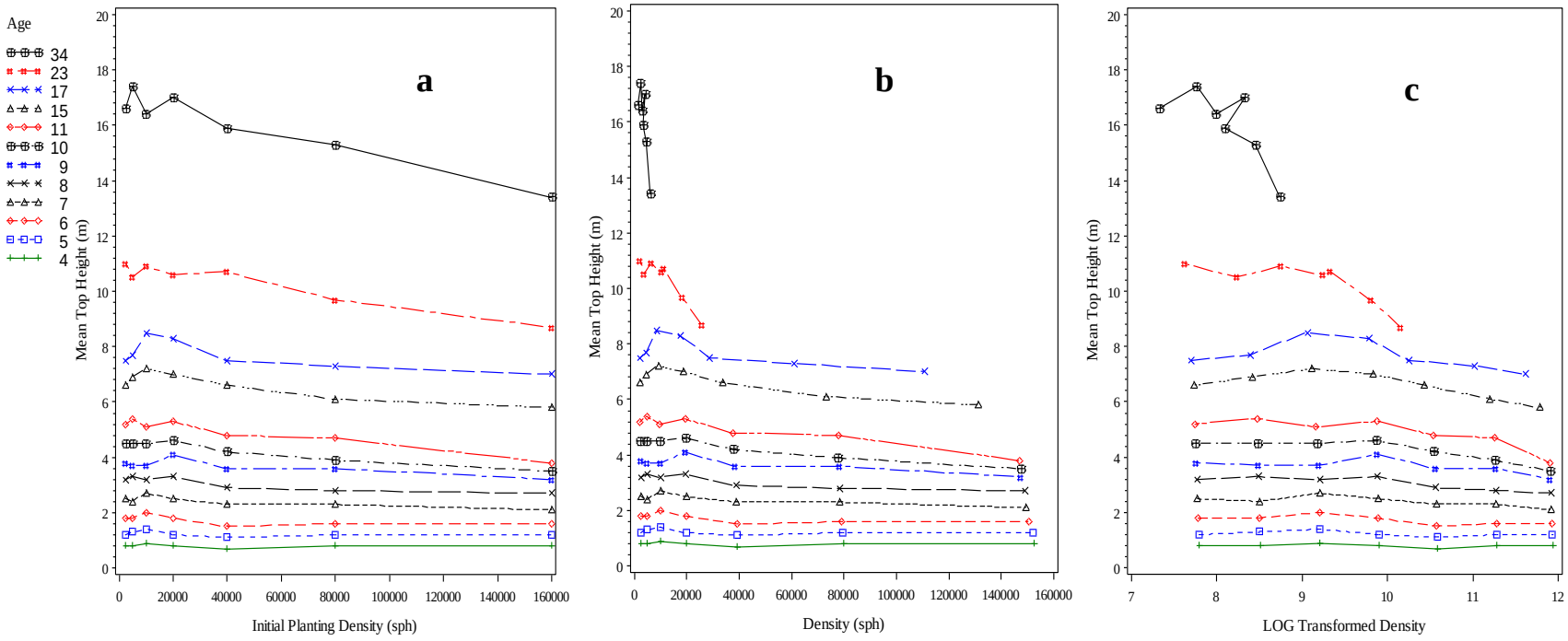


Figure 8. Top height development over treatment initial planting density (sph) (**a**) real-time stand density (**b**) and natural log transformed stand density (**c**) for the various measurement ages.

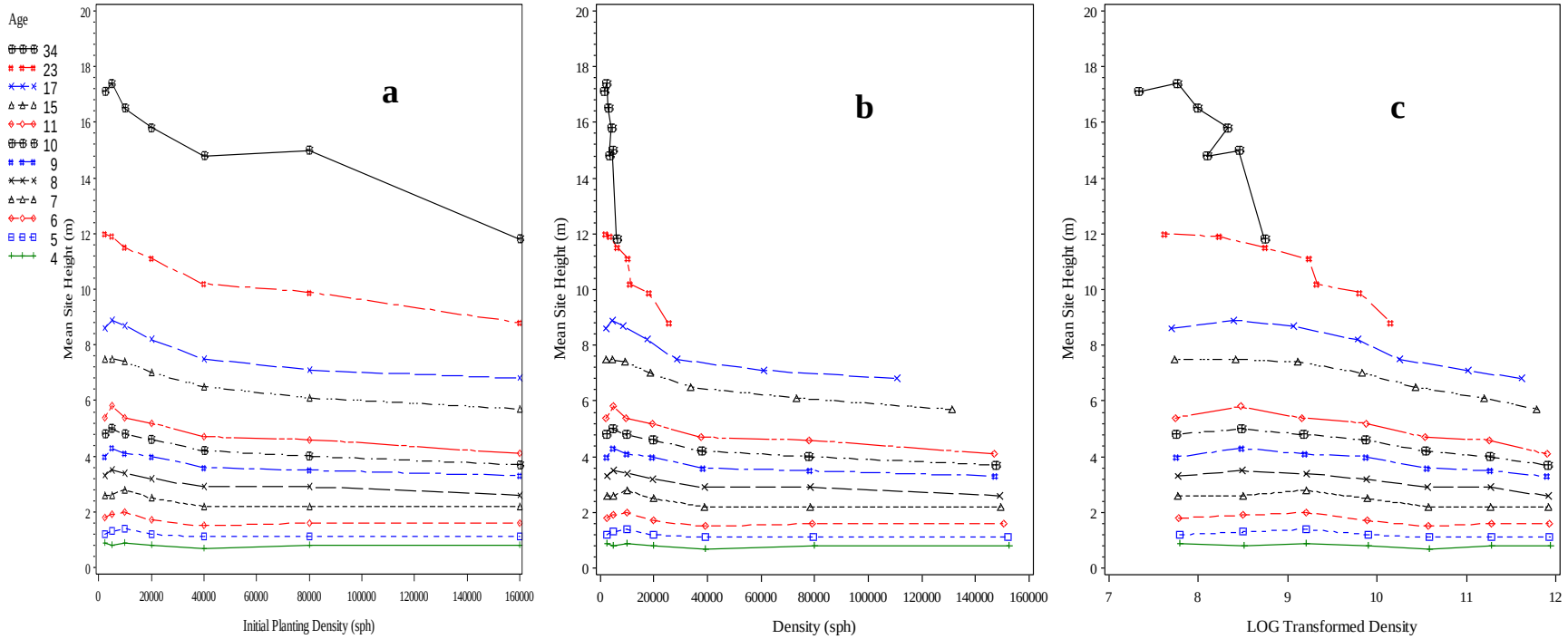


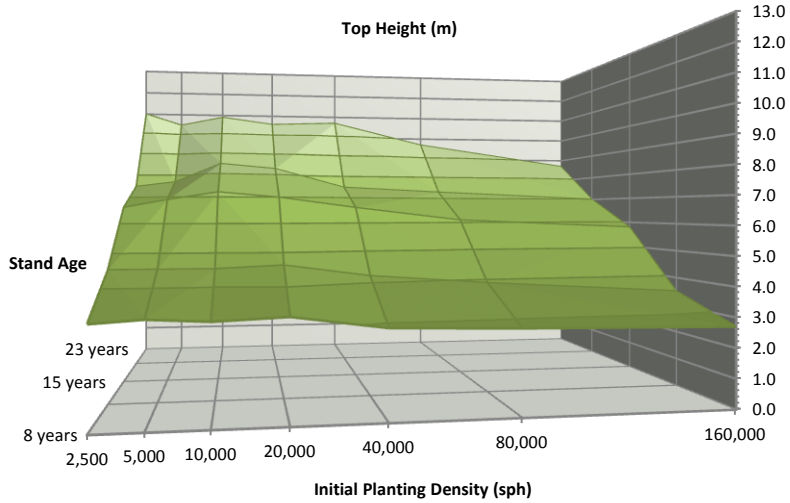
Figure 9. Site height development over treatment initial planting density (sph) (**a**) real-time stand density (**b**) and natural log transformed stand density (**c**) for the various measurement ages.

Table 2. Equation parameters for the quadratic model describing ***top height*** (m) over natural log (ln) of total density (tph) (lnNT) where the dependent variable top height = a (lnNT - b)^2 + c (alternate nonlinear equation form). Plot means were used (n = 28). Parameter "a" controls the parabola shape (concave down), "b" is the location of the extremum (lnNT) and "c" shifts the top height axis. See Figure 10.

Age[a]	a	b	c	R^2_{adj}	RMSE[b]	P value
4	0.00699	10.882	0.762	-0.003	0.0864	0.395
5	-0.00625	7.227	1.253	-0.004	0.1798	0.402
6	-0.0202	8.037	1.811	0.115	0.2408	0.0827
7	-0.0468	8.936	2.513	0.139	0.2967	*0.0589*
8	*-0.0447*	*8.367*	*3.226*	*0.306*	*0.2798*	***0.0039***
9	*-0.0791*	*9.129*	*3.858*	*0.256*	*0.3204*	***0.0095***
10	*-0.1203*	*8.863*	*4.578*	*0.572*	*0.3265*	***< 0.0001***
11	*-0.1562*	*8.863*	*5.328*	*0.556*	*0.4357*	***< 0.0001***
15	*-0.2059*	*9.178*	*7.068*	*0.615*	*0.368*	***< 0.0001***
17	*-0.2335*	*9.287*	*8.128*	*0.28*	*0.632*	***0.0063***
23	*-0.4329*	*8.2024*	*10.851*	*0.19*	*1.164*	***0.0274***
34	-0.6952	7.7304	16.532	0.11	1.33	0.107

[a] n = 28 per measurement period (age 4 – 34).

[b] Root mean squared error.



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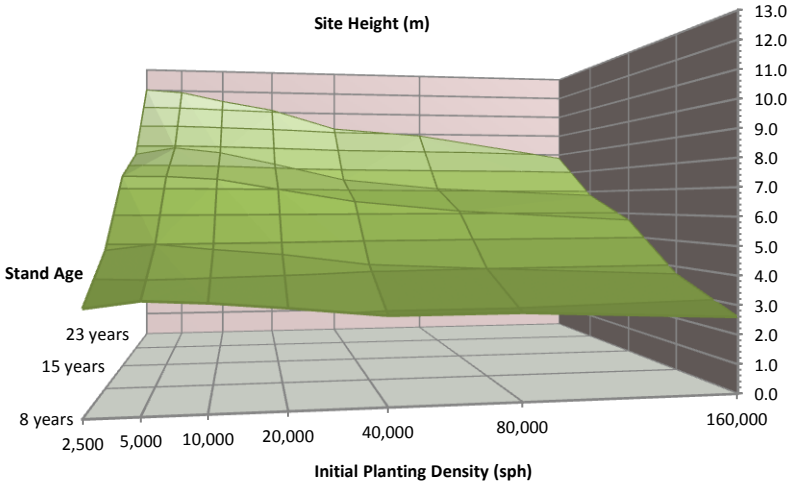
2 Figure 10. Three dimensional surface plot of top height (m) change with initial planting density

3 (sph) from age 8 to 23.



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5 Figure 11. Three dimensional surface plot of site height (m) change with initial planting density

6 (sph) from age 8 to 23.

Segmented Regression; Density Breakpoint Estimates for Dominant Height

A segmented regression model was used to test for and quantify a potential phase change in stand dominant height development with density. The quadratic model results which described the top height (Table 2) or site height (results not shown) parabolic decline with density was further refined to test for a divergence breakpoint in dominant height growth. Segmented regression has been used to quantify phase changes in similar size density relationships such as noted in VanderSchaaf and Burkhart (2008, 2015).

Table 3 presents the segmented regression results for top height. The quadratic model; top height = beta0 + beta1*InNT + beta2*(InNT - breakpoint), determines the trajectory slope pre breakpoint (beta1), y-intercept (beta0) and a post breakpoint test of slope change (beta2) as well as the estimate of the breakpoint (SAS Proc NLMIXED). Five measurement ages were found to provide significant breakpoint estimates between age 8 and 23 for top height. All breakpoint estimates indicated a decline in top height trajectory slope (beta2) which occurred between stand densities 11,200 – 24,300 sph.

Table 4 presents the segmented regression results for site height. Significant breakpoint estimates were available for every measurement age between 8 to 23 years. The breakpoint estimates across time ranged from 4700 to 7900 sph. Site height results were found to be much more consistent and frequent than the top height results. Site height breakpoint estimates were found to be at much lower densities than top height estimates. On average across ages top height breakpoint estimates were 17,000 sph versus 6,000 sph for site height. If one considers the breakpoint estimates as an indication of a threshold decrease in height growth, then this may be evidence of a significant height repression density affect.

Table 3. Equation parameters for nonlinear segmented regression describing ***top height*** (m) over natural log of total density (InNT) where the dependent variable top height = beta0 + beta1*InNT + beta2*(InNT - breakpoint) where breakpoint equals the segmented line slope change in density (InNT).

Age[a]	Breakpoint estimate (InNT) (standard error)	Breakpoint density & 95% confidence limits (tph)	beta0[b]	beta1[b]	beta2[b]	P-value[c]
8	9.81 (0.623)	2,507 - **18,215** - 131,927	3.23	-0.00012	-0.28	*0.0423*
10	9.88 (0.145)	12,283 - **19,536** - 30,822	4.17	0.04	-0.56	*0.0009*[d]
11	10.10 (0.353)	10,589 - **24,343** - 56,286	5.24	-0.00089	-0.72	*0.0423*
15	9.33 (0.0432)	9,818 - **11,271** - 12,917	3.24	0.43	-1.05	*0.0001*
23	9.48 (0.177)	7,473 - **13,095** - 23,047	11.84	-0.13	-2.76	*0.0106*

[a] n = 7 per measurement period (age 4 – 34) using treatment means.
[b] initial parameters chosen based on minimum sums of squares criteria.
[c] results for P-values ≤ 0.05 only. All others omitted (> 0.05).
[d] unresolvable convergence noted in model.

Table 4. Equation parameters for nonlinear segmented regression describing ***site height*** (m) over natural log of total density (InNT) where the dependent variable site height = beta0 + beta1*InNT + beta2*(InNT - breakpoint) where breakpoint equals the segmented line slope change in density (InNT).

Age[a]	Breakpoint estimate (InNT) (standard error)	Breakpoint density & 95% confidence limits (tph)	beta0[b]	beta1[b]	beta2[b]	P-value[c]
8	8.63 (0.234)	2,667 - **5,597** – 11,803	1.13	0.28	-0.56	*0.0099*
9	8.54 (0.167)	3,014 - **5,115** – 8,704	0.79	0.41	-0.72	*0.0064*
10	8.64 (0.13)	3,738 - **5,653** – 8,540	2.66	0.28	-0.69	*0.0009*
11	8.46 (0.126)	3,325 - **4,722** – 6,682	1.11	0.55	-1.03	*0.0004*[d]
15	8.97 (0.175)	4,513 - **7,864** – 13,703	7.5	0.0	-0.64	*0.0002*
17	8.61 (0.228)	2,646 - **5,486** – 11,313	5.27	0.43	-1.2	*0.0046*
23	8.91 (0.326)	2,633 - **7,406** – 20,977	15.38	-0.44	-1.64	*0.0155*

[a] n = 7 per measurement period (age 4 – 34) using treatment means.
[b] initial parameters chosen based on minimum sums of squares criteria.
[c] results for P-values ≤ 0.05 only. All others omitted (> 0.05).
[d] unresolvable convergence noted in model.

Top Height & Site Height Differences

A comparison of top height and site height means across the density range indicated these two dominant height variables were not always the same, particularly at lower treatment densities (see Tables A3 & A4). An example of these differences are shown in Figure 12a which presents age 17 top height and site height means along with mean height plot means over *In* transformed stand density. The various height changes with density suggest the largest diameter trees chosen as top height trees were not the tallest trees at treatment densities < 10,000 sph. Figure 12b presents the site height / top height ratio for each plot across *In* transformed stand density indicating a linear decline in relative site / top height ratio from approximately 1.15 to 0.98 from the lowest to highest densities. Together with observations of the ratios top height / mean height and site height / mean height it is apparent site height generally remains taller than top height for stand densities < 10,000 sph. At densities ≥ 10,000 sph site and top height generally appear similar. The relative height ratios of top height / mean height and, site height / mean height can be seen to exponentially increase from about 1.3 to 1.9 as stand densities increase beyond 20,000 sph as a result of a disproportionately greater decline in mean height than top and site height.

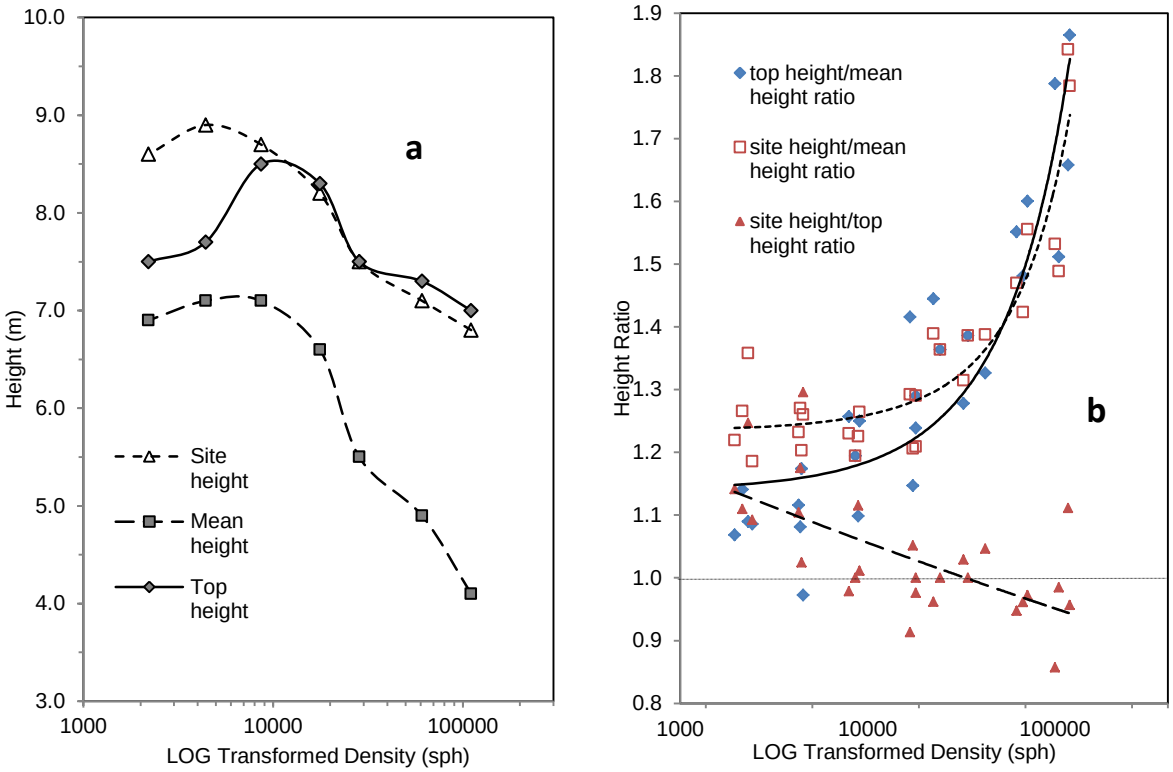

Figure 12. Treatment top height, site height and mean height for age 17 over stand density (a). Individual plot values are shown for ratio development; b) top height and site height means divided by plot level mean height as well as top height / site height ratios for age 17.

Stand Level Development

Mortality

Figure 14 provides the cumulative mortality results over the 34 years by treatment. Mortality increased dramatically with treatment density and age. A large increase in the 160,000 sph treatment mortality started at age 11 and increased exponentially through to age 23. Treatment densities 80,000 and 40,000 showed a significant increase in mortality from age 15 to 23. The 20,000 treatment density did not see significant mortality until after 17 years. Treatment densities < 10,000 sph showed relatively little mortality until after 23 years.

Mean treatment mortality numbers were calculated from the 4 plot level mortality statistics per treatment. As previously stated in the Analysis section, apparent site effects were noted. Figure 15 presents mortality trajectories for each of the 4 replications of the 2,500, 10,000, 40,000 and 160,000 treatments (a – d) including the mean values allowing for a reference to the physical treatment plot location (Figure 1) and the inherent variation noted between plots.

Stand density over age and top height are shown in Figures 16a and 16b respectively.

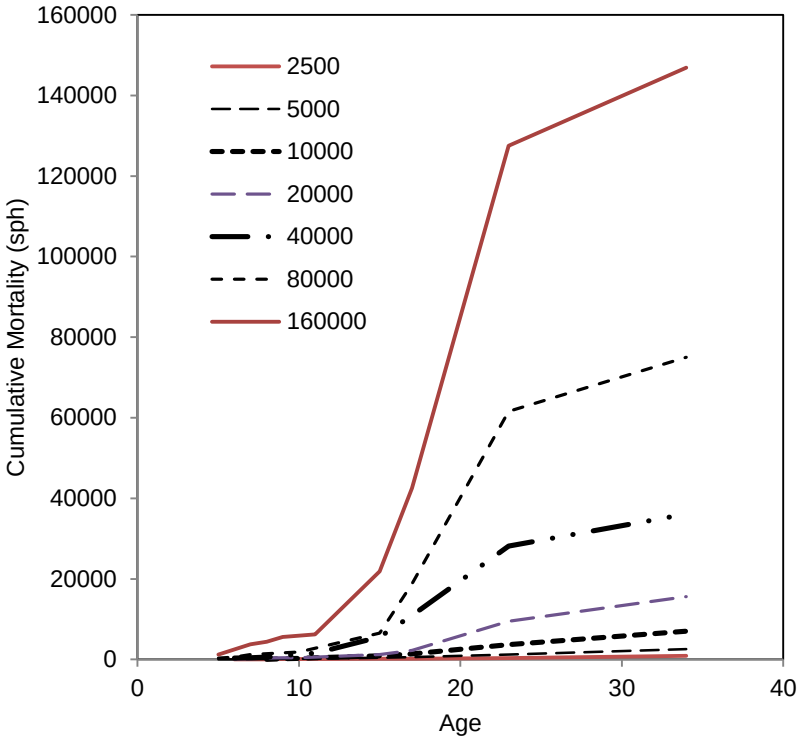

Figure 14. Mean treatment cumulative mortality (sph) over the 34 years post planting.

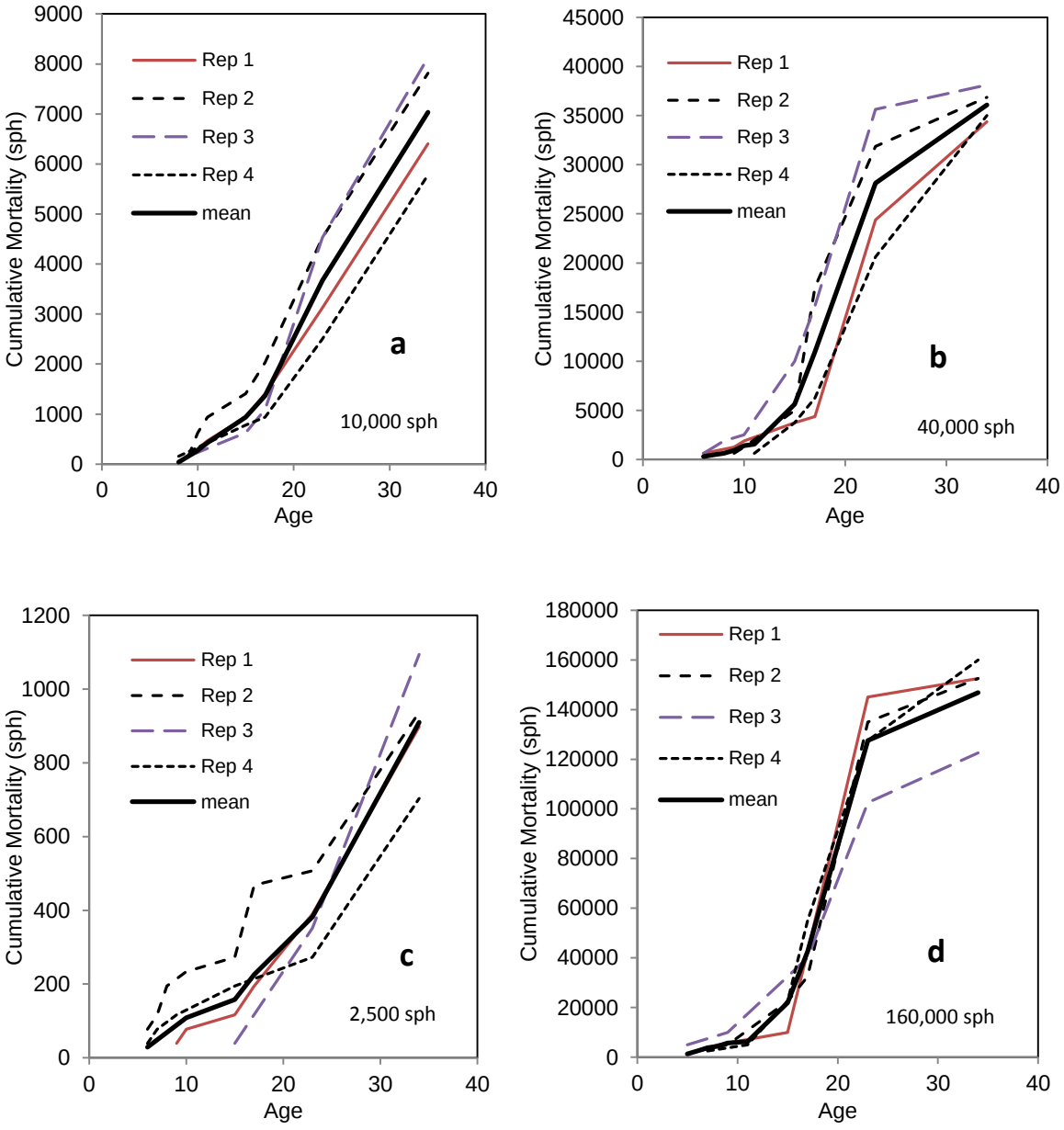

Figure 15. Individual treatment plot replicates and treatment means for cumulative mortality over the 34 years post for a) 10,000 sph, b) 40,000 sph, c) 2,500 sph and, d) 160,000 sph initial planting densities.

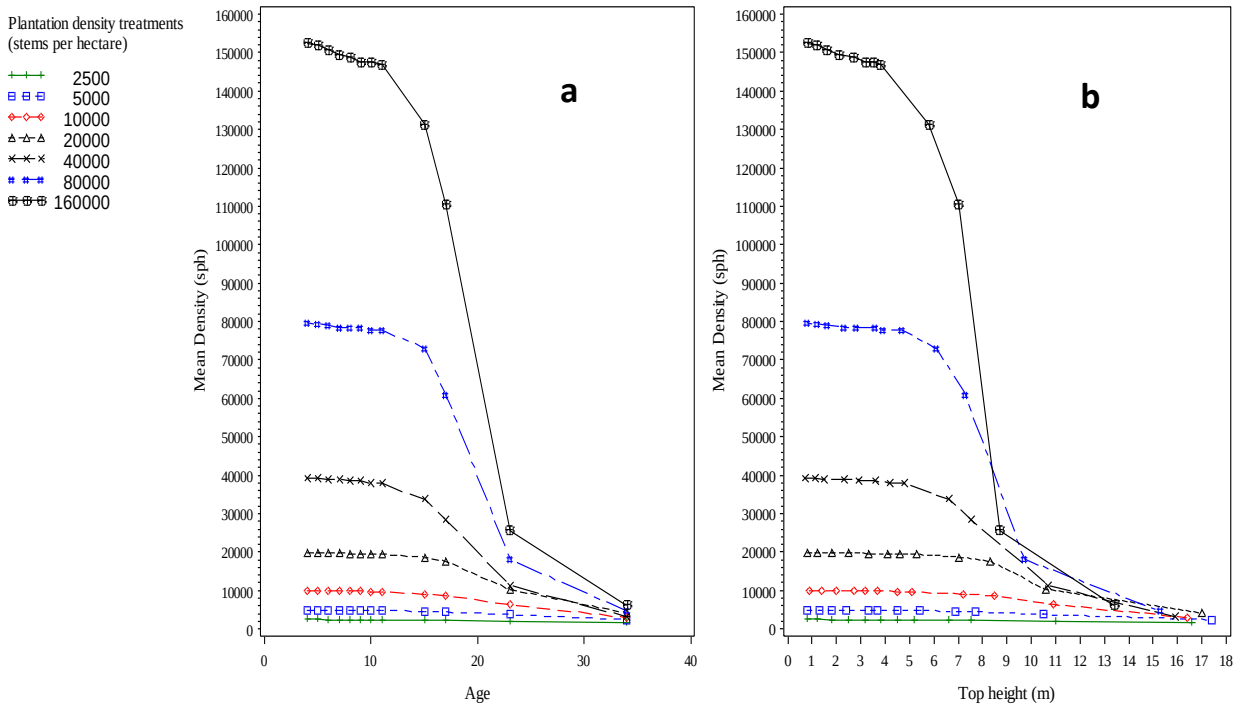

Figure 16. Stand density (sph) over age (a) or top height (m) for the various plantation density treatments.

Basal Area

The effect of treatment planting density on stand basal area over age or top height can be seen in Figure 17a & b. In general, basal area increased with treatment density and age up to and including age 11 (Table A7). It was difficult to compare pre and post ages, 11 and 15, because the transition from basal caliper to DBH measurements occurred during this time. This was also the period of increasing mortality as seen in Figures 14 -16 due to density dependent self-thinning. Between ages 17 and 23 basal area increment declined with increasing density such that treatment densities 2500 to 20,000 were the only treatments with continued increases in basal area. The 40,000 sph treatment basal area continued to decline with age since age 11. It should be noted that the 40,000 sph treatment mean appears out of context in comparison with the other treatment densities and may be related to the significantly lower plot results found in

rep # 3 (see Figure 15b & Figure B1(a)). By age 34 a convergence of basal area for treatments 2500 to 80,000 sph (except for the 40,000 sph) was noted between 28 – 34 m^2/ha. The 160,000 sph treatment remained the highest basal area without apparent decline since approximately age 17. However, the 160,000 sph treatment results for age 34 and 23 are potentially inflated due to the concurrent issues of small plot size and high mortality (as previously stated).

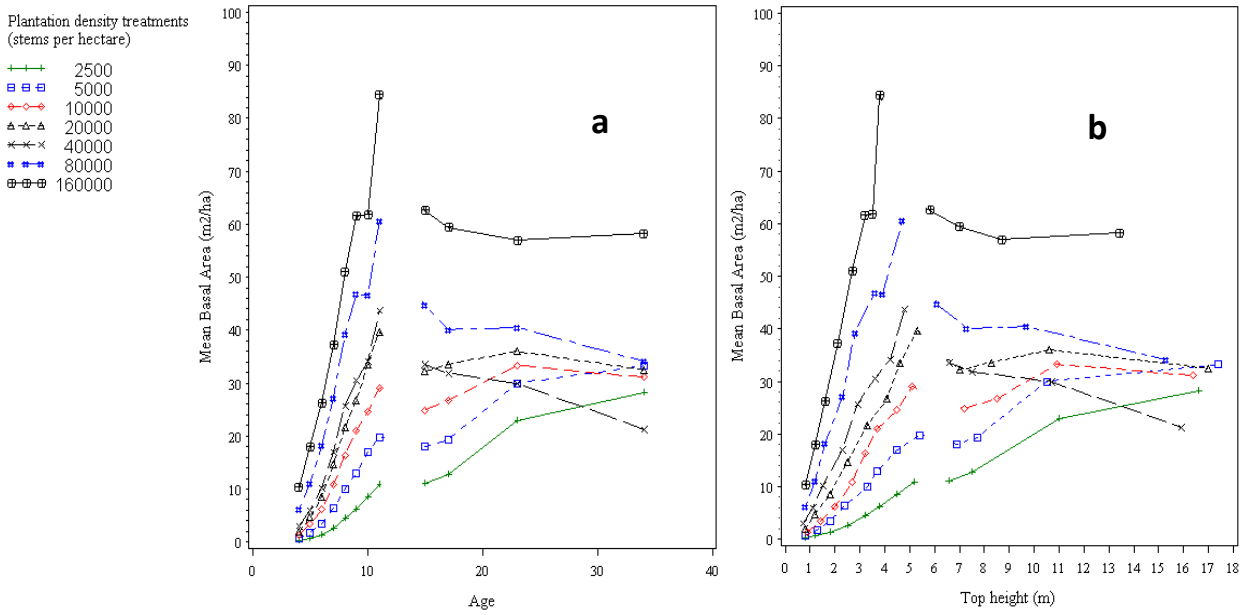

Figure 17. Mean treatment basal area (m^2/ha) over age (a) and top height (b). Note: diameter measures were basal caliper at 3 cm (age 4 – 11) and DBH (age 15 – 34).

Stand Volume and Mean Annual Increment

The effect of treatment planting density on stand total volume over age or top height can be seen in Figure 18a & b. In general, total volume increased with treatment density and age with the notable exception of the 40,000 sph treatment at 34 years. These density - volume trajectories suggest maximum total volume per hectare has yet to be reached. Based on the total volume treatment means comparison results (Table A8), treatment densities 2500, 5000 and those

>40,000 were all significantly different from each other from ages 5 through 17. Mean annual increment (MAI) results (Figure 19, Table A9) suggested maximum volume increment (culmination) was achieved at age 15 for treatment densities > 20,000 and, at age 23 for 20,000 and 10,000 sph. For treatment densities < 10,000 sph MAI appeared to increase to age 34. With allowances made for the 40,000 and 160,000 sph treatment uncertainties (as previously stated), age 34 MAI's for the 10,000 – 80,000 sph treatments appeared to be converging at 6.4 – 7.0 (m^3/ha/yr) respectively.

In volume per tree is presented in Figure 20a & b over *In* density providing additional visual evidence of treatment size – density trajectories. Volume by diameter and height classes are found in Figure B2 & B3 which show the increase in piece size distribution with a decrease in stand density.

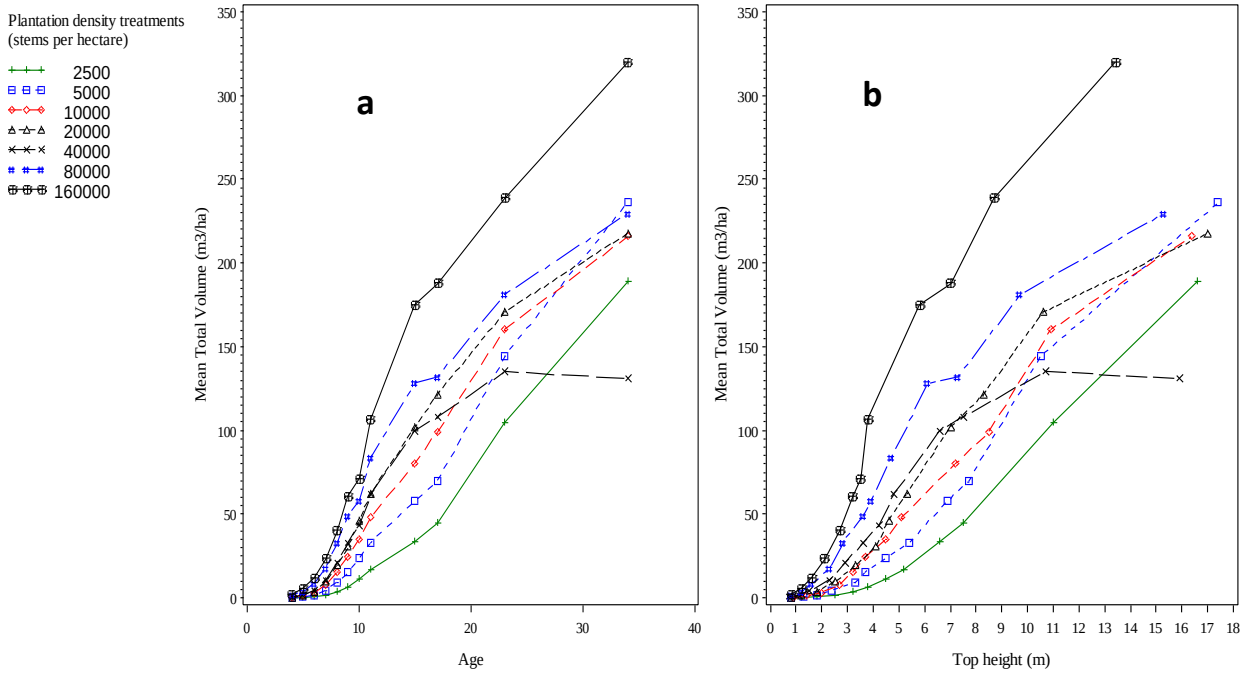

Figure 18. Mean treatment stand total volume (m^3/ha) over age (a) and top height (b).

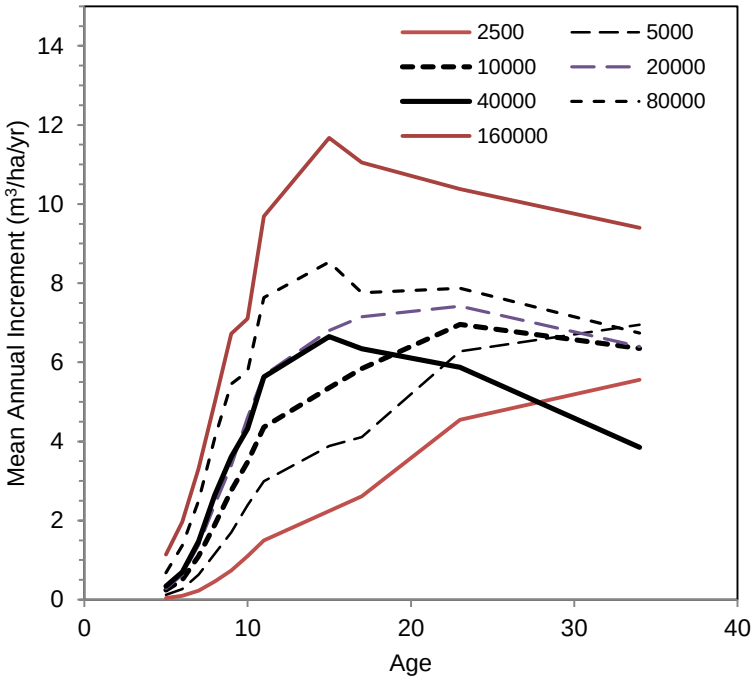

Figure 19. Mean annual increment (m^3/ha/yr) for total stand volume over age by treatment density.

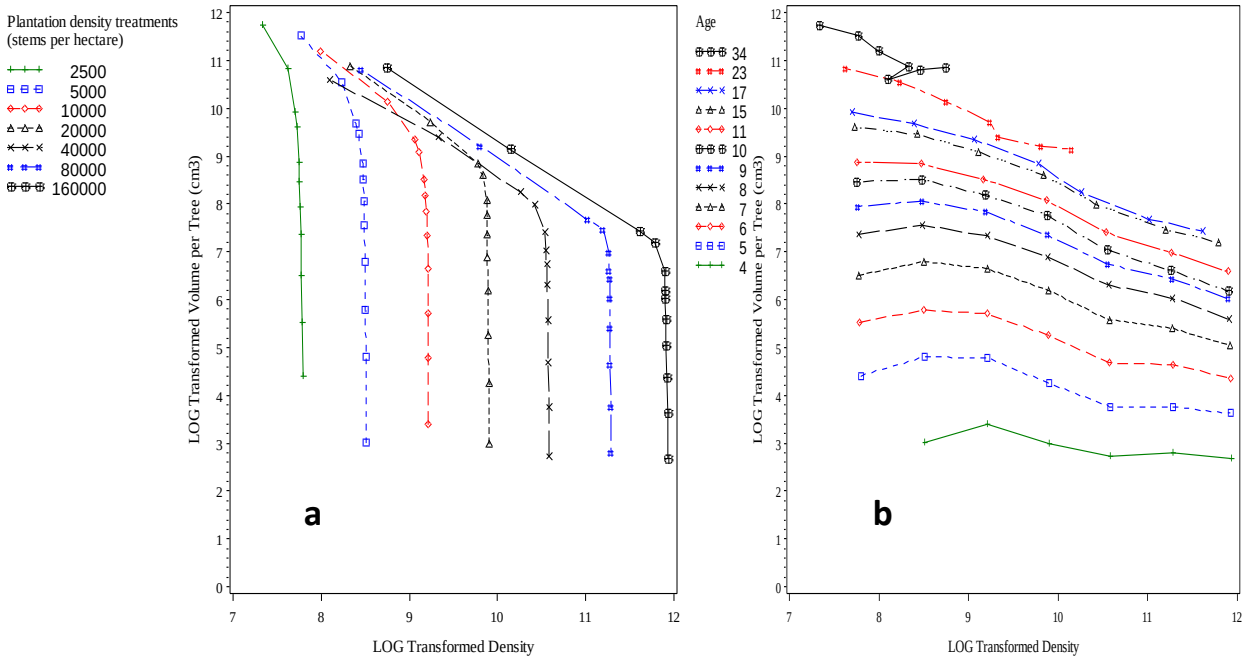

Figure 20. Natural log transformed Volume per tree (cm^3) over log transformed stand density trajectories for each initial treatment density (a) or age (b).

Branch Size

As expected, branch size was found to be dependent on density. Treatment branch diameters (for the largest branches) were found to decline exponentially with increasing treatment density (Figure 21). At age 23 the 2,500 sph treatment branch diameter was larger than all other treatments (Table 5). At age 23 the 5,000 sph treatment branch diameter was found significantly smaller than those of the 2500 treatment and larger than all treatments > 10,000 sph. There was no significant difference in largest branch size noted at either measurement age 23 or 34 years for treatments 20,000 – 160,000 sph.

In general, all treatment means for largest branch size were notably larger at age 23 compared to age 34. Whorl branch number at age 34 suggested a decline in branch number with increasing treatment density however, the p-value = 0.0659 was marginally insignificant. No significant difference in intermodal branch number was found.

Table 5. Mean largest branch diameter (mm), whorl branch and internodal branch count by treatment planting density and measurement age.[a]

Treatment Planting Density (sph)	Age 23 branch diameter (mm)	Age 34 branch diameter (mm)	Whorl branch number (age 34)	Internodal branch number (age 34)
2500	33.55 (0.65) a[b] (5 – 70)[c]	16.81 (0.678) a (8.1 – 31.5)	5.62 (0.362) (4 – 10)	0.201 (0.076) (0 – 4)
5000	25.49 (2.04) b (10 – 90)	14.13 (0.421) ab (8.5 – 21.8)	5.29 (0.171) (3 – 9)	0.388 (0.142) (0 – 4)
10000	21.68 (0.96) bc (8 – 50)	11.4 (0.327) bc (6.2 – 14.9)	5.03 (0.189) (3 – 8)	0.215 (0.18) (0 – 3)
20000	16.43 (0.766) cd (5 – 45)	8.57 (0.319) c (5 – 12.1)	5.35 (0.208) (4 – 7)	0.039 (0.039) (0 – 2)
40000	16.54 (2.801) cd (1 – 45)	7.56 (0.187) c (5.5 – 9.3)	4.92 (0.083) (3 – 7)	0.00 (0.0) -
80000	11.96 (1.812) d (4 – 45)	8.55 (0.35) c (6.4 – 10.4)	3.33 (0.333) (3 – 5)	0.0 (0.0) -
160000	11.38 (1.839) d (3 – 40)	8.17 (0.811) c (6.7 – 9.5)	4.00 (0.577) (3 – 5)	0.667 (0.667) (0 – 2)
P - value	***<0.0001***	***<0.0001***	*0.0659*	*0.2695*

[a] Planting densities with same letter are not significantly different (α = 0.05). If no letters appear after the number, then no differences were detected among the treatments using a Bonferroni correction and LSMEANS.
[b] Mean and standard error. [c] Range.

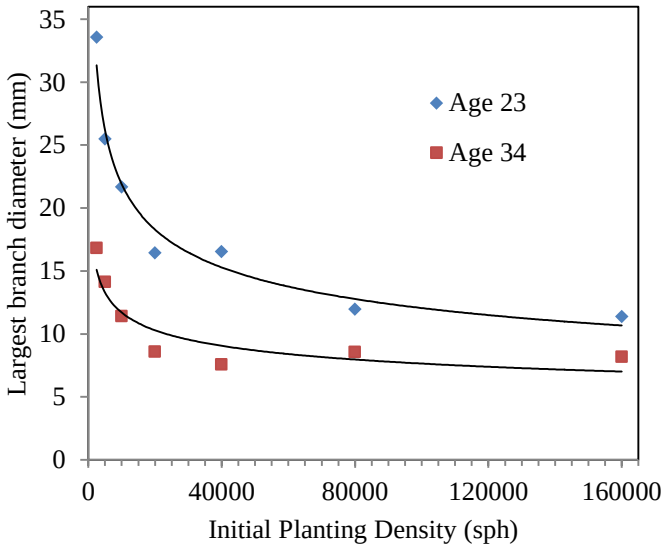

Figure 21. Mean largest branch diameter (mm) assessed in 2005 (age 23) and 2016 (age 34) with approximate exponential model representing branch diameter change with density.

Discussion

The Barnes Creek pine repression trial was establishment in 1984 through planting of pine at high densities chosen to emulate the anticipated growth repression densities noted in natural fire origin stands. Planting pine seedlings at controlled regular spacing within a tilled field environment created conditions which minimized between and within plot variation as well as created uniform competition neighbourhoods within the treatment densities. These rigorous experimental design efforts provided the foundation for quality early observations of treatment effects on pine growth and yield. However, upon analysis of the 34 years of measurements it is clear that issues of small plot size have restricted future work, particularly with the highest treatment densities where few if any pine remained alive to measure in 2016.

As expected, diameter development was consistent with other studies indicating bole size declined as stand density increased (Johnstone 1981, Bassman 1988, Johnstone and Pollack 1990). Even at an early age of 4 years the average pine diameter was found to be 8% smaller in the 160,000 sph than pine planted at 2500 sph (significant at $P = 0.0002$). By age 17, the average diameter of the 2500 sph density pine were 370% larger than the 160,000 sph density pine. The decline in diameter growth rate with increasing treatment density over the early development years (15 + years) has provided a clear indication of the cumulative, incremental influence of time and stand density on long term diameter growth. As stated by Johnstone and van Thienen (2010) this diameter response is “undoubtedly related to the size and persistence of crowns” which are competing for canopy growing space.

Historically, the focus of high density pine studies has been on exploring dominant height repression and the impacts to site fertility estimates (site index). Stand thinning and fertilization treatments have been tested in an attempt to alleviate site fertility repression (Farnden and

Herring 2002, Newsome and Perry 2003, Newsome 2007). Observations of height growth repression are not unique to lodgepole pine with density dependent height impacts noted in Jack pine and black spruce, ponderosa pine, Douglas-fir and Loblolly pine (for reviews see Blevins 2004, Newton 2015). It should be noted that the term "repression" usually refers to impairment of dominant height growth, however at times it has been loosely used to describe failure to meet stand volume or potential productivity expectations (B.C. Ministry of Forests 1999). It should also be noted that discussions on maximum density have been acknowledged to have little in common with repression densities (B.C. Ministry of Forests 1995) since the former has been a policy decision designed to address the risk to future timber supply objectives as opposed to a science based biological growth constraint. It is important to keep in mind the distinction between administrative and biological thresholds to avoid unnecessary confusion. The determination of maximum density for pine has historically incorporated repression density research but has also included additional factors such as forest estate modelling, stand density inventories, site productivity, forest health and forest product economics (Winkle 2005 & 2006, B.C. Ministry of Forests 2006, B.C. Ministry of Forests and Range 2007). In this report the key focus has been on quantifying potential biological thresholds as evidenced in the tree height development data.

Dominant Height

Several dominant height observations were of notable significance. Both site height and top height were found to significantly decline with increasing treatment density and age and, declining dominant height with stand density was found to occur *before* evidence of competition induced mortality was observed (self-thinning or density dependent mortality). This observation suggested top height and site height "repression" was independent of any density dependent self-

thinning which was noted at ages >10 years. Top height or volume over density trajectories indicated that all treatment plots were consistent with known mortality dynamics (Tait et al. 1988, Pretzsch 2009, Goudie 2015) suggesting that even at the highest treatment densities of 160,000 sph the pine were self-thinning along common size-density carrying capacity limits (see Figures 16 & 20). Stand total volume was found to increase with increasing treatment density and age providing no evidence of repression in total stand productivity.

Observations of declining heights (mean, top or site height) with increased density indicated height repression was competition induced starting at relatively young ages of 7-8 for mean and site height and a year later for top heights, first between the density extremes (160,000 versus 10,000 or < 20,000 sph) and as time progressed gaining additional treatment differences. Top height results were more variable than site and mean height. Site and mean height means tests clearly indicated a consistent difference existed between densities < 20,000 and > 20,000 sph. Simple linear models also provided clear evidence of declining heights with density at ages > 6 years (mean, top and site heights). The predictability of the linear models (R^2adj) was good but the linear nature of the models did not provide evidence towards possible threshold densities. Subsequent nonlinear modelling including segmented regression estimates provided some evidence of density thresholds. Both linear and nonlinear model results indicated an increase in the degree of height repression across density with increasing age (see model slope parameters Tables 2-4 and A5 & A6). These observations can be more simply interpreted as due to the incremental reduction in height development over time also noted as the increasing number of years required to obtain a similar top height across treatment densities > 20,000 sph (see Figure 7).

Segmented regression was used to help answer the question, at what density did dominant height significantly decrease? For site height the results suggested a repression threshold occurred on average at approximately 6,000 sph (for ages 8 – 23). For top height the results were variable and appeared higher for the early ages. On average across ages 8 to 23 the repression break point was approximately 17,000 sph however, for 8 -11 years it was approximately 21,000 and for 15-23 years it was around 12,000 sph (Figure 22). The notably lower site height breakpoint densities were likely influenced by the relative change in tallest or optimum height with density and age. The tallest or optimum site height occurred consistently at the 5,000 sph treatment density for ages 8 -17 (Table A4) (similar results noted for mean height, Table A2). For top height optimum levels varied between 20,000 and 5,000 during the same period (Table A3). The influence of increasing density on height can be described by the dynamics of intraspecific competition. Dominant larger diameter top height trees due to their preferential canopy position and size are likely to be less responsive to intraspecific competition due to their inherently larger crown size and canopy occupancy characteristics. Neighbourhood studies in pine stands have shown relative size is correlated with competition intensity indicating big trees have a disproportionately larger influence on neighbouring tree and stand growth (Harper 2017). Site height trees were selected based solely on superior height performance and not bole size which resulted in smaller diameter tree selection than top height trees (Figure 13, Tables A3 & A4) with concomitant smaller tree canopies which would be more sensitive to density related intraspecific competition.

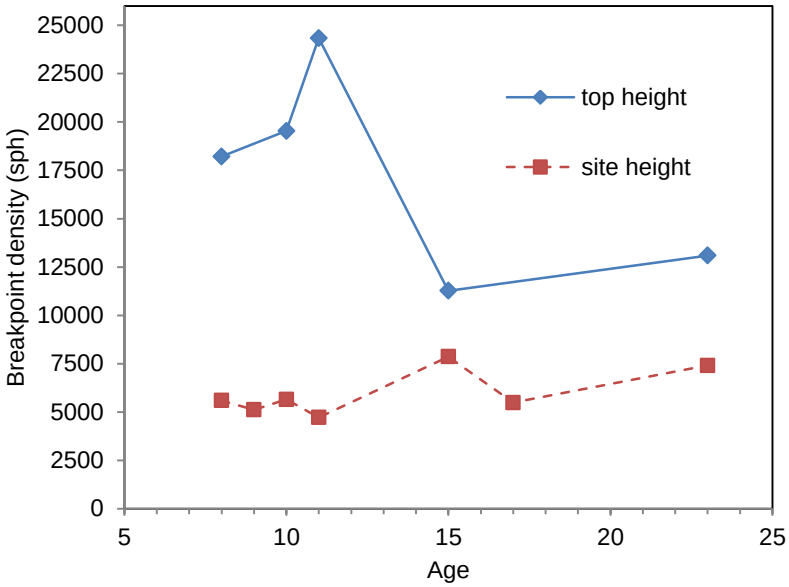

Figure 22. Top height and site height breakpoints (sph) over age from Tables 3 & 4.

A discussion of height repression results cannot be complete without some attempt to estimate site fertility. As indicated by Pretzch (2009) the history behind site fertility classification continues to evolve in response to questions and arguments around the suitable choice of age – height relationships in determining total stand productivity and site fertility. In BC, site index is simply defined as the height at breast height age (BHA) 50 of the largest diameter tree in a 100 m^2 plot (0.01 ha) (BC MOFR 2009). Also known as a top height or site tree (not to be confused with site height used here) this calculation is used as the indicator of site fertility. Site curves are a foundational element in stand growth and yield models used to predict managed stand yields. However, in order to estimate site index using published lodgepole pine curves (Goudie 1984, Nigh 1995 & 1999) there are a number of points that need to be considered;

- Site index stability is a concern when estimates are obtained from juvenile lodgepole pine which may be influenced by large early growth variation. Recommendations from

Huang et al. (2004) and others (Nigh 2017, pers comm.) suggest a stable site index estimate requires selection of trees with a minimum breast height age of at least 5 years.

- The relationship between age and height in young high density pine stands may be poorly represented by published site index curves due to the influences of extreme competition for limited above and below ground resources. Nigh and Love (1999) have acknowledged many of the site index models for lodgepole pine have significant weaknesses when used to estimate juvenile stand site fertility.
- Due to the variable plot size in this trial top height tree selection was based on a simplified sampling regime of usually one undamaged tree per plot which in many cases does not conform to the ministry top height tree definition (BC MOFR 2009).

Site Index Estimation

Site index estimates were calculated through the use of the application SITE TOOLS 4.0 (BC MFLNRO 2015b) using total age and both top height and site height treatment means. Select results for ages 15 and 23 are presented in Figure 23. Results from earlier ages resulted in site index estimates exceeding 27 m up to and including age 11 which was considered unreasonably high and potentially unstable due to the poor correlation with older age estimates. The 15 to 23 year results do suggested a repression in site index of approximately 3 to 4 m from 19-21 m for the 160,0000 sph treatment to 23-25 m for the 2500 sph treatment density at ages ≥ 15.

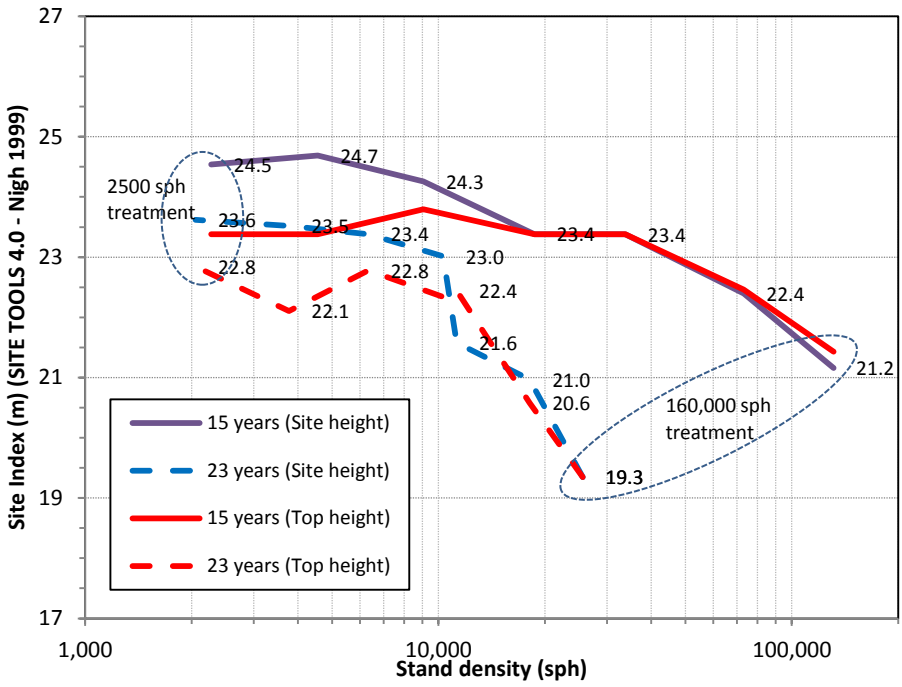

Figure 23. Site index estimates using top height and site height for age 15 and 23 over stand density. Initial planting densities increase left to right from 2500 to 160,000 sph (note ovals highlighting range of initial densities). Values calculated using Nigh (1999) curves found in SITE TOOLS 4.0 (BC MFLNRO 2015b).

Conclusions

As expected, stand yield increased with increasing stand density. Diameter growth was found to decline with increasing density as well as mean height. The degree of height repression that was noted with both mean height and the dominant height statistics (top and site height) increased with increasing stand density and incrementally over time (age). At what age and density did dominant height begin to show significant decline? The earliest height impacts became significant at age 8. Top height breakpoint was approximately 18,200 sph at age 8 and site height breakpoint 5,600 sph. In general, height analysis suggested that height repression occurred across the entire tree population becoming evident in the top height trees when densities exceeded those impacting mean and site height repression. In summary, the top height trees, as the largest occupants of the canopy, were the last tree cohort to have height development impacted by increases in stand density.

More research on height repression is needed to help define optimum stand density management regimes. Clarifying the lodgepole pine height repression – density relationship will improve future silviculture practices and inform policy governing maximum density as a component of stocking standards for regenerating stands (BC MOFR 2007).

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Appendix A (Tables)

Table A1. Mean diameter (cm) by treatment planting density and measurement age[a]. Diameter at 1.3 m (DBH) replaced basal diameter measurements in the 15th growing season (1997) and subsequent measurements (fall of 1999, 2005 and 2016).

	Age											
Treatment Planting Density (sph)	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**15**	**17**	**23**	**34**
2500	1.10 ab	1.70 ab	2.48 ab	3.60 a	4.73 ab	5.63 a	6.65 a	7.58 a	7.68 a	8.45 a	11.65 a	**15.10** a
5000	1.23 a	2.10 a	2.90 a	3.95 a	5.05 a	5.75 a	6.63 a	7.18 a	6.98 a	7.33 b	9.83 b	**13.10** ab
10000	1.20 a	2.08 a	2.78 ab	3.68 a	4.50 b	5.13 b	5.58 b	6.10 b	5.80 b	6.10 c	7.90 c	**11.45** bc
20000	1.10 ab	1.70 ab	2.30 b	3.03 b	3.70 c	4.13 c	4.60 c	5.00 c	4.58 c	4.80 d	6.48 cd	**10.13** c
40000	0.95 b	1.35 bc	1.75 c	2.28 c	2.83 d	3.13 d	3.28 d	3.70 d	3.35 d	3.58 e	5.73 de	**8.90** c
80000	0.98 b	1.30 bc	1.70 c	2.05 cd	2.45 de	2.68 de	2.65 de	3.03 e	2.63 de	2.70 f	5.00 de	**8.60** c
160000	0.90 b	1.20 c	1.45 c	1.73 d	2.03 e	2.22 e	2.18 e	2.55 e	2.18 e	2.28 f	4.53 e	**9.60** c
P - value	***0.0002***	***<0.0001***	***<0.0001***	***<0.0001***	***<0.0001***	***<0.0001***	***<0.0001***	***<0.0001***	***<0.0001***	***<0.0001***	***<0.0001***	***<0.0001***

[a] Within the same age planting densities with same letter are not significantly different ($\alpha = 0.05$). If no letters appear after the number, then no differences were detected among the treatments using a Bonferroni correction and LSMEANS. No transformation required based on assessment of residuals.

Table A2. Mean height (m) by treatment planting density and measurement age[a].

	Age											
Treatment Planting Density (sph)	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**15**	**17**	**23**	**34**
2500	0.58	0.83 ab	1.18	1.73 ab	2.35 abc	2.98 ab	3.58 ab	4.18 a	5.85 a	6.85 a	9.58 ab	14.48
5000	0.60	0.93 ab	1.35	1.95 ab	2.65 a	3.30 a	3.93 a	4.53 a	6.18 a	7.13 a	9.98 a	15.08
10000	0.60	0.98 a	1.40	2.00 a	2.63 a	3.28 a	3.90 a	4.43 a	5.98 a	7.10 a	9.63 ab	14.30
20000	0.60	0.88 ab	1.28	1.88 ab	2.48 ab	3.13 ab	3.68 a	4.18 a	5.65 a	6.55 a	9.25 ab	13.63
40000	0.53	0.78 b	1.10	1.68 ab	2.20 bc	2.75 bc	3.18 bc	3.55 b	4.70 b	5.50 b	8.68 bc	12.00
80000	0.58	0.85 ab	1.25	1.73 ab	2.20 bc	2.70 bc	3.08 cd	3.38 bc	4.18 bc	4.88 bc	8.18 c	12.13
160000	0.60	0.85 ab	1.18	1.60 b	2.00 c	2.40 c	2.68 d	2.93 c	3.60 c	4.13 c	6.63 d	11.20
P - value	*0.3245*	***0.0222***	***0.0568***	***0.013***	***<0.0001***	***<0.0001***	***<0.0001***	***<0.0001***	***<0.0001***	***<0.0001***	***<0.0001***	*0.1467*

[a] Planting densities with same letter are not significantly different (α = 0.05). If no letters appear after the number, then no differences were detected among the treatments using a Bonferroni correction and LSMEANS. No transformation required based on assessment of residuals.

Table A3. Mean top height (m) by treatment planting density and measurement age[a]. Largest top height at each age are highlighted.

	Age											
Treatment Planting Density (sph)	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**15**	**17**	**23**	**34**
2500	0.82	1.23	1.76	2.45	3.17	3.79 ab	4.48 a	5.15 a	6.63 abc	7.49	10.93	16.57 a
5000	0.78	1.22	1.74	2.39	3.25	3.71 ab	4.48 a	5.41 a	6.90 ab	7.71	10.50	17.37 a
10000	0.84	1.38	2.00	2.75	3.14	3.65 ab	4.48 a	5.04 a	7.20 a	8.53	10.90	16.35 ab
20000	0.75	1.17	1.77	2.43	3.30	4.08 a	4.63 a	5.29 a	7.00ab	8.30	10.63	16.98 a
40000	0.71	1.01	1.49	2.23	2.89	3.53 ab	4.15 ab	4.75 ab	6.63 abc	7.50	10.70	15.92 ab
80000	0.77	1.14	1.63	2.28	2.82	3.55 ab	3.88 ab	4.64 ab	6.13 bc	7.21	9.65	15.31 ab
160000	0.79	1.14	1.55	2.13	2.70	3.20 b	3.43 b	3.74 b	5.80 c	6.99	8.65	13.44 b
P- value	*0.513*	*0.147*	*0.108*	*0.112*	*0.081*	***0.04***	***0.0015***	***0.0006***	***0.0005***	***0.0264***	*0.0836*	***0.0248***

[a] Planting densities with same letter are not significantly different ($\alpha = 0.05$). If no letters appear after the number, then no differences were detected among the treatments using a Bonferroni correction and LSMEANS. No transformation required based on assessment of residuals.

Table A4. Mean site height (m) by treatment planting density and measurement age[a]. Largest top height at each age are highlighted.

Treatment Planting Density (sph)	**Age 4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**15**	**17**	**23**	**34**
2500	0.83	1.25 ab	1.80 ab	2.54 ab	3.32 ab	4.01 abc	4.81 ab	5.40 a	7.48 a	8.63 a	11.95 a	17.08 a
5000	0.81	1.27 ab	1.86 ab	2.62 ab	3.48 a	4.29 a	5.01 a	5.78 a	7.54 a	8.84 a	11.88 a	17.40 a
10000	0.87	1.37 a	1.99 a	2.74 a	3.37 ab	4.10 ab	4.74 ab	5.37 ab	7.38 a	8.72 a	11.45 ab	16.52 a
20000	0.75	1.16 ab	1.69 ab	2.44 ab	3.18 abc	4.01 abc	4.56 abc	5.15 abc	6.96 ab	8.17 ab	11.03 abc	15.76 a
40000	0.73	1.04 b	1.52 b	2.20 ab	2.87 bc	3.57 bcd	4.18 bcd	4.70 bcd	6.50 bc	7.49 bc	10.19 bcd	14.82 ab
80000	0.77	1.12 ab	1.59 ab	2.19 b	2.86 bc	3.49 cd	3.98 cd	4.54 cd	6.10 cd	7.11 c	9.85 cd	15.13 ab
160000	0.77	1.13 ab	1.56 ab	2.12 b	2.64 c	3.24 d	3.64 d	4.09 d	5.72 d	6.78 c	8.82 d	11.78 b
P- value	***0.095***	***0.0175***	***0.0148***	***0.0042***	***0.0003***	***<0.0001***	***<0.0001***	***<0.0001***	***<0.0001***	***<0.0001***	***<0.0001***	***0.0023***

[a] Planting densities with same letter are not significantly different ($\alpha = 0.05$). If no letters appear after the number, then no differences were detected among the treatments using a Bonferroni correction and LSMEANS. No transformation required based on assessment of residuals.

Table A5. Equation coefficients for the linear model describing top height (m) over real-time stand density (tph) where the dependent variables top height = a + b (tph). Treatment level means used (n = 7). See Figure 8b.

Age[a]	a	b	R^2_{adj}	RMSE[b]	P value
7	2.529	-0.000003	0.63	0.1165	*0.0203*
8	3.237	-0.0000042	0.751	0.1252	*0.0073*
9	3.846	-0.0000041	0.571	0.1762	*0.0301*
10	4.563	-0.0000075	0.939	0.1006	*0.0002*
11	5.327	-0.00001	0.921	0.1543	*0.0004*
15	6.966	-0.0000094	0.757	0.2466	*0.0068*
23	11.311	-0.000091	0.834	0.3355	*0.0026*
34	18.503	-0.000695	0.60	0.846	*0.025*

[a] n =7 per measurement period (age 4 – 34).
[b] Root mean squared error.

Table A6. Equation coefficients for the linear model describing site height (m) over real-time stand density (tph) where the dependent variables site height = a + b (tph). Treatment level means used (n = 7). See Figure 9b.

Age[a]	a	b	R^2_{adj}	RMSE[b]	P value
7	2.591	-0.0000034	0.474	0.177	0.0525
8	3.353	-0.0000055	0.8	0.1459	*0.0043*
9	4.092	-0.0000061	0.76	0.1781	*0.0065*
10	4.805	-0.0000085	0.867	0.1928	*0.0023*
11	5.462	-0.00001	0.812	0.2534	*0.0035*
15	7.377	-0.000014	0.87	0.2621	*0.0014*
23	12.3	-0.00014	0.946	0.2761	*0.0002*
34	19.435	-0.0011	0.787	0.8784	*0.0049*

[a] n =7 per measurement period (age 4 – 34).
[b] Root mean squared error.

Table A7. Mean basal area (m^2) by treatment planting density and measurement age[a].

Treatment Planting Density (sph)	**Age**											
	4	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**15**	**17**	**23**	**34**
2500	0.23 a	0.60 a	1.28 a	2.58 a	4.35 a	6.13 a	8.53 a	10.90 a	10.98 a	12.80 a	22.93	**28.28**
5000	0.63 b	1.80 b	3.45 b	6.25 b	9.98 b	13.00 b	16.90 b	19.83 b	17.98 b	19.33 b	30.03	**33.18**
10000	1.25 c	3.53 c	6.10 c	10.83 c	16.25 c	20.95 c	24.48 bc	29.10 c	24.93 c	26.73 bc	**33.28**	31.08
20000	1.93 cd	4.65 c	8.55 cd	14.68 cd	21.65 c	26.70 cd	33.63 cd	**39.58** d	32.18 cd	33.63 cd	35.98	32.48
40000	2.85 de	5.93 cd	10.18 cd	16.88 cd	25.65 cd	30.60 de	34.18 cd	**43.60** de	33.45 cd	31.93 cd	29.88	21.33
80000	6.15 ef	10.95 de	18.25 de	27.20 de	39.18 de	46.80 ef	46.63 d	**60.50** ef	44.73 de	40.13 cd	40.50	34.08
160000	10.25 f	17.98 e	26.23 e	37.25 e	50.98 e	61.45 f	61.85 d	**84.40** f	62.58 e	59.35 d	56.93	58.33
P- value	***<0.0001***	***<0.0001***	***<0.0001***	***<0.0001***	***<0.0001***	***<0.0001***	***<0.0001***	***<0.0001***	***<0.0001***	***<0.0001***	*0.4529*	*0.0782*

[a] Planting densities with same letter are not significantly different ($\alpha = 0.05$). If no letters appear after the number, then no differences were detected among the treatments using a Bonferroni correction and LSMEANS.
Transformation required to address variance homogeneity (*1/SQRT (total volume)* used).

Table A8. Mean total volume (m^3 / ha) by treatment planting density and measurement age[a].

	Age											
Treatment Planting Density (sph)	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**15**	**17**	**23**	**34**
2500	0.03 a	0.18 a	0.55 a	1.60 a	3.65 a	6.55 a	10.98 a	16.50 a	33.55 a	44.15 a	104.60	**188.95**
5000	0.13 a	0.58 b	1.63 b	4.35 b	9.25 b	15.30 b	23.90 b	32.90 b	58.23 b	69.9 b	144.28	**236.15**
10000	0.28 b	1.15 bc	3.00 c	7.65 bc	15.20 bc	24.83 c	34.80 bc	48.00 c	80.33 bc	99.3 bc	160.13	**215.88**
20000	0.38 b	1.40 c	3.80 cd	9.73 cd	19.25 cd	30.60 cd	45.98 c	62.38 cd	102.05 cd	121.6 c	170.58	**217.55**
40000	0.55 bc	1.65 c	4.20 cd	10.33 cd	21.18 cd	32.50 cde	43.18 c	61.78 cd	99.70 cd	107.75 bc	**135.13**	130.95
80000	1.25 c	3.35 c	8.18 d	17.48 cd	32.80 d	49.08 de	57.78 c	83.98 d	128.00 d	131.9 c	181.05	**229.18**
160000	2.20 c	5.65 c	11.75 d	23.18 d	40.08 d	60.55 e	70.95 c	106.60 d	175.05 d	187.8 c	238.68	**319.73**
P - value	***<0.0001***	***<0.0001***	***<0.0001***	***<0.0001***	***<0.0001***	***<0.0001***	***<0.0001***	***<0.0001***	***<0.0001***	***<0.0001***	*0.5811*	*0.1026*

[a] Within the same age planting densities with same letter are not significantly different ($\alpha = 0.05$). If no letters appear after the number, then no differences were detected among the treatments using a Bonferroni correction and LSMEANS.
Transformation required to address variance homogeneity (*1/SQRT (total volume)* used).

Table A9. Total volume mean annual increment (m^3/ha/yr) (MAI) by treatment planting density and measurement age[a].

	Age											
Treatment Planting Density (sph)	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**15**	**17**	**23**	**34**
2500	0.01 a	0.04 a	0.09 a	0.23 a	0.46 a	0.73 a	1.10 a	1.50 a	2.24 a	2.61 a	4.55	**5.56**
5000	0.03 a	0.12 b	0.27 b	0.62 b	1.16 b	1.70 b	2.39 b	2.99 b	3.88 b	4.11 b	6.27	**6.95**
10000	0.07 b	0.23 bc	0.50 c	1.09 bc	1.90 bc	2.76 c	3.48 bc	4.36 c	5.36 bc	5.84 bc	**6.96**	6.35
20000	0.09 b	0.28 c	0.63 cd	1.39 cd	2.41 cd	3.39 cd	4.60 c	5.67 cd	6.80 cd	7.15 c	**7.42**	6.40
40000	0.14 bc	0.33 c	0.70 cd	1.48 cd	2.65 cd	3.61 cde	4.32 c	5.63 cd	**6.65** cd	6.34 bc	5.88	3.85
80000	0.31 c	0.67 c	1.36 d	2.50 cd	4.10 d	5.45 de	5.77 c	7.63 d	**8.53** d	7.76 c	7.87	6.74
160000	0.55 c	1.13 c	1.96 d	3.31 d	5.00 d	6.72 e	7.10 c	9.69 d	**11.67** d	11.05 c	10.38	9.40
P - value	***<0.0001***	***<0.0001***	***<0.0001***	***<0.0001***	***<0.0001***	***<0.0001***	***<0.0001***	***<0.0001***	***<0.0001***	***<0.0001***	*0.5811*	*0.1026*

[a] Within the same age planting densities with same letter are not significantly different ($\alpha = 0.05$). If no letters appear after the number, then no differences were detected among the treatments using a Bonferroni correction and LSMEANS.
Transformation required to address variance homogeneity (*1/SQRT (total volume)* used).

Table A10. Mean annual height increment (cm) by treatment planting density[a].

	Age Increment										
Treatment Planting Density (sph)	**4-5**	**5-6**	**6-7**	**7-8**	**8-9**	**9-10**	**10-11**	**11-15**	**15-17**	**17-23**	**23-34**
2500	26.51	36.92	54.94 ab	63.71 ab	64.89 a	62.49 a	62.51 a	43.38 a	49.93 ab	44.86 a	31.61
5000	33.02	46.32	63.24 a	69.20 a	69.31 a	65.55 a	66.04 a	43.15 a	47.32 ab	42.86 a	27.40
10000	36.02	47.79	63.17 a	66.49 ab	68.98 a	63.49 a	60.43 a	40.12 ab	58.48 a	41.00 ab	21.07
20000	33.10	45.60	63.96 a	62.44 ab	68.04 a	57.21 ab	61.52 a	41.50 ab	52.17 ab	37.93 ab	20.82
40000	28.47	40.74	56.65 ab	59.78 ab	67.64 a	47.42 bc	56.38 ab	40.93 ab	49.29 ab	39.45 ab	14.22
80000	32.49	44.83	58.23 ab	57.64 bc	58.05 ab	54.87 ab	47.35 ab	33.85 ab	50.24 ab	38.30 ab	19.62
160000	31.11	37.33	47.37 b	48.24 c	45.14 b	41.58 c	39.63 b	30.74 b	39.91 b	27.27 b	15.60
P - value	*0.1509*	0.1180	***0.0010***	***<0.0001***	***0.0007***	***<0.0001***	***0.0022***	***0.0042***	***0.0141***	***0.0096***	0.0702

[a] Planting densities with same letter are not significantly different ($\alpha = 0.05$). If no letters appear after the number, then no differences were detected among the treatments using a Bonferroni correction and LSMEANS. No transformation required based on assessment of residuals.

Appendix B (Figures)

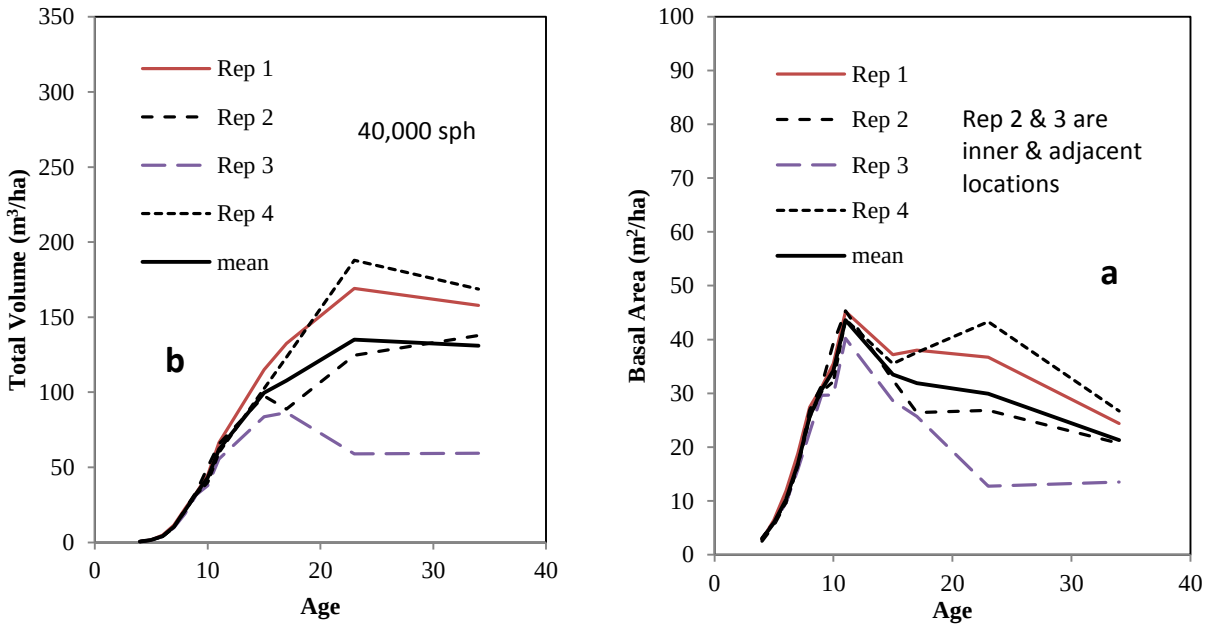
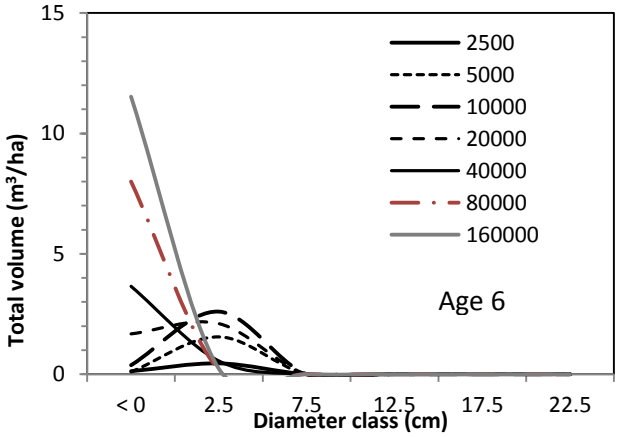
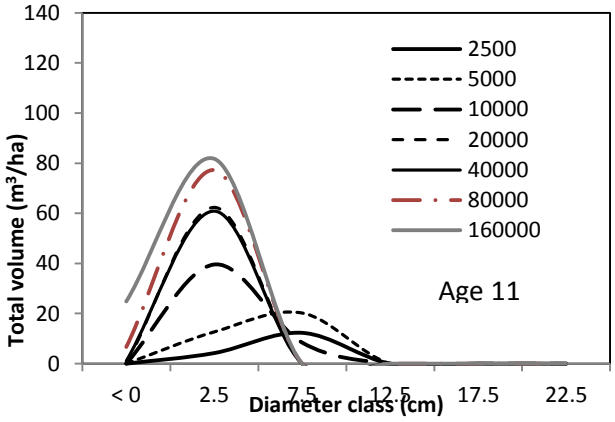
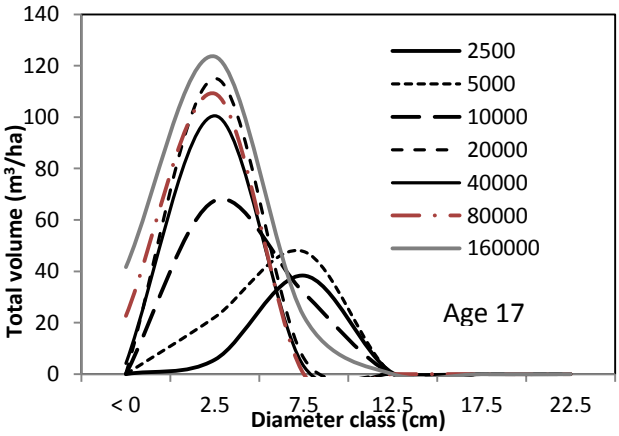


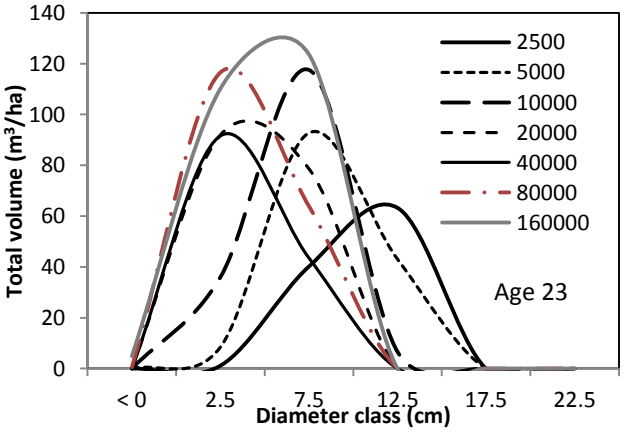
Figure B1. Basal area (a) and total volume (b) change with age for the 4 plot replicates of the 40,000 sph treatment density.

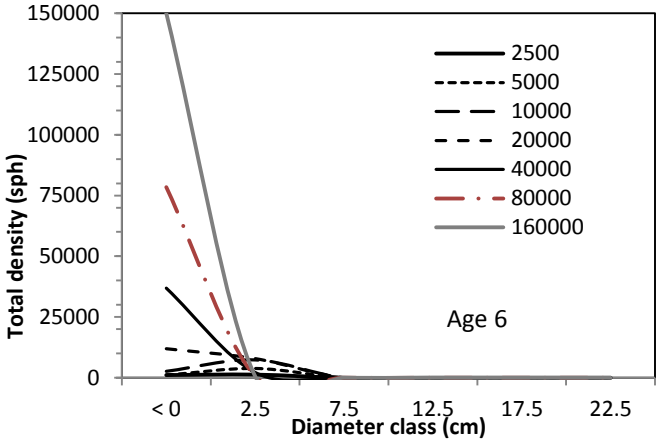
1

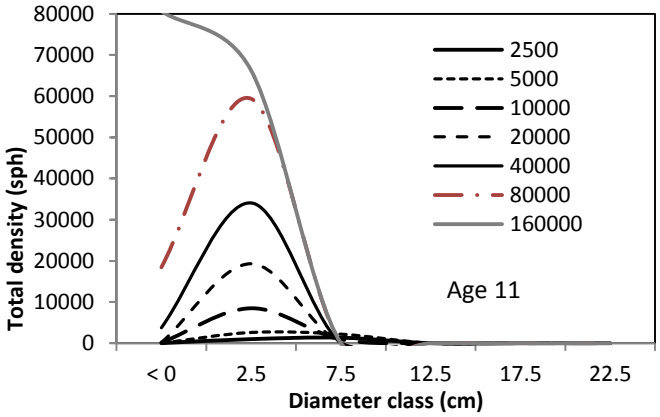


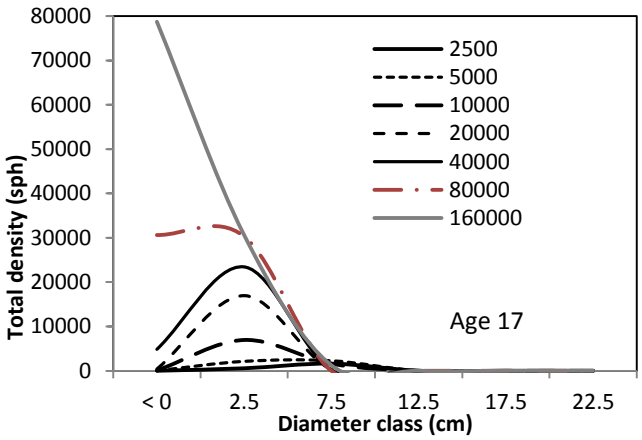












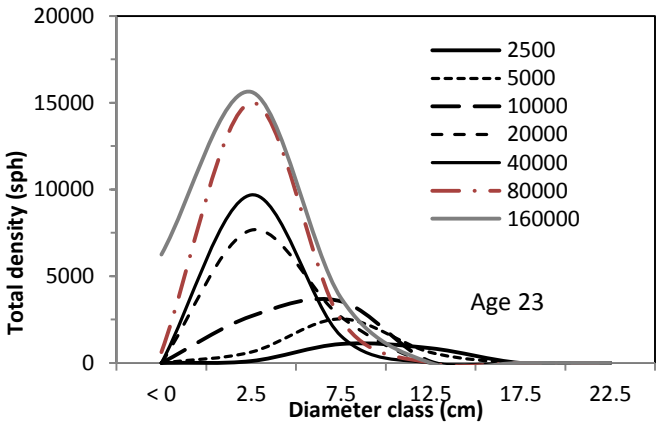


Figure B2. Total volume and density by diameter class (diameter class midpoint (cm)) at 6, 11, 17 and 23 years age.

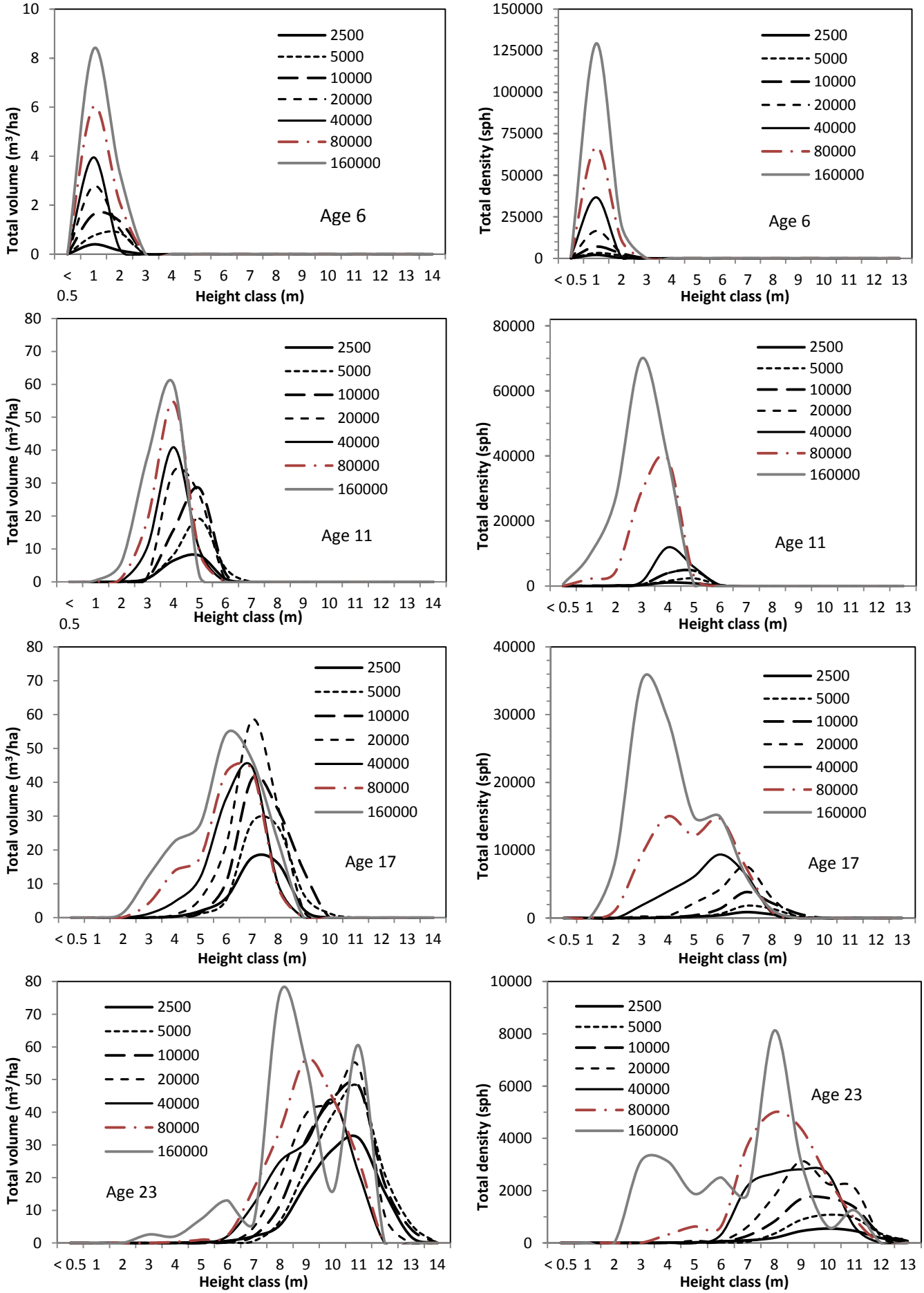


Figure B3. Total volume and density by height class (height class midpoint (m)) at 6, 11, 17 and 23 years age

Figure B4. Individual plot photos for replicate 2 treatments;160,000 sph (2-1), 80,000 sph (2-2), 40,000 sph (2-3) and 20,000 sph (2-4) (see Figure 1 for site location) taken from corner facing plot centre September 2016.

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5 Figure B5. Individual plot photos for replicate 2 treatments;10,000 sph (2-5), 5,000 sph (2-6) and 2,500 sph (2-

6 7) (see Figure 1 for site location) taken from corner facing plot centre September 2016.