Effects of Tree Planting Rectangularity on Wood Quality and Growth of Lodgepole Pine (*Pinus contorta*) in Sweden

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Master Thesis no. 220
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Bilateral Cooperation

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ABSTRACT

Lodgepole pine (*Pinus contorta*) was introduced on a production scale in Sweden during the mid 20th century. Traditional Swedish forestry practices include planting trees at evenly spaced rectangularities in order to maximize nutrient and light availability to individual trees, minimize branch diameter, and to encourage good stem form. In 1982, a study using Lodgepole pine was established to evaluate any differences in growth characteristics between planting rectangularities. This research study is a completely randomized block design rectangularity study where lodgepole pine was planted in three replications at five different rectangularities (0.8 x 5 m, 1 x 4 m, 1.33 x 3 m, 1.46 x 1.46 x 4 m, and 2 x 2 m) all at the same planting density of 2500 trees/hectare. At age 29, final harvest candidate trees were chosen in each rectangularity treatment, individual trees were divided into two competitive sectors relative to each dimension of the rectangularity, and growth differences were evaluated. Straightness and quality were positively correlated with each other in all rectangularities. Final harvest candidate branch diameter was correlated with branch angle, stem DBH, individual tree volume and the total number of branches per tree. Total height, height to live crown, individual stem volume, biggest branch in sector 2, sector location of the biggest branch, and average diameter at breast height all differed significantly among rectangularities at an α - level = 0.05. Rectangularities with higher competitive ratios displayed higher total tree heights, larger biggest branch and tree diameters, along with higher volume per hectare. Rectangularity 0.8 x 5 m produced the highest volume at age 29 while maintaining desirable wood quality measures.

Key words: timber quality, *Pinus contorta*, tree properties, planting pattern, rectangular planting, row planting.

DEDICATION

To my mother Nancy, my father ‘Butch’, and my siblings Michael, Rebecca, Natalie, Chris, Lisa, Jen and Jay. To my Aunt Cindy and Uncle Paul who inspired and fostered me in the field of science. To my wife, Yulia. To my family and friends all over the world who have always supported and guided me.

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1. INTRODUCTION

In the mid-20th century, Swedish forests were at risk of being overharvested in the near future, and a gap in the age-class distribution was predicted to develop in future years (Elfving *et al*. 2000). To curb the effects of this expected timber shortage, exotic faster growing species were considered for introduction (Nelbeck 1981; Hagner 1971, 1983, 1989). Lodgepole pine (*Pinus contorta*) was known to grow throughout the northern United States and across Canada (Wellner 1975) on site types similar to those found in Sweden (Wheeler and Critchfield 1985). The species' multiple varieties (var. *contorta*, var. *murrayana*, var. *latifolia*) are adapted to grow in a range of environmental conditions, including varied soil moisture, temperature, elevation and soil nutrient content. The species has adapted to grow in subalpine, maritime and continental climates (Pfister and Daubenmire 1975). This array of tolerances has resulted in the species being planted in both the Northern and Southern hemispheres for pulpwood and sawtimber supplies (Elfving *et al*. 2000). In its native environment *Pinus contorta* var. *latifolia* grows in conditions similar to those in Sweden which resulted in interest for the potential introduction of lodgepole pine into Sweden.

<u>Distribution in Sweden</u>

In 1928 lodgepole pine was introduced into southern Sweden. It was later found that it would provide higher quality and increased volume growth compared to Scots pine if planted further north (Hagner and Fahlroth 1974; Lindgren *et al*. 1988). Site indices are lower at these higher latitudes, and lodgepole pine consistently out performs native Scots pine (*Pinus sylvestris*) in terms of total yield on low productivity sites (Hagner 1971; Remrod 1977). In the south of Sweden, lodgepole pine produces less volume per hectare compared to Scots pine (Liziniewicz *et al*. 2011). In the 1970's large scale introduction of lodgepole pine was initiated, and it currently covers about 600,000 ha of land in mid to northern Sweden (Elfving *et al*. 2000). It is the only exotic species planted on a production scale in Sweden.

<u>Growth and Wood Characteristics</u>

Lodgepole pine has been found to grow an average of 36 percent faster than native Scots pine on northerly sites; it has a 2 percent higher initial survival rate and an 8 percent lower proportion of bark to stem volume (Norgren 1996). Lodgepole pine also has a 10-15 year shorter optimal rotation time in the north of Sweden compared to Scots pine. Negatively, lodgepole pine has a 5 percent higher mortality rate after the first thinning and a 3 percent lower wood density. The lower wood density however, should not affect the potential markets for lodgepole pine because it is not a large enough reduction to significantly lower strength and flexibility characteristics (Elfving and Norgren 1993; Persson 1993). Lodgepole pine has a higher proportion of heartwood to sapwood compared to Scots pine. Lodgepole pine has more slender and elongated tracheids which results in a lower tear resistance and higher breakage length. Lodgepole pine sawtimber produces higher export grade timber (the volume of knot free high quality timber obtained from a given log) and displays comparatively lower values at stress grading when compared to Scots pine (Persson 1993). The higher stem volume of lodgepole pine is explained by its' needle and shoot characteristics. It exposes new shoots earlier in the growing season, has longer needle longevity than Scots pine, closes its canopy sooner, and has a higher Leaf Area Index (LAI) than Scots pine (Leverenz and Hinckley 1990). Stahl and Persson (1988) found that tracheid length is longer, and the branch diameter is smaller in lodgepole pine when compared to Scots pine. This comparison between species was made using planted individuals on similar sites with similar diameters while minimizing age differences. The above mentioned studies display the relative superiority of lodgepole pine over Scots pine on the same site types in northern Sweden.

Previous studies have been conducted on biomass allocation as densities and spacings differ. It was found in a six-year-old miniature scale Loblolly pine (*Pinus taeda*) study that densities did not have a significant effect on biomass allocation between above and below ground tissues (Russell *et al*. 2009). According to Russell *et al*. (2009), stands planted at the same density would have no significant difference in biomass allocation between above and below ground woody tissue between planting rectangularities. Differences in biomass allocation may be different when trees are planted on a production scale and different between *Pinus contorta* compared to *Pinus taeda.*

Planting trees at the same density but varied spacing results in different plot dimensions, or rectangularities. Effects, or lack thereof, resulting from different rectangularities on growth characteristics is important to assess as the knowledge is applied to practical operations such as harvest strip road location. Stand planting design and harvest techniques can be altered to maximize efficiency if there is no effect of rectangularities on critical characteristics such as volume, branch diameter, and tree stem circularity. For example, strips roads could be organized at planting and volume losses can be reduced.

A density study by Liziniewicz and Agestam *et al*. (2011) found that total height differs between densities in lodgepole pine. When lodgepole pine is planted at lower densities per hectare the average total height increases per tree. Planting lodgepole pine at spacings of 2 x 2 m and 1.41 x 1.41 m produced the highest individual tree volume and volume per hectare depending on the site (Liziniewicz and Agestam 2011).

Wood quality is strongly correlated with the largest living branch between 1 – 2 m on the tree bole (Persson 1976). Larger branches result in lower wood quality because they create larger knots in the wood. The branch angle also affects the wood quality as it influences the knot size in the wood. The further the angle of a branch deviates from 90 degrees (°) perpendicular to the bole, the larger the knot becomes. Liziniewicz and Agestam *et al*. (2011) shows that Lodgepole pine planted at different spacings and densities, result in a significant difference in the wood quality of the tree stems between densities.

Objectives:

1. Evaluate effects of planting rectangularity on wood quality traits
2. Evaluate effects of planting rectangularity on circularity of tree stems
3. Determine trends in branch characteristics (diameters and angles) between rectangularities
4. Evaluate trends in volume/ ha of lodgepole pine in different planting rectangularities

1. METHODS

Study Site

Experimental plantations of lodgepole pine have been established at different latitudes in Sweden to study long term growth characteristics of the introduced species at different planting densities and spacings across space and time. In 1982 a study site was established at Kulbäcksliden experimental forest in northern Sweden by Professor Bjorn Elfving (Figure 1). The aim of this study design was to analyze potential differences among tree diameters, branch diameters, stem circularity and volume between rectangularities of the same density. The planting was a randomized complete block design (Figure 2), in which there are three replications (1, 2 and 3) and five different planting rectangularities (treatments) in each replication (Figure 3). These five rectangularities include trees planted on the following grids: 1 x 4 m, 1.33 x 3 m, 1.46 x 1.46 x 4 m, 2 x 2 m and 0.8 x 5 m. All rectangularities result in a planting density of 2500 trees/ha. The different treatments are referred to as rectangularities because in order to have 2500 initial trees per hectare, the planting designs varied the spacings of the trees. This resulted in different plot dimensions for the treatments. For example, the 1x4 m rectangularity had plot dimensions of 20 x 30 m while the 1.33 x 3 m rectangularity resulted in rectangular plot dimensions of 18 x 32 m (Figure 4). No secondary treatments (e.g. pruning or thinning) have been made to the stands since planting; they have been allowed to develop naturally. It was noted during data collection that overall quality and survival in replication three was poor due to visually apparent elevated moisture at the site and hypothesized excessive browsing by moose.

In 2004 and 2011 standard forest inventory data were collected at the study site located near Vindeln, Sweden, by field technicians from the Swedish University of Agricultural Science (SLU). These data were made available for analysis. During August of 2010, tree and branch characteristics from all replications and rectangularities were collected.

Figure 1: Location of the study site in Sweden. 64°10'20.72'' N, 19°33'04.62'' E at 306 meters above sea level. (Image obtained from maps.google.se, February 2nd, 2012)

Figure 2: Aerial photo (January, 1st, 2009) of the randomized complete block design at the study site in Kulbäcksliden, Sweden. The 3 replications are approximately outlined. (Image obtained from maps.google.se, February 2nd, 2012).

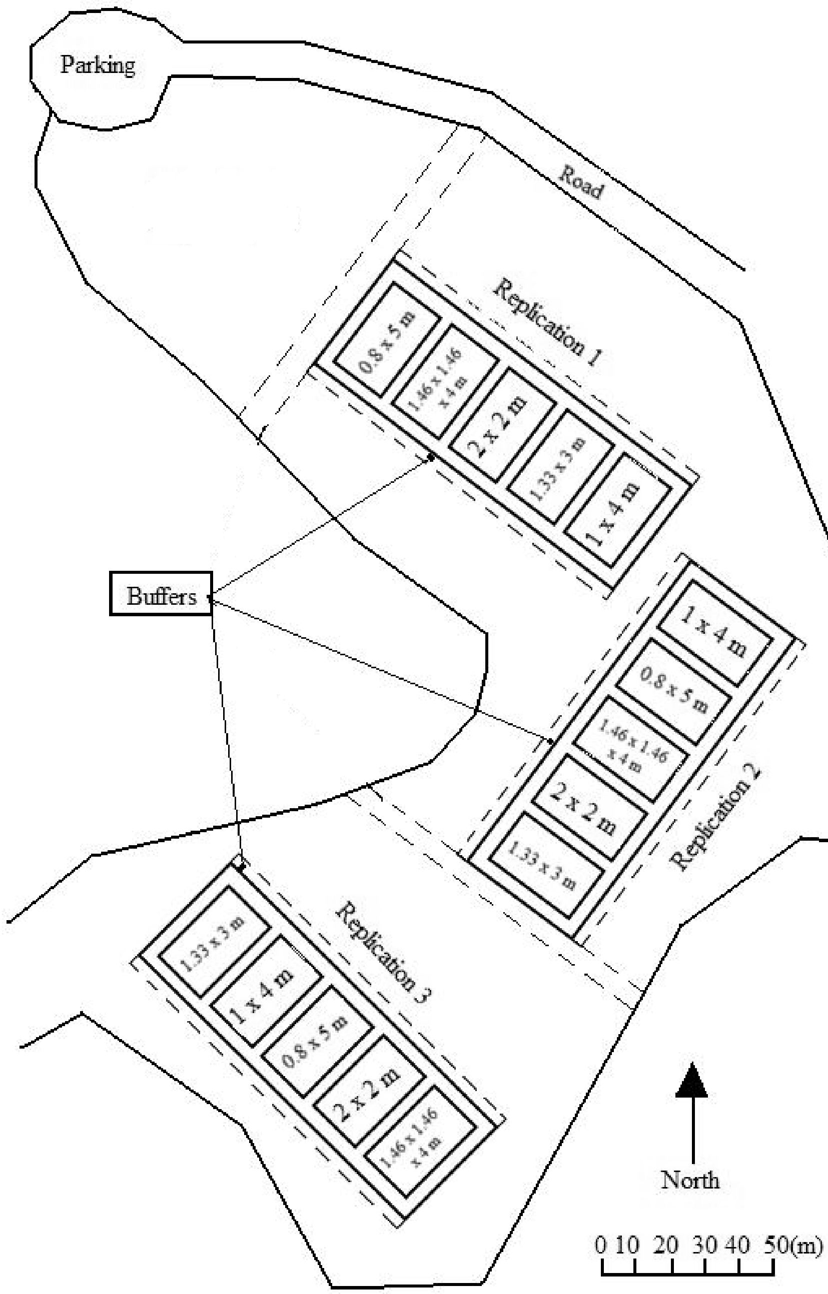

Figure 3: Study design layout and orientation of replications. According to the study design, rectangularities are randomly arranged in each replication; this is the actual arrangement.

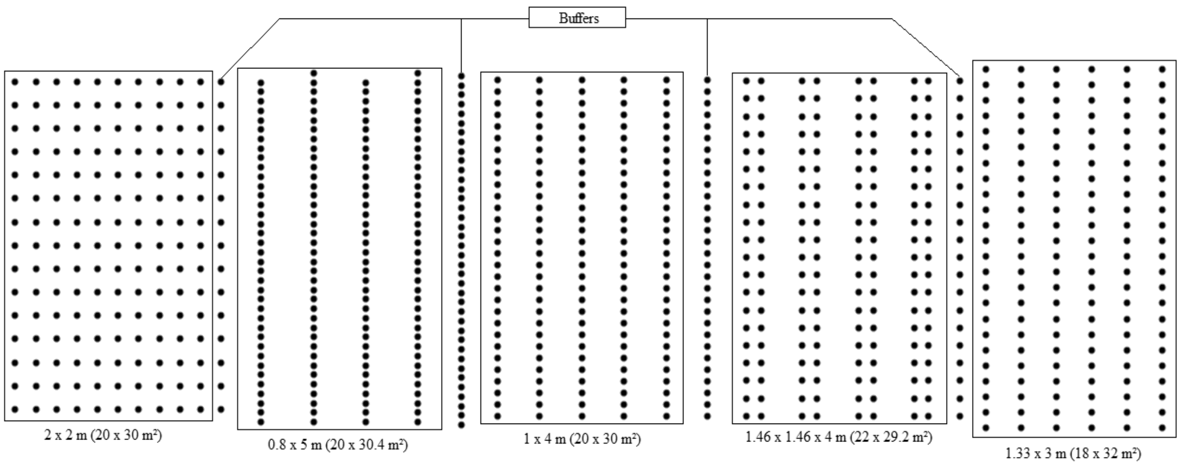

Figure 4: Example of spacing and plot size arrangement for each rectangularity treatment. Dimensions of each rectangularity are slightly different as a result of maintaining the planting density of 2500 trees/ha, while altering rectangularity. Buffer rows are located between and around (not pictured) each rectangularity.

Final Harvest Tree Selection

In each rectangularity among the three replications, potential final harvest candidate (crop) trees were chosen to result in a final harvest density at rotation of 500 trees/ha. These candidates were chosen to assess quality and growth characteristics on trees which will likely be harvested at rotation. A final harvest density of 500 trees/ha is typical for Scots pine sawtimber in northern Sweden. Rectangularities were broken down into multiple sections which corresponded to the number of rows. The total number of candidate trees per rectangularity was evenly divided among these sections, plus or minus one tree. Final harvest candidate trees were chosen visually according to location within the stand, height, diameter, straightness and quality. Trees that were straight, tall, of good visual quality and having a larger diameter were chosen first. Initially the most ideal final harvest candidate trees were selected, followed by trees which maintained desirable characteristics and were at appropriate locations for final harvest tree. Due to overall moderate to poor survival, straightness, and quality of the stands, some final harvest candidate trees may have deformities such as spike knots and forks. In which case, those trees with deformities which would least affect the potential for quality sawtimber were chosen. For example, when choosing between two trees, if one is forked at 3 m, while the other has a 0.5 m long vertical gash at the diameter at breast height (DBH), the second tree would be chosen as the final harvest candidate tree given the ability to remove the lower section of the tree and still have a large diameter section suitable for sawtimber. The first tree would not be chosen due to the height of the fork (too low for quality timber at base of

tree), and the smaller diameters of the two upper sections resulting from the fork at 3 m. Final harvest candidates were chosen and flagged within each rectangularity treatment prior to any measurements being taken.

Competitive Sectors

Each rectangularity treatment has the same planting density, resulting in five differently spaced plots in each replication (Figure 4). Due to the varied proximity to neighboring trees among rectangularities there is a different level of competition along the row (x-axis) and column (y-axis) axes. Consider a spacing of 1 x 4 m, on the 1 m axis trees are closer than on the 4 m axis. Thus, the level of competition in the 1 m direction is greater than in the 4 m direction. When gathering data, trees were considered to be made of 4 quadrants, each quadrant centered on the row or column axes (Figure 5). All final harvest candidate trees were divided in sectors of competition, each sector comprising 50% of each tree. These sectors of competition were visually determined individually for each tree at the time of measurement. This same principle was applied to all rectangularities so that sectors of competition were established among all treatments. These sectors will be referred to as sector 1 and sector 2. The rectangularity with a spacing of 1.46 x 1.46 x 4 m presented a problem because competition is not evenly split around the tree. This difference was disregarded so that sector 1 and sector 2 were assessed along the same axes and comprised the same portion of the tree stem as in all other rectangularities in order to keep measurements consistent.

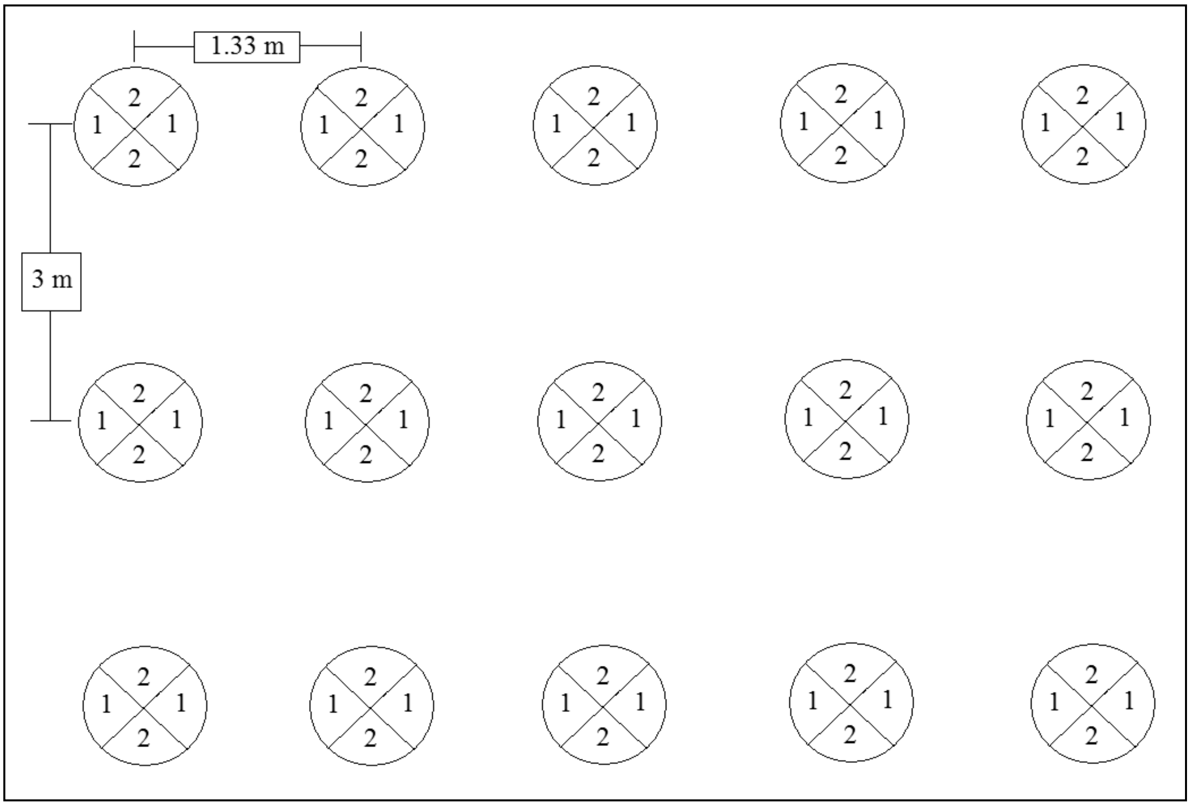

Figure 5: Example of competitive sectors in rectangularity 1.33 x 3 m as seen from an overhead view. Buffers surround trees at the same spacing as in the rectangularity (not pictured). There are two competitive sectors labeled 1 (Sector 1) and 2 (Sector 2), with each sector comprising 50% of the tree. Not to scale.

Rectangularity Ratio

The study was established in 1982 with the intention of being able to better understand how various rectangularities affect growth characteristics of lodgepole pine while accounting for any density effects by all being planted at 2500 trees/ha. At the time of establishment five different rectangularities were used, and they each corresponded to an initial planted competitive ratio (PCR) between trees. The highest planted competitive ratio (6.25:1) occurs in the rectangularity 0.8 x 5 m and the ratio decreases gradually until it reaches 1:1 at the rectangularity of 2 x 2 m. As tree mortality occurs over time there is an increased distance to neighboring trees resulting in a reduction in competition for nutrients and sunlight. This results in an overall decrease in the PCR at the stand level over time, creating an effective competitive ratio (ECR). Mortality of immediate row and column neighbor trees of final harvest candidates was recorded; mortality of trees not adjacent to final harvest trees at planting was not recorded. Between tree mortality changes the trees' competitive status, effectively reducing the competition between trees when one or more neighbors are dead. Final harvest candidate trees were not chosen due to consideration of its' proximity to dead trees, only the visual characteristics of the tree itself and location in relation to other final harvest candidates trees were considered, as previously described. In order to compare the rectangularities which are represented by the final harvest candidate trees, an ECR was calculated for each final harvest tree using neighbor mortality data by rectangularity and replication.

Height and Diameter Measurements

Three height measurements and two stem diameter measurements were taken on each final harvest candidate tree. All height measurements were recorded in meters to the nearest 0.1 m using a Vertex IV Hypsometer. Two diameter measurements to the nearest 0.1 cm were taken at breast height (1.37 meters) with a caliper to obtain DBH. The first DBH measurement was within the row, along the sector 1 axis. The second DBH was taken perpendicular to the first measurement, along the sector 2 axis. Consistency was kept when measuring DBH so that potential elliptical nature in tree stem growth could be compared between rectangularities. The lowest living branch in each competitive sector (1 and 2) was measured by visually inspecting each final harvest candidate tree to see where the lowest living branch connected to the tree bole (stem).

Straightness

Final harvest candidate trees were assigned a straightness rating that ranged from 1 (best) to 3 (worst) using integers. A visual assessment of each tree was made and compared with the other final harvest candidates to assign a straightness rating relative to others in the replication. Determinations of straightness were made by evaluating a 4 m section of the stem immediately above DBH. A straightness rating of 1 or 2 would be considered usable sawtimber, while a straightness rating of 3 indicates that the tree is too defective (e.g. crooked) to be used for sawtimber. All replications were field surveyed and visually analyzed prior to initiating relative straightness rating so that a conceptual range of straightness was established, reducing bias.

Quality

A subjective wood quality measure of all final harvest candidate trees was taken. The wood quality classification system ranged from 1 (best) to 5 (worst). Outer tree characteristics were evaluated and important variables including straightness, deformities (forks, broken tops, spike knots), diameter, foliage health/abundance and total height were considered. Quality was also field surveyed visually for all replications before scoring the individual tree ratings in order to reduce bias.

Branch Characteristics

On each final harvest candidate tree a total of six branches were measured, two branches on three different whorls. The lowest measured whorl was located immediately below breast height and the other two whorls were those two immediately above breast height. These whorls were chosen because they are located in the first 3 meters of the tree and were readily accessible. Of the two branches measured on each whorl, one branch was from sector1 and the other was from sector 2. The location where the branch connected to the tree bole was the deciding factor for which competitive sector that branch was located in. If a branch was partially located in both sectors, the sector which visually contained majority of the branches' diameter was chosen. In each whorl and for each sector the largest branch (diameter) occurring in that sector was chosen. The diameter of this branch was taken one cm away from the tree stem. Branch diameter measurements were taken vertically to the nearest 0.01 cm with a digital caliper. The underside angle of all branches was measured to the nearest degree (°) with a protractor. The protractor was placed parallel to the tree stem and a rotatable arm was moved until parallel with the branch section immediately exiting the tree stem. This section closest to the tree stem was considered because it is most closely related to the angle of the branch as it exits the tree bole and thus determining the size and angle of the interior knot. If the branch had living foliage, it was noted. It was also noted if the terminating end of the branch had grown away from its originating sector and into the other sector. These diameter and angle measurements, along with notes, were taken for all six branches on each selected final harvest candidate tree.

Statistics

In SAS 9.2 (SAS Institute Inc. 2008) proc GLM was used when calculating ANOVA for all variables between rectangularities and replications. This tested for Type III experiment wise error at an α-level = 0.05. Type II error occurs when a test fails to reject a false null hypothesis, which statistically occurs 1 in 20 times for ANOVA tests at an alpha level = 0.05. Given the number of ANOVA equations at an alpha level = 0.05 used to analyze data in this research, Type II error was statistically expected to occur at least once.

Summary statistics were calculated by rectangularity and replication for all variables. Pearson correlation statistics were computed for all combinations of variables among individual replications, and among each of the rectangularities within replications. ANOVA's were calculated using proc GLM to compare tree characteristics with replication and rectangularity as the class variables. Effective competitive ratios were calculated by tree for all rectangularities. This was done by dividing the total distance between neighboring trees in the column direction (y) by the total distance between neighboring trees in the row (x) direction. The form of the ratio formula was:

$$Tree_{Ratio_n} = \sum_{t=1}^{t=n} \frac{\frac{2C+(\#Dead_C*C)}{2}}{\frac{2R+(\#Dead_R*R)}{2}} \;/\; \mathrm{N}$$

Equation (1)

Where C represents column spacing (m), R represents row spacing (m), $\#Dead_{C,R}$ is the number of neighbor trees dead in the column and row directions respectively, and N represents the total number of final harvest candidate trees for each rectangularity. The ECR for final harvest candidates was calculated for each tree individually using survival information recorded on the four neighboring trees, two of the four were adjacent trees along the row axis and the other two were adjacent trees along the column axis. These ratios were then averaged for each rectangularity in each replication.

Individual tree volume was calculated for data gathered on sample and dominant trees in 2004 and 2011 by the SLU field technicians, and also for final harvest candidate trees identified for this research. SLU measured the diameter of all standing trees, along with the height of 15 sample trees and 5 dominant trees per rectangularity. Individual tree volumes (including bark) were calculated using an equation developed for lodgepole pine in Sweden. The volume equation calculates the total stem volume per tree to its tip. The volume equation was developed by stem sectioning lodgepole pine trees of various North American provenances which were planted at four different study sites in Sweden. The equation includes constants for both genetic provenance and site location which were determined and assigned (Stahl and Persson, 1988). For the site constant in this study, the value determined at the nearest site in Stahl and Persson (1988) was used. The lodgepole pine provenance used for this study is from Latitude 60.1° north and Longitude 128.2° west, which is 800 meters above sea level in the Yukon Territory, Canada. The form of the volume equation was:

$$\ln\widehat{\mathrm{V}} = \hat{\beta}_0 + \hat{\beta}_1 \ln(d) + \hat{\beta}_2 \ln(\mathrm{h}) \qquad \text{Equation (2)}$$

$\hat{\beta}_0 = -11.14193$ $\qquad$ $\hat{\beta}_1 = 1.78$ $\qquad$ $\hat{\beta}_2 = 0.97962$

Where $\widehat{\mathrm{V}}$ is the stem volume, $\hat{\beta}_0$ is a coefficient describing the growing region, $\hat{\beta}_1$ and $\hat{\beta}_2$ are coefficients pertaining to diameter and height respectively, which are both genetic provenance specific, d and h are diameter (mm) and height (cm) respectively.

Volume per hectare was calculated using 2011 data from SLU on sample and dominant trees. The average volume of a sample tree was multiplied by the total number of surviving stems for each rectangularity. This resulted in the standing volume (m^3) in each rectangularity, which was then converted into a per hectare volume.

Variables for which averages and statistical tests for mean difference were calculated include quality, straightness, DBH (1 and 2), branch diameters (whorls 1 to 3), branch angles (whorls 1 to 3), number of branches per whorl, distance between top and bottom whorls measured, height to live crown, and angle of the biggest branch found on each tree. In addition, the percentage of measured branches living and the tendency of the branch to grow out of the sector in which it connects to the tree bole were also analyzed. All variables were compared between rectangularities and between competitive sector 1 and sector 2.

Statistical power of ANOVA tests were calculated using the following equation:

$$P = \sqrt{\frac{n\sum_{i=1}^{k}(\mu_i - \mu)^2}{ks^2}} \qquad \text{Equation (3)}$$

Where P is power, n is sample size, μ_i and μ are individual sample values and mean, respectively, k is the number of groups and s^2 is variance.

2. RESULTS

Survival

An ANOVA between replication and survival at all ages which the stands were measured shows a statistically significant difference in survival between replications 1, 2 and 3, with a p-value of < 0.0001 (Table 1). No statistically significant difference was found in the number of living trees between replications 1 and 2 (Table 2). There was no statistically significant difference in the number of dead trees between rectangularities in replications 1 and 2 (Table 2). Utilizing data gathered in 2011 by SLU field technicians, results indicate 17%, 22.3% and 43.3% of trees died since planting in replications 1, 2 and 3, respectively (Figure 6; Appendix I). Replication 3 had from the significantly more dead trees than replications 1 and 2 (Figure 6). High level of mortality in replication three changed the planting rectangularity so that it was unrepresentative of the initial design. Due to these reasons replication 3 was removed from the analysis.

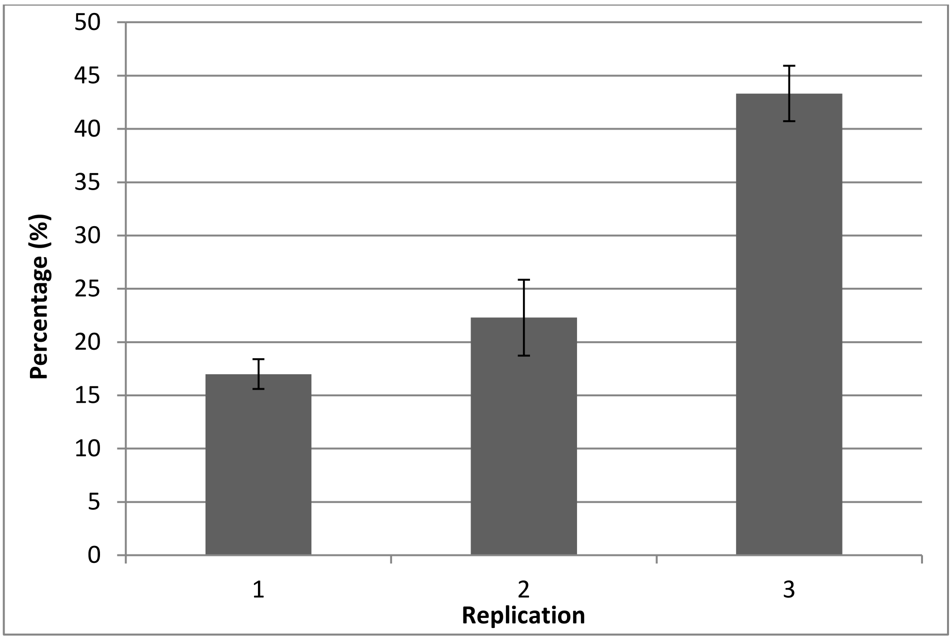

Figure 6: Percentage of mortality by replication recorded by the SLU field team in the spring of 2011. Confidence intervals of 95% are indicated.

Table 1: Probability that mortality is different at various times of measurement by replication across all three replications (degrees of freedom (DF) = 2). Variable Age = 29 relates to the number of dead trees recorded in 2011 by SLU compared to the number of trees planted, and Age = 22 relates to the number of dead trees recorded in 2004 by SLU, compared to the number of trees planted.

Variable	Probability
Age = 22	< 0.0001*
F-value	24.42
Age = 29	< 0.0001*
F-value	28.74

Table 2: Results of an ANOVA of mortality at various times of measurement between replications and between rectangularities across replications 1 and 2. Variable Age = 29 is the number of dead trees recorded in 2011 by SLU field technicians, and Age = 22 is the number of dead trees recorded in 2004 by SLU field technicians.

Variable	Class	Probability
Age = 22	Replication (DF = 2)	0.182
F-value	Replication (DF = 2)	2.60
Age = 22	Rectangularity(DF = 4)	0.126
F-value	Rectangularity(DF = 4)	3.51
Age = 29	Replication	0.208
F-value	Replication	2.25
Age = 29	Rectangularity	0.464
F-value	Rectangularity	1.10

Tree Diameters

The average final harvest candidate tree DBH differed between rectangularities with a p-value of 0.031 (Table 4). Diameters of trees were positively correlated with total height and the diameter of the biggest branch in all rectangularities (Appendix II). The effective competitive ratio of 5.52 (rectangularity 0.8 x 5 m) has the highest average tree diameter and the ECR of 3.86 (rectangularity 1 x 4) has the lowest average tree diameter (Figure 7). Stem diameters along the sector 2 axis differ between rectangularities 0.8 x 5 m and 1.46 x 1.46 x 4 m, and also between rectangularities 0.8 x 5 m and 1 x 4 m, as shown by a Tukey test (Appendix V). A paired T-test between the two diameter measurements within rectangularities shows no significant difference within rectangularity in either replication (Appendix VII). No statistically significant difference was found in the difference between diameters in sector 1 and sector 2, having a p-value of 0.087 over all rectangularities (Table 4).

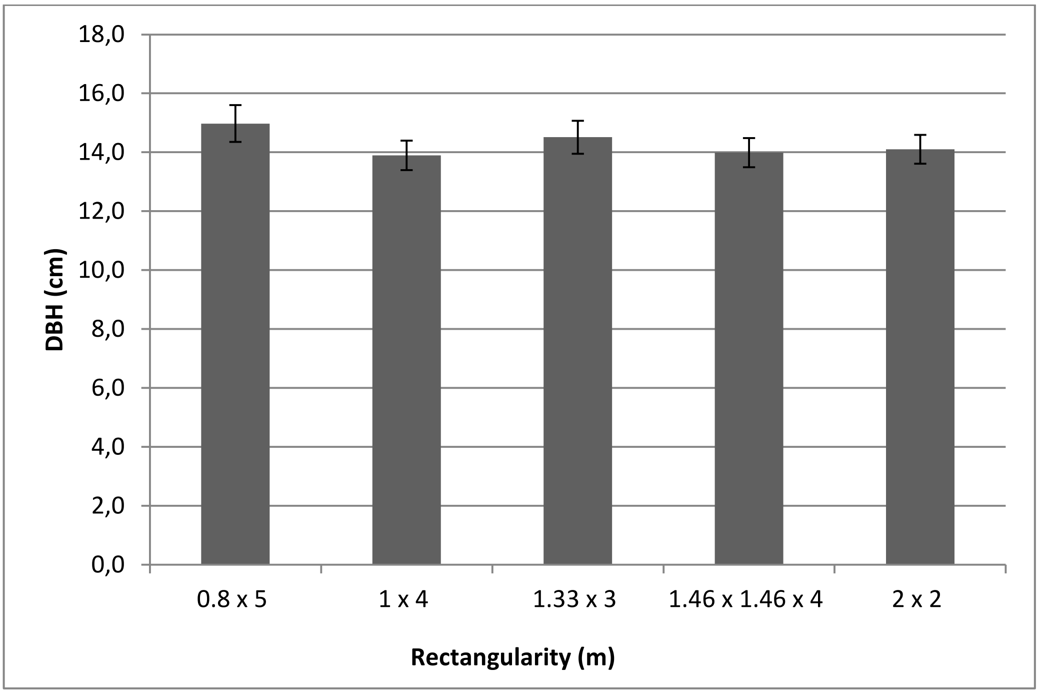

Figure 7: Average DBH of final harvest candidate trees by rectangularity for replications 1 and 2. Confidence intervals of 95% are indicated.

Total and Living Crown Heights

ANOVA showed that the total height and height to live crown were both significantly different in at least one of the rectangularities having p-values of 0.0015 and 0.0052, respectively (Table 4). It was found that the total height and height to live crown were correlated with each other in rectangularities with low effective competitive ratios (1.46 x 1.46 x 4 and 2 x 2 m) (Appendix II). Total height is positively correlated with DBH for all rectangularities, having a p-value of < 0.001 (Appendix II). Total height varies between rectangularities 0.8 x 5 m and 1.46 x 1.46 x 4 m, and between 1.33 x 3 m and 1.46 x 1.46 x 4 m. Height to live crown varies between rectangularities 1.33 x 3 m and 0.8 x 5 m, and between 1.33 x 3 m and 1.46 x 1.46 x 4 m (Appendix V). The difference in height to live crown between sector 1 and sector 2 varies significantly between rectangularities with a p-value of < 0.001 (Table 4). Rectangularities with smaller ECR have lower average total heights when compared to rectangularities with higher ECR (Figure 8). Tukey's test on the average heights to live crown show differences between rectangularities 0.8 x 5 m and 1.33 x 3 m (Figure 9; Appendix V).

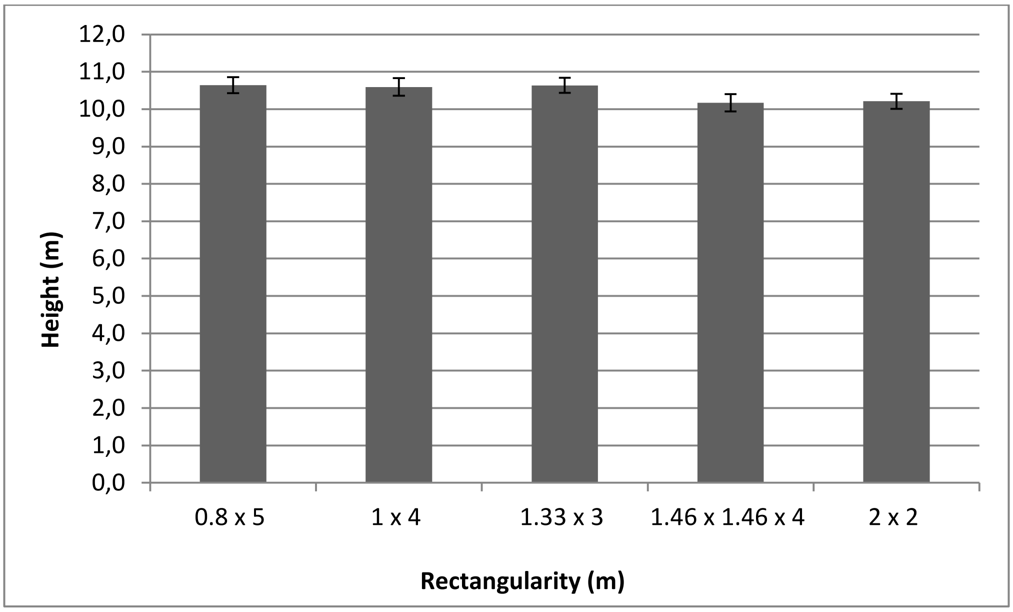

Figure 8: Average total height by effective competitive ratio (ECR) of final harvest candidates. Confidence intervals of 95% are indicated.

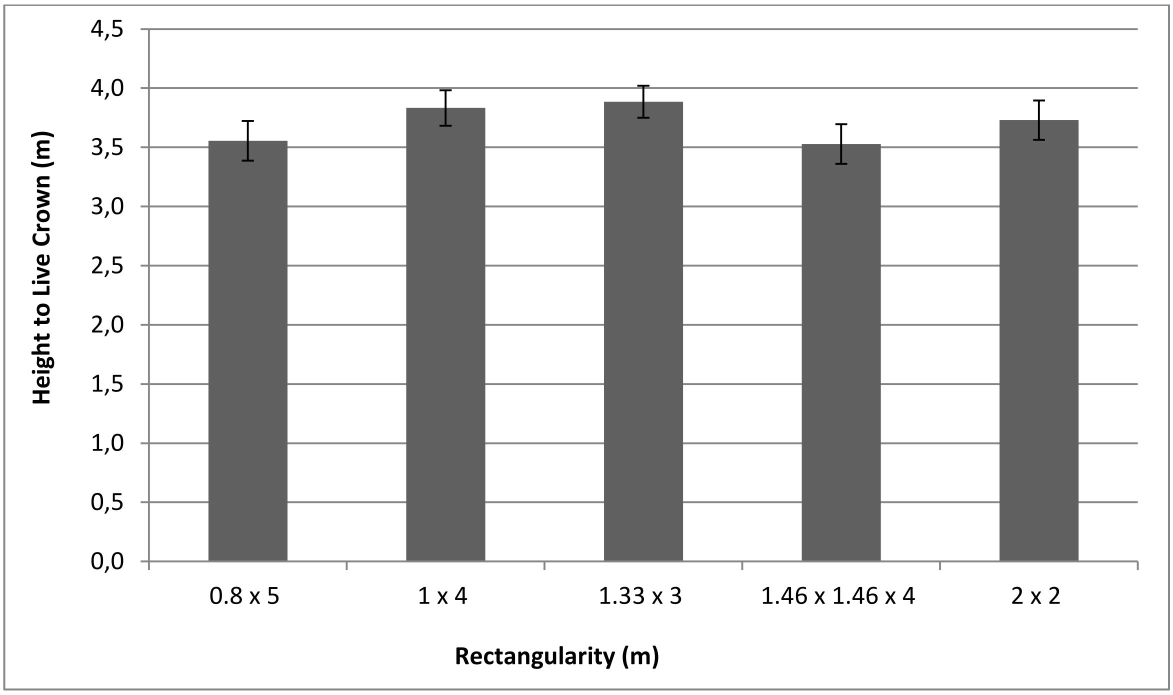

Figure 9: Average height to live crown by rectangularity. Confidence intervals of 95% are indicated.

Volume

An ANOVA on individual tree volume between rectangularities resulted in a p-value of 0.010, showing that there is a statistically significant difference between rectangularities (Table 4). Final harvest candidate individual tree volume was found to be significantly higher in rectangularity 0.8 x 5 m compared to individual tree volume found in rectangularity 1.46 x 1.46 x 4 m according to Tukey test (Appendix V).

When looking solely at the data collected on final harvest candidate trees, the highest average individual tree volume per plot occur in rectangularities 0.8 x 5 m and 1.33 x 3 m, at 112.2 dm^3 and 105.9 dm^3, respectively (Table 3). The lowest average individual tree volume per plot for final harvest candidates (FHC) was seen in the 2 x 2 m rectangularity. The difference in the average volume production per tree between rectangularities 0.8 x 5 m and 2 x 2 m is about 11% (Table 3). The same relationship between rectangularities and volumes is evidenced by data collected by the SLU field team in 2004 and 2011, with the highest volumes occurring in rectangularities 0.8 x 5 m and 1.33 x 3 m (Table 3, Appendix VI). Individual tree volume of final harvest candidates was correlated with DBH, total height, and the total number of branches per tree for all rectangularities (Appendix II).

Moving from rectangularity 0.8 x 5 m to 2 x 2 m there is a general decrease in total individual stem volume. Average individual tree volume for final harvest candidates was higher than the average individual tree volume found in 2011 for rectangularities 0.8 x 5 m, 2 x 2 m and 1.33 x 3 m, while it was lower in rectangularities 1.46 x 1.46 x 4 m and 2 x 2 m (Figure 10).

Stand volume per hectare was highest in rectangularity 0.8 x 5 m and lowest in rectangularity 1.46 x 1.46 x 4 m, with standing volumes of 185 m^3 and 144 m^3, respectively (Table 4).

Table 3: Mean individual tree volumes, heights and diameters in replications 1 and 2 for each rectangularity in 2004, 2011 and for final harvest candidates (FHC). Data collected in 2004 and 2011 was done by the SLU field team in which they measured diameters on all trees, and heights only on dominant trees.

Time	Rectangularity	n	Diameter(cm)	Height(m)	Volume (dm^3)
2004	0.8 x 5	68	14.8	9.8	74.0
2011	0.8 x 5	39	14.2	10.6	105.4
FHC	0.8 x 5	60	15.0	10.6	112.2
2004	1 x 4	73	12.2	8.2	59.0
2011	1 x 4	40	13.4	10.6	95.2
FHC	1 x 4	60	13.9	10.6	97.2
2004	1.33 x 3	62	12.8	8.1	64.2
2011	1.33 x 3	39	14.1	10.5	102.1
FHC	1.33 x 3	58	14.5	10.6	105.9
2004	1.46 x 1.46 x 4	74	12.0	7.7	55.0
2011	1.46 x 1.46 x 4	38	13.9	10.2	96.1
FHC	1.46 x 1.46 x 4	64	14.0	10.2	94.6
2004	2 x 2	67	12.0	7.7	55.0
2011	2 x 2	39	14.2	10.6	101.3
FHC	2 x 2	60	14.1	10.2	96.0

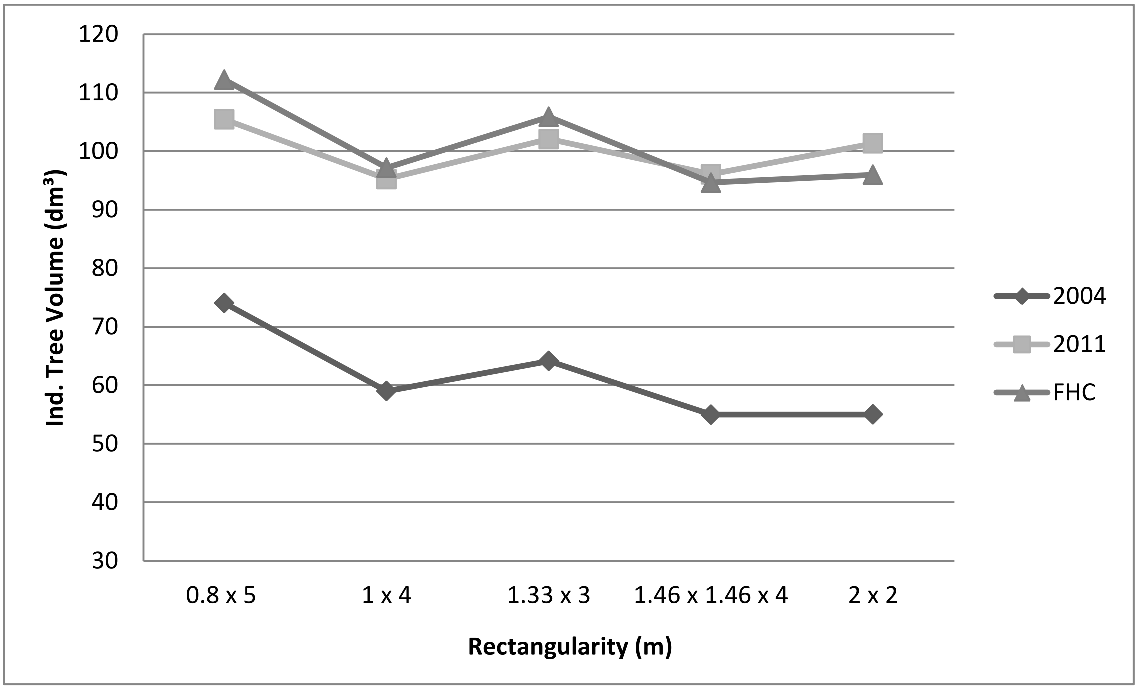

Figure 10: Trend in average individual tree volume in 2004, 2011 and for final harvest candidates (FHC) by rectangularity over replications 1 and 2.

Table 4: Standing volume per hectare for all rectangularities in replications 1 and 2. Volume per hectare was calculated using height and diameter data gathered on sample and dominant trees in 2011 (Age = 29) by SLU.

Rectangularity (m)	Volume (m^3/ha)
0.8 x 5	185
1 x 4	151
1.33 x 3	181
1.46 x 1.46 x 4	144
2 x 2	171

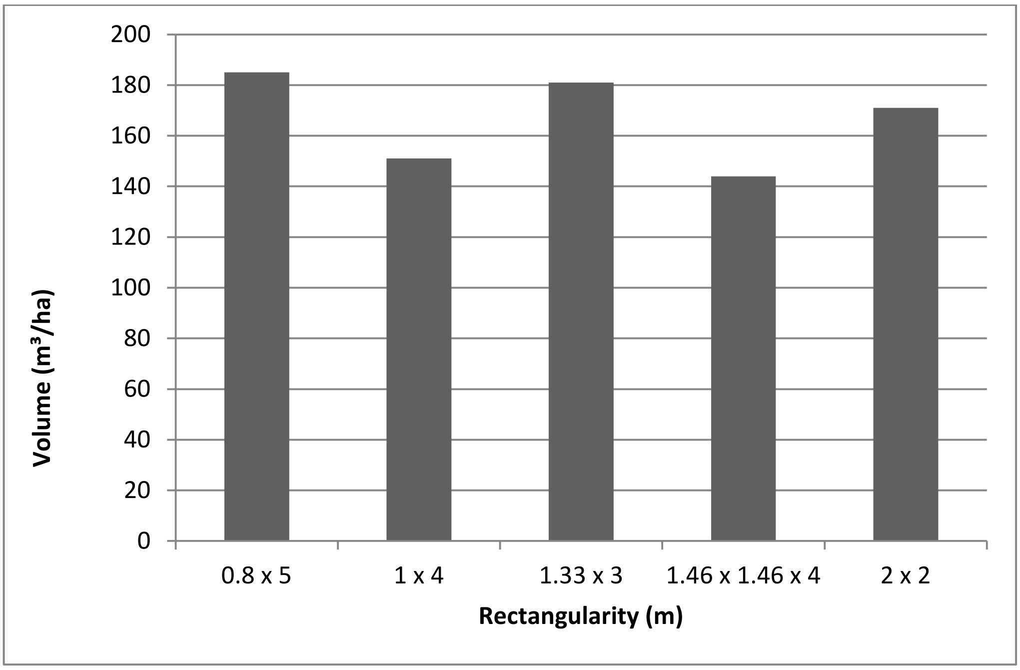

Figure 11: Volume of each rectangularity by hectare.

Ratio

Effective competitive ratios (ECR) show an overall reduction when compared to the planted competitive ratios (PCR) for all rectangularities (Figure 12). Trends in ratios across rectangularities are the same for the PCR and the ECR. Percentage differences between PCR and ECR range from 3.53% in rectangularity 1 x 4 m to 12.36% in rectangularity 2 x 2 m (Table 5). Replication 3 displays similar trends in competitive ratio between rectangularities, although average effective competitive ratios are lower than those found in replications 1 and 2 (Figure 12).

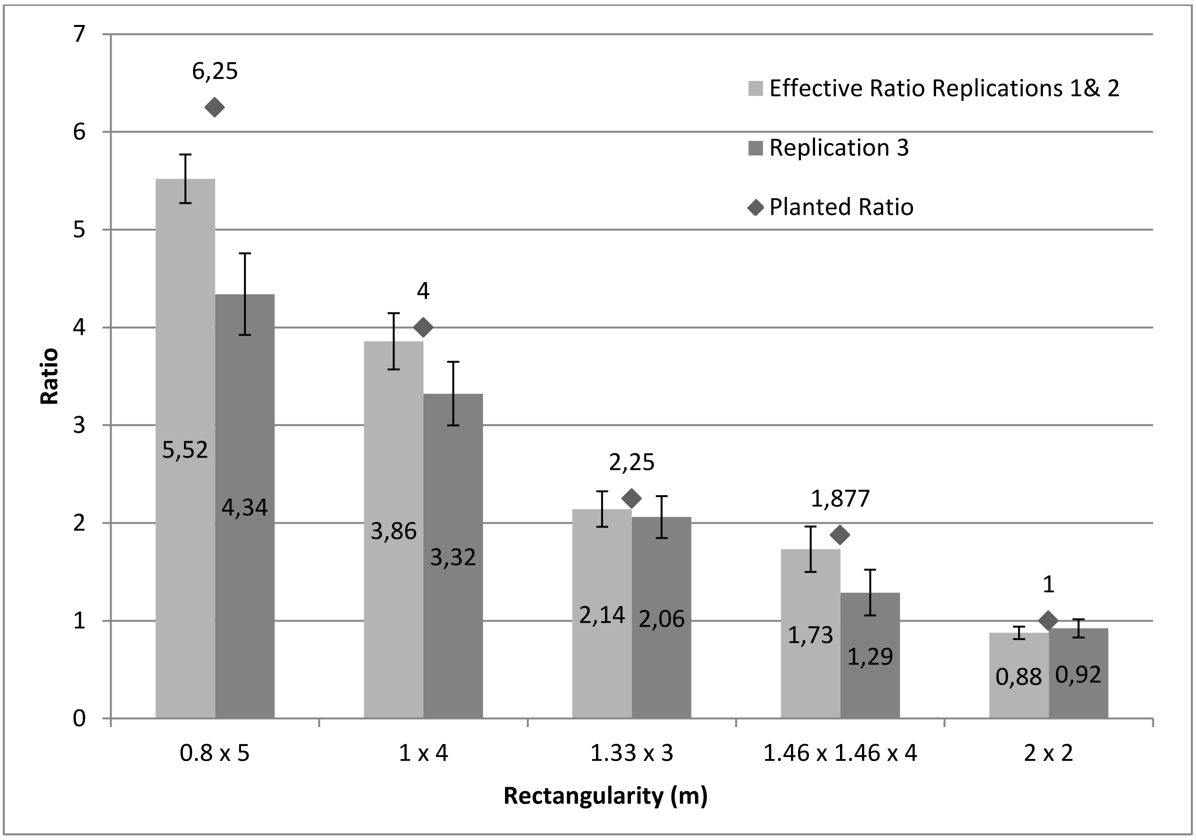

Figure 12: Average planted competitive ratio (PCR) and effective competitive ratio (ECR) per final harvest candidate tree by rectangularity at age =29. Bars represent the ECR per tree (labeled within) and circles represent the PCR (labeled above). Confidence intervals of 95% are indicated.

Table 5: Summary statistics for planted competitive ratio (PCR) and effective competitive ratio (ECR) by replication. PCR and ECR were calculated individually for each final harvest candidate tree and then averaged by rectangularity and replication.

Replication	Rectangularity (m)	ECR	PCR	Difference (%)
1	0.8 x 5	5.83	6.25	6.72
2	0.8 x 5	5.21	6.25	16.64
1	1 x 4	4.00	4	0.00
2	1 x 4	3.71	4	7.25
1	1.33 x 3	2.25	2.25	0.00
2	1.33 x 3	2.03	2.25	9.78
1	1.46 x 1.46 x 4	1.87	1.87	0.00
2	1.46 x 1.46 x 4	1.57	1.87	16.04
1	2 x 2	0.84	1	16.00
2	2 x 2	0.91	1	9.00
1 and 2	0.8 x 5 m	5.52	6.25	11.67
1 and 2	1 x 4	3.86	4	3.53
1 and 2	1.33 x 3	2.14	2.25	4.79
1 and 2	1.46 x 1.46 x 4	1.73	1.88	7.79
1 and 2	2 x 2	0.88	1	12.36

Pearson correlation statistics showed statistically significant correlations for some variables across all rectangularities while certain variables were only found to be correlated in a limited number of rectangularities (Appendix II). ANOVA were calculated for all variables by rectangularity in replications 1 and 2, and multiple variables were found to differ significantly between certain rectangularities (Table 6; Appendix III). Major variables which differed significantly between rectangularities are total height, height to live crown, volume, and average DBH. Notice, quality and straightness did not differ significantly. Tukey's test was computed for all variables which determined those rectangularities with averages for a variable that differ significantly from the means of another rectangularity.

Table 6: ANOVA probability results for final harvest candidate trees occurring in replications 1 and 2 in all rectangularities after taking the effect of different replications into account.

Variable	Probability of Significant Rectangularity Effect
Difference in Height to Live Crown	<0.001*
Live Crown Height Sector 2	<0.001*
Difference in Biggest Branch Diameter	<0.001*
Height to Live Crown	0.005*
Tip Growth, Whorl 1, Sector 1	0.006*
Volume per tree	0.010*
Biggest Branch Sector 2	0.013*
Total Height	0.015*
Total Branches Whorl 1	0.015*
DBH 2	0.016*
Basal Area per tree	0.017*
Sector of Biggest Branch Occurrence	0.018*
Branch Diameter, Whorl 2, Sector 2	0.025*
Average Tree DBH	0.031*
Branch Diameter, Whorl 3, Sector 2	0.036*
Height to Live Crown Sector 1	0.047*
Tip Growth into Sector 2	0.049*
Straightness	0.077
Tree Diameter Difference	0.087
Stumpage Value	0.096
Biggest Branch Diameter	0.141
Quality	0.805
Whorl Distance	0.808
Biggest Branch Angle	0.954

* Indicates significance at a 0.05 alpha-level.

Quality and Straightness

Final harvest candidate tree quality as assessed using the wood quality classification system, was found to be positively correlated with straightness in all rectangularities with a p-value of < 0.001 (Appendix II). In some rectangularities quality was correlated with whorl distance, height to living branches and branch diameters, but none of these relationships occurred consistently in all rectangularities (Appendix II). The average quality between rectangularities did not differ significantly, having a p-value of 0.805 (Table 6; Figure 13).

Straightness does not differ significantly between rectangularities with a p-value of 0.077 (Table 6; Figure 14; Appendix IV). Tukey tests support the results that neither quality nor straightness show statistically significant differences between rectangularities (Appendix V).

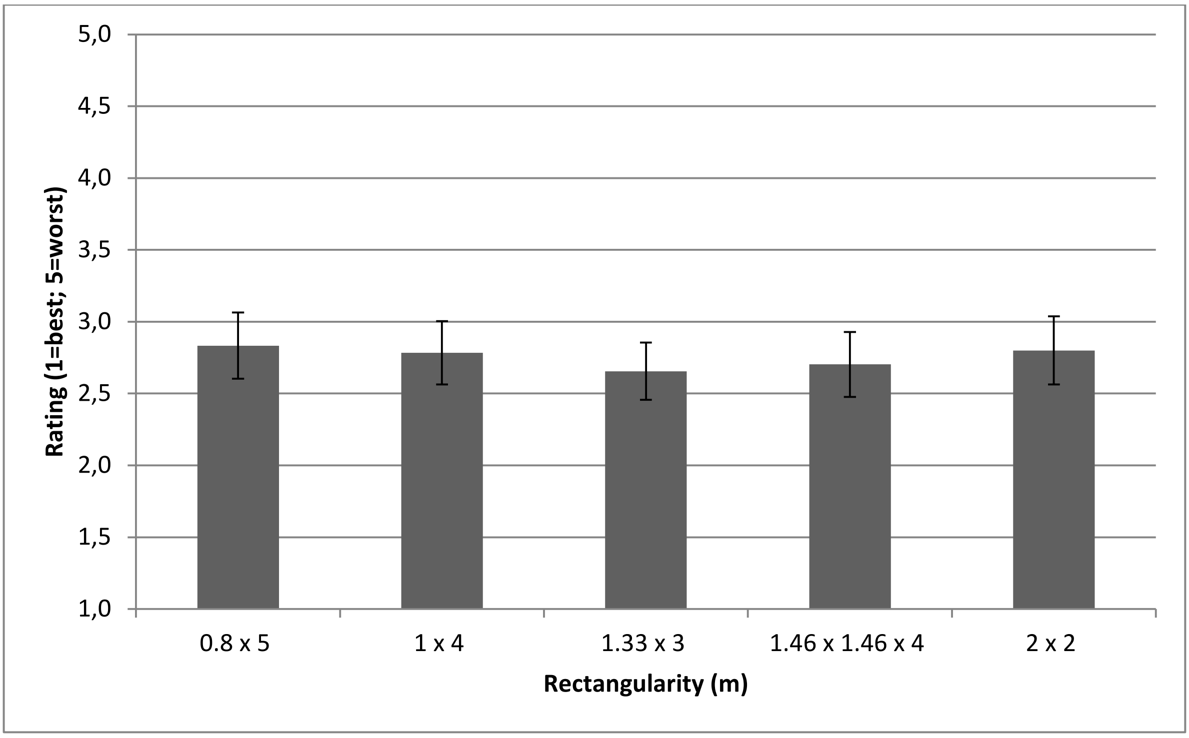

Figure 13: Average quality rating for final harvest candidate trees by rectangularity in replications 1 and 2. Confidence intervals of 95% are indicated.

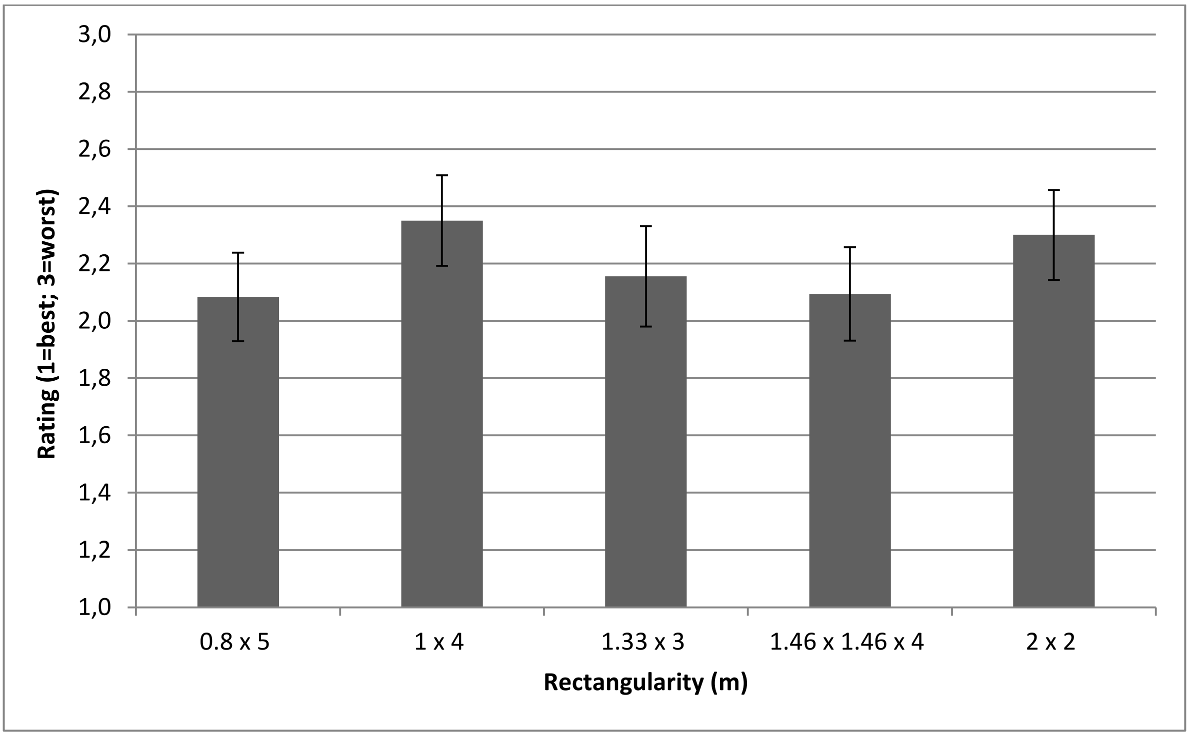

Figure 14: Average straightness ratings for final harvest candidate trees by effective competitive ratio. Those averages which are higher indicate poorer average straightness, while those values closer to a value of 1.0 indicate that the overall straightness was better. Confidence intervals of 95% are indicated.

Branch Analysis

The total numbers of branches occurring in all three whorls per tree were found to be consistently correlated with DBH and tree level branch diameter in all rectangularities (Appendix II). An ANOVA p-value of 0.018 for total branches occurring in whorl one shows that there is a significant difference between rectangularities (Appendix III). This difference occurs between rectangularities 0.8 x 5 m and 1.33 x 3 m (Appendix V).

The angles of the biggest branches were found to have a positive correlation with branch diameters in all rectangularities (Appendix II). Branch angle was correlated with the branch diameter in all rectangularities (Appendix II). No significant differences were found between rectangularities when comparing angles from different sectors (Appendix III). The number of branches per whorl, total branches occurring in the three measured whorls and the distance between whorls are not consistently correlated with any variable among rectangularities (Appendix II).

No statistically significant differences were found when comparing the average distance between measured whorls on each tree between rectangularities. In addition, there was no significant difference between the total number of branches per tree between rectangularities (Appendix III). The total number of branches occurring in whorl one differs significantly between rectangularities with a p-value of 0.0015 (Table 6). This difference occurs between rectangularities 0.8 x 5 m and 1.33 x 3 m (Appendix V).

In rectangularity 0.8 x 5 m over 75% of the biggest branches were found in sector 2 (the 5 m direction), and moving toward an even rectangularity (2 x 2 m) the biggest branches occur at almost evenly split percentages between sectors (Figure 15). At higher competitive ratio rectangularities bigger branch averages are seen in sector 2 and as the rectangularities approach an even spacing (2 x 2 m) the average branch diameters found in each sector approach each other (Figure 16). On the tree level there is a significant difference between rectangularities in the sector where the biggest branch occurs on each tree, with a p-value of 0.018 (Table 6). This difference occurs between the two most extreme rectangularities, 0.8 x 5 m and 2 x 2 m (Appendix V). At high ECR (5.52 and 3.86), the biggest branch diameters found in sector 2 are larger than those in sector 1. These ECR values correspond to rectangularities 0.8 x 5 m and 1 x 4 m. Branch diameters between sector 1 and 2 do not differ at smaller effective competitive ratios (Figure 16).

On the tree level, the diameter of the biggest branch in sector 2 was found to differ significantly between rectangularities with a p-value of 0.013 (Table 6). The biggest branch in sector two differs between rectangularities 0.8 x 5 m and 1.46 x 1.46 x 4 m, and between 0.8 x 5 m and 2 x 2 m (Appendix V). An ANOVA on tree level branch characteristics occurring in sector 1 supports the null hypothesis that there is no statistically significant difference in the diameter or angle between rectangularities (Appendix III). Branch diameters in sector 2 which occurred in the two whorls above DBH displayed significant differences between rectangularities, both having p-values less than 0.05 (Appendix III). For both of these variables the difference occurred between rectangularities 0.8 x 5 and 2 x 2 m (Appendix V).

Tip growth was recorded as the tendency of a branch to be attached to the tree in one sector (either 1 or 2) while its tip (whether dead or living) was found in the other sector. This was not found to be consistently correlated with any one variable. Correlations were sporadically found between tip growth occurring in different whorls, between biggest branch diameters, and angles (Appendix II).

An ANOVA revealed that significant differences exist between the average tendency of branches to grow out of their originating sector and into another sector. On the tree level it was found that between rectangularities a trees branches display a significantly different tendency to grow out of sector 1and into sector 2, with a p-value of 0.0497 (Table 6). Tip growth out of sector 1 into sector 2 in the whorl below DBH shows a statistically significant difference between rectangularities with a p-value of 0.0055. Tukey tests reveal that on the tree level differences in branch tendency to grow out of sector 1 and into sector 2 exist between rectangularities 1 x 4 m - 0.8 x 5 m, 1 x 4 m - 2 x 2 m, and 1 x 4 m - 1.46 x 1.46 x 4 m (Appendix V).

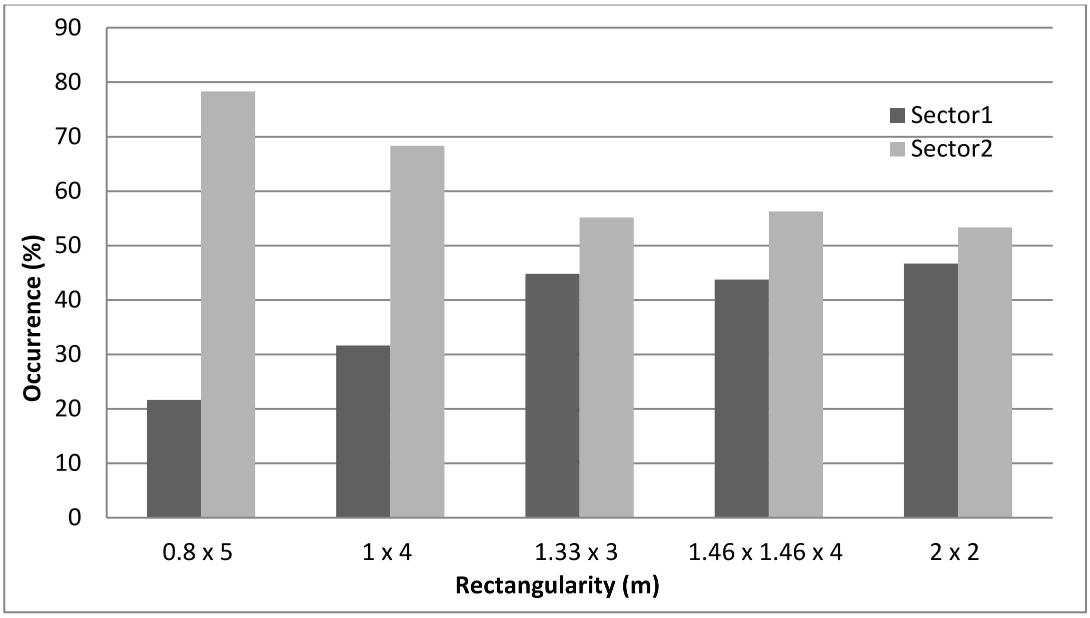

Figure 15: Trends found pertaining to where the biggest branch on each final harvest candidate tree was located by effective competitive ratio.

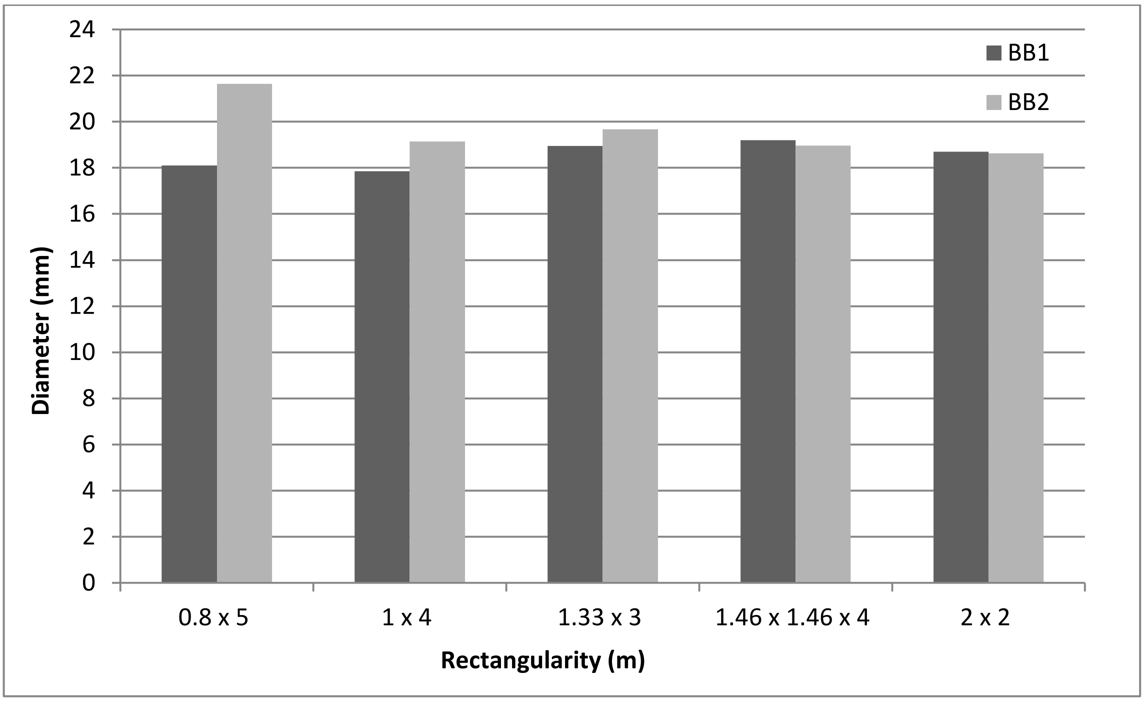

Figure 16: Average diameter of the biggest branch found in sector 1 and sector 2 on each final harvest candidate tree by effective competitive ratio. BB1 refers to the average biggest branch diameter per tree occurring in sector 1 on any of the three whorls measured. BB2 refers to the average biggest branch diameter per tree occurring in sector 2 on any of the three whorls measured.

Power of ANOVA Statistics

Power was calculated for each variable in all rectangularities (see Equation 3). It was found that for all ANOVA calculations in each rectangularity, power ranged from 40%-45% (Table 7). Power was highest in rectangularity 1.46 x 1.46 x 4 m and lowest in rectangularity 1.33 x 3 m, which had sample sizes of 64 and 58, respectively.

Table 7: Power Analysis for all ANOVA calculations (Appendix III) using data from replications 1 and 2.

Rectangularity	Power
0.8 x 5 m	42.1
1 x 4 m	42.1
1.33 x 3 m	40.7
1.46 x 1.46 x 4 m	44.9
2 x 2 m	42.1

3. DISCUSSION

Survival – Replication 3 had noticeably and significantly less survival than replications 1 and 2 (Table 1; Figure 6). Replication 3 was situated on a wetter site and had noticeably more moisture present when data was collected during August 2010. Visually, tree stems in replication 3 also had more browse damage compared to the other two replications. Upon visiting the sites during the winter of 2011, snow damage was noted across all replications, but it was more pronounced in replication 3. The moisture and increased browsing may have increased mortality and inhibited the growth of lodgepole pine in replication 3. Reduction of stand density resulting from mortality pre-disposed replication 3 for increased snow damage by enabling increased crown growth in surviving stems. Significantly higher amounts of mortality in replication 3 drastically changed both the rectangularity and density of the treatments. As a result of these circumstances replication 3 was excluded from analysis.

Diameter – Average tree diameters for final harvest candidates were correlated with total tree height and the diameter of the biggest branch on each tree. There is no significant difference for the average variation between two caliper diameter measurements on trees between or within rectangularities; that is, there was no elliptical nature of trees noted in more rectangular spacings. *Pinus contorta* maintains circular stem form when planted close to its neighbors at high competitive ratios. The diameter at breast height on final harvest candidate trees differed significantly between rectangularities (p-value = 0.017); this has an effect on individual stem volume as well as the marketability of wood. Surprisingly, rectangularity 0.8 x 5 m had the highest average diameter at breast height for final harvest candidate trees at 14.98 cm, followed by rectangularity 1.33 x 3 m at 14.51 cm (Appendix IV). By planting lodgepole pine at a density and rectangularity that results in larger stem diameters it would be possible to increase the merchantable timber, provided the total height is not significantly reduced as an effect of this rectangularity.

Total Heights – Total height of final harvest candidate trees was found to differ significantly (p-value = 0.0015) between rectangularities. This difference has a direct effect on the individual stem volume, as shorter heights result in lower individual tree volumes for the same DBH (see equation 2). When looking at the combined diameter and total height results for final harvest trees, rectangularities with higher effective competitive ratios have larger diameters and higher total heights. Results from this research combined with Liziniewicz and

Agestam *et al*. (2011) indicate that using planting densities between 2500 trees/ha and 5000 trees/ha at a high competitive ratio will increase total volumes per hectare.

Volume – Individual stem volume was calculated using an equation developed for lodgepole pine in Sweden (Stahl and Persson 1988). Rectangularities 0.8 x 5 m and 1.33 x 3 m produced the highest individual stem volumes among final harvest candidate trees. Using data collected by SLU on dominant trees in 2011 the same trends occur in volume, with rectangularities 0.8 x 5 m and 1.33 x 3 m having the highest volumes. The standing volumes per hectare for all trees surviving in 2011 since planting are currently low with values ranging from 144 m^3/ha to 185 m^3/ha (Table 4). Volumes of the final harvest candidate trees compared to volumes of dominant trees in 2011 were slightly higher in those rectangularities with high effective competitive ratios and slightly lower in those rectangularities with lower effective competitive ratios (Figure 10). Volumes were not projected into the future and although the current relationship between volumes and rectangularities is expected to hold over time, it is difficult to predict environmental and physical changes into the future.

Economics – Assessing the standing value of timber (stumpage value) in a forest stand is largely based on the diameters and quality of trees. At age 29 the highest volume was in rectangularity 0.8 x 5 m, while the lowest volume was in rectangularity 1.46 x 1.46 x 4 m (Table 4). Rectangularity 0.8 x 5 m had the highest average tree diameter which increases stumpage value at this rectangularity (Figure 7). Larger tree diameters increase the percentage of sawtimber in a stand and in turn increase the stumpage value because sawtimber is a higher value product than pulpwood. Thinnings will change stand structures, allowing for increased diameter, total height and volume growth. Lodgepole pine produces significantly more volume of the same quality than Scots pine over the same rotation time. Thus, it is expected that lodgepole pine will net more income over a rotation. Timber economics are a dynamic topic and are subject to market changes, timber stocking and availability, demand, and the overall state of global economic health. Due to these reasons the superiority of lodgepole pine over Scots pine may change over time.

Ratio –Effective competitive ratios were determined for all rectangularities, showing a decrease in all ratios between the time of planting and in 2010 when final harvest candidates were surveyed (Table 5). The effective competitive ratio created as a result of rectangularity spacings was believed to influence certain growth characteristics such as tree diameter growth, total height, individual stem volume, branching patterns and branch diameters. Even though the competitive ratio decreased over time because of mortality, similar relationships held between rectangularities. These competitive ratio differences between rectangularities did have an influence on multiple variables (see below) that are important to forest managers. Better understanding of the differences resulting from adjustment of rectangularity dimensions and thereby changing the competitive ratio will lead to better management.

Straightness – Straightness was not found to be significantly different between rectangularities, having a p-value of 0.08. These findings are also supported by previous research in which 23 year old *Pinus contorta* stands were studied in southern Sweden (Liziniewicz *et al*. 2011). There is no general trend in the average stem straightness rating as one moves from more tightly spaced rectangularities with high effective competitive ratios toward rectangularities with equal spacing and lower effective competitive ratios. Based on the results of this research, planting trees at different rectangularities but at the same density per hectare does not affect straightness. This research only looked at densities of 2500 trees/ha at five different rectangularities, including more densities and rectangularities may result in significant differences in straightness between treatments.

Live Crown Heights - The height at which living branches are found on a tree is important when considering wood quality. Lower living branches result in knots persisting lower on the stem, if these low living branches become large in diameter and are never removed by "self pruning" the overall quality class of a log can be reduced. Lodgepole pine is a naturally self-pruning tree but it is not as effective at self-pruning compared to Scots pine. Thus the effects of rectangularity and spacing on the height of living branches can be used as a management tool to accelerate self pruning and reduce the height at which living branches are found. ANOVA results show that the difference in crown height between sector 1 and sector 2 differs significantly between rectangularities. This is a result of rectangularities with high effective competitive ratios having much more open space in sector 2 which allows light to reach lower on the trees and for branches to survive longer. Lower heights to live crown are seen in rectangularities 0.8 x 5 m and 1.46 x 1.46 x 4 m.

Branches per Whorl – The total number of branches per whorl differed between rectangularities for only the first measured whorl immediately below breast height. Variation in individual branch competition for light is affected by planting competitive ratio and height of the branch in the canopy. When branches in lower whorls begin their growth the trees are young and the influence of neighboring trees is less pronounced. As the trees age the canopy quickly closes and competition for light increases. At a low competitive ratio competition for light is less for a longer period of time compared to rectangularities planted at a high ratio, resulting in differences related to branch occurrence. As the trees age, competition between neighbor's increases and the number of branches occurring per whorl becomes more similar between rectangularities.

Biggest Branches – Rectangularity 0.8 x 5 m was shown to have significantly larger branch diameters at the tree level when compared to other rectangularities (Figure 16). Liziniewicz and Agestam (2011) found that the biggest branch size at the tree level increased as spacings became more open and planting density decreased, and also that the biggest branch is positively correlated with tree DBH. As summarized in the results, it was found that the biggest branch diameter in sector 1 did not significantly differ between rectangularities, while within sector 2 the branch diameter differed significantly between rectangularities. This shows that the diameter of a branch in a competitive sector is affected by the rectangularity at which the trees are planted. High densities and evenly planted rectangularities reduce branch diameters. The presence of significantly large branch diameters occurs when the spacing between rows is greater than 3 m at a planting density of 2500 trees/ha. To reduce negative influence on quality, planting at rectangularities which result in a between row spacing equal to or less than 3 m should be used.

Branch Angles – Angles of branches are another factor that has an influence on wood quality; they are directly correlated with the knot size in the tree. Steeper branch angles create larger knots and therefore reduce the quality. On the tree and sector levels biggest branch angles did not differ significantly between rectangularities (Appendix III). Since branch angles did not differ significantly between rectangularities at a planting density of 2500 trees/ha, they do not have a significant effect on the wood quality. However, there was a tendency for branch angles in sector 1 to become smaller as rectangularities approached lower effective competitive ratios (Appendix IV).

Tip Growth and Living Branches – It was found that branches in whorl one have a significantly different tendency to grow out from sector 1 (within row) and into sector 2 (between row) between rectangularities. Rectangularity 1 x 4 m had a higher tendency for its' branches to grow from sector 1 and into sector 2 compared to rectangularities 0.8 x 5 m, 1.46 x 1.46 x 4 m, and 2 x 2 m (Appendix V). The tendency of branches to grow out from sector 1 and into sector 2 is more pronounced at tighter rectangularities and in the lower whorls. As the trees grow and light is intercepted by higher branches, lower branches grow toward the available light between the rows. This is not expected to have any effect on the angle of the knot in the tree, but if the branch survives longer it will grow to a larger diameter and have a greater negative impact on wood quality. Tree branches grow toward openings and quickly fill all available space in the canopy which reduces any branching pattern differences resulting from varied rectangularity dimensions at a density of 2500 trees/ha. There were no significant findings when the percentage occurrence and sector location of living branches were compared between rectangularities.

Quality – Stem quality and straightness ratings were positively correlated with each other having a p-value <0.0001 in all rectangularities (Appendix II). An ANONA supports the null hypothesis that there is no significant difference in stem quality between rectangularities, with a p-value of 0.81 (Appendix III). The stem quality rating is subjective and human error or inconsistency could have influenced the findings. Persson (1973) found that branch diameter was correlated with tree stem quality. Findings in this study show that the average diameter of the biggest branch in sector 2 (between row sector), but not in sector 1 (within row sector), differ significantly between rectangularities. The largest branch per tree occurring in either sector among all whorls was not found to differ significantly between replications. Combination of these findings imply that on the sector level stem quality is different between rectangularities because rectangularity is correlated with branch diameter in sector 2, which is in turn correlated with quality. On the tree level findings in this research support that quality does not differ between rectangularities, as the average diameter of the largest branch on each tree does not differ significantly between rectangularities. These findings differ from those of Liziniewicz, Eko, and Agestam (2011) where quality differences were found between different spacings. In this research, tree density was held constant at 2500 trees/ha and this may account for different findings.

Optimum Planting Rectangularity – All rectangularities were planted at a density of 2,500 trees/ha, only the rectangularity dimensions at which the trees were planted varied between treatments. Choosing the ideal rectangularity at which to plant lodgepole pine is dependent on the desired timber product. If the timber is going to be used for pulpwood where quality is of less importance, then it is prudent to plant lodgepole pine at rectangularities with higher competitive ratios which result in significantly more volume production per hectare. Rectangularity 1.33 x 3 m is second to rectangularity 0.8 x 5 m in final harvest candidate individual tree volume (Table 3) and total volume per hectare (Table 4). Rectangularity 1.33 x 3 m was found to have a significantly higher height to live crown compared to rectangularity 0.8 x 5 (Appendix V), and was visually assessed as having the highest quality of all rectangularities. The higher height to live crown in rectangularity 1.33 x 3 m results in fewer persisting branches and their resulting knots lower on the tree stem. Rectangularity 1.33 x 3 m displayed a low (good) straightness rating, which is crucial when evaluating log quality. To achieve high quality, economy and high volume production, planting at a rectangularity with a spacing of 1.33 x 3 m is recommended based off this research.

Quality is largely determined by tree diameters, heights, straightness, deformities, branch diameters, branch angles and height to live crown. In order to plant lodgepole pine in the most ideal rectangularity the first thing to determine is the goal or end product for the timber. Once this is determined, results in each of these categories (quality and volume) need to be considered in terms of importance pertaining to the goal, and from this the most appropriate rectangularity can be chosen.

Site Variation – Other site factors may have influenced findings between rectangularities. These factors include soil characteristics, moisture regime, orientation, elevation, increased browsing, wind throw and snow damage. In previous studies it was shown that row orientation did not have a significant effect on basal area or dominant height in 20 year old Loblolly pine (*Pinus taeda*) plantations (Amateis *et al*. 2009). This supports the theory that row orientation does not have an effect on tree level variables, though *Pinus contorta* may respond differently than *Pinus taeda* to differences in row orientation. It should be noted that the study above referencing *Pinus taeda* was at lower geographic latitude and the angle of the sun does not vary as much at these sites compared to the site in Sweden where the *Pinus contorta* study was located. Differences in latitude play a large role in exposure to sunlight throughout the year; this may alter results related to the effects of row orientation. Amateis (2009) did not investigate sector level branch characteristics which may be influenced by row orientation. Replications 1 and 2 in this research were adjacent to each other and at the same elevation, soil characteristics and hydrology did not differ between them and had no major effect on values found between replications. There was no noticeable difference in moisture between replications 1 and 2. Although, they were surveyed during the summer and differences in moisture regimes may be more pronounced during the wettest months of the year. Snow and wind were expected to be the same at both replications.

Power - Eliminating data from the third replication reduced the sample size and the number of groups in calculations, which in turn reduces statistical power of tests. Thomas (1997) states that the calculation used to estimate power is redundant with statistical significance and leads to uninformative results with widely varying confidence intervals. Formulas used to calculate power and statistical significance both use the observed sample size but in an inverse manner, leading to results displaying high p-values also having low power statistic values (Thomas 1997). Power results are weak in this research and in order to improve them the sample size needs to be increased in future studies or the variance reduced.

Future Research – Future recommended research should include stand thinnings in order to promote quality and volume growth. Different thinning regimes should be implemented so that the effects of each can be studied over time. Recent snow events have damaged many trees in the stands as seen on a field visit during February of 2011. An assessment of the susceptibility to snow damage is recommended to determine between which planting rectangularities there is a difference in resistance to snow break, if any.

4. CONCLUSIONS

Planting rectangularity significantly affected the total height, tree diameter, branch diameter, height to live crown, basal area and individual tree volume of lodgepole pine (*Pinus contorta*) trees when planted at 2500 trees/ha. The difference in the circularity of trees was not found to differ significantly between or within rectangularities. Total heights, diameters, individual tree volumes and live crown heights all increase for final harvest candidate trees as rectangularities become more tightly spaced within rows and more widely spaced between rows. There were no significant differences among rectangularities for quality, straightness, or branch diameter at an α - level of 0.05. Branch angles did not differ significantly among rectangularities, so there was no noted effect on wood quality. Diameters of biggest branches differ significantly among rectangularities along with the competitive sector in which they occur. Rectangularity 0.8 x 5 m is recommended for planting because it produced the highest volume while maintaining desirable wood characteristics. Although rectangularity 0.8 x 5 m had a larger average branch size of 3 mm, this has no effect on merchandizing. Differences were found between rectangularity 0.8 x 5 m and various other rectangularities pertaining to volume, height to live crown and branch characteristics, but these variances in mean values were not large enough to result in differences for potential uses of timber.

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APPENDICES

Appendix I: Stem survival at various times during the study period across all rectangularities and repetitions.

Rep	Rectangularity (m)	Planted Trees	Surviving (Age = 22)	Surviving (Age = 29)	Dead (%)
1	.8x5	150	131	130	13.33
1	1x4	150	124	125	16.67
1	1.33x3	144	113	114	20.83
1	1.46x1.46x4	160	124	131	18.13
1	2x2	150	118	126	16.00
2	.8x5	150	129	129	14.00
2	1x4	150	122	123	18.00
2	1.33x3	144	115	118	18.06
2	1.46x1.46x4	160	114	114	28.75
2	2x2	150	97	101	32.67
3	.8x5	150	84	81	46.00
3	1x4	150	83	85	43.33
3	1.33x3	144	77	78	45.83
3	1.46x1.46x4	160	86	83	48.13
3	2x2	150	96	100	33.33
1	all	754	610	626	16.99
2	all	754	577	585	22.29
3	all	754	426	427	43.33
all	.8x5	450	344	340	24.44
all	1x4	450	329	333	26.00
all	1.33x3	432	305	310	28.24
all	1.46x1.46x4	480	324	328	31.67
all	2x2	450	311	327	27.33

Appendix II: Pearson Correlation results for all major variables.

Rectangularity 0.8 x 5 m (n=60)									
	Straight	Quality	DBH Average	Total Height	Whorl Distance	Branch Diameter	Branch Angle	Live Crown	Total Branches
Straight	1.00	-	-	-	-	-	-	-	-
p-value	-	-	-	-	-	-	-	-	-
Quality	0.52	1.00	-	-	-	-	-	-	-
p-value	<.0001	-	-	-	-	-	-	-	-
DBH	-0.03	0.15	1.00	-	-	-	-	-	-
p-value	0.82	0.25	-	-	-	-	-	-	-
Total Height	0.14	-0.02	0.45	1.00	-	-	-	-	-
p-value	0.27	0.88	<.0001	-	-	-	-	-	-
Whorl Dist.	-0.25	-0.35	-0.24	-0.03	1.00	-	-	-	-
p-value	0.05	0.01	0.07	0.80	-	-	-	-	-
Branch Diam.	-0.05	0.15	0.64	0.31	-0.24	1.00	-	-	-
p-value	0.70	0.25	<.0001	0.02	0.07	-	-	-	-
Branch Angle	0.06	-0.09	0.41	0.26	0.09	0.43	1.00	-	-
p-value	0.62	0.49	<.0001	0.05	0.50	<.0001	-	-	-
Live Crown	0.39	0.04	-0.27	0.20	0.05	-0.32	-0.12	1.00	-
p-value	<.0001	0.79	0.04	0.12	0.72	0.01	0.37	-	-
# of Branches	-0.07	0.16	0.57	0.26	-0.25	0.61	0.20	-0.23	1.00
p-value	0.59	0.22	<.0001	0.05	0.05	<.0001	0.13	0.08	-
Volume	-0.02	0.10	0.97	0.64	-0.21	0.62	0.42	-0.19	0.55
p-value	0.91	0.44	<.0001	<.0001	0.11	<.0001	<.0001	0.15	<.0001

Rectangularity 1 x 4 m (n=60)									
	Straight	Quality	DBH Average	Total Height	Whorl Distance	Branch Diameter	Branch Angle	Live Crown	Total Branches
Straight	1.00	-	-	-	-	-	-	-	-
p-value	-	-	-	-	-	-	-	-	-
Quality	0.51	1.00	-	-	-	-	-	-	-
p-value	<.0001	-	-	-	-	-	-	-	-
DBH	-0.18	0.11	1.00	-	-	-	-	-	-
p-value	0.16	0.40	-	-	-	-	-	-	-
Total Height	-0.21	-0.04	0.65	1.00	-	-	-	-	-
p-value	0.11	0.74	<.0001	-	-	-	-	-	-
Whorl Dist.	0.09	0.13	<.0001	-0.19	1.00	-	-	-	-
p-value	0.47	0.31	0.98	0.14	-	-	-	-	-
Branch Diam.	-0.06	0.10	0.70	0.53	0.09	1.00	-	-	-
p-value	0.63	0.45	<.0001	<.0001	0.52	-	-	-	-
Branch Angle	-0.12	-0.11	0.26	0.34	0.02	0.52	1.00	-	-
p-value	0.37	0.41	0.04	0.01	0.91	<.0001	-	-	-
Live Crown	-0.06	0.03	-0.25	0.05	-0.03	-0.21	0.13	1.00	-
p-value	0.65	0.83	0.05	0.68	0.84	0.11	0.34	-	-
# of Branches	-0.09	0.08	0.61	0.30	-0.04	0.56	0.27	-0.35	1.00
p-value	0.50	0.55	<.0001	0.02	0.76	<.0001	0.04	0.01	-
Volume	-0.22	0.06	0.96	0.80	-0.04	0.73	0.33	-0.20	0.56
p-value	0.09	0.62	<.0001	<.0001	0.74	<.0001	0.01	0.12	<.0001

Rectangularity 1.33 x 3 m (n=58)									
	Straight	**Quality**	**DBH Average**	**Total Height**	**Whorl Distance**	**Branch Diameter**	**Branch Angle**	**Live Crown**	**Total Branches**
Straight	1.00	-	-	-	-	-	-	-	-
p-value	-	-	-	-	-	-	-	-	-
Quality	0.59	1.00	-	-	-	-	-	-	-
p-value	<.0001	-	-	-	-	-	-	-	-
DBH	0.04	0.09	1.00	-	-	-	-	-	-
p-value	0.74	0.50	-	-	-	-	-	-	-
Total Height	0.01	0.08	0.59	1.00	-	-	-	-	-
p-value	0.94	0.55	<.0001	-	-	-	-	-	-
Whorl Dist.	0.23	0.31	0.16	0.05	1.00	-	-	-	-
p-value	0.08	0.02	0.22	0.71	-	-	-	-	-
Branch Diam.	0.14	0.17	0.60	0.35	0.43	1.00	-	-	-
p-value	0.28	0.20	<.0001	0.01	<.0001	-	-	-	-
Branch Angle	-0.20	-0.11	-0.07	0.06	0.07	0.41	1.00	-	-
p-value	0.14	0.41	0.62	0.64	0.58	<.0001	-	-	-
Live Crown	-0.19	0.05	-0.03	0.21	-0.15	-0.28	-0.06	1.00	-
p-value	0.16	0.69	0.83	0.11	0.25	0.04	0.64	-	-
# of Branches	0.15	0.14	0.26	0.25	0.20	0.46	0.19	-0.23	1.00
p-value	0.25	0.30	0.04	0.06	0.13	<.0001	0.15	0.08	-
Volume	0.04	0.11	0.98	0.70	0.17	0.60	-0.05	0.03	0.31
p-value	0.75	0.42	<.0001	<.0001	0.21	<.0001	0.70	0.83	0.02

Rectangularity 1.46 x 1.46 x 4 m (n=64)									
	Straight	**Quality**	**DBH Average**	**Total Height**	**Whorl Distance**	**Branch Diameter**	**Branch Angle**	**Live Crown**	**Total Branches**
Straight	1.00	-	-	-	-	-	-	-	-
p-value	-	-	-	-	-	-	-	-	-
Quality	0.76	1.00	-	-	-	-	-	-	-
p-value	<.0001	-	-	-	-	-	-	-	-
DBH	0.16	0.19	1.00	-	-	-	-	-	-
p-value	0.21	0.13	-	-	-	-	-	-	-
Total Height	0.07	0.12	0.63	1.00	-	-	-	-	-
p-value	0.59	0.36	<.0001	-	-	-	-	-	-
Whorl Dist.	0.58	0.46	0.18	0.20	1.00	-	-	-	-
p-value	<.0001	<.0001	0.16	0.11	-	-	-	-	-
Branch Diam.	0.06	0.02	0.59	0.26	0.14	1.00	-	-	-
p-value	0.61	0.88	<.0001	0.04	0.25	-	-	-	-
Branch Angle	0.07	0.01	0.26	0.10	0.11	0.63	1.00	-	-
p-value	0.60	0.92	0.04	0.45	0.38	<.0001	-	-	-
Live Crown	0.13	0.17	0.22	0.46	-0.10	-0.11	-0.16	1.00	-
p-value	0.31	0.18	0.08	<.0001	0.41	0.38	0.20	-	-
# of Branches	0.18	0.14	0.40	0.21	0.16	0.51	0.32	0.06	1.00
p-value	0.16	0.26	<.0001	0.10	0.20	<.0001	0.01	0.65	-
Volume	0.14	0.18	0.97	0.76	0.19	0.57	0.28	0.32	0.36
p-value	0.27	0.16	<.0001	<.0001	0.13	<.0001	0.03	0.01	<.0001

Rectangularity 2 x 2 m (n=60)

	Straight	Quality	DBH Average	Total Height	Whorl Distance	Branch Diameter	Branch Angle	Live Crown	Total Branches
Straight	1.00	-	-	-	-	-	-	-	-
p-value	-	-	-	-	-	-	-	-	-
Quality	0.72	1.00	-		-	-	-	-	-
p-value	<.0001	-	-	-	-	-	-	-	-
DBH	-0.26	-0.21	1.00	-	-	-	-	-	-
p-value	0.05	0.11	-	-	-	-	-	-	-
Total Height	-0.14	-0.14	0.58	1.00	-	-	-	-	-
p-value	0.28	0.27	<.0001	-	-	-	-	-	-
Whorl Dist.	-0.19	-0.26	<.0001	0.05	1.00	-	-	-	-
p-value	0.15	0.05	0.99	0.69	-	-	-	-	-
Branch Diam.	-0.07	-0.01	0.53	0.32	-0.05	1.00	-	-	-
p-value	0.57	0.95	<.0001	0.01	0.70	-	-	-	-
Branch Angle	<.0001	0.04	-0.04	0.19	0.01	0.52	1.00	-	-
p-value	1.00	0.73	0.78	0.15	0.92	<.0001	-	-	-
Live Crown	0.10	0.23	<.0001	0.48	0.12	0.03	0.27	1.00	-
p-value	0.45	0.07	0.98	<.0001	0.37	0.79	0.03	-	-
# of Branches	-0.15	0.05	0.50	0.37	0.13	0.37	0.13	0.18	1.00
p-value	0.24	0.72	<.0001	<.0001	0.31	<.0001	0.34	0.18	-
Volume	-0.25	-0.21	0.97	0.76	0.01	0.52	0.04	0.12	0.49
p-value	0.05	0.11	<.0001	<.0001	0.94	<.0001	0.74	0.37	<.0001

Appendix III: ANOVA results between rectangularities using proc GLM in SAS 9.2 for various dependent variables.

Dependent Variable: Straightness

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Model	5	14.36	2.87	6.79	<.0001
Error	296	125.17	0.42		
Corrected Total	301	139.47			

R-Square	CV	Root MSE	Mean
0.103	29.61	0.65	2.20

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Replication	1	10.76	10.76	25.45	<.0001
Rectangularity	4	3.60	0.90	2.13	0.077

Dependent Variable: Quality

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Model	5	8.29	1.66	2.08	0.0673
Error	296	235.57	0.80		
Corrected Total	301	243.87			

R-Square	CV	Root MSE	Mean
0.034	32.38	0.89	2.75

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Replication	1	7.01	7.01	8.80	0.0033
Rectangularity	4	1.29	0.32	0.40	0.81

Dependent Variable: DBH 2

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Model	5	112.16	22.43	4.95	0.0002
Error	296	1341.65	4.53		
Corrected Total	301	1453.81			

R-Square	CV	Root MSE	Mean (cm)
0.077	14.79	2.13	14.40

Source	DF	Type I SS	Mean Square	F Value	Pr > F

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Replication	1	56.22	56.22	12.40	0.0005
Rectangularity	4	55.94	13.99	3.09	0.016

Dependent Variable: Average Tree DBH

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Model	5	122.41	24.48	5.47	<.0001
Error	296	1325.89	4.479		
Corrected Total	301	1448.30			

R-Square	CV	Root MSE	Mean (cm)
0.085	14.81	2.12	14.29

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Replication	1	74.06	74.06	16.53	<.0001
Rectangularity	4	48.35	12.09	2.70	0.031

Dependent Variable: Difference between DBH 1 and DBH 2

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Model	5	6.92	1.39	5.65	<.0001
Error	296	72.54	0.25		
Corrected Total	301	79.47			

R-Square	Coeff Var	Root MSE	Mean
0.087	-244.69	0.49	-0.20

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Replication	1	4.91	4.91	20.03	<.0001
Rectangularity	4	2.02	0.50	2.06	0.087

Dependent Variable: Total Height

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Model	5	55.91	11.182	14.65	<.0001
Error	296	225.89	0.76		
Corrected Total	301	281.81			

R-Square	CV	Root MSE	Mean (m)
0.198	8.36	0.87	10.44

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Replication	1	42.13	42.13	55.21	<.0001
Rectangularity	4	13.78	3.45	4.51	0.0015

Dependent Variable: Tip Growth Whorl 1, Sector 1

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Model	5	2.43	0.49	3.15	0.0087
Error	296	45.74	0.16		
Corrected Total	301	48.17			

R-Square	CV	Root MSE	Mean
0.051	35.33	0.39	1.11

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Replication	1	0.12	0.12	0.77	0.3805
Rectangularity	4	2.31	0.58	3.74	0.0055

Dependent Variable: Total Branches Whorl 1

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Model	5	42.56	8.51	5.17	0.0001
Error	296	487.63	1.65		
Corrected Total	301	530.19			

R-Square	CV	Root MSE	Mean
0.080	34.46	1.28	3.73

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Replication	1	21.73	21.73	13.19	0.0003
Rectangularity	4	20.83	5.21	3.16	0.0145

Dependent Variable: Branch Diameter Whorl 2, Sector 2

Source	DF	Type III SS	Mean Square	F Value	Pr > F

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Model	5	1031.91	206.38	5.42	<.0001
Error	296	11263.32	38.052		
Corrected Total	301	12295.23			

R-Square	CV	Root MSE	Mean (mm)
0.084	31.59	6.17	19.53

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Replication	1	602.30	602.30	15.83	<.0001
Rectangularity	4	429.61	107.40	2.82	0.0253

Dependent Variable: Branch Diameter Whorl 3, Sector 2

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Model	5	945.88	189.18	3.59	0.0036
Error	296	15610.14	52.74		
Corrected Total	301	16556.02			

R-Square	CV	Root MSE	Mean (mm)
0.057	34.20	7.26	21.24

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Replication	1	397.01	397.01	7.53	0.0064
Rectangularity	4	548.88	137.222	2.60	0.0362

Dependent Variable: Distance Between Whorls 1 - 3

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Model	5	6603.14	1320.63	3.47	0.0046
Error	296	112567.70	380.30		
Corrected Total	301	119170.84			

R-Square	CV	Root MSE	Mean (cm)
0.055	26.13	19.50	74.63

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Replication	1	5992.92	5992.92	15.76	<.0001
Rectangularity	4	610.22	152.56	0.40	0.8078

Dependent Variable: Height to Live Crown, Sector 1

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Model	5	14.16	2.83	5.72	<.0001
Error	296	146.48	0.50		
Corrected Total	301	160.64			

R-Square	CV	Root MSE	Mean (m)
0.088	18.46	0.70	3.81

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Replication	1	9.34	9.34	18.87	<.0001
Rectangularity	4	4.83	1.21	2.44	0.0472

Dependent Variable: Height to Live Crown, Sector 2

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Model	5	20.66	4.13	9.43	<.0001
Error	296	129.77	0.44		
Corrected Total	301	150.43			

R-Square	CV	Root MSE	Mean (m)
0.137	18.42	0.66	3.59

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Replication	1	7.95	7.95	18.13	<.0001
Rectangularity	4	12.71	3.18	7.25	<.0001

Dependent Variable: Difference Between Height to Live Crown in Sector 2 and Sector 1

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Model	5	4.77	0.95	6.36	<.0001
Error	296	44.44	0.15		
Corrected Total	301	49.21			

R-Square	CV	Root MSE	Mean
0.097	112.40	0.39	0.35

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Replication	1	0.10	0.10	0.67	0.4147
Rectangularity	4	4.67	1.168	7.78	<.0001

Dependent Variable: Biggest Branch

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Model	5	943.45	188.70	3.89	0.0020
Error	296	14368.92	48.54		
Corrected Total	301	15312.42			

R-Square	CV	Root MSE	Mean (mm)
0.062	28.22	6.97	24.69

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Replication	1	605.63	605.63	12.48	0.0005
Rectangularity	4	337.86	84.47	1.74	0.1411

Dependent Variable: Biggest Branch Sector 2

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Model	5	837.01	167.40	6.25	<.0001
Error	296	7924.16	26.77		
Corrected Total	301	8761.17			

R-Square	CV	Root MSE	Mean (mm)
0.096	26.40	5.17	19.60

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Replication	1	490.19	490.19	18.31	<.0001
Rectangularity	4	346.82	86.70	3.24	0.0127

Dependent Variable: Difference in Biggest Branch Diameter between Sector 2 and Sector 1

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Model	5	144.85	28.97	5.51	<.0001
Error	296	1556.18	5.26		
Corrected Total	301	1701.03			

R-Square	CV	Root MSE	Mean (mm)
0.085155	88.16	2.29	2.60

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Replication	1	10.38	10.38	1.97	0.1610
Rectangularity	4	134.47	33.62	6.39	<.0001

Dependent Variable: Angle of Biggest Branch per Tree

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Model	5	2670.00	534.00	4.38	0.0007
Error	296	36075.40	121.88		
Corrected Total	301	38745.40			

R-Square	CV	Root MSE	Mean (°)
0.069	10.23	11.04	107.91

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Replication	1	2587.60	2587.60	21.23	<.0001
Rectangularity	4	82.40	20.60	0.17	0.9541

Dependent Variable: Sector of Biggest Branch Occurrence

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Model	5	3.10	0.62	2.71	0.0207
Error	296	67.86	0.23		
Corrected Total	301	70.97			

R-Square	CV	Root MSE	Mean
0.044	29.51	0.48	1.62

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Replication	1	0.33	0.33	1.44	0.2304
Rectangularity	4	2.77	0.69	3.02	0.0182

Dependent Variable: Height to Live Crown

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Model	5	14.90	2.98	7.18	<.0001
Error	296	122.87	0.42		
Corrected Total	301	137.77			

R-Square	CV	Root MSE	Mean (m)
0.108	17.40	0.64	3.70

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Replication	1	8.638	8.63	20.79	<.0001
Rectangularity	4	6.27	1.57	3.77	0.0052

Dependent Variable: Total Number of Branches

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Model	5	255.78	51.16	5.59	<.0001
Error	296	2710.21	9.17		
Corrected Total	301	2965.99			

R-Square	CV	Root MSE	Mean
0.086	25.20	3.026	12.01

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Replication	1	190.73	190.73	20.83	<.0001
Rectangularity	4	65.05	16.26	1.78	0.1336

Dependent Variable: Tip Growth into Sector 2

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Model	5	0.44	0.09	2.54	0.0288
Error	296	10.29	0.03		
Corrected Total	301	10.73			

R-Square	CV	Root MSE	Mean
0.041	9.86	0.19	1.89

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Replication	1	0.11	0.11	3.06	0.0813
Rectangularity	4	0.33	0.08	2.41	0.0497

Dependent Variable: Basal Area of Final Harvest Candidates

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Model	5	<.0001	<.0001	5.81	<.0001
Error	296	<.0001	<.0001		
Corrected Total	301	<.0001			

R-Square	CV	Root MSE	Mean (m^2)
0.089	29.55	<.0001	0.016

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Replication	1	<.0001	<.0001	16.75	<.0001
Rectangularity	4	<.0001	<.0001	3.08	0.0166

Dependent Variable: Individual Tree Volume

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Model	5	34980.48	6996.10	8.45	<.0001
Error	296	245209.73	828.41		
Corrected Total	301	280190.21			

R-Square	CV	Root MSE	Mean (dm^3
0.125	31.028	28.78	92.76

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Replication	1	23803.37	23803.37	28.73	<.0001
Rectangularity	4	11177.11	2794.28	3.37	0.0102

Appendix IV: Summary of all variables for all rectangularities using the data from replications 1 and 2.

Rectangularity 0.8x5m (N=60)				
Variable	**MIN**	**MAX**	**MEAN**	**STD**
Quality	1.0	5.0	2.83	0.91
Straight	1.0	3.0	2.08	0.65
DBH 1 (cm)	9.6	21.2	14.80	2.49
DBH 2 (cm)	10.4	21.7	15.16	2.55
Delta DBH (cm)	-1.6	1.3	-0.4	0.6
DBH average (cm)	10.0	21.5	14.98	2.50
Total Height (m)	8.0	13.2	10.64	1.02
Branch Diameter, Whorl 1,Sector 1 (cm)	7.5	42.7	16.26	6.30
Branch Angle Whorl 1, Sector 1 (°)	80.0	139.0	97.85	10.38
Alive in Whorl 1, Sector 2	0.0	0.0	0.00	0.00
Tip Growth, Whorl 1, Sector 1	0.0	2.0	1.05	0.43
Branch Diameter, Whorl 1,Sector 2 (cm)	8.9	39.5	19.46	6.19
Branch Angle Whorl 1, Sector 2 (°)	75.0	133.0	97.55	11.69
Alive in Whorl 1, Sector 2	0.0	0.0	0.00	0.00
Tip Growth, Whorl 1, Sector 2	1.0	2.0	1.88	0.32
Total Branches Whorl 1	1.0	6.0	3.35	1.25
Branch Diameter, Whorl 2,Sector 1 (cm)	7.8	34.0	18.15	5.63
Branch Angle Whorl 2, Sector 1 (°)	80.0	123.0	101.23	9.18
Alive in Whorl 1, Sector 1	0.0	0.0	0.00	0.00
Tip Growth, Whorl 2, Sector 1	0.0	2.0	1.22	0.52
Branch Diameter, Whorl 2,Sector 2 (cm)	6.7	39.7	21.76	7.56
Branch Angle Whorl 2, Sector 2 (°)	83.0	125.0	101.43	9.75
Alive in Whorl 2, Sector 2	0.0	0.0	0.00	0.00
Tip Growth, Whorl 2, Sector 2	1.0	2.0	1.95	0.22
Total Branches Whorl 2	0.0	7.0	3.98	1.43
Branch Diameter, Whorl 3,Sector 1 (cm)	7.3	36.0	19.89	6.35
Ang31 (°)	88.0	127.0	104.83	10.28
Alive in Whorl 3, Sector 1	0.0	0.0	0.00	0.00
Tip Growth, Whorl 3, Sector 1	0.0	2.0	1.18	0.43
Branch Diameter, Whorl 3,Sector 2 (cm)	9.0	60.3	23.72	9.85
Ang32 (°)	76.0	142.0	105.45	11.85
Alive in Whorl 3, Sector 2	0.0	1.0	0.02	0.13
Tip Growth, Whorl 3, Sector 2	1.0	2.0	1.92	0.28
Total Branches Whorl 3	1.0	8.0	4.17	1.50
Whorl Distance (cm)	44.5	120.7	76.70	16.43
Height to Live Crown Sector 1 (m)	1.8	5.4	3.81	0.72
Height to Live Crown Sector 2 (m)	1.8	4.8	3.30	0.77
Biggest Branch (cm)	12.4	60.3	26.69	8.93
Biggest Branch Sector 1 (cm)	8.8	34.5	18.10	4.93
Biggest Branch Sector 2 (cm)	10.5	41.6	21.65	6.74
Biggest Branch Angle (°)	83.0	127.0	107.23	10.49
Biggest Branch Occurrence	1.0	2.0	1.78	0.42
Height to Live Crown (m)	1.8	4.9	3.56	0.68
Total Branches	4.0	17.0	11.50	3.12
Biggest Branch Angle, Sector 1 (°)	84.0	119.0	101.31	7.75
Biggest Branch Angle, Sector 2 (°)	81.7	122.3	101.48	9.42
Tip Growth out of Sector 1	0.7	2.0	1.15	0.28
Tip Growth out of Sector 2	1.3	2.0	1.92	0.17
Volume (dm^3)	43.8	195.2	102.77	34.96
Stumpage (SEK/ha)	0	94.66	40.82	23.39

Rectangularity 1x4m (N=60)				
Variable	**MIN**	**MAX**	**MEAN**	**STD**
Quality	1.0	4.0	2.78	0.87
Straight	1.0	3.0	2.35	0.63
DBH 1 (cm)	8.0	18.2	13.80	2.04
DBH 2 (cm)	8.4	17.3	14.00	1.96
Delta DBH (cm)	-1.3	1.2	-0.2	0.5
DBH average (cm)	8.2	17.6	13.90	1.98
Total Height (m)	8.1	13.1	10.59	0.96
Branch Diameter, Whorl 1,Sector 1 (cm)	7.6	35.6	16.32	5.82
Branch Angle Whorl 1, Sector 1 (°)	80.0	125.0	97.20	9.88
Alive in Whorl 1, Sector 2	0.0	0.0	0.00	0.00
Tip Growth, Whorl 1, Sector 1	1.0	2.0	1.27	0.45
Branch Diameter, Whorl 1,Sector 2 (cm)	7.1	30.4	17.63	5.14
Branch Angle Whorl 1, Sector 2 (°)	70.0	116.0	96.35	9.61
Alive in Whorl 1, Sector 2	0.0	0.0	0.00	0.00
Tip Growth, Whorl 1, Sector 2	1.0	2.0	1.93	0.25
Total Branches Whorl 1	0.0	7.0	3.55	1.35
Branch Diameter, Whorl 2,Sector 1 (cm)	7.4	61.7	18.57	7.81
Branch Angle Whorl 2, Sector 1 (°)	79.0	153.0	102.68	12.40
Alive in Whorl 1, Sector 1	0.0	0.0	0.00	0.00
Tip Growth, Whorl 2, Sector 1	0.0	2.0	1.12	0.52
Branch Diameter, Whorl 2,Sector 2 (cm)	6.4	33.5	18.90	6.34
Branch Angle Whorl 2, Sector 2 (°)	77.0	123.0	100.95	10.03
Alive in Whorl 2, Sector 2	0.0	0.0	0.00	0.00
Tip Growth, Whorl 2, Sector 2	0.0	2.0	1.97	0.26
Total Branches Whorl 2	0.0	7.0	3.98	1.62
Branch Diameter, Whorl 3,Sector 1 (cm)	9.1	36.4	18.68	6.56
Ang31 (°)	89.0	138.0	106.55	10.72
Alive in Whorl 3, Sector 1	0.0	1.0	0.02	0.13
Tip Growth, Whorl 3, Sector 1	0.0	2.0	1.22	0.45
Branch Diameter, Whorl 3,Sector 2 (cm)	2.6	40.1	20.89	7.43
Ang32 (°)	83.0	129.0	106.13	10.18
Alive in Whorl 3, Sector 2	0.0	1.0	0.02	0.13
Tip Growth, Whorl 3, Sector 2	1.0	2.0	1.88	0.32
Total Branches Whorl 3	1.0	7.0	4.05	1.53
Whorl Distance (cm)	40.6	142.9	75.49	21.89
Height to Live Crown Sector 1 (m)	2.4	5.2	3.96	0.68
Height to Live Crown Sector 2 (m)	1.8	4.9	3.71	0.65
Biggest Branch (cm)	13.8	61.7	24.18	7.96
Biggest Branch Sector 1 (cm)	8.6	38.3	17.86	5.74
Biggest Branch Sector 2 (cm)	9.3	31.1	19.14	5.40
Biggest Branch Angle (°)	79.0	153.0	107.98	11.80
Biggest Branch Occurrence	1.0	2.0	1.68	0.47
Height to Live Crown (m)	2.1	5.0	3.83	0.61
Total Branches	2.0	18.0	11.58	3.40
Biggest Branch Angle, Sector 1 (°)	83.7	134.7	102.14	9.33
Biggest Branch Angle, Sector 2 (°)	77.7	119.0	101.14	8.47
Tip Growth out of Sector 1	0.3	1.7	1.20	0.29
Tip Growth out of Sector 2	1.3	2.0	1.93	0.16
Volume (dm^3)	28.3	158.0	89.30	27.42
Stumpage (SEK/ha)	0	71.8	34.23	16.94

Rectangularity 1.3x3m (N=58)				
Variable	**MIN**	**MAX**	**MEAN**	**STD**
Quality	1.0	4.0	2.66	0.83
Straight	1.0	3.0	2.16	0.72
DBH 1 (cm)	10.2	20.9	14.45	2.38
DBH 2 (cm)	10.3	20.0	14.58	2.32
Delta DBH (cm)	-1.2	0.9	-0.1	0.5
DBH average (cm)	10.4	20.5	14.51	2.33
Total Height (m)	8.5	12.3	10.64	0.83
Branch Diameter, Whorl 1,Sector 1 (cm)	7.0	35.7	17.77	5.59
Branch Angle Whorl 1, Sector 1 (°)	76.0	130.0	96.74	11.06
Alive in Whorl 1, Sector 2	0.0	0.0	0.00	0.00
Tip Growth, Whorl 1, Sector 1	0.0	2.0	1.16	0.41
Branch Diameter, Whorl 1,Sector 2 (cm)	7.5	32.8	17.92	5.32
Branch Angle Whorl 1, Sector 2 (°)	73.0	119.0	95.59	8.95
Alive in Whorl 1, Sector 2	0.0	0.0	0.00	0.00
Tip Growth, Whorl 1, Sector 2	1.0	2.0	1.88	0.33
Total Branches Whorl 1	0.0	8.0	4.14	1.46
Branch Diameter, Whorl 2,Sector 1 (cm)	9.6	33.6	18.29	5.33
Branch Angle Whorl 2, Sector 1 (°)	80.0	124.0	99.62	9.93
Alive in Whorl 1, Sector 1	0.0	0.0	0.00	0.00
Tip Growth, Whorl 2, Sector 1	0.0	2.0	1.17	0.42
Branch Diameter, Whorl 2,Sector 2 (cm)	6.4	33.0	19.79	5.81
Branch Angle Whorl 2, Sector 2 (°)	84.0	127.0	100.79	9.15
Alive in Whorl 2, Sector 2	0.0	0.0	0.00	0.00
Tip Growth, Whorl 2, Sector 2	1.0	2.0	1.86	0.35
Total Branches Whorl 2	1.0	7.0	4.14	1.30
Branch Diameter, Whorl 3,Sector 1 (cm)	7.8	34.9	20.79	5.95
Ang31 (°)	85.0	138.0	107.10	10.69
Alive in Whorl 3, Sector 1	0.0	0.0	0.00	0.00
Tip Growth, Whorl 3, Sector 1	1.0	2.0	1.28	0.45
Branch Diameter, Whorl 3,Sector 2 (cm)	10.0	33.1	21.29	5.64
Ang32 (°)	84.0	135.0	105.62	10.76
Alive in Whorl 3, Sector 2	0.0	0.0	0.00	0.00
Tip Growth, Whorl 3, Sector 2	0.0	2.0	1.78	0.46
Total Branches Whorl 3	1.0	8.0	4.31	1.33
Whorl Distance (cm)	38.1	135.3	73.19	20.71
Height to Live Crown Sector 1 (m)	2.4	5.4	3.95	0.65
Height to Live Crown Sector 2 (m)	2.7	5.4	3.82	0.55
Biggest Branch (cm)	12.8	35.7	23.94	5.53
Biggest Branch Sector 1 (cm)	10.9	29.2	18.95	4.78
Biggest Branch Sector 2 (cm)	9.9	30.0	19.67	4.65
Biggest Branch Angle (°)	88.0	135.0	107.71	10.52
Biggest Branch Occurrence	1.0	2.0	1.55	0.50
Height to Live Crown (m)	2.8	5.4	3.89	0.57
Total Branches	3.0	18.0	12.59	2.99
Biggest Branch Angle, Sector 1 (°)	84.0	123.7	101.16	8.70
Biggest Branch Angle, Sector 2 (°)	83.3	122.0	100.67	7.79
Tip Growth out of Sector 1	0.7	2.0	1.20	0.25
Tip Growth out of Sector 2	1.3	2.0	1.84	0.20
Volume (dm^3)	41.4	182.0	97.08	32.84
Stumpage (SEK/ha)	0	87	38	21.33

Rectangularity 1.46x1.46x4m (N=64)				
Variable	**MIN**	**MAX**	**MEAN**	**STD**
Quality	1.0	4.0	2.70	0.97
Straight	1.0	3.0	2.09	0.75
DBH 1 (cm)	9.4	20.0	13.91	2.09
DBH 2 (cm)	9.4	20.6	14.07	1.95
Delta DBH (cm)	-1.4	0.8	-0.2	0.5
DBH average (cm)	9.4	20.3	13.99	2.01
Total Height (m)	7.0	12.5	10.17	1.04
Branch Diameter, Whorl 1,Sector 1 (cm)	8.6	32.8	17.62	5.53
Branch Angle Whorl 1, Sector 1 (°)	80.0	141.0	97.33	10.62
Alive in Whorl 1, Sector 2	0.0	0.0	0.00	0.00
Tip Growth, Whorl 1, Sector 1	0.0	2.0	1.03	0.31
Branch Diameter, Whorl 1,Sector 2 (cm)	0.0	31.8	17.48	5.94
Branch Angle Whorl 1, Sector 2 (°)	0.0	120.0	95.42	15.29
Alive in Whorl 1, Sector 2	0.0	0.0	0.00	0.00
Tip Growth, Whorl 1, Sector 2	0.0	2.0	1.83	0.49
Total Branches Whorl 1	1.0	7.0	3.80	1.25
Branch Diameter, Whorl 2,Sector 1 (cm)	9.3	35.4	19.22	5.09
Branch Angle Whorl 2, Sector 1 (°)	83.0	137.0	102.77	9.41
Alive in Whorl 1, Sector 1	0.0	0.0	0.00	0.00
Tip Growth, Whorl 2, Sector 1	0.0	2.0	1.16	0.41
Branch Diameter, Whorl 2,Sector 2 (cm)	0.0	36.0	18.73	6.51
Branch Angle Whorl 2, Sector 2 (°)	0.0	122.0	99.95	15.76
Alive in Whorl 2, Sector 2	0.0	0.0	0.00	0.00
Tip Growth, Whorl 2, Sector 2	0.0	2.0	1.83	0.46
Total Branches Whorl 2	1.0	8.0	3.95	1.28
Branch Diameter, Whorl 3,Sector 1 (cm)	7.3	55.0	20.77	7.41
Ang31 (°)	85.0	138.0	104.61	10.37
Alive in Whorl 3, Sector 1	0.0	0.0	0.00	0.00
Tip Growth, Whorl 3, Sector 1	1.0	2.0	1.08	0.27
Branch Diameter, Whorl 3,Sector 2 (cm)	4.1	39.5	20.68	7.34
Ang32 (°)	87.0	154.0	104.92	10.49
Alive in Whorl 3, Sector 2	0.0	0.0	0.00	0.00
Tip Growth, Whorl 3, Sector 2	0.0	2.0	1.94	0.30
Total Branches Whorl 3	1.0	7.0	4.09	1.28
Whorl Distance (cm)	36.8	123.2	72.93	20.68
Height to Live Crown Sector 1 (m)	2.1	5.3	3.65	0.79
Height to Live Crown Sector 2 (m)	2.1	5.1	3.41	0.70
Biggest Branch (cm)	12.5	55.0	24.80	6.97
Biggest Branch Sector 1 (cm)	9.9	31.7	19.20	4.88
Biggest Branch Sector 2 (cm)	9.7	33.1	18.96	5.24
Biggest Branch Angle (°)	85.0	138.0	107.78	9.58
Biggest Branch Occurrence	1.0	2.0	1.56	0.50
Height to Live Crown (m)	2.1	5.1	3.53	0.71
Total Branches	5.0	17.0	11.84	2.74
Biggest Branch Angle, Sector 1 (°)	86.7	119.0	101.57	8.06
Biggest Branch Angle, Sector 2 (°)	72.0	125.0	100.10	8.84
Tip Growth out of Sector 1	0.7	1.7	1.09	0.20
Tip Growth out of Sector 2	1.3	2.0	1.86	0.24
Volume (dm^3)	32.5	177.0	86.99	27.94
Stumpage (SEK/ha)	0	85.83	32.78	18.28

Rectangularity 2x2m (N=60)				
Variable	**MIN**	**MAX**	**MEAN**	**STD**
Quality	1.0	5.0	2.80	0.94
Straight	1.0	3.0	2.30	0.62
DBH 1 (cm)	9.3	18.5	14.02	2.00
DBH 2 (cm)	9.5	18.9	14.18	2.02
Delta DBH (cm)	-1.1	0.8	-0.2	0.5
DBH average (cm)	9.4	18.7	14.10	2.00
Total Height (m)	8.6	12.0	10.21	0.87
Branch Diameter, Whorl 1,Sector 1 (cm)	8.5	36.4	17.01	5.14
Branch Angle Whorl 1, Sector 1 (°)	77.0	126.0	95.23	8.26
Alive in Whorl 1, Sector 2	0.0	0.0	0.00	0.00
Tip Growth, Whorl 1, Sector 1	0.0	2.0	1.07	0.36
Branch Diameter, Whorl 1,Sector 2 (cm)	8.2	31.4	17.73	5.41
Branch Angle Whorl 1, Sector 2 (°)	71.0	158.0	96.58	11.31
Alive in Whorl 1, Sector 2	0.0	0.0	0.00	0.00
Tip Growth, Whorl 1, Sector 2	1.0	2.0	1.97	0.18
Total Branches Whorl 1	1.0	7.0	3.80	1.25
Branch Diameter, Whorl 2,Sector 1 (cm)	9.3	36.5	19.26	5.63
Branch Angle Whorl 2, Sector 1 (°)	80.0	144.0	101.87	9.85
Alive in Whorl 1, Sector 1	0.0	0.0	0.00	0.00
Tip Growth, Whorl 2, Sector 1	0.0	2.0	1.10	0.35
Branch Diameter, Whorl 2,Sector 2 (cm)	8.4	33.2	18.51	5.09
Branch Angle Whorl 2, Sector 2 (°)	78.0	133.0	101.65	9.46
Alive in Whorl 2, Sector 2	0.0	0.0	0.00	0.00
Tip Growth, Whorl 2, Sector 2	1.0	2.0	1.93	0.25
Total Branches Whorl 2	1.0	8.0	4.37	1.55
Branch Diameter, Whorl 3,Sector 1 (cm)	7.8	33.2	19.82	6.21
Ang31 (°)	82.0	138.0	104.80	11.57
Alive in Whorl 3, Sector 1	0.0	0.0	0.00	0.00
Tip Growth, Whorl 3, Sector 1	1.0	2.0	1.23	0.43
Branch Diameter, Whorl 3,Sector 2 (cm)	6.2	34.0	19.65	5.55
Ang32 (°)	87.0	154.0	105.32	10.49
Alive in Whorl 3, Sector 2	0.0	0.0	0.00	0.00
Tip Growth, Whorl 3, Sector 2	1.0	2.0	1.82	0.39
Total Branches Whorl 3	1.0	8.0	4.38	1.54
Whorl Distance (cm)	34.3	113.7	74.90	19.74
Height to Live Crown Sector 1 (m)	1.7	5.5	3.71	0.77
Height to Live Crown Sector 2 (m)	1.7	5.2	3.76	0.72
Biggest Branch (cm)	14.8	36.5	23.80	5.42
Biggest Branch Sector 1 (cm)	10.7	31.2	18.70	4.47
Biggest Branch Sector 2 (cm)	10.9	28.3	18.63	4.22
Biggest Branch Angle (°)	77.0	158.0	108.83	14.18
Biggest Branch Occurrence	1.0	2.0	1.53	0.50
Height to Live Crown (m)	1.7	5.2	3.73	0.73
Total Branches	6.0	21.0	12.55	3.35
Biggest Branch Angle, Sector 1 (°)	82.0	129.3	100.63	7.67
Biggest Branch Angle, Sector 2 (°)	80.7	136.0	101.18	8.40
Tip Growth out of Sector 1	0.7	2.0	1.13	0.23
Tip Growth out of Sector 2	1.7	2.0	1.91	0.15
Volume (dm^3)	37.3	162.4	88.22	26.65
Stumpage (SEK/ha)	0	76.24	33.28	18.32

Appendix V: Significant results for Tukey Tests. Where rectangularities are 0.8 x 5 m (1), 1 x 4 m (2), 1.33 x 3 m (3), 1.46 x 1.46 x 4 m (4) and 2 x 2 m (5).

Variables	Rectangularity Comparison	Difference Between Means	Lower CI	Upper CI
DBH 2	1 - 4	1.087	0.036	2.137
DBH 2	1 - 2	1.163	0.097	2.230
DBH Average	1 - 2	1.080	0.019	2.141
Total Height	1 - 4	0.468	0.037	0.899
Total Height	3 - 4	0.464	0.030	0.899
Tip Growth, Whorl 1, Sector 1	2 - 5	0.200	0.003	0.397
Tip Growth, Whorl 1, Sector 1	2 - 1	0.217	0.020	0.414
Tip Growth, Whorl 1, Sector 1	2 - 4	0.235	0.042	0.429
Total Branches Whorl 1	3 - 1	0.788	0.139	1.437
Branch Diameter, Whorl 2, Sector 2	1 - 5	3.251	0.160	6.342
Branch Diameter, Whorl 3, Sector 2	1 - 5	4.071	0.432	7.710
Live Crown Sector 2	3 - 4	0.413	0.084	0.743
Live Crown Sector 2	3 - 1	0.522	0.188	0.857
Live Crown Sector 2	5 - 4	0.346	0.019	0.672
Live Crown Sector 2	5 - 1	0.455	0.123	0.787
Live Crown Sector 2	2 - 1	0.407	0.075	0.739
Difference in Height to Live Crown	1 - 4	0.243	0.052	0.434
Difference in Height to Live Crown	1 - 3	0.276	0.080	0.471
Difference in Height to Live Crown	1 - 5	0.377	0.183	0.571
Difference in Height to Live Crown	2 - 5	0.195	0.001	0.389
Branch Diameter Sector 2	1 - 4	2.683	0.131	5.235
Branch Diameter Sector 2	1 - 5	3.016	0.424	5.609
Difference in Biggest Branch	1 - 2	1.167	0.018	2.316
Difference in Biggest Branch	1 - 4	1.486	0.355	2.617
Difference in Biggest Branch	1 - 5	1.648	0.499	2.797
Difference in Biggest Branch	1 - 3	1.935	0.776	3.094
Branch Sector	1 - 5	0.250	0.010	0.490
Average Height to Live Crown	3 - 1	0.330	0.005	0.656
Average Height to Live Crown	3 - 4	0.358	0.037	0.679
Basal Area	1 - 4	0.002	0.000	0.005
Basal Area	1 - 2	0.003	0.000	0.005
Volume	1 - 5	14.552	0.129	28.975
Volume	1 - 4	15.778	1.582	29.974

Appendix VI: Summary of diameter, total heights and mean individual tree volumes for each rectangularity calculated for each time data was collected.

Time	Replication	Rectangularity	n	Diameter (cm)	Height (m)	Volume (dm^3)
2004	1	0.8 x 5	35	16.6	10.9	76.5
2011	1	0.8 x 5	19	13.6	10.1	93.9
FHC	1	0.8 x 5	30	14.5	10.1	99.5
2004	1	1 x 4	38	11.8	8.0	54.2
2011	1	1 x 4	21	13.2	10.3	89.1
FHC	1	1 x 4	30	13.7	10.4	92.9
2004	1	1.33 x 3	31	12.7	8.1	62.5
2011	1	1.33 x 3	19	13.9	10.5	97.9
FHC	1	1.33 x 3	29	14.0	10.4	96.3
2004	1	1.46 x 1.46 x 4	39	11.8	7.4	51.2
2011	1	1.46 x 1.46 x 4	20	13.1	9.7	81.8
FHC	1	1.46 x 1.46 x 4	32	13.4	9.7	82.6
2004	1	2 x 2	36	11.7	7.6	50.9
2011	1	2 x 2	19	13.7	10.1	90.4
FHC	1	2 x 2	30	13.5	9.9	85.3
2004	2	0.8 x 5	33	13.1	8.7	71.6
2011	2	0.8 x 5	20	14.8	11.0	117.0
FHC	2	0.8 x 5	30	15.5	11.2	124.9
2004	2	1 x 4	35	12.5	8.5	63.8
2011	2	1 x 4	19	13.7	10.9	101.4
FHC	2	1 x 4	30	14.1	10.8	101.5
2004	2	1.33 x 3	31	12.8	8.1	65.8
2011	2	1.33 x 3	20	14.2	10.5	106.3
FHC	2	1.33 x 3	29	15.1	10.8	115.4
2004	2	1.46 x 1.46 x 4	35	12.2	7.9	58.8
2011	2	1.46 x 1.46 x 4	18	14.6	10.6	110.3
FHC	2	1.46 x 1.46 x 4	32	14.6	10.7	106.6
2004	2	2 x 2	31	12.3	7.8	59.1
2011	2	2 x 2	20	14.7	11.1	112.2
FHC	2	2 x 2	30	14.7	10.6	106.6

Appendix VII: Paired T-test results for comparison between DBH1 and DBH2 for all rectangularities in replications 1 and 2.

Replication	Rectangularity (m)	DF	P-value
1	0.8 x 5	30	0.7974
2	0.8 x 5		0.6152
1	1 x 4	30	0.7322
2	1 x 4		0.549
1	1.33 x 3	29	0.7481
2	1.33 x 3		0.4448
1	1.46 x 1.46 x 4	32	0.6681
2	1.46 x 1.46 x 4		0.5948
1	2 x 2	30	0.6931
2	2 x 2		0.5637

Appendix VIII: Definition of Variables in Raw Data Set

- Quality = quality rating on entire tree (1-5 with 1 as the best quality and 5 as the worst)
- Straight = straightness rating on bottom 4 meters (1-3 with 1 being the best and 3 being the worst)
- DBH1 = diameter at breast height parallel to rows, cm
- DBH2 = diameter at breast height perpendicular to rows, cm
- TH = Total tree height, m
- $Diam_{ij}$ = diameter of biggest branch in whorl (i) and sector (j), mm
- Ang_{ij} = underneath angle of the biggest branch in whorl (i) and sector (j), (°)
- Liv_{ij}= measure of branch mortality in whorl (i) and sector (j), (0 recorded if dead and 1 recorded if alive)
- TG_{ij}= record of where the tip of a branch was found to be growing which attaches to the bole in whorl (i) and sector (j), (1 or 2 was recorded which defines the sector the tip was found growing in)
- TG1 = ratio of how many branches which stayed in and grew out of sector 1
- TG2 = ratio of how many branches which stayed in and grew out of sector 2
- $TotB_i$ = Total branches greater than 1cm found in whorl (i)
- WhorlDist = distance between the lowest whorl and highest whorl from which measurements were taken, cm
- LH1= height to lowest living branch in sector 1, m
- LH2 = height to lowest living branch in sector 2, m
- BBang = average angle of the biggest branches, (°)
- Sector 1 = percentage of biggest branches which occurred in sector , (%)
- Sector 2 = percentage of biggest branches which occurred in sector 2, (%)