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Variability in Outerwood Density in the 1990 Silviculture Breed and Ultra-high Pruning Trials

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EXECUTIVE SUMMARY

Within-tree-variability in wood properties, important for timber processing, is determined by the environmental conditions prevailing at the time each cell was formed, i.e., within-tree-variability is influenced by site, stand structure, and the prevailing weather conditions. Compression wood is formed to correct for any stem lean. Many previous studies have avoided sampling compression wood, and consequently do not allow within-tree circumferential variability in wood properties to be studied.

Further data are therefore necessary to characterise within-tree circumferential variability for all site types, silvicultural treatments and material planted.

The question was raised as to the value of taking outerwood density measurements at the time of routine PSP re-measurement for:

- characterising within-tree variability with respect to site, silvicultural treatment and/or material planted, and
- determining which trials and silvicultural treatments should be targeted for further destructive sampling.

During winter 2009, outerwood density cores were collected for all trees in selected permanent sample plots (PSPs) with different treatments in the six 1990 silviculture breed trials and two of the ultra-high pruning trials, in order to characterise within-tree variability in outerwood density. Two cores were collected per tree at 180 degrees to each other, the first being on the upper side of any lean (i.e., to avoid compression wood), and the second on the underside of any stem lean (i.e., so the sample would pass through any compression wood present).

Analysis of 50 mm outerwood density cores indicated that within a tree, the difference in outerwood density between different directions was highly variable, and that the difference was greater on known windy sites.
The mean 50 mm outerwood density for an individual tree was also highly variable. In the 1990 silviculture breed trials, the plot mean was higher on the more northern sites and lower at known windy sites. Within a site, the plot mean varied with seedlots, but not between the two final crop stockings considered (200 and 1000 stems/ha). In the ultra-high pruning trials there were no significant differences between the treatments examined.

Examination of the relationship between 50 mm outerwood density and other variables indicated that:

- there was a slight curvilinear relationship between mean outerwood density for an individual tree and both current tree DBH, and DBH increment in the last two years; and
- there was also a positive correlation between tree mean outerwood density and the standing-tree sonic velocity. However the relationship varied with site, silviculture treatment and seedlot.

Note: analysis of the standing-tree sonic velocity data is presented in the companion report, FFR 052).

This analysis of 50 mm outerwood density data indicated complex interactions between site, seedlot and final crop stocking. In particular these data highlight the importance of the wind environment to the structure of the tree, with within-tree variability in outerwood density increasing on known windy sites. Previous studies have shown that wind environment is important when considering incidence of stem damage and branching patterns.

Due to the complex interactions between sites, seedlots and silviculture, this study has raised more questions than it has answered. Two studies are recommended to address these questions:

- The 1987 silviculture-breed trials need to be monitored (possibly with dendrometers) at more frequent intervals over the next few years to determine the impact of recent (2010) coring on future growth. We need to be certain that coring selected trees will not compromise trials from the perspective of analysing growth responses.
- Five-ring outerwood density needs to be measured for one or more of the 1990 silviculture breed trials to confirm whether the observed curvilinear trends with stem dimensions on these sites is true, or an artefact of using 50 mm cores.

The large variation observed between sites, silvicultural treatments and seedlots, means that more data are required for understanding and modelling the country-wide variation, particularly for newer seedlots, and first-rotation sites because it is “dangerous” to extrapolate empirical models developed outside the range of data used in their development.

In terms of non-destructive studies, the authors recommended that pith-to-bark cores (analysed using SilviScan) will provide more valuable information than outerwood density cores and standing tree sonic velocity, particularly with regard the response to silviculture.

Based on the current data, no simplifications to destructive sampling methodology could be recommended, i.e., destructive sampling should cover all major site types, all major seedlots and a wide range of silvicultural treatments. When considering silvicultural treatments, factors that need to be considered include initial stocking, final stocking, timing of thinning, severity of thinning, timing of pruning, pruning severity and final pruned height. At least three data points for each silvicultural factor are recommended in order to determine whether relationships are curvilinear.

In terms of future non-destructive studies, it is desirable to characterise within-tree variability in wood properties with respect to site, silviculture and material planted in more of the current trial series.

- Pith-bark cores (analysed using SilviScan), in preference to standing tree sonic velocity and outerwood density cores, should be collected in 1991 silviculture breed trials at age 19 years. Branching data (TreeD) should be collected at the same time to determine whether useful relationships between branching patterns and wood properties can be determined.
- Pith-to-bark cores (analysed using SilviScan) are collected in the 1992 and 1994 special purpose breed trials at their next re-measurement. These are the first growth-monitoring trials containing seedlots selected for improved wood properties, and we need to know whether relationships developed using other seedlots will hold for these seedlots.

Given that the variation in wood properties is important for processing, the authors recommend that:

- in the future, outerwood density cores and pith-to-bark cores are sampled to record, rather than avoid within-stem variability;
- the decision on when to use 50 mm, five-ring cores or pith-to-bark cores is re-visited; and
- future PSPs established are of a sufficient size that there are likely to be a minimum of 30 trees at the end of rotation (i.e., allow for likely mortality), in order to provide the recommended 30 trees for outerwood density studies.

INTRODUCTION

Many radiata pine trials have been established to examine the influence of site and/or silvicultural treatment and/or genetic material planted on stem growth, in order to provide data for developing growth models. These trials are equally useful for determining the influence of site and/or silvicultural treatment and/or genetic material planted on crown development and stem wood properties, and to provide data for developing crown and wood property models.

Detailed wood property data are required to build within-stem wood property models for individual trees, but, because of the number of measurements required per tree, are expensive to collect.

As we have limited knowledge of the impacts of different genetic material and silviculture treatments on wood properties, a study was initiated to examine the value of taking standing tree sonic velocity and/or outerwood density cores to (a) characterise the influence of site $\times$ silvicultural treatment $\times$ genetic material (which will be useful for estimating carbon), and (b) determine which treatment combinations should be sampled more intensively from large trials.

A previous report [1] presented an analysis of the standing tree sonic data collected during the winter of 2009 from selected treatments in the 1990 silviculture breed trials and two of the ultra-high pruning trials.

In this report, which complements the above report, the following are presented:

- a graphical and statistical analysis of outerwood density data, collected in the above two trial series during winter 2009, and
- an examination of the relationships between outerwood density and standing tree sonic velocity.

1990 Silviculture Breed Trials

The 1990 Silviculture Breed Trials were planted in 1990 [2, 3] There are six current trials:

- FR121/1, Tungrove (Medium site index, Clays Region)
- FR121/2, Atiamuri/ Kinleith (Medium site index, Central North Island)
- FR121/3, Gwavas (Low site index, Hawkes Bay)
- FR121/4, Tairua (High site index, Clays Region)
- FR121/6, Tarawera (High site index, Central North Island)
- FR121/7, Huanui (High basal area, East Coast region).

The PSPs selected for measurement came from two different silvicultural treatments and four (two sites) or five (four sites) different seedlots (see Appendix 1).

Ultra-High Pruning Trials

The ultra-high pruning trials were selected for study as they have a wide range of crown structures. It was considered that the different crown structures would influence tree movement and consequently wood property distributions [4].

Four ultra-high pruning trials were established [5], and two trials were selected for this study:

- FR201, Ngaumu, planted in 1985 and established as a trial in 1993 with a GF14 seedlot on a very windy site.
- FR243, Waiotahi, planted in 1988 and established as a trial in 1995 with a GF17 seedlot on a sheltered site.

For this study, six different silvicultural treatments, in terms of crown structure and stocking, were selected for measurement at both sites (see Appendix 2, Tables 1 and 2). These allow the comparison of:

- unpruned trees at two different stockings, and
- different final prune heights, where a given crown length was left after each pruning lift.

To provide a contrast in crown structure and spacing, two treatments were selected for analysis, i.e., 4.9 m crown length remaining at 200 stems/ha, and 7.9 m crown length remaining at 350 stems/ha.

METHODS

In all trials, two outerwood breast height cores were collected per tree from all trees in the selected PSPs. The number of trees in a PSP varied between 15 and 44 (see Appendices 1 and 2), whereas 30 trees are recommended for outerwood density studies (D. Cown, pers. comm., June 2010). The directions were selected with the aim of quantifying within-tree variability in outerwood density. The first core was taken from the concave (upper) side of the stem and the second core at 180 degrees to the first one (i.e., it would contain compression wood if the tree was leaning). These directions correspond to those measured in the 1987 silviculture-breed trial series [6], but contrast with general practice where outerwood density is sampled at right-angles to any stem lean. Historically, the decision to avoid compression wood was made because it was felt that compression wood was a relatively rare and unpredictable feature. (D. Cown, pers. comm., June 2010).

For one site (Waiotahi) four cores at right angles were sampled.

Outerwood density cores may be analysed as five-ring cores (five annual growth rings) or outer 50 mm cores. There are advantages and disadvantages to both approaches. For five-ring cores, one needs to carefully examine the core to determine the outer five growth rings, which substantially increases processing time. For 50 mm cores, one just needs to cut the core at 50 mm. In mature stands, outer five rings and 50 mm cores previously gave virtually identical values. Current practice is to use 50 mm cores in stands 15 years and older and five rings in younger stands because density gradients stabilise with tree age, particularly after 15 years on most sites (D. Cown, pers comm., June 2010).

The current analysis used 50 mm outerwood density cores. However there is still the option of collecting the data for five-ring outerwood density cores, because five-ring data have already been collected on cores where five rings was longer than 50 mm.
In the laboratory at Scion, all cores were trimmed to the appropriate length (50 mm) and basic density was determined by the maximum moisture content method [7]. All pairs of cores with a density difference > 80kg/m^3 were retested to confirm the large variation. This variation is attributed to compression wood.

The difference between direction 1 (on the upper side of any lean) and direction 2 (on the lower side of any lean) was highly variable, with both positive and negative values (see Appendix 3, Figure 14). As a consequence the following values were calculated for each tree:

- tree mean density, by averaging across the two cores for all sites except Waiotahi, where the mean was calculated from the four cores sampled; and
- within-tree difference in density, by subtracting the highest core density from the lowest core density.

The data were graphically examined using the SAS procedure, PROC GPLOT. A graphical examination of data is an essential first step in any data analysis in order to determine the variability and any trends in the data, and to provide an intuitive feeling of the importance of observed relationships.

Two alternative SAS procedures (PROC MIXED and PROC GLM) were used to determine whether there were any statistically significant differences between site, and treatments, with the assumption of equal variance between treatments. For both analyses, the error term was at the plot rather than the individual tree level, as this allows the examination of differences between treatments. It is important to remember that a statistically significant result may or may not be of practical significance and vice versa.

In the 1990 silviculture breed trials teo analyses were carried out. The SAS procedure, PROC MIXED, examined whether seedlot, final crop stocking (FCS) and/or seedlot × FCS were statistically significant with site being a random variable. The SAS procedure PROC GLM, calculated whether any of the following terms were statistically significant:

- site
- seedlot
- final crop stocking (200 stems/ha (sph) or 1000 sph)
- site × final crop stocking
- site × seedlot
- seedlot × final crop stocking.

In the ultra-high pruning trials, the SAS procedure, PROC GLM, was used to determine whether any of the following terms were significant at each site:

- final crop stocking (200 sph or 350 sph)
- amount of stem pruned in three classes (unpruned, one log pruned, two logs pruned).

The low number of plots measured precluded the examination of interactions.

For both trial series, the relationships between outerwood density and other tree characteristics were examined, namely:

- The relationship between both current DBH and DBH increment in the previous two years. To determine average trends, DBH and DBH increment have been split into 10-cm and 2-cm classes, respectively.
- The relationship between mean core density and standing tree sonic velocity.

RESULTS

Definitions

- The mean outerwood density for an individual tree was obtained by averaging across the cores sampled in that tree (two cores for all sites except Waiotahi, where four cores were sampled)
- Within-tree difference in outerwood density was obtained by subtracting the highest core density from the lowest core density.
- The variance s^2 for a set of observations is calculated as:

$$s^2 = \frac{\sum (x - \bar{x})^2}{n - 1}$$

Where:

x is the value for an individual observation

$\bar{x}$ is the mean value for all the observations
n is the number of observations

- The standard deviation for a set of observations is the square root of the variance.

Note: Larger versions of the graphs presented in the Results section are given in the Appendices.

1990 Silviculture Breed Trials

To provide clarity to the graphs, the variable "site number" (the sub-experiment number) is used in preference to the forest name on several of the graphs (Table 1). Sub-experiment 5 was abandoned in November 1997 due to major mortality and gorse problems. Many of the graphs show the data points for individual trees, allowing the reader to visualise the variability between individual trees. Mean values across trees in a PSP (a given combination of site, silviculture and seedlot) have been joined by a solid line, as this highlights the mean values. Note that the shape of the line has no meaning and depends on the order of the sites; and that the GF13/LI25 was not planted at site numbers 4 or 7.

Table 1. Site numbers, latitude and altitude for the 1990 silviculture breed trials.

Forest	Trial	Site Number	Latitude (degrees south)	Altitude (m)
Tungrove	FR121/1	1	35.5	160
Atiamuri	FR121/2	2	38.4	280
Gwavas	FR121/3	3	39.7	410
Tairua	FR121/4	4	37.2	10
Tarawera	FR121/6	6	38.1	60
Huanui	FR121/7	7	38.3	250

Tree Mean Outerwood Density

The individual tree mean outerwood density is highly variable for a given combination of site × seedlot × FCS (illustrated by large scatter in data points) (Figure 1, Appendix 3, Figure 21 and Figure 22). The data show the tendency for mean density for a given site and seedlot to increase as one goes further north, as has been found previously [8, 9]. Site 1, Tungrove is the furthest north, followed by site 4, Tairua. The density tends to be lowest for the known windy sites (site 3, Gwavas, and site 7, Huanui, see Appendix 6 for values). Across sites, density tends to be lowest for the GF25 seedlot and highest for the GF7 seedlot (illustrated by lines joining mean values).

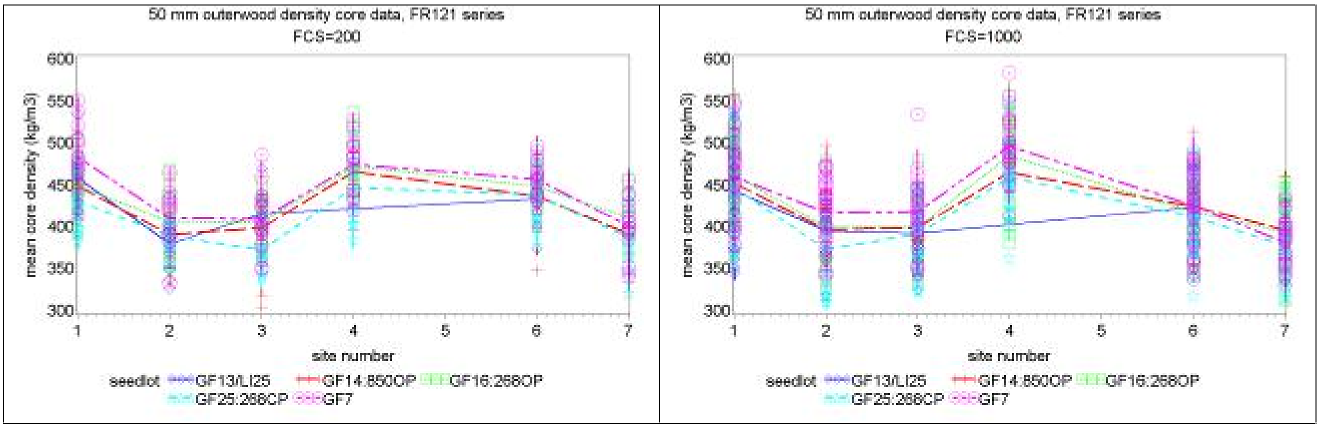


Figure 1. Variation in individual tree mean core density with site and seedlot at final crop stockings (FCS) of 200 and 1000 stems/ha.

The variance in mean outerwood density was examined for each combination of site, seedlot and final crop stocking (FCS) (Figure 2). It can be seen that the variance between trees within a plot is less at 200 stems/ha than at 1000 stems/ha. At 200 stems/ha, the variance is similar across sites and silvicultural treatments. At 1000 stems/ha, the variance is noticeably higher at site number 1 (Tungrove) than at the other sites. These plots were all together in one corner of the trial, but, when visited, they did not stand out as being different from the rest of the trial. The seedlot with the least variance between trees is not consistent across final crop stockings.

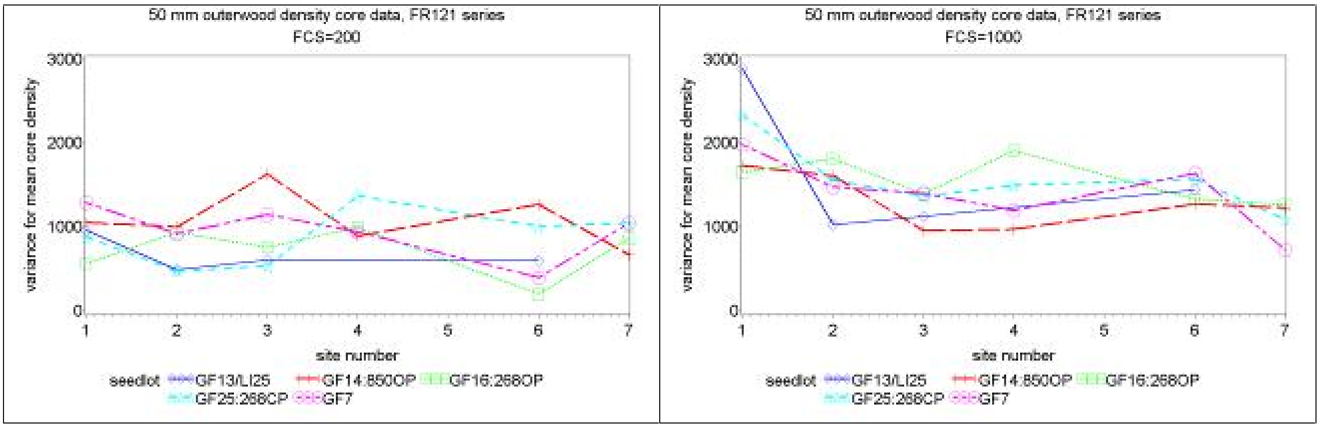


Figure 2. Variance for mean core density by site number, seedlot and final crop stocking

The SAS procedure PROC MIXED indicated significant differences between seedlots, but not between final crop stockings.

The SAS procedure PROC GLM indicated that two variables were statistically significant (probability of observing a greater F value was less than 0.01):

- site
- seedlot.

That there is no significant difference between the two final crop stockings is illustrated by the fact that the individual tree values for the two stockings are highly variable with similar means (Appendix 3, Figure 15 to Figure 20).
The mean values for tree mean outerwood density for a given site and seedlot are shown in Table 2.

Table 2. Mean values for tree mean outerwood density (kg/m^3) by site and seedlot.

Seedlot	GF7	GF14:850OP	GF16:268OP	GF25:268CP	GF13/LI25
Site Number, Forest					
1, Tungrove	468	450	457	442	448
2, Kinleith	415	395	403	380	387
3, Gwavas	415	399	402	385	400
4, Tairua	489	466	480	455	-
6, Tarawera	435	429	428	419	427
7, Huanui	388	394	398	380	-

Within-tree Difference in Outerwood Density

The within-tree difference in outerwood density (highest – lowest) is also highly variable (Figure 3, Appendix 3, Figure 29 and Figure 30). The mean value for a given combination of site, seedlot and final crop stocking was around 30 kg/m^3. The within-tree difference was over 60 kg/m^3 for a number of trees. The mean values for the individual treatments were similar, with little difference between seedlots and final crop stockings (Appendix 3, Figures 23-28). The mean values were slightly higher on the known windy sites (sites 3, Gwavas and site 7, Huanui (Table 3).

Table 3. Mean values for difference in outerwood density (kg/m^3) by site.

Site Number, Forest	Mean difference in outerwood density
1, Tungrove	21.2
2, Kinleith	16.0
3, Gwavas	33.1
4, Tairua	27.9
6, Tarawera	22.0
7, Huanui	31.6

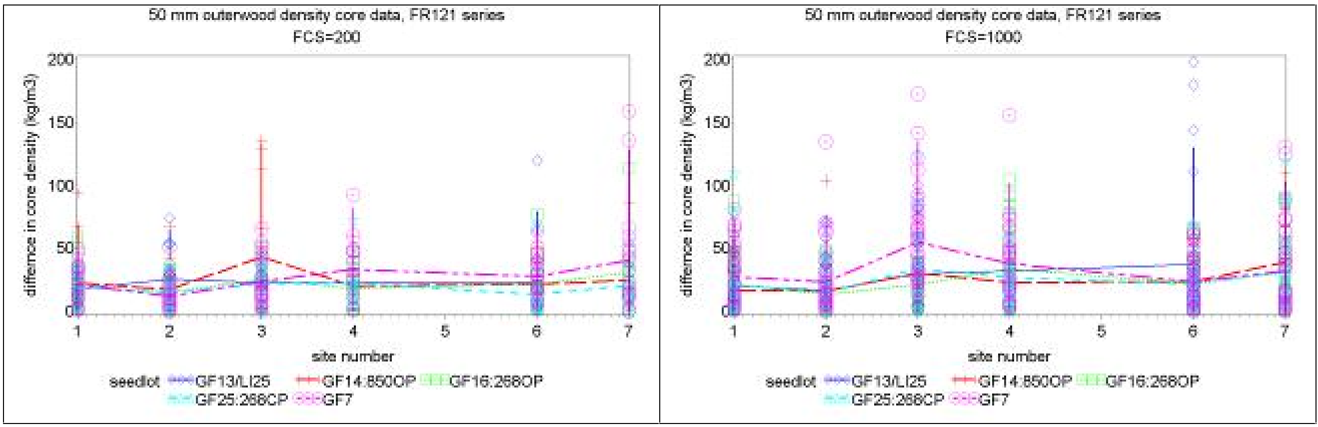


Figure 3. Within-tree difference in outerwood density (highest – lowest) with site and seedlot for final crop stockings (FCS) of 200 and 1000 stems/ha.

The variance for within-tree difference in outerwood density was noticeably higher for a few combinations of site × seedlot × final crop stocking (Figure 4). At 200 stems/ha, the variance was particularly high for the GF14 seedlot at Gwavas (site Number 3) and the GF7 seedlot at Huanui (site number 7). These are known windy sites. Possibly these plots are particularly exposed compared to other plots in the experiment, but this is unlikely from looking at the trial layout. At 1000 stems/ha, the GF13/LI25 seedlot at Tarawera has a particularly high variance. This plot is in one corner, but is adjacent to the other plots at 1000 stems/ha. The reason for these plots having a high variance should be investigated. This will help to understand the reasons for between-tree variability. The effect of within-site variation could not be examined because there was no replication within the trials.

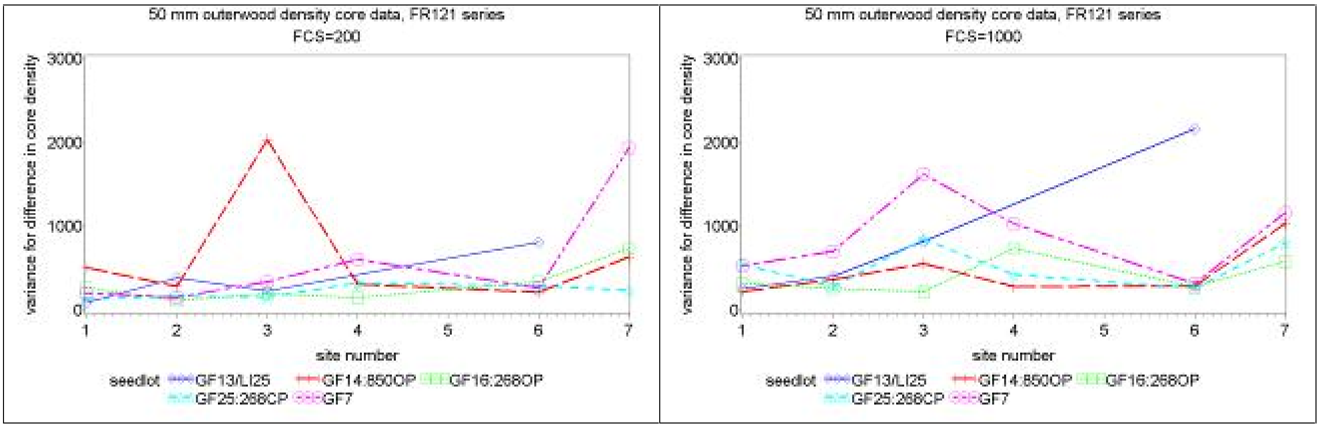
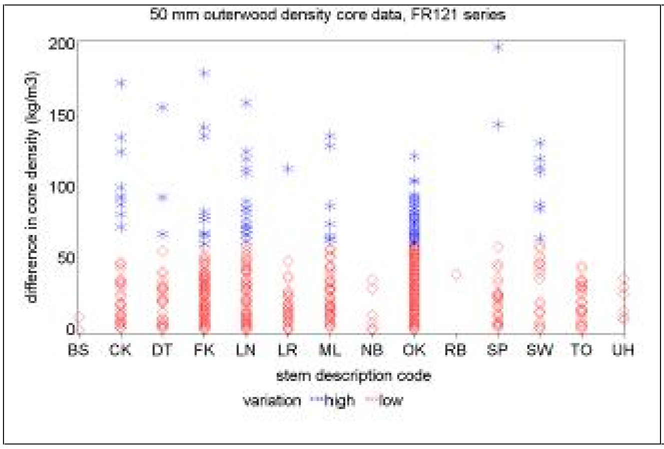


Figure 4. Variance for within-tree difference in outerwood density for a given combination of site number, seedlot and final crop stocking.

A difference of 60 kg/m^3 (approximately double the mean) was selected as a boundary between “low” and “high” within-tree variation, and the differences were examined with respect to stem description codes recorded at the last PSP re-measurement (Figure 5). Some trees that have good stem form (coded “OK”) have large variations in outerwood density, whilst some swept and leaning trees (coded “BS”, “CK”, “LN”, or “SW”) have very low variation. This result is in agreement with previous research [10].



BS =extreme butt sweep
CK=crooked (hockey stick)
DT=dead, broken or defective top
FK=forked
LN=leaning, growing with excessive lean
ML=multi-leader
NB=new band – shift in dbh band
OK=no code assigned in PSP system
RB=resin bleeding
SP=suppressed
SW=sweep-gentle
TO=top out
UH=unhealthy

Figure 5. Highest–lowest tree outerwood density for individual trees with respect to stem description codes recorded at the last PSP remeasurement.

Stem Dimensions

Figure 2 and Figure 4 showed that the variance for tree mean outerwood density and within-tree difference in outerwood density varied between treatments. The variance was generally higher at 1000 stems/ha than at 200 stems/ha, but there were a few plots with an unusually high variance compared to other plots. The graphs (Figure 6) illustrate that the higher variance at 1000 stems/ha is likely to be a result of the greater variance in tree DBH at 1000 stems/ha than at 200 stems/ha. However the variance in DBH does not provide a logical reason for the unusually higher variances observed previously. Another point to note is the higher variance for DBH at site 4 (Tairua).

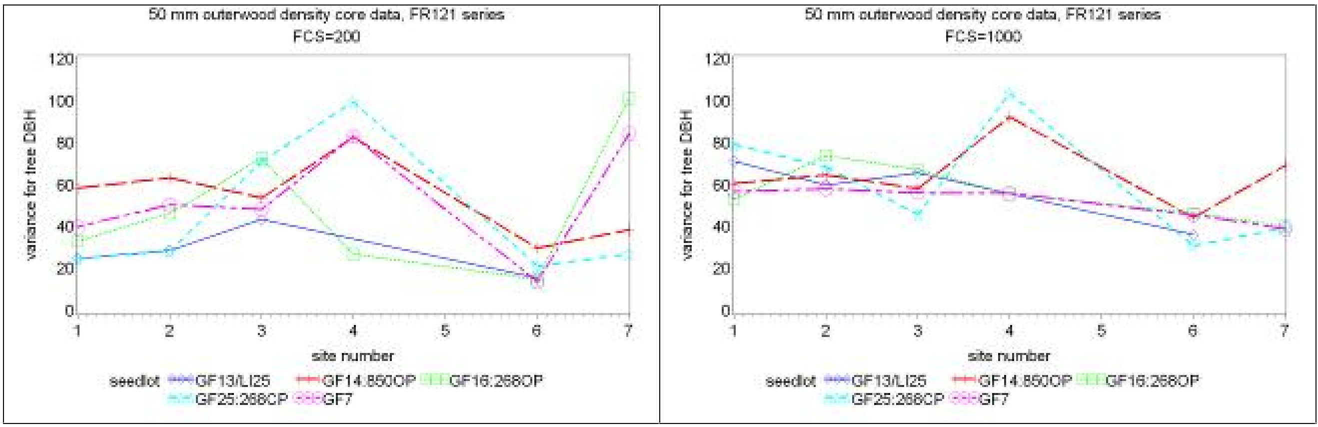


Figure 6. Within-plot variance for tree DBH.

Relationship with Stem Dimensions – Tree Mean Outerwood Density

The graphs (Figure 7, Appendix 3, Figures 31 and 32) which show the tree mean core density averaged over trees in 10 cm DBH classes and 2 cm DBH increment classes clearly indicate the influence of site, with higher density on the northern sites, which is in agreement with previous work [8] [9] and lower density on the more exposed sites. Interestingly the graphs indicate that there may be a curvilinear relationship between mean outerwood density and tree DBH. It is possible that using 50 mm outerwood density cores, rather than five-ring cores may have contributed to these trends. Even though the trees are 19 years old, some trees have a DBH of less than 20 cm, so a 50 mm core would have sampled approximately half of the stem radius, and density is known to increase with increasing tree age. Further research is needed to determine whether the same result is obtained using five-ring increment cores.

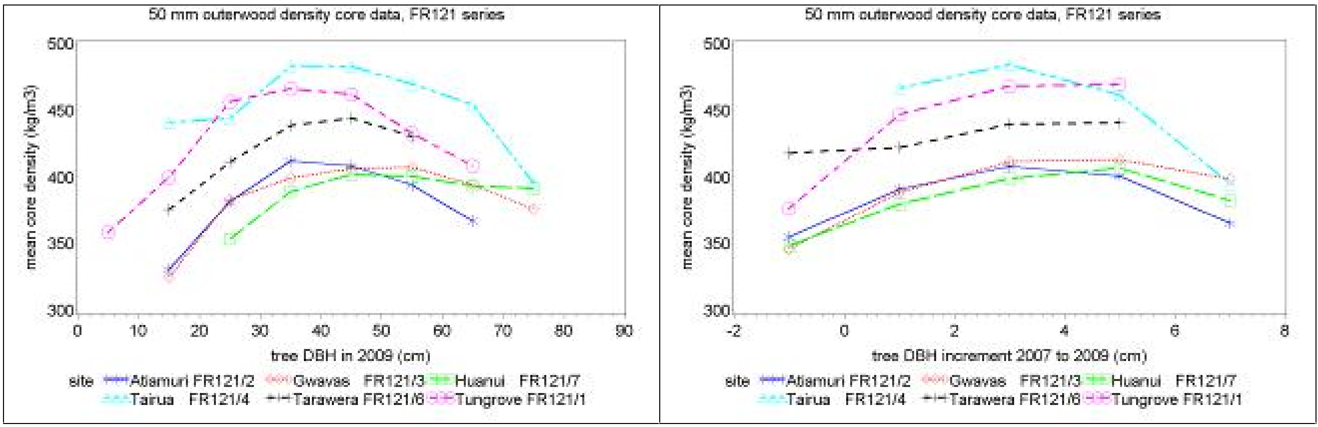


Figure 7. Tree mean core density for individual sites averaged over 10 cm DBH classes and 2 cm DBH increment classes.

Relationship with Stem Dimensions – Within-tree Difference in Outerwood Density

The graphs (Figure 8, Appendix 3, Figures 33 and 34) show the within-tree difference in core density averaged over all trees in 10 cm DBH classes and 2 cm DBH increment classes. The graphs clearly show a higher variation on the known windy sites, but no consistent trend with DBH or DBH increment across sites.

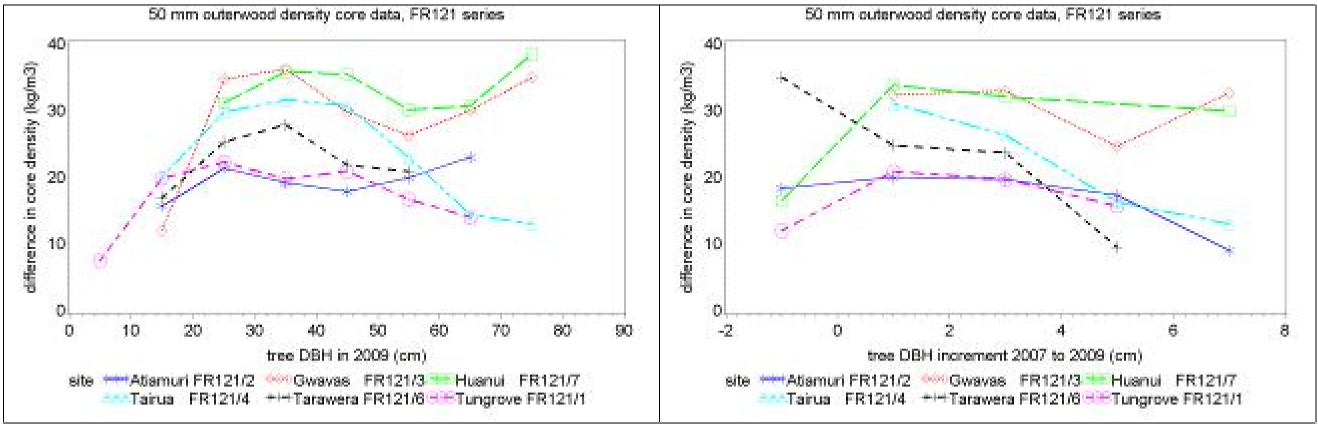


Figure 8. Within-tree difference in outerwood core density for individual sites averaged over 10 cm DBH classes and 2 cm DBH increment classes.

Ultra-high Pruning Trials

The ultra-high pruning trials at Ngaumu and Waiotahi were not identical in design (see Appendix 2 for details). Six treatments were selected for this study rather than the complete trial. These treatments were contrasting within trials with respect to the amount of crown removed, but similar between trials.

All four cores collected at Waiotahi have been used in the analysis below, as there was very little difference between taking cores with the lean or at right angle to any lean at this sheltered site (Appendix 4, Figure 39 and Figure 40).

Tree Mean Outerwood Density

The mean outerwood density for an individual tree was highly variable for a given final pruned height (illustrated by large scatter in data points), but there was little difference for the two final crop stockings (illustrated by lines joining mean values) (Figure 9, and Appendix 4, Figures 35-36). The SAS procedure PROC GLM indicated that there was no significant difference between treatments at each site. However at both sites there is a very slight tendency for outerwood density to increase with final prune height. All pruning treatments were completed at least 10 years prior to the outerwood density cores being collected. A previous study [11] showed that pruning tended to increase mean wood density by up to 7% for two to three years after treatment.

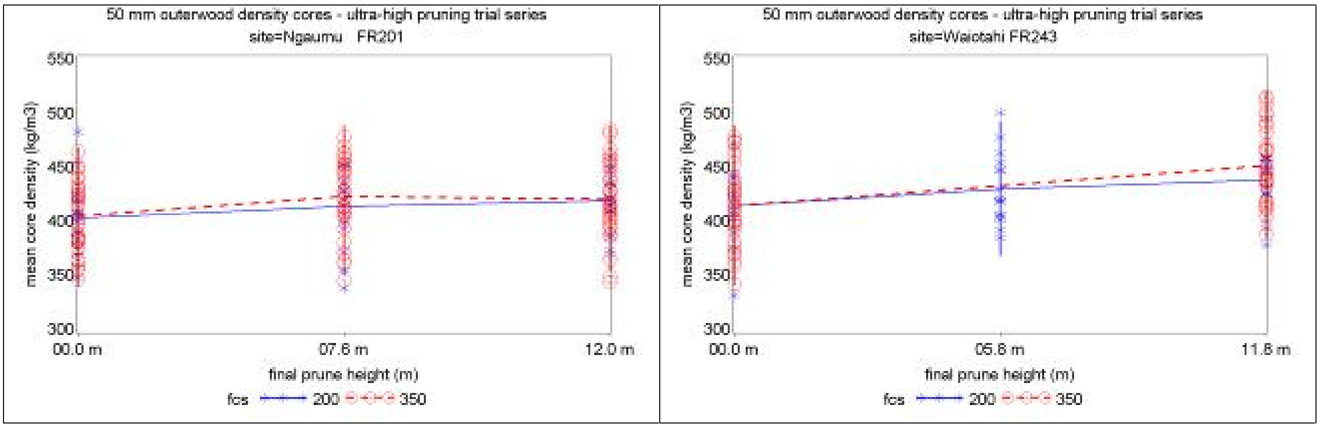


Figure 9. Individual tree mean outerwood core density for six different silvicultural treatments at Ngaumu and Waiotahi.

Within-tree Difference in Outerwood Density

The within-tree difference in outerwood density was highly variable within a treatment (Figure 10, Appendix 4, Figures 37-38). However there were no statistically significant differences between treatments within a site.

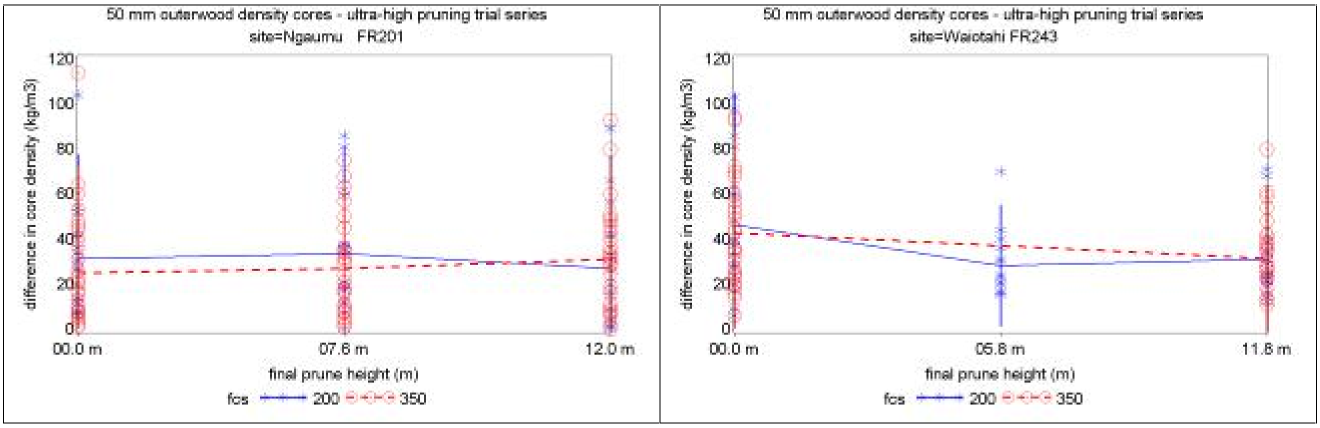


Figure 10. Within-tree difference in outerwood core density from six different silvicultural treatments at Ngaumu and Waiotahi.

Relationship with Stem Dimensions – Tree Mean Outerwood Density

Tree mean outerwood core density averaged over 10 cm DBH classes and 2 cm DBH increment classes is shown in Figure 11. These curves indicate that density tends to be slightly higher at Waiotahi (the sheltered site) than at Ngaumu (the windy site), in agreement with 1990 trial results. The curvilinear relationship with DBH class, observed in the 1990 silviculture breed trials, is also observed at Waiotahi, but not at Ngaumu. The curvilinear relationship with DBH increment class observed in the 1990 silviculture breed trials is also observed at both Ngaumu and Waiotahi. Fitting quadratic regression equations to the raw data confirmed the significance of the observed quadratic relationships.

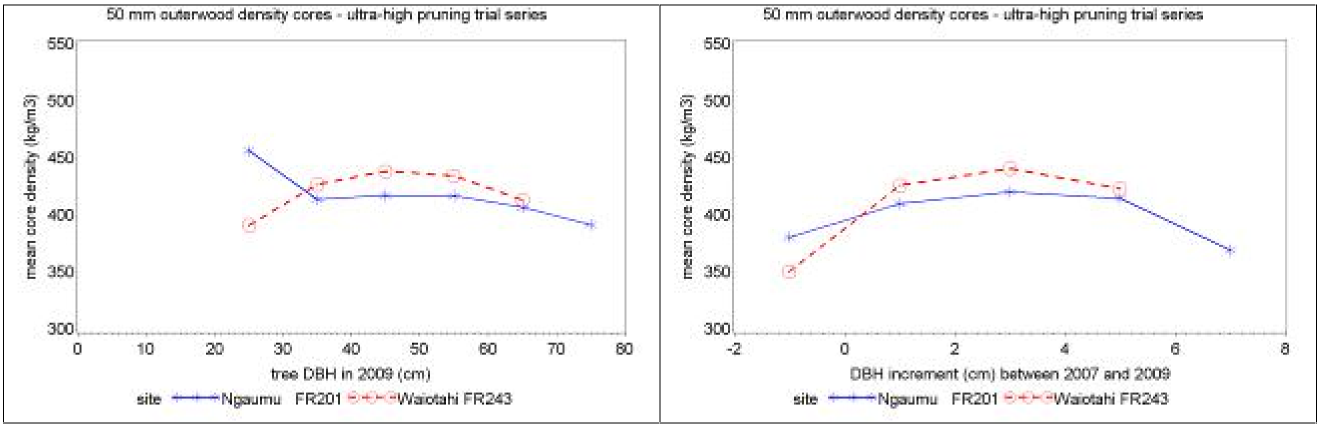


Figure 11. Mean core density for individual sites averaged over 10 cm DBH classes and 2 cm DBH increment classes.

Relationship with Stem Dimensions – Difference in Outerwood Density

The within-tree difference in outerwood core density averaged over 10 cm DBH classes and 2 cm DBH increment classes is shown in Figure 12. There is not a consistent relationship across DBH classes. However the within-tree difference tends to increase with increasing DBH increment at these two sites. This indicates that outerwood density is likely to be more variable for larger trees. This trend was not obvious in the 1990 silviculture breed trials.

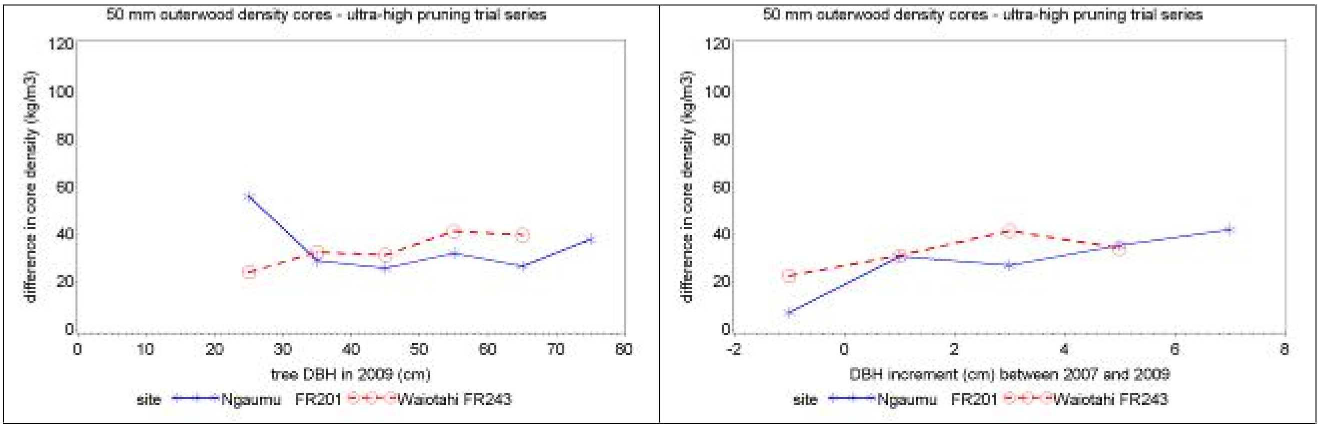


Figure 12. Within-tree difference in core density for individual sites averaged over 10 cm DBH classes and 2 cm DBH increment classes.

Relationship between Standing Tree Velocity and 50 mm Outerwood Density

Considering the 1990 silviculture breed trials together, there is a slight curvilinear relationship between individual tree mean outerwood density and standing tree velocity (Figure 13). The relationship clearly varies with site, and the correlation is always positive. The following non-linear model was fitted to the data:

$$\text{Mean core density} = a + b \times \text{standing tree velocity}^{c}$$

Where a, b, c are the fitted model coefficients.

Examination of the model residuals, both graphically and using the SAS procedure PROC GLM, indicated that the relationship between the tree mean outerwood density and standing tree velocity varies with site, seedlot and final crop stocking. This means that it is not appropriate to fit one relationship between these two variables.

In the ultra-high pruning trials, the trend appears linear rather than curvilinear with little difference between the two sites (Figure 13). The following linear model was fitted to the data:

$$\text{Mean core density} = a + b \times \text{standing tree velocity}$$

Where a, and b are the fitted model coefficients.

Examination of the model residuals, both graphically and using the SAS procedure PROC GLM, indicated that there were no significant differences between sites, final crop stocking and pruned height.

These results mean that there is no simple country-wide relationship between outerwood density and standing tree sonic velocity, and the relationship needs to be determined for each site × seedlot × silvicultural treatment. Further data covering a far wider range of sites, silviculture, treatments and seedlots will allow for a better understanding of country-wide variability in the relationship.

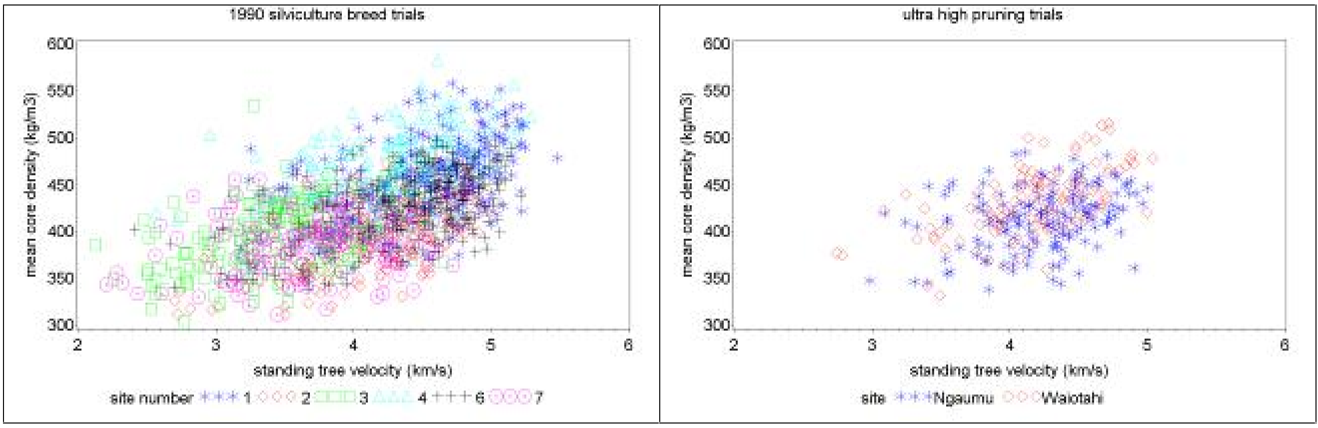


Figure 13. Relationship between individual tree mean outerwood core density and standing tree velocity.

DISCUSSION

Trees need to be mechanically reliable to grow and survive over a rotation. Trees adjust their mechanical properties through the addition of new cells and through the structure of these new cells[12]. Both tree flexure (when the stem moves in response to wind and returns to a vertical position), and lean correction (which occurs when a stem has been "permanently" displaced from the vertical) contribute to varying cell structures [4]. Cell structure changes that occur with tree movement and compression wood formation include increased density and lower stiffness.

Density and stiffness are two important wood properties for the forest industry. Methods have been developed by WQI to predict outerwood density and standing tree velocity from topographic and growth variables [9] [13]. It is assumed that the density model does not account for compression wood, as the generally accepted method of collecting outerwood density has been to avoid compression wood. Density is important to the calculation of carbon stored in forests, and within stem variability in wood properties is particularly important when the wood is processed.

Outerwood Density

This study differed from many other studies, in that compression wood was deliberately sampled in order to provide an indication of within-tree circumferential variability. The within-tree difference in outerwood density was higher on known windy sites. On some sites there was a trend for the within-tree difference in outerwood density to increase with increasing DBH. A previous study [14] indicated that the average compression wood in a tree tended to increase with increasing DBH. Hence tree size and site conditions are two variables that influence within-stem variability in wood properties.

There were a few treatments for which the variance for within-tree difference in outerwood density was particularly high. Lack of replication within the trial precluded determining whether the high variances where due to location within the trial.

Tree mean outerwood density tended to be higher on more northern sites as found in previous studies [8] [9]. The current data also indicated that tree mean outerwood density was lower on the windy sites, and was influenced by seedlot but not by the two final crop stockings considered.

There was an indication of a slight curvilinear relationship between tree mean outerwood density and DBH, which may explain why final crop stocking was not significant in this study. It is probable that the curvilinear relationship is a result of using 50 mm outerwood cores (which means the number of growth rings sampled will vary with tree DBH). The relevance of this curvilinear relationships needs to be confirmed or otherwise by examining the relationship between tree DBH and five-ring outerwood density for one or more of these sites.

A similar study in the 1987 silviculture breed trials [6], when the trees were 16.5 years old, used five-ring rather than 50 mm cores. In contrast to the current study, outerwood density was found to increase with increasing stocking. We need to determine whether the difference between studies is due to the core type or the particular sites sampled. In agreement with this study, there were differences between seedlots and also more exposed sites tended to have more compression wood than more sheltered sites (i.e., likely to be more variation in outerwood density).

Relationship between Outerwood Density and Standing Tree Velocity

Both standing tree velocity and mean outerwood density are highly variable for a given treatment. Statistical analysis showed the mean outerwood density was related to seedlot but not final crop stocking, whereas the comparable statistical analysis of the standing tree velocity data indicated that standing tree velocity was influenced by stocking and not seedlot. Overall there was a slight curvilinear relationship between the two variables and, in the 1990 silviculture breed trials, the relationship between the two variables varied with site, silviculture treatment and seedlot; i.e., the relationship between the two measures is complex.

Breast-height SilviScan data from the 1975 final crop stocking trials [15] indicated that the difference in ring average microfibril angle (related to standing tree sonic velocity) between different final crop stockings tended to decrease with increasing time from silviculture, whereas treatment differences in ring average density tended to be maintained. These results suggest that the observed relationship between outerwood density and standing tree sonic velocity is likely to depend on tree age; i.e., if these variables are sampled in trials, then they need to be sampled at fixed ages for comparative purposes.

These SilviScan data also indicated that responses to silvicultural treatment were greatest close to the time of silviculture, and that microfibril angle showed a far greater response than density. The authors therefore recommend that pith-to-bark cores analysed using SilviScan to provide microfibril angle, density and estimated modulus of elasticity are far more useful than outerwood density cores and standing tree velocity if one wishes to understand the response to silvicultural treatment.

CONCLUSION

The value of routine collection of outerwood density cores and standing tree velocity for characterising variability with respect to site, silvicultural treatment and/or material planted needs to be carefully considered. There are pluses and minuses.

This and previous studies have indicated complex relationships between sites, silviculture and genetic material planted. This is the first study where the directions of the outerwood density cores have been chosen to measure within-tree variability rather than the previous, biased approach of avoiding compression wood. Only a limited number of combinations of site × silviculture treatment × material planted were sampled on North Island sites. More data would provide a better understanding of the country-wide patterns of variability (and averages), and such knowledge will become increasingly important for estimating carbon stocks.

Other studies have shown that there are strong trends in wood properties with tree age, so routine non-destructive assessment of outerwood density and standing tree velocity will need to be at specified age(s). As the data from the 1990 silviculture breed trials were collected at age 19 years, and a comparable series of trials was planted in 1991, the authors recommend that this age be selected as an age to sample around mid-rotation.

There are also changes in wood properties with silviculture. For example microfibril angle has been found to increase immediately after silviculture, and the differences between treatments to decrease with time. A better understanding of responses to silvicultural treatment would be obtained by using pith-to-bark cores analysed using SilviScan to provide microfibril angle, density and estimated modulus of elasticity. The authors recommend the use of SilviScan in preference to outerwood density and standing tree velocity measurements for understanding the complex interactions between sites, silvicultural treatment, genetic material planted and tree age.

As within-tree variability is important, the authors recommend that the sampling directions be changed to above and below any stem lean, rather than at right angles to any lean. To create a link between new and previous data outerwood density data, four cores should be collected on a number of sites with a range of different exposures. For the sheltered site sampled in this study, there was little difference in sampling with or at right angles to any stem lean.

On the negative side, taking a core creates a wound that the tree will need to heal. Pith-to-bark cores will create a bigger wound than 50 mm cores. Whether this has any measurable impact on tree growth needs to be investigated. Visually there are changes (Appendix 5, Figure 41). This is particularly important for trials which are designed for monitoring tree growth. For example, in a separate study, several cores have been collected from only the GF7 seedlot in several trials including the 1987 silviculture breed trials. If there is an impact on the growth of the GF7 seedlot, then this will impact on the estimated gain for other seedlots. Growth in the 1987 silviculture breed trials in response to the latest coring (in 2010) needs to be monitored.

Outerwood density cores and standing tree sonics sample only a very small portion of the stem. Pith-to-bark cores sample slightly more of the stem, but have the advantage of sampling wood formed around the time of silviculture treatment. It would be useful if there were other external variables that could be measured that would provide an idea of within-stem variability in wood properties. Stem shape is not appropriate, as straight trees may be full of compression wood [10]. Branch dimensions may be useful, as compression wood was found to be more frequent under large branches[15]. Also the size and angle of branches attached to the main stem provide some clues as to the previous history of the stem (i.e., whether there has been a change in leader and in consequence compression wood).

It would be interesting to know the relative importance of wood properties compared to stem form and branching patterns in determining the usefulness of a particular stem.

Overall, there seem to be more advantages than disadvantages to collecting cores from standing trees. Pith-to-bark cores analysed using SilviScan provide more information and are recommended in preference to outerwood density cores and standing tree sonic velocity.

The authors recommend the following:

- Pith-to-bark cores (to be analysed using SilviScan) are collected in preference to outerwood density cores and standing tree velocity in the 1991 silviculture breed trials at age 19 years (i.e. NOW) to provide a better understanding of the countrywide variation and relationships between density, microfibril angle and modulus of elasticity. (All the 1990 series were in the North Island. The 1991 trials include South Island sites). Branching data (TreeD) should be collected at the same time to allow the investigation of links between branching and wood properties.
- Pith-to-bark cores (to be analysed using SilviScan) are collected in the 1992 and 1994 special purpose breed trials at their next re-measurement. These are the first growth-monitoring trials containing seedlots selected for improved wood properties, and we need to know whether relationships developed using other seedlots will hold for these seedlots.
- The 1987 silviculture-breed trials continue to be monitored to determine the impact of cores collected in 2010 on future growth.
- Five-ring outerwood density be determined for one or more of the 1990 silviculture breed trials to confirm whether the observed curvilinear trends with stem dimensions is true, or an artefact of using 50 mm cores.
- That the recommendations on when to use five-ring or 50 mm outerwood density cores are revisited.
- In future outerwood and pith-bark density cores are sampled to record, rather than avoid within-stem variability.
- In future PSPs are of a sufficient size to contain a minimum of 30 trees at the end of the rotation in order to provide sufficient trees for sampling wood properties.

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REFERENCES

1. Grace, J.C. and Bennett, J. *Graphical data analysis: standing tree sonic velocity in the 1990 silviculture breed and ultra-high pruning trials.* FFR Report R052. 2010.
2. Hayes, J.D. *Trials designed to quantify growth and yield gains from genetically improved radiata pine - Fourth revision.* Stand Growth Modelling Cooperative, Report 100. 2001.
3. Hayes, J.D. *Workplans for trials with genetically improved radiata pine planted between 1978 and 1994.* Stand Growth Modelling Cooperative, Report 103. 2001.
4. Telewski, F.W., *Structure and function of flexure wood in Abies fraseri.* Tree Physiology, 1989. **5**: p. 113-121.
5. Dean, M. *Second log pruning trials - installation report.* Plantation Management Cooperative, Report 22. 1995.
6. Carson, S., Cown, D., Hayes, J.D., Carson, M., McKinley, R. and Lee, J. *Effects of site and silviculture on density, sound velocity, and compression wood- analyses of data from the 1987 silviculture/breed trials.* Wood Quality Initiative Report RES 25. 2004.
7. Smith, D.M. *Maximum moisture content method for determining specific gravity of small wood samples.* US Forest Service, Forest Products Laboratory, Paper No. 2014. 1954.
8. Cown, D.J. and McConchie, D.L. *Radiata pine wood properties survey (1977-1982).* FRI Bulletin No. 50. 1983.
9. Woollons, R. and Manley, B. *Prediction of stand breast height outer wood density through topographic and growth predictor variables.* Wood Quality Initiative Report INT 15. 2008.
10. Burdon, R.D., *Compression wood in Pinus radiata clones on four different sites.* New Zealand Journal of Forestry Science, 1975. **5**(2): p. 152-164.
11. Cown, D.J., *Effects of severe thinning and pruning treatments on the intrinsic wood properties of young radiata pine.* New Zealand Journal of Forestry Science, 1973. **3**(3): p. 379-389.
12. Wilson, B.F. and Archer, R.R., *Tree Design: Some biological solutions to mechanical problems.* BioScience, 1979. **29**: p. 293-298.
13. Woollons, R. and Manley, B. *Prediction of average ST300 standing tree accoustic velocity through topographic and stand growth predictor variables.* Wood Quality Initiative Report INT 16. 2008.
14. Grace, J.C., Pont, D., Brownlie, R.K. and Hayes, J.D. *Compression wood in stems: Influence of site, stem form and clone.* Wood Quality Initiative, Report STA 14. 2004.
15. Grace, J.C., McKinley, R., Cown, D. and Lee, J. *1975 Final crop stocking trials: Assessment of crown and wood properties for trees from different silvicultural treatments.* FFR Report R020. 2009.

APPENDICES

APPENDIX 1. List of Permanent Sample Plots in the 1990 Silviculture Breed Trials for which outerwood density data were collected.

Treatments sampled: **FR121/1, Tungrove (site number 1)**

Plot Number	Number of trees	Initial/final stocking	Seedlot
8/12	19	500/200	GF25 ‘268’ control-pollinated
5/12	20	500/200	GF16 ‘268’ open-pollinated
4/12	20	500/200	GF14 ‘850’ open-pollinated
6/12	20	500/200	GF7
7/12	20	500/200	GF13/LI25
20/17	38	1000/1000	GF25 ‘268’ control-pollinated
21/17	44	1000/1000	GF16 ‘268’ open-pollinated
19/17	31	1000/1000	GF14 ‘850’ open-pollinated
22/17	37	1000/1000	GF7
16/17	41	1000/1000	GF13/LI25

Treatments sampled: **FR121/2, Atiamuri/Kinleith (site number 2)**

Plot Number	Number of trees	Initial/final stocking	Seedlot
3/12	20	500/200	GF25 ‘268’ control-pollinated
10/12	19	500/200	GF16 ‘268’ open-pollinated
4/12	20	500/200	GF14 ‘850’ open-pollinated
8/12	20	500/200	GF7
9/12	20	500/200	GF13/LI25
28/17	43	1000/1000	GF25 ‘268’ control-pollinated
25/17	39	1000/1000	GF16 ‘268’ open-pollinated
29/17	36	1000/1000	GF14 ‘850’ open-pollinated
26/17	38	1000/1000	GF7
27/17	37	1000/1000	GF13/LI25

Treatments sampled: **FR121/3, Gwavas (site number 3)**

Plot Number	Number of trees	Initial/final stocking	Seedlot
4/12	15	500/200	GF25 ‘268’ control-pollinated
6/12	19	500/200	GF16 ‘268’ open-pollinated
5/12	16	500/200	GF14 ‘850’ open-pollinated
10/12	19	500/200	GF7
11/12	19	500/200	GF13/LI25
20/16	33	1000/1000	GF25 ‘268’ control-pollinated
22/16	21	1000/1000	GF16 ‘268’ open-pollinated
19/16	43	1000/1000	GF14 ‘850’ open-pollinated
21/16	32	1000/1000	GF7
18/16	40	1000/1000	GF13/LI25

Treatments sampled: **FR121/4, Tairua (site number 4)**

Plot Number	Number of trees	Initial/final stocking	Seedlot
4/12	18	500/200	GF25 ‘268’ control-pollinated
5/12	19	500/200	GF16 ‘268’ open-pollinated
6/12	18	500/200	GF14 ‘850’ open-pollinated
3/12	16	500/200	GF7
18/17	34	1000/1000	GF25 ‘268’ control- pollinated
17/17	40	1000/1000	GF16 ‘268’ open-pollinated
15/17	21	1000/1000	GF14 ‘850’ open-pollinated
16/17	28	1000/1000	GF7

Treatments sampled: **FR121/6, Tarawera (site number 6)**

Plot Number	Number of trees	Initial/final stocking	Seedlot
4/12	20	500/200	GF25 ‘268’ control-pollinated
12/12	19	500/200	GF16 ‘268’ open-pollinated
5/12	20	500/200	GF14 ‘850’ open-pollinated
6/12	19	500/200	GF7
11/12	20	500/200	GF13/LI25
24/17	41	1000/1000	GF25 ‘268’ control-pollinated
20/17	40	1000/1000	GF16 ‘268’ open-pollinated
21/17	41	1000/1000	GF14 ‘850’ open-pollinated
23/17	42	1000/1000	GF7
25/17	41	1000/1000	GF13/LI25

Treatments sampled: **FR121/7, Huanui (site number 7)**

Plot Number	Number of trees	Initial/final stocking	Seedlot
6/12	18	500/200	GF25 ‘268’ control-pollinated
5/12	14	500/200	GF16 ‘268’ open-pollinated
3/12	16	500/200	GF14 ‘850’ open-pollinated
4/12	18	500/200	GF7
16/17	38	1000/1000	GF25 ‘268’ control-pollinated
17/17	38	1000/1000	GF16 ‘268’ open-pollinated
18/17	29	1000/1000	GF14 ‘850’ open-pollinated
15/17	38	1000/1000	GF7

APPENDIX 2. List of Permanent sample plots in the Ultra-high Pruning Trials for which outerwood density were collected.

Treatments sampled: Ngaumu, FR201 when trees were 24 years old

Plot Number	Number of trees	Final stocking (SPH)	Crown length remaining (m)	Final pruned height (m)
20/0/13	18	200	unpruned	0.0
20/49/1	19	200	4.9	7.6
20/49/10	19	200	4.9	12.0
35/0/16	35	350	unpruned	0.0
35/76/6	34	350	7.9	7.6
35/76/7	34	350	7.9	12.0

Note: all plots in this trial had received a pruning to approx. 4.0 m at age 6.5 years, prior to the experiment being established.

Treatments sampled Waiotahi, FR243, when trees were 21 years old

Plot Number	Number of trees	Final stocking (SPH)	Crown length remaining (m)	Final pruned height (m)
20/0/1	19	200	unpruned	0.0
20/49/22	18	200	4.9	5.8
20/49/14	18	200	4.9	11.8
35/0/17	29	350	unpruned	0.0
35/79/3	-	350	7.9	5.8
35/79/12	33	350	7.9	11.8

Note: The unpruned plots were not pruned during the experiment, but have since received an access pruning

APPENDIX 3. Outerwood Density in the 1990 Silviculture/breeds Trials

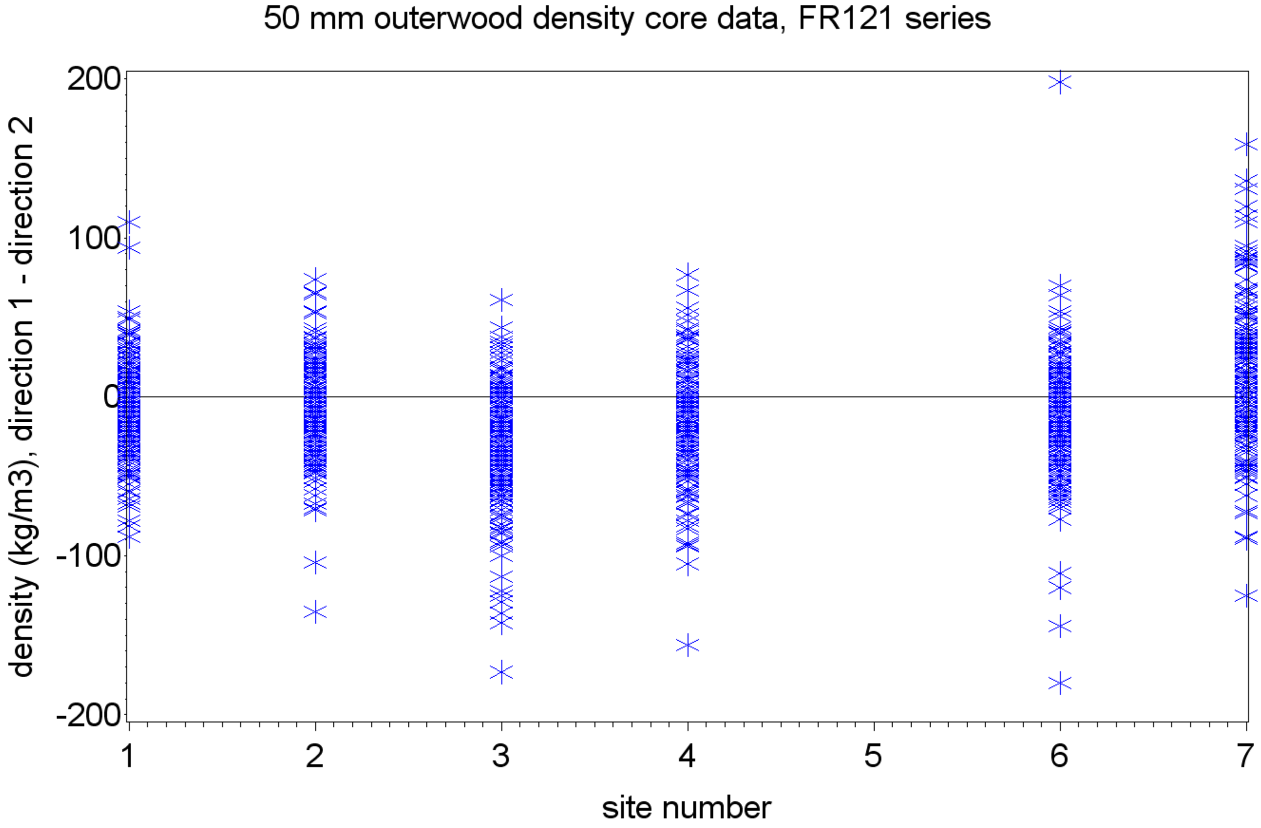

Figure 14. Difference in outerwood density, direction 1 (upper side of any lean) – direction 2 (lower side of any lean).

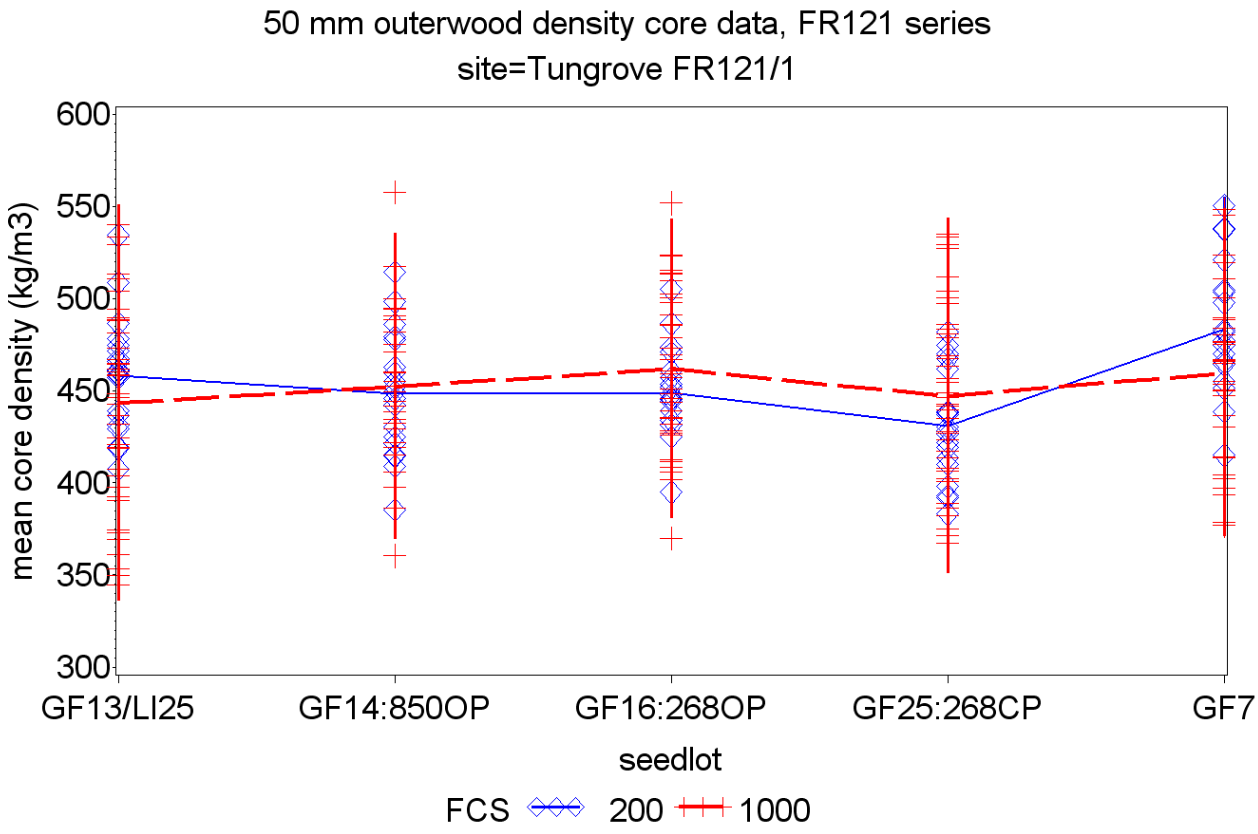

Figure 15. Mean 50 mm outerwood density for individual trees from different seedlots at two final crop stockings (FCS). The lines join the mean value for each seedlot and final crop stocking.

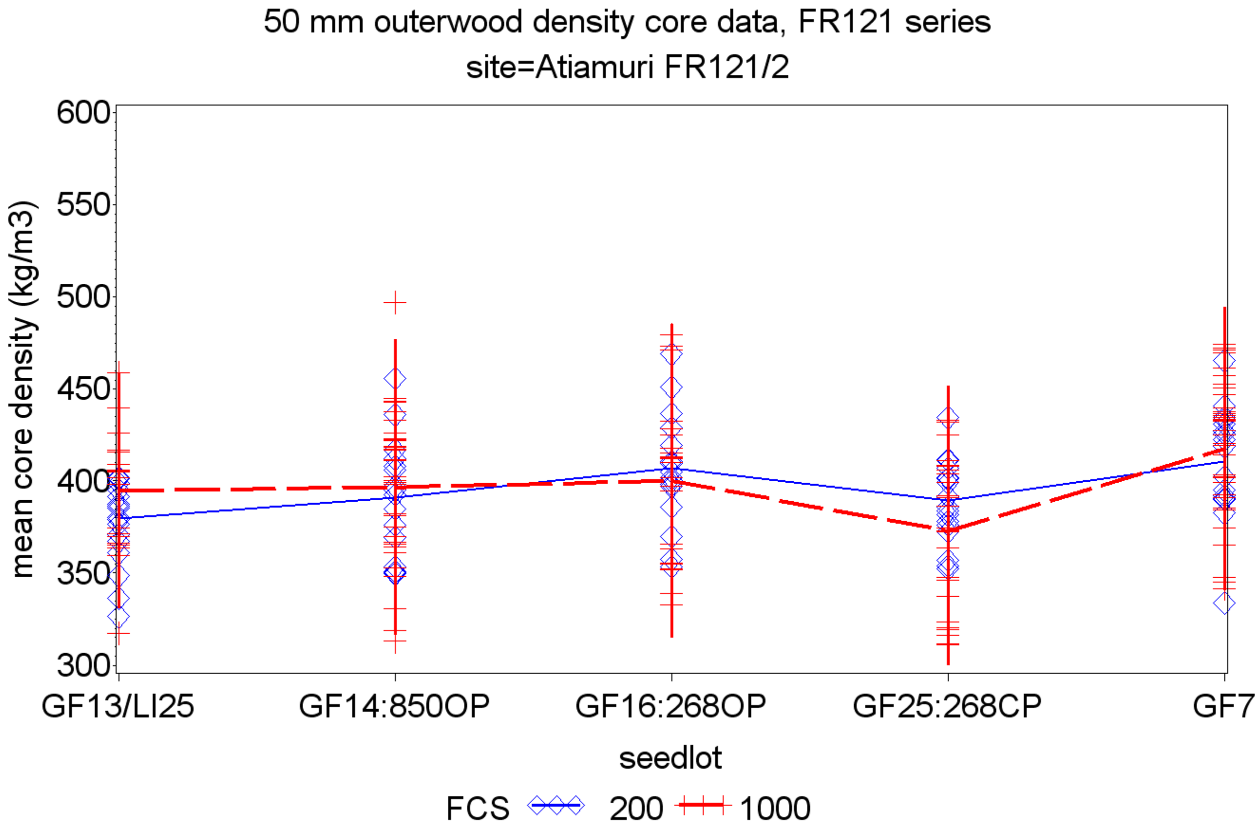

Figure 16. Mean 50 mm outerwood density for individual trees for different seedlots at two final crop stockings (FCS). The lines join the mean value for each seedlot and final crop stocking.

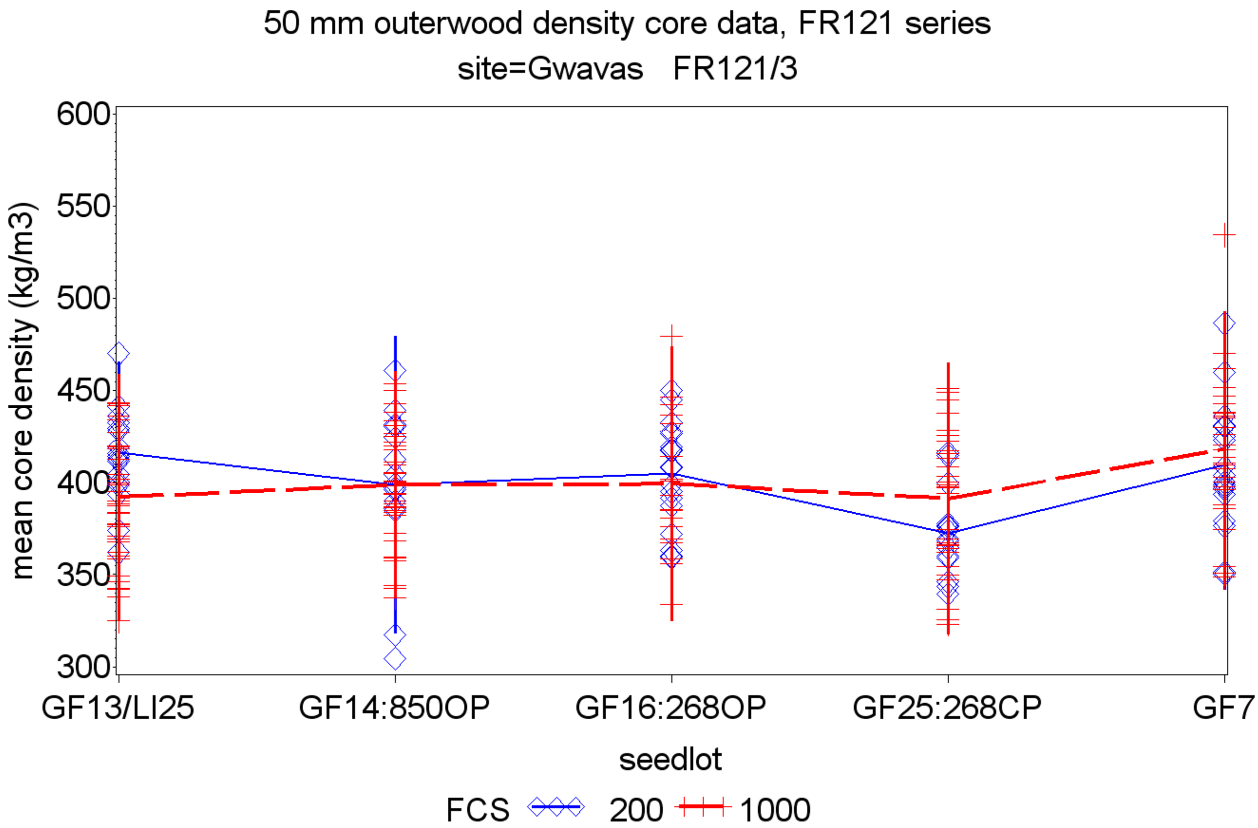

Figure 17. Mean 50 mm outerwood density for individual trees for different seedlots at two final crop stockings (FCS). The lines join the mean value for each seedlot and final crop stocking.

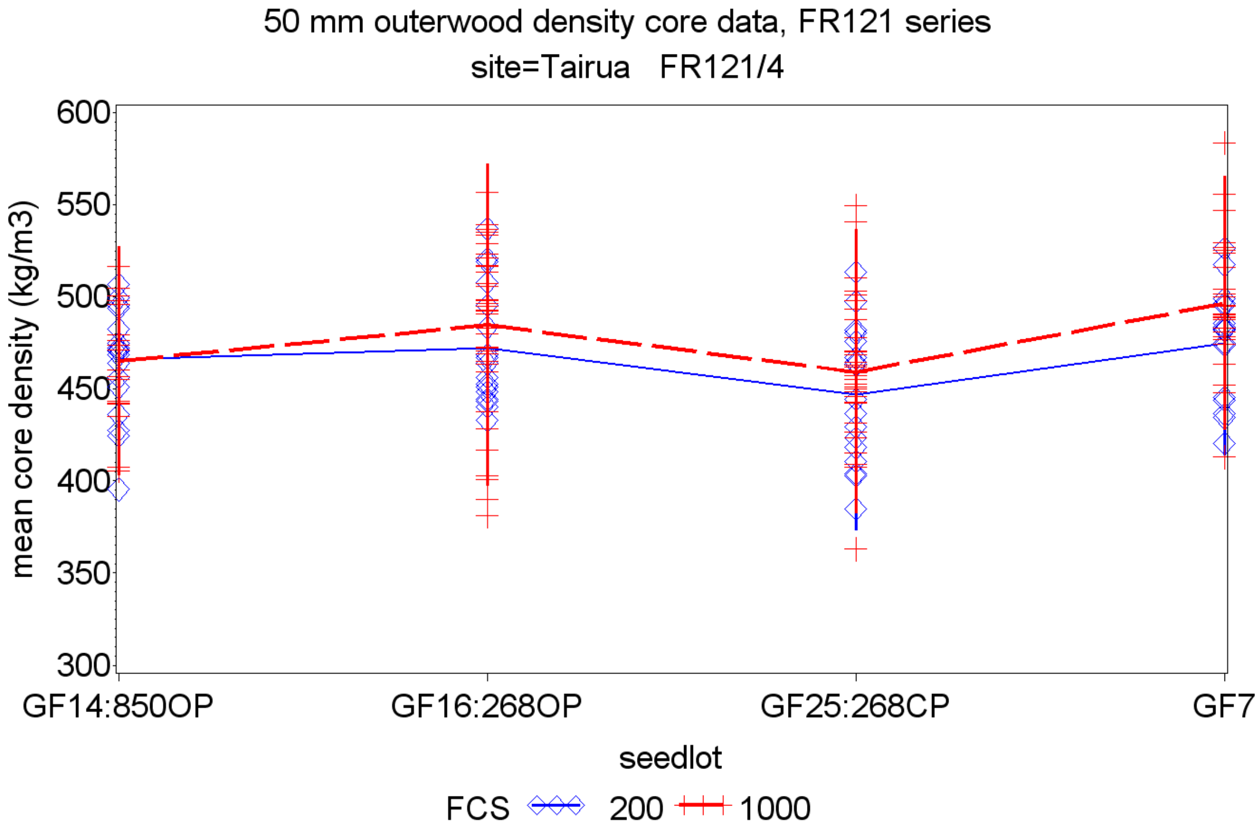

Figure 18. Mean 50 mm outerwood density for individual trees for different seedlots at two final crop stockings (FCS). The lines join the mean value for each seedlot and final crop stocking.

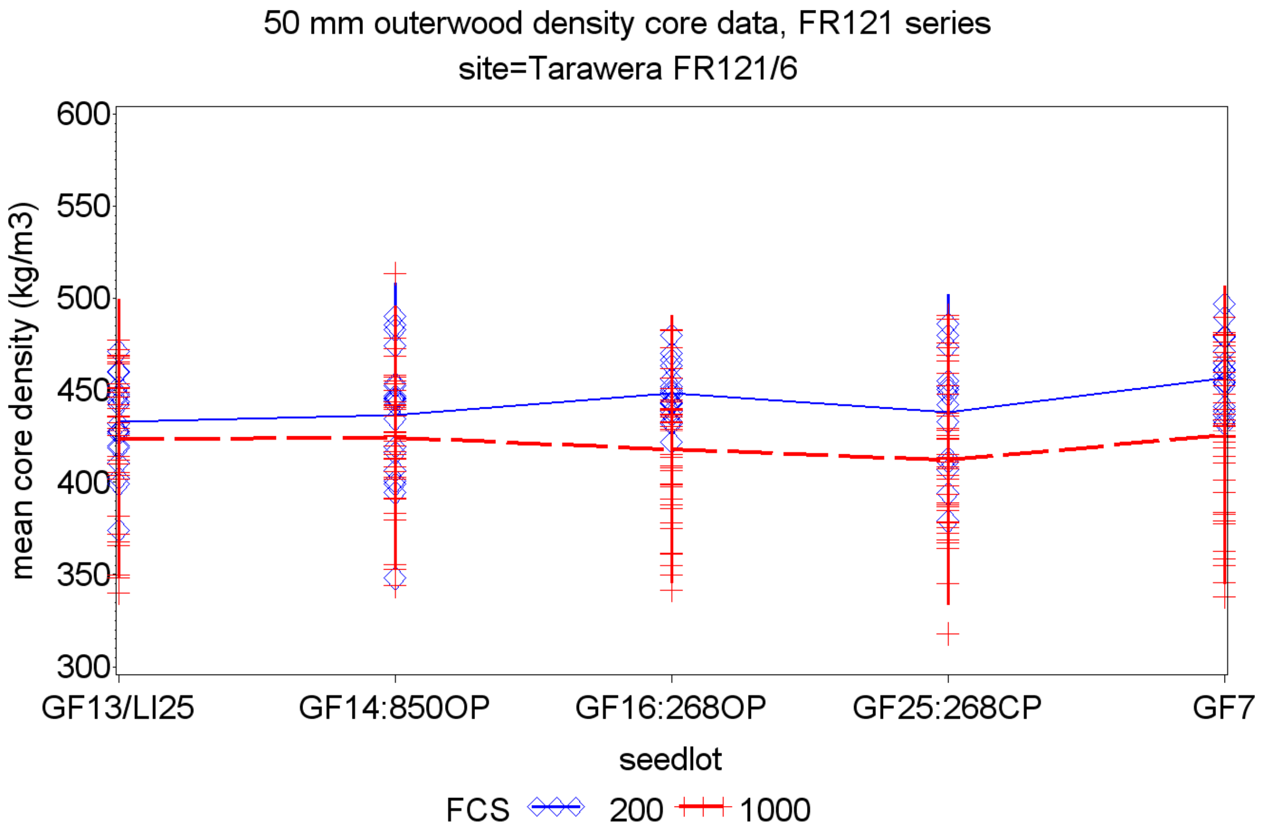

Figure 19. Mean 50 mm outerwood density for individual trees for different seedlots at two final crop stockings (FCS). The lines join the mean value for each seedlot and final crop stocking.

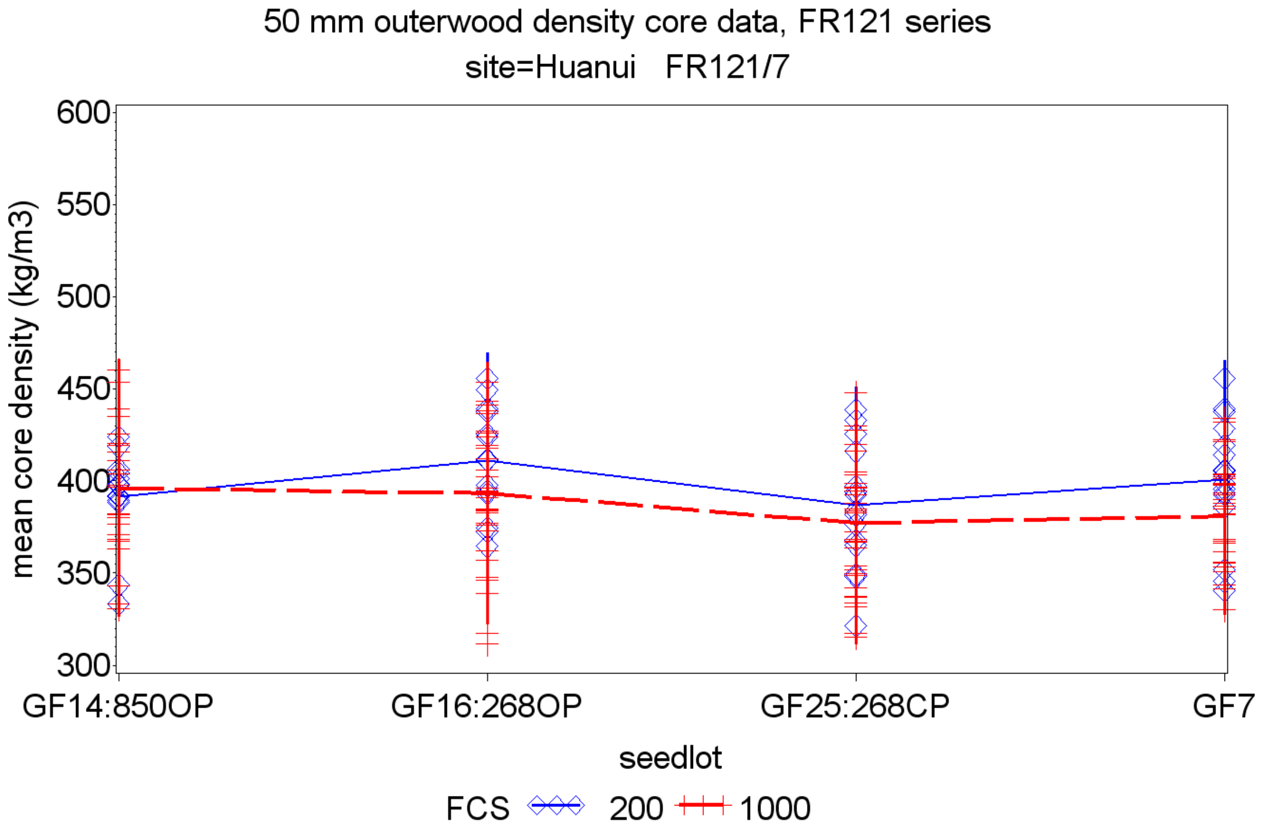

Figure 20. Mean 50 mm outerwood density for individual trees for different seedlots at two final crop stockings (FCS). The lines join the mean value for each seedlot and final crop stocking.

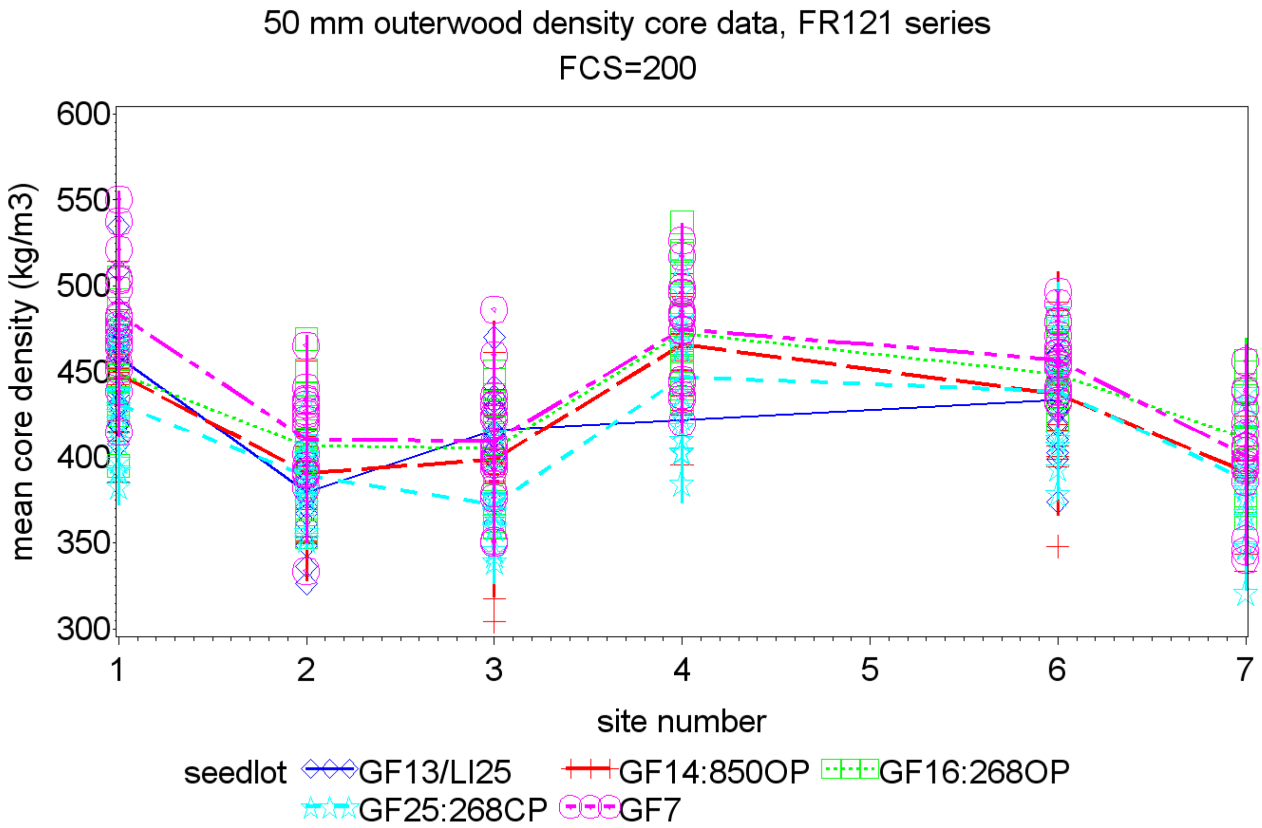

Figure 21. Variation in individual tree mean core density with site and seedlot for a final crop stocking (FCS) of 200 stems/ha.

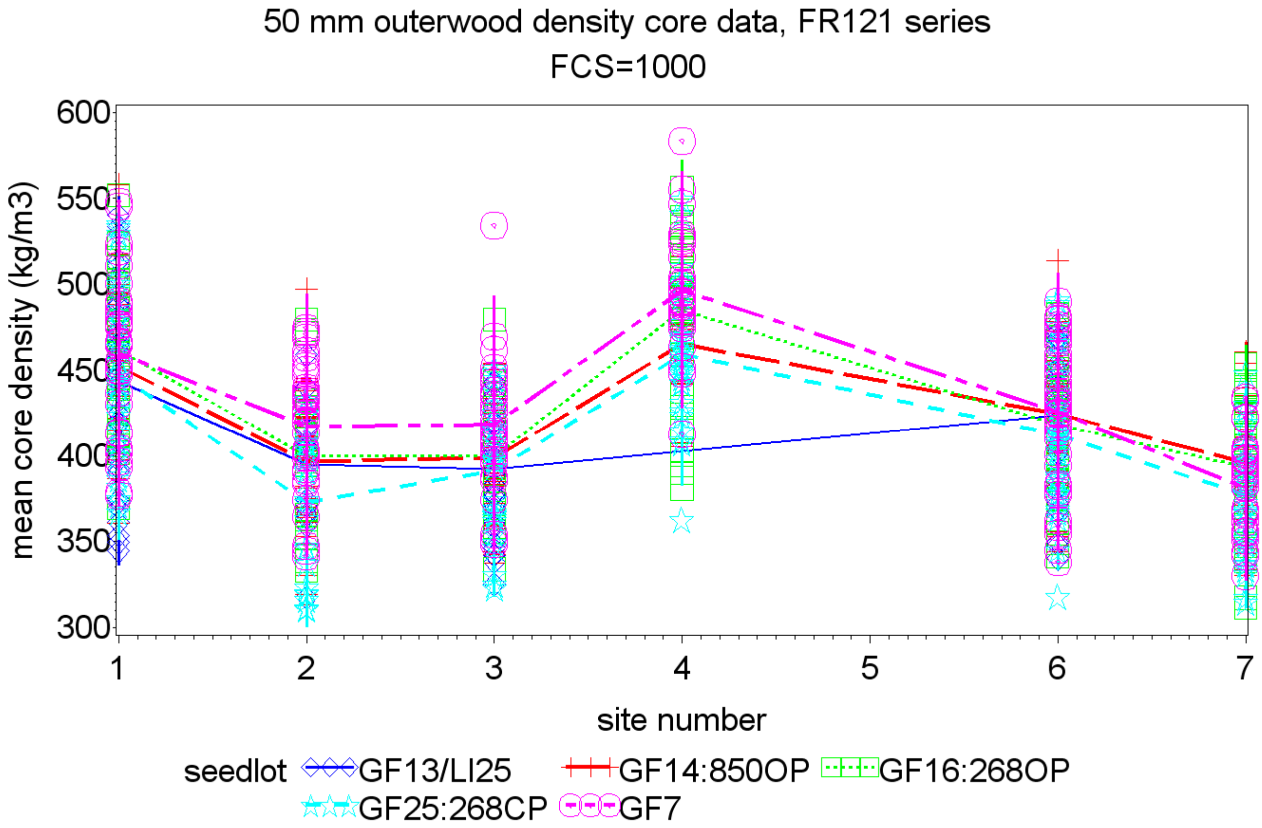

Figure 22. Variation in individual tree mean core density with site and seedlot for a final crop stocking (FCS) of 1000 stems/ha.

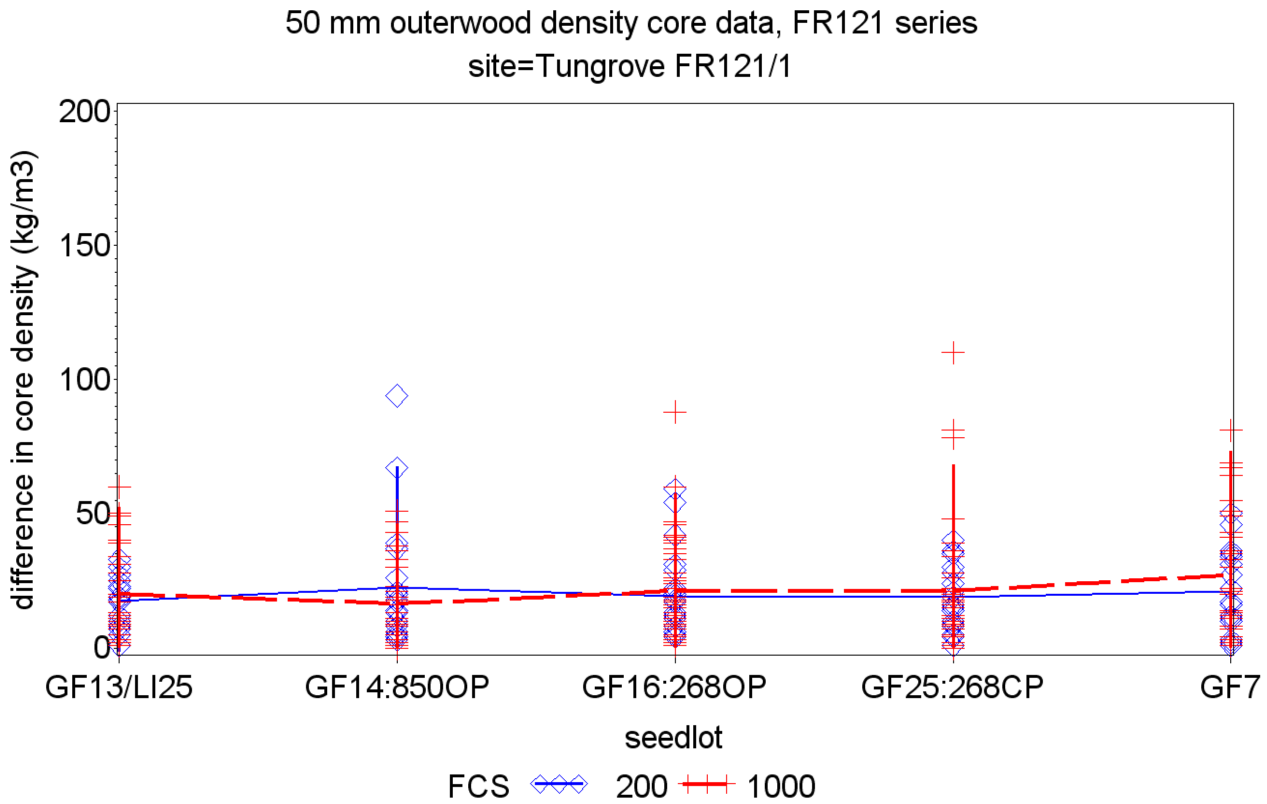

Figure 23. Difference in 50 mm outerwood density for individual trees for different seedlots at two final crop stockings (FCS). The lines join the mean value for each seedlot and final crop stocking.

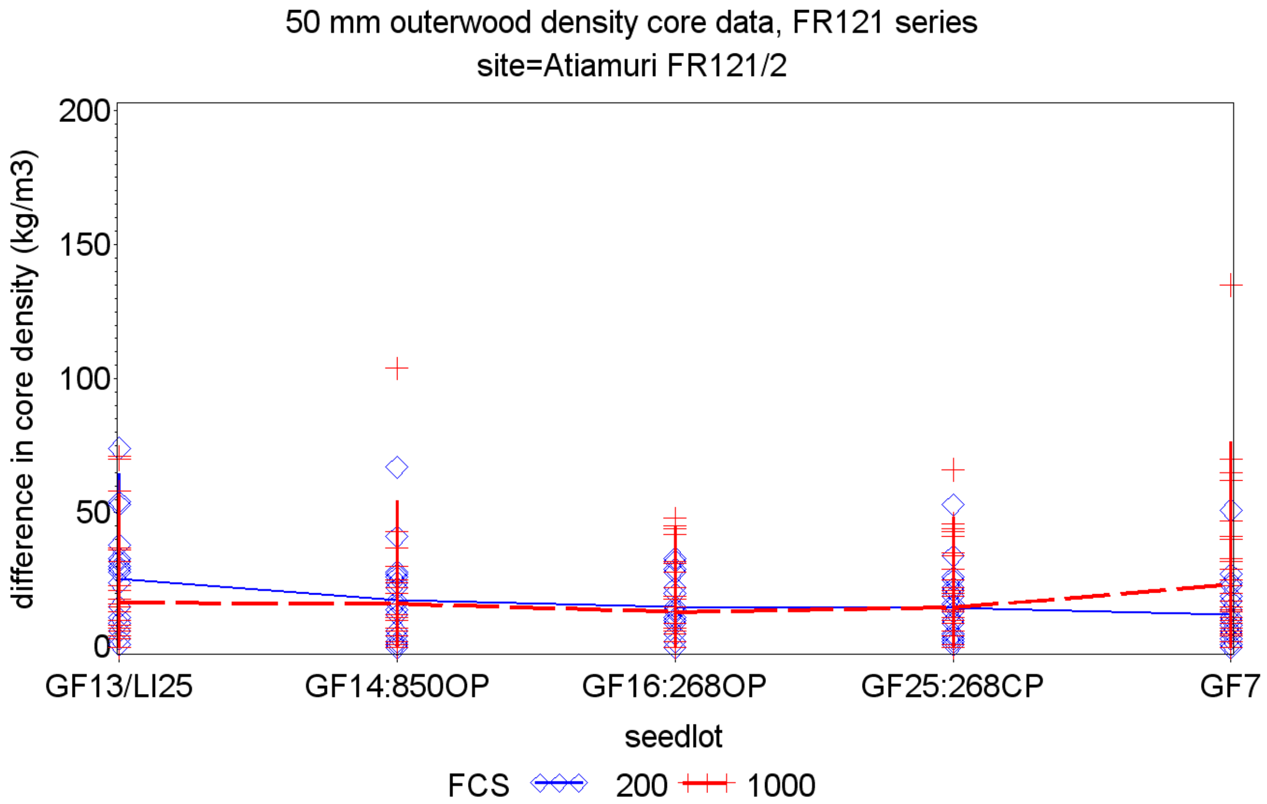

Figure 24. Difference in 50 mm outerwood density for individual trees for different seedlots at two final crop stockings (FCS). The lines join the mean value for each seedlot and final crop stocking.

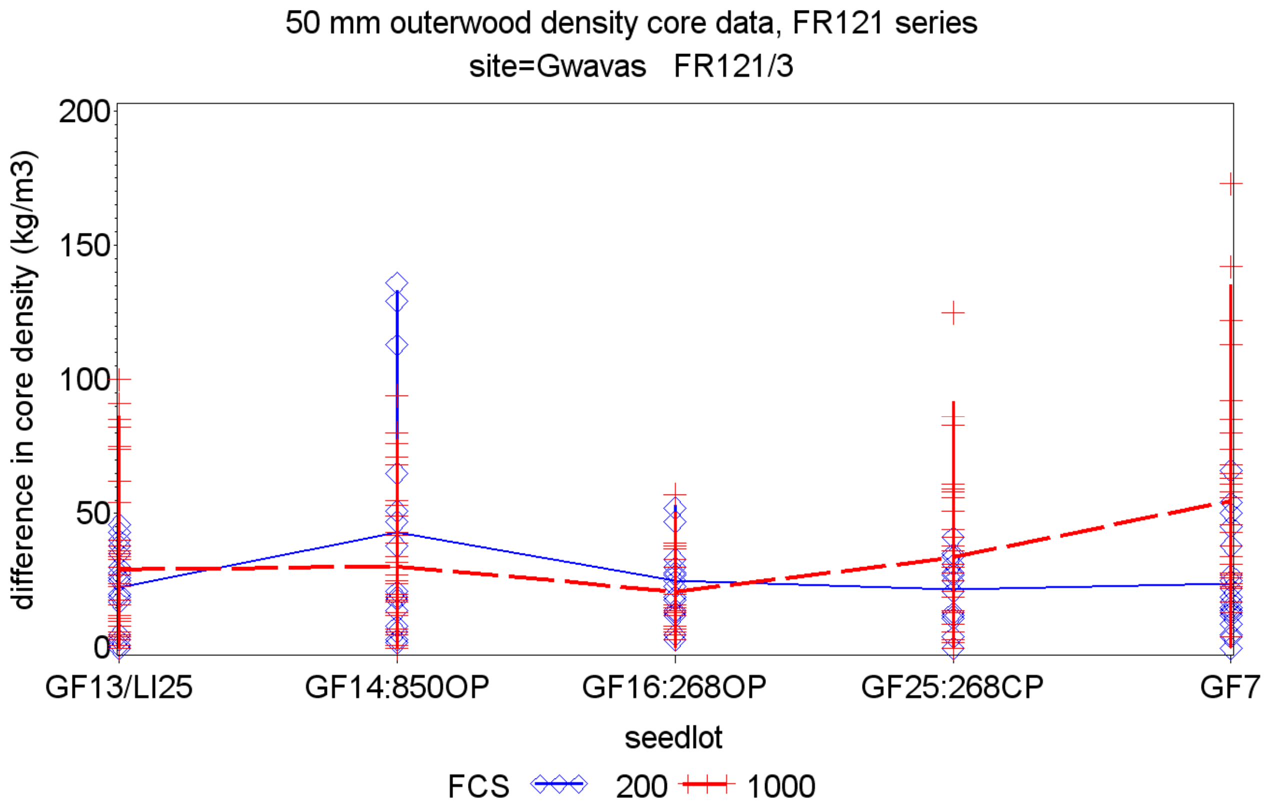

Figure 25. Difference in 50 mm outerwood density for individual trees for different seedlots at two final crop stockings (FCS). The lines join the mean value for each seedlot and final crop stocking.

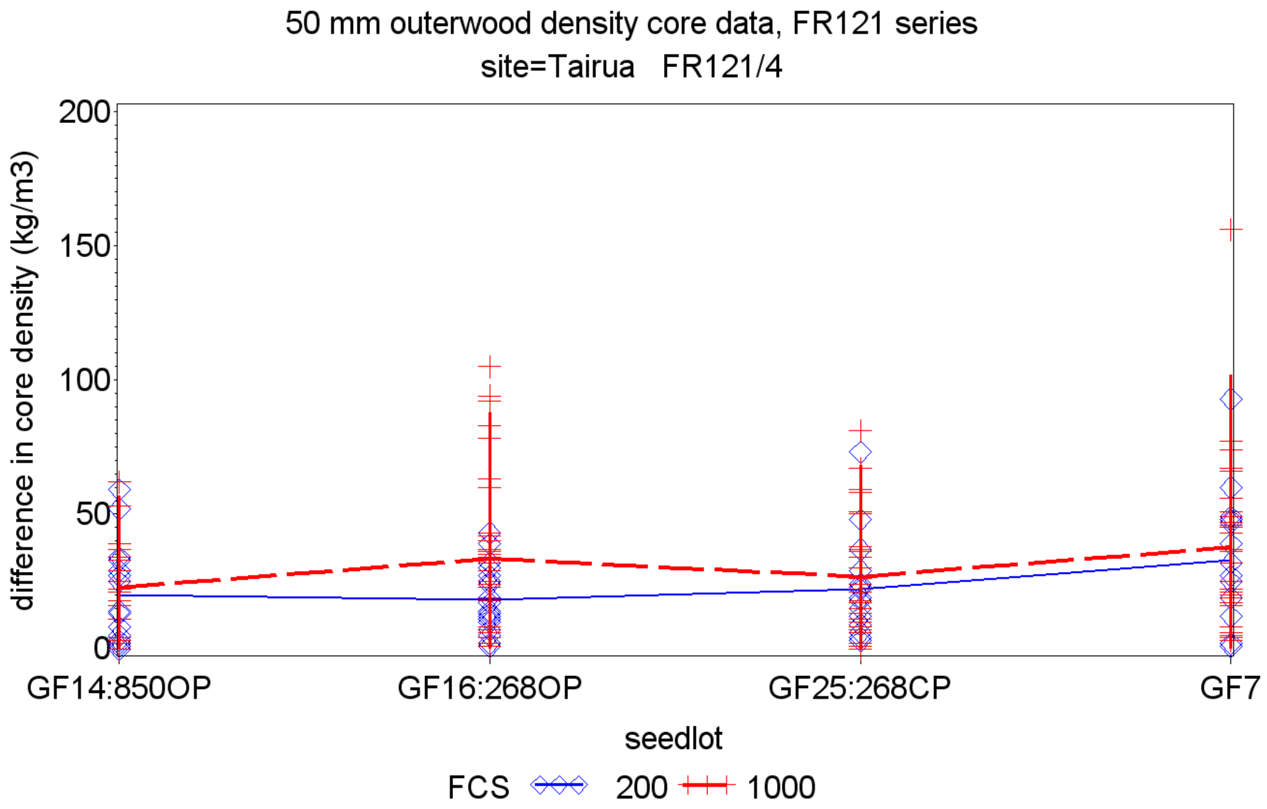

Figure 26. Difference in 50 mm outerwood density for individual trees for different seedlots at two final crop stockings (FCS). The lines join the mean value for each seedlot and final crop stocking.

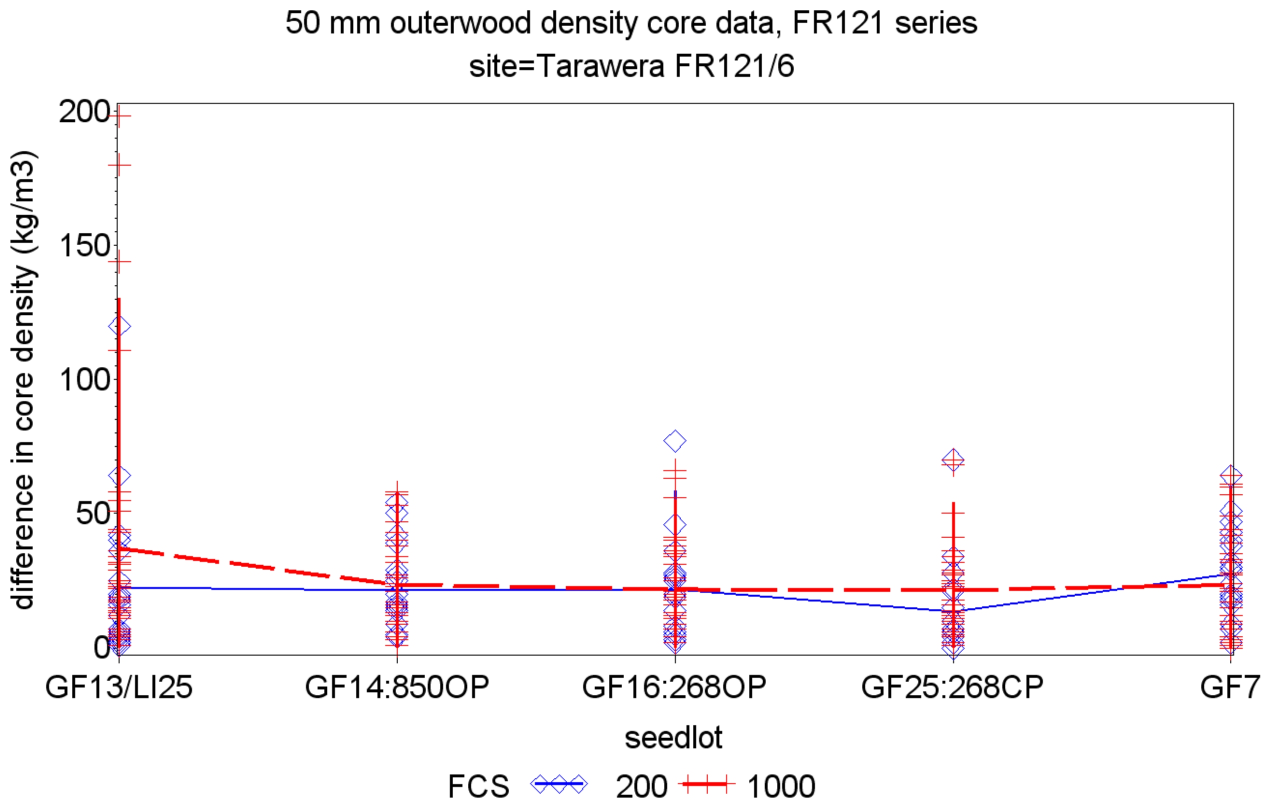

Figure 27 Difference in 50 mm outerwood density for individual trees for different seedlots at two final crop stockings (FCS). The lines join the mean value for each seedlot and final crop stocking.

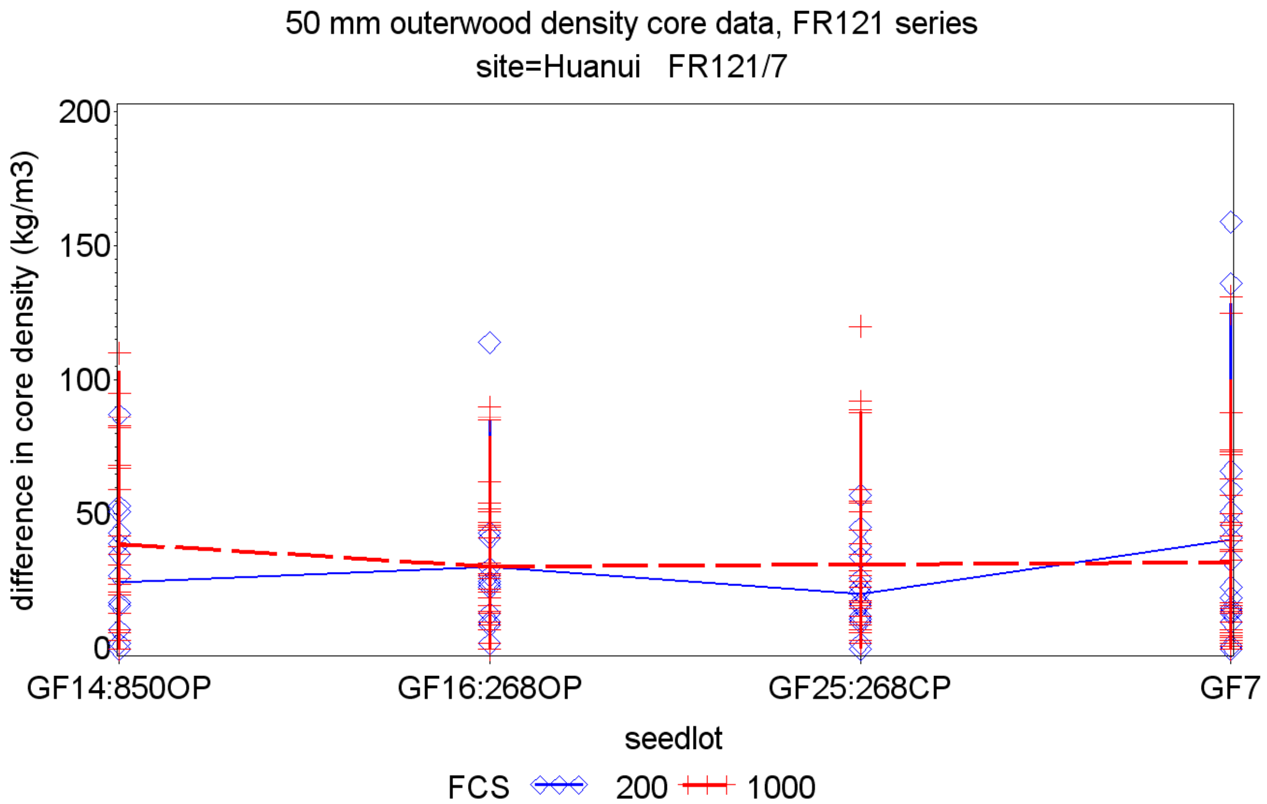

Figure 28. Difference in 50 mm outerwood density for individual trees for different seedlots at two final crop stockings (FCS). The lines join the mean value for each seedlot and final crop stocking.

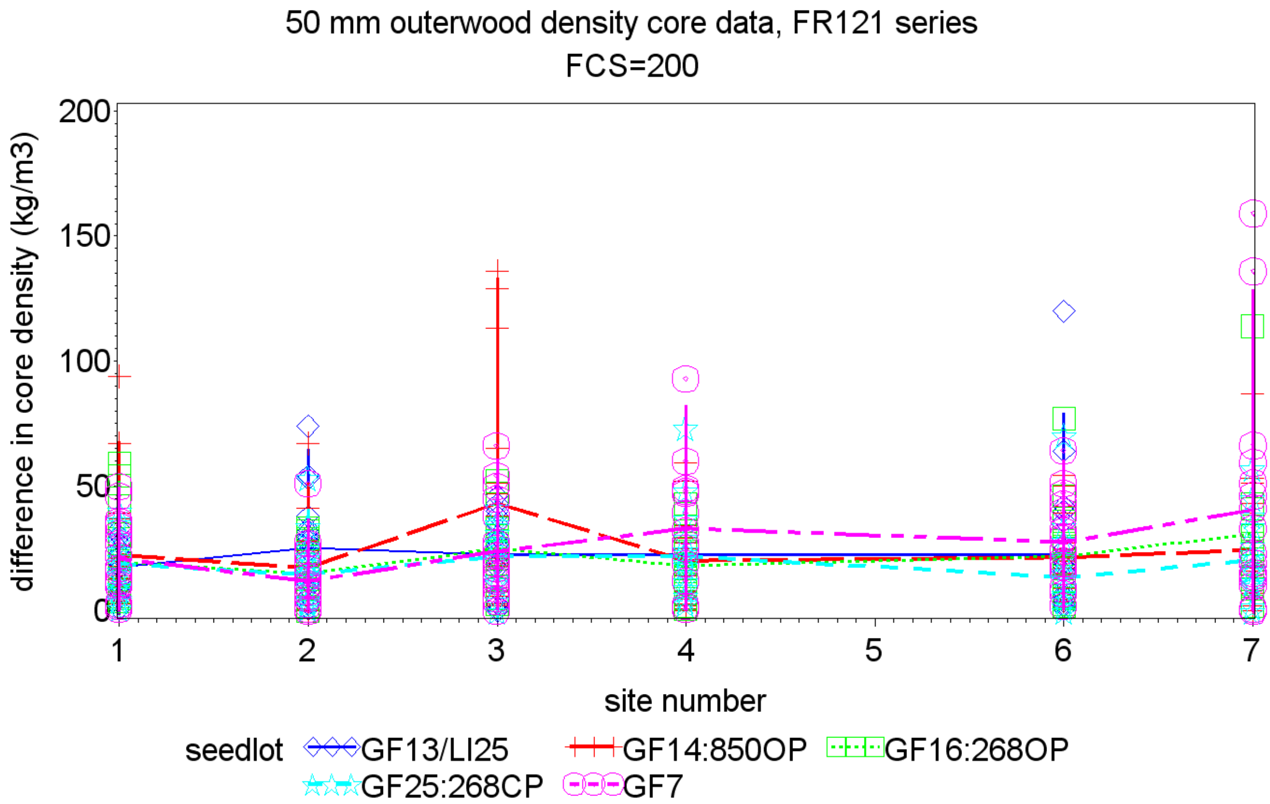

Figure 29. Difference in 50 mm outerwood density for individual trees from different seedlots and sites at a final crop stocking (FCS) of 200 stems/ha. The lines join the mean value for each seedlot.

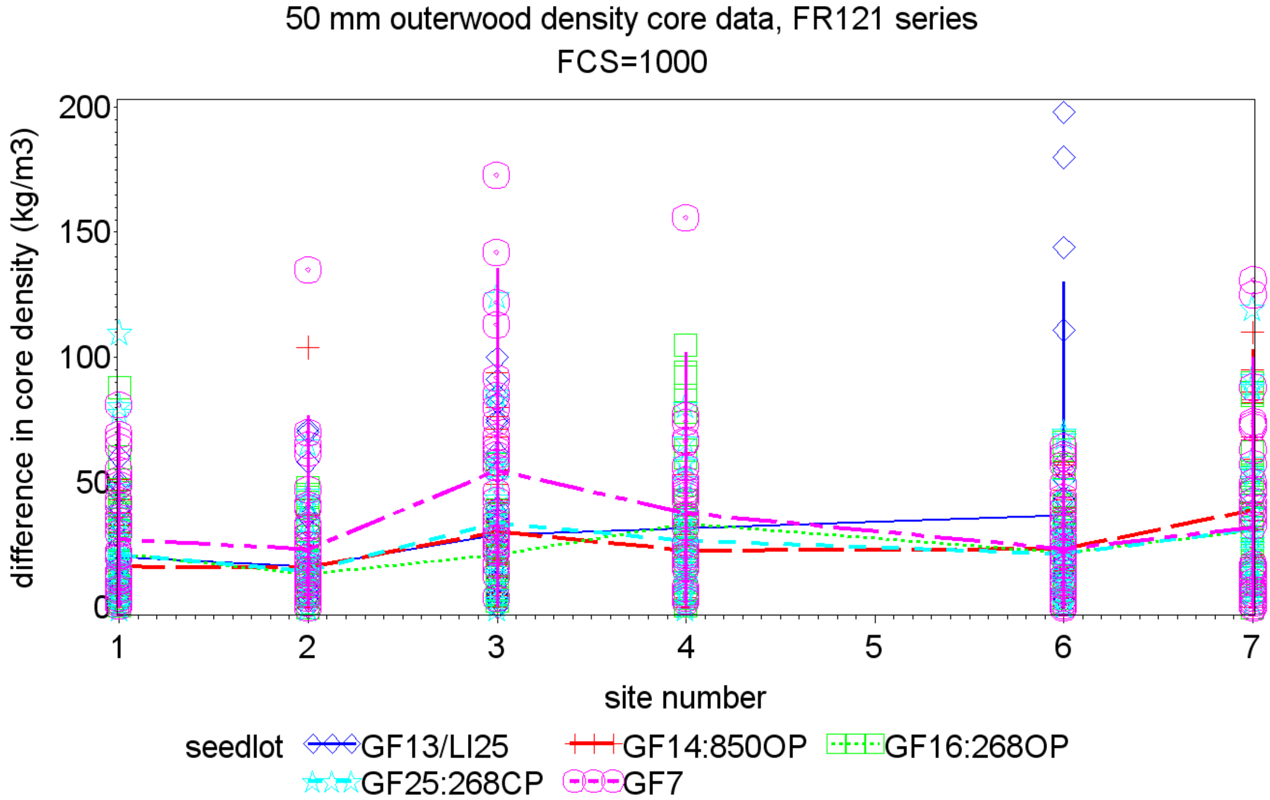

Figure 30. Difference in 50 mm outerwood density for individual trees from different seedlots and sites at a final crop stocking (FCS) of 1000 stems/ha. The lines join the mean value for each seedlot.

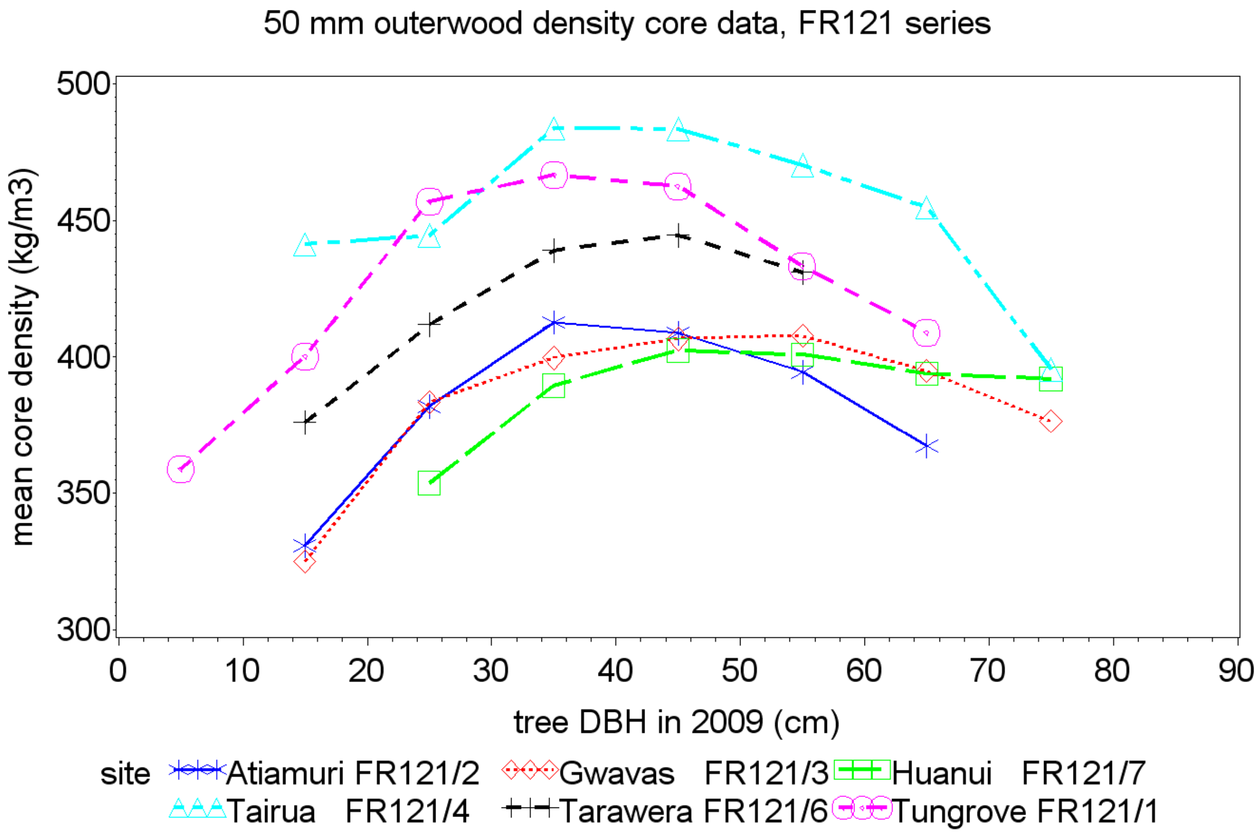

Figure 31. Mean 50 mm outerwood density, averaged over 10 cm DBH classes.

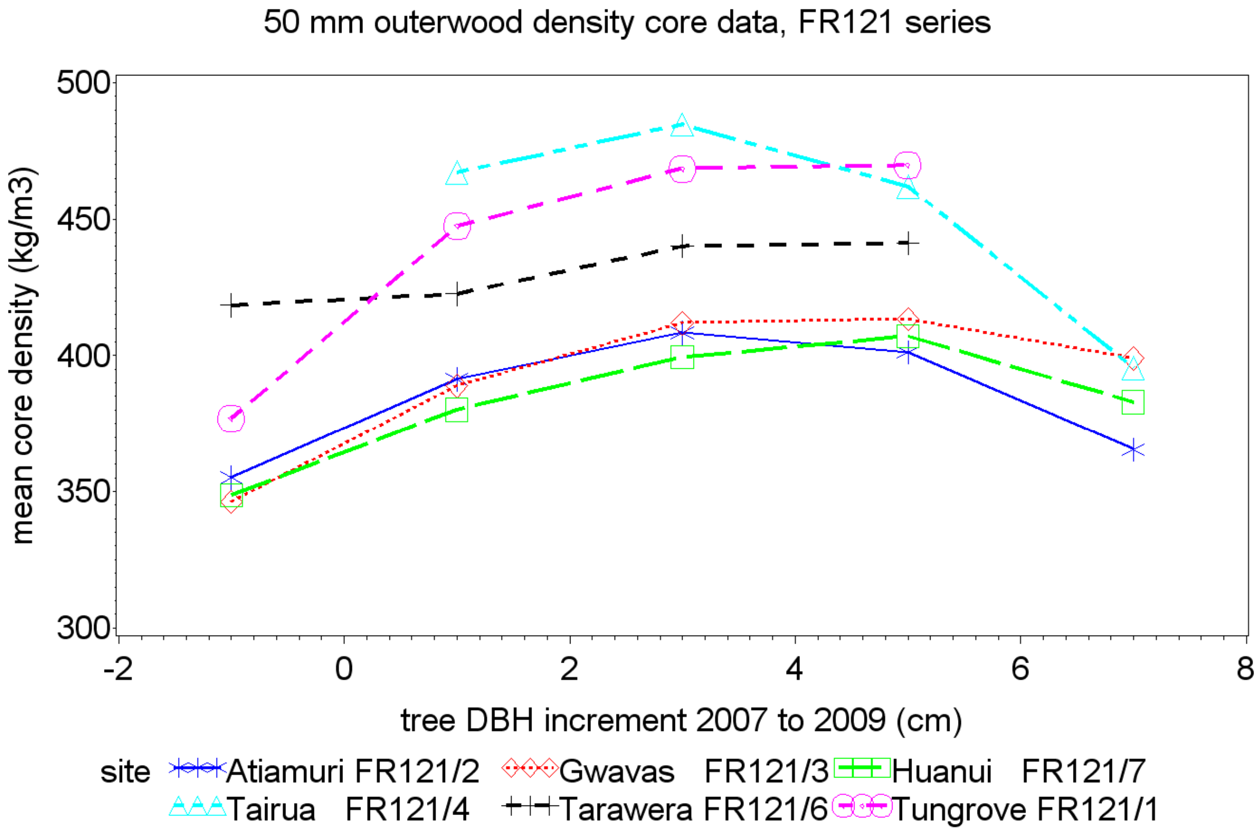

Figure 32. Mean 50 mm outerwood density, averaged over 2 cm DBH increment classes.

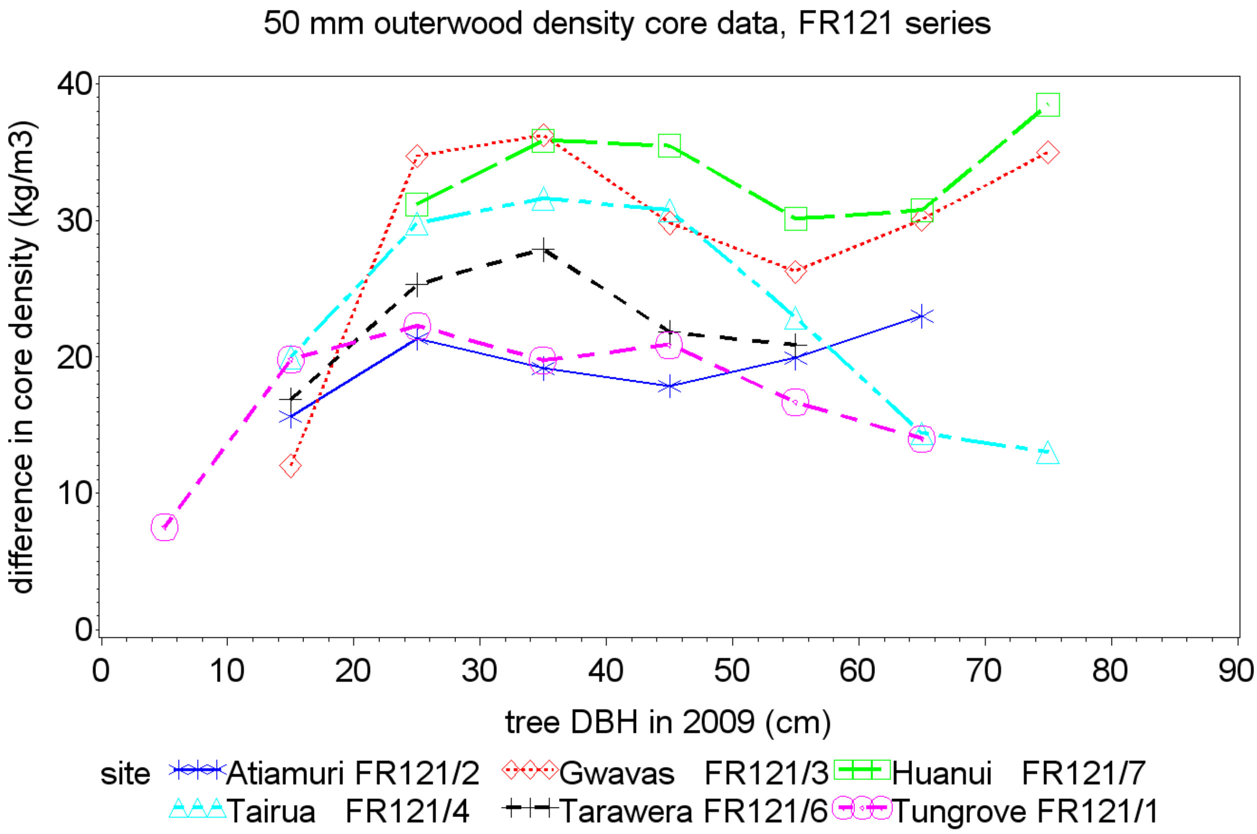

Figure 33. Difference in 50 mm outerwood density averaged over 10 cm DBH classes.

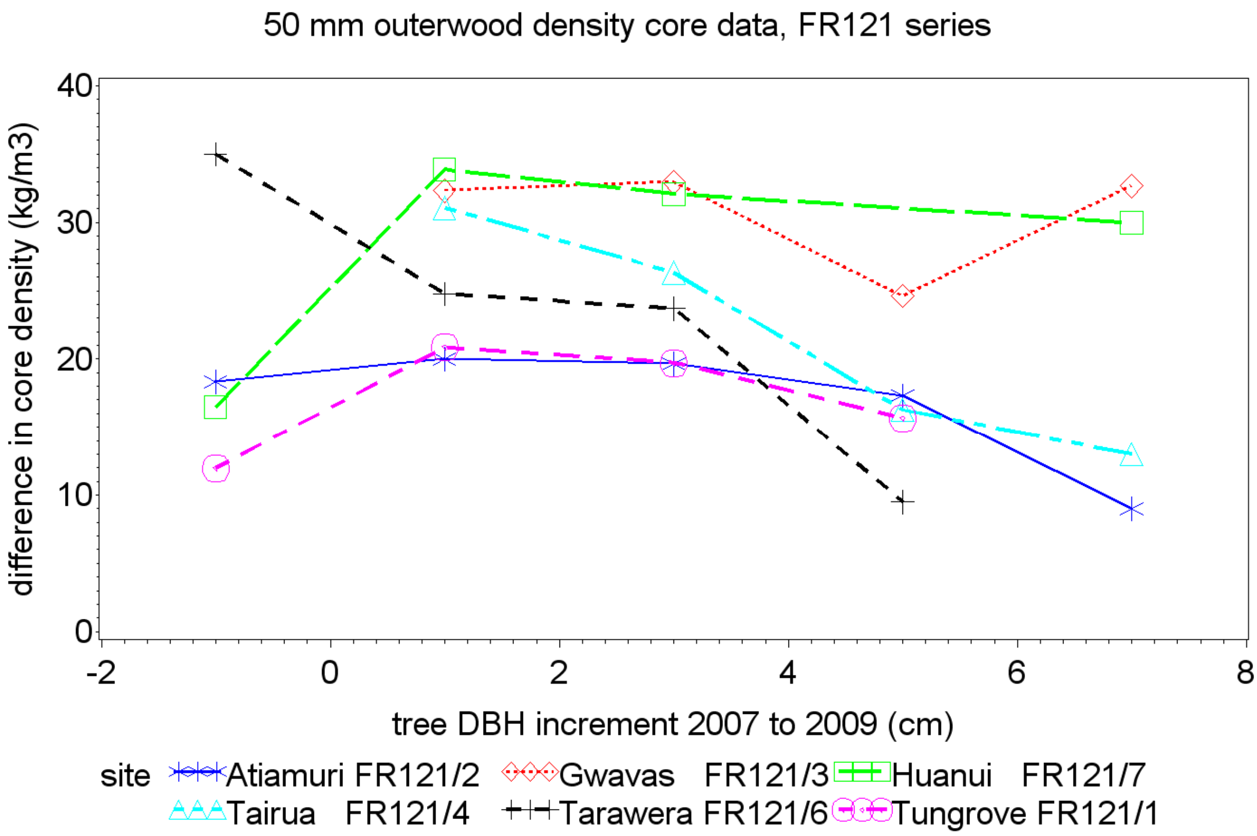

Figure 34. Difference in 50 mm outerwood density averaged over 2 cm DBH increment classes.

APPENDIX 4. Outerwood Density in the Ultra-high Pruning Trials

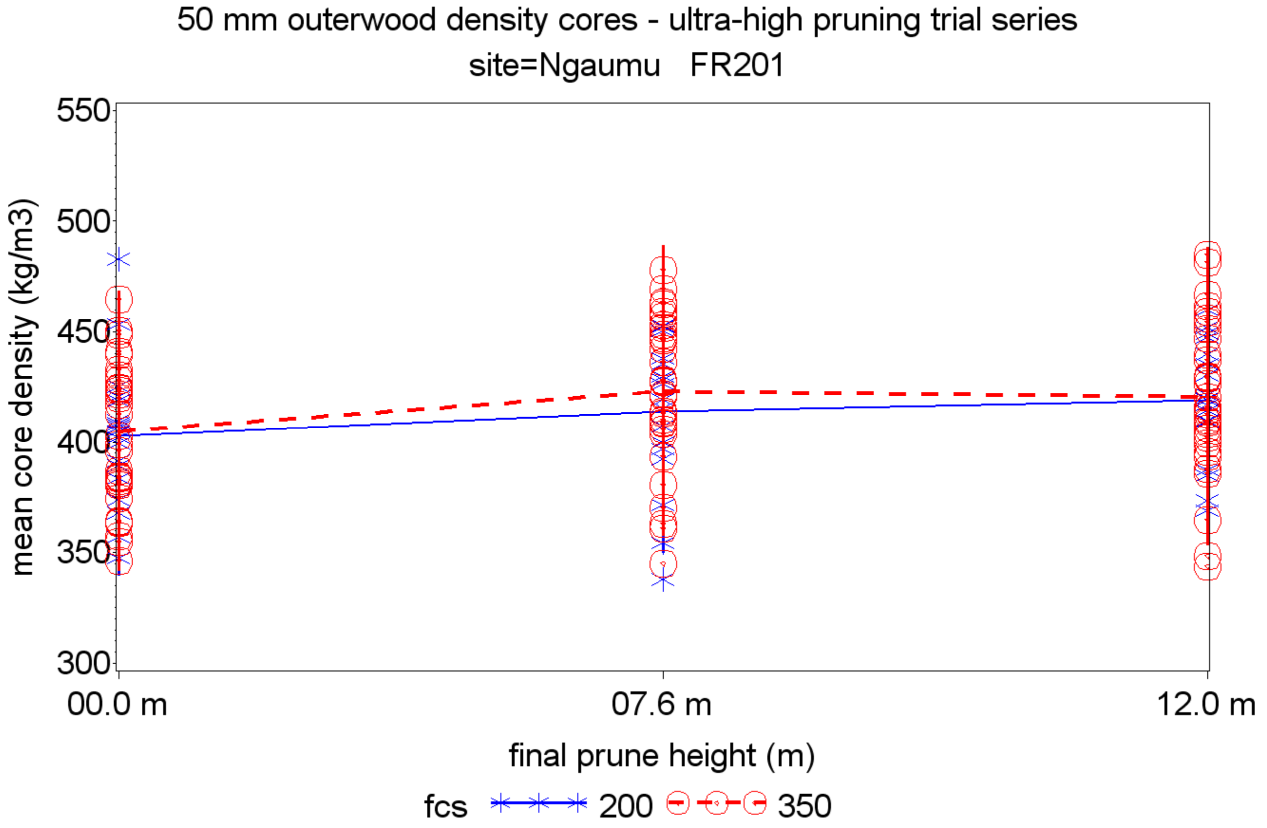

Figure 35. Mean 50 mm outerwood density for individual trees for different treatments at Ngaumu.

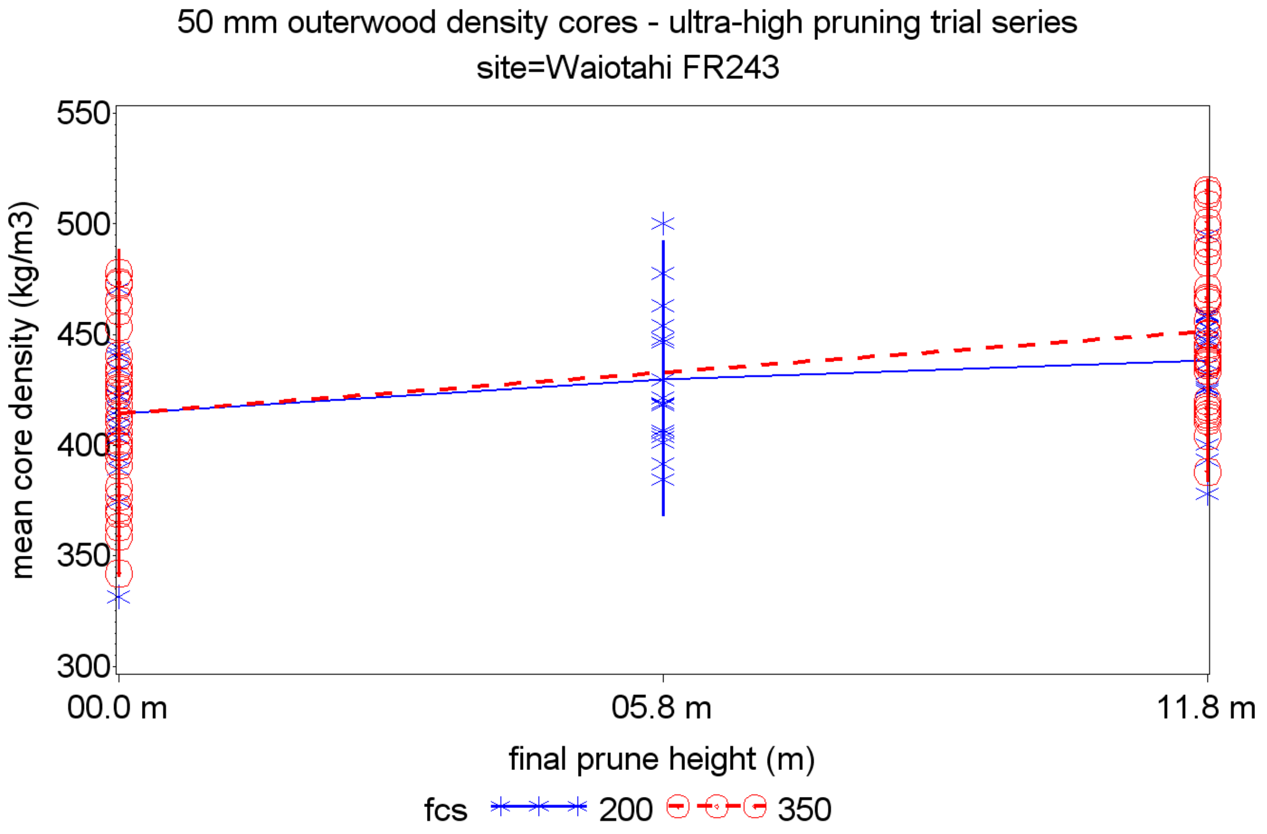

Figure 36. Mean 50 mm outerwood density for individual trees for different treatments at Waiotahi.

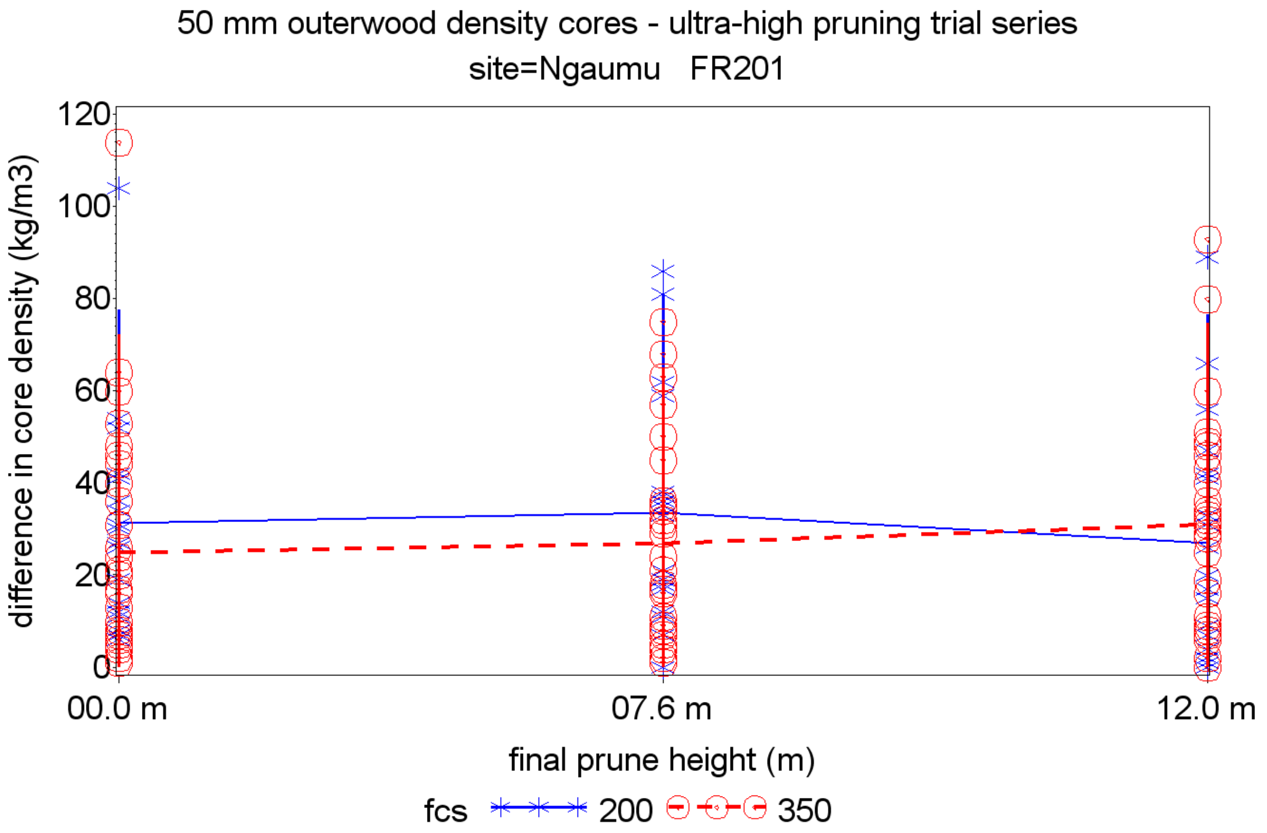

Figure 37. Difference in 50 mm outerwood density for individual trees for different treatments at Ngaumu.

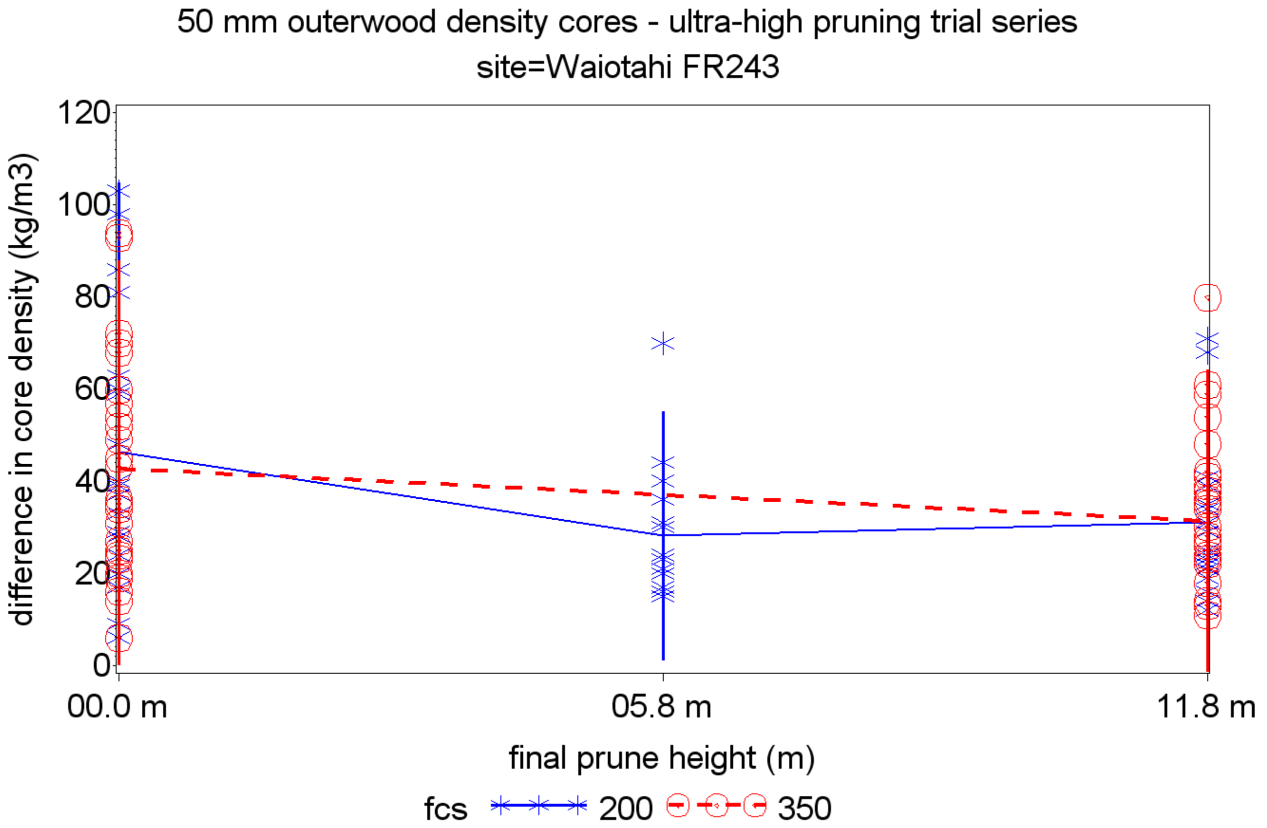

Figure 38. Difference in 50 mm outerwood density for individual trees for different treatments at Waiotahi.

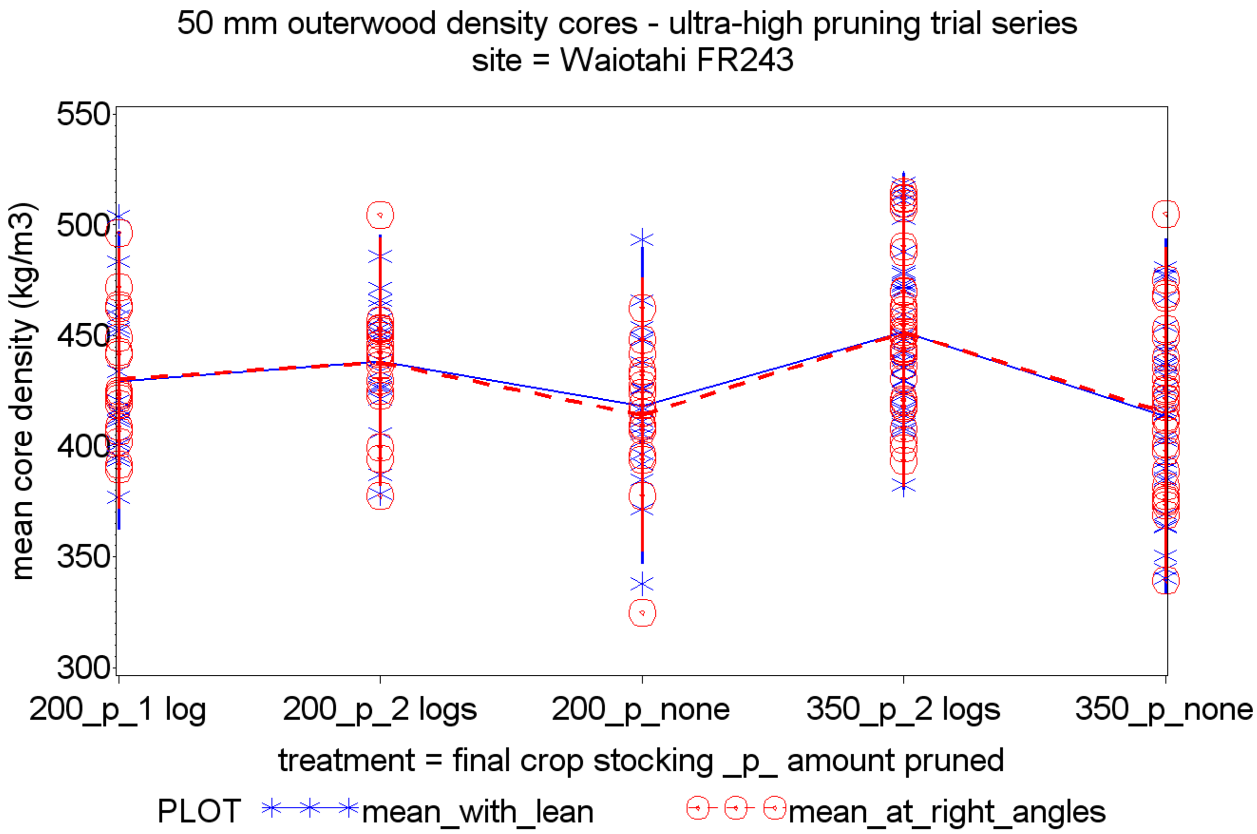

Figure 39. Comparison of mean core density where two cores are taken parallel or at right angles to any stem lean.

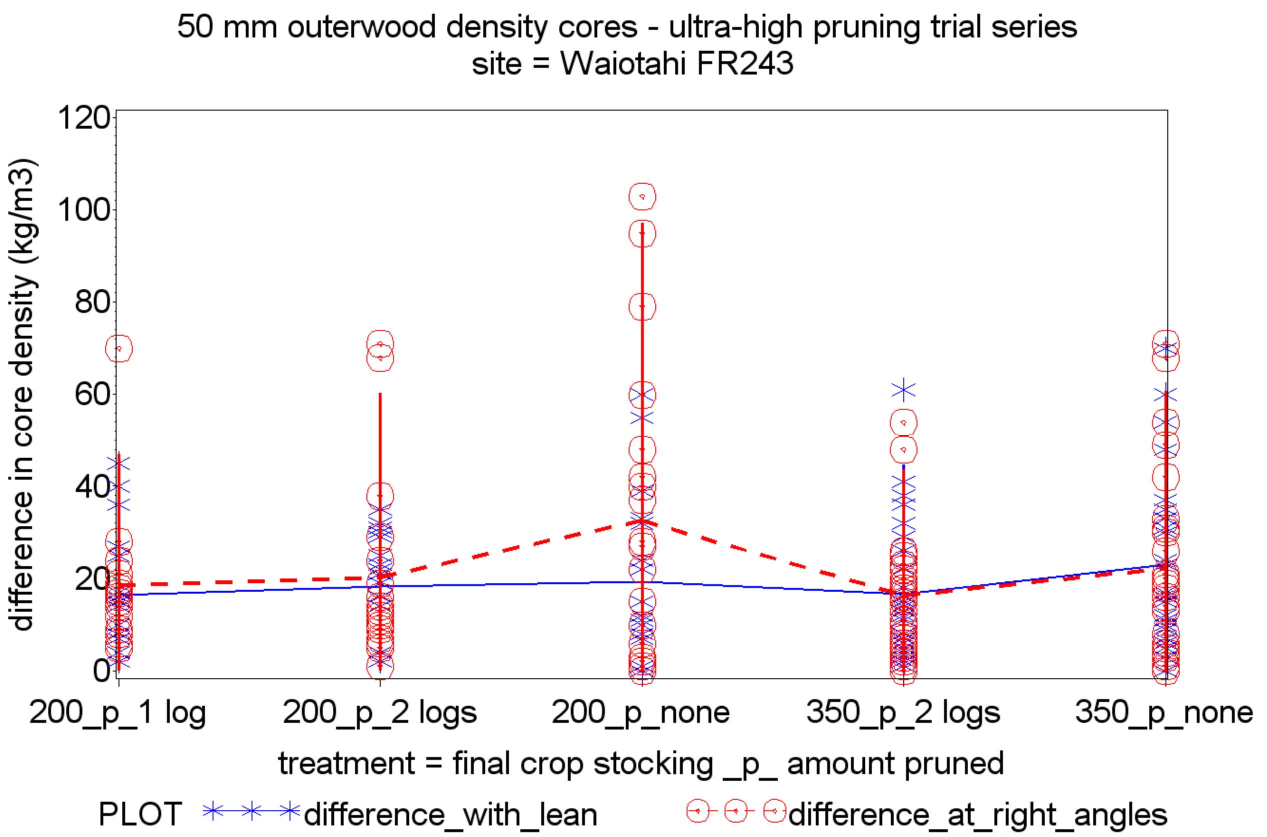

Figure 40. Comparison of difference in core density where two cores are taken parallel or at right angles to any stem lean.

APPENDIX 5. Effect of Coring on Stem Growth

Figure 41. Image showing the impact of wood cores on stem growth. It can be seen that darker wood (probably compression wood) has been formed to heal the wound from the earlier core.

APPENDIX 6. Site Characteristics and Maps

Table 4. Site and tree conditions in FR121 series trials.

Site	Observations by Rod Brownlie during TreeD studies	Average daily wind speed (km/hr)
FR121/1, Tungrove	Very branchy trees Form generally OK	10.9
FR121/2, Kinleith	Sheltered site - many needles hung up in trees Lots of branches Tree form generally good	5.6
FR121/3, Gwavas	Severe wind damage in eastern plots Generally poor tree form	12.0
FR121/4, Tairua	Tree form generally good	10.3
FR121/6, Tarawera	No TreeD study completed	5.4
FR121/7, Huanui	Large branches Many malformed trees, particularly at low stockings	15.2