THE PERFORMANCE OF BLOCKS OF CLONES IN A RADIATA PINE PRODUCTION FOREST

A dissertation submitted in partial fulfilment of the requirements for

the Bachelor of Forestry Science Degree with Honours.

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ABSTRACT

Problem: Genetically identical clones of *Pinus radiata* are being planted in New Zealand plantation forests. There have been many clonal trials carried out; however there is a weakness in published literature surrounding the performance of clones in production blocks.

Method: Five comparisons in four of Pan Pac Forests Products production forests were measured. Three comparisons were measured at age 4.5 years old and two were measured at 7.5 years old. There were six Forest Genetics clones and three different control-pollinated seedlots measured in these comparisons. Each comparison had a different number and selection of seedlots. There were six different traits measured for the trees; diameter at breast height over bark, height, acoustic velocity, straightness, branching habit, and malformation.

The different traits were compared between the seedlots within each comparison. The differences in variation for diameter at breast height and modulus of elasticity were compared between clones and control-pollinated seedlots. Finally, the results by clone for the traits, excluding height, were compared to the expected performance supplied by Forest Genetics.

Results: There were differences in performance between seedlots. Four clones performed well across a range of traits. One clone performed well in the 7.5 year old blocks but not in the 4.5 year old blocks. One clone did not perform well in size and stiffness. Clones were significantly less variable than control-pollinated seedlots for diameter at breast height but not for modulus of elasticity. The performance of each clone in Pan Pac Forest Products forests was very similar to the expected performance provided by Forest Genetics.

Implications: There are clones that can produce desired yield, stiffness and form. Clones will provide a more uniform crop in diameter than control-pollinated seedlots. Pan Pac Forest Products can rely on Forest Genetics prediction of clonal performance as a guide to performance in their forests.

Keywords: *Pinus radiata*; clone; clonal forestry; control-pollinated seedlings; modulus of elasticity; growth; form; variation;

TABLE OF CONTENTS

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1. INTRODUCTION

Pinus radiata D. Don is the most economically important tree species in New Zealand forestry. Genetic improvement on *P. radiata* has been occurring since the early 1950s starting at the Forest Research Institute (Burdon, 1966, 1992). Initially breeding focused on growth and form traits, to later include adaptability traits (for example *Dothistroma pini* resistance) and wood properties (for example basic density and modulus of elasticity). The deployment of improved material was a key part of the tree improvement process as it allowed the breeding gains to be captured in commercial forestry. Clonal forestry was the latest development in deployment and is defined here as the commercial planting of tested clones. Forest Genetics is a New Zealand company that produces clones using a somatic embryogenesis process and sells them to commercial forestry companies.

Pan Pac Forest Products Ltd (Pan Pac) has been buying and planting clones for several years. Pan Pac is an integrated forestry company that is comprised of a pulp mill, an appearance grade sawmill, and forest management of around 35,000 ha. Clones have become a large part of their planting program, however the current knowledge of clonal performance on their estate is based on small trials and a small number of permanent sample plots (PSPs).

The published literature on clones is mostly, if not entirely, based on trials as opposed to production situations, which means that unless companies carry out their own production block trials this information is not available to them. Trial performance has the potential to be different to production performance, as trials are likely planted more carefully and are often treated with different silviculture regimes than production stands. For example, many trials are 100% pruned where as some companies choose not to prune and others only prune a selected proportion of their estate. Different silvicultural decisions impact the performance of trees.

There is a gap in published literature surrounding the performance of clones in a large production situation. This study provides information on clonal performance, primarily in growth and stiffness with an insight into form characteristics, to increase understanding in this research area. Clones are compared to control-pollinated seedlots and/or each other in five different comparisons. The study includes six Forest Genetics clones. Each seedlot block is measured using six plots.

In addition to studying the performance of clones, this performance is compared to the trait descriptions of each clone provided by Forest Genetics. This is a way of comparing the performance of clones in a production setting with that of the results from trials.

2. RESEARCH HYPOTHESES

1. Clones do not perform differently to control-pollinated seedlots.
2. Clones do not perform differently to each other.
3. Clones do not differ in variability to control-pollinated seedlots in diameter at breast height over bark.
4. Clones do not differ in variability to control-pollinated seedlots in green m
5. odulus of elasticity.
6. Production clones do not perform differently than the expectations based on trial results.

Note: performance is measured by diameter, height, green modulus of elasticity, and form in branching, straightness, and malformation.

3. LITERATURE REVIEW:

3.1. PROGRESSION OF GENETIC IMPROVEMENT OF *PINUS RADIATA*:

3.1.1. The beginnings of *Pinus radiata* genetic improvement in New Zealand:

P. radiata has been a prominent plantation forest species in New Zealand since the 1920s (Burdon et al., 2008). In the 1950s the decision was made to genetically improve *P. radiata* in an intensive breeding program managed by the Forest Research Institute, part of the New Zealand Forest Service (Burdon, 1966, 1992). The initial genetic improvement involved selecting superior trees (plus-trees) from near-mature age existing plantations from 1953 to 1958 (Burdon, 1992; Shelbourne, 1986b). In the 1960s a more extensive approach was carried out in younger stands aged 12 to 15 years to select a larger number of plus-trees for the program (Burdon, 1992; Shelbourne, 1986b). Ten years into the progeny testing of this second contingent of plus-trees, the superior individuals were selected and grafted into seed orchards as the first forward selection.

At first, it was thought that tree breeding would work best if it was split into four regional breeding populations, with each population bred to suit a specific area of New Zealand

(Burdon, 1966). After more research in the 1980s and 1990s of genetic x environment interactions (G x E), it was thought that they were not large enough to warrant a splitting of the breeding program. If the breeding program was split, genetic gain would be reduced, due to a lower gene pool per region and lower selection intensity, as well as being more expensive. Based on this, it was thought that managing one nationwide breeding program would be more efficient and effective (Carson, 1991). However, even more recent research has found that for growth traits there is still substantial G x E (Cullis et al., 2014) but not for basic density (Apiolaza, 2012). The implications from Cullis et al. (2014) are still being discussed within the industry.

In 1987 a partnership between the Forest Research Institute (FRI) and forestry companies formed as the New Zealand Radiata Pine Breeding Co-operative (NZRPBC) which became the manager of the tree breeding program previously only run by the FRI (Jayawickrama et al., 1997). From this the industry had more input into breeding as well as providing increased funding. In 2000 to 2002 the RPBC became a Limited Liability Company and changed name to Radiata Pine Breeding Company (Burdon, 2008).

3.1.2. Methods of crossing:

The initial method of crossing selected trees for breeding was open pollination (Burdon, 1966). Open pollination is unassisted pollination that relies on wind, the natural means of pollination (Vincent, 1986). To achieve improvement using this system, cuttings from the plus-trees were grafted onto stumps in several seed orchards from the Central North Island down to Southland (Shelbourne, 1986b). The open pollinated (OP) seed from this orchard was then used as an improved seedlot for the start of progeny testing in 1968 (Shelbourne, 1986b). An important limiting factor of genetic gain using the OP method is pollen contamination (Shelbourne, 1988).

One of the developments of the breeding program in the 1970s and 1980s was the inclusion of controlled-pollination where known superior parents were crossed in the effort to produce superior off-spring (Carson, 1986a; Carson, 1996; Vincent, 1986). Cross-pollination prevents pollen contamination from outside the seed orchard, therefore genetic gain is not diluted (Burdon, 1992; Shelbourne, 1986b; Vincent, 1986). OP seedlots have been found to have only 50% to 80% of the genetic gain of CP seedlots (Shelbourne, 1988). Part of CP selection criteria was to choose families that had a good general combining ability, the ability to pass superior genetics to offspring in a wide range of crosses, so that the breeding population will produce superior off-spring in every cross (Carson, 1986a, 1986b).

CP has the added benefit of creating crosses to meet specific needs and selection criteria called “designer seedlots” (Burdon, 1992). These seedlots allowed forest owners to grow a more valuable crop with higher levels of gain than OP seedlots, as well as to buy seedlots that more accurately meet their needs (Shelbourne, 1988; Vincent, 1986).

3.1.3. Selection criteria over time:

The initial plus-trees were selected on being dominant, having good health, no malformation, and having light, flat-angled branching (Burdon, 1966, 1992; Shelbourne et al., 1997). Over time selection criteria changed. In 1970, one group of plus trees were selected for being uninodal, having fewer branch whorls with long sections of internode, to create a Long Internode breed (Burdon, 1992; Burdon et al., 2008; Shelbourne, 1986b). In the 1960s and 1970s a subset of the main breeding population was tested for *Dothistroma pini* resistance (Bail, 1992) and resistant families were selected to become the Dothistroma Breed (Burdon, 1992; Carson, 1986, 1996). By 1997, a wider range of breeding objective traits had been suggested by Shelbourne et al. (1997) that included stiffness and strength.

3.1.4. Deploying gain:

The initial method of providing nursery stock on a commercial scale was through seed (Shelbourne, 1986a; Vincent, 1986). This seed was either sold as is or was grown into seedlings before sale (Burdon, 1992). Providing seed for commercial plantations was important as the overall goal of the tree breeding program was to improve the stock used in plantations.

Vegetative multiplication was developed and tested in the 1980s to produce cuttings as an alternative to seed being used in some commercial nurseries (Shelbourne, 1986a, 1986b). Vegetative multiplication involves taking cuttings from seedlings grown as hedges or stool beds and growing those cuttings to be sold to forest growers (Bail, 1992; Menzies & Aimers-Halliday, 1997). Taking these cuttings multiplies the number of individual seedlings that can be grown of high quality genetics from controlled crosses (Burdon, 1992; Shelbourne, 1988). Despite these efforts, clonal forestry was still not possible in the 1980s due to ageing problems (Shelbourne, 1986b). Several years after planting the hedges became too old and the quality and growth rate of the cuttings fell, so producing enough clonal cuttings for commercial forestry was not possible (Shelbourne, 1986b).

Clonal propagation of *P. radiata* became possible with the development of somatic embryogenesis (SE), which involves multiplying embryos and cryopreserving them; both of which were developed in the 1980s and 1990s (Attree & Fowke, 1993; Sutton, 2002). The embryos chosen for multiplication come from CP crosses of superior parents. All copies of an embryo have the same genotype and are therefore clones (Johnson, 1988). The multiplied embryos can be cryopreserved to prevent maturation, meaning that clones can be produced and tested while there are copies of the same clones preserved as embryos for future planting should the clones test well (Hargreaves et al., 1997; Horgan et al., 1997; Sutton, 2002). SE also allows for a large number of copies to be made relatively cheaply (Burdon et al., 2008; Menzies & Aimers-Halliday, 1997). Using vegetative multiplication along with SE allows for even larger numbers of clones available for commercial planting.

3.1.5. Clonal forestry:

The clones are tested before being sold commercially. The clonal testing stage is an important part of clonal forestry, as it results in only the highest performing clones being reproduced and sold commercially (Aimers-Halliday & Burdon, 2003). Testing can also provide information on the performance of clones across sites provided the test clones are planted in multiple locations. Multiple tests ensure breeders can choose clones that are stable performers no matter what the site or to get information for site-matching of clones (Aimers-Halliday & Burdon, 2003). It is crucial to consider the site to better maximise the genetic gain so that the cost of producing the clones becomes smaller relative to the end revenue.

The benefits aimed for by clonal propagation are primarily an increase in genetic gain and stand uniformity (Aimers-Halliday et al., 1997; Carson et al., 2015; Johnson, 1988; Kube & Carson, 2004). Increased genetic gain is thought to come from non-additive genetic variation as well as additive, though this varies by trait and is mainly applicable to growth. It would be possible to plant a genotype that had beneficial non-additive variation that cannot be captured any other way apart from cloning. Increased reliability in genetic gain is possible due to the rigorous clonal testing carried out.

Despite the benefits it is believed that there are risks of planting clones, such as reduced genetic diversity of the forest rendering the plantation vulnerable to widespread failure (Johnson, 1988), though genetic diversity can be increased by planting large numbers of different clones in a block mosaic (Carson et al., 2015). Failure agents could be both biotic and abiotic impacts on the stand that negatively affect the few genotypes planted (Kube & Carson, 2004). There also may be risk involved with not setting up a breeding program appropriately, such as inaccuracies in breeding material, program goals and mating designs, therefore not achieving the desired levels of gain (Kube & Carson, 2004). There may also be failures in the multiplication and propagation techniques.

3.2. GROWTH, FORM AND MODULUS OF ELASTICITY OF *PINUS RADIATA*:

3.2.1. Growth and genetics:

Growth results from clonal trials have not been widely published and represent a gap in the current literature. A study by Sharma et al. (2008) found that diameter significantly differed between clones in monoclonal plots, indicating that there is some genetic control of growth rate. Early tree height has been found to be a good indicator of later stem diameter (Burdon et al., 1992b), indicating that taller trees in young stands may grow more in diameter later on.

Growth traits tend to have low heritability. A clonal stability study found that over 6 trials in New Zealand and Australia, broad-sense heritabilities ranged from 0.05 to under 0.35 for diameter at breast height (DBH), at 1.4 m, and from under 0.1 to 0.3 for height (Baltunis & Brawner, 2010). Another study also found intermediate heritability for diameter and height (Cotterill & Zed, 1980). A third study also found low heritabilities of 0.1 for diameter and 0.1-0.2 for height (Burdon et al., 1992a). Wu et al. (2008) found that broad-sense heritability, from genetically identical comparisons, was higher than the narrow-sense heritability, from genetically related comparisons, for growth with a value of 0.39 compared to 0.21, indicating that clonal forestry may have the ability to provide more gains each generation.

Baltunis and Brawner (2010) found that the genetic correlation of DBH between sites ranged from -0.15 to 0.99 and the correlation of height between sites ranged from 0.33 to almost total correlation. Despite the high ranges in heritabilities and correlations in this study, it was found that stable clones can be chosen for reliable growth performance within New Zealand. Another international study found between-site correlations of above 0.5 for most sites (Burdon et al., 1998). These results are positive for plantation forestry because if these clones are identified, companies can rely on achieving some genetic gain on untested sites.

3.2.2. Form and genetics:

Overall, subjectively measured form traits have been found to have a strong performance correlations between age 8 and 11.5 years (Burdon et al., 1992b), therefore form measurements on young trees will be reasonably good indicators of older performance.

3.2.2.1. Internode length:

Mean internode length has been found to be significantly controlled by genetics (Carson & Inglis, 1988; Turner et al., 1997). Jayawickrama (2001) found a branch cluster frequency heritability of 0.33 and Wu et al. (2008) found a similar heritability of 0.35. The branch cluster breeding value was also found to be strongly correlated to the mean internode length of families (Turner et al., 1997).

Little environmental effect on internode length was found and the rankings of different genotypes stayed similar in one study (Carson & Inglis, 1988), however in another study there was a significant interaction between clone and site (Burdon, 1971). These differing results create some doubt about how clones will perform on untested sites; however, Burdon (1971) attributes the interaction mostly to a phosphorous deficiency in the soil, so on non-deficient sites, the results in Carson and Inglis (1988) may be more applicable.

3.2.2.2. Stem straightness:

Stem straightness has been found to have high clonal repeatability (Burdon, 1971), medium/low heritability (Cotterill & Zed, 1980; Jayawickrama, 2001), and strong general combining ability effects (Wilcox et al., 1975), indicating that stem straightness is partially controlled by genetics. In sites of phosphorous deficiency, there was an interaction between clone and site for straightness, as well as branching frequency (Burdon, 1971). Between international sites covering South Africa, Australia, and New Zealand, stem straightness had a reasonable site-site correlation of over 0.6 in most cases (Burdon et al., 1998), indicating that trial sites should be a reasonable indicator for straightness on untested sites.

Stem straightness is positively correlated to diameter and height (Cotterill & Zed, 1980). Positive correlations for these desired traits indicate that breeding for diameter will have a positive impact on straightness results as well.

3.2.2.3. Malformation:

Malformation, as measure of forking and ramicorn branches, has been found to have reasonably low heritabilities (Burdon et al., 1992a; Cotterill & Zed, 1980). This makes breeding for malformation more difficult than for traits with high heritability. To remedy this in clonal forestry, malformation can be part of the selection criteria when testing clones and can be reduced by avoiding clones with tendencies of high rates of malformation. Malformation site-site correlations have been found to be high (Burdon et al., 1998), so genotypes with low malformation should have low malformation on untested sites as well.

3.2.3. Modulus of elasticity and genetics:

Modulus of elasticity (MoE) has been a trait studied at length for *Pinus radiata* clones. MoE is important because it is a direct measure of stiffness. Stiffness is a desired trait in structural timber. Stiffness is also important for appearance and industrial sawmills because it is negatively correlated with longitudinal shrinkage (Evans et al., 2010; Lindström et al., 2005). Less shrinkage leads to less distortion when drying the timber so there are benefits for all sawmills.

MoE has been found to be significantly affected by clone in many studies (Evans et al., 2010; Lasserre et al., 2005, 2008; Lasserre et al., 2009; Mason, 2006; Xue et al., 2013). Wu et al. (2008) found an estimated heritability of 0.5 for MoE. Xue et al. (2013) found the effect of genetics to be greater than that of site and weed control effects which indicates that it is worthwhile for companies to consider genetics when aiming to improve the MoE of their plantation.

Microfibril angle (MFA) is a major contributing factor to MoE (Apiolaza, 2009; Evans et al., 2010; Lindström et al., 2004). MFA is also significantly affected by genetics (Lasserre et al., 2009).

Improvement in corewood MoE is linked to improved outerwood MoE due to an increase in MoE over time (Dungey et al., 2006; Lasserre et al., 2009; Menzies et al., 2004).

Evans et al. (2010) found that the rankings of the clones changed over time, indicating that different clones increase in MoE at different rates over time so future remeasurement of the plots in this dissertation would be valuable. This same study also found that the gain in MoE for clones increased significantly over time from that of open pollinated (OP) stock.

Many studies have found that clone and site have a significant interaction (Hawkins et al., 2010; Lasserre et al., 2008; Xue et al., 2013). Hawkins et al. (2010) found that some clones performed consistently and others changed rank more frequently, therefore there may be a chance to select clones that consistently perform well on a range of sites or to match different clones to particular site types. Considering the results from both Hawkins et al. (2010) and Baltunis and Brawner (2010), it is important to try and find clones that are stable for both growth and MoE for growers that are concerned with both of these traits.

Choosing cuttings versus seedlings can have an effect on MoE due to the physiological age differences. Cuttings have higher MoEs than seedlings and an older cutting age leads to a higher MoE (Waghorn et al., 2007). The clones and CP seedlots used in this study were all cuttings though the age of the cuttings may differ.

3.3. METHODS RESEARCH:

3.3.1. Methods of collection:

Measuring for acoustic velocity at young ages has been found to be sufficiently accurate when predicting microfibril angle (MFA) and therefore stiffness (Apiolaza, 2009). Earlier selection for stiffer varieties is possible at a reasonably accurate level to reduce the length of the breeding cycle (Kumar et al., 2006). Kumar et al. (2006) found that selection from rings 3-5 at breast height provided 90% of the gain from choosing families based on rings 1-10. Time-of-flight measurements, such as FAKOPP, have been found to have a strong relationship with resonance methods (Chauhan & Walker, 2006; Emms et al., 2013; Lindström et al., 2004).

Subjective measurements for form have been used in multiple studies (Burdon et al., 1992b; Burdon et al., 1998; Gapare et al., 2012).

3.3.2. Methods of analysis:

Lindström et al. (2004) created multivariate models using stepwise regression which determined the most accurate model in terms of the highest R^2 value and the best Mallow's Cp. The model was used to build relationships between key wood traits and other measured traits. Correlations were calculated between traits and analysis of variance (ANOVA) was carried out.

Kumar et al. (2008) also carried out multivariate analysis to derive correlations between traits. A simple model was used as opposed to deriving their own as done by Lindström et al. (2004).

4. METHOD:

4.1. SITE SELECTION:

Site selection for this study was a challenge. As the study was intended to be based on productive stands the only option was to measure what was already planted in Pan Pac's production forest. The clonal material available had not been planted with the knowledge that a study would be carried out in the future so they were not set up to any strict experimental design. There was also little replication of any chosen comparison.

The lack of strict experimental design partially confounds any statistical conclusions, although the degree of confounding is probably small. The data is confounded because the blocks were not planted in a randomised and replicated pattern at each site so any differences cannot be guaranteed to be entirely due to genetics. The situation was accepted as it was the only way to achieve production comparisons.

All of the clone blocks on Pan Pac's estate were viewed on maps and the blocks which were not appropriate for comparison were disregarded. Once possible comparisons were selected by map, they were visited in person to check what state the stands were in and whether they were still appropriate to include in the study. Some comparisons were disregarded through this process.

The clones measured in the study were a selection of Forest Genetics production clones. Five areas of comparison were selected. Two of the comparisons were aged 7.5 years at the time of measurement and three other comparisons were aged 4.5 years.

To choose which clonal and control-pollinated (CP) blocks to measure several site characteristics were compared; altitude, aspect, slope, and distance between blocks. The blocks within each comparison also had to have received the same silvicultural regime. The greatest distance between blocks within each comparison was around 800 m. It was necessarily assumed that within this distance, the blocks were close enough to have similar climates and soils, assuming that the other site characteristics were similar.

4.2. GENETIC MATERIAL:

4.2.1. Gwavas forest comparison 1:

In the Gwavas comparison 1, four clonal blocks and one CP block were tested. The four clones tested were B, D, E, and F. The age of the material in this comparison was 4.5 years at the time of testing.

4.2.2. Gwavas forest comparison 2:

In the Gwavas 2 comparison, two clonal blocks and one CP block were tested. The two clones tested were A and F. The CP material was the same as that in the Gwavas 1 comparison. The age of the material in this comparison was 4.5 years at the time of testing.

4.2.3. Mohaka forest comparison:

In the Mohaka comparison, one clonal block and one CP block were tested. The clone was E. The CP material was different to that of the two Gwavas comparisons. The age of the material in this comparison was 4.5 years at the time of testing.

4.2.4. Esk forest comparison:

In the Esk comparison, two clonal blocks and one CP block were tested. The clones were A and E. The CP material was different to the CP material in other comparisons. The age of the material in this comparison was 7.5 years at the time of testing.

4.2.5. Tangoio forest comparison:

In the Tangoio comparison, three clonal blocks were tested. The clones were B, C and E. The age of the material in this comparison was 7.5 years at the time of testing.

4.3. DATA COLLECTION:

4.3.1. Plot design:

The plots are circular and are 0.04 ha in size. The size was chosen to capture around 30 trees in each plot. Each tree was numbered and ribbon was put around the end trees in each row to mark out the plot for potential remeasurement in the future.

Six plots were measured per block of genetic material. The plots were placed as close together as possible to reduce the environmental variation between plots. There was a buffer gap between the edges of each plot of around 20 metres to reduce the risk of overlap, but because of the markings of each plot, it can be guaranteed that there was in fact no overlap. The plots were also placed with at least 10 m between the stand edge and the plot edge.

4.3.2. Measurement:

Tree diameter was measured using a diameter tape at breast height (1.4 m). Tree diameter was measured on every tree.

Tree height was measured with a vertex. The transponder was placed at breast height and the vertex took readings from breast height and then the top of the tree to gain height. Height was measured on at least 15 trees per plot.

Acoustic velocity was measured using a FAKOPP tool. This tool had two probes; one was the starter probe and the other was the stop probe. The probes were placed into the tree one metre apart with the DBH mark located between the two probes. To get a reading, the start probe was tapped with the provided hammer and the reading provided was the time taken for the sound wave from the tap in the start probe to reach the stop probe. Three readings were taken from each point. The trees were measured for acoustic velocity on two opposite sides of each measured tree to average any within-tree variation (Chauhan and Walker, 2006). Trees were measured 90° to the prevailing wind to avoid measuring compression wood (Grabianowski et al, 2006). Acoustic velocity was measured on five trees per plot for clonal blocks and eight trees per plot for CP blocks.

Three form traits were measured by eye on each tree. Each trait was measured on a scale from one (poor) to three (excellent). For straightness a rating of one was totally not straight and three was nearly perfectly straight. For internode length (branching) a rating of one was an average internode length of less than 300 mm and three was an average internode length of over 600 mm. The internode lengths were based on the cuttings grade boards produced by Pan Pac Forest Products. For malformation a rating of one was a tree that had severe malformation, such as multiple leaders or a large basket whorl, two was a tree with a few minor defects, such as three or more ramicorns, or a small basket whorl, and three was a tree with up to two ramicorns.

4.4. DATA ANALYSIS:

Data analysis involved creating linear mixed-effects models and ANOVA in R to create relationships and judge the significance. The linear mixed-effects models were used for basal area, green MoE, and height. Linear mixed-effects models incorporate both fixed- and random-effects on the mean which is useful when measurements are made for one variable in multiple related units, such as diameter being measured in the multiple plots located in the same block of trees. A different model was created for each variable and these models were tested separately for each comparison. The general model tested was:

$$Trait = Intercept + Seedlot + Plot + error$$

In the model the intercept and seedlot are the fixed effects and plot and error are the random effects. Plot and error have a mean of 0, while their variances were s_p^2 and s_e^2 respectively.

My analysis differed to that of previous analysis (Lindström et al., 2004; Kumar et al., 2008), as my regression models were univariate, not multivariate.

The limitations in site selection left no alternative but to use stands of different ages for different comparisons to get more data. Having two different age groups in the data causes complications in the analyses, as the variation in the two age groups cannot be compared. Variation is naturally larger for the older trees as they are larger individuals.

To compare the variation between clones and CP these distinctions were recognised by splitting the data into four groups; old clones, old CP, young clones, and young CP. The “young” seedlots were those aged 4.5 years and the “old” seedlots were those aged 7.5 years. ANOVA was carried out on the standard deviations from each group to determine whether there were significant differences. Comparisons could only be made within each age group.

The standard deviation was used instead of the coefficient of variation to analyse variation differences. The coefficient of variation would lead to biased results as it is the deviation adjusted by means and the clones have larger means overall – that is the mean is a treatment effect. The standard deviation was used because having established differences in the size of the clones, the variation needed to be analysed as well as this.

Forest Genetics Ltd produces ratings for how each clone performs in each trait using a star rating system, where the higher number of stars indicates a better performance (Appendix Table 15). These ratings are available to forest growers so that they can choose which clones to plant based on their priority traits. To compare if the production plantings of clones measured in this study performed the same as in the trials, the ratings system was compared to the performance of the clones. This comparison was done with personal judgement given the rating system available. The rating system did not include the ratings for height, so only diameter at breast height, MoE, straightness, branching, and freedom from malformation were used as measures. The measurement system carried out by Forest Genetics for the three form traits was also based on a numbering system measured by personal judgement and were based on the same criteria so they are comparable.

5. RESULTS:

5.1. COMPARISON RESULTS:

5.1.1. Gwavas 1 comparison:

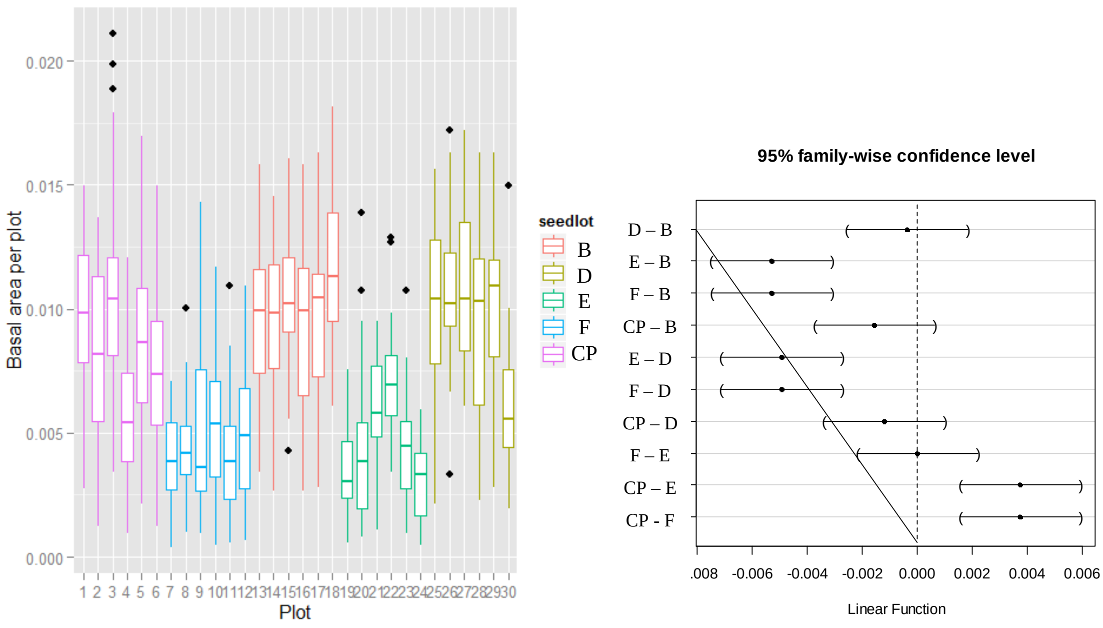

Figure 1: The basal area results per plot for each seedlot and the statistical differences for each match in the Gwavas 1 comparison.

The box plot graph shows the data for the six plots of each seedlot in the comparison. The confidence level graph on the right shows 95% confidence limits for the difference between each pair in the comparison. The confidence limits that do not cross the dotted line, so the confidence limits to not contain 0, are statistically significant differences.

Clones B and D had the largest basal areas though there was no statistically significant difference between them and CP (Figure 1). Clones E and F had the smallest basal areas. Clones D and B were the tallest clones as well as largest in diameter (Appendix Figure 1). CP was significantly taller than clones E and F.

There was no statistically significant difference in stiffness amongst the four clones and CP tested in this comparison (Appendix Figure 2). Clones D, F and B appear to be slightly superior when looking at means.

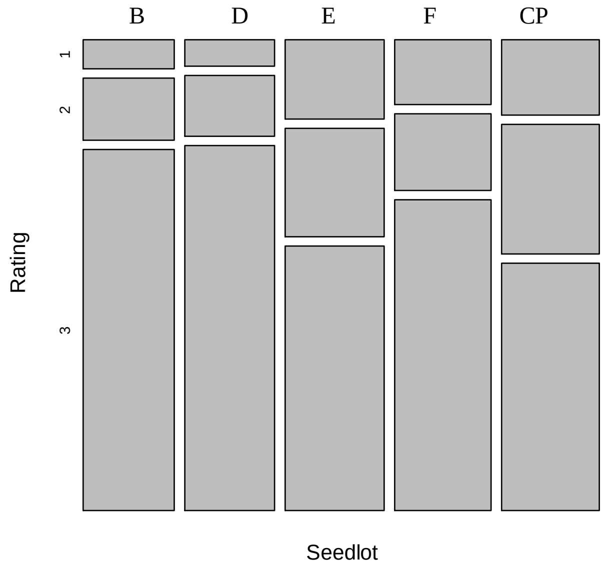

Figure 2: Mosaic plot of the malformation rating proportions for each seedlot in the Gwavas 1 comparison.

The mosaic plot above shows the proportions of trees in each rating system for the given form trait for each seedlot to compare the distribution of ratings. The seedlot labels are above the bars.

Clones F and E were the straightest seedlots (Appendix Figure 3). Clones B and D both appear to be straighter than CP, with clone B being slightly straighter than D. The internode characteristics appeared to be very similar in all of the seedlots (Appendix Figure 4). The seedlot with the longest internodes was CP and clone B appeared to have the shortest internodes. Clones D and B appeared to have the least malformation, CP appeared to have the most, and clones E and F were in the middle (Figure 2).

5.1.2. Gwavas 2 comparison:

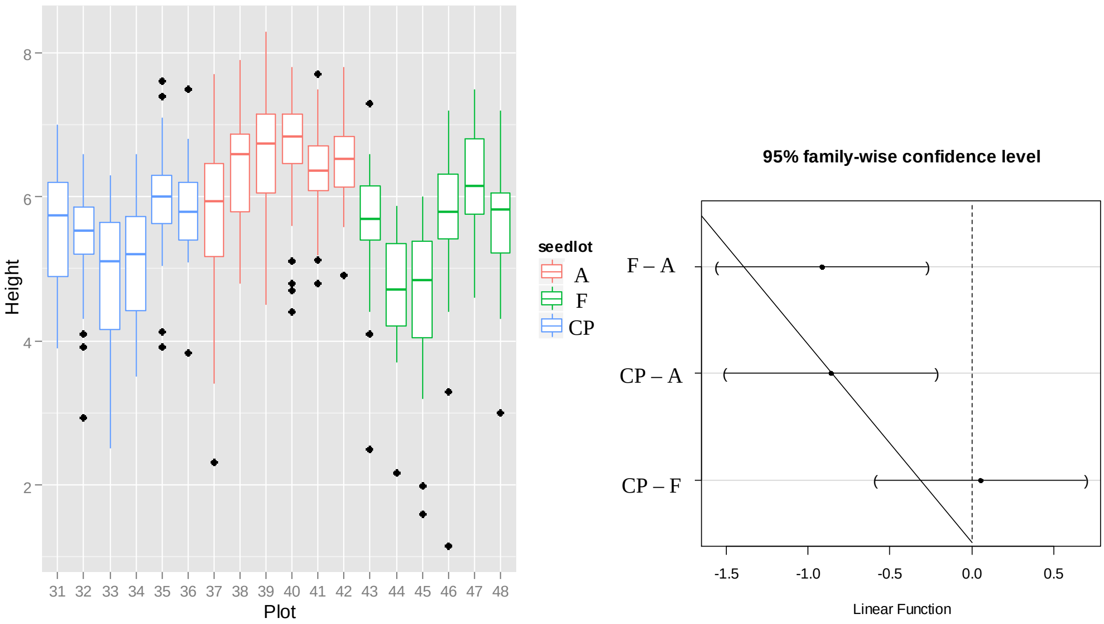

Figure 3: The height results per plot for each seedlot and the statistical differences for each match in the Gwavas 2 comparison.

Clone A was taller than both CP and clone F. There was no significant difference between CP and clone F (Figure 3). Clone A was significantly greater in basal area than clone F (Appendix Figure 5). There was no significant difference in basal area between CP and either clone.

Clone A was stiffer than both clone F and CP. There was no significant difference in stiffness between CP and clone F (Appendix Figure 6).

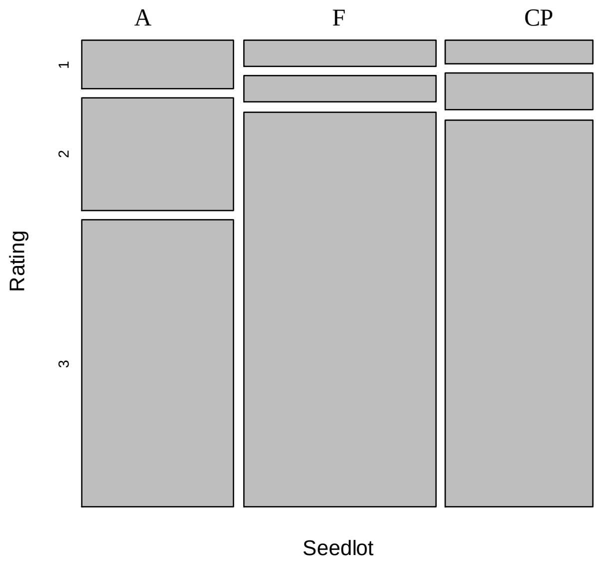

Figure 4: Mosaic plot of the malformation rating proportions for each seedlot in the Gwavas 2 comparison.

The CP seedlot had by far the least malformation and clones F and A had similar malformation (Figure 4). CP was straighter than both clones F and A (Appendix Figure 7). There was little difference between clones A and F though clone F may have been slightly straighter than clone A. Clones F and A appeared to have similar ratings of internodes and CP had the shortest internodes out of the three seedlots (Appendix Figure 8).

5.1.3. Mohaka comparison:

The CP seedlot was statistically larger in both basal area and height than clone E (Appendix Figures 9 and 10).

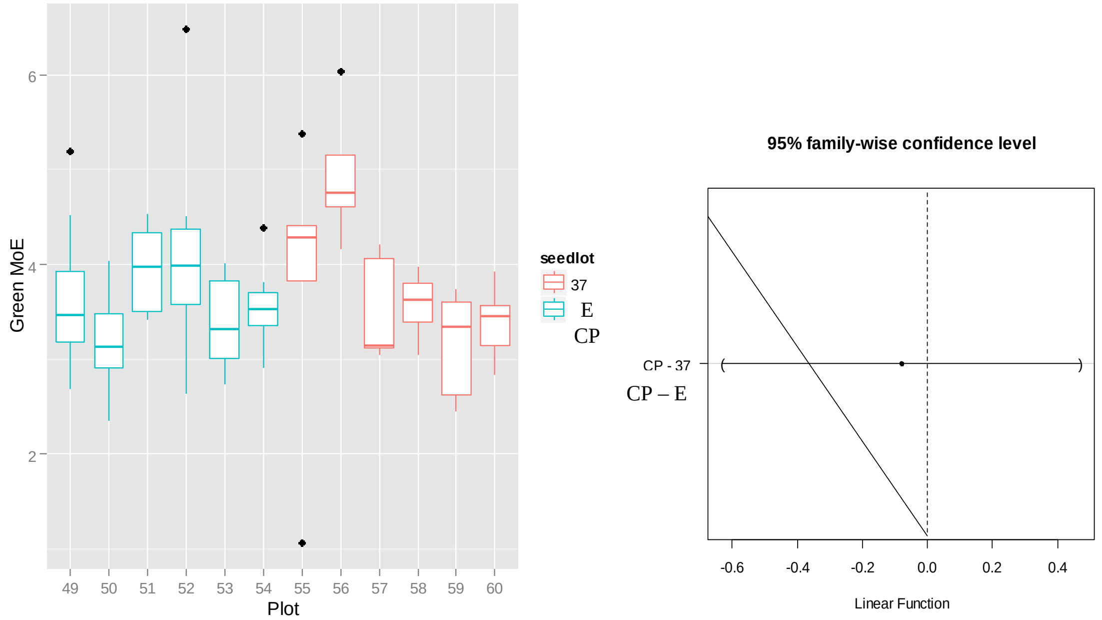

Figure 5: The modulus of elasticity results per plot for each seedlot and the statistical differences for each match in the Mohaka comparison.

There was no significant difference in stiffness between the CP and clone E seedlots (Figure 5).

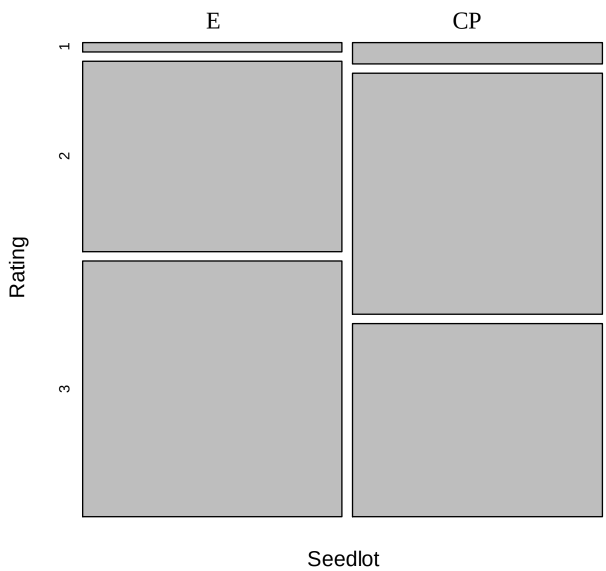

Figure 6: Mosaic plot of the straightness rating proportions for each seedlot in the Mohaka comparison.

Clone E was straighter than CP (Figure 6). There was very little difference in internodes between clone E and CP though clone E appeared to have slightly longer internodes (Appendix Figure 11). Clone E was less malformed overall than CP (Appendix Figure 12).

5.1.4. Esk comparison:

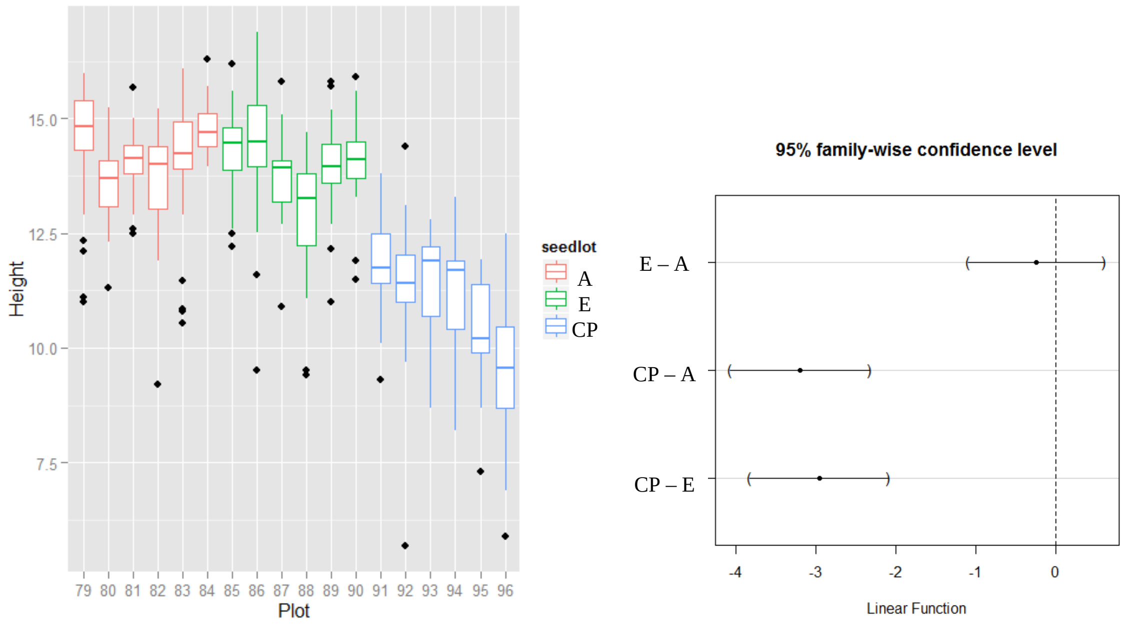

Figure 7: The height results per plot for each seedlot and the statistical differences for each match in the Esk comparison.

Both clones A and E were significantly taller than the CP but weren't significantly different from each other (Figure 7). Clone A had larger basal areas than CP (Appendix Figure 13). There was no significant difference between basal area of clone E with both clone A and CP.

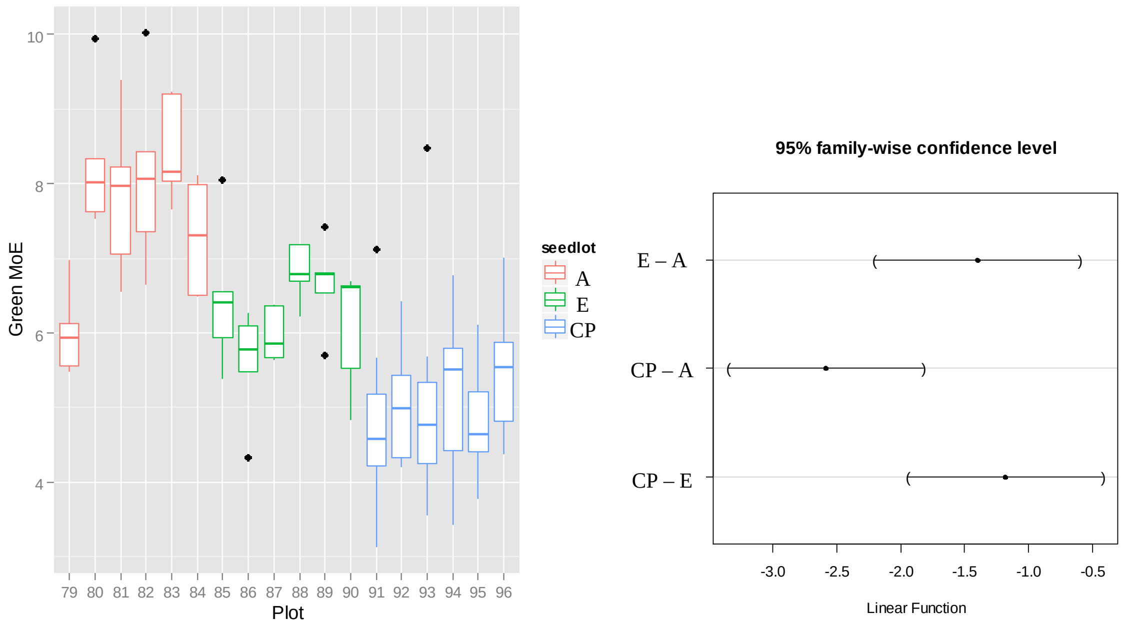

Figure 8: The modulus of elasticity results per plot for each seedlot and the statistical differences for each match in the Esk comparison.

Clone A was stiffer than both clone E and CP. Clone E was also stiffer than CP (Figure 8). As a MoE of 8 GPa is the cut-off for structural timber, it is promising that the mean MoE for four of the Clone A plots is already at this level, indicating that the non-structural defect core for these trees will likely be smaller than those of the clone E and CP seedlots.

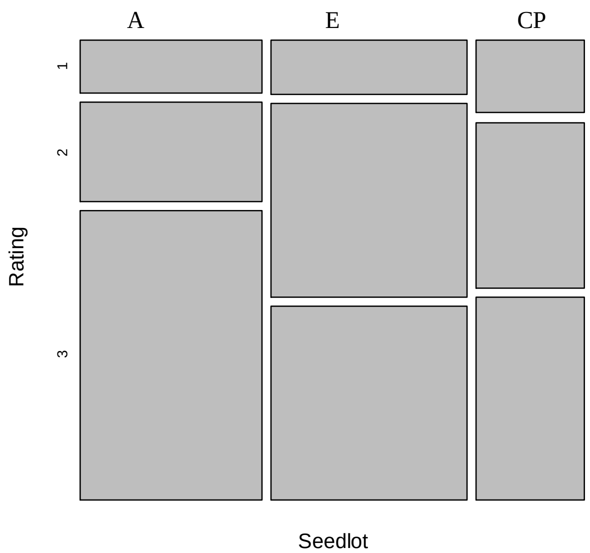

Figure 9: Mosaic plot of the malformation rating proportions for each seedlot in the Esk comparison.

Clone A had the least amount of malformation (Figure 9). Clone E appeared to have the least malformation-free trees, however, it had fewer “write-offs” than CP. Clones E and A were straighter than CP but were very similar in rating to each other (Appendix Figure 14). Clone E had slightly longer internodes than clone A and both had longer internodes than CP (Appendix Figure 15). The CP plots had no trees that had an average internode length of over 600 mm (rating of three).

5.1.5. Tangoio comparison:

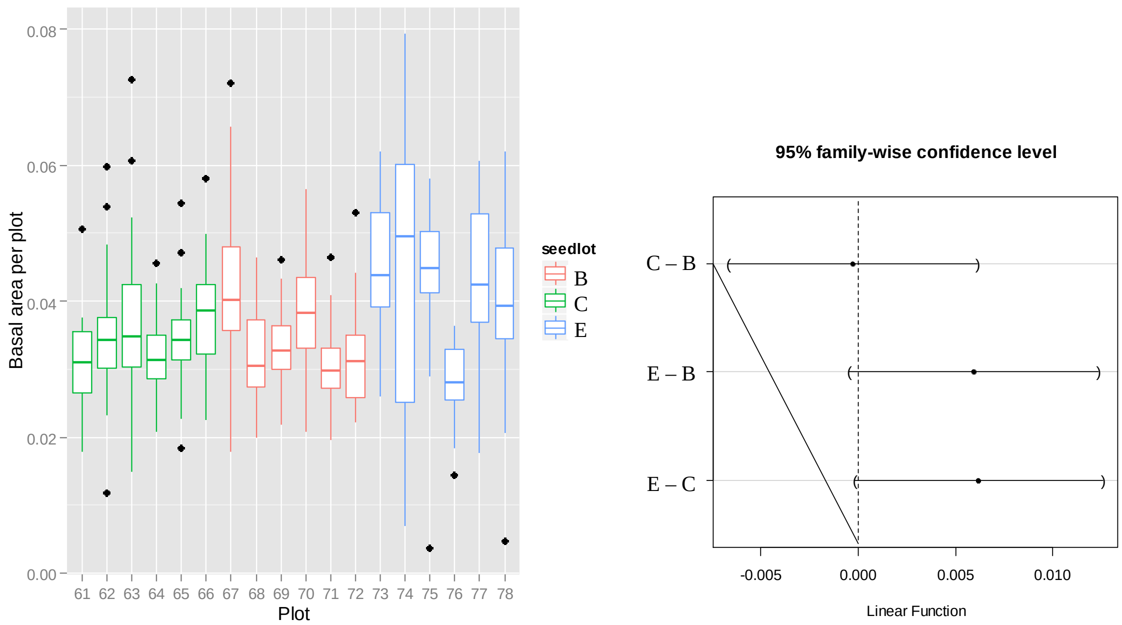

Figure 10: The basal area results per plot for each seedlot and the statistical differences for each match in the Tangoio comparison.

There was no statistical significant difference in basal area between clones B, E and C, however the mean of clone E was higher than clones B and C (Figure 10). There was no significant difference in height between the three seedlots (Appendix Figure 16).

Clone C was significantly stiffer than clone B with three of the plots having an average MoE of over 8 GPa (Appendix Figure 17). There was no significant difference between clone E and clones C and B though the mean of clone E was in between the other two.

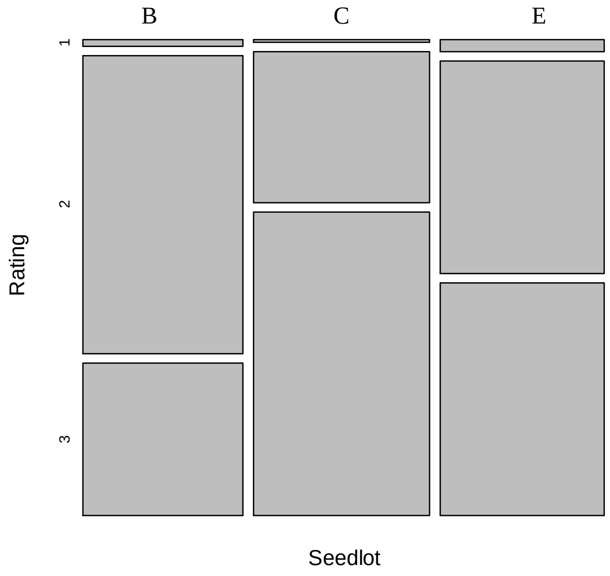

Figure 11: Mosaic plot of the straightness rating proportions for each seedlot in the Tangoio comparison.

Clone E was the straightest seedlot in the Tangoio comparison (Figure 11). There was very little difference in straightness between clones B and C. Clone E appeared to have the largest internodes (Appendix Figure 18). There was very little difference in internodes between clones B and C. Clone E had both more write-off's as well as more trees with little malformation than the other two clones (Appendix Figure 19). The other two clones had very little difference in malformation.

5.2. VARIABILITY RESULTS:

5.2.1. Diameter at breast height variability:

Table 1: The mean standard deviation for diameter at breast height for each of the four groups of old and young CP and clones.

Group	N	Mean standard deviation	Change from clones
Old CP	6	3.197	+15.9%
Old Clones	30	2.689	
Young CP	18	2.071	+9.3%
Young Clones	42	1.878	

CP seedlots were statistically significantly more variable than clone seedlots (p-value = 0.0227). The increase in variability for old CP over old clone was 15.9% and for young CP over young clone it was 9.3% (Table 1). Figure 12 shows a graphic representation of the distributions of DBH measurements.

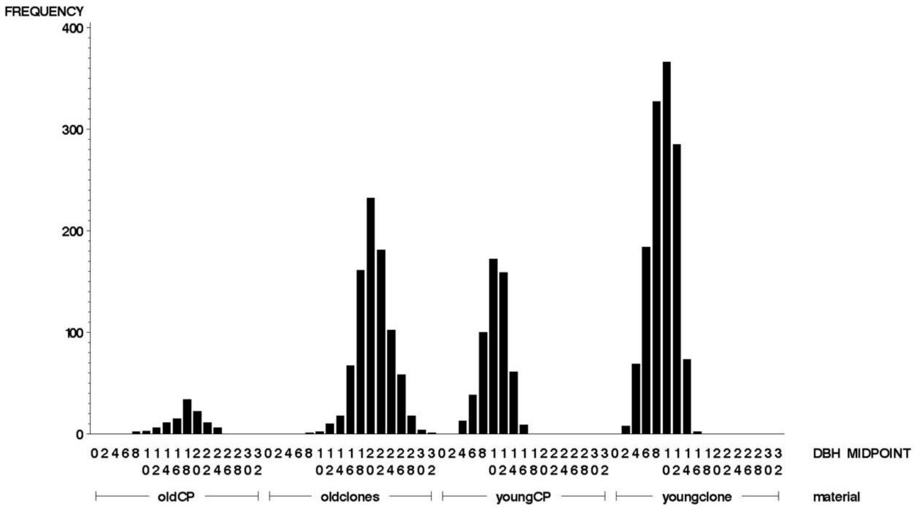

Figure 12: The frequency distributions of DBH measurements for the four groups of old and young CP and clones

5.2.2. Modulus of elasticity variability:

Table 2: The mean standard deviation for modulus of elasticity for each of the four groups of old and young CP and clones.

Group	N	Mean standard deviation	Change from clones
Old CP	6	1.031	+13.8%
Old Clones	30	0.889	
Young CP	18	0.579	+1.04%
Young Clones	42	0.573	

There was no significant different between clone and CP variation for MoE (p-value = 0.646). There was very little increase in variation for young CP from young clones (1.04%), however the increase for old CP from old clones was 13.8% (Table 2). Figure 13 shows the distributions of MoE measurements in each group.

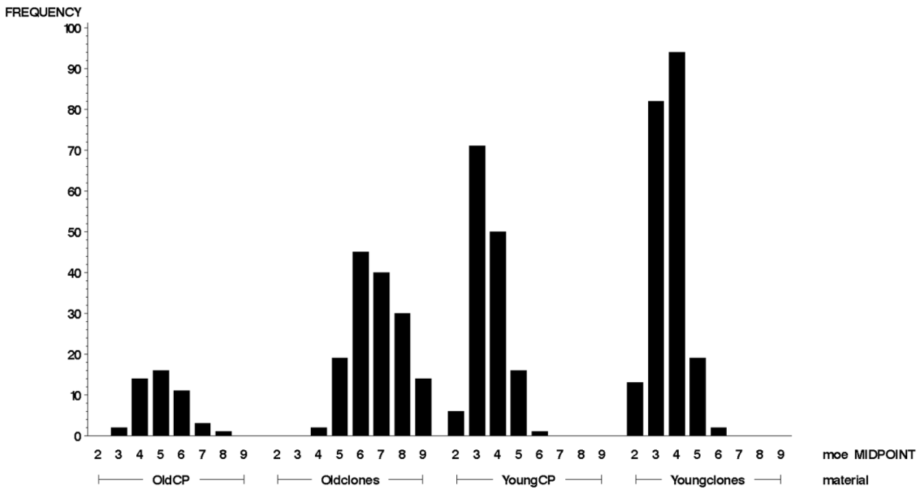

Figure 13: The frequency distributions of MoE measurements for the four groups of old and young CP and clones

5.3. EXPECTED RESULTS VERSUS ACTUAL RESULTS:

Table 3: Each clones performance in the study compared to trial performance for five traits.

Clone	DBH	Corewood stiffness (MoE)	Branching	Straightness	Freedom from Malformation
A	Yes	Yes	Yes	Yes	Yes
B	Yes	Yes	Yes	Yes	Yes
C	Yes	Yes	Bit less	Bit less	Bit less
D	Better than expected	Yes	Yes	Yes	Yes
E	Yes in age 7. Not in age 4.	Yes	Better than expected	Yes	Yes
F	Bit less	Yes	Better than expected	Yes	Bit less

Table 3 describes the performance of each clone for five of the studied traits in this study compared to their performance in the trials. The ratings produced by Forest Genetics can be found in the appendix (Table 20). Overall, the clones performed the same in Pan Pac Forest Products' production forests as they did in Forest Genetics' trials. Clones A and B performed the same in all five traits. Clone C performed the same in diameter and MoE but slightly under-performed in the production forests for the three form traits compared to the trials. Clone D performed the same in MoE and the form traits and was better than expected for diameter. Clone E performed as expected for MoE, straightness and freedom from malformation and better than expected for branching, meaning it had slightly longer internode lengths in the production forests. Clone E had interesting results for diameter; in the older age class blocks in Tangoio and Esk, clone E had a reasonably large diameter, however in the younger age class blocks, clone E was smaller than expected compared to other clones and CP seedlots.

6. DISCUSSION

6.1. CLONAL PERFORMANCE:

Genetics had a significant effect on the performance of different clones and CP across the comparisons. There were only four instances where there was no statistically significant difference between the all of the different seedlots in a comparison for the growth and wood quality traits. There was no significant difference in Tangoio for both diameter and height, and Gwavas 1 and Mohaka for MoE. As the form traits were not analysed for statistical differences, only qualitative differences, the statistical significance of any differences could not be defined.

Overall the clones performed well. There were four clones, A, B, C, and D, that performed well each time they were measured, which for some was only once. It is recommended that Pan Pac continue to purchase and plant these clones for generally good performance in volume and in stiffness. Clone A was an exceptional performer in growth, stiffness and form. Clone B performed well in growth and form, though it had small internode lengths and above average stiffness. Clone C performed well in size and stiffness and was slightly better than average in form except for straightness in some cases. Clone D was larger than expected in the Gwavas 1 comparison, had similar stiffness to other clones and had above average form.

Clone E performed well in Tangoio and Esk forests at age 7.5 years, however it did not perform well in the Gwavas 1 and Mohaka comparisons at age 4.5 years. If only considering the older age class, it would be recommended that Pan Pac planted clone E, however until the plots are remeasured in the future, it cannot be confirmed whether this clone is reliable or not. There is a chance that clone E is very vulnerable when young and if a detrimental event, such as a drought, occurs, deployed blocks of clone E may be held back and therefore perform poorly. Finally, for clone F there were two different blocks measured in Gwavas Forest that were on two different aspects and it did not perform well in either of these blocks. From this performance, it is not recommended that Pan Pac plant more of this clone unless it is necessary to increase the genetic diversity of their clonal estate.

6.2. BETWEEN-TREE VARIABILITY:

6.2.1. Diameter:

Clones were more uniform than CP seedlots in DBH for both the 4.5 year old age classes and the 7.5 year old age class in production forest blocks. The older age class had a greater difference in variability between the clones and the CP which may indicate that the natural variation of larger objects is not as wide in clones though this can only be substantiated with future re-measurement. The increased uniformity of clones is widely talked about in the forest industry, however there is no research proving it on a large production scale as yet. Uniformity is one of the main selling points of clones and it has the potential to increase the efficiency of forestry, harvesting, and mill operations.

6.2.2. Green modulus of elasticity:

There was no statistical difference between clones and CP for between-tree variation in MoE. This was likely driven by the young age class as there was only 1% difference in variation compared to a 14% variation for the old age class. The MoE variation data also seems to show that the difference in variation increases with age, however only re-measurement in the future would be able to confirm this.

6.3. COMPARISON OF TRIAL PERFORMANCE AND BLOCK PERFORMANCE:

The production plantings of clones in Pan Pac’s forests have been found to perform very similarly to their performance in Forest Genetics’ trials. This is very beneficial to Pan Pac as it indicates that they can rely on the ratings derived by Forest Genetics as a measure of the performance of clones on their forest estate. From this information, any new clonal varieties that become available through Forest Genetics can be reliably bought or rejected depending on whether the ratings for each trait matches the priorities of Pan Pac. The ramifications are that although this study is only a snapshot of clonal varieties available at time of planting, it has use beyond the clones measured.

6.4. LIMITATIONS:

6.4.1. Confounding:

The main limitation in this study is that there is no true replication of blocks of clones within and between each comparison. The blocks of clones were not planted in randomised experimental format as it was not known at the time of planting that they would be used in a study. Ideally there would be replications of blocks of clones within each comparison as well as the same clones planted in multiple comparisons. Replication would allow for any environmental effects to be accounted for; however as the study stands, the environmental effects could not be accounted for so there is some confounding between environmental effects and genetic effects in the results.

To minimise this confounding, only comparisons that had blocks that were close together with similar sites and the same silviculture were measured. The strict criteria for the comparisons reduced the environmental differences within comparisons as much as possible in the given circumstances. The impact of confounding should not significantly reduce the quality of the results and the implications of this study remain valid and important for the industry.

6.4.2. Difference in planting months:

Within two of the comparisons the different blocks weren't planted at the same time. Within the Gwavas 1 comparison the range of planting dates between the blocks were from late May to early September and this is the largest difference out of all of the comparisons. The only other comparison that had a difference was in Mohaka where the clonal block was planted in June and the CP block was planted in late April. The issue with the different planting dates is that the growth rates may differ between those that have spent longer planted on the site compared to those that spent longer in the nursery. The effect of having different planting dates is unknown and it has been assumed that it does not have a large effect on the results given that the differences in planting months were over winter when little growth occurs.

6.4.3. Different CP seedlots between comparisons:

There were different CP seedlots involved in the comparison. One seedlot was planted in both of the Gwavas comparisons so these are comparable, however for the Mohaka and the Esk comparisons, there are two different seedlots. Part of the issue is that CP seedlots are continuously changing based on the age of the hedges used by nurseries as over time the hedges become too mature and are replaced. This is the likely reason for the Esk seedlot being different. The other part of the issue is that there are only limited numbers of each seedlot available and many different seedlots to choose from so with the planting distribution decided on by Pan Pac, the same seedlot was not planted in the Mohaka comparison. This was a nuance of the study and was due to the conditions in which it was carried out.

The main issue with having different CP seedlots between comparisons is that the CP is not a common benchmark off which the clones can be compared on different sites. The only comparison possible on different sites is comparing clones when they have been planted on multiple sites. Including the CP seedlots in the comparison was still worthwhile as Pan Pac only plants clones and CP so each individual comparison resembles their two different options and can aid in making the decision about how many clones to plant.

6.4.4. Limited number of acoustic velocity measurements:

There were five measurements of acoustic velocity per plot for clonal blocks and eight per plot for CP blocks. Despite having a larger number of measurements of other traits, the decision was made to do fewer measurements of acoustic velocity as it was the most time consuming measurement. Having fewer measurements means that there is less information available to compare the variability between CP and clones for MoE and this may have been part of the non-significant outcome of the ANOVA.

7. CONCLUSION:

Several clones performed well in Pan Pac's production forests and will provide Pan Pac with large logs of good stiffness. There were significant differences between different clones and between clones and CP seedlots. The null hypotheses for research questions one and two is rejected.

Clones are significantly less variable than controlled-pollinated seedlings for diameter though not for modulus of elasticity. Increased diameter uniformity of clones over seedlings is discussed but as yet has not been proven on a large scale such as this study. Clones have the potential to provide efficiencies for forestry companies. The null hypothesis for the third research question is rejected but for the fourth research question, it is accepted.

The rating system carried out by Forest Genetics did indeed match the performance of their clones in Pan Pac's forests so Pan Pac can continue to rely on these ratings for choosing their clonal planting stock each year, possibly even for future clones and current clones that were not included in this study. The null hypothesis for the fifth research question is accepted.

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9. APPENDIX

9.1. COMPARISON RESULTS

9.1.1. Gwavas 1 comparison

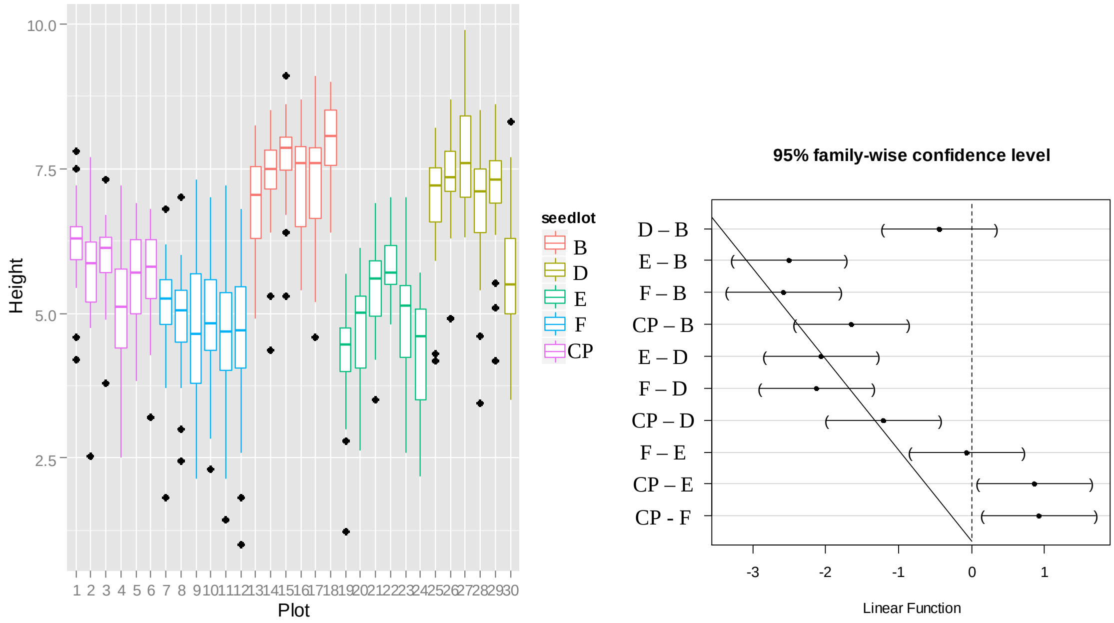

Figure 1: The height results per plot for each seedlot and the statistical differences for each match in the Gwavas 1 comparison.

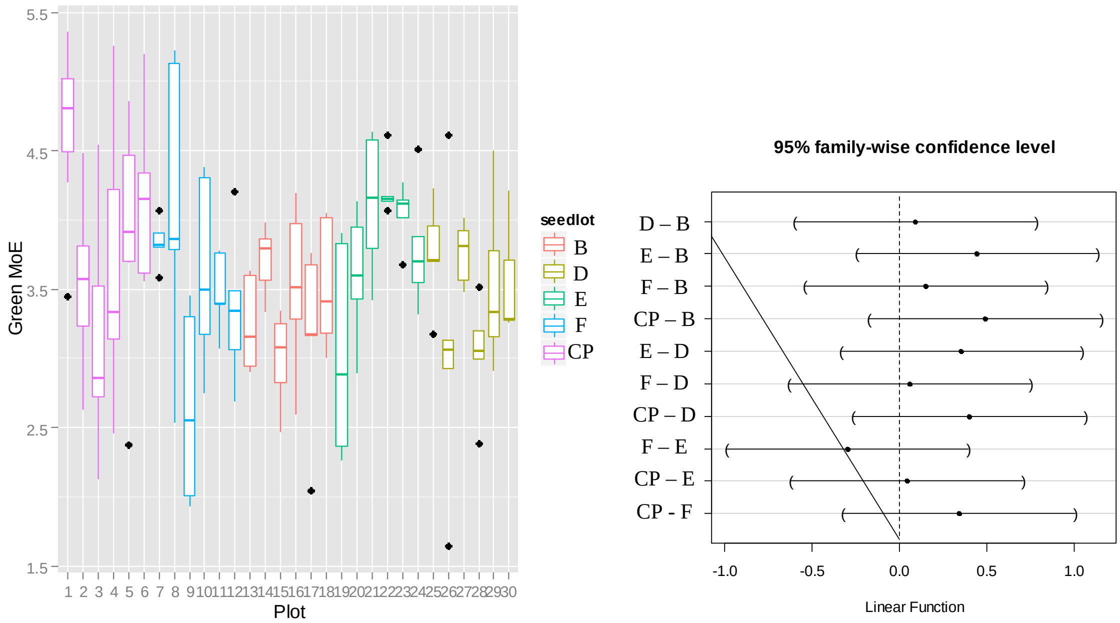

Figure 2: The modulus of elasticity results per plot for each seedlot and the statistical differences for each match in the Gwavas 1 comparison.

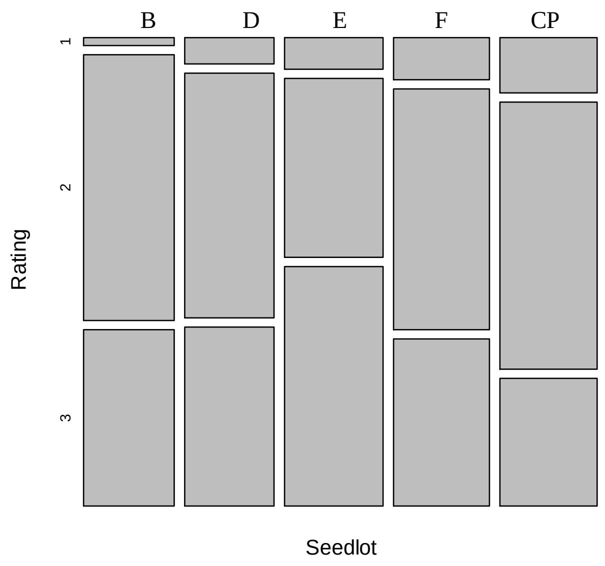

Figure 3: Mosaic plot of the straightness results per plot for each seedlot in the Gwavas 1 comparison.

Table 1: The numbers of trees in each rating category for each seedlot for straightness in the Gwavas 1 comparison (Figure 3).

Seedlot/Rating	1	2	3	Total
Clone B	3	102	68	173
Clone D	10	93	68	171
Clone E	13	75	100	188
Clone F	17	98	68	183
CP	23	110	53	186

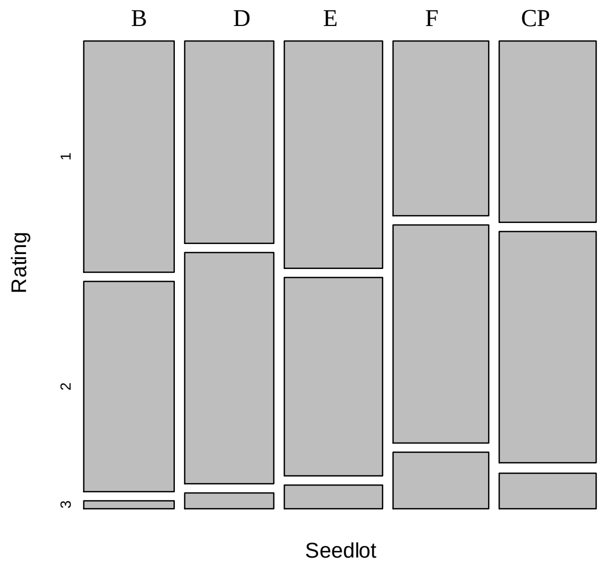

Figure 4: Mosaic plot of the branching results per plot for each seedlot in the Gwavas 1 comparison.

Table 2: The numbers of trees in each rating category for each seedlot for branching in the Gwavas 1 comparison (Figure 4).

Seedlot/Rating	1	2	3	Total
17	89	81	3	173
24	77	88	6	171
37	95	83	10	188
38	71	89	23	183
CP	75	96	15	186

Table 3: The numbers of trees in each rating category for each seedlot for malformation in the Gwavas 1 comparison (Results Figure 2).

Seedlot/Rating	1	2	3	Total
17	11	24	138	173
24	10	23	138	171
37	33	45	110	188
38	26	31	126	183
CP	31	53	102	186

9.1.2. Gwavas 2 comparison

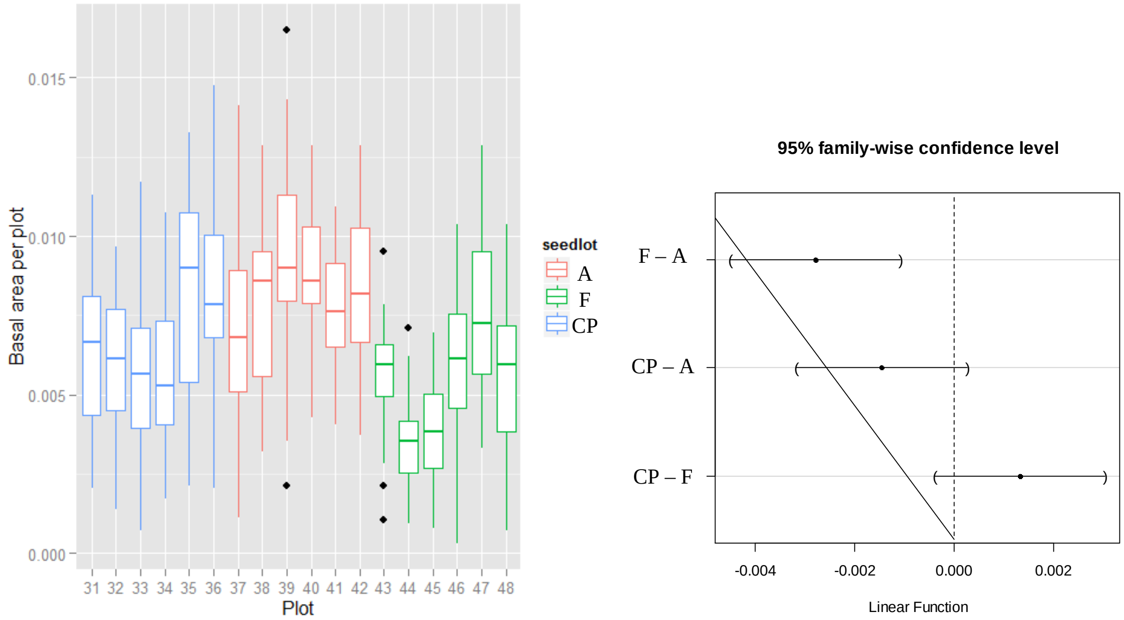

Figure 5: The basal area results per plot for each seedlot and the statistical differences for each match in the Gwavas 2 comparison.

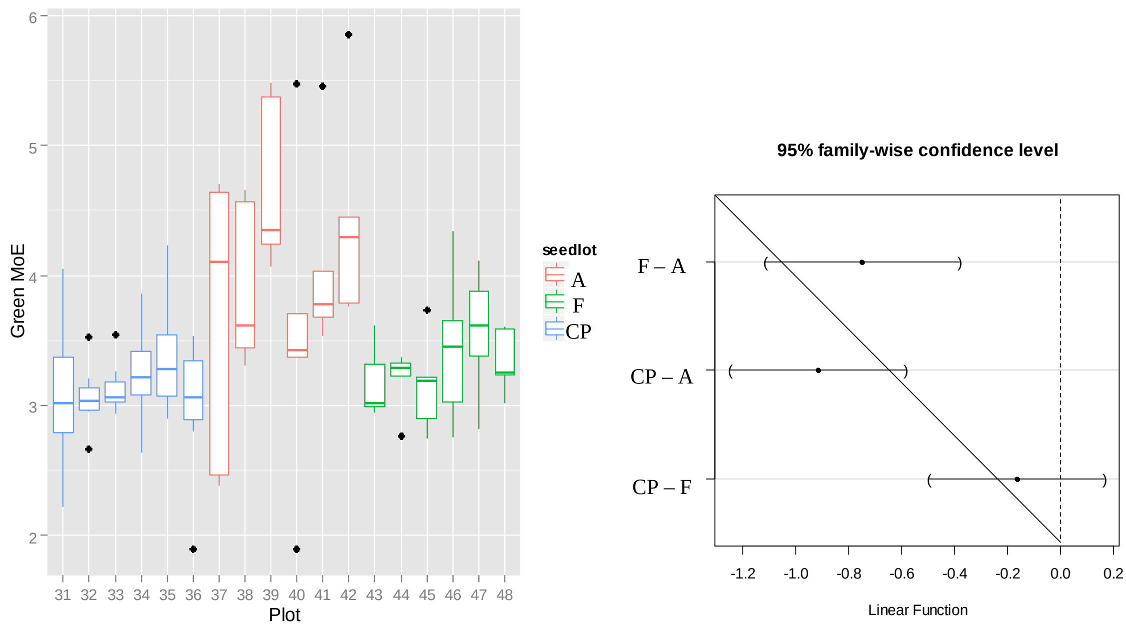

Figure 6: The modulus of elasticity results per plot for each seedlot and the statistical differences for each match in the Gwavas 2 comparison.

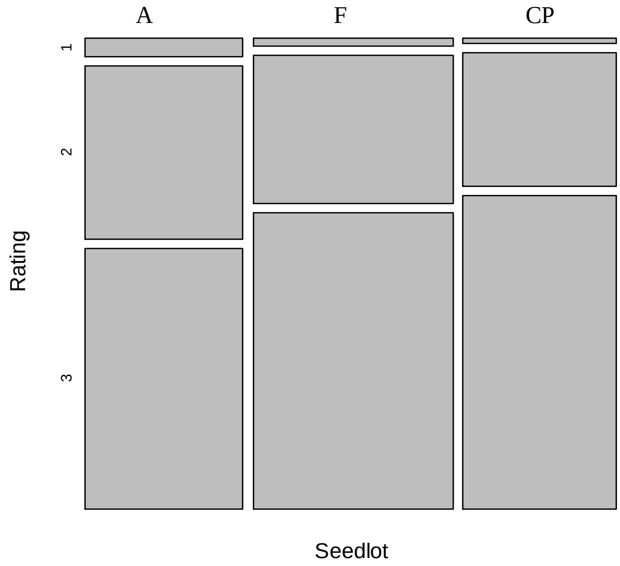

Figure 7: Mosaic plot of the straightness results per plot for each seedlot in the Gwavas 2 comparison.

Table 4: The numbers of trees in each rating category for each seedlot for straightness in the Gwavas 2 comparison (Figure 7).

Seedlot/Rating	1	2	3	Total
Clone 15	7	67	101	175
Clone 38	4	72	145	221
CP	2	50	118	170

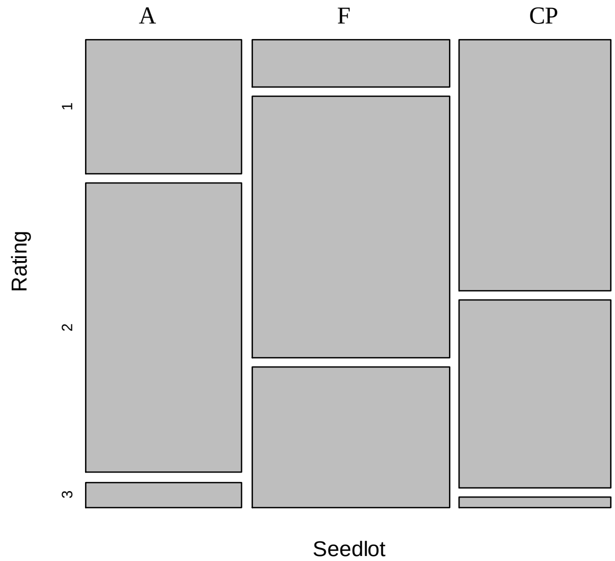

Figure 8: Mosaic plot of the branching results per plot for each seedlot in the Gwavas 2 comparison.

Table 5: The numbers of trees in each rating category for each seedlot for branching in the Gwavas 2 comparison (Figure 8).

Seedlot/Rating	1	2	3	Total
Clone 15	52	113	10	175
Clone 38	23	129	69	221
CP	95	71	4	170

Table 6: The numbers of trees in each rating category for each seedlot for malformation in the Gwavas 2 comparison (Results Figure 4).

Seedlot/Rating	1	2	3	Total
Clone 15	19	44	112	175
Clone 38	13	13	195	221
CP	9	14	147	170

9.1.3. Mohaka comparison:

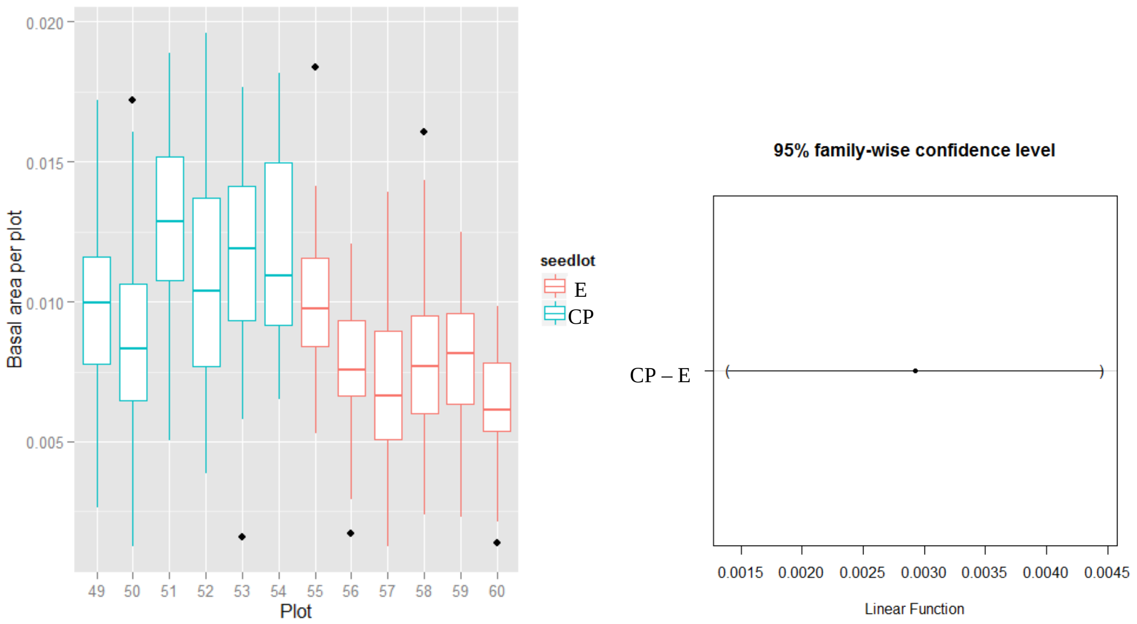

Figure 9: The basal area results per plot for each seedlot and the statistical differences for each match in the Mohaka comparison.

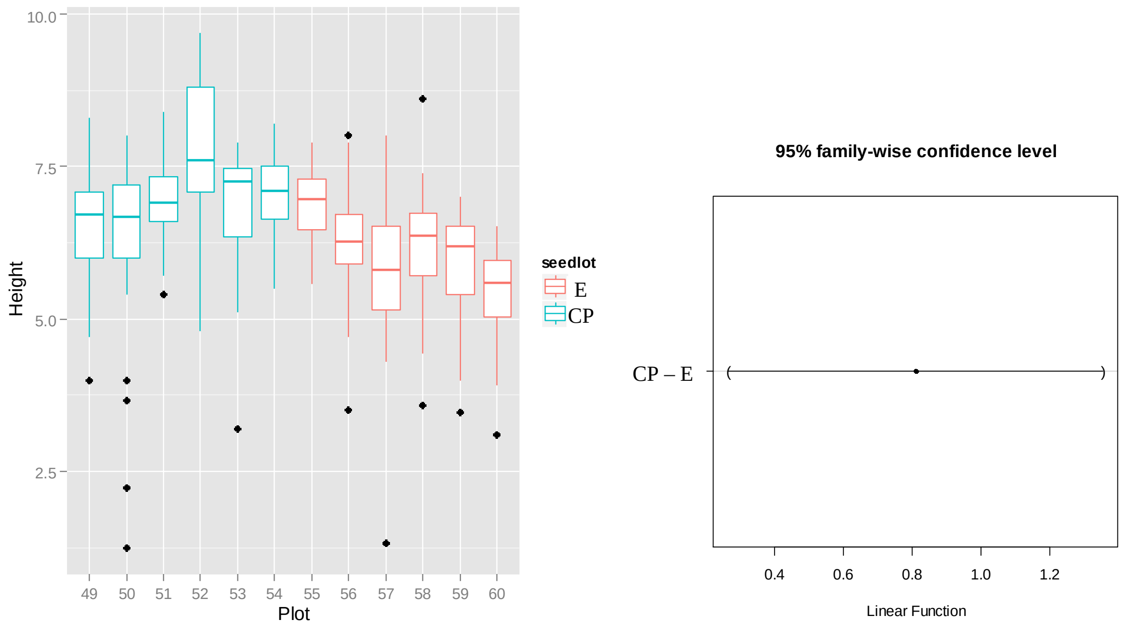

Figure 10: The height results per plot for each seedlot and the statistical differences for each match in the Mohaka comparison.

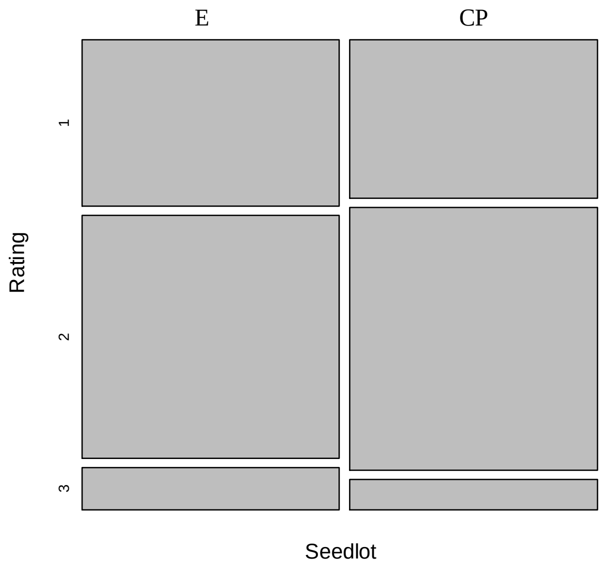

Figure 11: Mosaic plot of the branching results per plot for each seedlot in the Mohaka comparison.

Table 6: The numbers of trees in each rating category for each seedlot for branching in the Mohaka comparison (Figure 11).

Seedlot/Rating	1	2	3	Total
Clone 37	75	109	19	203
CP	69	114	13	196

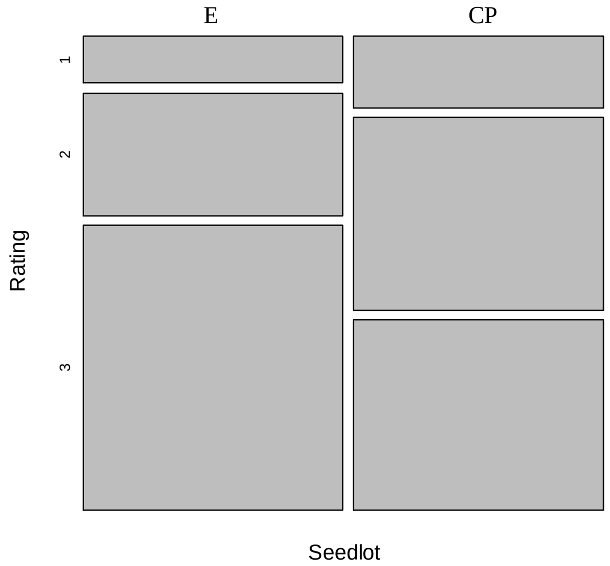

Figure 12: Mosaic plot of the malformation results per plot for each seedlot in the Mohaka comparison.

Table 7: The numbers of trees in each rating category for each seedlot for malformation in the Mohaka comparison (Figure 12).

Seedlot/Rating	1	2	3	Total
Clone 37	21	55	127	203
CP	31	83	82	196

Table 8: The numbers of trees in each rating category for each seedlot for straightness in the Mohaka comparison (Results Figure 6).

Seedlot/Rating	1	2	3	Total
Clone 37	4	85	114	203
CP	9	104	83	196

9.1.4. Esk comparison:

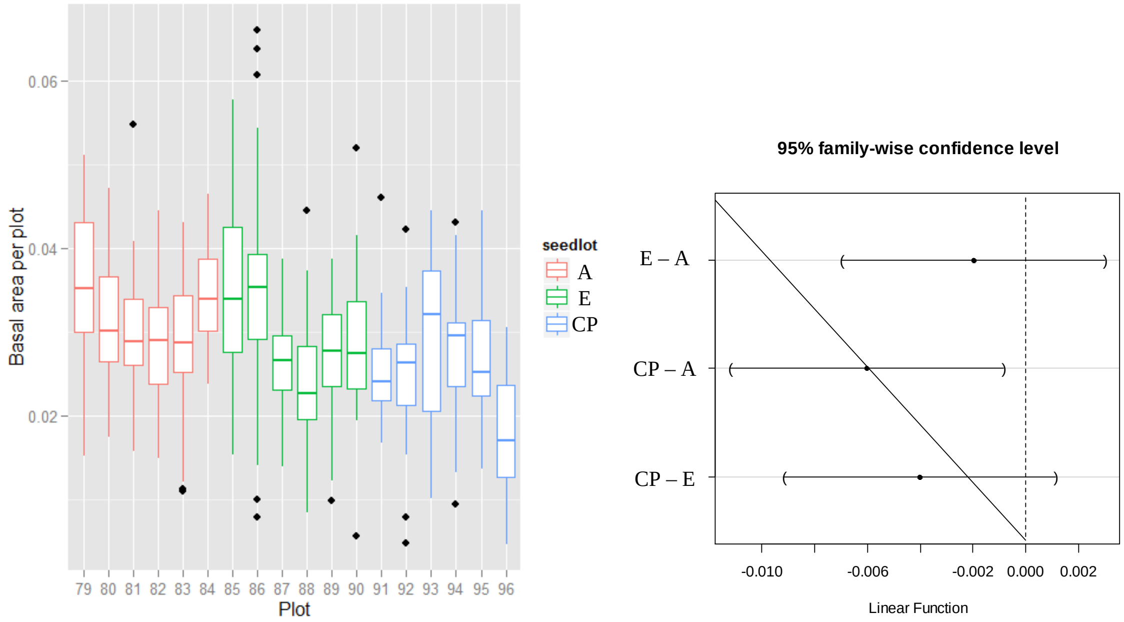

Figure 13: The basal area results per plot for each seedlot and the statistical differences for each match in the Esk comparison.

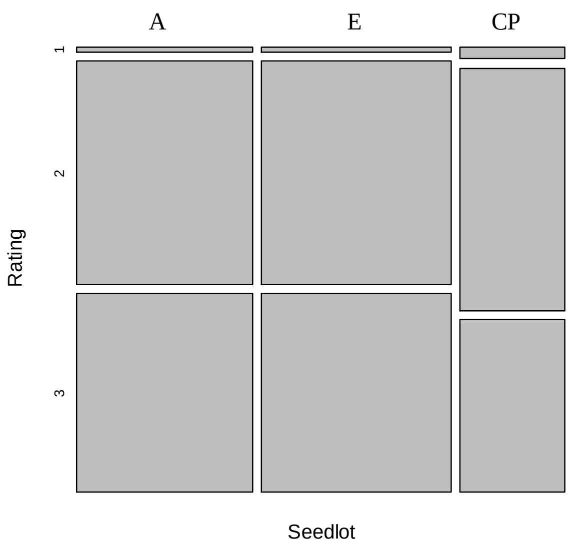

Figure 14: Mosaic plot of the straightness results per plot for each seedlot in the Esk comparison.

Table 9: The numbers of trees in each rating category for each seedlot for straightness in the Esk comparison (Figure 14).

Seedlot/Rating	1	2	3	Total
Clone 15	2	96	85	183
Clone 37	2	103	91	196
CP	3	62	44	109

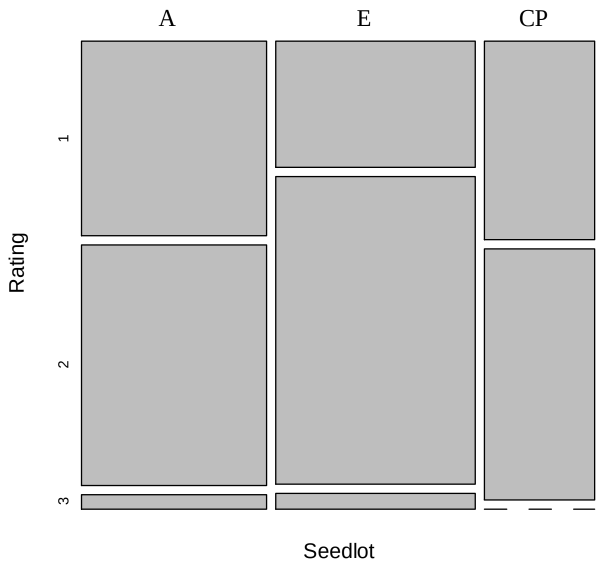

Figure 15: Mosaic plot of the branching results per plot for each seedlot in the Esk comparison.

Table 10: The numbers of trees in each rating category for each seedlot for branching in the Esk comparison (Figure 15).

Seedlot/Rating	1	2	3	Total
Clone 15	79	98	6	183
Clone 37	55	134	7	196
CP	48	61	0	109

Table 11: The numbers of trees in each rating category for each seedlot for malformation in the Esk comparison (Results Figure 9).

Seedlot/Rating	1	2	3	Total
Clone 15	79	98	6	183
Clone 37	55	134	7	196
CP	48	61	0	109

9.1.5. Tangoio comparison:

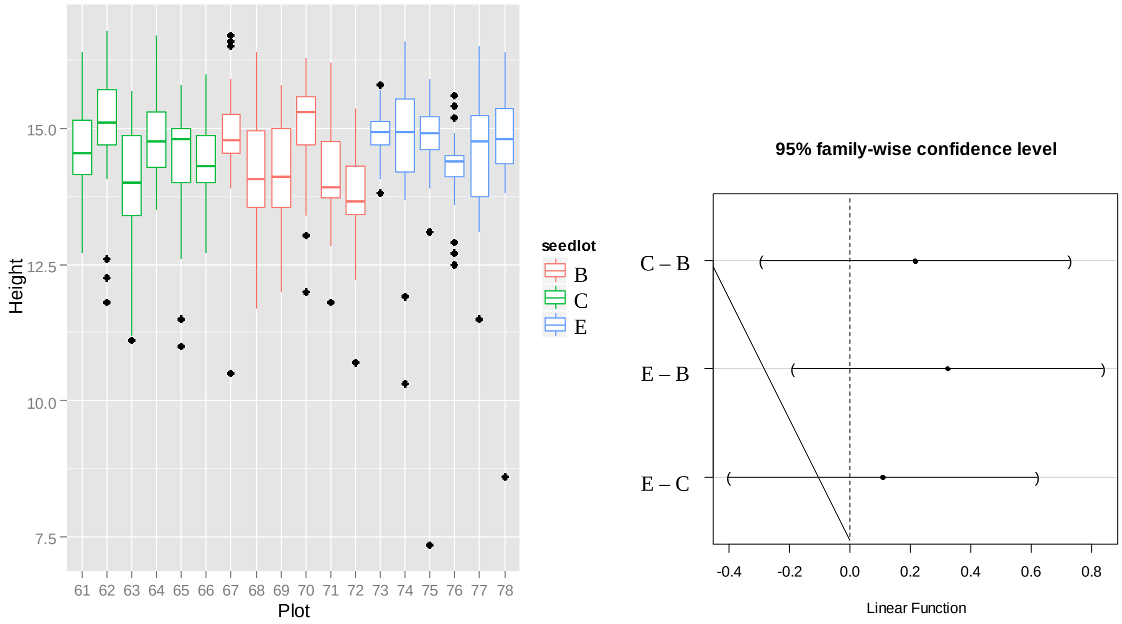

Figure 16: The height results per plot for each seedlot and the statistical differences for each match in the Tangoio comparison.

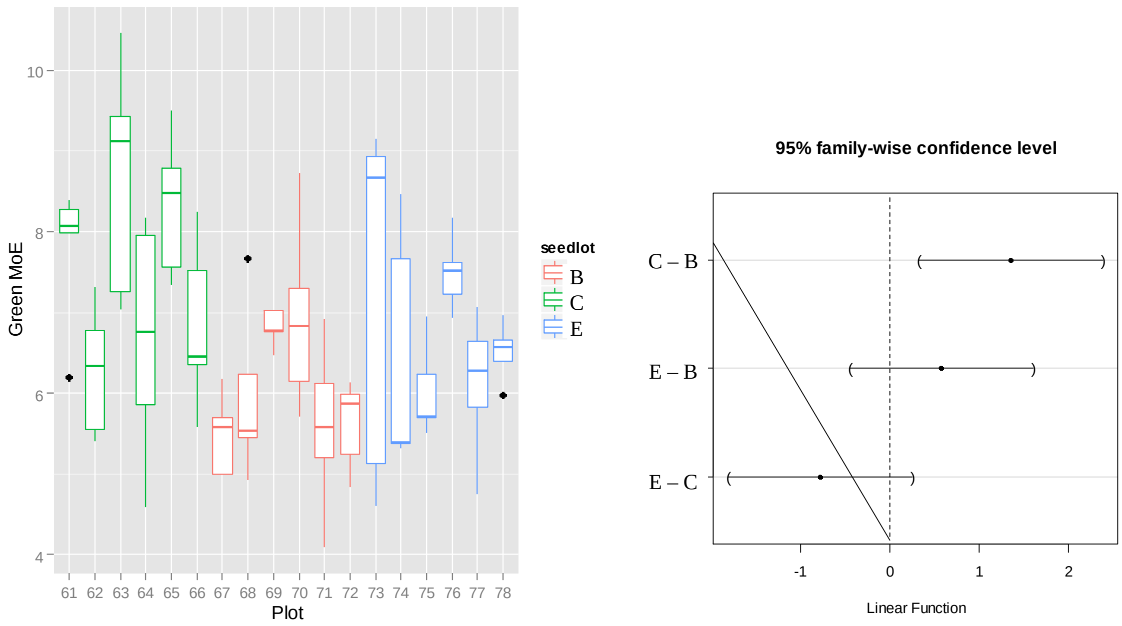

Figure 17: The green modulus of elasticity results per plot for each seedlot and the statistical differences for each match in the Tangoio comparison.

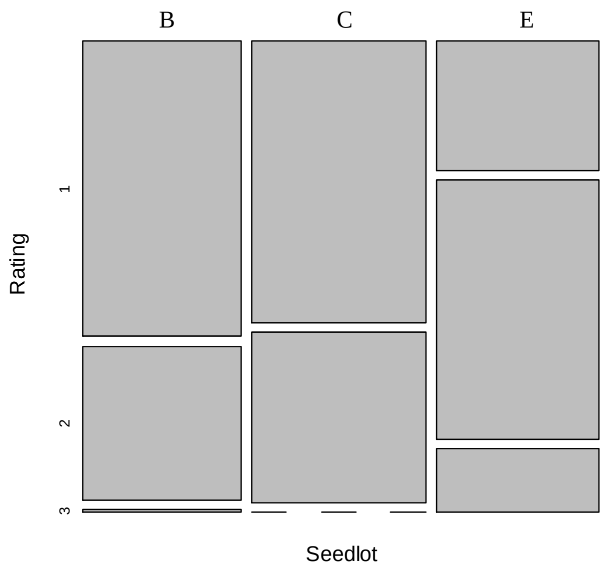

Figure 18: Mosaic plot of the branching results per plot for each seedlot in the Tangoio comparison.

Table 12: The numbers of trees in each rating category for each seedlot for branching in the Tangoio comparison (Figure 18).

Seedlot/Rating	1	2	3	Total
Clone B	100	52	1	153
Clone C	104	62	0	166
Clone E	45	90	22	157

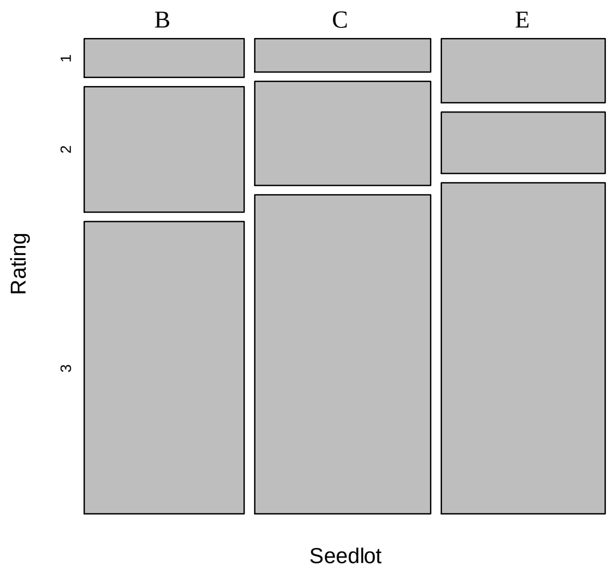

Figure 19: Mosaic plot of the malformation results per plot for each seedlot in the Tangoio comparison.

Table 13: The numbers of trees in each rating category for each seedlot for malformation in the Tangoio comparison (Figure 19).

Seedlot/Rating	1	2	3	Total
Clone B	13	42	98	153
Clone C	12	38	116	166
Clone E	22	21	114	157

Table 14: The numbers of trees in each rating category for each seedlot for straightness in the Tangoio comparison (Results Figure 11).

Seedlot/Rating	1	2	3	Total
Clone B	2	100	51	153
Clone C	1	55	110	166
Clone E	4	73	80	157

9.2. EXPECTED PERFORMANCE

Table 15: The rating system provided by Forest Genetics Ltd for the clones present in the trial

Nursery code	**DBH**	**Corewood stiffness**	**Branching**	**Straightness**	**Freedom from Malformation**
A	***	***	***	***	***
B	***	**	**	***	***
C	**	***	***	***	***
D	*	**	**	**	**
E	**	**	*	***	**
F	**	**	#	****	****

KEY

**** = exceptionally high

*** = high

** = above average

* = average

= below average

= very low