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Standing-tree Sonic Velocity in Silvicultural Breeds and Ultra-high Pruning Trials

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EXECUTIVE SUMMARY

Our understanding of how site, silviculture and seedlot/genotype contribute to the within-stem distribution of wood properties and how this distribution influences end-product performance is limited. An important issue is what wood property data should be collected and at what level of detail in order to make decisions about material planted and silvicultural treatments for a given site.

Wood properties may be measured at several levels of detail, each approach providing different information and having different uses. Detailed wood property data are required to understand the within-stem variability in wood properties, and to build within-stem wood property models for use in the prediction of end-use product performance. Such wood property data are currently collected by destructive sampling. However, the number of measurements required for an individual tree makes such data expensive to collect. Moderately non-destructive measurements such as outerwood density and standing tree sonic velocity (hereafter referred to as tree velocity) provide a snapshot of wood properties for a tiny portion of the stem, but are insufficient to characterise within-stem wood properties for an entire tree. Forest inventory techniques characterise trees and stands in terms of likely log grades by assessing branching and stem form, two features that influence wood property distributions within trees.

Standing tree velocity is a measure of the time taken for a sound wave to travel though a given length of stem. In combination with density, it is related to wood stiffness. This study examines the value of measuring standing tree velocity at the time of routine PSP re-measurement for either:

1. characterising PSPs and/or investigating the effects of site, silvicultural treatment and/or tree-stock, or
2. Determining which trials and silvicultural treatments should be targeted for destructive sampling.

In winter 2009, in addition to the annual re-measurement, standing tree velocity was measured for selected treatments at the six sites in the 1990 silviculture breed trial series and two sites from the ultra high pruning trial series. In the 1990 silviculture breed trial series, standing tree velocity was measured for PSPs at two different stockings (200 and 1000 stems/ha) for up to five different seedlots. In the ultra high pruning trial series, standing tree velocity was measured for a selection of six PSPs with different pruning and stocking treatments.

Outerwood density cores were also collected at the same time and the results are documented in FFR Radiata Management Theme Report No. R058.

This analysis of the standing tree velocity data indicated that:
In the 1990 silviculture-breed trials:

- Standing tree velocity varies considerably between individual trees within a treatment.
- Standing tree velocity tends to be lower at lower stockings. However the difference between different final crop stockings is more pronounced on known windy sites.
- No single seedlot consistently has a higher standing tree velocity across all sites.
- The variance in standing tree velocity within a treatment was not consistently less in control-pollinated seedlots (as might be expected) compared to open-pollinated seedlots.

In the ultra-high pruning trials:

- Standing tree velocity varies considerably between individual trees within a treatment.
- There was little variation in average standing tree velocity between the different pruning treatments.

The knowledge gained from this and earlier studies indicate that:

- Standing tree velocity tools only sample wood in the outer growth rings. As stiffness and other wood properties vary with tree age, the age at which measurements are taken is an important consideration.
- There is evidence that differences between treatments reduce with increasing tree age.
- Differences observed in standing tree velocity between seedlots selected for growth and form are minor compared to differences observed between site and silviculture.
- Standing tree velocity for an individual tree is weakly related to tree characteristics such as DBH, DBH increment at the ratio of height to DBH (stem slenderness).

Two questions were posed for this study:

1. Is there value in collecting standing tree velocity as a routine measurement on selected PSPs, trials or during forest inventory?

From this analysis, our conclusions are:

- There would be limited value in routinely measuring standing tree velocity as it is weakly related to tree taper, and differences between treatments appear to converge with increasing tree age.
- Standing tree velocity should be measured on trees in the 1991 silviculture breed trials during winter 2010 (at age 19 years) to complement the data from the 1990 trial series, and confirm that these results apply to a wider range of sites.
- Standing tree velocity in the special purpose breed trials should be measured, preferably also at age 19 years, to determine whether these relationship hold within seedlots selected for wood properties.

2. Is measuring standing tree velocity useful for making decisions about where destructive sampling should take place?

From this analysis, our conclusions are:

- It would be of limited value in rotation-aged trees as differences between trees appear to converge with increasing tree age.
- It is of limited value in trials, such as the ultra-high pruning trials where stands have received different treatments to reach the same final crop stocking, because standing tree velocity only considers the outer sheath of wood, not wood formed around the time of the silvicultural treatments.
- In the 1990 silvicultural breed trials, the results suggest it may be sufficient to destructively sample one or possibly two seedlots.

INTRODUCTION

Many radiata pine trials were established to determine how one or more of site, silvicultural treatment, and genetic material planted, influence stem growth; and to provide data for developing growth models. In addition, these trials are equally useful for determining the influence of the above variables on crown development and stem wood properties, and to provide data for developing crown and wood property models.

As it is expensive to destructively sample trees to determine within stem distribution of wood properties, and because we have limited knowledge of the impacts of different genetic material and silviculture treatments on wood properties, the following questions were posed:

- Is there value in characterising sites using non-destructive techniques such as standing tree sonic velocity?
- Can standing tree sonic velocity and/or outer wood density measurements help in targeting which combinations of site $\times$ silvicultural treatment $\times$ genetic material should be sampled more intensively from trials with many different combinations?

To address these questions, standing tree velocity was measured for selected treatments in two trials series during the winter of 2009.

Standing tree sonic velocity tools provide an estimate of the velocity of a sound wave through the outer few cm of a tree stem. The velocity is measured over a distance of approximately 1 m at one or more points around the stem. This velocity is related to stiffness through the formula:

$$E_d = \rho V^2$$

Where:

E_d is the dynamic modulus of elasticity

ρ is the green density of the wood

V is the acoustic (sonic) velocity.

1990 Silviculture Breed Trials

The 1990 Silviculture Breed Trials were planted in 1990 [1,2]. 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)

Objectives for the analysis included:

- To determine whether standing tree velocity varies between seedlots with the same silvicultural treatment.
- To determine the differences in standing tree velocity with different silvicultural treatments for the same seedlot.
- To determine whether the between tree variability in standing tree velocity is lower in control- pollinated seedlots than open- pollinated seedlots .
- To determine the site differences in standing tree velocity for a given seedlot and silvicultural treatment.

- To determine whether there is a treatment and genetics effect over and above the effect of tree DBH.

The PSPs selected for measurement came from two different silvicultural treatments and four (2 sites) or five (4 sites) different seedlots (see Appendix 1). Note: the long-internode seedlot,GF13/LI25, was not planted at FR121/4 or FR121/7.

Ultra-High Pruning Trials

The ultra-high pruning trials were selected for study as they have a wide range of crown structures. It was hypothesised that the different crown structures would influence the tree movement and consequently wood property distributions [(3)].

Four ultra-high pruning trials were established [(4)]. 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.
- 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 after each pruning lift at 200 stems/ha and 7.9 m crown length remaining after each pruning lift at 350 stems/ha.

METHODS

Standing tree velocity was measured using the ST 300 and PDA unit. Care was taken to ensure that the unit was used according to the manufacturer's recommendations. In brief these included, calibrating the PDA to the correct temperature before beginning work, maintaining at least a one metre distance between probes, inserting the probes to the recommended depth, maintaining correct probe alignment, regular battery checks and striking the lower probe with the same force eight times in succession for three individually recorded readings which are averaged to give the standing tree velocity measurement used in this study.

For the selected PSPs on all sites (Appendix 1 and 2), one set of standing tree velocity measurements were taken. This was on the concave (upper) side of the stem, if any sweep / lean was present. In addition, at Waiotahi and Tungrove, a second set of standing tree velocity measurements was taken at 180 degrees to the first set. This was on the convex side of the stem if any sweep / lean was present.

Forked stems were treated either as one stem if the fork was above approximately 2m, or if the fork was below 2 m, then it was sampled and recorded as two individual stems. Trees forked below 2 m have been excluded from this analysis. If an alive toppled stem was encountered, e.g., one side of the stem was lying on the ground, then the stem was sampled once only on the upward side and noted. Stems that had a DBH of 10 cm or less were noted and excluded from the sample.

Any stems that displayed characteristic differences from the rest of the PSP being sampled were also identified and noted on the PDA for possible exclusion or explanation in the data analysis.

The data were graphically examined using the PROC GPLOT procedure within SAS. A graphical examination of data is important to determine any trends in the data, and provide an intuitive feeling of the importance of observed relationships.

Using the data from the 1990 silviculture breed trials, the relationships between site, silvicultural treatment and seedlot were examined.

Using the data from the ultra-high pruning trials, the relationships between silvicultural treatments were examined. There are differences between the two trials that need to be taken into consideration when comparing relationships across the two sites, namely the different seedlots planted, and the fact that one trial had received a 4 m pruning lift before any treatments were established.

The data were examined at a plot level and at an individual tree level. At the tree level, standing tree velocity was examined in relation to three different tree measurements:

- Tree DBH (chosen because it is an easily measured variable, and has previously been related to stiffness [(5)]).
- DBH increment between the last two measurements (chosen because the instruments only measure velocity in the outer wood).
- Tree height / DBH ('slenderness', chosen because it has been found to be a useful predictor of stiffness[(6)], however this ratio can only be calculated for a limited set of the data as height is only measured on selected trees within a sample plot).

RESULTS

Notes:

- For ease of comparison, all graphs are listed in the appendices. They are best viewed electronically or printed in colour.
- For clarity mean values have been joined by a solid line.
- The variable 'siteno' is used in preference to the forest name on several of the graphs as this provided better clarity for the graphs. The 'siteno' for each forest is given in Appendix 1.

1990 Silviculture Breed Trials (see Appendix 3 for figures)

Site Relationships

The mean standing tree velocity was always higher for plots at 1000 stems/ha than for plots at 200 stem/ha. The difference between the two stockings was larger on known windy sites, such as Gwavas FR121/3 and Huanui FR121/7 (see Appendix 3, Figures 1 to 6 and Appendix 6, Figure 27). These sites also stood out as having lower standing tree velocities compared to other sites (see Appendix 3, Figure 7, and Appendix 6, Figure 26). Across the sites, no seedlot stood out as having consistently higher standing tree velocity (Appendix 3, Figure 7).

The SAS procedure PROC GLM indicated that the following terms were significant:

- Site
- Final crop stocking
- The interaction between site and final crop stocking

There were no significant differences between the different seedlots.

Seedlot Variance

One aim of tree-breeding is to reduce the variability between trees. The plot variance in standing tree velocity was calculated for each site, seedlot and stocking combination. The seedlot with the least variance was not consistent across sites, or across different final crop stockings (see Appendix 3, Figure 8).

Tree Level Relationships

At an individual tree level, the relationships between DBH, DBH increment and the ratio of height to DBH were rather weak with no obvious and consistent relationships between the different seedlots. To provide clarity to the relationships, the data were divided into classes of DBH, DBH increment, and the ratio of tree height to DBH. The mean value of standing tree velocity for each class at each site was calculated (Appendix 3, Figures 9 to 11). These results suggest that the relationships may be curvilinear, and illustrate that the relationship differs with site. Gwavas FR121/3 and Huanui FR121/7, which are known windy sites, have consistently lower values.

DBH, DBH increment and the ratio of height to DBH would be equally applicable for predicting standing tree velocity. The implications of using the ratio of height to DBH when height is only measured on selected trees, and generally those with better stem form needs to be considered.

Standing tree velocity was consistently higher for height trees compared to trees not measured for height (Appendix 3, Figure 12). The difference was generally significant ($p <= 0.05$) for an individual site and final crop stocking.

In a PSP re-measurement, features of the stem such as top-out, sweep, etc. are recorded as a descriptive code. For this analysis, trees without a descriptive code (stem_class) were labelled as 'good' and those with a descriptive code were labelled as 'poor'. On average the standing tree velocity tended to be slightly lower for trees with a 'poor' descriptive code (Appendix 3, Figure 13). The difference was generally significant ($p<=0.05$) for an individual site and final crop stocking). More detailed analysis in relation to the individual descriptive codes is needed, but this raises the question of whether stem wood property distributions influence the likelihood of a stem being damaged and / or wood property distributions are altered by events that influence stem form.

Ultra-High Pruning Trials (see Appendix 4 for figures)

The ultra high pruning trials at Ngaumu and Waiotahi were planted three years apart and with different seedlots. Six silvicultural treatments (Appendix 2) were examined on both sites to allow the impact of different pruning and stocking treatments to be examined. While the two sites have been included on the same graphs, it is important to remember the difference in age, seedlot planted, and the fact that one site was pruned prior to establishment. They are also up to 5 years older than the 1990 silviculture breed trials.

Site and Treatment Relationships

The relationship between standing tree velocity and silvicultural treatment varied with site conditions. At Ngaumu, a windy site, mean standing tree velocity was lower at 200 stem/ha compared to 350 stem/ha, regardless of pruning treatment (Appendix 4, Figure 14). At Waiotahi, a sheltered site, this was not the case (Appendix 4, Figure 15).

Examining the unpruned treatments (Appendix 4, Figure 16), standing tree velocity was higher at 350 stems/ha compared to 200 stem/ha at both sites. Standing tree velocity was slightly, but not significantly, higher at Ngaumu, compared to Waiotahi. This is in contrast to the 1990 silviculture breed trials, where the windy sites had lower standing tree velocities. The reason for the current result is not known, but could be due to one or more of the differences between the two trials (see above).

At a final crop stocking of 350 stems/ha, the pruning treatments retained 7.9 m of crown at each pruning lift. For both sites, standing tree velocity tended to be slightly higher when the ultimate pruning height was higher (Appendix 4, Figure 17).

At a final crop stocking of 200 stems/ha, the pruning treatments retained 4.9 m of crown at each pruning lift. For both sites, standing tree velocity tended to decrease when the ultimate pruning height was higher (Appendix 4, Figure 18).

These results suggest that there are complex interactions between crown structure, stand structure, and the development of wood properties.

Tree Relationships

At both sites in 2009, there is a slight curvilinear trend in the relationship between standing tree velocity and tree DBH (Appendix 4, Figure 19).

There was a weak, probably curvilinear trend with respect to DBH increment. Visually, standing tree velocity tended to be less in the unpruned treatments for a given tree DBH increment (Appendix 4, Figure 20).

There was a weak trend with respect to the ratio of tree height to DBH. Visually, there are no obvious differences in the relationship due to the different treatments (Appendix 4, Figure 21). The disadvantage of the height / DBH ratio, is that height is only measured on selected trees, and generally those with good form. As with the 1990 silviculture breed trials, standing tree velocity tended to be slightly higher for trees with height measurements compared to trees without height measurements (Appendix 4, Figure 22), and slightly lower for trees that had a stem description code assigned in the PSP system (labelled as ‘poor’) (Appendix 4, Figure 23). The differences were generally not significant ($p<=0.05$).

Difference Between Measurements of Standing Tree Velocity at Two Different Positions Around the Stem (see Appendix 5 for figures)

It is useful to examine the difference in standing tree velocity taken in different directions to determine if there are any situations which may lead to larger differences, or to identify the situations that will require taking measurement in more than one direction.

The absolute difference for an individual tree was examined with respect to tree DBH, DBH increment between the last two re-measurements (2007-2009), and stem description codes recorded in the PSP.

1990 Silviculture-breed Trial, Tungrove, FR121/1

The absolute difference in standing tree velocity could be over 1 km/s, and there were no obvious patterns with respect to DBH, DBH increment, or stem description codes. The observed pattern with respect to DBH is shown in Appendix 5, Figure 24.

Ultra-High Pruning Trial, Waiotahi, FR243

The absolute difference in standing tree velocity was higher for small diameter increments in two different silvicultural treatments (Appendix 5, Figure 25):

- Unpruned trees at 200 stems/ha, and
- Trees at 350 stems/ha that were pruned to 5.8 m with 7.8 m of crown remaining.

The structure of wood cells is influenced by the movement of the tree[(3)]. In a given environment, one might therefore expect that trees at a tighter stocking would experience less movement (and have a higher stiffness) than trees at wider stockings, and unpruned trees with a lower centre of gravity to move less than pruned trees with a higher centre of gravity. On this basis, there does not appear to be any logical explanation for the above result. A possible explanation could be differences in the local micro-environment of the plot which have influenced tree movement.

Another interesting observation is the high diameter growth for the treatment:

- Trees at 200 stem/ha that were pruned to 11.8 m with 4.9 m of crown remaining at each lift. This may be an attempt to make the trees more stable after the severe pruning.

DISCUSSION

Standing tree velocity has previously been measured in a number of other trials. In combination with green density, it provides an estimate of stiffness in the outer sheath of a tree.

Standing tree velocity was measured in two Canterbury radiata pine trials that examined the interactions between stocking and genetic material. In both these studies, the standing tree velocity was converted to green dynamic modulus of elasticity (E_d). In an 11-year-old experiment[(5)], E_d was on average 34% higher at 2500 stem/ha compared to 883 stems/ha. If differences in DBH were not considered, there were no significant difference in E_d between GF1 and GF27 seedlots. In a 17 year-old Nelder trial[(6)], E_d increased by 39% from the lowest stocking of 209 stem/ha to the highest stocking of 2551 stems/ha; and by an estimated 6% between 883 stems/ha and 2550 stems/ha. There was no significant difference in E_d between seedling populations from 850, 268, 870 series.

Standing tree velocity was measured at age 17 years for a random sub-set of trees for selected combinations of seedlot and final crop stocking in the five of the 1987 silviculture breed trials [(7)]. There was no apparent difference between the different seedlots considered.

It was suggested that differences in outerwood E_d with stocking may converge with increasing age[(6)], and this is supported by another study[(8)], which showed no significant difference in standing tree velocity between plots at 100 and 625 stems/ha at age 27 years. Such results have implications for using standing tree velocity to elucidate differences between treatments in older trials.

For the current analysis, standing tree velocity was measured in the 1990 silviculture breed trials, at age 19 years, for up to 5 different seedlots and two final crop stockings (200 and 1000 stems/ha). At each site, the % difference in standing tree velocity between the two stockings was less than 15% compared with approximately 30% for a comparable stocking range in 17-year-old Nelder[(6)]. The low difference between the two stockings may be further evidence of the convergence with age.

An interesting result from the current analysis is that the effect of stocking was influenced by the windiness of the site, with very small differences at Tarawera, a sheltered site (Appendix 3, Figure 5).

In terms of seedlot, no one seedlot was consistently better across all sites. The fact that the differences between seedlots are smaller than the differences between silviculture treatments is in agreement with a previous WQI study[(7)].

In the ultra-high pruning trials, the differences in standing tree velocity between treatments at 200 versus 350 stems/ha were small, as was the case in as was the case for this stocking range in the Nelder trial[(6)].

Considering the relationships between standing tree sonic velocity and other tree measures, there were weak trends with respect to tree DBH, DBH increment and the ratio of tree height to diameter.

An interesting point that needs further consideration is the fact that standing tree velocity does not appear to be influenced by seedlot, but standing tree velocity appears to be influenced by the ratio of tree height to tree DBH. Studies have shown that tree height varies little between different seedlots, but there are much larger differences in basal area per hectare[(9)]. So, the seedlots with the higher basal area growth would tend to have lower height to DBH ratios, and as a consequence, lower standing tree velocity. However comparing the basal area trends[(9)] with the current data, the seedlots with the highest basal area do not necessarily have the lowest standing tree velocity.

CONCLUSION

Standing tree velocity measures the time taken for a sound wave to travel though a given length of stem. In combination with density, it is related to wood stiffness. However the standing tree velocity is only a point measure for a tree, and provides little information about the within stem patterns of wood properties. The tool was used in this study to (1) gain an idea of likely variability between different combinations of sites, silvicultural treatments and seedlots, and (2) determine whether it was a useful tool to provide guidelines about where more detailed measurements should be collected using destructive sampling techniques.

The 1990 silviculture breed trial series contained a range of treatments with different initial and final crop stockings and different seedlots. In this trial series, the thinning ratio was the same for all thinning treatments. Hence trends observed in the outer wood are likely to be mirrored in the interior of the stem. Important points to note from the measurements taken in this trial series are:

- There was an influence of site with standing tree velocities tending to be lower on known windy sites.
- There was an influence of stocking, with standing tree velocity tending to be lower at lower stockings. The difference varied with site being more pronounced on known windy sites.
- Differences between seedlots were minimal, but remember that the seedlots in this trial series were not selected for wood properties.
- The variance in standing tree velocity for a given seedlot was not consistent across sites, and was not noticeable less in the control pollinated seedlot compared to the open-pollinated seedlots.

In the ultra-high pruning trials, treatments were imposed on an established stand, and plots with a given final crop stocking, received a range of different pruning treatments, altering the crown structure of the stand. There were only small differences between the different pruning treatments. However we do not know whether these trends in the outerwood will be mirrored in the inner growth rings formed at the time the different pruning treatments were applied. A small-scale destructive sampling study needs to be carried out to determine whether there are treatment differences in the interior of the stem before standing tree sonic measurements are recommended in trials, such as pruning trials, where plots reach the same final crop stocking via different routes.

In conclusion, standing tree velocity measurements will provide useful information in certain situations. Further data collection in other trials, need to consider the following:

- The age of the trial
- The previous silvicultural history
- The value of the data compared to alternative measurement techniques.

Recommendations

Further Collection of Standing Tree Velocity Measurements

There are indications in the literature that differences in standing tree velocity between different treatments may be influenced by age of measurement. Useful information was obtained from the 1990 silviculture breed trial series, it is recommended that age 19 years be used as a common age of measurement in other trial series that are approaching 19 years of age.

On this basis it is recommended that:

- Standing tree velocity measurements are collected in the 1991 silviculture breed trials during winter 2010. These trials have essentially the same design as the 1990 series and this would provide coverage of a wider range of sites at a common age.

- Standing tree velocity measurements are to be collected in the 1992 special purpose breed trial series in 2011 and in the 1994 special purpose breed trial series in 2013. To our knowledge these are the earliest large-block trials containing seedlots selected for different wood properties.

Destructive Sampling

A small destructive sampling study should be carried out in the ultra-high pruning trial to determine whether differences between different pruning treatments are more pronounced in the interior of the stem, in particular in the growth rings formed immediately after silvicultural treatment, and at different heights in the stem.

At the time of clearfelling, destructive sampling studies in the 1990 silviculture breed trials could be limited to one seedlot or two seedlots on a known windy (e.g. Gwavas) and a known sheltered site (e.g. Tarawera). Data were previously collected in the 1991 silviculture breed trial at Shellocks Canterbury prior to clearfelling for land conversion (10), and any future data collection should aim to provide compatibility with this previous study.

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APPENDICES

APPENDIX 1. List of Permanent Sample Plots in the 1990 Silviculture Breed Trials for which standing tree velocity data were collected.

Treatments sampled: **FR121/1, Tungrove (siteno 1) (290 trees)**

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 (siteno 2) (292 trees)**

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 (siteno 3) (257 trees)**

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 (siteno 4) (194 trees)**

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 (siteno 6) (303 trees)**

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 (siteno 7) (209 trees)**

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 standing tree velocity data were collected.

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

Plot Number	Final stocking (SPH)	Crown length remaining (m)	Final pruned height (m)
20/0/13	200	unpruned	0.0
20/49/1	200	4.9	7.6
20/49/10	200	4.9	12.0
35/0/16	350	unpruned	0.0
35/76/6	350	7.9	7.6
35/76/7	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	Final stocking (SPH)	Crown length remaining (m)	Final pruned height (m)
20/0/1	200	unpruned	0.0
20/49/22	200	4.9	5.8
20/49/14	200	4.9	11.8
35/0/17	350	unpruned	0.0
35/79/3	350	7.9	5.8
35/79/12	350	7.9	11.8

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

APPENDIX 3. Graphical analysis of data from the 1990 silviculture breed trials

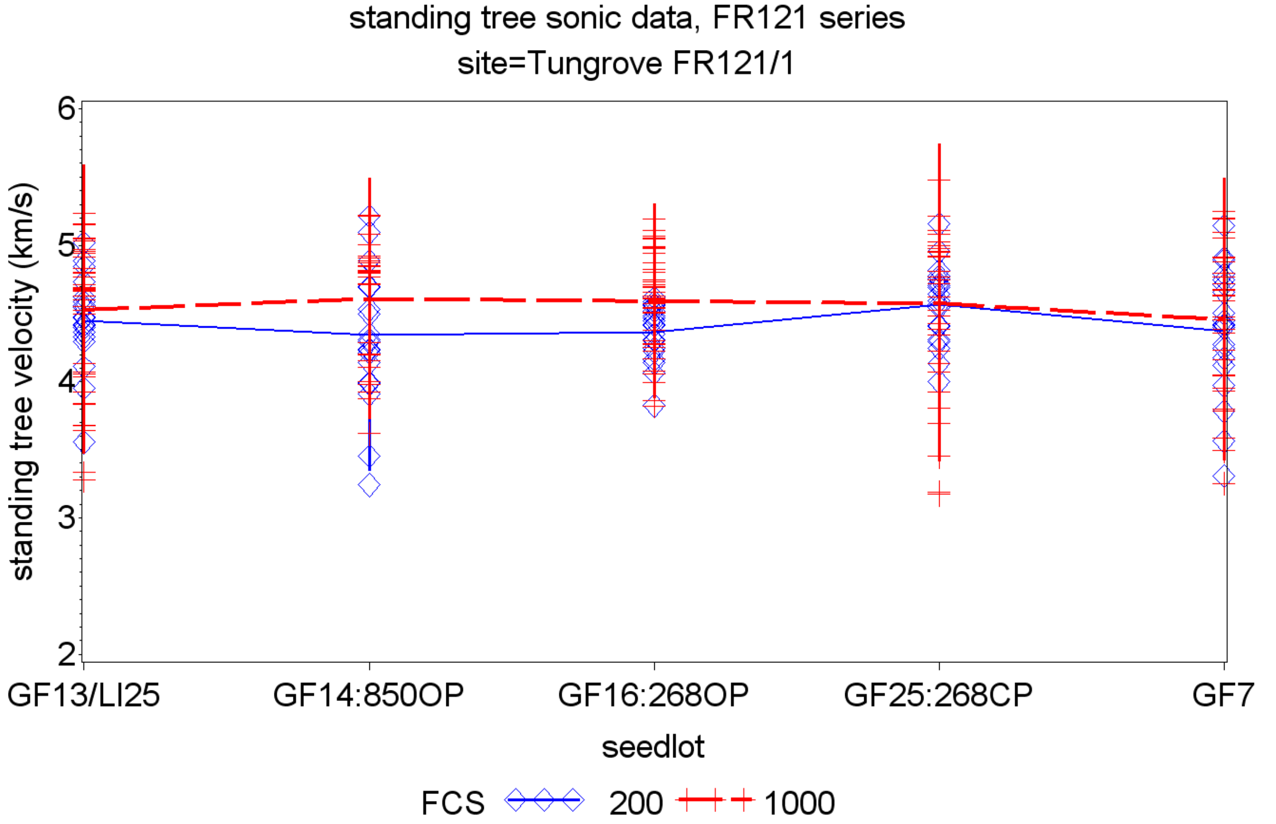


Figure 1. Individual standing tree velocity for different seedlots at two final crop stockings (FCS). The lines join the mean value for each seedlot and final crop stocking.

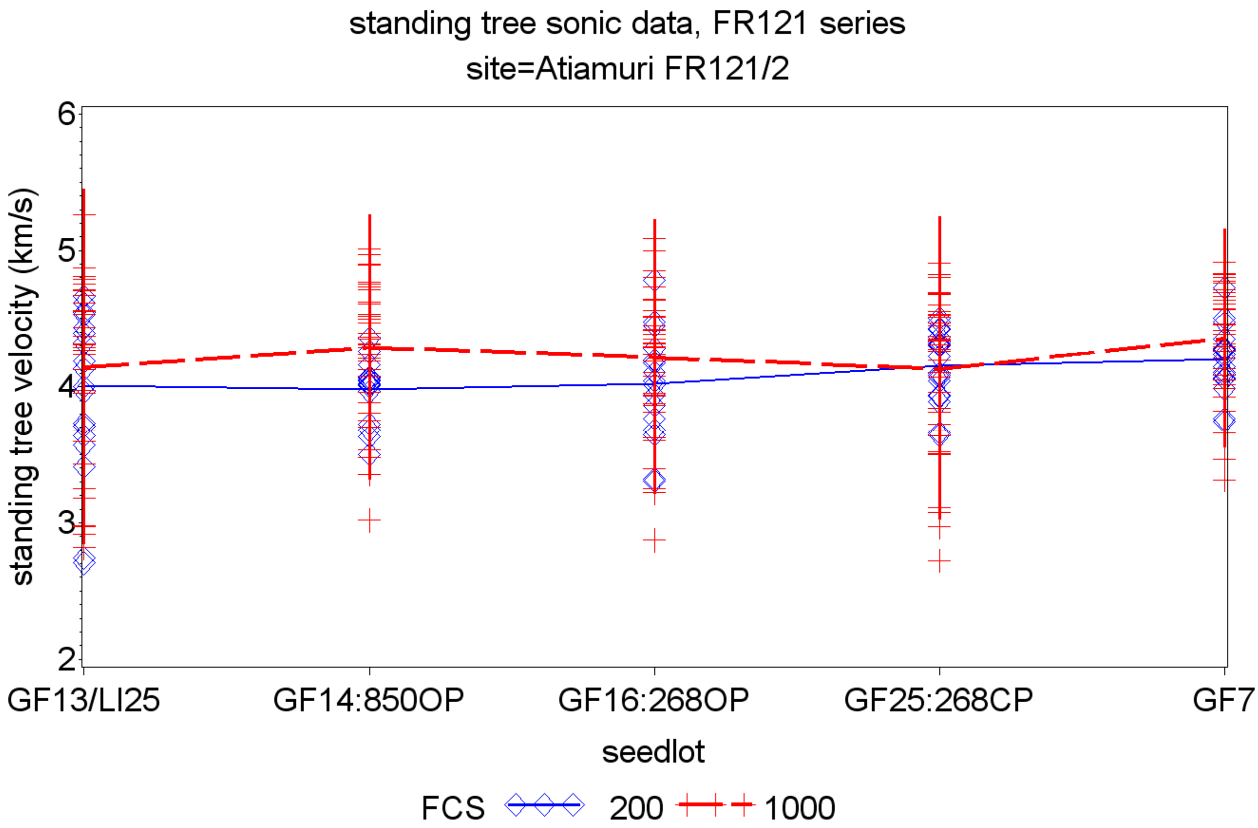


Figure 2. Individual standing tree velocity for different seedlots at two final crop stockings (FCS). The lines join the mean value for each seedlot and final crop stocking.

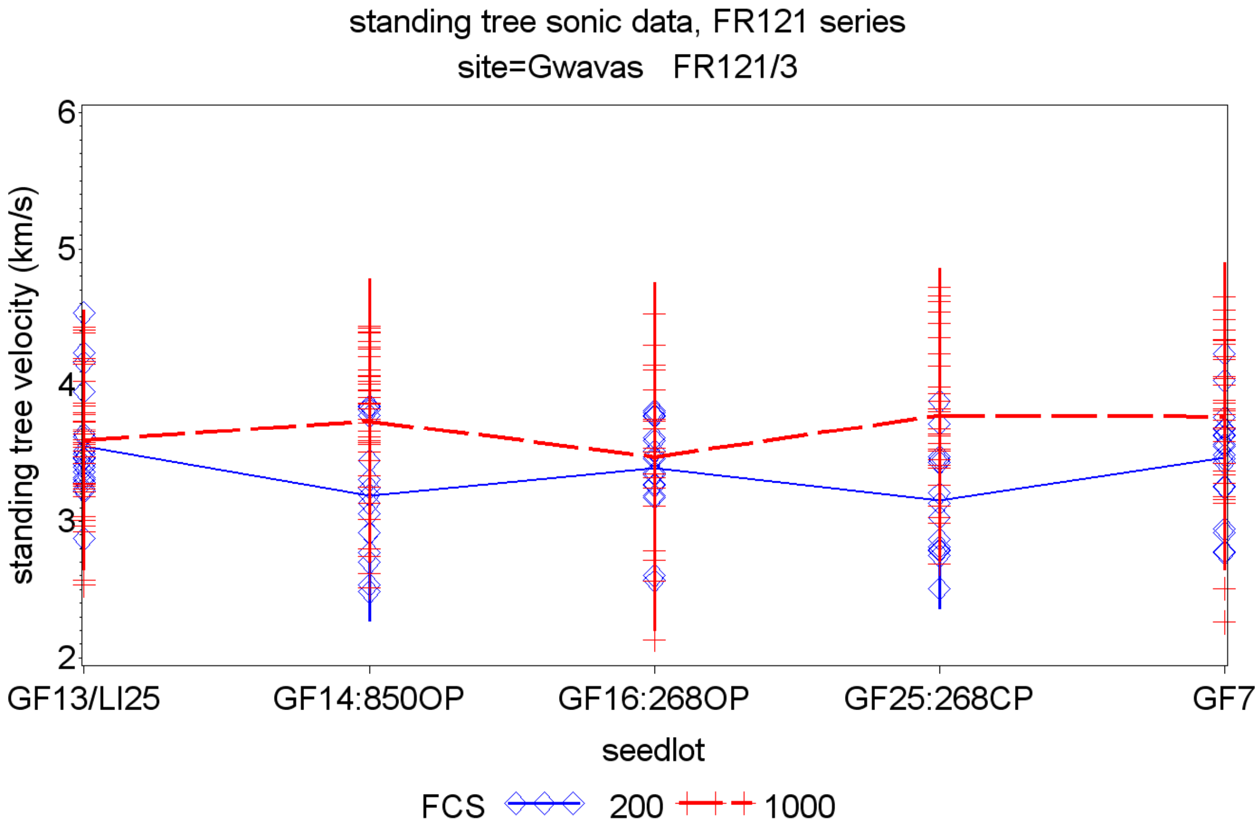


Figure 3. Individual standing tree velocity for different seedlots at two final crop stockings (FCS). The lines join the mean value for each seedlot and final crop stocking.

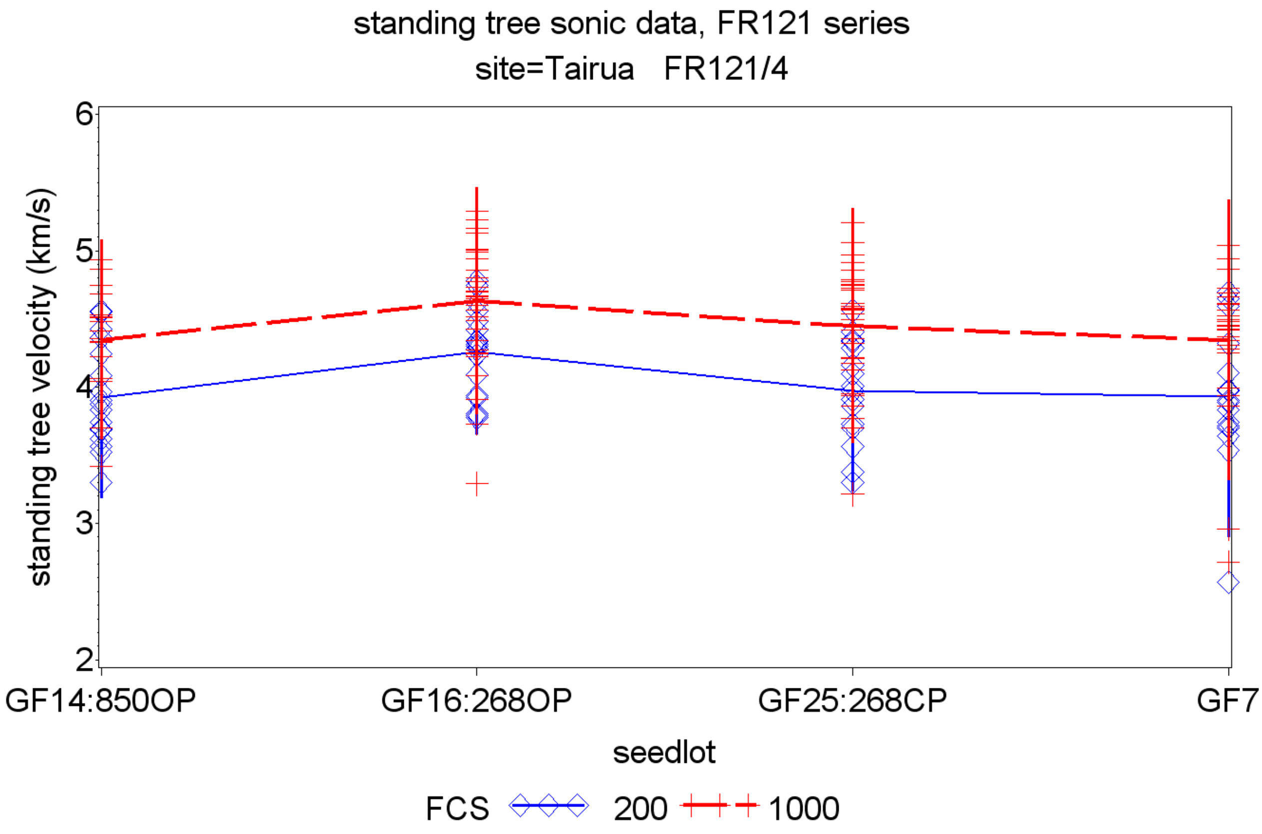


Figure 4. Individual standing tree velocity for different seedlots at two final crop stockings (FCS). The lines join the mean value for each seedlot and final crop stocking.

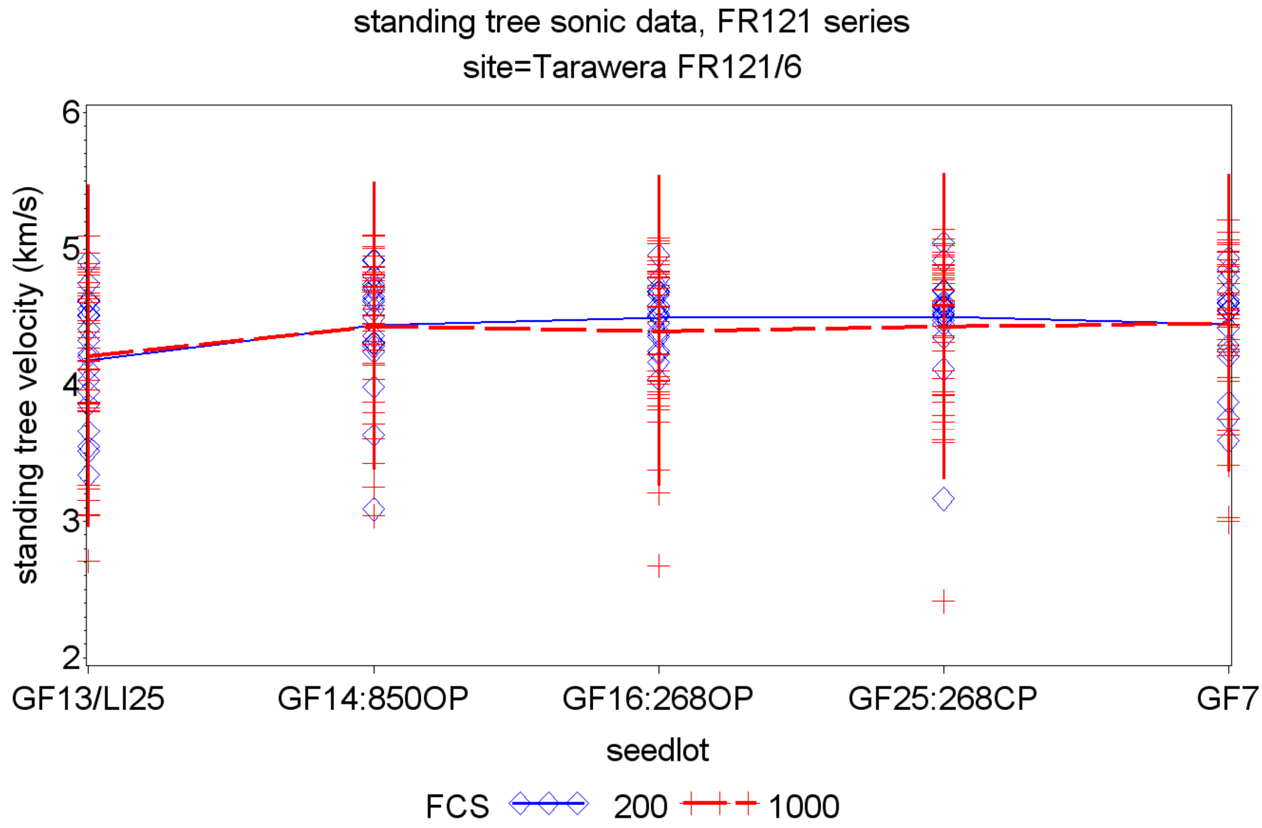


Figure 5. Individual standing tree velocity for different seedlots at two final crop stockings (FCS). The lines join the mean value for each seedlot and final crop stocking.

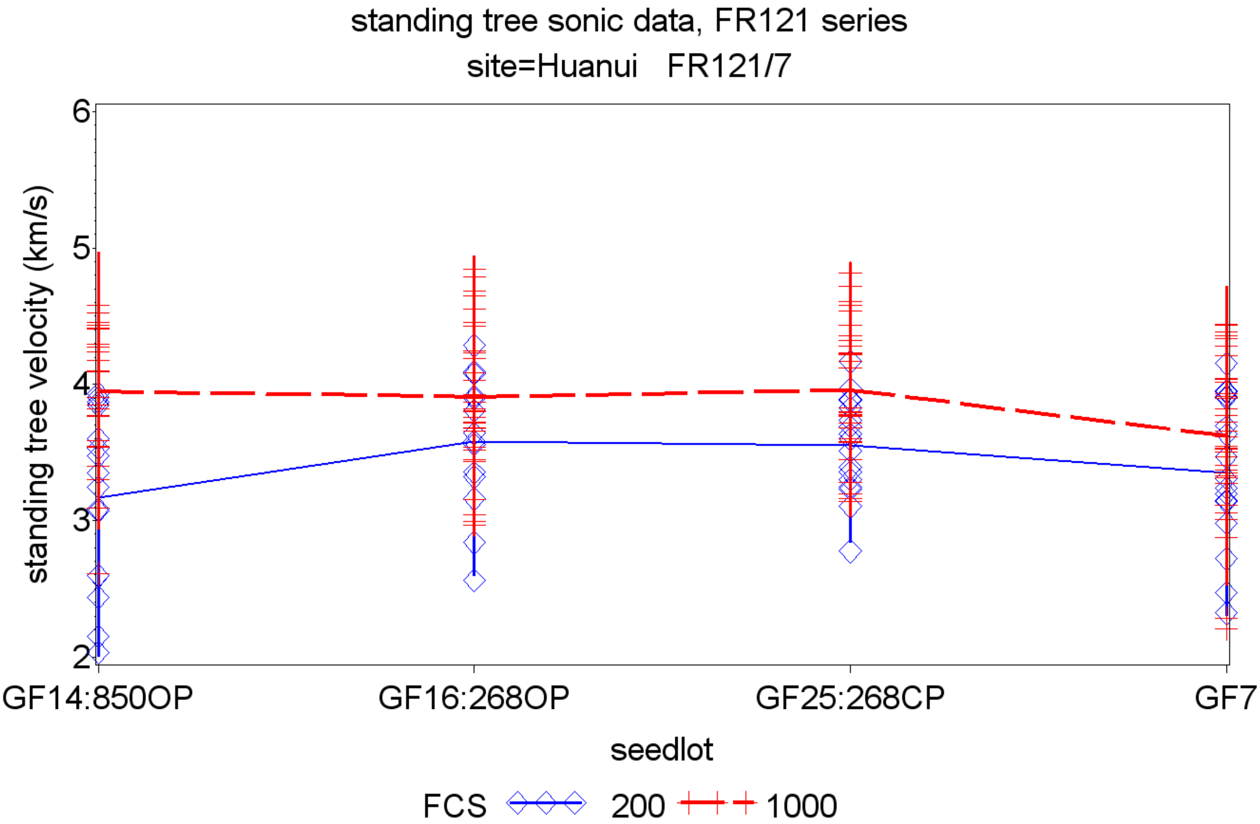
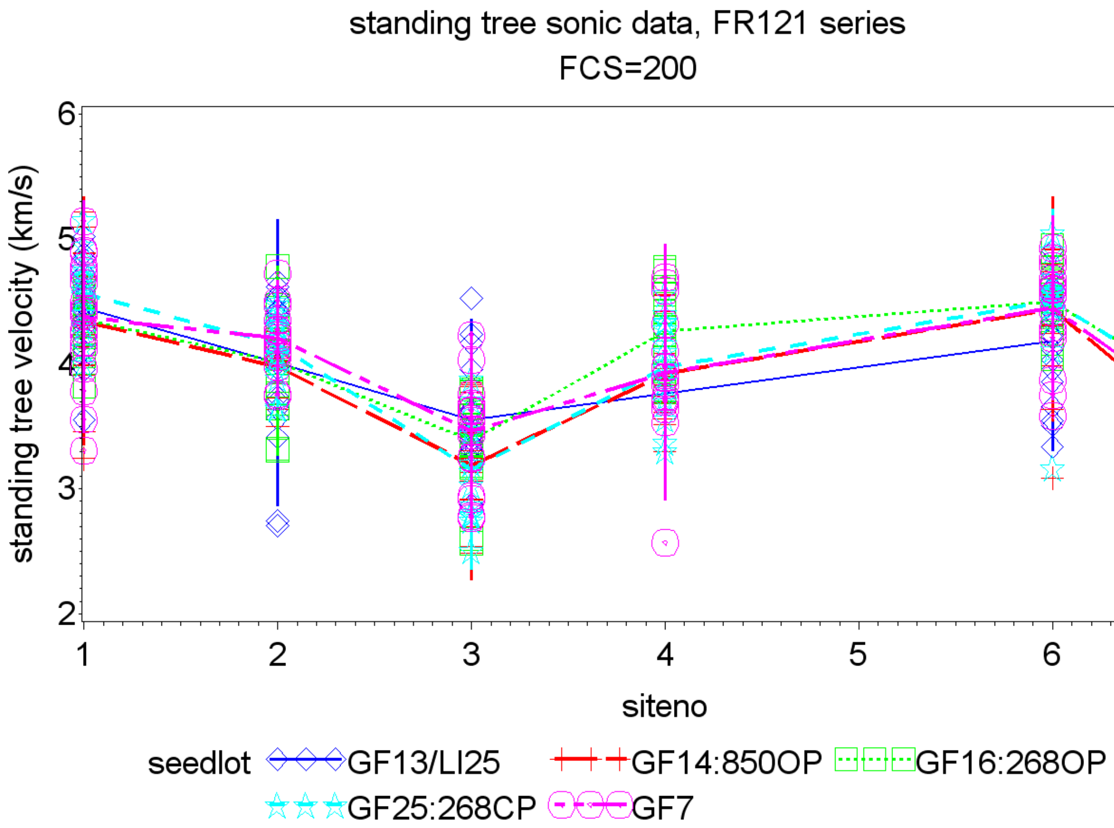


Figure 6. Individual standing tree velocity for different seedlots at two final crop stockings (FCS). The lines join the mean value for each seedlot and final crop stocking.


standing tree sonic data, FR121 series
FCS=200
standing tree velocity (km/s)
2
3
4
5
6
1
2
3
4
5
6
7
siteno
seedlot
GF13/LI25
GF14:850OP
GF16:268OP
GF25:268CP
GF7

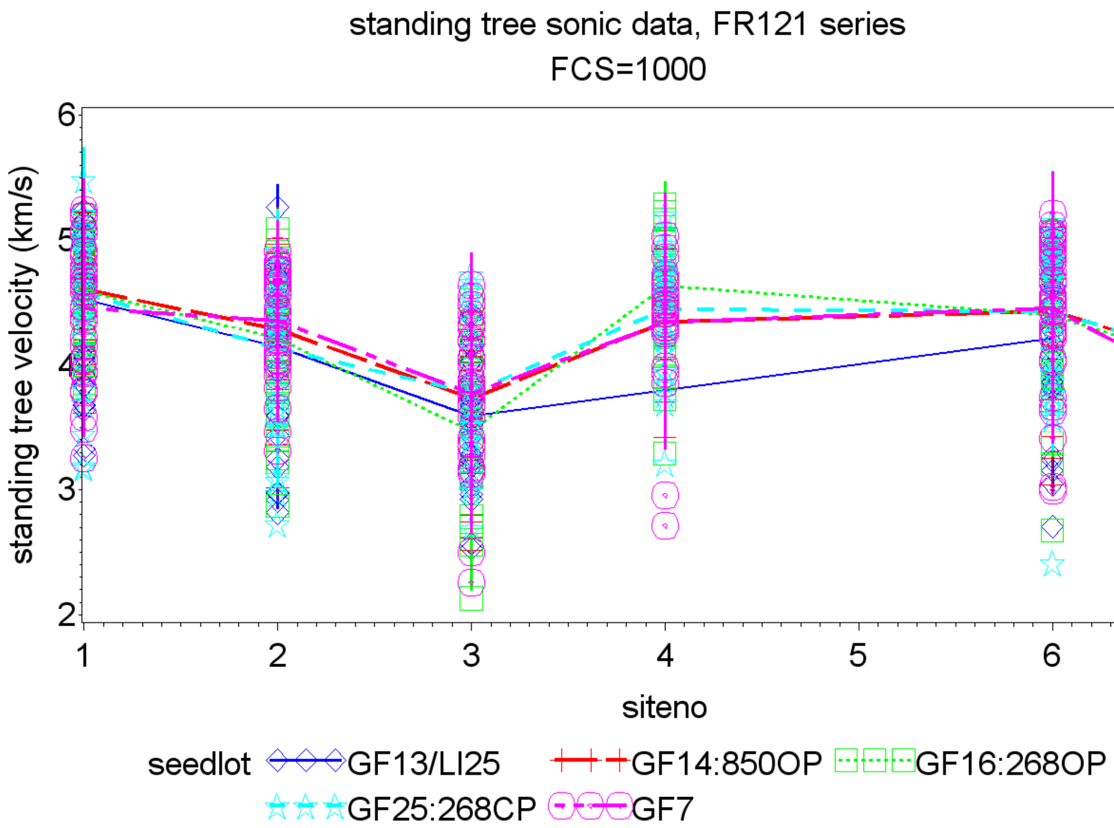
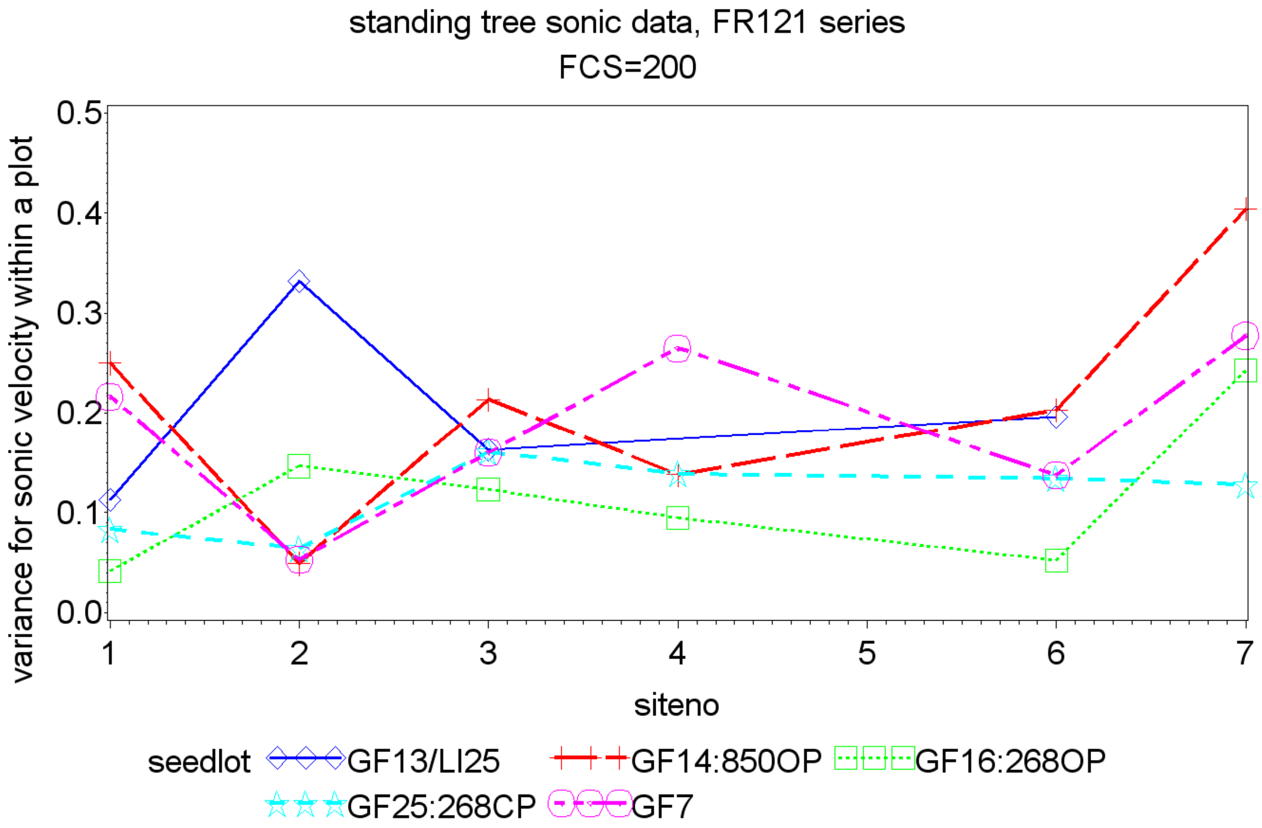

standing tree sonic data, FR121 series
FCS=1000
standing tree velocity (km/s)
2
3
4
5
6
1
2
3
4
5
6
7
siteno
seedlot
GF13/LI25
GF14:850OP
GF16:268OP
GF25:268CP
GF7

Figure 7 a,b. Standing tree velocity for different seedlots at the different sites within the 1990 silviculture breed trials (a) at a final crop stocking (FCS) of 200 stems/ha, (b) at a final crop stocking of 1000 stems/ha. The lines join mean values. Note: no GF13/LI25 seedlot at siteno 4 or 7.



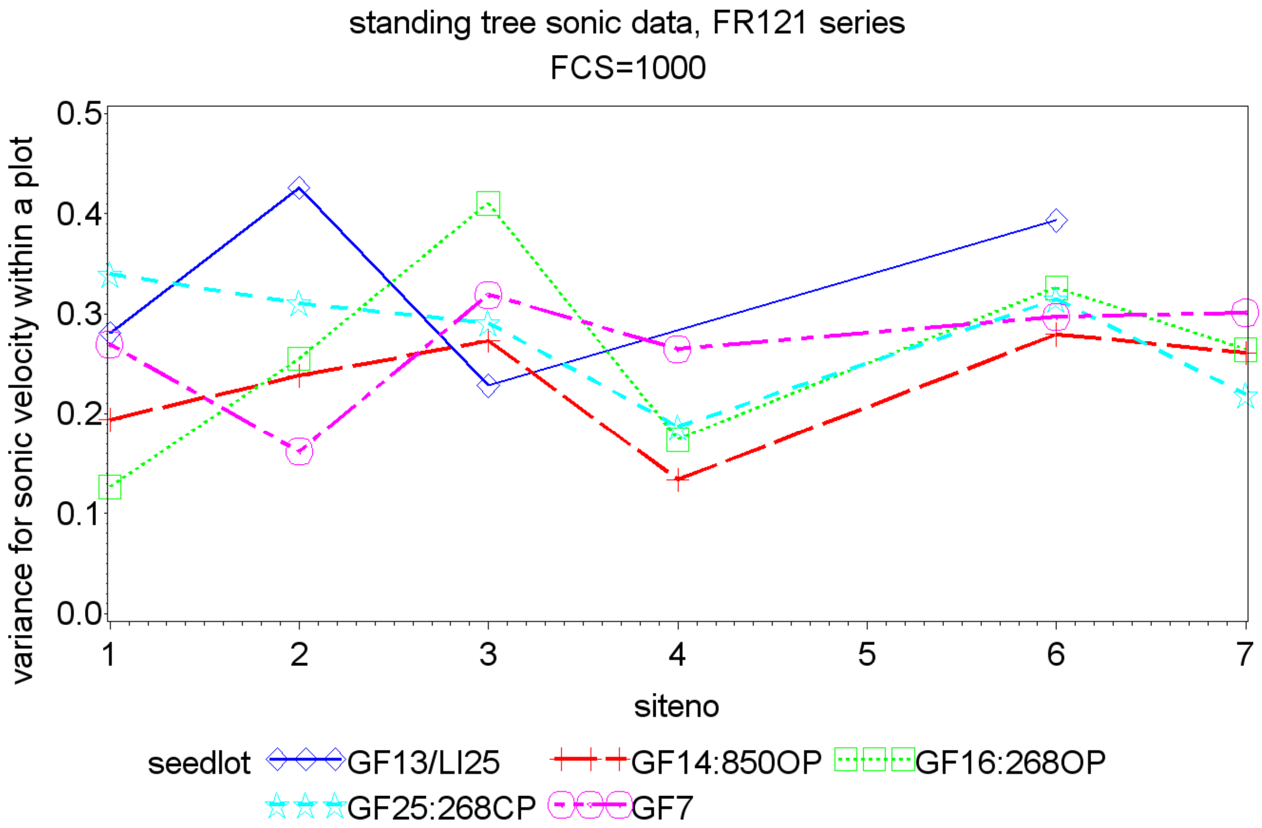


Figure 8 a,b. Plot variance in standing tree velocity for different seedlots at the different sites within the 1990 silviculture breed trials (a) at a final crop stocking (FCS) of 200 stems/ha, (b) at a final crop stocking of 1000 stems/ha. The lines join mean values. Note: no GF13/LI25 seedlot at siteno 4 or 7.

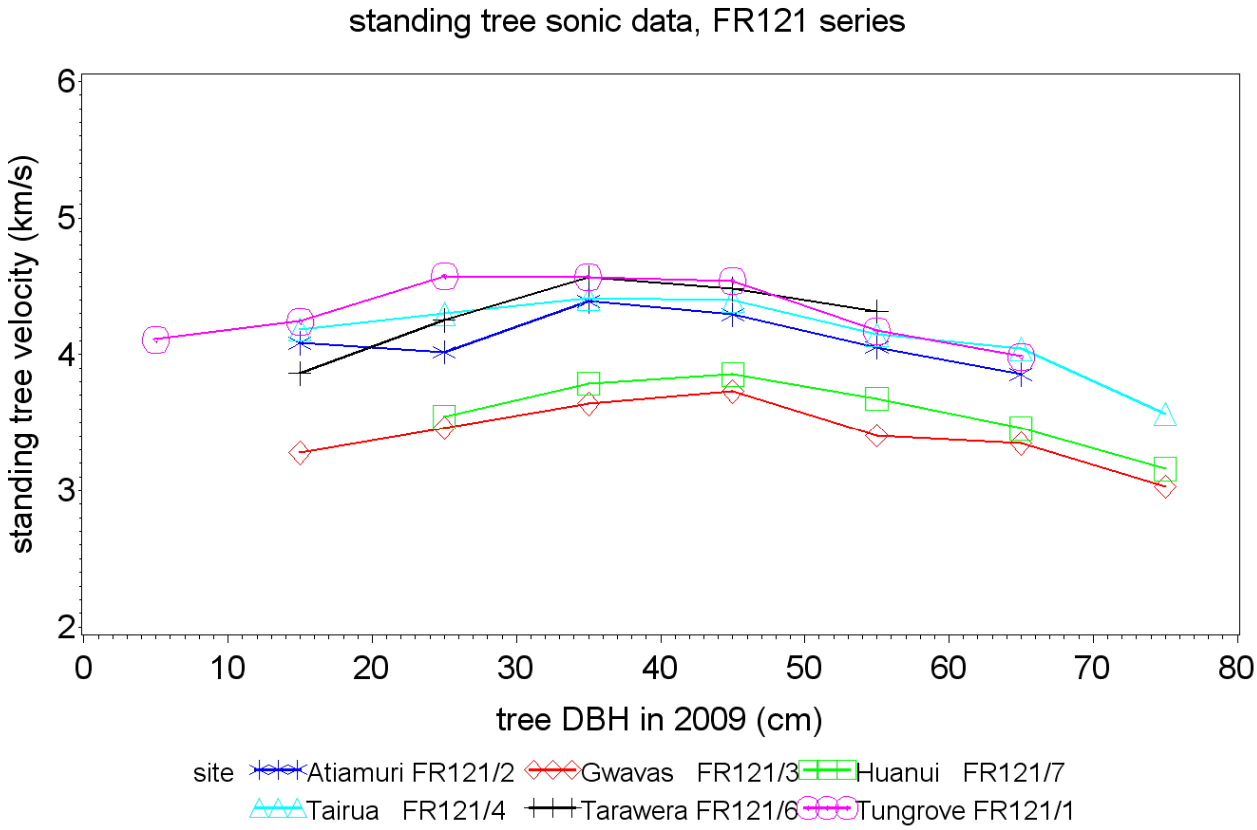


Figure 9. Mean values of standing tree velocity for different diameter classes.

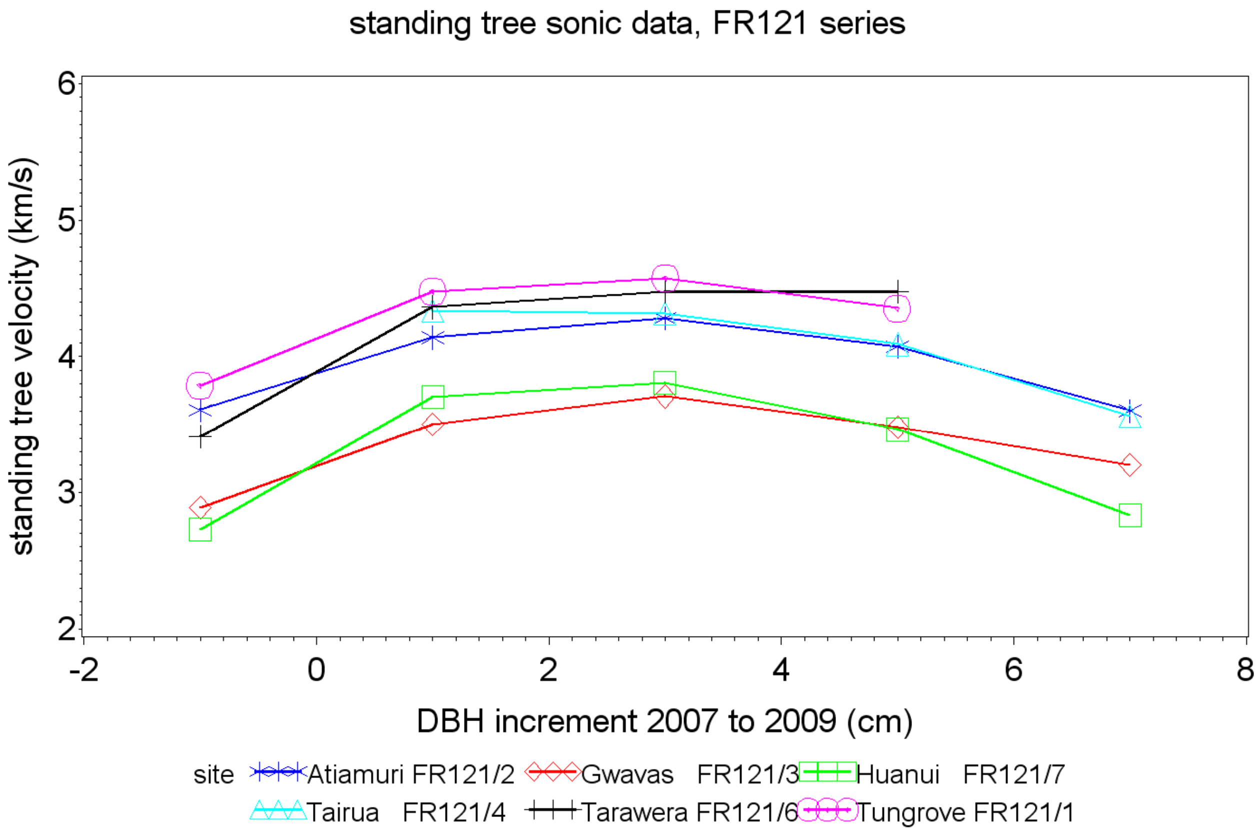


Figure 10. Mean values of standing tree velocity for different breast height diameter increment classes at for the different sites in the 1990 silviculture breed trial series.

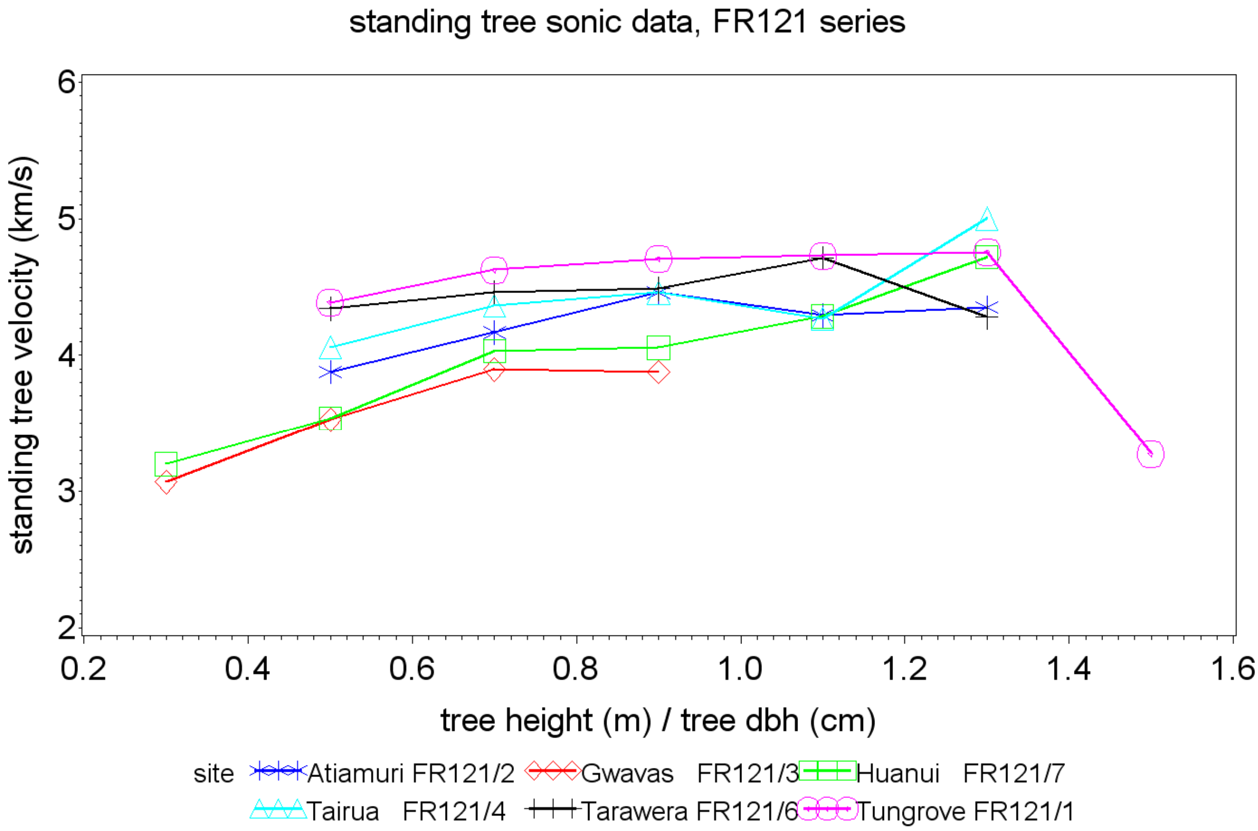


Figure 11. Mean values of standing tree velocities for different classes of tree height/ tree DBH.

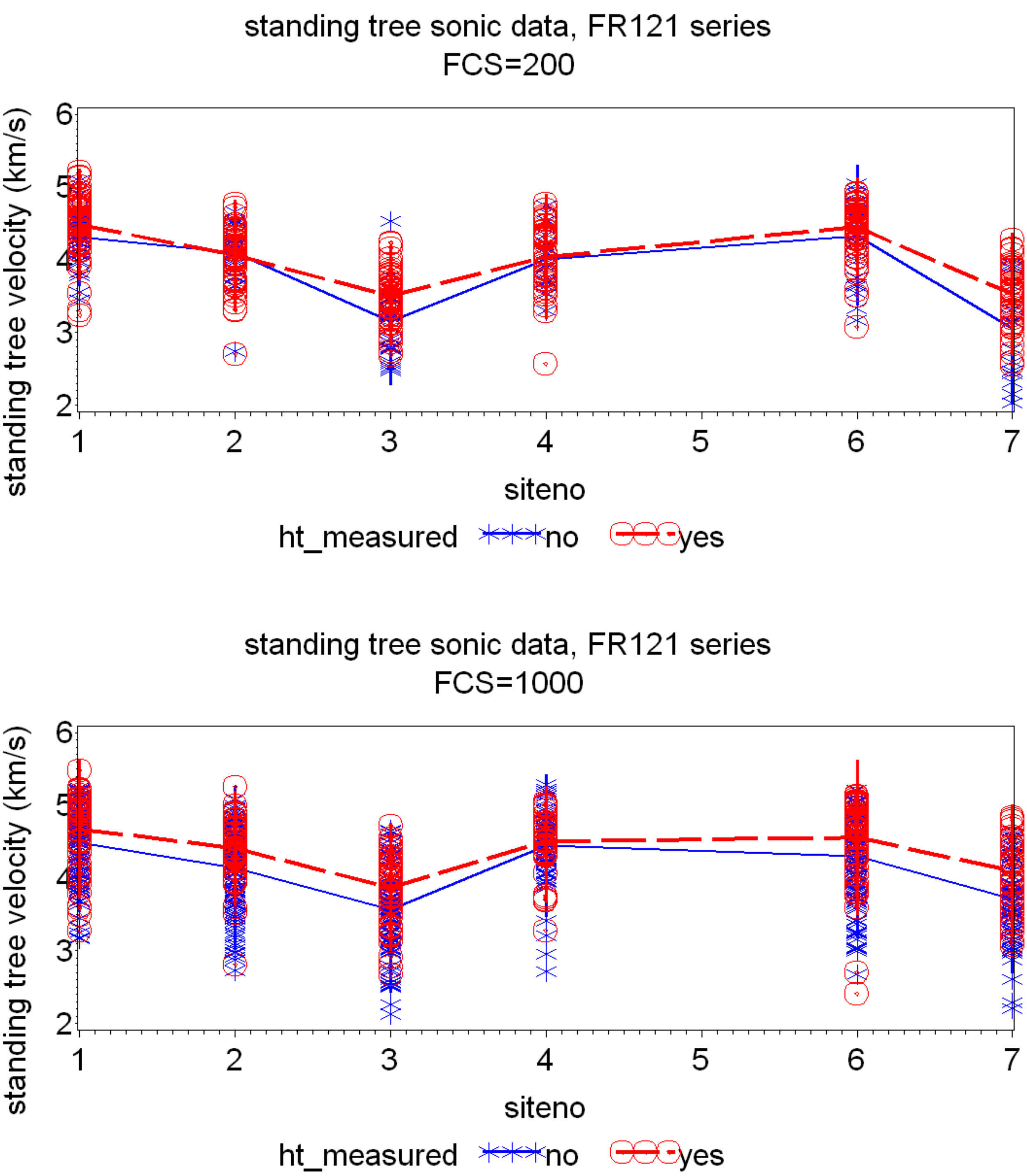
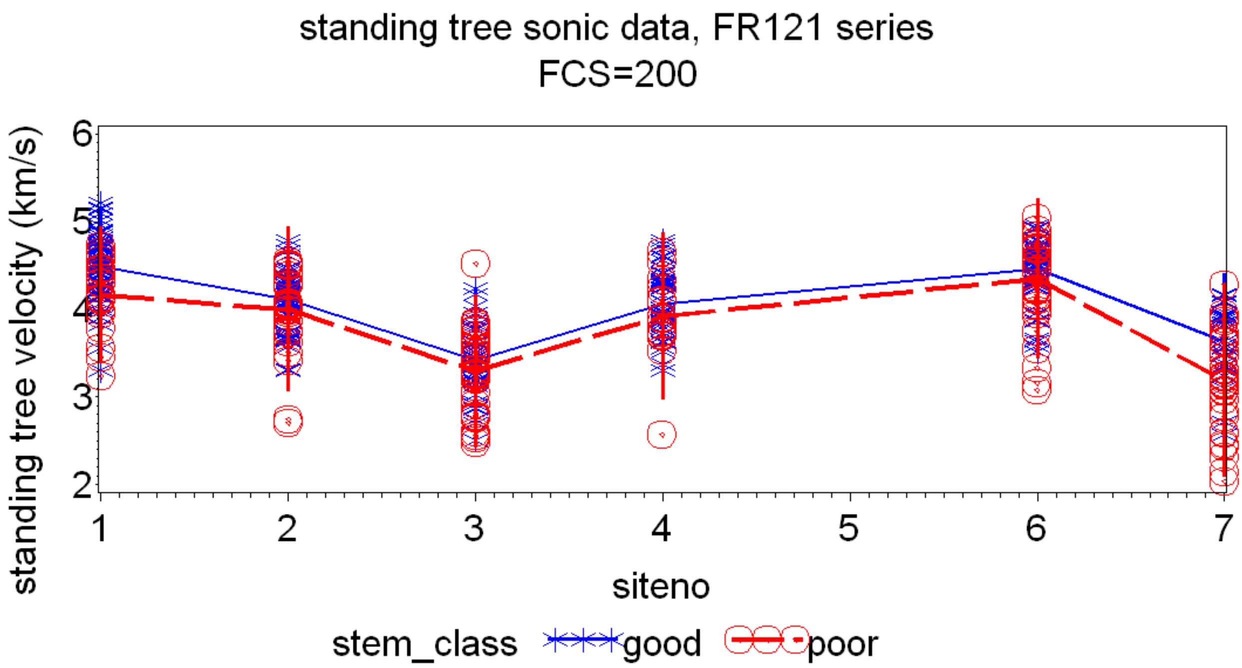


Figure 12. Standing tree velocity for trees that were or were not measured for height at the different sites within the 1990 silviculture breed trial series at (a) 200 stems/ha and (b) 1000 stems/ha.



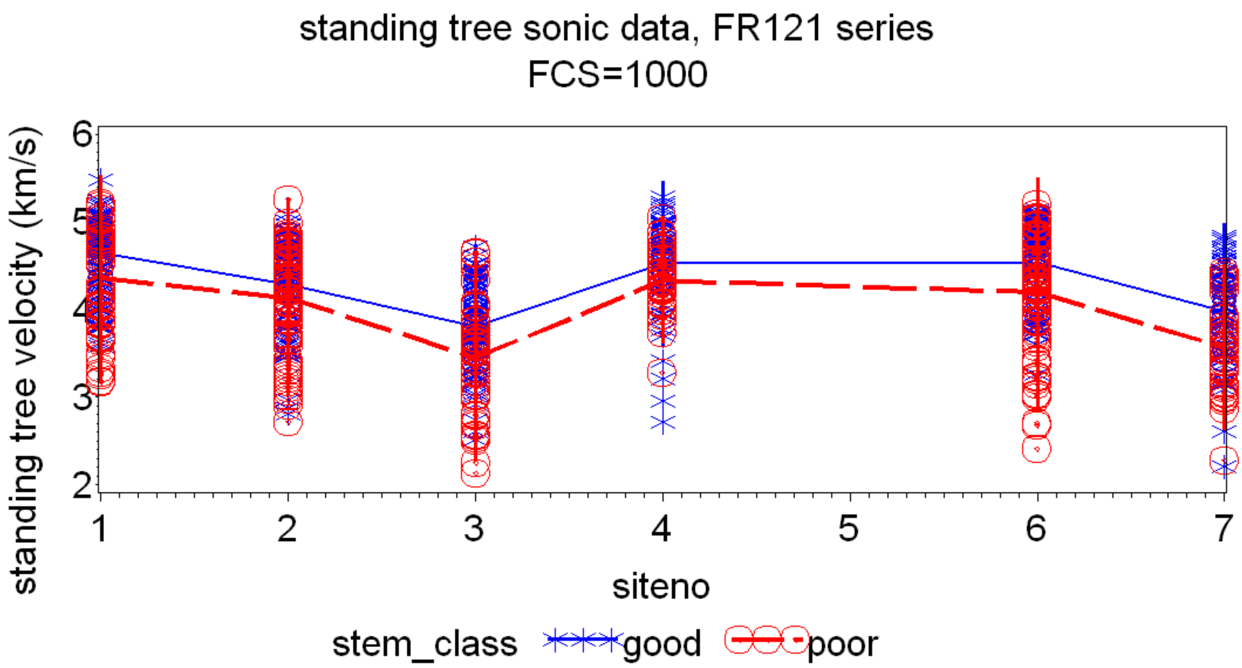


Figure 13. Standing tree velocity for trees that had (poor) or had not (good) a stem description code recorded in the PSP system for the different sites within the 1990 silviculture breed trial series at (a) 200 stems/ha and (b) 1000 stems/ha.

APPENDIX 4. Graphical analysis of data from the ultra-high pruning trials (note: trials were not the same age).

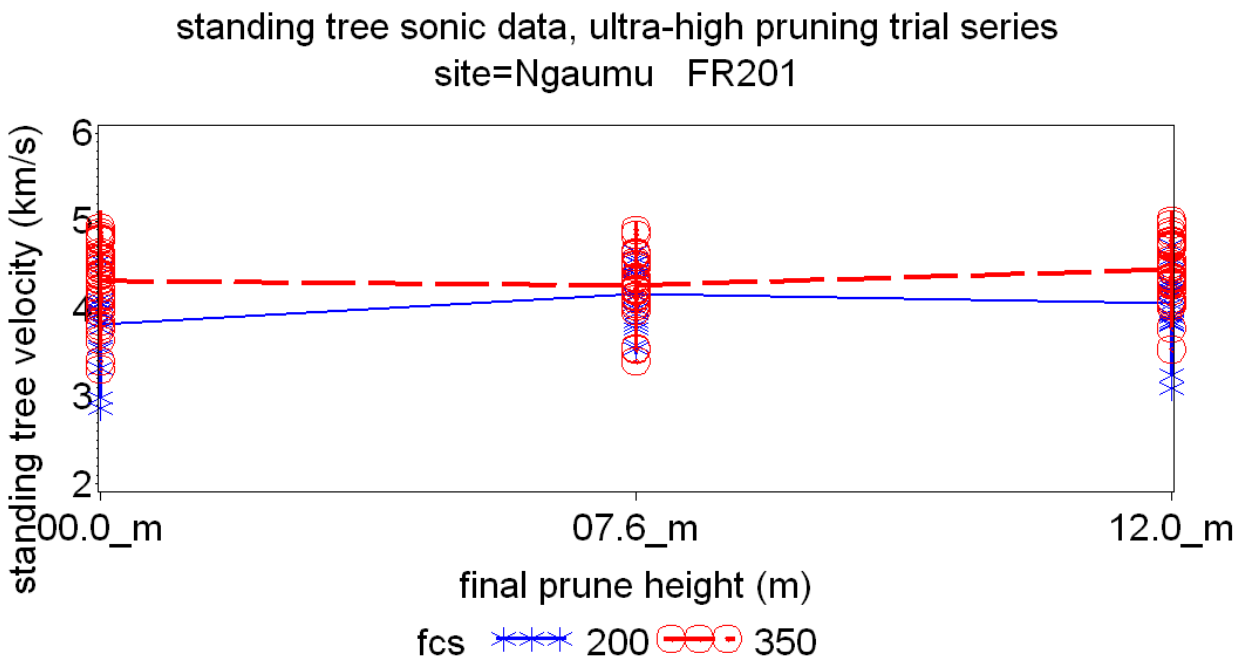


Figure 14. Standing tree velocity six treatments within the ultra-high pruning trial at Ngaumu. Mean values for the two final crop stockings (fcs) are joined by lines.

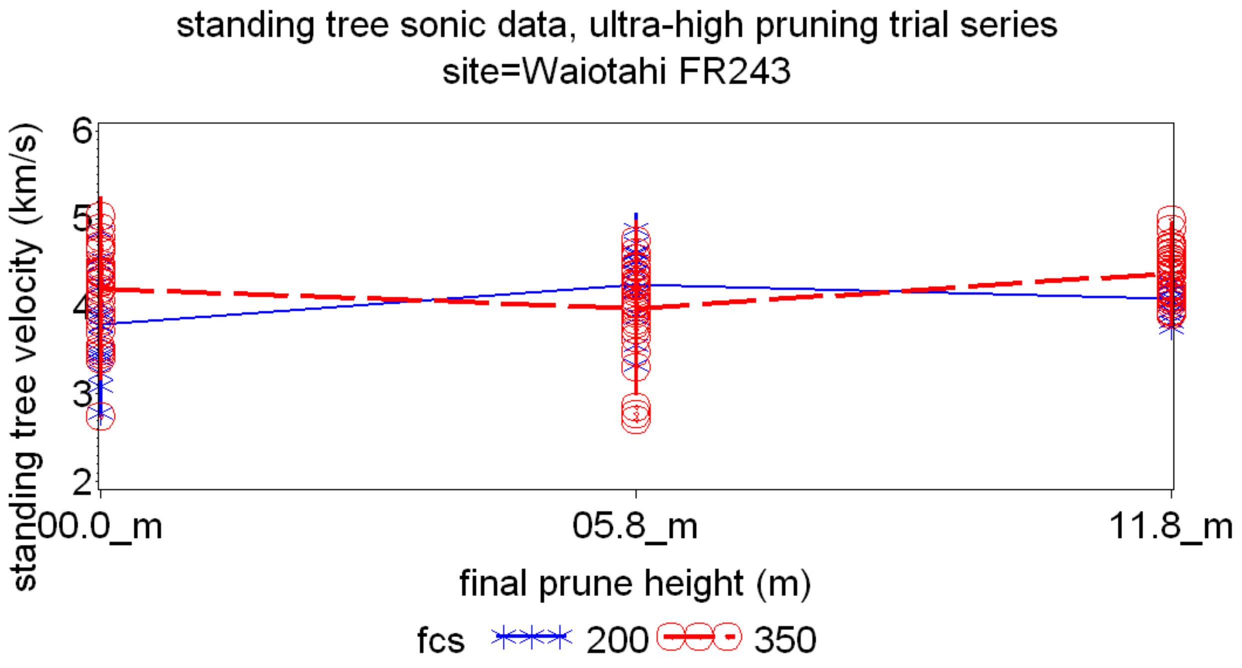


Figure 15. Standing tree velocity six treatments within the ultra-high pruning trial at Waiotahi. Mean values for the two final crop stockings (fcs) are joined by lines.

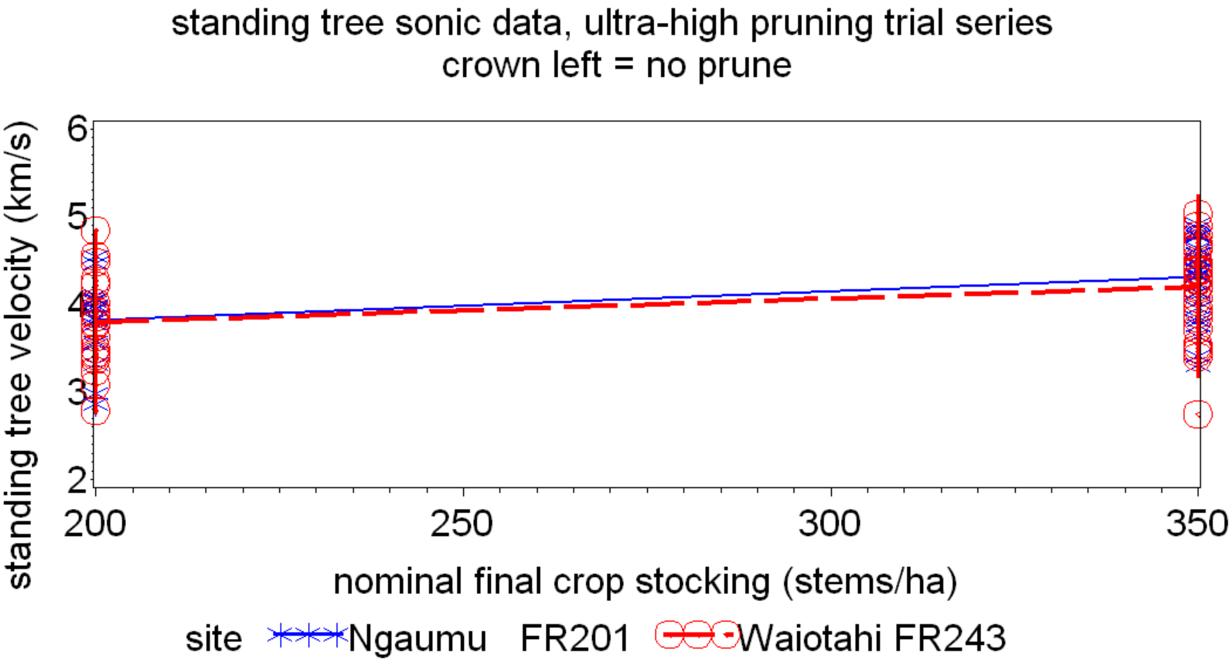


Figure 16. Standing tree velocity for unpruned treatments in two ultra-high pruning trials. Mean values are joined by lines.

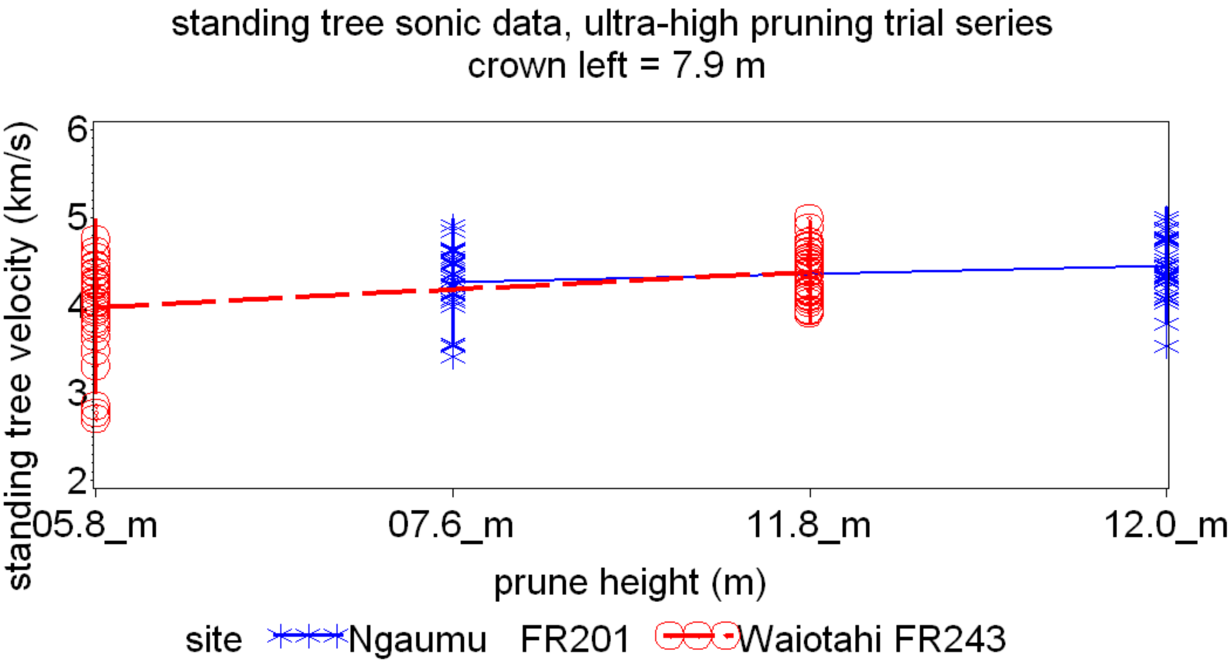


Figure 17. Standing tree velocity for treatments where the 7.9 m of crown remained after each pruning lift. Mean values are joined by lines.

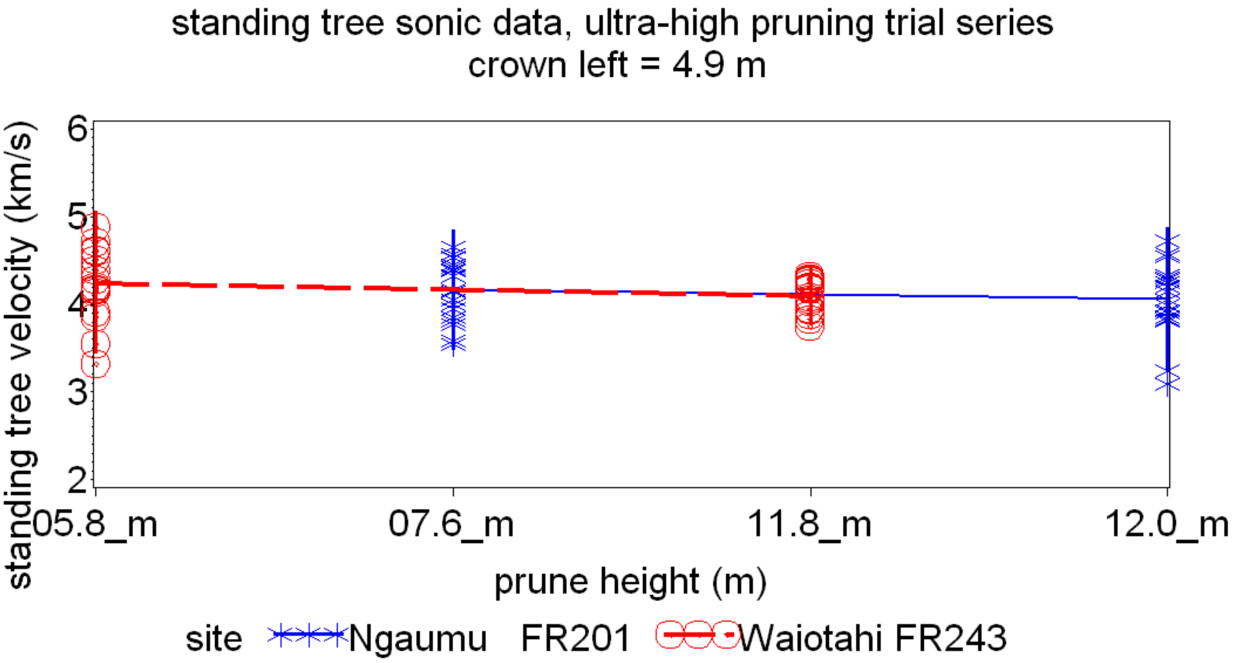
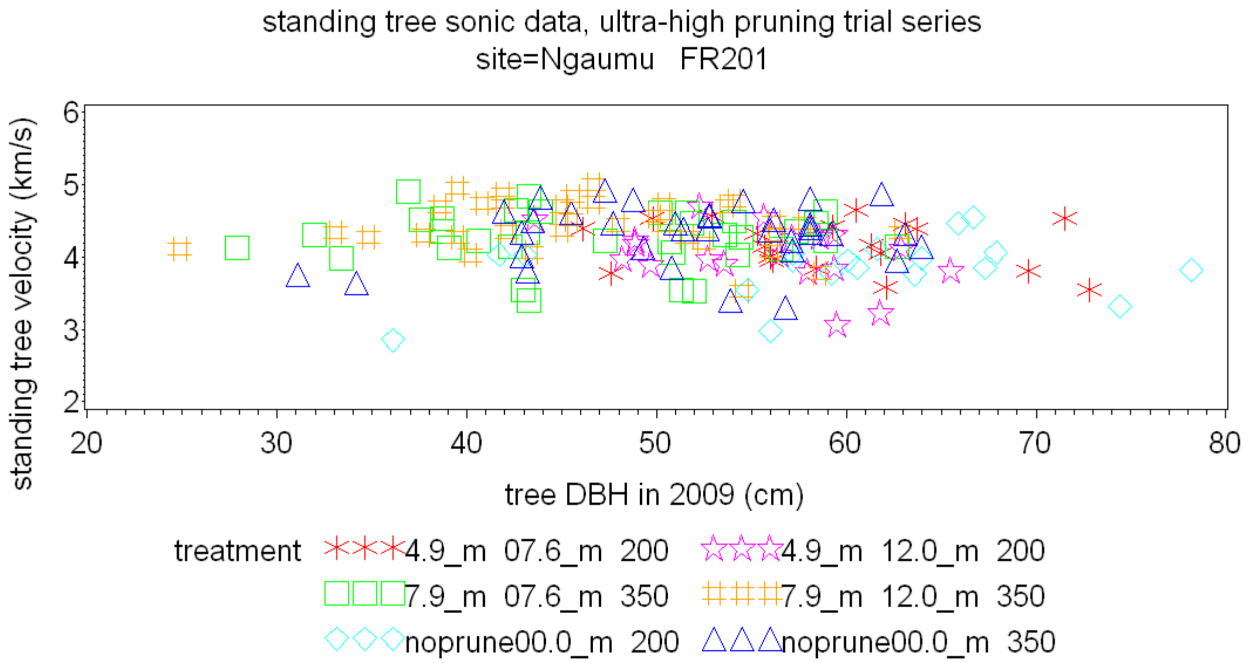


Figure 18. Standing tree velocity for treatments where the 4.9 m of crown remained after each pruning lift. Mean values are joined by lines.



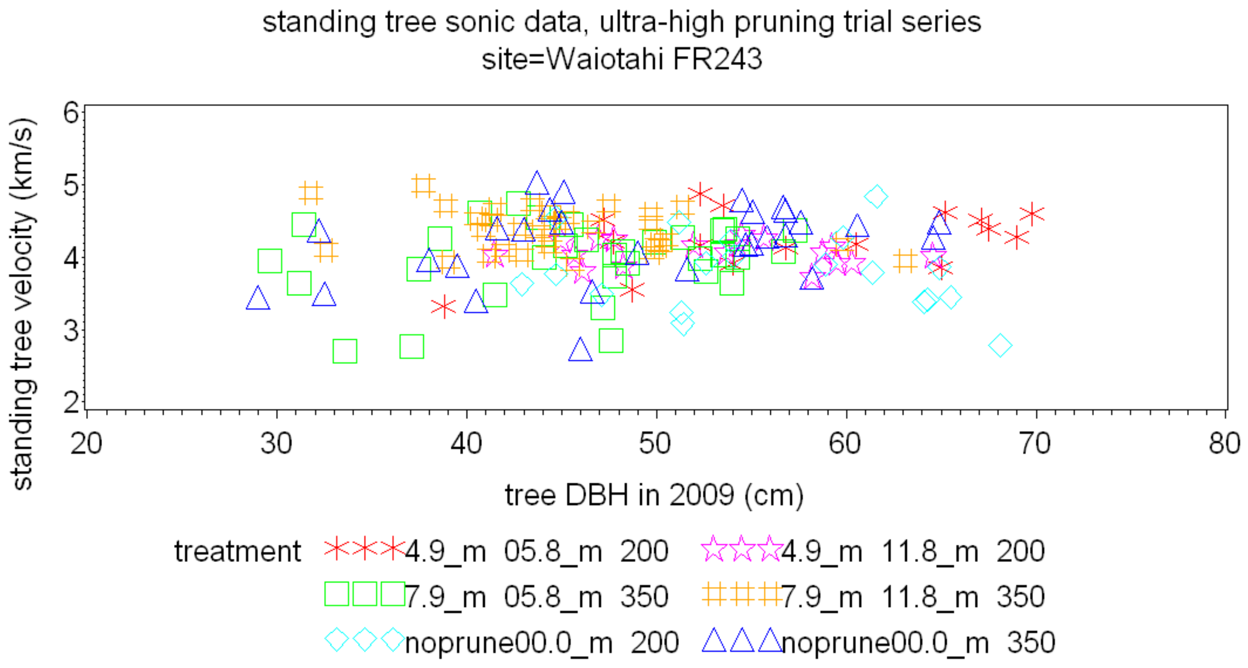
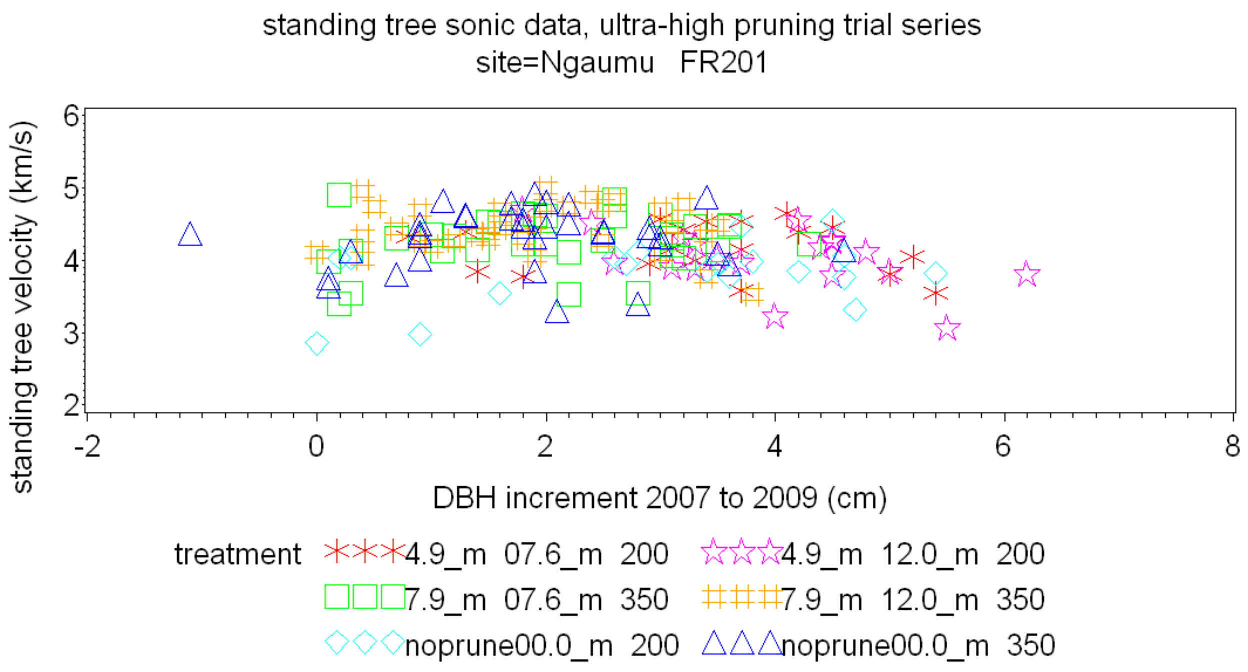


Figure 19. Relationship between standing tree velocity and tree DBH at (a) Ngaumu and (b) Waiotahi.



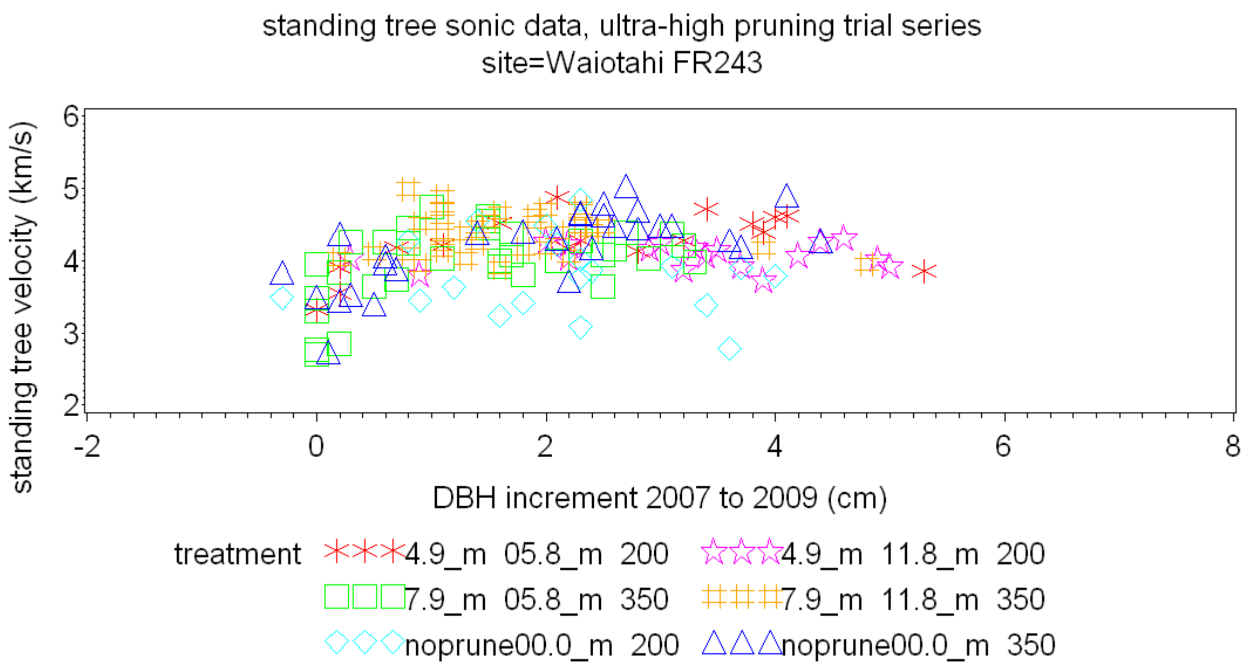
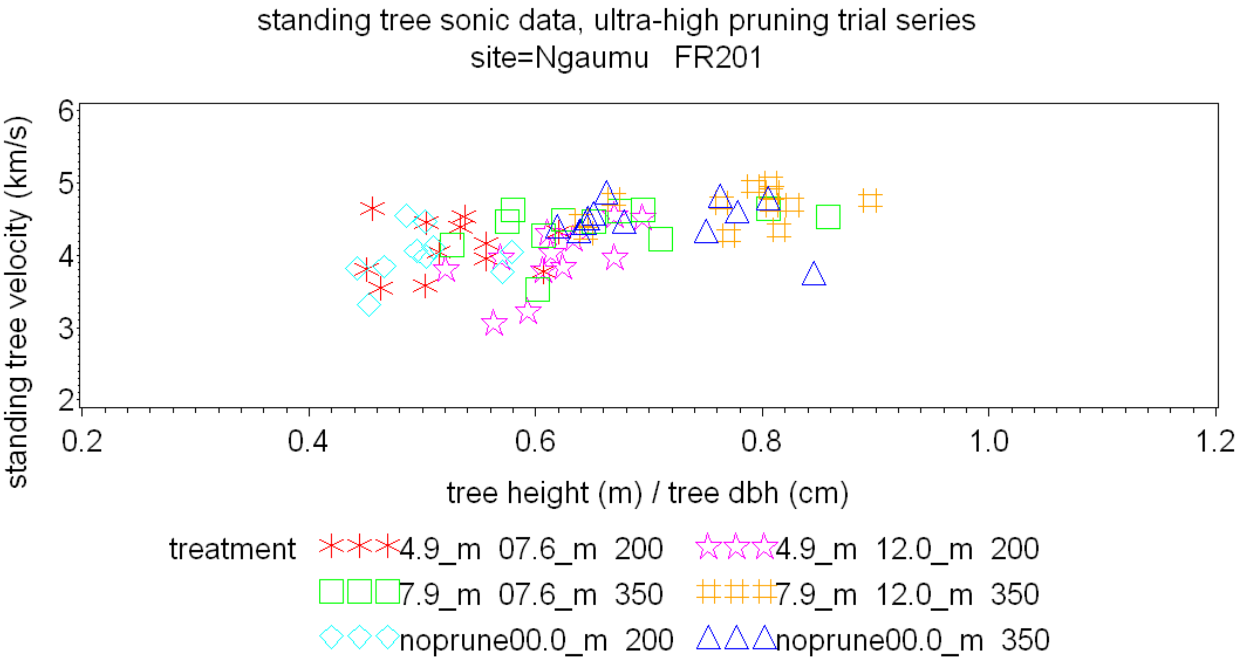


Figure 20. Relationship between standing tree velocity and breast height diameter increment at (a) Ngaumu and (b) Waiotahi.



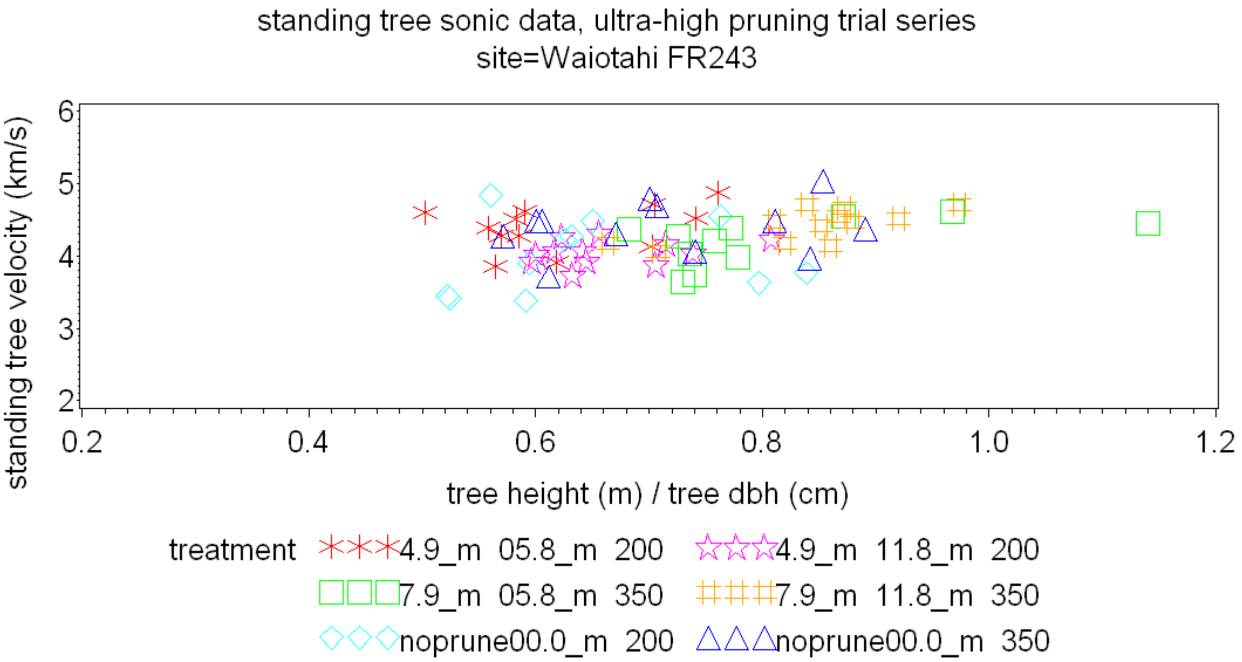


Figure 21. Relationship between standing tree velocity and the ratio of tree height to DBH at (a) Ngaumu and (b) Waiotahi.

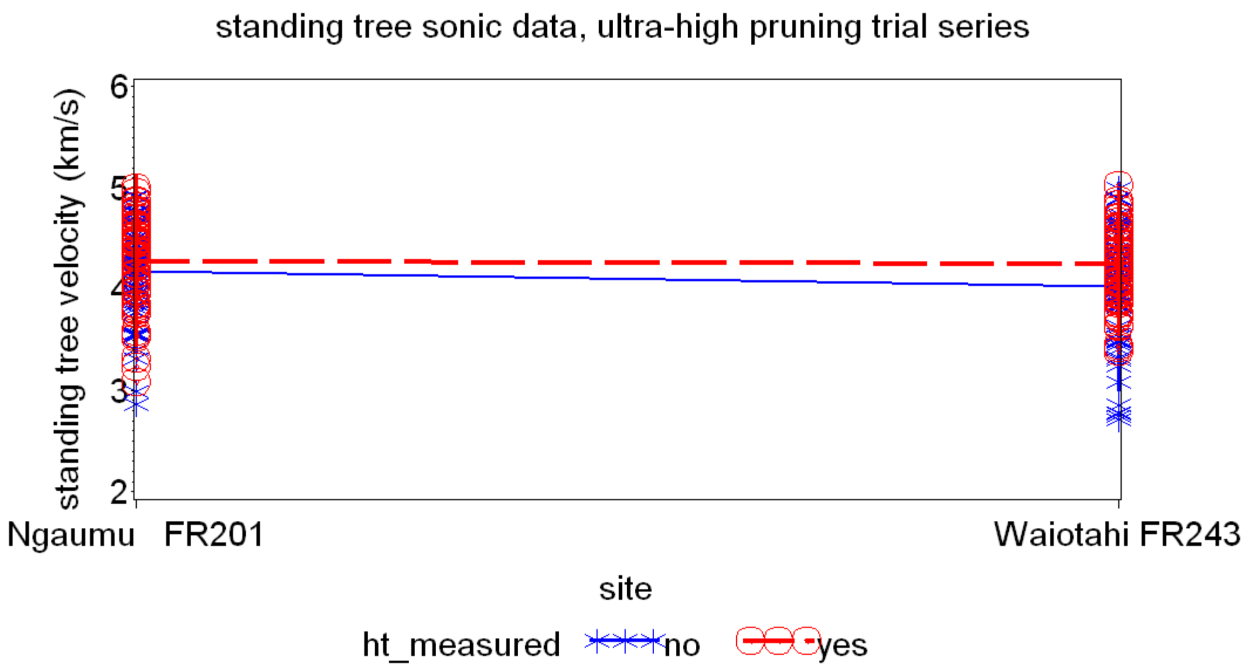


Figure 22. Comparison of standing tree velocity for trees with and without height measurements. Mean values are joined by lines.

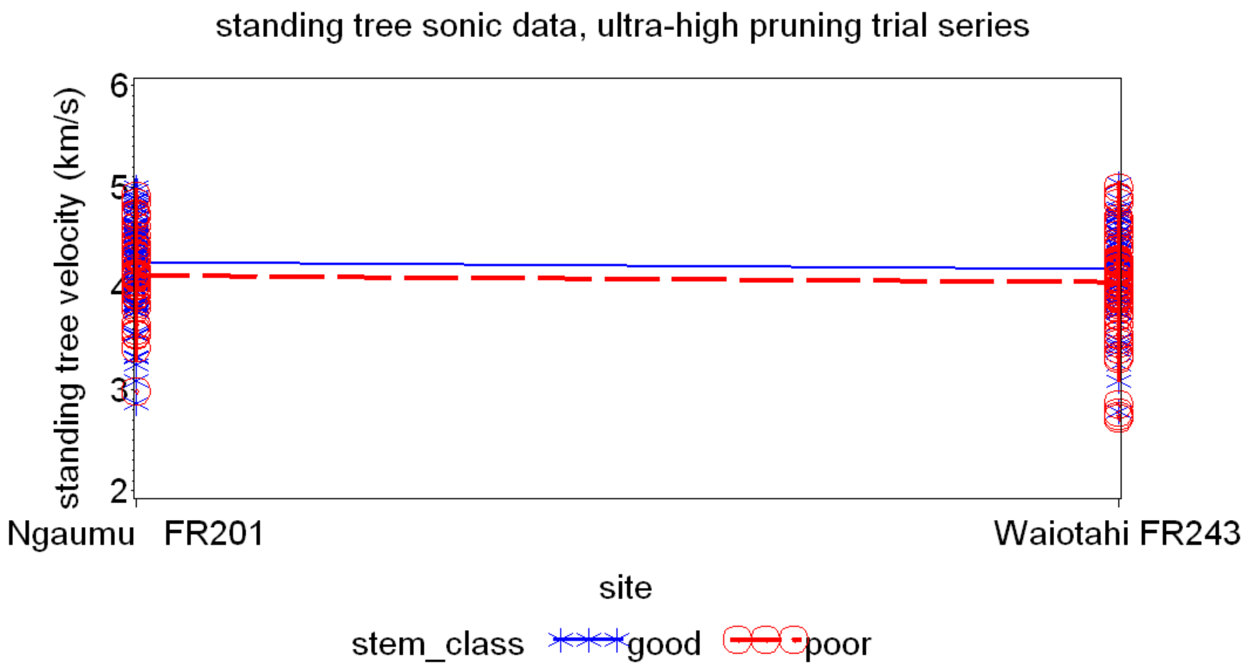


Figure 23. Standing tree velocity for trees that have (stem_class=poor) or did not have (stem_class= good) a description code assigned in the PSP system. Mean values are joined by lines.

APPENDIX 5. Difference between two measurements of standing tree velocity on an individual tree.

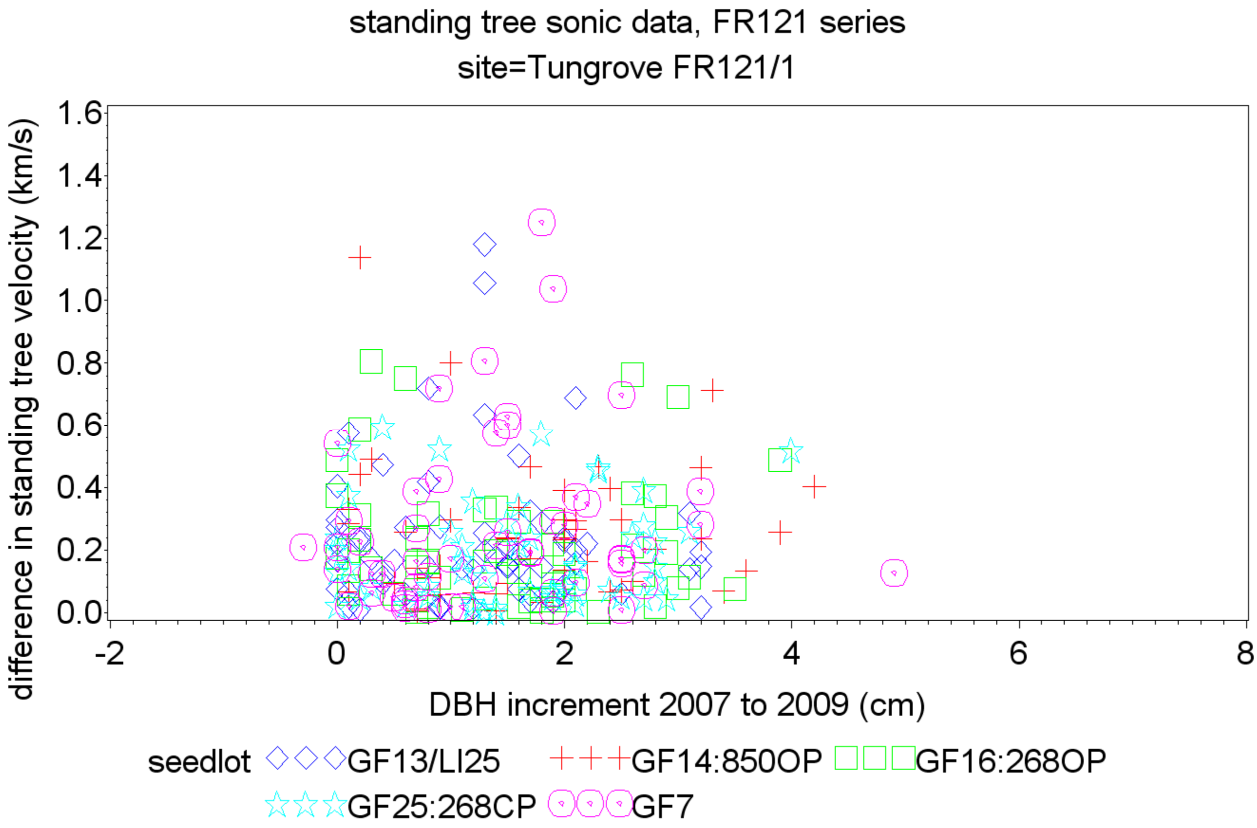
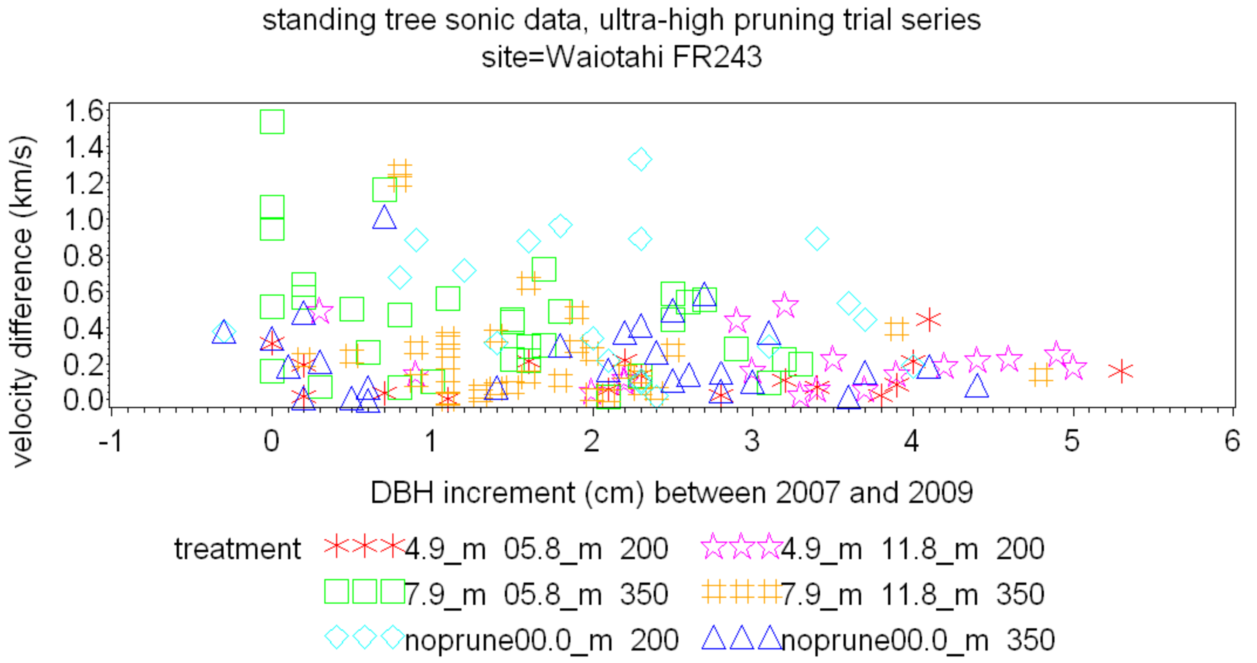


Figure 24. Absolute difference between two measures of standing tree velocity at 180° to each other versus tree DBH increment.



Note: the treatment is a combination of “crown remaining at each pruning lift”, “prune height”, and final crop stocking.

Figure 25. Absolute difference in standing tree velocity between two measurements at 180° to each other versus DBH increment.

APPENDIX 6. Site characteristics and maps.

Table 1. 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

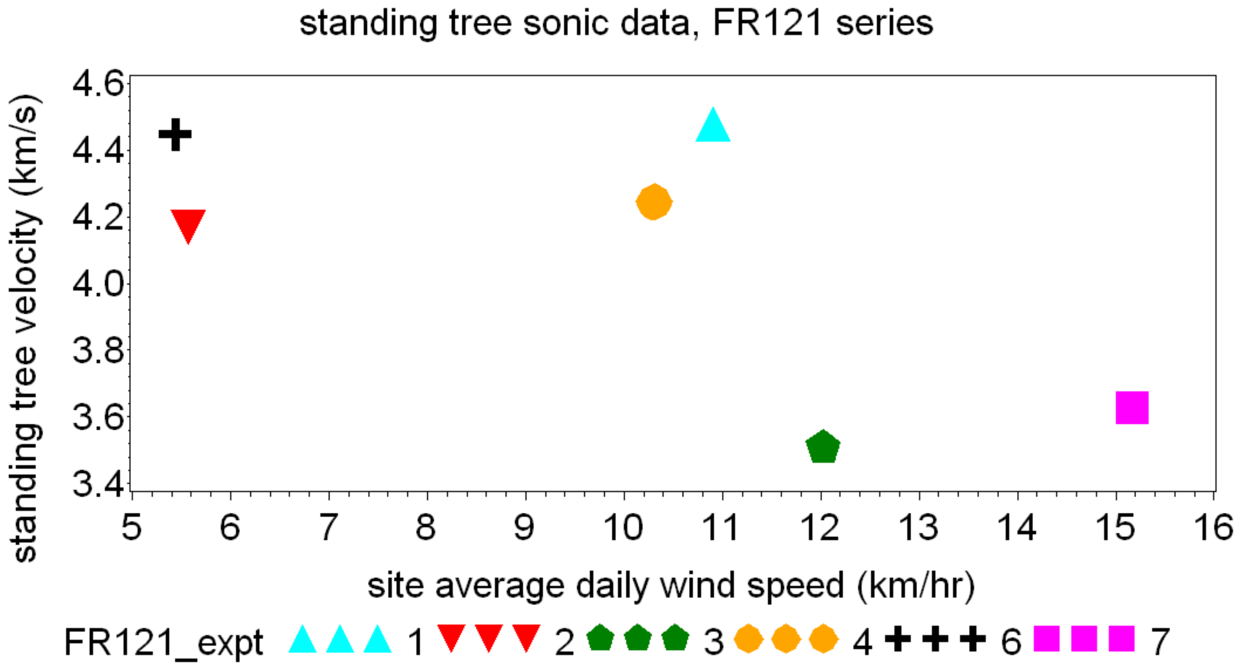


Figure 26. Site average standing tree velocity versus site average daily wind speed. (Note. Long-internode seedlot excluded from calculations as it was not present on all sites).

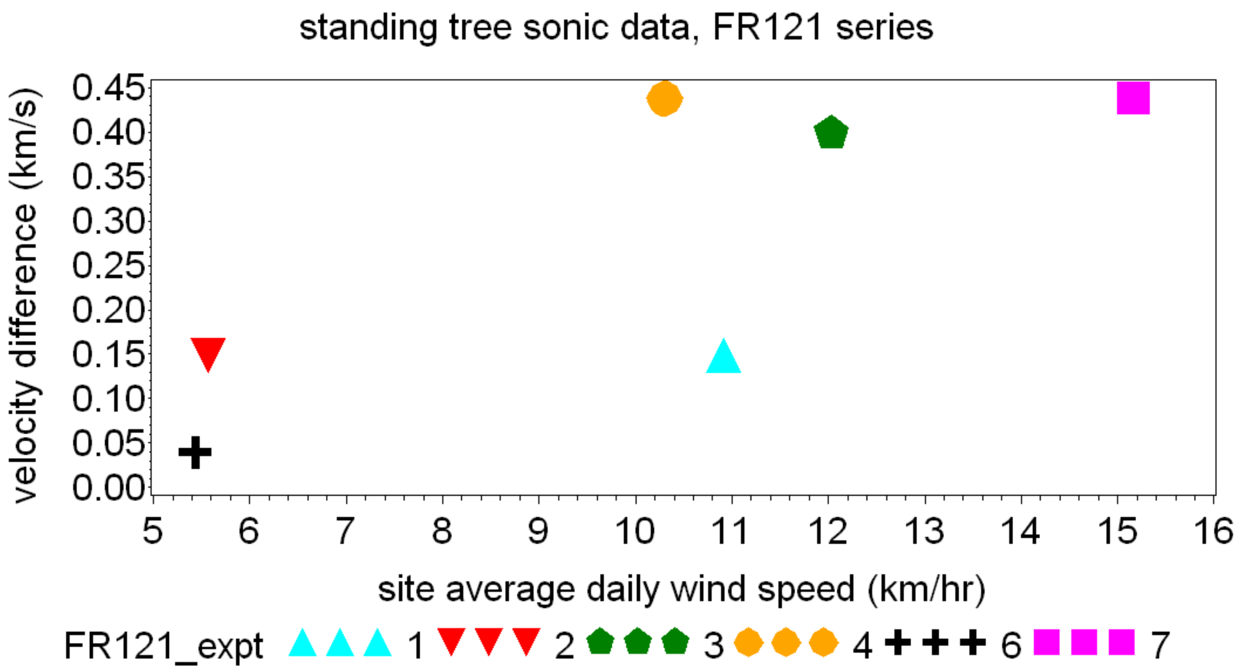


Figure 27. Average standing tree velocity at 1000 sph –minus average standing tree velocity at 200 sph versus site average wind speed (Note. Long-internode seedlot excluded from calculations as it was not present on all sites).