DEVELOPING A SAMPLING STRATEGY FOR MEASURING ACOUSTIC VELOCITY IN STANDING *PINUS RADIATA* USING THE TREETAP TIME OF FLIGHT TOOL

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(Received for publication 1 December 2005; revision 27 June 2006)

ABSTRACT

Acoustic velocity, measured using time of flight tools, provides a non-destructive measure of wood stiffness in standing trees. In order to assess how best to assess a stand of trees to a given level of precision, acoustic velocity was measured across three sites in New South Wales, Australia. All sites had similar climatic conditions and had had the same silviculture but different establishment dates. Analysis of variance and regression analysis were used to determine the components of variation and relationships between acoustic velocity, diameter at breast height, and age.

The variation within a stand was greatest between trees, followed by that between sides within trees, between plots, and within each side of a tree. There was a significant positive relationship between acoustic velocity squared and age, but little relationship between acoustic velocity squared and diameter at breast height. An optimal sampling strategy was developed that involved sampling four plots per stand, each plot containing 12 trees, and acoustic velocity measurements being taken four times on each of the two sides of the trees being sampled. With this strategy the mean acoustic velocity squared of a stand can be estimated to within at least ±10% of the mean.

Keywords: acoustic tools; modulus of elasticity; sampling strategy; wood stiffness; *Pinus radiata*.

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INTRODUCTION

Traditional inventory assessment for tree growth and form is a routine forest operation considered essential for management of future wood flows. However, until recently, little attention has been paid to determining the quality and variability of wood properties within a forest estate. Early resource assessment programmes have focused on wood density (Cown *et al.* 1991; Roper *et al*. 2004a; Raymond & Joe 2007) but attention is now shifting to variability in wood stiffness as well as density.

Non-destructive determination of elastic properties for trees, logs, and lumber using acoustics is a well-established technique that has been used for over 35 years (Visser & Parker 1999). For *Pinus radiata* D. Don, strong correlations exist between acoustic stiffness and traditional bending tests (Lindstrom *et al.* 2002), between the stiffness of the outermost wood and the whole stem (Lasserre *et al.* 2005), and between acoustic stiffness and value of sawn product recovered (Roper *et al*. 2004b). Two types of acoustic tools are available: resonance and time of flight. Resonance tools include Hitman and Woodspec and require the specimen to have two cut ends and so the stress wave, once introduced, is reflected back and forth from the cut ends (Grabianowski 2003) which means they cannot be used to assess the stiffness of standing trees. On the other hand, the time of flight tools, which include Metriguard, Silvatest, Fakopp 2D, IML Hammer, and TreeTap, measure the time it takes for the introduced stress wave to travel between two points. Such tools provide the only practical acoustic method for measuring modulus of elasticity in standing trees (Andrews 2000), and a robust method for estimating the outerwood stiffness of trees (Chauhan & Walker 2006). Time of flight tools are unaffected by bark mass, whereas resonance tools measure an acoustic velocity that is averaged over the whole cross-sectional average, including both bark and corewood (Grabianowski *et al.* 2006).

Dynamic modulus of elasticity (MOE) can be estimated from the acoustic velocity measured using time of flight tools through the one-dimensional wave equation (Young's modulus equation):

$$\mathrm{MOE} = \rho V^2$$

where ρ is green density of the material (kg/m^3),

V is the velocity of sound (m/s) (Wang *et al.* 2001; Kollmann *et al.* 1975).

For young *P. radiata*, green density is assumed to be a constant (Grabianowski *et al.* 2006) and so modulus of elasticity is directly related to the square of velocity.

Grabianowski (2003), studying 27-year-old trees in Eyrewell Forest, observed a broad range in acoustic velocities within permanent sample plots, but with surprisingly little difference in the mean acoustic velocity amongst these plots, despite the significantly different stockings. This emphasises the huge variation in wood stiffness within and between trees within any stand. Another study on *P. radiata* sampled trees on two sides to avoid the problems associated with compression wood, and noted a significant variation within individual trees which increased with stand age (Chauhan & Walker 2006).

In pines there is a stiffness gradient across the stem (Huang *et al.* 2003), with a large increase in stiffness from pith to cambium (Tsehaye *et al.* 1995). However, there is little difference in average stiffness with height in the stem (Huang *et al.* 2003; Tsehaye *et al.* 1995). Huang *et al.* (2003) showed that average stiffness of *P. radiata* can vary by a factor of two and even as much as four (Harris & Andrews 1999), even when the trees are the same age and from within the same forest. This large variation is due to environmental conditions and genetic diversity. Within a stand, acoustic velocity is much more variable than are the outerwood green and basic densities: this larger variability in acoustic velocity makes it more efficient as a wood quality variable for screening trees (Chauhan & Walker 2006).

The ability to determine the stiffness of standing trees and logs has both short- and long-term advantages. In the short term the ability to sort standing trees and logs prior to processing could result in substantial gains in revenues (Visser & Parker 1999; Roper *et al*. 2004b). An effective means of sorting is essential where trees of varying quality exist together (Grabianowski *et al.* 2006) and, with structural lumber grades becoming stricter, a stiffness qualifier will be valuable as forest owners may gain premiums by providing wood of known stiffness. To sort individual trees into stiffness classes before they leave the bush would require significant investment in money and labour. However, sorting and ranking stands, forests, and regions is becoming increasingly achievable. In the long term the ability to capture information on the intrinsic properties — stiffness in particular — will have distinct advantages for genetic breeding opportunities (Lindstrom *et al.* 2002; Lasserre *et al.* 2005).

There is no published analysis on optimal sampling strategies, despite the increasing use of acoustics in the forest. There is extensive literature on the use of acoustics for measuring modulus of elasticity in standing trees (Booker 1997; Wang *et al.* 2001; Lindstrom *et al.* 2002; Grabianowski 2003), as well as the non-destructive evaluation and sorting of logs (Buchanan *et al*. 1999; Visser & Parker 1999; Dickson *et al.* 2003; Tsehaye *et al*. 2000; Albert *et al.* 2002; Wang *et al.* 2002, 2004). Information is also available on the variation of stiffness within and between trees (Tsehaye *et al.* 1995), and the factors that influence the acoustic properties within trees (Grabianowski *et al.* 2004). Significant proportions of this information relate to studies carried out in New Zealand on *P. radiata*. Visser & Parker (1999) indicated that the acoustic behaviour of *P. radiata* is similar to that of other species, making much of the overseas literature also relevant to this study.

To develop an effective and efficient sampling strategy for measuring the stiffness of standing trees it is important to sample enough trees to ensure a sufficient level of precision, while at the same time ensuring that resources are not wasted by over-sampling. Several key questions must be addressed:

(1) How many measurements are required per side (1–8), and how many sides are required (1, 2, or 4) to estimate the acoustic velocity squared for each tree to a specific level of precision (maximum of ±10%)?

(2) On which side(s) of the trees should acoustic velocity measurements be taken?

(3) How many trees per plot, and plots per stand (compartment), are required to estimate the acoustic velocity squared to a specified level of precision (maximum of ±10%)?

(4) Is there a relationship between acoustic velocity squared and diameter at breast height (dbh)?

(5) Can the same sampling strategy be used at different ages?

The analysis was done using acoustic velocity squared as this is directly proportional to outerwood modulus of elasticity. To assess the effect that diameter at breast height and age have on acoustic velocity squared, sites were selected to keep soil type, environmental conditions, and silvicultural history constant. The methodology for determining sample size followed that used by Raymond & Muneri (2001) and Downes *et al.* (1997) and is based on determining the distribution of the variability within a data set. Determining the number of stands to be sampled across an estate was beyond the scope of the current study and would require knowledge of both the size and the degree of variability within the estate.

METHODS

Three age-classes of *P. radiata* were sampled in stands established in 1985, 1990, and 1995 and aged 20, 15, and 10 years at the time of measurement. The sample sites were located in the Hume Region of the Forests NSW estate, Australia, and had the same silvicultural history, being unpruned and unthinned. The sites were within 4 km of each other at altitudes between 750 m and 850 m above sea level and relatively flat, with slopes between 4° and 13°. The sites were exposed to large variations in temperature between the winter and summer months, and had an average yearly temperature of 11.0°C. The average annual rainfall for the forest was 1270 mm. Initial stockings were very similar for the three different age-classes, with the 20- and 10-year age-classes having initial stockings of 935 and 936 stems/ha respectively. The stocking of the 15-year age-class was slightly higher at 1089 stems/ha.

The soils at the three sites differed slightly; however, they were all derived from Silurian granodiorite (Stace *et al.* 1968; Northcote 1979). The site of the 20-year age-class had brown podzolic soils on the upper slopes and yellow leached earth on the lower slopes. The sites of the 15- and 10-year age-classes contained red earth on the well-drained slopes, red leached earth on the mid slopes, and yellow podzolic soils on the lower slopes (Stace *et al.* 1968; Northcote 1979).

Field work was undertaken over a 3-week period in January 2005. The sampling strategy was designed to ensure that reliable estimates of variance could be calculated from the data gathered. More locations and more trees were sampled than would be expected to be required for an optimal sampling strategy. Within each age-class four plots of 20 trees were established and eight acoustic velocity measurements were taken at each of the four cardinal points (north, east, south, and west) on each tree using TreeTap. Plots were placed to provide a fair representation of the stand, and any natural regeneration within the plot was not measured. Diameter at breast height (1.3 m) was measured on all trees and any trees with dbh <90 mm were not included in the sample as this diameter is the lower limit on the inventory strategy currently used by Forests NSW.

The acoustic testing was done using a TreeTap time of flight tool, designed by Dr Michael Hayes at the University of Canterbury, New Zealand. TreeTap measures acoustic velocity in the outermost growth rings (Andrews 2000; Wang *et al.* 2002). This recently developed instrument is similar in appearance to the Fakopp 2D and uses two Fakopp piezo-elements transducers as active probes, plus an inert starter probe placed below the active probes. The stress wave is initiated by tapping the starter probe with a 200-g hammer (Hayes unpubl. data) and both active probes receive the same waveform. The active probes are set at 0.5 m and 2.0 m above ground level at an angle of less than 45° to the stem top (*see* Fig. 1) and the starter probe is set at 0.2 m above ground at an angle greater than 135°. Trees that were measured were pruned to allow for easy alignment of the probes.

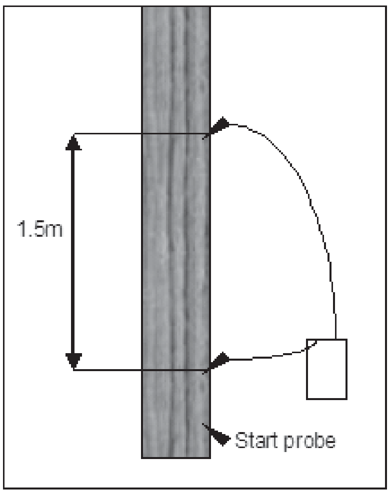

FIG. 1–Positioning of TreeTap probes.

The timing of the stress wave begins as it is detected passing the first active probe, and the clock is stopped when the impulse wave is detected by the second active probe. The acoustic velocity is found by dividing the distance between the two active probes by the transit time (Hayes unpubl. data). Inserting, measuring, and removing the TreeTap probes takes a lot longer (1–2 minutes) than the actual data capture, which can be done at around 1 tap per second.

In total 240 trees were sampled across the three age-classes. Of the 7680 individual acoustic velocity measurements taken (readings from a single tap), 28 were deleted (<0.04%) because long rise times (indicative of a broad, shallow, indistinct "rolling" acoustic wave) were not consistent or the readings were outside the usual range.

As the equation for determining sample size was based on using a normally distributed variable, the distribution of velocity squared was examined for each age-class. Data were used to estimate variance components according to the hierarchical structure for each age-class: for variance within each side, between sides within trees, between trees within plots, and between plots within stands. The variance components (σ^2) were then used to determine the sample size required (n) to estimate the mean of the side, tree, plot, and stand to a required level of precision ($\pm$ L) with a 95% confidence interval, using the equation:

$$n = 4\sigma^2/L^2$$

from Snedecor & Cochran (1967). Curves of diminishing returns were plotted and the number of samples required for the 95% confidence interval to be equal to or less than 10% of the mean value was determined. Throughout the analysis, each level of the strategy (within sides, trees, plots, and stands) was treated independently.

An optimum sampling strategy was developed based on the results of the above analysis. The key aim was to minimise the total number of measurements whilst maintaining the required degree of precision ($\pm$10% of the mean) at each level. Where differences in variance were observed between age-classes, the most variable age was used to define the new strategy. This optimum strategy was then used to build a new data set. To check that the new sampling strategy would provide similar results, the relationships between tree and plot means from the original and new sampling strategies were determined. The relationships between acoustic velocity squared, age, and diameter at breast height were determined using regression analyses.

RESULTS

The average velocity and diameter at breast height for each plot are listed in Table 1, together with the mean and standard deviation of velocity squared. The minimum diameter at breast height measured was 92 mm, the maximum 354 mm, and the

TABLE 1–Mean values for diameter at breast height (dbh), acoustic velocity and its square, and standard deviation for velocity squared for each sample plot.

Age (years)	Plot No.	Dbh (mm)	Mean acoustic velocity (km/s)	Mean acoustic velocity^2 ((km/s)^2)	Standard deviation velocity^2 ((km/s)^2)
10	5	205	2.60	6.82	1.35
10	6	198	2.59	6.77	1.25
10	7	184	2.70	7.35	1.08
10	8	200	2.69	7.29	1.23
15	1	190	3.36	11.37	1.52
15	2	204	3.17	10.12	1.48
15	3	202	3.13	9.86	1.55
15	4	187	3.48	12.15	1.55
20	9	210	3.95	15.66	1.13
20	10	212	3.82	14.62	1.40
20	11	213	3.93	15.45	1.36
20	12	236	3.76	14.20	1.55
Overall mean		203	3.27	10.97	1.37

mean 203 mm. The range in diameter at breast height was small (262 mm) considering three different age-classes were measured. The minimum acoustic velocity squared was 3.96 (km/s)^2 with the maximum being 18.33 (km/s)^2 , a range of 14.37 (km/s)^2. The mean acoustic velocity squared for the age-10 stand was 7.06 (km/s)^2 with the age-15 and age-20 stands having a mean acoustic velocity squared of 10.88 and 14.98 (km/s)^2 respectively. Velocity squared data were approximately normally distributed around the mean for each age-class (Fig. 2).

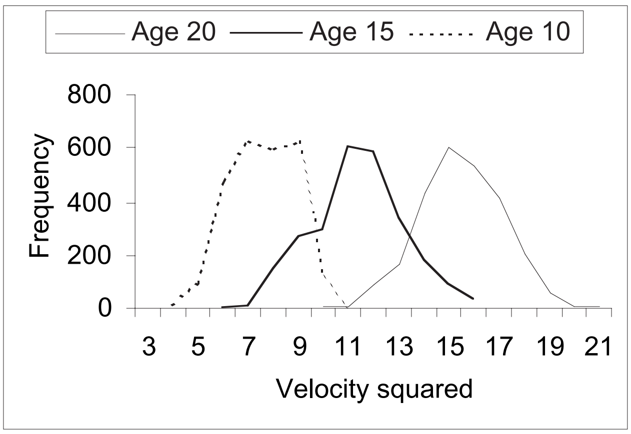

FIG. 2–Histogram of individual readings of acoustic velocity squared (km/s)^2 for each age-class.

Components of variations in acoustic velocity squared (Table 2) indicate that the 15-year-old stand expressed the greatest total variation and the 10-year-old stand the least. The 15-year-old stand showed more variation between plots than the other age-classes. Across all age-classes the major source of variation was that between trees, which, on average contributed 70% of the total variation. Variation between sides averaged 14% of the total and differences between plots averaged 14.5%. Only 1.4% of the total was due to the variation within sides.

TABLE 2–Components of variation for differences between plots, trees within plots, sides within trees, and within each side of the tree, and their percentage contribution to the total variation.

	Age 10		Age 15		Age 20		Total
	Variance	Percentage of total	Variance	Percentage of total	Variance	Percentage of total	(%)
σ^2 between plots	0.016	1.0	1.047	30.0	0.38	12.6	14.5
σ^2 between trees	1.500	94.3	2.118	60.7	1.663	55.3	70.1
σ^2 between sides	0.068	4.3	0.297	8.5	0.878	29.2	14.0
σ^2 within sides	0.006	0.4	0.030	0.8	0.089	2.9	1.4
Total	1.59		3.49		3.01		100.0

Number of Measurements Required

The variation within an individual side of a tree was extremely low but increased with age. A single valid measurement on each side was sufficient for the means of all three age-classes to be estimated to a precision of ±4% which was well below the criterion of ±10%. However, from a practical point of view, it would make little sense to capture only a single reading per side as inserting and removing the probes takes a lot longer than the actual data capture. If only a single tap was recorded per location it would be more difficult to determine the false readings. Out of the 7680 taps recorded in this study, 28 were rejected. *A priori,* there may be no reason for rejecting a single measurement unless the rejection was to be validated by repeated measurements. For these reasons capturing more than one tap remains an appropriate sampling strategy.

Variation between sides of the tree was greater than within sides and increased with age. For the most variable age-class (age 20), measuring on only one side of the tree would estimate the mean to within ±13%; measuring two sides increases the precision to ±9%. No systematic effect of cardinal direction was apparent. Further analyses used the north face as the single side, north and south for two sides, and north, south, and east for three sides. The correlation between measuring only one side and measuring all four sides (Fig. 3) was strong (r = 0.91) overall; however, it was much stronger for the age-15 (r = 0.96) and age-10 (r = 0.98) stands. When

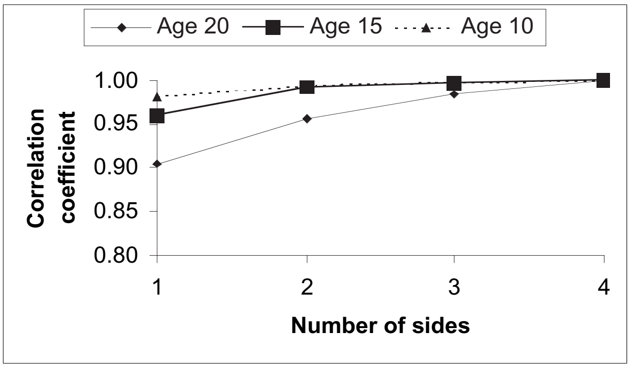

FIG. 3–Correlation between measuring one, two, and three sides compared with measuring all four sides.

measurements were taken on two sides the correlation strengthened. The age-20 stand showed the poorest correlation (r = 0.96), although this was still strong.

Measuring two sides was considered to be sufficient as it estimated the tree mean to ±9% or better and provided a correlation coefficient of r = 0.96 with four sides. In practice, having decided to measure on two sides, there are six possible pairs to choose from. The correlation coefficients indicate that there is very little difference in precision between the different combinations. However, in situations where there is noticeable stem lean or strong prevailing winds the choice of sides for sampling will be more important.

The greatest variation in acoustic velocity squared was between trees (average of 70%); thus a larger number of trees was required to estimate the plot mean. Variation between trees was greatest in the young stand and sampling 12 trees was found to estimate the plot mean to ±10% or better for all age-classes. Increasing the number of trees sampled beyond 12 had little effect on improving the precision; sampling an additional eight trees would improve the precision only to ±8%.

Variation between plots was relatively low (Table 2) and showed no clear trend with age. Sampling four plots would estimate the mean to within ±10% for all age-classes.

An Optimal Sampling Strategy

On the basis of these results, an optimal sampling strategy was designed that would estimate each of the mean values to ±10% or better. The new sampling strategy involved taking four measurements on two sides of each tree (north and south), and sampling the first 12 trees in each plot and four plots in each stand. A new data set was constructed by selecting a subsample from the original data set using these criteria.

The means and standard deviations for both sampling strategies were very similar (Table 3). Regression analyses (Fig. 4) indicated that, for the individual tree values, the relationship was strongest at age 10 ($R^2 = 0.99$), followed by age 15 ($R^2 = 0.98$), and age 20 ($R^2 = 0.91$).

TABLE 3–Plot means and standard deviations for initial and optimal sampling strategies.

Age (years)	Plot No.	Initial strategy (20 trees) Mean	Std dev.	Optimal strategy (12 trees) Mean	Std dev.
10	5	6.82	1.35	7.20	1.22
10	6	6.77	1.25	6.39	1.30
10	7	7.35	1.08	7.25	1.10
10	8	7.29	1.23	7.19	1.30
15	1	11.37	1.52	11.24	1.57
15	2	10.12	1.48	10.04	1.51
15	3	9.86	1.55	10.10	1.32
15	4	12.15	1.55	12.24	1.41
20	9	15.66	1.13	15.34	1.16
20	10	14.62	1.40	14.52	1.48
20	11	15.45	1.36	15.36	1.43
20	12	14.20	1.55	13.32	1.47

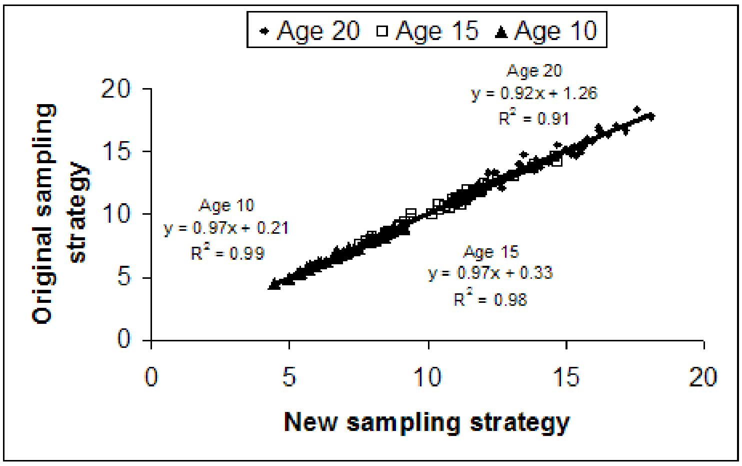

FIG. 4–Relationship between individual tree values for the original sampling strategy and the optimal sampling strategy.

Acoustic Velocity Squared *vs* Diameter at Breast Height

Regressions for tree mean acoustic velocity squared on diameter at breast height for each age-class indicated very low R^2 values (0.07, 0.09, and 0.04 for ages 10, 15, and 20 respectively). Regression coefficients for ages 10 (–0.014) and 15 (–0.012) were statistically significantly different from zero ($p<0.05$) but very small. When all three age-classes were combined the $R^2 = 0.00$.

Relationship Between Acoustic Velocity Squared and Age

The mean acoustic velocity squared for each tree was plotted against its corresponding age-class (Fig. 5). Regression analysis showed a strongly significant relationship ($p < 0.05$) between acoustic velocity squared and age with an $R^2 = 0.81$. As the age of the stand increased the mean tree acoustic velocity squared increased by 0.76 $(km/s)^2$ per year between ages 10 and 20.

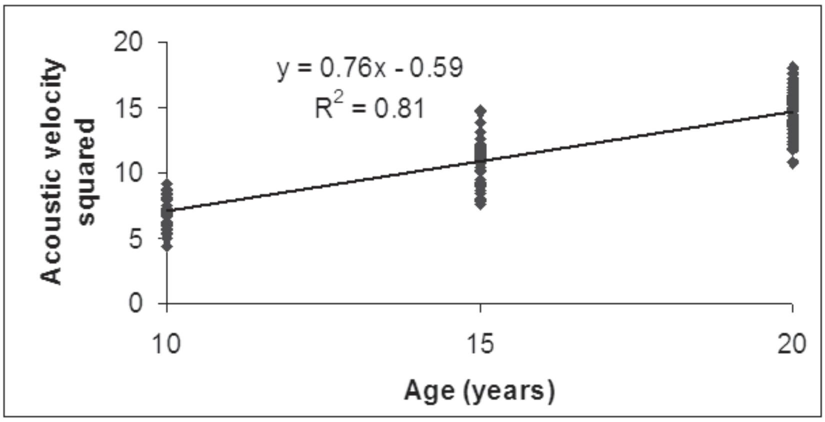

FIG. 5–Relationship between individual tree values and age.

DISCUSSION

Assessment of outerwood properties of standing trees ideally requires comparison between trees of the same genetic origin and similar silvicultural treatment (Grabianowski *et al.* 2006). A sampling strategy to assess the effect of diameter at breast height and age required that the influence of site, climate, genetic origin, and silviculture be minimised. This approach may have reduced the overall variation in the data. The proposed strategy may require amendment when sampling across wider geographical areas, differing silvicultural treatments, within genetics trials, in older stands, if pronounced compression wood is expected, or if using a different acoustic testing tool. However, a similar statistical approach should be used in determining the required sampling strategy.

The variation within the sides of individual trees was extremely small and had little effect on the overall precision of the sampling strategy. The 1.5-m distance between stop probes is the largest distance easily manageable in the forest: if shorter distances are used it is likely that variation will increase (Grabianowski 2003). Occasional false readings occur due to miss-hits, poor probe contact with the stem wood, or for unknown reasons. More readings are commonly taken than are actually required due to the difference in the time required to set up and remove the probes *vs* collecting the data. For example, Grabianowski (2003) suggested five measurements per side were adequate when using a Fakopp @2D on 27-year-old *P. radiata*.

Variation between sides was much higher, averaging 14% of the total variation. Even in straight trees a difference between sides can be expected; Hayes (unpubl. data) reported differences of 5% at age 8, 10% at age 16, and 15% at age 24. A similar trend with age was found here and sampling two sides of a stem is recommended to account for the within-tree variability. As the sites sampled in the current study were selected to avoid compression wood, and were not exposed to strong prevailing winds, no particular combination of sides was found to be better. However, if sampling a steeply sloping or wind-prone site or one with leaning stems it would be preferable to sample perpendicular to the prevailing slope, wind direction, or lean to avoid sampling compression wood Grabianowski (2003).

As expected, differences between trees were responsible for over 50% of the variation in all three age-classes, indicating that a large number of trees need to be sampled to assess a stand accurately (Visser & Parker 1999). Increasing the number of trees sampled will have the greatest effect on increasing the precision of the sampling strategy. In contrast, variation between plots within a site was relatively small and only four plots per stand are recommended.

Within each age-class there was little relationship between velocity squared and tree diameter, which is similar to the results of Grabianowski (2003) and Grabianowski *et al.* (2004) for standing trees. In contrast, Lasserre *et al.* (2004, 2005) reported a significant negative relationship between diameter at breast height and modulus of elasticity in young trees (age 11). Diameter has also been shown to be important when cut logs are tested, with acoustic modulus of elasticity showing increasing deviation from static modulus of elasticity as diameter increases (Chauhan & Walker 2006; Wang *et al.* 2004). However, results of the current study indicate that differences in breast height diameter do not need to be accounted for when developing a strategy for sampling standing trees.

The strong positive relationship between acoustic velocity squared and age (increasing by 0.76 $(km/s)^2$ per year between ages 10 and 20) is similar to that found by Grabianowski (2003) and Grabianowski *et al.* (2006). In a study in Greymouth, New Zealand, Grabianowski (2003) found average velocities of 2.02, 2.39, and 2.87 km/s at ages 8, 16, and 26 years respectively, implying a gradual increase in acoustic velocity, and therefore in stiffness of newly formed outerwood.

As trends in distribution of the variation showed no consistent pattern with increasing age, separate sampling strategies were not required for each age-class.

By developing one optimal sampling strategy for all three age-classes, the robustness of the strategy is increased. As the optimal strategy was based on the age-class with the greatest variability at each level, the other age-classes will be sampled to a higher level of precision than is strictly necessary. The recommended optimal sampling strategy provided results that were very strongly related (R^2 = 0.91 or greater) to those from the initial sampling strategy.

Other factors that may influence acoustic velocity include temperature and moisture content (Visser & Parker 1999; Kang & Booker 2002) plus stocking. Mixed results have been found for stocking effects, with Grabianowski *et al.* (2004) reporting no significance difference in acoustic velocity between stockings in old stands. In contrast, Lasserre *et al.* (2004, 2005) found that stiffness increased as the stocking increased in young stands.

In any form of sampling there will always be a trade-off between precision and the cost of sampling and it is important to consider the end use for the data. Sampling individual trees to rank them prior to processing will cost significantly more than assessing silvicultural treatments on a stand or forest level. Using the optimal sampling strategy developed alongside conventional pre-harvest inventory would provide a cost-effective means of assessing stiffness of a stand at forest level. Inevitably, the final sampling strategy used will be a trade-off between the cost of sampling and the degree of precision required. The optimum combination of plots and trees per plot for a given total sample size (VC) occurs when the product of the variance of the sample mean (from Snedecor & Cochran 1967) and the cost of measurement is minimised:

$$VC = \left[\frac{\sigma_p^2}{n_p} + \frac{\sigma_t^2}{n_p n_t}\right]\left(c_p n_p + c_t n_p n_t\right)$$

where: σ_p^2 = the variance between plots within a stratum
σ_t^2 = the variance between trees within a plot
n_p = the number of sample plots per stratum
n_t = the number of sample trees per plot
c_p = the cost of sampling a plot
c_t = the cost of sampling and processing the sample from a tree.

In the above equation the relative costs per tree and per plot become critical, and the final sampling strategy for an organisation will need to be determined using realistic cost structures in combination with the observed patterns of variation.

CONCLUSION

The greatest variation in velocity squared was in the age-15 stand, followed by the age-20 and age-10. When the data were pooled, the largest contributor to total variance was the difference between trees, followed by the variation between sides, and between plots, with the variation within sides the smallest. Based on the results of the analysis of variance, and using curves of diminishing return, an optimal sampling strategy was developed which involves:

- Four acoustic velocity readings on each of two sides (north and south used here)
- 12 trees in each plot
- Four plots in each stand.

By using this sampling strategy, the mean acoustic velocity squared within a side is estimated to within ±2% of the mean, the mean tree acoustic velocity squared is estimated to within ±9%, the plot mean is estimated to within ±10%, and the mean stand acoustic velocity squared within ±10%. The optimal sampling strategy developed showed a very strong correlation to the initial sampling strategy used.

There was a strongly significant relationship between acoustic velocity squared and age; however, as variation was not consistent with age, only one overall sampling strategy was developed. The optimal strategy was not adjusted for diameter at breast height. This study is somewhat limited in that it was developed for a particular location. By reducing the influences of site, climate, genetic origin, and silviculture in order to assess the effect of diameter at breast height and age on acoustic velocity squared, the overall variation may have been reduced. This may limit the strategy's use for assessing other regions, silvicultural regimes, and seasons. However, the approach taken to develop the strategy should remain the same, and little work would be required to adjust the strategy for use in other areas.

ACKNOWLEDGMENTS

We would like to thank Forests NSW, Hume Region, and in particular Duncan Watt, for allowing Michael Toulmin to collect the data and make this study possible. We would also like to thank Bruce Manley and John Walker for their comments on the manuscript. Lastly, we would like to acknowledge the financial support provided to Michael Toulmin by the Holt Forest Trust.

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