ESTIMATING INDIVIDUAL TREE STIFFNESS USING SMALL CLEARS

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ABSTRACT

Static bending of small clear specimens is one of the most commonly used methods for assessing the stiffness (Modulus of Elasticity) of sawn timber and trees. Small clears have traditionally been cut from the same growth rings on opposing radii, at breast height; thus seeking to minimise the radial and longitudinal variation. The remaining (residual) variation between small clears determines the precision of the estimate of the tree mean, but has rarely been analysed in detail. To investigate this, stiffness measurements previously collected from small clears taken from opposing radii at breast height from New Zealand grown radiata pine and Douglas-fir were reanalysed to ascertain the magnitude of the residual variation at breast height. Expressed as coefficient of variance between small clears from the same radial position (growth ring), the variation ranged from 8 to 32% for radiata pine and from 7 to 13% for Douglas-fir. Using two small clears, the associated margin of error for estimates of mean stiffness of individual trees ranged from 70 to 260% for radiata pine and 80 to 125% for Douglas-fir. It is recommended to use at least four small clears (margins of error of 10-40%) when estimating the mean stiffness of individual trees from small clears extracted at the same height from the same growth ring.

Keywords

New Zealand, small clear specimens, sample size, Douglas-fir, radiata pine

INTRODUCTION

As more of the world's supply of wood comes from fast-growing tree species managed in shorter rotations, there is an increasing need to investigate and evaluate the physical properties of the wood produced (Mamdy *et al.* 1999, Jayawickrama 2001, Huang *et al.* 2003). In particular, if the wood is to be used for structural purposes it is important to investigate the structural properties, particularly stiffness (Modulus of Elasticity, in GPa) (Madsen 1995). There are many ways of measuring stiffness of wood, which include: ultrasound (Sandoz and Lorin 1994), piece matching (Noren 1994), the modulometre (Mamdy *et al.* 1999, Rozenberg *et al.* 1999), acoustic methods (Wang *et al.* 2000, Huang *et al.* 2003), near infrared reflectance spectrometry (So *et al.* 2002), and x-ray densitometric and diffractometric methods (Evans and Ilic 2001). See also Forest Products Laboratory (1999), which provides a comprehensive review of methods.

Standard in-grade testing of sawn timber is considered to be the best and most direct method of measuring stiffness, but it is expensive and not always practical. An alternative method is testing of small clear specimens[1], or 'small clears' for short. Due to its early standardisation and relative ease of use, it is one of the most widely applied methods, e.g. Mack (1977), Okstad and Karstad (1985), Ishengoma and Nagoda (1987), Okstad (1987), Kliger *et al.* 1998, Bier and Britton (1999), Flaete and Kucera (1999), Evans *et al.* (2000), Burdon *et al.* (2001). Furthermore, recent advances in technology have allowed for small clears to be extracted from living trees without felling them, thus making this method available also to tree breeders (Jayawickrama 2001).

Despite its status as a *de facto* standard, both Madsen (1995) and Jayawickrama (2001) raise concerns about the small clears method. This concern mainly evolves around the fact that small clears are considered to be samples of the whole tree and standard sampling theory applied, i.e. the mean stiffness of a set of small clears is assumed to be an unbiased estimator for the mean of the tree or the sawn board. The problem with this approach is that the small clears reflect wood properties at a much smaller scale than at the level of the tree or the board. An estimate of the mean for an individual tree or board is therefore influenced by the within-tree variation at the level of the small clears.

Within-tree variation of wood properties (including stiffness) can be grouped into three components: 1) radial, 2) longitudinal (height), and 3) tangential (circumferential) (Tsoumis 1991). The radial variations represent the within and between year changes in wood properties. These changes are reasonably well understood and described, e.g. Zobel and Buijtenen (1989), Tsoumis (1991), Walker *et al.* (1994), Lausberg *et al.* (1995), So *et al.* (2002), Knowles *et al.* (2003). It is also generally accepted that stiffness in conifers more or less increases with height above the ground (So *et al.* 2002, Knowles *et al.* 2003). The tangential variation on the other hand shows no consistent pattern either across or within species (Tsuomis 1991, Walker *et al.* 1994), or is traditionally considered to be insignificant, and is thus ignored (Nicholls 1986).

In estimating individual-tree mean MoE the within-tree variation at the level of the small clear is minimised by extracting small clears at breast height only, and by assigning each small clear to a specific radial position (ring number) relative to the pith. This, however, does not account for the circumferential variation, which together with measurement errors makes up the remaining (residual) within-tree variation. The precision of the estimates of the mean is determined by the amount of residual within-tree variance, but the magnitude of this variation has rarely been analysed in detail.

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[1] British Standards BS 373:1956(1986), American Society for Testing and Materials ASTM D143-94(2000)e1., or the French Norm NF B 51-016.

This purpose of this study is to:

1) Examine and describe the residual (part circumferential) within-tree variation in stiffness of small clears using historical records of small clears extracted from New Zealand-grown radiata pine and Douglas-fir.
2) Based on sampling theory and the results from the first part of the study, to ascertain the minimum number of small clears required for estimating the mean stiffness of individual trees, with a given precision.

MATERIAL

The data consist of static bending stiffness measurements (MoE) of small clear specimens extracted from New Zealand-grown radiata pine and Douglas-fir, and is summarised in Table **1**.

Data from a total of thirty-three shipments of small clears from radiata pine were available, each representing one stand, i.e. one age, location and genotype. Each shipment consisted of small clears from four or five trees, with two to eighteen small clears from each tree. All clears had been cut in pairs at equidistant positions from the pith along two opposing radii centred at breast height (1.4m). A full description of the data is available in Walford (1985).

Only two Douglas-fir data sets of small clears were available. The first set was from sixty trees in an 18-year-old stand in Tapanui, Compartment 202, West Tapanui Forest. In each tree, two pairs of small clears had been cut from opposing radii, centred on the fifth and tenth growth ring at breast height. The second shipment originated from a 41-year-old stand in Rotoehu Forest, Compartment 55, where a total of eighteen trees had been sampled. Four to six small clears had been cut in pairs at equidistant positions (5-ring intervals) from the pith on opposing radii at each of five heights up each stem.

Species	Location	Age (yr)	Shipments	Trees	Radial positions per tree	Height positions per tree	Small clears per tree	Pairs of small clears in total
Radiata pine	New Zealand	9-41	33	161	1-9	1	2-18	841
Douglas-fir	Tapanui	18	1	60	2	1	4	101
Douglas-fir	Rotoehu	41	1	18	2-3	3-5	6-14	176

Table 1 - Species, location, age, and number of small clears

METHODS

Background and assumptions

The confidence limits for an estimate of a single mean (for a normal population) are defined as:

$$\mu \pm t_{\alpha,n-1}\frac{s}{\sqrt{n}}. \qquad (1)$$

Where μ is the mean, $t_{\alpha, n-1}$ is the value of the cumulated *t*-distribution with (n-1) degrees of freedom at confidence level α, s is the standard deviation, and n is the number of observations (Weisstein 2002). Knowledge of the standard deviation (s) thus allows for estimation of the number of samples (n) required to obtain an estimate within a certain margin of error. The problem is that the standard deviation for a particular population is rarely known prior to a study. By studying similar historical data it is, however, possible to get a useful estimate of its range. The data in this study consist entirely of pairs of stiffness measurements, which do not allow the application of, for example, circular statistics (Batschelet 1981). However, because the observations in each pair were extracted at the same height and the same distance from the pith, it is assumed that the difference between them is independent of the radial and longitudinal within-tree trends in stiffness – thus reflecting the residual variation only (part of which is circumferential variation).

To analyse the data it is assumed that each measurement in a pair is drawn from the same normal distribution with some mean (μ) and standard deviation (σ_x). The difference (z) between the measurements is thus normally distributed with a mean of zero and a standard deviation of $\sigma_z = \sqrt{\sigma_x{}^2 + \sigma_x{}^2} = \sigma_x\sqrt{2}$. Finally, it is assumed that the *z*-values are the same for all trees within specific groups. Thus, by analysing the standard deviation (σ_z) of the *z*-values for a group of trees, it is possible to estimate the magnitude and variation of the residual within-tree variation for trees in that group.

Analyses

The *z*-values were plotted against pair mean stiffness, radial position, shipment and where possible also, height. The graphs were visually analysed in order to ascertain any trends.
The *z*-values from radiata pine were divided into groups by radial position (nominal positions), mean stiffness (in intervals of 1GPa), shipment, tree, or radial position within shipment. For each group σ_z was calculated, and the normality assumption was tested, using Shapiro-Wilks test, as implemented in PROC UNIVARIATE in SAS. The distribution of σ_z values across groups were summarised by descriptive statistics, i.e. mean, standard deviation, minimum and maximum values. For Douglas-fir the *z*-values were divided into groups based on height (nominal groups and only for the Rotoehu data), radial position (intervals of five annual rings), mean stiffness (in intervals of 1GPa) or tree, and the standard deviation (σ_z) was calculated for each group.
The residual within-tree standard deviation was then estimated from σ_z using

$$\sigma_x = \sigma_z / \sqrt{2}, \qquad (2)$$

and expressed in terms of coefficient of variance, by division by mean stiffness.
Finally, the margin of error (R), in percentage of the mean, was calculated by

$$R = t_{\alpha,n-1}\frac{\sigma_x}{\mu\sqrt{n}}, \qquad (3)$$

and iterated for α = [0.975], n = [2, 4, 6, 8, 10, 12, 14, 16], and coefficients of variance (σ_x / μ) between 0 and 30%. The margin of error thus express the 95 percent confidence limits of the estimate for the mean, e.g. a margin of error of 50 percent means that the estimated mean with 95 percent confidence is within ±50 percent of the true mean.

RESULTS

Trends in z-values

The *z*-values are plotted against mean stiffness and radial position for radiata pine in Figure 1 and Figure 3, and for Douglas-fir in Figure 2 and Figure 4. There were no trends in *z*-values with height for the Douglas-fir data from Rotoehu. The radiata pine *z*-values are plotted by shipment in Figure 5.

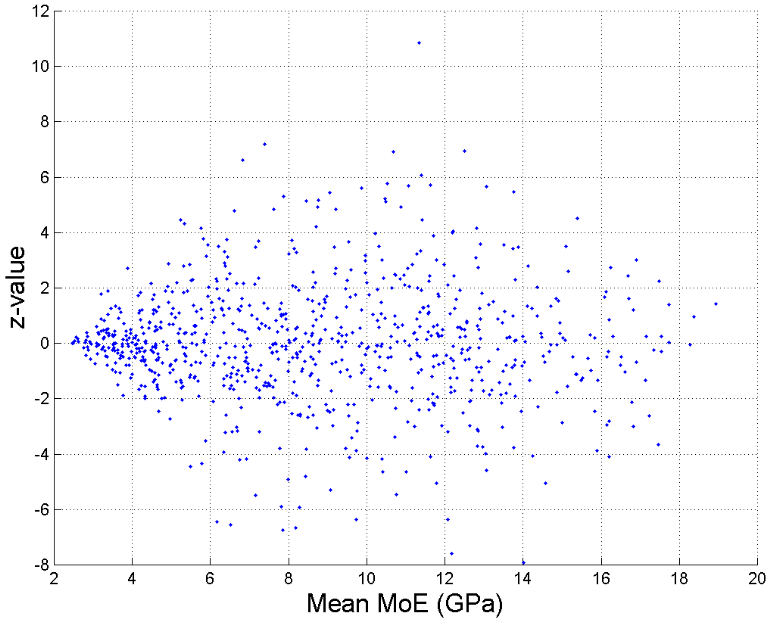

Figure 1 - Radiata pine *z*-values (GPa) against mean stiffness

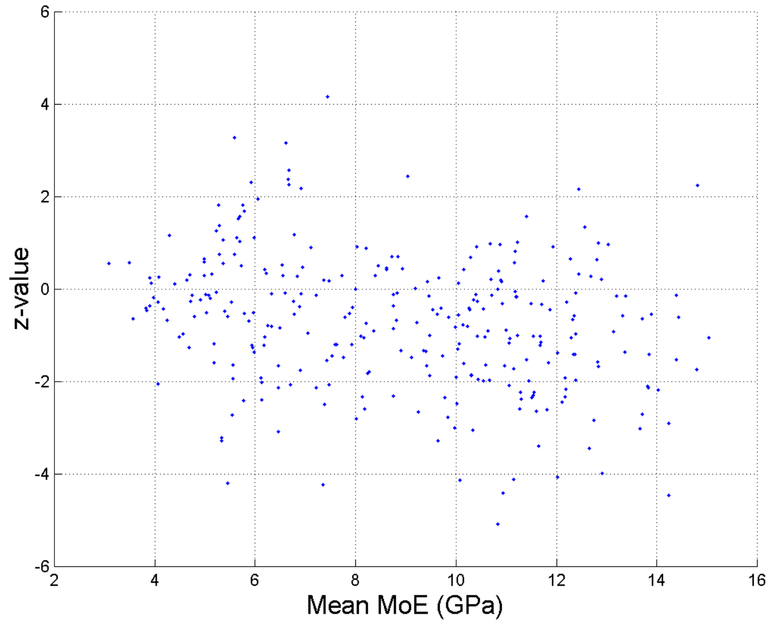

Figure 2 - Douglas-fir *z*-values (GPa) against mean stiffness

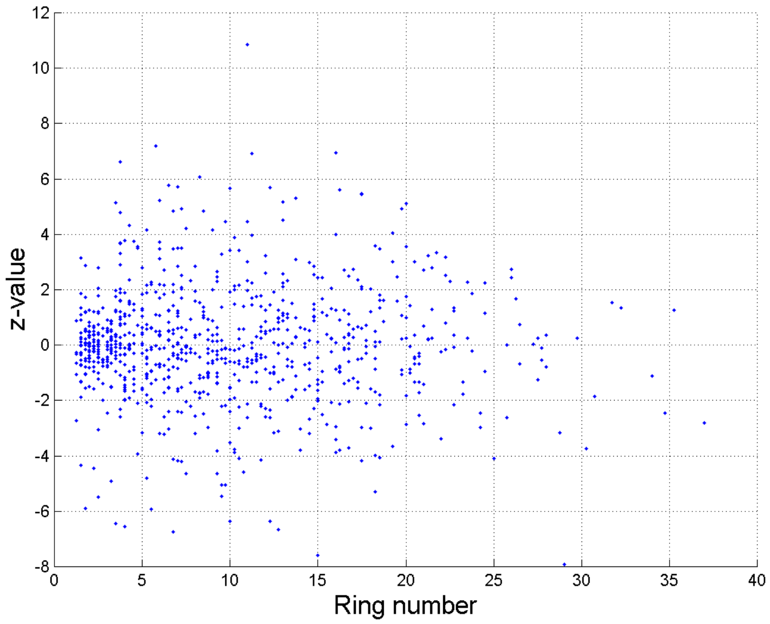

Figure 3 - Radiata pine *z*-values (GPa) against radial position

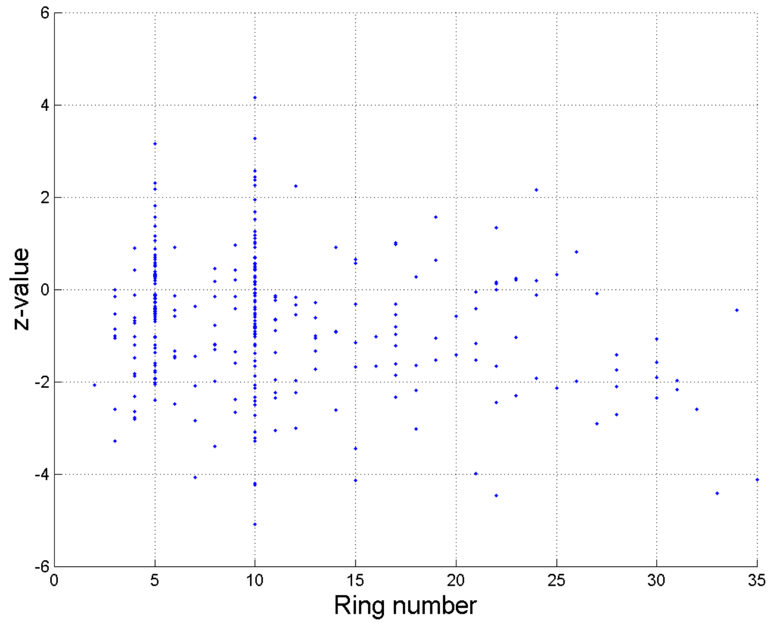

Figure 4 - Douglas-fir *z*-values (GPa) against radial position

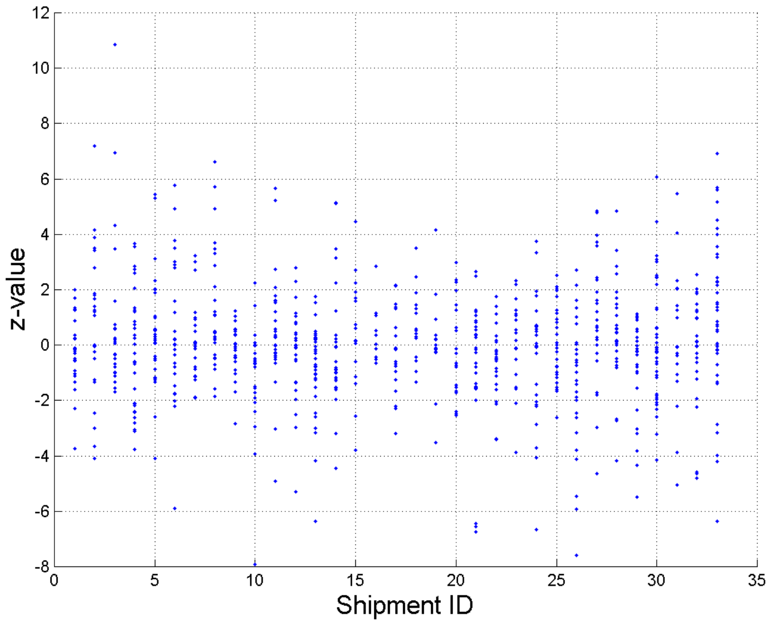

Figure 5 - radiata pine *z*-values (GPa) by shipment

Standard deviation of z-values

The standard deviations of *z*-values for radiata pine are presented in Table 2 and for Douglas-fir in Table 3 and Table 4.

Group	All	Radial position	Mean stiffness	Shipment	Tree	Shipment and radial position
Number of groups	1	10	15	33	161	196
Average number per group	841	84.1	56.07	25.48	5.22	3.95
Mean of σ_z	2.1030	2.1912	2.0803	1.9344	1.5462	1.7850
Standard deviation of σ_z	-	0.3804	0.5576	0.5124	0.8561	1.0520
Maximum of σ_z	-	2.5776	2.6454	2.8870	4.2350	7.1849
Minimum of σ_z	-	1.2873	0.6941	0.9600	0.2156	0.3111
Failed Shapiro-Wilk test (95% confidence)	-	None	None	2%	10%	15%

Table 2 - Summary statistics of the standard deviation for *z*-values for radiata pine

Group	All	Height	Radial position	Mean stiffness	Tree
Number of groups	1	5	5	8	18
Average number per group	176	35.20	35.20	22.13	9.78
Mean of σ_z	1.3106	1.2952	1.3330	1.3008	1.2150
Standard deviation of σ_z	-	0.1589	0.1372	0.3626	0.3708
Maximum of σ_z	-	1.5378	1.5372	1.9959	1.9100
Minimum of σ_z	-	1.1516	1.2039	0.8644	0.7600

Table 3 - Summary statistics of the standard deviation for *z*-values for Douglas-fir from Rotoehu

Group	All	Radial position	Mean stiffness
Number of groups	1	2	6
Average number per group	101	50.5	16.83
Mean of σ_z	1.4978	1.4646	1.5983

Table 4 - Summary statistics of the standard deviation for *z*-values for Douglas-fir from Tapanui

The average within-group standard deviation of *z*-values for radiata pine varies between 1.54 and 2.10, which convert to residual within-tree standard deviation of 1.09 and 1.48. For Douglas-fir the similar values are 1.30 for Rotoehu and 1.50 for Tapanui, which convert to residual within-tree standard deviation of 0.92 and 1.06, respectively.

The average stiffness by shipment for radiata pine varies from 4.61 to 13.06 GPa, which gives estimates of residual within-tree coefficients of variance between 1.09/13.06 = 8% and 1.48/4.61 = 32%. In Douglas-fir the mean stiffness by tree ranges from 8.2 to 13.07 GPa. This leads to residual within-tree coefficients of variance between 7% and 13%.

Margin of error and number of samples required

The margins of error (equation 1) for different sample sizes, using coefficients of variance in the order of those found for small clears (i.e. irrespective of species), are plotted in Figure 6 and Figure 7.

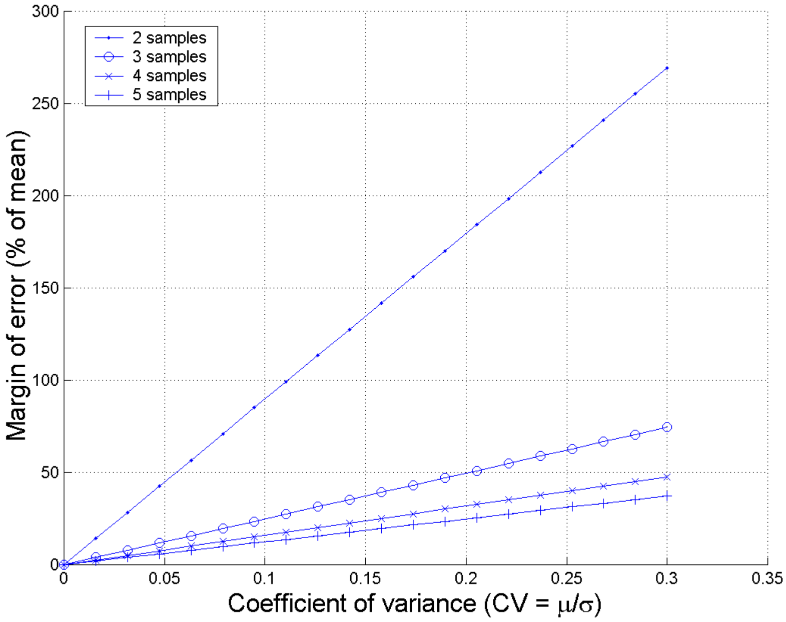

Figure 6 - Margin of error (±% of the mean) against coefficient of variance for sample sizes of between two and five, using a significance level of $\alpha = 95\%$

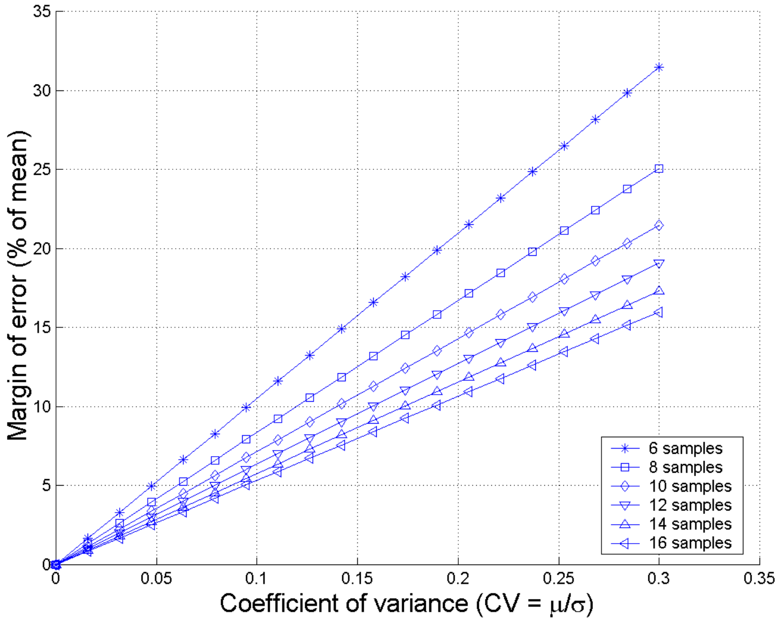

Figure 7 - Margin of error (±% of the mean) against coefficient of variance for sample sizes of between six and sixteen, using a significance level of $\alpha = 95\%$

DISCUSSION

From Figure 1 it is evident that the distribution of differences between pair-wise stiffness measurements (*z*) in radiata pine is quite independent of mean stiffness for values from 4 to 14 GPa. A similar result (Figure 2) seems valid for Douglas-fir even though there is a slight tendency to decreasing differences for increasing mean stiffness. This is most likely an effect of the few data available for Douglas-fir, which is also indicated by the overall mean difference being negative. In effect, the data does not comply with the normality assumption, or there was some sort of consistent lean in the investigated stands (both stands were situated on quite steep slopes). With respect to radial position there seems to be no effect on the *z*-values both for radiata pine and Douglas-fir (Figure 3 and Figure 4). In combination, the independence of *z*-values from radial position and mean stiffness indicates that it is fair to assume that the *z*-values are also independent of individual tree effects (within groups).

From Figure 5 it is evident that in radiata pine there is variation between shipments, with some varying widely, and again others with mostly negative differences (similar to the Douglas-fir shipments). Making *a priori* assumptions of standard deviations less than the average found in this study therefore seems to be unwise, as some trees and stands show considerably more residual within-tree variation.

From Table 2, Table 3 and Table 4 it is evident that the variation in *z*-values, regardless of how the observations are grouped, seems to be quite stable within species. For radiata pine the mean standard deviation is around 2 GPa with a standard deviation around the mean of 0.5 GPa, except when the observations are extensively divided into groups, i.e. few observations in each group. The latter corresponds with an increasing number of failed Shapiro-Wilk tests, indicating that the intensive grouping to some extent violates the normality assumption upon which the analyses are based. For Douglas-fir there is also a difference between the shipments, with a standard deviation at Rotoehu of 1.3 and Tapanui of 1.5. However, within shipments the amount of variation is very similar across the different groups.

The residual within-tree variation in stiffness of small clears for both species expressed as coefficient of variance vary from 7 to 32%. Looking up these values in Figure 6 and Figure 7, the margin of error using two small clears, for example, is between 65 and 270 percent. In other words, estimating the mean stiffness of an individual tree based on two outer-wood small clears extracted at breast height may give very faulty estimates, e.g. under the best conditions up to 60 percent difference from the actual mean. However, simply by using four small clears (e.g. cruciform sampling) the margin of error is reduced to between 15 and 75 percent. Increasing the number of samples even further to sixteen brings the margin of error to between 5 and 15 percent. Note that all the above assumes that the small clears are extracted at the same growth ring from the pith and at the same height.

CONCLUSION

The within-tree variation of stiffness measured by small clears recovered from the same growth ring on opposing radii at breast height, expressed as coefficients of variance, ranges from 8 to 32 percent for radiata pine and from 7 to 13 percent for Douglas-fir. Using two small clears per tree, the associated margin of error for estimates of individual tree mean stiffness (with 95 percent confidence) ranges from 70 to 260 percent for radiata pine and 80 to 125 percent for Douglas-fir. Using four small clears per tree, the margin of error reduces to between 20 and 75 percent for radiata pine and 17 to 32 percent for Douglas-fir. The number of small clears required to achieve a reliable estimate of the stiffness of individual trees depends on the allowable margin of error. However, it seems untenable to use fewer than four small clears extracted cruciformly at the same ring and longitudinal position, while using more than eight seems excessive.

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