Assessment of acoustic tools to measure the stiffness of standing trees, logs and timber of New Zealand-grown Douglas-fir

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NZ Douglas-fir Cooperative

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ASSESSMENT OF ACOUSTIC TOOLS TO MEASURE THE STIFFNESS OF STANDING TREES, LOGS AND TIMBER OF NEW ZEALAND-GROWN DOUGLAS-FIR

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ABSTRACT

The purpose of this study was to use a range of different acoustic tools to ascertain the MoE at tree, log and timber-level, and compare the results with the stiffness of the final wood product (dry timber MoE).

Measurements of sonic velocities, at all levels from tree to timber, are correlated to dry timber stiffness. The best measurements are those gathered from green timber, followed by dry timber, logs, and last from standing trees. For standing trees the IML hammer is the best tool, and on logs and timber the Director (Hitman) provides the best results.

In combination with other variables (e.g. density) the sonic velocities provide even greater correlation to dry timber stiffness. The sonic velocity provided by the Director (Hitman) tool in combination with green density is so well correlated to end-product stiffness that it could provide the standard method for stiffness assessment.

INTRODUCTION

Traditionally, Douglas-fir timber has been sold either ungraded, or visually graded. Both these methods fail to differentiate the typically greater stiffness of Douglas-fir timber relative to for example radiata pine. Early attempts to objectively grade Douglas-fir lumber focused on stress grading the timber as a plank by measuring the minimum MoE (Whiteside *et al.* 1977, Shelbourne *et al.* 1973). Recently developed timber grading methods, such as the A-grader, measure the average MoE acoustically (Table 3).

A previous detailed timber utilisation-study based on sawing eighteen 41-year-old Douglas-fir trees, coupled with more intensive sampling using SilviScan2 and small clear samples, illustrated typical trends within and between trees in variation of MoE and its related traits; i.e. density and microfibril angle (MFA) (Knowles *et al.* 2003). In addition to using traditional methods, the trees, logs, timber, and small clears were all assessed for MoE using sound velocity or sound resonance. The standing trees were assessed using the IML hammer, the logs using the FCF SWAT instrument, the timber using the IML hammer, and the small clears using the PUNDIT. In order of precision, the measurement of sound velocity on standing trees was the least accurate, and was more precise on the logs, with measurements of timber and small clears being the most precise. Acoustic measurements on timber and small clears were also very highly correlated with static MoE of timber, as measured by four-point bending as a joist, in accordance with the NZ standards.

The IML measurement of sound velocity on the standing trees in the study by Knowles *et al.* (2003) used the original screws for insertion in the stem supplied with the instrument. Subsequently the IML hammer has been used with short spikes on an 18-year-old Douglas-fir stand at Cpt 201 West Tapanui (Knowles *et al.* 2004). This was a much quicker method, but correlation with MoE of small clears was about the same as with density (a correlation coefficient of around 0.4). More recent use of longer spikes on radiata pine has shown further improvement in consistency of results, permitting more confidence in using the IML on standing trees.

Subsequently, in trials on radiata pine of a variety of acoustic tools, the IML hammer and TreeTap (developed by the University of Canterbury in conjunction with the Radiata Pine Breeding Company) proved to be amongst the better performing tools (Grabianowski *et al.* 2006).

The FibreGen (NZ) tool Director (previously known as Hitman, see Table 3) has been widely applied for research projects and in industry applications for log grading of radiata pine logs.. This has confirmed the usefulness of acoustic methods on logs. Similarly has the development of the A-grader on sawn timber. Tools such as these are now considered the standard for their particular applications.

SilviScan assessment of density, microfibril angle, and predicted MoE uses x-ray diffraction and x-ray densitometry of 2mm strips cut from 10 mm cores, or cut from radial strips recovered from disks. The SilviScan MoE has shown a high correlation with actual MoE of sawn Douglas-fir timber (Knowles *et al.* 2002), and small clears (Knowles *et al.* 2004).

The purpose of this study was to use a range of different acoustic tools to ascertain the MoE at tree, log and timber-level, and analyse the results in conjunction with accurate measurements of dry timber MoE. Furthermore, to analyse if a range of tree and log variables may supplement the acoustic measurements in providing a more accurate prediction of timber MoE. Hence, ultimately determine the sampling and measurement methods for standing trees, logs and timber, which best correlate with the MoE of the end-product (dry timber MoE) for Douglas-fir in New Zealand.

METHODS AND MATERIAL

This study was based on trees from a 32-year-old Douglas-fir stand in Cpt. 21, Whaka Forest (S 38^0.13’, E176^0.16’, altitude 420m asl). It was planted in 1972 at around 1,500 sph, and thinned to 360 sph in 1987 (age 15 years). The site index (mean top height at age 40) is 30m, which is slightly below the New Zealand average. The mean annual volume increment when adjusted to 500 stems/ha (i.e. 500-index ,Knowles, 2005) is approximately.14 m^3/ha/year, which is low for Douglas-fir in New Zealand (average of around 17 m^3/ha/year).

The trial consists of open-pollinated progenies of plus trees selected in 1969 in stands in Kaingaroa Forest of Washington origin. A sample of 100 trees was chosen arbitrarily, mainly within a group of 33 nominated families (three trees per family), all selected trees being of ‘normal’ form and covering the ‘merchantable’ diameter range. Trees were not selected that were sub-dominant, forked, bent, leaning, kinked or with obvious ramicorn branches.

The 100 selected trees were measured for sound velocity using the IML hammer (Table 3) by taking two readings on opposite sides of the tree at breast height. Thirty of the 100 trees sampled were then selected for more intensive study. The subset of 30 trees was selected to represent the distribution of IML hammer sound velocities among the original 100 trees (same mean and standard deviation).

The 30 trees received an additional two measurements of sound velocity using another IML tool and a different operator. They were similarly assessed for sound velocity using an acoustic tool called TreeTap (Table 3). Finally the trees were assessed for outer-wood density taking two 5mm cores at breast height. The trees ranged from 319mm to 527mm in diameter at breast-height, with a basal-area weighed mean of 379mm.

Subsequently, the subset of 30 trees was felled. A single log, 5m in length, was recovered from the 1.4 m - 6.4 m section. Branch index (BIX) and the number of branch clusters was assessed for each log according to standard practice. In addition, three discs 50 mm in thickness were removed from the large end and two disks from the small end of each log. One set of discs were measured for green and basic density. From the other discs two horizontal strips were extracted to simulate cores taken from the standing tree. These were analysed using SilviScan2 (Table 3) giving measures of density, micro-fibril angle and stiffness.

The 5m log-length permitted two studs 2.4 m in length to be recovered, together with a total trim allowance of 200 mm. Previous studies (e.g. Knowles *et al.* 2003) have shown that because the vertical within-tree gradient for MoE in Douglas-fir is relatively flat, sampling additional log height classes is not necessary to assess whole-tree characteristics. The logs were measured for small-end-diameter (SED), taper, volume, and assessed for sonic velocity using IML hammer, Hitman and SWAT (Table 3). The log ends were marked by paint with a unique colour/pattern for each individual log. The inner 10 rings were differentiated, so that mean ring position could be inferred from the marks left on the end of each board.

Each log was sawn by Red Stag Timber at their Waipa sawmill to maximise recovery of 50mm by 100mm timber. Only full-length or close-to-full-length 50*100mm pieces were numbered as they came off the green chain, and assessed ungauged for actual dimensions (including length), green weight, and sound velocity using Hitman and IML. The average sonic velocity of the timber was estimated as the volume-weighted average sound velocity of the pieces, for both Hitman and IML measurements. Similarly, the average green density was estimated for each log.

The timber was then dried and gauged by Red Stag Timber, and weighed and assessed at the Forest Research Timber Engineering Laboratory in Rotorua, using certified static testing equipment, to determine the static bending timber stiffness (MoE) properties of each piece as a joist. Dry density was determined from the weights, and the average dry density for the tree/log was calculated as the volume-weighted average of all the individual pieces. The average dry timber MoE for each tree/log was estimated as the volume-weighted average MoE of all recovered timber in the tree/log. This measurement of timber stiffness was set as the benchmark against which all other measurements were compared.

Finally, the dry timber was assessed using the acoustic tool Hitman, and the volume-weighted average velocity was calculated.

A summary of the levels, methods, variables, number of samples, and repetitions is given in Table 1).

Table 1. Summary of number of samples, measurements and methods

Level	Method / variable	No of samples	Reps.
Tree	IML initial measurement	100 trees	2
Tree	IML second operator	30 trees	2
Tree	TreeTap	30 trees	4
Tree	Breast-height outer-wood density	30 trees	2
Tree/Log	SilviScan2	30 trees	2
Log	BIX	30 logs	1
Log	Hitman	30 logs	1
Log	SWAT	30 logs	1
Log	IML hammer	30 logs	1
Timber (green)	Hitman	237 pieces	1
Timber (green)	IML	219 pieces	1
Timber (green)	Weight	237 pieces	1
Timber (dry)	Hitman	205 pieces	1
Timber (dry)	Weight	222 pieces	1
Timber (dry)	Static MoE	222 pieces	1

Analyses
Each of the measured sonic velocities (i.e. different tools at different levels from tree to timber) were compared to a so-called ‘true MoE’, which was set to be the static bending test of the dried timber (volume-weighted average MoE). The comparisons were based on standard analyses of variance using the model:

true MoE ~ sonic velocity + error.

Subsequently, the sonic tools (at different levels) were ranked based on their correlation coefficient (r-squared) to the dry timber MoE. To illustrate the variation in the simple relationships between sonic velocity of the different tools (and levels) and dry timber MoE, a series of point-plots along with linear relationships were produced.

A range of variables for each tree, log and board were also measured, i.e. diameter at breast height (DBH), breast-height outer-wood density, small-end diameter (SED), branch index (BIX), taper, green density, dry density and volume. These variables were used along with sonic measurements in standard analysis of variance models in correlations to MoE of the dry timber.

true MoE ~ sonic velocity + var1 + var2 ... + error

A simple manual backwards elimination procedure, that discarded the least significant variable, was applied until only significant variables were left ($P<0.05$). The best model for each acoustic tool was then ranked according to their r-squared (correlation) to dry timber MoE. The r-squared values of the extended models were also compared and ranked relative to the simple models involving sonic velocity alone.

All figures, statistical analyses and calculations were completed with the functions ‘*lm*’, ‘*anova*’ and ‘plot’ of the statistical software system R - Version 2.4.0, Mac OS X GUI 1.17 (3868) (R Development Core Team 2006).

RESULTS

The analysis of variance for each of the acoustic tools and the dry timber MoE is summarised in Table 2. Only models with significant variables are included, and only the significant variables are presented in this table. The column ‘ANOVA F-test probability’ contains the probability from an F-test that the variable (presented in the ‘Variables’ column) is a significant part of each model.

Table 2. Results from analysis of variance models for each of the tools. Significance levels are: *** = <0.001, ** = <0.01, * = <0.05

Method / Tool	**Variables**	**Level**	**ANOVA F-test probability**	**r-squared**
Hitman	Velocity Density (green)	Timber (green)	8.21E-13 *** 1.57E-06 ***	0.8699
IML hammer	Velocity Density (green)	Timber (green)	3.82E-09 *** 0.00087 ***	0.7451
Hitman	Velocity Density (dry)	Timber (dry)	1.40E-06 *** 3.87E-06 ***	0.7046
Hitman	Velocity	Log	1.19E-08 ***	0.6891
IML hammer	Velocity	Timber (green)	4.85E-08 ***	0.6680

Hitman	Velocity	Timber (green)	8.00E-08 ***	0.6503
IML hammer	Velocity DBH	Tree	4.00E-07 *** 0.02795 *	0.6349
SWAT	Velocity	Log	1.85E-07 ***	0.6214
-	BH Density (basic) DBH	Tree	3.58E-06 *** 0.01234 *	0.5725
TreeTap	Velocity DBH BH Density (basic)	Tree	3.01E-05 *** 0.01332 * 0.01063 *	0.5610
IML hammer	Velocity	Tree	5.91E-07 ***	0.5520
IML hammer	Velocity	Log	1.99E-06 ***	0.5428
-	BH Density (basic)	Tree	1.40E-05 ***	0.4780
-	SilviScan MoE	Tree/Log	2.20E-05 ***	0.4615
Hitman	Velocity	Timber (dry)	0.00024 ***	0.3639
TreeTap	Velocity	Tree	0.00025 ***	0.3557

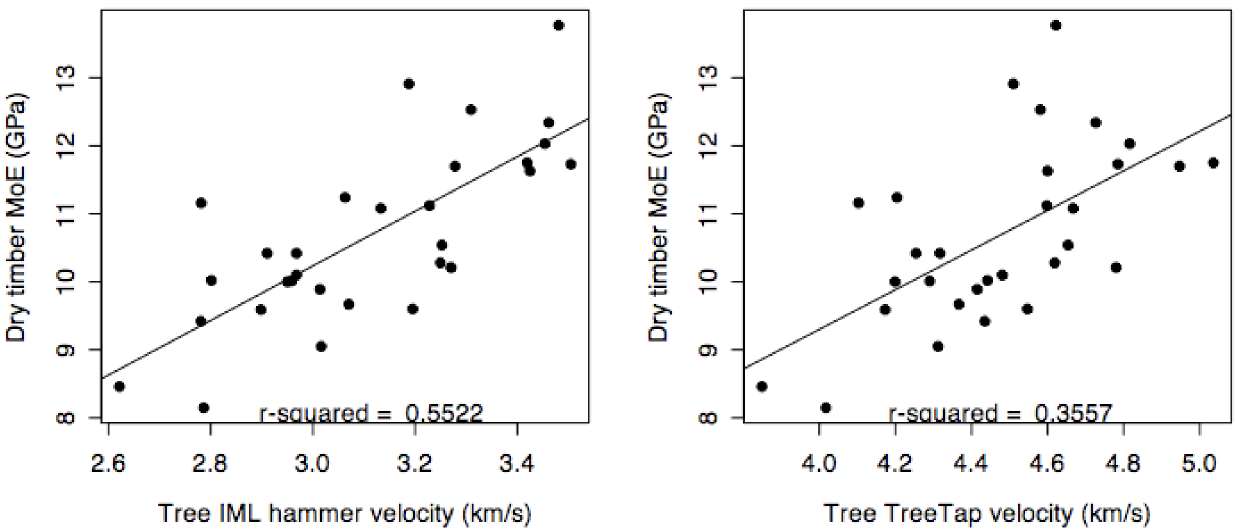

Figure 1. Correlation between dry timber MoE and sonic velocities for IML hammer and Tree-Tap on standing trees.

From Figure 1 it is evident that the TreeTap velocities contain a lot of variation, and the residuals increase for increasing velocity. The IML hammer velocities are also quite variable, but form a more tight cloud around the regression-line.

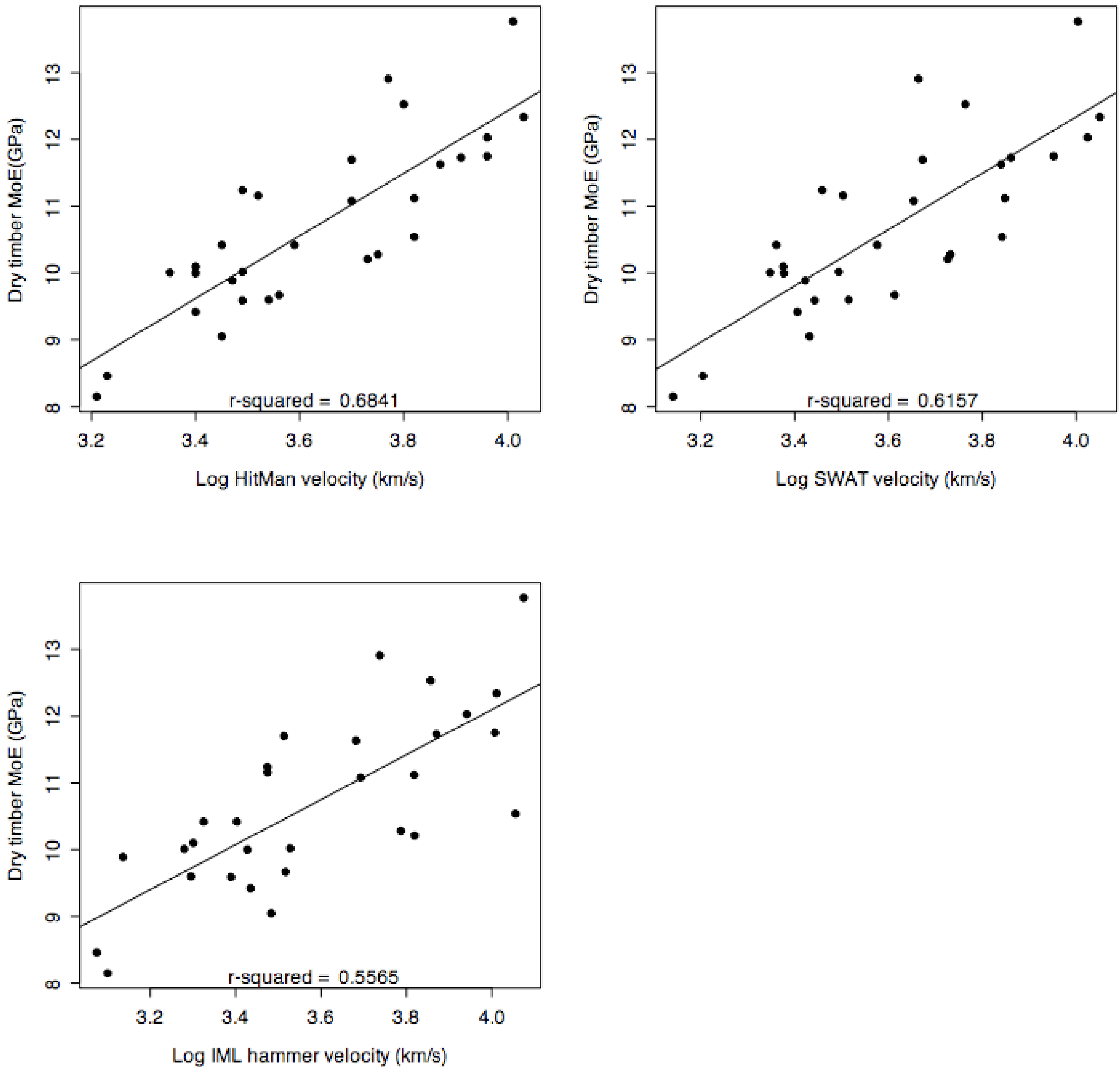

Figure 2. Correlation between dry timber MoE and sonic velocities measured by Hitman, SWAT and IML hammer on freshly cut logs

From Figure 2 it may be seen that the Hitman velocities are forming a tight band around the line, whereas SWAT and IML hammer both form a more cone-like shape. In other words, the residuals around the line increase for increasing velocity for IML hammer and SWAT.

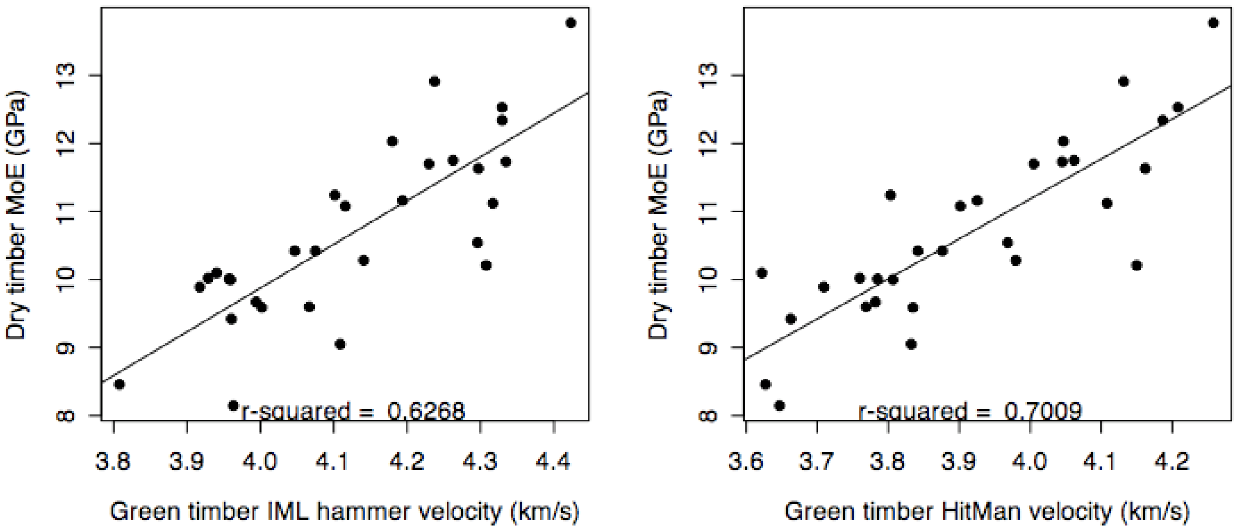

Figure 3. Correlation between dry timber MoE and sonic velocities on the green timber measured by Hitman and IML hammer

From Figure 3 it is evident that the Hitman green timber velocity provides a quite tight relationship with dry timber MoE, with approximately the same standard deviation for all velocities. By comparison, the residuals for the IML hammer velocities show a wider scatter.

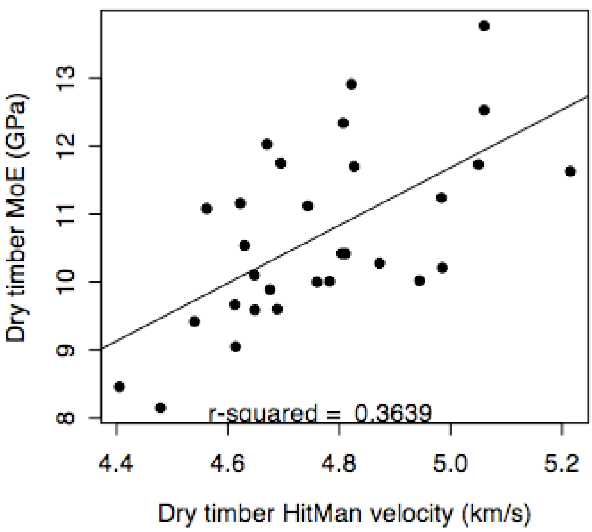

Figure 4. Correlation between dry timber MoE and sonic velocity on the dry timber measured by Hitman

From Figure 4 it is evident that similar to the other measurement levels, the Hitman tool measurements form a band around the regression line. However, contrary to the other measurement levels, the band is quite wide for the dry timber.

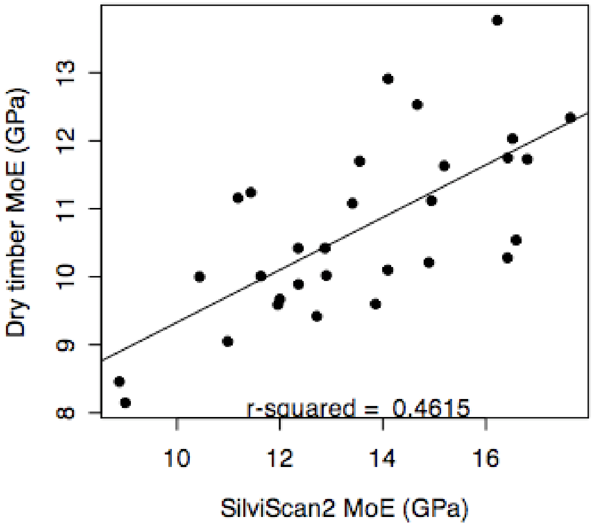

Figure 5. Correlation between dry timber MoE and mean SilviScan2 MoE of two cores at breast height

From Figure 5 it is evident that similar to IML hammer on standing trees, the MoE from SilviScan2 provide a good correlation to dry timber MoE. However, the variance seems to increase with increasing MoE, and therefore the correlation coefficient is reasonably low compared to the IML. One has to note, however, that SilviScan2 provides a direct estimate of MoE, whereas the sonic methods provide the sound velocity alone.

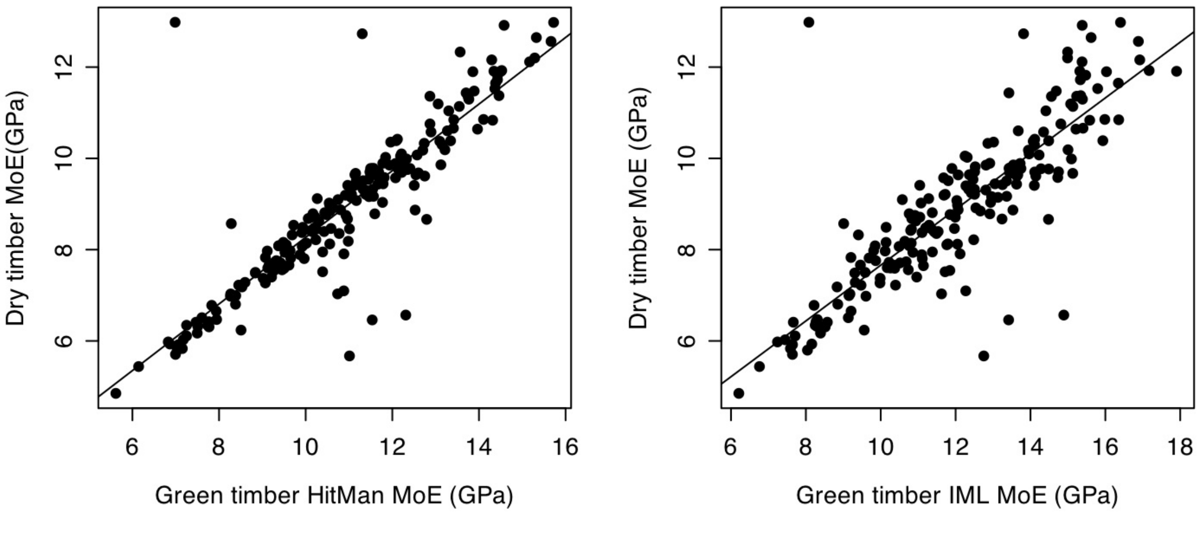

Figure 6. Correlation between green timber MoE and acoustic MoE (green density times velocity squared) for individual boards

Figure 6 shows the correlation between dry timber MoE and acoustic MoE of green boards for all individual boards. From these graphs it is evident that there is a very high correlation between green timber acoustic MoE and dry timber MoE. Hitman provides a much tighter estimate of individual board stiffness than does IML hammer. There are also some outliers.

The visual grades of individual boards when graded according to NZS 3602 are presented in Table 3.

Table 3. Number of boards by grade when visually graded

	No 1 framing	No 2 framing	Box
No of boards	165	43	5

DISCUSSION

From Table 2 it is evident that all the assessed acoustic tools provide measurements of sonic velocity that are highly correlated to the stiffness (MoE) of the end product (dried timber). If density (green as well as basic) is taken into consideration along with sonic velocity the correlation is very high (maximum of 0.8699 for Hitman MoE on green timber). An r-squared of this magnitude is well within the range of experimental error for the standard static MoE test itself. Hence, sonic velocity and green density of the timber in combination provides as accurate a measure of dry timber MoE as does the current standard test.

Of the two tools tested, the IML hammer is the best tool on standing trees, with TreeTap providing a significantly poorer result. The Hitman is consistently better than any of the other tools for logs and timber. The SWAT, which was used on logs only, is better than the IML hammer for logs, however the SWAT tool is no longer in production. All acoustic tools (except for TreeTap) provide a better correlation to end-product stiffness than measurements of basic density of breast-height outer-wood (increment cores). Combining sonic velocities with other variables (e.g. DBH, density) Hitman again stands out as the best. The IML hammer comes in second and SWAT and TreeTap are last.

That TreeTap provides the poorest results may be explained by its relatively short spikes. TreeTap was developed on and for young radiata pine on which the length of the spike is of little significant. However, on Douglas-fir, previous experience with the IML hammer have shown that the use of long spikes is particular beneficial. TreeTap may therefore have been unjustly handicapped by its shorter spikes.

The best supplement to sonic velocity is, not surprisingly, the green density of the wood. This is an obvious and direct consequence of the general physical relationship that states that the stiffness of a homogenous material equals its sonic velocity squared times the green density of the material. All other variables investigated, i.e. tree DBH, tree breast-height outer-wood density, log taper, log SED, and log volume, provided little or no improvement over density and velocity. Two exceptions from this rule were: 1) the model with TreeTap velocity, for which also the breast-height diameter (DBH) and the breast-height outer-wood density were significant ($P<0.05$). And 2) breast-height outer-wood density and DBH in combination also provided good correlation to dry timber stiffness (in accordance with the findings of Whiteside *et al.* (1977) and Shelbourne *et al.* (1973)).

With respect to the level of measurement (i.e. tree, log, timber) the general rule was, not surprisingly, that the further away from the final product the measurement was taken, the poorer the correlation to end-product stiffness. There were two exceptions to this general rule:

1. Hitman velocity on dry timber stands out with the single lowest correlation to dry timber static MoE. This may be explained by the fact the acoustic properties of green and dry wood are markedly different, and that the Hitman was invented for and therefore adapted to logs (freshly cut).
2. The IML surprisingly shows a higher correlation for the tree-level measurements than for log-level measurements. There is no apparent explanation for this oddity, other than 'experimental noise'. This seems a likely explanation, as the two sets of measurements show very much the same correlation (0.5520 and 0.5428, respectively).

The correlation between SilviScan MoE and dry timber MoE was among the poorest in this study. There are no apparent reasons for this rather remarkable result, i.e. previous studies have all found very high correlation between static MoE of small clear samples and the SilviScan derived MoE. Another issue of concern with respect to SilviScan estimated MoE was the variation/difference between two strips from the same tree. The area-weighted mean MoE for two strips from the same tree and disc could differ up to 5 GPa, with an average difference of 0.93 GPa. Based on this it is not recommended to base a whole-tree estimate of stiffness simply on one SilviScan-core only.

The visual grading (Table 3) gave a result that is typical of previous studies in NZ grown Douglas-fir i.e. that visual grading results in significantly more timber residing in lower grades than is indicated by the more objective acoustic or MSG (machine stress grading). With visual grading, some 48 pieces (22%) were designated F2 or poorer, whereas 4-point bending, Hitman MoE, and IML MoE indicate only around 6 pieces (3%) in these grades.

CONCLUSIONS

Measurements of sonic velocities, at all levels from tree to timber, provide a good measure of the stiffness (MoE) of the final product (dried timber) for New Zealand-grown Douglas-fir.
The most accurate estimates of dry timber stiffness are those gathered from green timber, followed by dry timber, logs, and last from standing trees. Hence, with the exception of dry timber, the further away from the end-product, the less accurate the prediction of end-product stiffness (regardless of which acoustic tool is used).

All the acoustic tools used in this study varied in their ability to give accurate measurements of sonic velocities. However, they all provided sonic velocities that were highly correlated to end-product stiffness (MoE). For standing trees the IML hammer was the best tool, and on logs and timber the Hitman gave the best results.

In combination with other variables (e.g. green density) the sonic velocities provide even greater correlation to dry timber stiffness. The sonic velocity provided by the Hitman tool in combination with green density is so well correlated to end-product stiffness that it could provide the standard method for stiffness assessment.

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APPENDIX – TOOLS USED FOR MEASURING SONIC VELOCITY

Table 4. Tools for measuring stiffness and other wood properties

Tool	**Method**	**Producer**
IML Electronic Hammer	Acoustic Time of Flight (standing tree, logs and sawn timber)	IML-Instrumenta Mechanik Labor GmbH Großer Stadtacker 2 D- 69168 Wiesloch Tel.: (+49) 6222/6797-0 Durchwahl: (+49) 6222/6797-15 Fax: (+49) 6222/6797-35 internet: www.iml.de
FCF SWAT	Acoustic Frequency (logs and sawn timber)	Fletcher Challenge Forests
PUNDIT	Acoustic Time of Flight (Small clear samples)	C.N.S. Electronics LTD, London England
Director (Hitman)	Acoustic Frequency (logs and sawn timber)	FibreGen http://www.fibregen.com/hm200.html
TreeTap	Acoustic Time of Flight (standing tree)	University of Canterbury, Canterprise Limited 2007. http://www.cant.canterbury.ac.nz/showcase/trends.shtml#tree
SilviScan*	X-ray diffraction and densitometry	CSIRO Business Solutions. SilviScan. : http://www.ffp.csiro.au/BS-SilviScanAndWoodQuality.asp

* Provides estimates of intrinsic wood properties, including MoE