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NZ Douglas-fir Cooperative

Report No. 35, December 2003

EVALUATION OF NON-DESTRUCTIVE METHODS FOR ASSESSING STIFFNESS OF DOUGLAS-FIR TREES

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Abstract

Identification and selection of superior trees in forest management and breeding programmes provide a means to improve the properties and value of future wood products. Non-destructive stiffness assessment of standing trees enables selection of individuals based on their stiffness. This study evaluated the accuracy and cost of four such methods: 1) IML hammer, 2) 5mm outer-wood density cores, 3) Pilodyn, and 4) SilviScan-2.

Sixty 18-year old Douglas-fir trees were assessed and the results compared with static MoE measurements of small clears centred on the 10th annual ring at breast height. Data was analysed using linear models and descriptive statistics, and the effects and costs of selection were modelled.

The IML Hammer and outer-wood density cores both provided a corrected selection differential of 11-16 percent with respect to stiffness at a cost of NZ$20-30 per tree selected. The Pilodyn was also quite cheap, but failed to give an appropriate measure of stiffness. SilviScan-2, as it was used in this study, provided a more accurate assessment and subsequent higher corrected selection differential of 22 percent at a cost of around NZ$500 per selected tree. Technology developments currently being implemented will reduce this cost over time. Selection for volume growth alone decreased average stiffness by around 10 percent.

Keywords

Timber stiffness, MoE, small clears, IML, SilviScan, sound velocity, density, pilodyn, growth and form.

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Introduction

Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) is a well-established species in international timber markets. Due to its moderate density, straight grain, good stiffness and dimensional stability it is mainly used for structural purposes, e.g. as joists and roof trusses. Increasing the timber stiffness is likely to result in increased market demand and subsequent higher returns.

Knowles *et al.* (2003) found that much of the variation in stiffness of Douglas-fir trees could be attributed to differences between individual trees. Lausberg *et al.* (1995) found a much larger density variation within provenances (between trees) than between provenances. Hence, there are good prospects for increasing timber stiffness through selection.

Selection for stiffness requires a measure of stiffness, or its main determinants, i.e. density and microfibril angle (Zobel and Buijtenen 1989, Evans and Ilic 2001, Knowles *et al.* 2003). However, measuring microfibril angle is cumbersome and costly. Rapid non-destructive screening methods for stiffness are therefore required, as also pointed out by Mamdy *et al.* (1999). A range of such methods for sawn timber and logs exist, but their accuracy, efficiency and associated costs when used on standing trees are not well documented (Wang *et al.* 2000a, 2000b).

The purpose of this study is to evaluate the accuracy, cost and applicability of four non-destructive rapid screening methods for assessing stiffness of standing Douglas-fir trees, with selection for stiffness in view. This is achieved through comparing individual tree measurements from each method to stiffness as measured by static testing of small clears centred on the 10th annual ring at breast height. Based on the data analysis the selection differential by method and the associated costs are modelled.

Methods and Material

Methods

Four methods of assessing stiffness are examined:

1. The IML Hammer[1] is a stress-wave technique. It measures the velocity of a longitudinal sound wave, which is propagated along the grain of the stem, e.g. see Sandoz and Lorin (1994), Betge and Mattheck (1998), Wang *et al.* (2000a, 2000b) and Wagner *et al.* (2003). The sound wave velocity may be used as an indicator of stiffness in itself, or it may be combined with density measurements to give an estimate of dynamic MoE, i.e. $MoE_{dynamic} = \rho\omega^2$, where ρ is the average green density of the stem, and ω is the sound velocity (Lindström *et al.* 2002).

2. 5mm outer-wood density cores are wood samples extracted from the stem using an increment corer. The wood samples are measured for basic density using a gravimetric method.

[1] IML - Instrumenta Mechanik Labor GmbH, Großer Stadtacker 2, D- 69168 Wiesloch, Germany.

3. Pilodyn measures the distance a spring-loaded steel pin travels when driven into the wood with a known force. The Pilodyn was originally developed to test for rot in telephone poles, but it was discovered to give an estimate of density in standing stems, whilst causing minimal damage to living trees. Hence, it has been used extensively in the past, e.g. Smith and Morrell (1986), Hall (1988), Giefing and Lewark (1990), Hylen (1996), Greaves *et al.* (1996), Watt *et al.* (1996).
4. SilviScan-2 is a laboratory-based instrument for measuring a range of wood properties (Evans and Ilic 2001, http://www.ffp.csiro.au/tigr/silviscan/). The stiffness estimate produced by SilviScan is based on the diffractometric and densitometric properties of the wood, calibrated using the sonic resonance technique (Kollmann and Krech 1960, Ilic 2001). Stiffness values using this technique are higher than those obtained by static bench.

Material

The 18-year-old Douglas-fir stand assessed is located in compartment 202, West Tapanui Forest, South Otago (S45º65", E169º22"). The entire compartment covers 14 hectares, of which the investigated stand constitutes 0.9 hectare. The stocking rate was approximately 600 stems per hectare and the site index (mean top height at age 40 years) was estimated to be 33m. All trees originate from seeds from plus-trees identified in the Rankelburn provenance trial (Miller and Knowles 1994, Lausberg *et al.* 1995). The original provenances from which seed trees were selected are: 636 Deadwood, Oregon; 642 Berteleda, California; 659 Stinson Beach, California; 603 Eel River, California; 647 Mad River, California, and 530 Kaingaroa Forest, New Zealand.

180 trees were selected for sampling based on their growth and form. These trees were subject to the following procedures:

1. Each tree was numbered, and assessed for growth by measuring DBH and height. Individual stem volumes were calculated using volume equation '*T136*' (Katz *et al.* 1984).

2. Tree form was assessed using a subjective scoring system, in effect ranking the trees.

3. Two 5mm outer-wood increment cores were extracted at breast height perpendicular to each other. Each core was measured for basic outer-wood density in the laboratory using a gravimetric method.

4. Each tree was assessed for stiffness using the Pilodyn. Two bark windows were prepared at breast height on opposite sides of the tree, and the travelling distance of the Pilodyn pin measured once in each window.
5. Each tree was assessed for stiffness using the IML Hammer. Two spikes were inserted into the stem exactly one metre apart, each at a 45-degree angle relative to the stem surface. The velocity of the sound wave travelling from one spike to the other was measured. The procedure was repeated on the opposite side of each stem.

Based on the IML Hammer measurements the 20 trees with the highest velocities, the 20 trees with the slowest velocities, and 20 trees with average velocities were identified. This 60-tree sub-sample was subject to more intensive measurements.

1. A single 10mm nominal pith-to-bark core was extracted at breast height. The cores were refrigerated and pith-to-bark profiles of density (50 μm radial steps), MFA and MoE (5mm radial steps) obtained by CSIRO Melbourne using SilviScan-2.

2. The trees were felled and a billet cut at breast height. Two standard small clears (20mm × 20mm × 300mm finished sizes) centred on the 10th growth ring were extracted from opposite radii on the billet. The small clears were dried for a month in an equilibrium moisture content room at a constant temperature of 20°C and 60% humidity. Having reached a moisture content of approximately 18%, a mild kiln-drying regime was used over 5 days to reach 12% moisture content (wet bulb temperature of 34°C and a dry bulb temperature of 40°C). Nine small clears were rejected for grain deviation, giving a total of 111 small clears measured for stiffness on a static bench machine in accordance with standards[2].

Data analysis
The measurements are tested to be normally distributed using a Shapiro-Wilks test through PROC UNIVARIATE in SAS 8.2. The cumulated distributions for density, IML and Pilodyn measurements from the 60-tree subset are compared visually to those of the 180-tree set.

The stiffness screening methods are applied to the same trees, and the individual measurements compared against the actual stiffness (MoE) as obtained by the measurements of the small clears. The latter values are for simplicity hereafter simply termed *M*. The comparison involves descriptive statistics, correlation and linear models, i.e.

$$M_{i,j} = \alpha_j + \beta_j x_i + \varepsilon_0$$

Where $M_{i,j}$ is average MoE of the small clear samples for tree *i* using assessment method *j*, x_i is the value for *i*'th tree, α_j and β_j are assessment method specific parameters, and ε_0 is a normally distributed error term with zero mean and some variance. Parameters are estimated using PROC REG of SAS 8.2

Sorting the trees by their stiffness as measured by one particular assessment method (*m*) and selecting the best proportion of the trees gives a set with the $n_{m,I}$ best trees. The average stiffness of these is calculated as

$$\overline{M}_{m,I} = \frac{1}{n_{m,I}} \sum_{i=1}^{n_{m,I}} M_i$$

The increase in average stiffness (ΔM_m) of that selection relative to the average ($\overline{M}$), hereafter called selection differential (Lindgren and Nilsson 1985), is calculated as

$$\Delta M_{m,I} = \overline{M_{m,I}} - \overline{M},$$

where $\overline{M_{m,I}}$ is the selection intensity. The calculation of selection differential at proportions from 5 to 50 percent is iterated for all methods and plotted.

[2] BS 373:1956(1986), Methods of Testing Small Clear Specimens of Timber. The employed Instron static bench machine has a certified Grade 1 Verification Certificate under International Standard ES ISO 7500-1 1999.

Modelling selection differential
The differential of selection by M at proportions from 5 to 50 percent is modelled using a linear model,

$$\Delta M_M(I) = \alpha + \beta I + \varepsilon_0$$

Parameters α and β are estimated using PROC REG of SAS 8.2, assuming the error (ε_0) to be normally distributed with zero mean and some variance. The estimated regression is plotted together with the calculated selection differentials.

Each assessment method provides an estimate of stiffness, but because this introduces a measurement error the selection differential using one particular assessment method is less than if the actual stiffness was the basis for selection. The selection differential relative to the maximum achievable selection differential, i.e. selection by M, is calculated as

$$R_m(I) = \frac{\Delta M_m(I)}{\Delta M_M(I)}$$

Under the assumption that the relative selection differential ($R_m(I)$) is independent of proportion, the relative selection differential for each method (R_m) is estimated as the mean of the relative differentials over proportions from 5 to 50 percent, i.e. as

$$R_m = \overline{R_m(I)}$$

That by definition sets the selection differential for selection by M to 1 (100 percent).

The selection differential for each method is subsequently modelled by multiplying the regression for maximum selection differential with the average relative differential by method, i.e.

$$\Delta M_m(I) = (\alpha + \beta I) R_m$$

Using the linear models of selection differentials, the proportion (I) required in order to obtain a certain selection differential is estimated for each method by inversion, i.e.

$$I_m(\Delta M) = \frac{\Delta M_m}{\beta R_m} - \frac{\alpha}{\beta}$$

Finally, the cost (C_m) for each method (m) of selecting the required proportion (I_m) is calculated based on the costs per tree (P_m) and method in Table 1, i.e.

$$C_m = P_m I_m(\Delta M) = P_m \left(\frac{\Delta M_m}{\beta R_m} - \frac{\alpha}{\beta} \right)$$

	Fieldwork	Labwork	Shipping	Equipment	Total
IML	$ 3			$ 1	**$ 4**
IML - Density	$ 5	$ 5		$ 2	**$ 12**
Density core	$ 2	$ 5		$ 1	**$ 8**
Pilodyn	$ 3			$ 1	**$ 4**
SilviScan-2	$ 2	$ 96	$ 1	$ 4	**$ 103**

Table 1 – Cost P_m (NZ$) per tree for different assessment methods[3]

Other factors that influence the results

Knowles *et al.* (2003) described distinct radial and vertical patterns in wood properties (i.e. density, MFA, MoE) in mature Douglas-fir. Radial variations in properties may influence the assessment methods in this study, as three of them assess the outer-wood only. To ascertain the effects of this, the radial patterns are studied through the data from SilviScan-2. The average wood property with distance from pith is calculated and depicted for three sets of ten trees each being the best, worst and average when ranked for *M*. To reduce the effect of large within-ring variation the pith-to-bark pattern is calculated as the moving average in steps of 2cm.

The sampling strategy does not provide an unbiased sample. Consequences of this are examined through simulated sampling. The simulation assigns stiffness values (*M*) to trees at random from a normal distribution, using the same average and standard deviation as in the data set. The IML velocities and densities are estimated assuming the same linear relationships with *M* as in the data set, including the normally distributed random error terms. From this population of measurements a subset is selected, mimicking the sampling procedure. The effects of selection are calculated as the difference between the effects of selection in the sampled subset as against the whole population. The calculation of bias is iterated 1,000 times and the average bias calculated.

Results

Data analysis

The Shapiro-Wilks test of normality for the entire population of *M* measurements gives a test value of W = 0.9807, which corresponds to a probability of 0.4593. The test can therefore not reject the hypothesis that the *M* measurements are normally distributed. All other measures are significantly different (at the 5 percent level) from being normally distributed. A visual comparison of the cumulative distributions, however, shows that for density and Pilodyn the distributions of the measurements from the 60-tree subset are similar to those of the 180 trees initially selected for sampling.

The data from the 60-tree subset are summarised in Table 2, the correlation matrix is presented in Table 3, and a summary of the linear regressions of *M* in Table 4.

	Unit	N	Mean	Std.	CV	Min.	Max.	Median
M	*GPa*	*60*	*6.47*	*1.35*	*21%*	*3.49*	*9.47*	*6.46*
DBH	cm	60	27.08	3.46	13%	17.30	34.50	26.85
Height	m	60	16.17	1.46	9%	12.10	18.90	16.15
Form	-	60	5.20	1.39	27%	1.00	8.00	5.50
IML	m/s	60	2345	372	16%	1642	2886	2393
IML-Density	$(m/s)^2g/cm^3$	60	203	69	34%	84	315	203
Density	g/cm3	60	357	23	6%	312	407	361
Pilodyn	mm	60	15.15	1.44	10%	11.75	19.00	15.00
SilviScan-2	GPa	60	8.95	1.58	18%	5.37	12.19	9.03

Table 2 – Descriptive statistics for all stiffness assessment methods.

3 - The cost of SilviScan-2 assumes the use of 50mm long outerwood cores, not pith-to-bark cores as used in this study.

	M	IML	IML-Density	Density	Pilodyn	SilviScan-2	DBH	Form	Volume
M	1.00								
IML	0.37	1.00							
IML-Density	0.42	0.98	1.00						
Density	0.44	0.52	0.64	1.00					
Pilodyn	0.00	-0.23	-0.29	-0.42	1.00				
SilviScan-2	0.71	0.54	0.59	0.57	-0.12	1.00			
DBH	-0.33	-0.28	-0.30	-0.14	0.25	-0.26	1.00		
Form	-0.12	0.01	0.02	-0.03	-0.18	-0.15	-0.20	1.00	
Volume	-0.28	-0.20	-0.21	-0.08	0.23	-0.21	0.96	-0.15	1.00

Table 3 – Correlation matrix

Method	α	β	F-test	Pr > F
IML	3.354	0.0013	9.01	0.0039
IML-Density	4.784	0.0083	12.64	0.0008
Density	-2.895	0.0262	14.26	0.0004
Pilodyn	6.463	0.0004	0.00	0.9975
SilviScan-2	1.032	0.0607	60.43	<0.0001

Table 4 – Linear regression models for *M*

Modelling selection differential

The selection differential by method and proportion is plotted in Figure 1. The linear model for selection differential for selection by *M* is also plotted in Figure 1. The regression parameters are α = 43.9932 and β = -0.5922, with an R^2 of 0.98 and a highly significant F-test value of 3,283, both indicating a very good fit. The relative selection differentials are plotted by method in Figure 2. The average selection differentials are given in
Table 5.

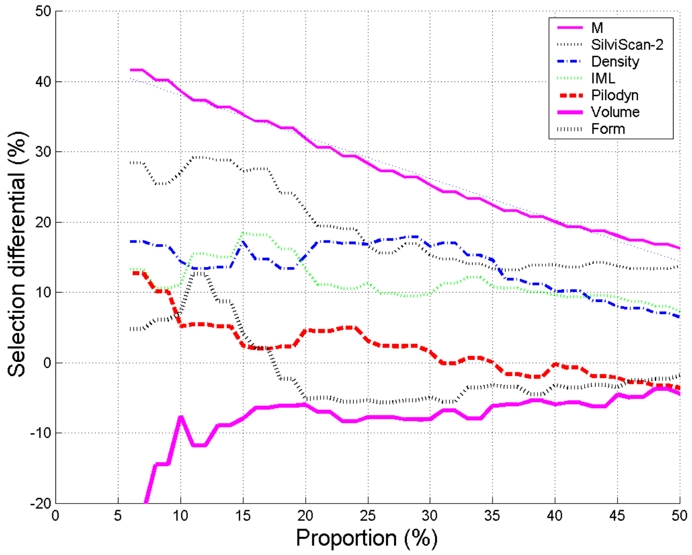

Figure 1 - Selection differential by assessment method and proportion

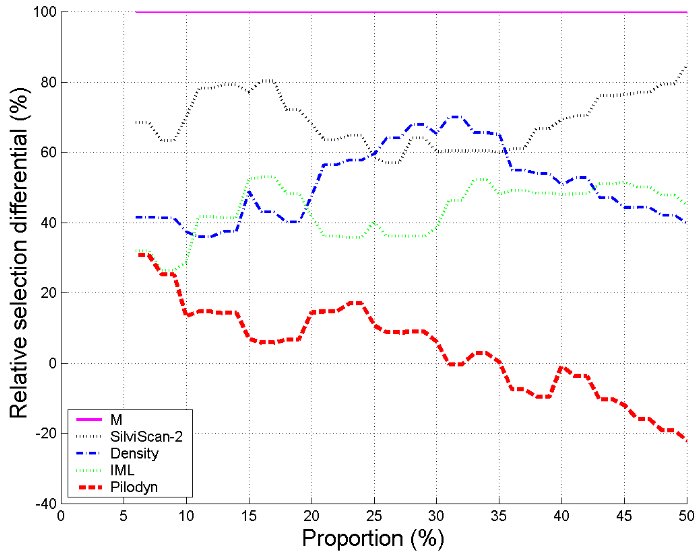

Figure 2 – Selection differential by assessment method relative to maximum possible increase (selection by *M*) as a function of proportion.

Method	Relative increase
True (M)	100%
IML	40%
IML-MoE	45%
Density	51%
Pilodyn	14%
SS2-MoE	68%
DBH	-35%
Form	-3%

Table 5 – Estimated relative selection differential by method.

The modelled proportion required to obtain a certain selection differential is plotted in Figure 3. The abrupt ends of each graph indicate the bounds for selection differential, e.g. using a proportion of 20%, or 1:5, SilviScan-2 allows for a maximum selection differential of about 26 percent of the population mean.

Multiplication of the required proportion functions (Figure 3) by the cost per tree for each assessment method gives the cost-per-tree selected in Figure 4. For instance, a 10 percent selection differential can be achieved through all assessment methods. The cost of SilviScan-2 is around $520 per tree selected, while the cost is around $20, $30 and $50 for the IML Hammer, density core and the combination, respectively.

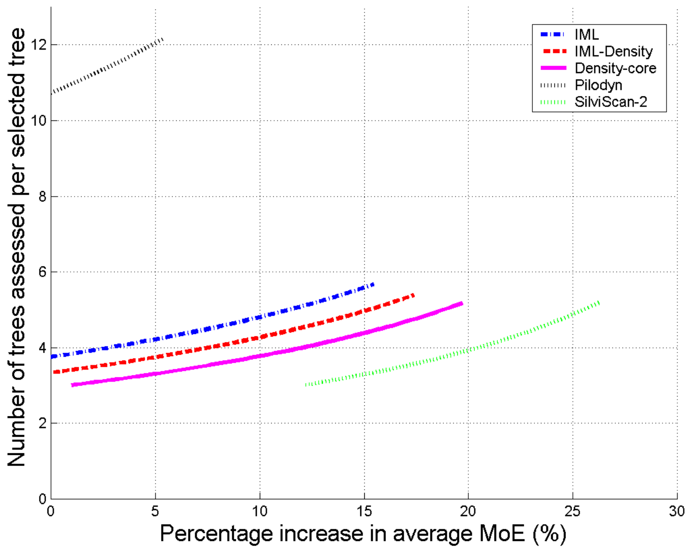

Figure 3 – Number of trees assessed per selected tree required achieve a certain percentage increase in average MoE

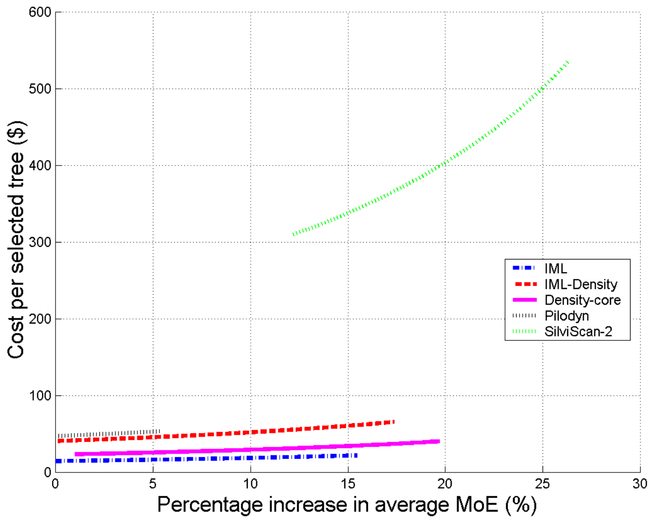

Figure 4 – The cost per selected tree to achieve a certain percentage increase in average MoE

Other factors that influence the results

The pith-to-bark patterns of wood properties at breast height from SilviScan-2 reveal that the density profiles (Figure 5) of the different selections do not differ markedly at 0-4cm from the pith. The MFA profiles (Figure 6) are distinctly different at and around the pith, with the differences becoming even more apparent with distance from the pith. The MoE profiles (Figure 7) show a combination of the density and MFA profiles, i.e. an intermediate pattern, with little difference around the pith and increasing difference with distance from the pith.

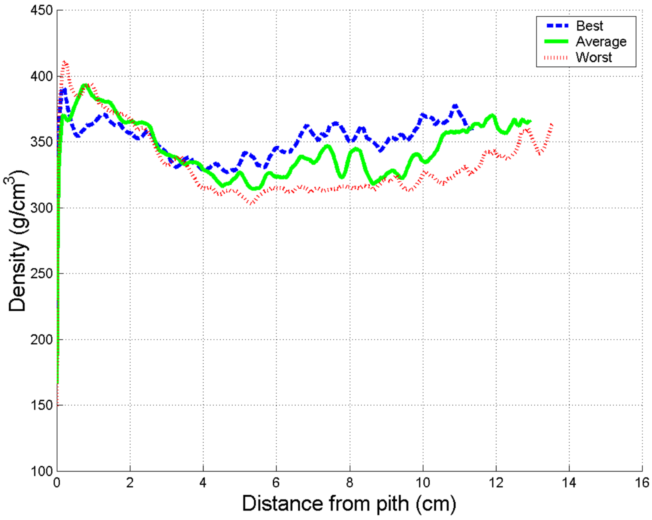

Figure 5 – 2cm moving average pith-to-bark variation in density for different selections

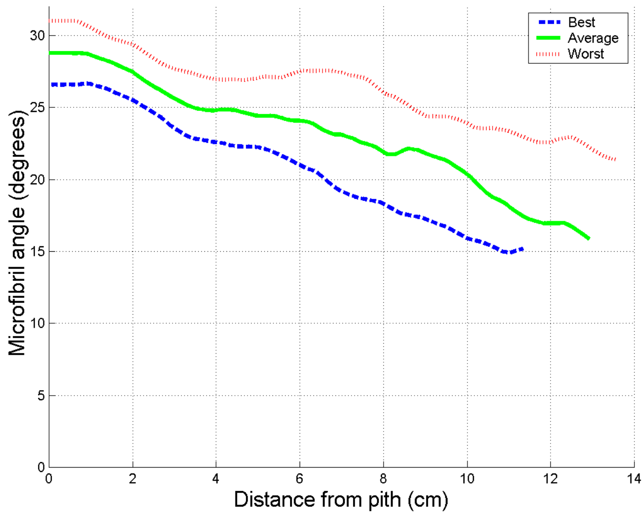

Figure 6 – 2cm moving average pith-to-bark variation in microfibril angle for different selections

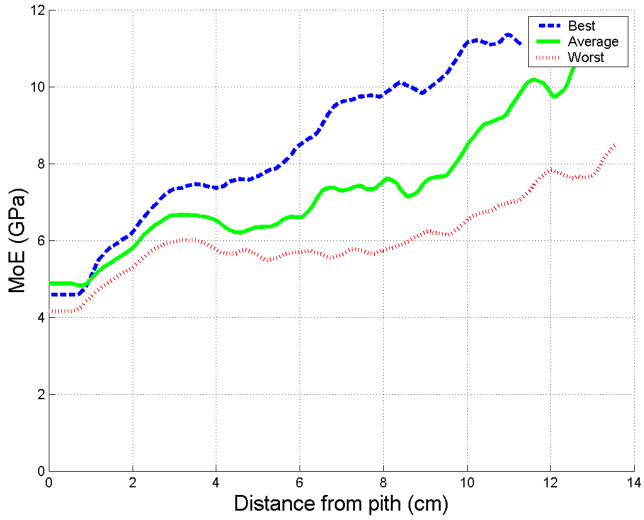

Figure 7 – 2cm moving average pith-to-bark variation in stiffness (MoE) for different selections

The sampling simulation reveals that the estimated and modelled selection differentials generally are over-predicted. The over-prediction estimate is fairly robust and constant, though slightly increasing for decreasing proportions. For proportions from 5 to 50 percent the effects of selection are on average over-estimated by approximately 4 percentage points. A predicted improvement of 15-20 percent is therefore more likely to be of the order of 11-16 percent after allowing for this bias.

Discussion

Sampling bias

The 60-tree sub-sample was selected based upon the IML Hammer measurements of 180 trees. Clearly, selecting the twenty stiffest trees (33 percent) or less, as measured by their IML velocity, and calculating the average *M* gives an unbiased estimate for this particular selection, i.e. the twenty trees with the highest IML velocities are present in the data set. For all other assessment methods and for proportions higher than 33 percent, this is not the case.

Because extreme IML velocity trees are over-represented and because there is a correlation between IML velocity and stiffness, there is an under-representation of average stiffness trees. Some of these average stiffness trees will measure comparably higher for density than those sampled. Hence, the trees in a selection for density from the whole population will on average be less stiff (contain more average stiffness trees), than if the same proportion is selected from the sample in this study. The magnitude of this over-estimation is found to be in the order of 4 percentage points, independent of proportion and assessment method.

Another effect of the sampling procedure is skewed distributions, resulting in biased correlation coefficients. However, because the distribution of measurement values for the 60-tree sub-sample is nearly identical to the 180-tree sample (despite not being normal), it can be concluded that the sampling procedure did not interfere markedly with the distribution characteristics for other than the IML Hammer measurements. Hence, the interpretation of the values in the correlation-matrix (Table 3) is reasonably strait forward, except for the IML Hammer where correlations might be over-estimated.

The IML Hammer, density and Pilodyn all measure the properties of the outer-wood. From the analysis of radial variation in wood properties it is evident that at 18yrs of age, such outer-wood properties are adequately differentiated, and, in accordance with Knowles *et al.* (2003) most probably reflect whole-tree properties. Furthermore, it is also evident that there is little differentiation in density inside 4cm from the pith, while MFA and MOE are more differentiated throughout. 12-20 years of age appears to be a suitable time for sampling the outerwood of Douglas-fir for MoE.

Modelling assumptions

From Figure 1 it is evident that the linear regression of maximum selection differential (selection for *M*) at proportions from 5 to 50 percent fits well. However, the assumption that the other assessment methods provide a smaller and constant selection differential relative to this (independent of proportion) is more conspicuous (Figure 2). Obviously, the selection differential is quite varying in proportion and method. For example, selection by SilviScan-2 varies from 60 to 80 percent of the maximum, and the effect of density seems to decrease with proportion.

These discrepancies may in part be explained by the small sample, causing the individual estimates to vary considerably, especially for smaller proportions. The problems of the linear relative increase assumption must, however, be weighed against the simplification it provides. Without this simplification it would be necessary to model the effects of selection individually for each assessment method. In turn this requires further assumptions about the effects of each method, which the data might not sustain. The relatively simple modelling approach therefore seems a somewhat crude but necessary simplification. The conclusive power of the analyses must, however, be evaluated upon this basis.

Comparison of methods

MoE measured by SilviScan-2 stand out as well correlated to the small clears MoE. The correlation is almost twice that of the other assessment methods. This is also reflected in Figure 1, Figure 3, Table 2 and
Table **5**, where SilviScan-2 clearly provides the most accurate non-destructive assessment and the highest relative selection differential at 68 percent of the maximum. SilviScan-2, as it was used in this study, generated considerable more information than the other methods, particularly with respect to radial variation and annual ring properties. The costs per tree could be reduced significantly by optimising the analysis and technology for applications of this sort.

The IML Hammer, the density core and their combination provide almost the same intermediate relative selection differential (40-51 percent) and correlation coefficients of 0.37-0.44. Comparing the IML Hammer with outer-wood density measurements, the IML Hammer provides a slightly poorer selection differential, however it does provide the advantage of immediacy, while the density assessment is slightly more expensive. However, in light of the data, it is obvious that even small changes may result in both of the above conclusions to shift in favour of one method or the other. An improvement of the IML Hammer measurements may be achieved through additional measurements on each tree, or by combining radial, transverse and longitudinal measurements (e.g. Wang *et al.* 2000a, 2000b). Future studies are required to address this issue.

The Pilodyn measurements correlate poorly to the small clears MoE, and stand out as the least useful method. This result is somewhat surprising, as the Pilodyn have been used extensively in the past to assess standing trees for density, which is a major component of stiffness. A reason for the lack of success may be that only two measurements were taken per tree. Taking several measurements in each window, and measuring more windows on each tree should reduce the between-tree variation, and thus provide a more accurate measure of stiffness.

DBH, volume and form correlates negatively to stiffness, with selection differentials of about minus 10 percent. This is in full accordance with the observation of Harris and Orman (1958) and Zobel and van Buijtenen (1989) who concluded that fast growing trees generally have poorer wood quality.

Taking the cost into account (Figure 4) the IML Hammer and density both stand out as the cheapest methods. However, this comes at the expense of not being able to achieve more than an 11-16 percent selection differential, whereas SilviScan-2 potentially provides for a 22-26 percent selection differential. This potential, however, comes at a considerable cost, despite taking into account that assessment of outer-wood cores alone is probably sufficient to identify individuals with superior stiffness (Figure 5 - Figure 7). Furthermore, current technological development indicates that the cost of SilviScan-2 for this sort of application may decrease significantly in the future.

Seed stand selection traditionally use proportions in the order of 20 to 50 percent (i.e. 1:5 to 1:2). For this purpose, the most cost-effective tools are the density cores and the IML Hammer, with the latter as the fastest and simplest method. Similar conclusions may be drawn when higher proportions are required, e.g. selection of individuals as ‘plus’ trees, for addition of grafted scion material to seed orchards. However, because SilviScan-2 provides more accurate and detailed information it may be more appropriate to use it on selected individuals, despite the cost. For instance, exploring general patterns of within-tree and between-tree variation in wood properties. SilviScan-2 may also have a role in more precisely defining the MoE of trees previously screened using the IML Hammer.

Conclusion

Outer-wood density cores and the IML Hammer both provided cheap and reasonably accurate methods for stiffness assessment of individual standing Douglas-fir trees. They provided a corrected selection differential of 11-16 percent, at a cost of NZ$20-30 per tree selected. SilviScan-2 provided a more accurate assessment and subsequent higher selection differential (up to 22 percent). The Pilodyn and form assessments were cheap in comparison, but provided no significant selection differential. Selection for growth (DBH) has the potential to reduce the stiffness of the selected trees by around 10 percent.

Acknowledgements

The authors wish to thank the following persons and organisations for their contributions to this study. John Parish and Phil Delamare of Ernslaw One Ltd, Tapanui, provided the stand for sampling, and recovered the billets. Hamish McConnon, School of Forestry, Canterbury University, assisted with field procedures. John Lee, Forest Research, Rotorua, carried out the IML Hammer assessment, and Steve Riley, Forest Research, dried the small clears. Doug Gaunt and Barry Penellum, Forest Research, assessed the small clears for static MoE. Sharee Harper, CSIRO, Melbourne, provided the SilviScan assessments. Tony Shelbourne is thanked for comments on earlier versions of this paper. Funding was jointly provided by FRST Contract No CO4X0010, the NZ Douglas-fir Research Cooperative, and CSIRO, Melbourne.

References

BETGE, K. AND MATTHECK, C. **1998**. Instruments for Detection and Evaluation of Decay and Wood Quality in Standing Trees. *Proceedings of the 11th International Symposium on Non-destructive Testing of Wood*, pp105-115.

EVANS, R. AND ILIC, J. **2001**. Rapid Prediction of Wood Stiffness from Microfibril Angle and Density. *Forest Products Journal* **51**(3):53-57.

GIEFING, D. AND LEWARK, S. **1990**. Rohdichteuntersuchungen von Buchen in Berliner und nordpolnischen Bestanden. *Forstarchiv* **61**(1):6-10

GREAVES, B.L., BORRALHO, N.M.G., RAYMOND, C.A. AND FARRINGTON, A. **1996**. Use of Pilodyn for the indirect selection of basic density in Eucalyptus nitens. *Canadian Journal of Forest Research* **26**:1643-1650.

HALL, J. **1988**. Using the Pilodyn tester in selecting plus trees. *Northern Journal of Applied Forestry* **5**(3):170-171.

HARRIS, J.M. AND ORMAN, H.R. **1958**. The mechanical properties of NZ grown Douglas fir. *Technical paper* No.24. Forest Research Institute, New Zealand Forest Service. Wellington, New Zealand.

HYLEN, G. **1996**. Variation in basic density and its relationship to diameter and pilodyn penetration in provenances of Norway spruce (*Picea abies*). *Meddelelser fra Skogforsk* **47(**10).

ILIC, J. **2001**. Relationship among the dynamic and static elastic properties of air-dry *Eucalyptus delegatensis* R. Baker. *Hols and Rog- und Werkstoff* **59**:169-175.

KATZ, A., DUNNINGHAM, A.G. AND GORDON, A. **1984**. *A compatible volume and taper equation for New Zealand Pinus Radiata D. Don grown under the direct sawlog regime*. New Zealand Forest Service, Forest Research Institute Bulletin No. 67.

KNOWLES, L., HANSEN, L., DOWNES, G., KIMBERLEY, M., GAUNT, D., LEE, J. AND ROPER, J. **2003**. *Modelling within-tree and between-tree variation in Douglas-fir wood and lumber properties*. Paper presented at the IUFRO All Division 5 Conference, Rotorua, NZ, 11-15 March 2003.

KOLLMAN, F. AND KRECH, H. **1960**. Dynamische Messungen der elastischen Holzeigenschafter und der Dampfung (in German). *Holz als Roh- und Werkstoff* **18**:41-54.

LAUSBERG, M.J.F., COWN, D.J., MCCONCHIE, D.L. AND SKIPWITH, J.H. **1995**. Variation in some wood properties of Pseudotsuga menziesii provenances grown in New Zealand. New Zealand Journal of Forestry Science 25(2):133-146.

LINDGREN, D. AND NILSSON, J-E. **1984**. *Calculations concerning selection intensity*. Report 5. Swedish Agricultural University, Department of Forest Genetics and Plant Physiology, Umea.

LINDSTRÖM, H., HARRIS, P. AND NAKADA, R. **2002**. Methods for measuring stiffness of young trees. *Holz als Roh- und Werkstoff* **60**(3):165-174.

MAMDY, C., ROZENBERG, P., FRANC, A., LAUNAY, J., SCHERMANN, N. AND BASTIEN, J.C. 1999. Genetic control of stiffness of standing Douglas Fir; from the standing stem to the standardised wood sample, relationships between modulus of elasticity and wood density parameters. Part 1. *Annals of Forest Science* **56**:133-143.

MILLER, J.T. AND KNOWLES, F.B. **1994**. *Introduced forest trees in New Zealand*. Forest Research Bulletin 124. New Zealand Forest Research Institute Ltd. New Zealand.

SANDOZ, J.L. AND LORIN, P. **1994**. Standing tree quality assessments using ultrasound. *Proceedings of the First European Symposium on Nondestructive Evaluation of Wood*. pp496-502.

SMITH, S.M. AND MORRELL, J.J. **1986**. Correcting Pilodyn measurements of Douglas-fir for different moisture levels. *Forest Products Journal* **36**(1):45-46.

WATT, M.S., GARNETT, B.T. AND WALKER, J.C.F. **1996**. The use of the Pilodyn for assessing outerwood density in New Zealand radiata pine. *Forest Products Journal* **46**(11/12):101-105.

WAGNER, F.G., GORMAN, T.M. AND WU, S-Y. **2003**. Assessement of intensive stress-wave scanning of Douglas-fir trees for predicting lumber MoE. *Forest Products Journal* **53**(3):36-39.

WANG, X., ROSS, R.J., MCCLELLAN, M., BARBOUR, R.J., ERICKSON, J.R., FORSMAN, J.W. AND MCGINNIS, G.D. **2000a**. Strength and stiffness assessment of standing trees using a non-destructive stress wave technique. *Forest Products Laboratory Report* 585. United States Department of Agriculture, Forest Service.

WANG, X., ROSS, R.J., ERICKSON, J.R., FORSMAN, J.W., FORSMAN, MCGINNIS, G.D. AND PELLERIN, R.F. **2000b**. Nondestructive evaluation of standing trees with stress wave methods. *Proceedings of the 12th International Symposion on Nondestructive Testing of Wood. University of Western Hungary, Sopron, 13-15 september 2000.* University of Western Hungary, Sopron, Hungary.

ZOBEL, B.J. AND BUIJTENEN, J.P. **1989**. *Wood variation: its cause and control.* 1st edn. Springer Verlag, Berlin, Germany. ISBN 038750298X.