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 for their stiffness, and so the accuracy and cost of four methods for assessing stiffness were evaluated: (1) IML hammer, (2) 5-mm outerwood density cores, (3) Pilodyn penetrometer, and (4) SilviScan-2®.

Sixty 18-year-old *Pseudotsuga menziesii* (Mirb.) Franco (Douglas fir) trees were assessed for stiffness and the results compared with static modulus of elasticity (MoE) measurements of small clears centred on the tenth annual ring at breast height. Data were analysed using linear models and descriptive statistics, and the effects and costs of selection were modelled.

The IML Hammer and outerwood density cores both gave corrected selection differentials of 11–16% 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 informative measure of stiffness. SilviScan-2® provided a more accurate assessment and subsequent higher estimated selection differential of 22% at a cost of around NZ$500 per selected tree. Technology developments currently being implemented may reduce this cost over time. Selection for stem volume growth alone decreased average stiffness by around 10%.

Keywords: timber stiffness; modulus of elasticity; small clears; SilviScan®; sound velocity; density; Pilodyn; growth and form.

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INTRODUCTION

Douglas fir is a well-established species in international timber markets. Due to its moderate density, straight grain, good stiffness, and dimensional stability it is used mainly 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) reported 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 one or more of its main determinants, i.e., density and/or microfibril angle (Zobel & Buijtenen 1989; Evans & Ilic 2001; Knowles *et al.* 2003). However, measuring microfibril angle is cumbersome and costly (Butterfield 1997). Rapid non-destructive screening methods for stiffness are therefore required, as pointed out by Mamdy *et al.* (1999). There is a range of such methods for sawn timber and logs (Wang, Ross, McClellan, Barbour, Erickson, Forsman & McGinnis 2000; Wang, Ross, Erickson, Forsman, McGinnis & Pellerin 2000), but their accuracy, efficiency, and associated costs when used on standing trees are not well documented.

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

METHODS AND MATERIAL

Methods

Four methods of assessing stiffness were examined:

(1) The IML Hammer* is a stress-wave technique. It measures the velocity of a longitudinal sound wave, which is propagated along the grain of the stem (*see*, for example, Sandoz & Lorin 1994; Betge & Mattheck 1998; Wang, Ross, McClellan, Barbour, Erickson, Forsman & McGinnis 2000; Wang, Ross, Erickson, Forsman, McGinnis & Pellerin 2000; 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). In this study this is termed IML-density.

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* IML = Instrumenta Mechanik Labor GmbH, Großer Stadtacker 2, D-69168 Wiesloch, Germany.

(2) Five-millimetre outerwood 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.

(3) The Pilodyn penetrometer 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 found useful for obtaining an estimate of density in standing stems, whilst causing minimal damage to living trees. It has been used extensively for this in the past (e.g., Smith & Morrell 1986; Hall 1988; Giefing & 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 (CSIRO 2004). The stiffness estimate produced by SilviScan-2® is based on the diffractometric and densitometric properties of the wood, calibrated using the sonic resonance technique (Kollmann & Krech 1960; Ilic 2001). Stiffness values using this technique are higher than those obtained by static bending.

Material

The 18-year-old Douglas-fir stand assessed was located in Cpt 202, West Tapanui Forest, West Otago (lat.45º65´S, long.169º22´E). The entire compartment covers 14 ha, and the study area constituted 0.9 ha of this. The stocking rate was approximately 600 stems/ha and the site index (mean top height at age 40 years) was estimated to be 33 m. All trees originated from seeds from plus-trees identified in a provenance trial at Rankleburn (Miller & Knowles 1994; Lausberg *et al.* 1995). The original provenances from which seed was collected were: 636 Florence, Oregon; 641 Four Mile, Oregon; 642 Berteleda, California; 647 Mad River, California; 654 Fort Bragg, California; 659 Stinson Beach,California.

One hundred and eighty trees were selected for sampling based on their superior growth and form. These trees were subjected to the following procedures:

(1) Each tree was numbered, and growth was assessed by measuring diameter at breast height 1.4 m (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. Major emphasis was placed on selecting where possible for straight stems and avoiding steep-angled branches.

(3) Two 5-mm outerwood increment cores were extracted at breast height, perpendicular to each other. Each core was measured for green and basic outerwood 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 penetration distance of the Pilodyn pin was measured once in each window.

(5) Each tree was assessed for stiffness using the IML Hammer. Two spikes were inserted into the stem exactly 1 m apart, each at a 45° 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 subjected to more intensive measurements.

(1) A single 10-mm 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), microfibril angle (MFA), and MoE (5-mm radial steps) were obtained by CSIRO Melbourne using SilviScan-2®.

(2) The trees were felled and a billet was cut at breast height. Two standard small clears (20 × 20 × 300 mm finished sizes), centred on the tenth 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 bending machine in accordance with Standards*. For 51 trees, stiffness was calculated as the mean of two small clears. The other nine trees were represented by just one small clear.

Data Analysis

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

The stiffness screening methods were applied to the same set of 60 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 involved descriptive statistics, correlations, and linear models. Parameters were estimated using PROC REG of SAS 8.2

Assessing the trees by their stiffness as measured by one particular assessment method (m) and selecting the best proportion (I) of the trees gave a set with the $n_{m,I}$ top-ranked trees. The average stiffness of these was calculated as

$$\bar{M}_m(I) = \frac{1}{n_m(I)} \sum_{i=1}^{n_m(I)} M_i$$

The increase in average stiffness ($\Delta M_m(I)$) of that selection relative to the average ($\bar{M}$) of the population, hereafter called selection differential (Lindgren & Nilsson 1985), was calculated as

$$\Delta M_m(I) = \overline{M_m(I)} - \bar{M}$$

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

The calculation of selection differential at proportions from 5% to 50% was repeated for all methods and plotted against proportion.

Modelling Selection Differential

The differential of selection by M at proportions from 5% to 50% was modelled using a linear model,

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

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

Each assessment method provided an estimate of stiffness, but because the estimates also included a measurement error the selection differential was less than if the actual stiffness (as measured by the small clears) was the basis for selection. The selection differential relative to the maximum achievable selection differential, i.e., selection by M, was calculated as

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

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

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

That, by implication, set the differential for selection by M to 1 (100%).

The selection differential for each method was subsequently modelled by multiplying the regression for maximum selection differential by 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 was 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) to achieve a given selection differential was calculated based on the costs per tree (P_m) and method outlined in Table 1.

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

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 have

TABLE 1–Cost (NZ$) per tree ($P_m$) for different assessment methods*

	Field work	Lab work	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

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

influenced the assessment methods in this study, as three of them assess the outerwood only. To ascertain the effects of this, the radial patterns were studied through the data from SilviScan-2®. The average wood property, with distance from pith, was calculated and depicted for three sets of 10 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 was calculated as the moving average in 2-cm steps.

The sampling strategy did not provide an unbiased sample. Consequences of this were examined through simulated sampling. The simulation assigned 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 were 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 was selected, mimicking the sampling procedure. The effects of selection were calculated as the difference between the effects of selection in the sampled subset and the whole population. The calculation of bias was iterated 1000 times and the average bias calculated.

RESULTS

Data Analysis

The Shapiro-Wilk test of normality for the entire population of *M* measurements gave a test value of W = 0.98, which corresponds to a probability of 0.46. The test cannot therefore reject the hypothesis that the *M* measurements were normally distributed. All other measures were significantly different (at the 5% level) from a normal distribution. A visual comparison of the cumulative distributions, however, showed that for density and Pilodyn the distributions of the measurements from the 60-tree subset were similar to those of the 180 trees initially selected for sampling.

The data for 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* is given in Table 4.

Modelling Selection Differential

The estimated selection differentials by method and proportion are plotted in Fig. 1, and the linear regression model for differential for selection by *M* is also presented there. The regression parameters were $\alpha = 43.99$ and $\beta = -0.59$, with an R^2 of 0.98 and a highly

TABLE 2–Descriptive statistics for all stiffness assessment methods for the 60-tree subsample.

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

* Modulus of elasticity

TABLE 3–Correlation matrix

	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 4–Linear regression models for *M*

Method	α	$\sigma(\alpha)$	β	$\sigma(\beta)$	F-test	Pr > F
IML	3.354	1.050	0.0013	0.0004	9.01	0.0039
IML-Density	4.784	0.500	0.0083	0.0023	12.64	0.0008
Density	–2.895	2.491	0.0262	0.0070	14.26	0.0004
Pilodyn	6.463	1.863	0.0004	0.1224	0.00	0.9975
SilviScan-2®	1.032	0.710	0.0607	0.0781	60.43	<0.0001

significant F-test value, both indicating a very good fit. The relative selection differentials are plotted by method in Fig. 2, and the average selection differentials are given in Table 5.

The modelled proportion required to obtain a certain selection differential is plotted in Fig. 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% of the population mean.

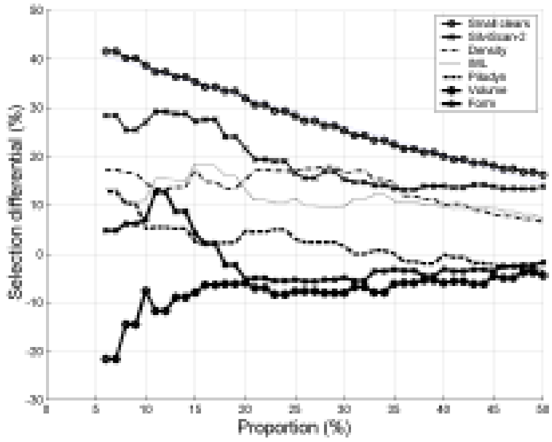

FIG. 1–Selection differential by assessment method and proportion

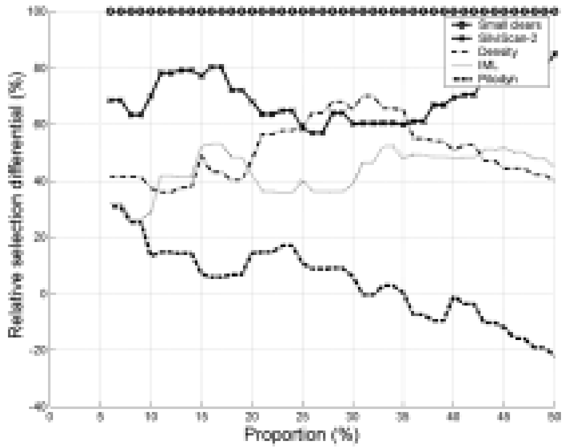

FIG. 2–Selection differential by assessment method relative to maximum possible increase (selection by *M*) as a function of proportion

TABLE 5–Estimated relative selection differential by method.

Method	Relative increase (%)
M	100
IML	40
IML-Density	45
Density	51
Pilodyn	14
SilviScan-2®	68
Dbh	–35
Form	–3

Multiplication of the required proportion functions (Fig. 3) by the cost per tree for each assessment method gives the cost per tree selected (Fig. 4). For instance, a 10% selection differential could 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.

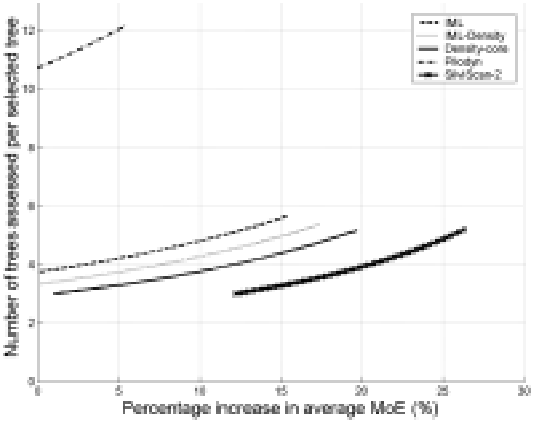

FIG. 3–Number of trees assessed per selected tree required to achieve a certain percentage increase in average modulus of elasticity

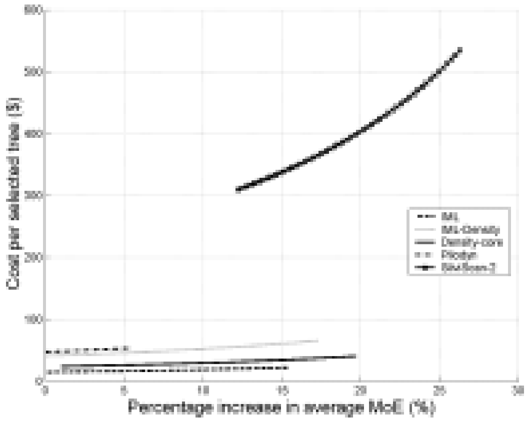

FIG. 4–The cost per selected tree to achieve a certain percentage increase in average modulus of elasticity

Other Factors that Influence the Results

The pith-to-bark patterns from SilviScan-2® of wood properties at breast height revealed that the density profiles (Fig. 5) of the different selections did not differ markedly at 0–4 cm from the pith. The MFA profiles (Fig. 6) were distinctly different at and around the pith, with the differences becoming even more apparent with distance from the pith. The MoE profiles (Fig. 7) showed 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.

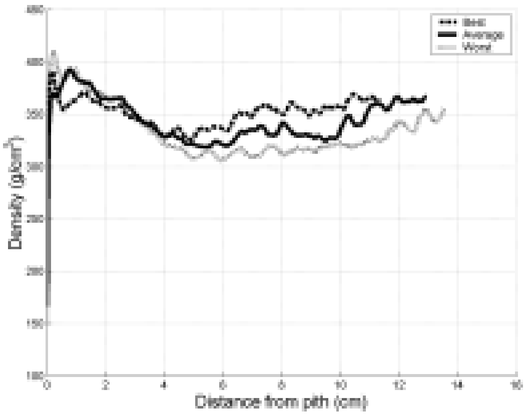

FIG. 5–Pith-to-bark variation in density for different selections (2-cm moving averages)

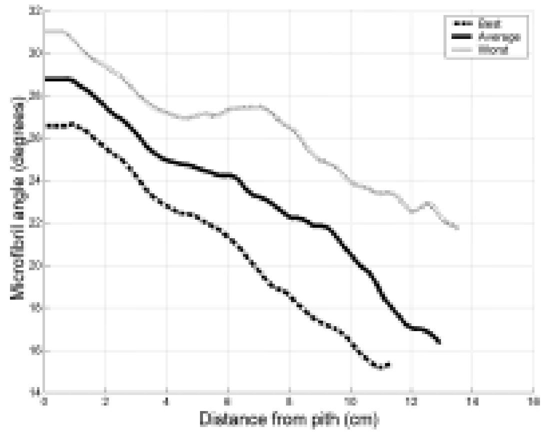

FIG. 6–Pith-to-bark variation in microfibril angle for different selections (2-cm moving averages)

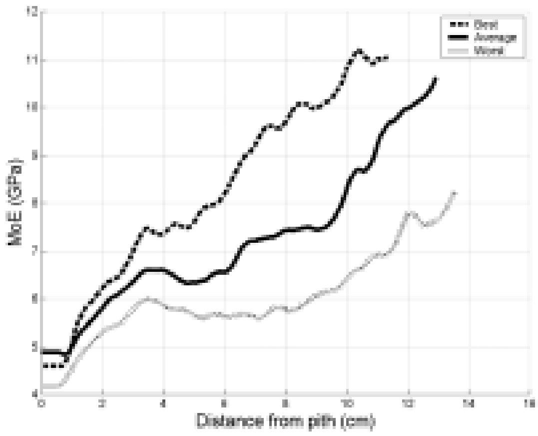

FIG. 7–Pith-to-bark variation in stiffness (MoE) for different selections (2-cm moving averages)

The sampling simulation revealed that the estimated (and modelled) selection differentials generally were over-predicted. The over-prediction was fairly constant, though slightly increasing for decreasing proportions. For proportions from 5% to 50% the predicted effects of selection were on average over-estimated by approximately four percentage points. A predicted improvement of 15–20% is therefore more likely to be of the order of 11–16% 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 20 stiffest trees (33%) or less, as measured by their IML velocity, and calculating the average *M* gave an unbiased estimate for this particular selection, i.e., the 20 trees with the highest IML velocities are present in the data set. For all other assessment methods and for selecting over 33%, this was not so.

Because trees of extreme (low and high) IML velocity were over-represented in the sample, and because the correlation between IML velocity and stiffness is not 100%, there was an under-representation of average-stiffness trees in the sample. Hence, because some of these "missing" average-stiffness trees would have high density, a selection for density from the whole population would on average be less stiff (contain more average-stiffness trees) than the same procedure applied to the sample in this study. The calculated magnitude of this over-estimation was of the order of four percentage points, independent of proportion and assessment method.

Another effect of the sampling procedure may be non-normal distributions, resulting in biased correlation coefficients. However, because the distribution of measurement values for the 60-tree sub-sample was nearly identical to that of 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) was reasonably straightforward, except for the IML Hammer where correlations might be over-estimated.

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

Modelling Assumptions

Logically, the selection differential is hyperbolic in selection intensity. Despite this, it is evident (Fig. 1) that the linear form fits well for proportions from 5% to 50%. The assumption that the other assessment methods provide a smaller and constant selection differential relative to this (independent of proportion) is more conspicuous (Fig. 2). Obviously, the selection differential is quite varying in proportion and method. For example, selection by SilviScan-2® varied from 60% to 80% of the maximum, and the effect of density seemed to decrease with proportion. Similarly, the Pilodyn results increased for decreasing proportion.

These discrepancies may be explained in part 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 justify. The relatively simple modelling approach therefore seems a somewhat crude but necessary simplification. The conclusive power of the analyses must, however, be evaluated on this basis.

Comparison of Methods

Modulus of elasticity measured by SilviScan-2® stood out as well correlated with the small clears MoE. The correlation was almost twice that of the other assessment methods (Table 2). This is also reflected in Fig. 1, Fig. 3, Table 2, and Table 5, where SilviScan-2® clearly provided the most accurate non-destructive assessment and the highest relative selection differential which averaged 68% of the maximum. SilviScan-2®, as it was used in this study, generated considerably 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 outerwood density core, and their combination provided almost the same intermediate relative selection differential (40–51%) and correlation coefficients of 0.37–0.44. In comparison with outerwood density measurements, the IML Hammer provided a slightly poorer selection differential; it did provide the advantage of immediacy, while the density assessment was slightly more expensive. However, in light of the data, neither conclusion was clear-cut. An improvement of the IML Hammer measurements might be achieved through additional measurements on each tree, or by combining radial, transverse, and longitudinal measurements (e.g., Wang, Ross, McClellan, Barbour, Erickson, Forsman & McGinnis 2000; Wang, Ross, Erickson, Forsman, McGinnis & Pellerin 2000). Future studies are required to address this issue.

The Pilodyn measurements correlated poorly with the small clears MoE, and it stood out as the least useful method. This result was somewhat surprising, as the Pilodyn has 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 fit may be the extreme earlywood/latewood differentiation of Douglas fir. Another reason 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.

Diameter at breast height, volume, and form correlated negatively with stiffness, with selection differentials of about minus 10%. This accords with the observations of Harris & Orman (1958) and Zobel & van Buijtenen (1989) who concluded that fast-growing trees generally have poorer wood quality.

The IML Hammer and density stood out as the cheapest methods (Fig. 4), although they were unable to achieve more than an 11–16% selection differential. SilviScan-2® potentially provided for a 22–26% selection differential but this potential came at a considerable cost, despite applying the price for outerwood core assessment only (Fig. 5–7). 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 uses proportions of the order of 20–50% (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 the fastest and simplest method. Similar conclusions may be drawn when more intensive selection is required, e.g., selection of individuals as "plus-trees" for additional scion material for seed orchards. However, because SilviScan-2® provides more accurate and detailed information it may be more appropriate to use it on provisionally selected individuals in spite of the cost — for instance, in exploring general patterns of within-tree and between-tree variation in wood properties. SilviScan-2® may also have a role in more precisely characterising the MoE of trees previously screened using the IML Hammer.

CONCLUSION

Outerwood density cores and the IML Hammer both provided cheap and reasonably accurate methods for breast height stiffness assessment of individual standing Douglas fir trees. They provided a corrected selection differential of 11–16% 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%). The Pilodyn penetrometer 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%.

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