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# Effect of Green Density Values on *Pinus radiata* Stiffness Estimation using a Stress-wave Technique.

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## Abstract

Use of acoustic tools for assessing stiffness of green wood in standing trees relies on the assumption of a constant value for wood density. This study examined the variability in the green density of the outerwood (outer 5 rings) of 13-year-old *Pinus radiata* D.Don trees and determined the error introduced by using a constant value.

Assuming a constant green density introduced a small (~3%) error in the calculated modulus of elasticity (i.e. density 'as measured' x acoustic velocity$^2$). Acoustic velocity was the dominant term in the equation. Green density of the fresh core samples showed little variation (coefficient of variation = 2.8%) and was more strongly determined by the sample's moisture saturation than the amount of wood material (basic density). Modulus of elasticity was inversely related to diameter at 1.3 m ($R^2$ = 0.20). Basic density and fresh moisture content were inversely related ($R^2$ = 0.82). Basic density and fresh moisture content both influenced the acoustic velocity ($R^2$ ~ 0.07), but their effects were weak and opposite. The effect on the acoustic velocity of fresh moisture content at a level between 110% and 230% was less than found previously at lower fresh moisture contents.

**Keywords:** *Pinus radiata*, standing tree acoustic tools, dynamic modulus of elasticity, basic density, moisture content

## Introduction

Acoustic tools use sound or stress waves to calculate the modulus of elasticity (MOE), a measure of stiffness (X. Wang et al., 2001, 2002; Carter et al., 2005). The use of sound to measure the MOE of wood has been researched for over 50 years (Schultz, 1969; Pellerin & Ross, 2001) but only recently has the technique seen widespread application. Two types of tools are available: (i) resonance tools for use on logs; and (ii) time of flight (TOF) tools suitable for use on both standing trees and logs. Resonance tools such as Fibre-gen's Director HM200 were the first to see routine application in Australia and New Zealand (Tsehaye et al., 1997; Ridoutt et al., 1999; Dickson et al., 2004a). As a proportion of *Pinus radiata* (radiata pine) logs fail to meet the requirements of machine stress graded timber (i.e. F5 or below) (Walker & Nakada, 1999),

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structural grade recovery can be improved significantly by screening logs and diverting those below a certain MOE threshold to other applications (Young, 2002; Dickson et al., 2004a, b; Carter et al., 2006), thus avoiding the expense of processing wood that will not meet final specifications (Tsehaye et al., 2000; Matheson et al., 2002).

Standing tree tools are considered less accurate than resonance tools (Andrews, 2002). Time of flight is typically measured between two accelerometer probes hammered into the side of the tree (see X. Wang et al., 2000). Accuracy problems include variation in the hammer impact, the spacing of probes, signal detection thresholds, variation in location, number and size of branches, and unknown density variation (Lindström et al., 2002). Standing tree tools only sample a small section of the stem, with the main wavefront detected passing longitudinally through the outermost growth rings. Time of flight is sensitive to imperfections such as compression wood (X. Wang et al., 2002), spiral grain, temperature or moisture content of the wood. Despite these problems, standing tree tools would be of great value for breeding as the potential parent can be tested and remain intact (Kumar et al., 2002). Accuracy problems could also be partly overcome by the development of reliable field procedures, improved tool design and more intensive within-tree sampling.

Variation in wood stiffness would be expected between genotypes. However, differences may also exist in green density due to variation in wood microstructure or level of water saturation. This study was designed to determine whether differences in green density will introduce a bias into dynamic MOE ($E_d$) results.

## Materials and Methods

Sample trees were growing in a tree breeding trial (35° 28'N 148° 04'E; 830 m above sea level) located in Green Hills forest south of the town of Tumut, New South Wales, Australia. The site had previously carried a crop of radiata pine and was underlain by granite diorite (Parent Rock Code 5, Turner et al., 1996), had a mean annual temperature of 10.9 °C and an average rainfall of 1270 mm (Forests NSW, unpublished data). The site is roughly level (0-5° slope) but some soil differences were noticed between replicates with part of one replicate having only shallow soil over parent rock.

The trial was planted in June 1993 using a randomised complete block design containing 10 replicates of 54 seedlots planted in three-tree plots. All trees in the trial had been assessed for growth and form traits in April-May, 2005 when survival was approximately 90%. Wood quality sampling was undertaken the following summer, during January and February 2006. Sample trees were selected on the basis that their diameter at 1.3 m was greater than 15 cm, they did not have excessive lean or sweep or a fork or a stem shift below 2 m in height.

### Standing tree acoustic measurements

Dynamic modulus of elasticity ($E_d$) is calculated from the TOF using the following equation:

$$E_d = \rho v^2 \times 10^{-3} \qquad [1]$$

where $v$ is the stress wave velocity (km/s) and $\rho$ is the density 'as measured' (kg/m³). In practice, the sapwood density of living radiata pine trees is normally assumed to be a constant at 1000-1100 kg/m³ (e.g. Grabianowski et al., 2004; Lasserre et al., 2004). Similarly, when density of freshly harvested trees is used to estimate log volumes from their weight for haulage and billing purposes a constant value of 1000 kg/m³ may be used (Cown, 1999). A more precise definition of green density was needed for this study to allow for quantification of potential sources of error. The term 'fresh density' is used here as the density of wood in an 'as alive' condition. Fresh density is composed of two components, wood cell material (basic density) and water. The water component is expressed here as the relative traits moisture content and moisture saturation. Fresh moisture content ($MC_{fresh}$) is defined here as the weight of water in fresh wood relative to the weight of wood. Moisture saturation (*Sat*) is volume of water relative to the theoretical maximum volume of water ($MC_{max}$).

The TreeTap is an instrument for measuring acoustic velocity in standing trees (Lasserre et al., 2005). TreeTap was designed by Dr. Michael Hayes and Dr. Michael Wang from the School of Engineering, University of Canterbury, in collaboration with Prof. John Walker from the School of Forestry, University of Canterbury. Most standing tree tools have two probes: one that starts the timer when struck; and a second that stops it when the wave is detected. The TreeTap has a third, inert starter probe that is struck to initiate the stress-wave. This prevents damage to the sensor probe crystals, and may allow more precise TOF measurements. There are subtle design differences, but measurements are comparable to those found using similar tools (e.g. the FAKOPP®, or Fibre-gen's Director ST300).

A TreeTap instrument was used to sample 554 trees growing in a tree breeding trial. The established field methodology for the TreeTap was adopted (M. Hayes, personal communication). The trees were pruned to 2.1 m for easy access and the probes were orientated

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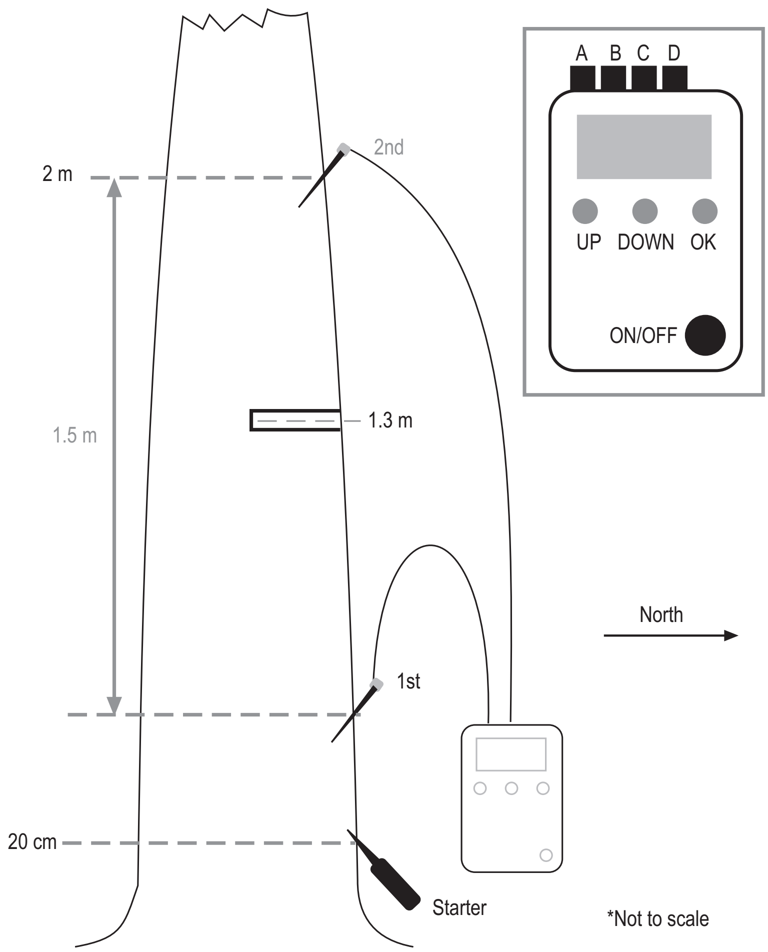


FIGURE 1: Positioning of sensor probes and outerwood coring with a close-up of the TreeTap stress-wave timer inset (top-right)

on the northern face of the trees (Figure 1). The top sensor probe (2nd) was set at 2.0 m, the 1st sensor probe was set 1.50 m below the top probe, and the starter probe was set a further 30 cm below the 1st sensor probe. The position of the probes was altered slightly (±100 mm) to avoid knots or other defects, but the distance between the 1st and 2nd sensor probes was measured as accurately as possible (±10 mm). The sensor probes were inserted at 45-55° to the trunk, and the starter probe was inserted at 135-145°. A dead blow hammer was used to insert the sensor probes, and a 200 g steel hammer was used on the starter probe. The steel hammer produces a stress-wave, and the TOF is measured between the 1st and 2nd probes. By striking the starter probe repeatedly, eight TOF readings were taken per tree. Readings were stored in the data logger until being downloaded after each day's fieldwork.

Data were checked after every tree, and again after the data had been downloaded. Dubious readings (greater than 1.5 standard deviations from the mean) were deleted. The mean TOF value for each tree was converted to an acoustic velocity and three separate $E_d$ values were calculated for each tree using three different density ($\rho$) values:

1. $E_d$*-Const* calculated using a constant $\rho$ value of 1080 kg/m³, determined from our mean fresh density data;
2. $E_d$*-Fresh* using the actual fresh density ($\rho_{fresh}$) of each tree; and
3. $E_d$*-Basic* using basic density ($\rho_{basic}$). $E_d$*-Basic* is an index, rather than a measure of timber stiffness *per se*, but, arguably, it may be a useful wood quality trait.

**Outerwood cores**

Fresh and basic density, and moisture status of the outerwood were determined using short (12 mm diameter) cores extracted at breast height (1.3 m) (Figure 1) using a motorised corer (Downes et al., 1997). Outerwood was defined as the five outside growth rings (Harris & Cown, 1991) not including the earlywood laid down in 2005. A preliminary experiment


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demonstrated that the samples could be immersed in water, and measured reasonably accurately in the laboratory later that day.

The volume for each sample was determined using liquid displacement. Samples were surface-dried and weighed green and then oven-dried at 105 °C until reaching a stable weight (Standards Australia, 1997; 2000). The cores were removed from the oven in batches of 20–40, and placed into a desiccator to cool before being weighed. Fresh density, basic density, fresh moisture content, and moisture saturation were calculated using Equations [2]–[6] below (Harris & Cown, 1991; Kininmonth, 1991):

$$\rho_{fresh} = \frac{Wt_{fresh}}{V_{fresh}} \qquad [2]$$

$$\rho_{basic} = \frac{Wt_{oven\text{-}dry}}{V_{fresh}} \qquad [3]$$

$$MC_{fresh} = \frac{Wt_{fresh} - Wt_{oven\text{-}dry}}{Wt_{oven\text{-}dry}} \times 100 \qquad [4]$$

$$Sat = \frac{MC_{fresh}}{MC_{max}} \times 100 \qquad [5]$$

$$MC_{max} = \frac{1500 - \rho_{basic}}{1.5 \times \rho_{basic}} \times 100 \qquad [6]$$

where $\rho_{fresh}$ is fresh density, $\rho_{basic}$ is basic density, $MC_{fresh}$ is percent moisture content of the fresh wood, *Sat* is percent moisture saturation, $Wt_{fresh}$ is sample weight in ‘as live’ condition, $Wt_{oven\text{-}dry}$ is oven-dried weight, $V_{fresh}$ is the volume of fresh wood, $MC_{max}$ is theoretical maximum moisture content of fresh wood and 1500 kg/m³ is density of oven-dry wood cell material.

**Data analysis**

Preliminary data checking was conducted with the software package JMP IN Version 4.0.4 (SAS Institute, 2001). Correlations between traits were determined and stepwise regression used to explore significant explanatory variables for traits of interest (Ramsey & Schafer, 2002). The variable with the highest F ratio was fitted at each step. Mallow’s Cp statistic was used to choose the number of variables as the use of $R^2$ values favours the selection of too many variables. The Cp statistic gauges the trade off between biases from too few variables, and noise from including too many (Ramsey & Schafer, 2002). The model where Cp first approached c was generally chosen (c = the number of variables + 1).

## Results

After checking the data for potential errors and inconsistencies, the distribution of each trait was checked. All traits except fresh density and moisture saturation were approximately normally distributed. Means for fresh density, fresh moisture content and moisture saturation were typically lower than those normally found with destructive sampling of similar age trees (J. Moreno. PhD Student with Forest NSW, personal communication, 12 January 2006). For example, a mean fresh density of 1150 kg/m³ or more is expected for outerwood disc sections. This suggests that more moisture was lost during coring than was replaced by soaking the samples for 2–8 hrs.

The term $E_d$-*Const* is effectively the acoustic velocity squared and, therefore, has twice the variance of acoustic velocity. Acoustic velocity is only of interest as it determines the dynamic MOE ($E_d$). Variability in $E_d$ was almost three times that of basic density. Variability in fresh density and moisture saturation was relatively low, so the variability of $E_d$-*Fresh* was not much greater

TABLE 1: Means and variability in measured traits.

| Trait | Mean | N | Std. error | CV (%) |
|---|---|---|---|---|
| DBH (cm) | 19.8 | 549 | 0.143 | 16.9 |
| *v* (km/s ) | 2.72 | 554 | 0.011 | 9.05 |
| $\rho_{fresh}$ (kg/m³) | 1080 | 486 | 1.37 | 2.81 |
| $MC_{fresh}$ (%) | 174 | 486 | 0.758 | 9.63 |
| *Sat* (%) | 92.5 | 486 | 0.171 | 4.07 |
| $\rho_{basic}$ (kg/m³) | 395 | 554 | 1.13 | 6.76 |
| $E_d$-*Const* (GPa) | 7.96 | 554 | 0.061 | 18.0 |
| $E_d$-*Fresh* (GPa) | 7.99 | 486 | 0.062 | 18.4 |
| $E_d$-*Basic* (index) | 2.96 | 554 | 0.026 | 20.9 |

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TABLE 2: Pairwise correlation coefficients.

(N = 486 except for correlations with DBH where N = 481)

| | DBH | $\rho_{basic}$ | Fresh density | $MC_{fresh}$ | *Sat* | $E_d$-*Const* | $E_d$-*Basic* |
|---|---|---|---|---|---|---|---|
| $\rho_{basic}$ | 0.005 | | | | | | |
| $\rho_{fresh}$ | 0.068 | 0.409** | | | | | |
| $MC_{fresh}$ | 0.027 | - 0.906** | 0.005 | | | | |
| *Sat* | 0.073 | 0.075 | 0.940** | 0.342** | | | |
| $E_d$-*Const* | - 0.457** | 0.268** | 0.089* | - 0.261** | - 0.002 | | |
| $E_d$-*Basic* | - 0.394** | 0.555** | 0.209** | - 0.517** | 0.023 | 0.949** | |
| $E_d$-*Fresh* | - 0.436** | 0.325** | 0.240** | - 0.254** | 0.143* | 0.988** | 0.957** |

Probability that correlations are greater than 0: * $p < 0.05$, ** $p < 0.0001$

than $E_d$-*Const*. However, the use of basic density in $E_d$-*Basic* added considerable variance.

### Relationships between dynamic MOE and other traits

A correlation matrix was constructed as an initial means of identifying relationships between traits (Table 2). Even low correlations were significantly greater than zero due to the large sample sizes. The correlations between fresh moisture content and basic density, and moisture saturation and fresh density were high. These relationships were analysed further using linear regression. All dynamic MOE ($E_d$) traits were very strongly correlated as expected considering similarity of derivations. $E_d$-*Const* was not correlated with the fresh density. Basic density had a moderate positive correlation with $E_d$-*Const* whilst fresh moisture content had moderate negative correlation with $E_d$-*Const*. Diameter at Breast Height (DBH) was negatively correlated with all $E_d$ traits but not with basic density.

Results of the stepwise regression analysis (Table 3) indicated no strong models for acoustic velocity. Diameter at Breast Height and basic density formed the best model explaining 28% of the total variation. The addition of fresh moisture content did not improve the model even though it was correlated with acoustic velocity. Whilst the effects of DBH and basic density were cumulative, the effects of basic density and fresh moisture content largely overlapped. Ramsey and Schafer (2002) noted that where correlated variables are involved the interpretation of individual model effects may not be practically possible. The effect of one variable, holding others constant, can not be realistically extrapolated because the data does not experience this condition. Wood with a high basic density will generally not have a high fresh moisture content because the two were found to be inversely related.

In contrast, acoustic velocity explained over 97% of the variation in $E_d$-*Fresh*. The remaining 3% can be attributed to fresh density and a small interaction term. So, the assumption of a constant density in trees introduced an error of around 3%. Similarly, basic density explained an additional 9% of the variation in $E_d$-*Basic* when sequentially adding acoustic velocity and then basic density.

### Wood - water relationships

Basic density only accounted for 17% of the variation in fresh density (Figure 2), while moisture saturation explained over 88% (Figure 3), i.e. the fresh density was mainly determined by amount of water held by the trees, rather than the amount of wood

TABLE 3: Stepwise regression of explanatory variables for acoustic velocity.

| Step | Variables | $R^2$ | Cp | C |
|---|---|---|---|---|
| 1 | DBH | 0.20 | 48.81 | 2 |
| 2 | DBH, $\rho_{basic}$ | 0.28 | 2.01 | 3 |
| 3 | DBH, $\rho_{basic}$, $MC_{fresh}$ | 0.28 | 4.81 | 4 |
| 4 | $\rho_{basic}$, $MC_{fresh}$ | 0.07 | 136 | 3 |
| 5 | $MC_{fresh}$ | 0.07 | 138 | 2 |

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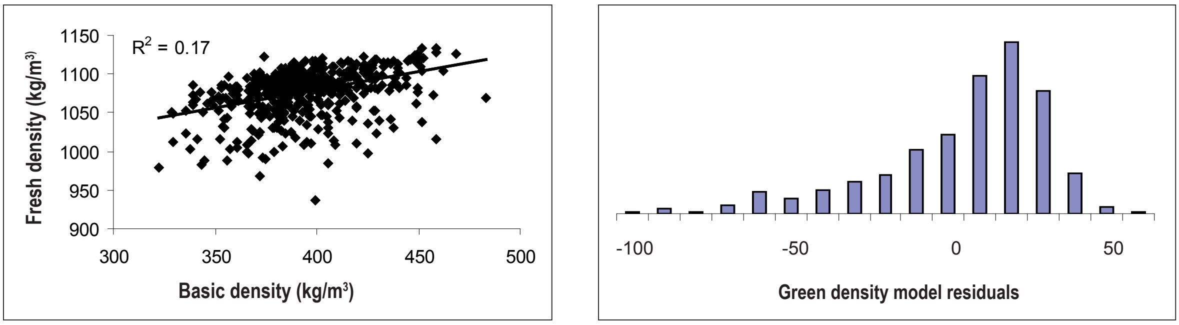



| Source | DF | Mean Square | F ratio |
|---|---|---|---|
| Model | 1 | 74600 | 97.5 *** |
| Error | 484 | 765 | |

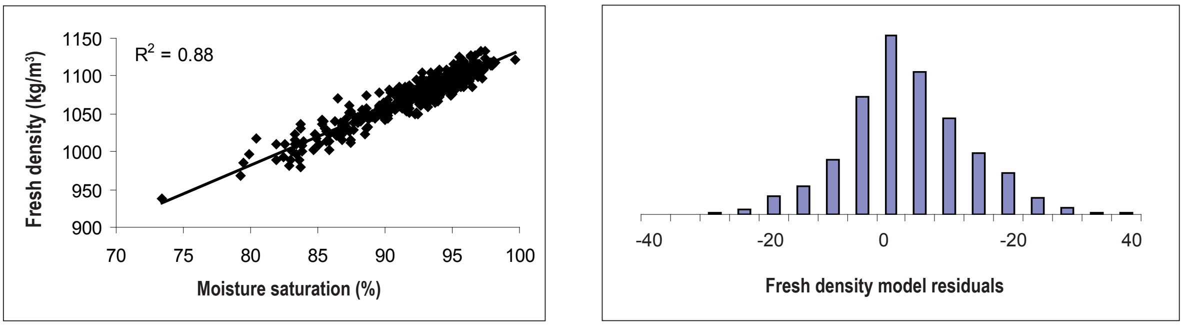
*** $p$<0.0001

Relationship between fresh and basic density: $\rho_{fresh}$ = 892.6 + 0.466 x $\rho_{basic}$
[18.7] [0.047]

FIGURE 2: Regression plots, analysis of variance, residuals distribution plot and predicted models with standard errors [in brackets] for fresh density ($\rho_{fresh}$) by basic density ($\rho_{basic}$).

material. A strong inverse relationship was found between basic density and fresh moisture content, which may help to explain this finding (Figure 4).

The distribution of residuals for the fresh moisture content by basic density, and fresh density by basic density models were distinctly skewed to the left. Since this violates an assumption of linear regression, the standard errors reported may be slightly underestimated. The distribution of residuals also demonstrates the asymptotic nature of these relationships. For a given basic density, the fresh moisture content of most of the samples approached complete saturation ($MC_{max}$). Further, there were a percentage of samples that were less saturated than most.




| Source | DF | Mean Square | F ratio |
|---|---|---|---|
| Model | 1 | 393000 | 3690 *** |
| Error | 484 | 107 | |

*** $p$<0.0001

Relationship between fresh density and moisture saturation: $\rho_{fresh}$ = 376 + 7.57 x *Sat*
[11.5] [0.125]

FIGURE 3: Regression plots, analysis of variance, residuals distribution plot and predicted models with standard errors [in brackets] for fresh density ($\rho_{fresh}$) by moisture saturation (*Sat*).

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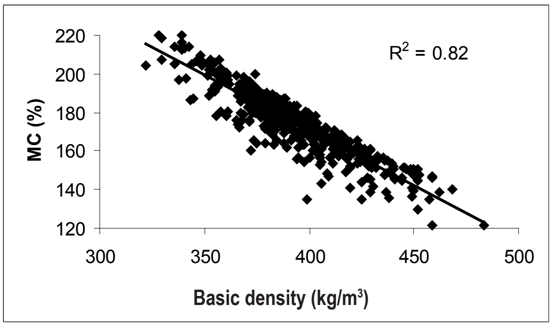


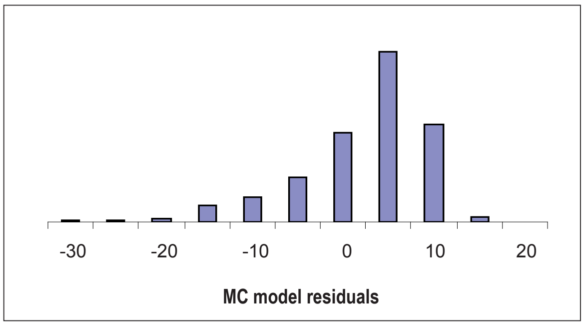


| Source | DF | Mean Square | F ratio |
|---|---|---|---|
| Model | 1 | 111000 | 2230 *** |
| Error | 484 | 50 | |

*** $p$<0.0001

Relationship between fresh moisture content and basic density: $MC_{fresh} = 399 - 0.570 \times \rho_{basic}$
[4.79] [0.0121]

FIGURE 4: Regression plots, analysis of variance, residuals distribution plot and predicted model with standard errors [in brackets] for fresh moisture content ($MC_{fresh}$) by basic density ($\rho_{basic}$).

## Discussion

Using fresh density as the $\rho$ value in the calculated MOE may not improve the meaningfulness of acoustic measurements on trees. The correlations amongst $E_d$-*Const*, $E_d$-*Fresh* and $E_d$-*Basic* were above 0.90, hence the $\rho$ value used was almost statistically redundant. The assumption of a constant density (either the mean value or a fixed constant) would only introduce around a 3% error when compared to $E_d$-*Fresh*.

Fresh density can be divided into its components, wood cell material (basic density) and water. The water component has been expressed here as the relative traits: fresh moisture content and moisture saturation. Fresh moisture content is the weight of water relative to the weight of wood. Moisture saturation is volume of water relative to the theoretical maximum volume of water ($MC_{max}$). The fresh density varied little because water tended to occupy most of the available space. In effect, the presence of free-water in the trees partly masked the influence of basic density on the calculated $E_d$. The static MOE in service is of greater interest than precise measurements on green samples. For this reason a new trait was introduced, $E_d$-*Basic*, with basic density being used instead of the fresh density. The above analysis suggests that $E_d$-*Basic* will more closely reflect the static MOE in service, but this could not be established without further research.

S. Wang, Chiu and Lin (2002, 2003) recommended that Equation [7] below be applied to all acoustic measurements, making them independent of fresh moisture content.

$$MOE_{adjusted} = v^2 \times \rho_{effective} / g \qquad [7]$$

where

$$\rho_{effective} = \frac{(100 + 28)\,\rho_{basic}}{(100 + MC)\rho_{basic}} \times \left(1 - \frac{(1 - k)(MC - 28)}{(100 + MC)}\right)$$

where: $\rho_{effective}$ is effective density; $MC$ is the actual moisture content of the wood; $v$ is acoustic velocity; 28 is the moisture content of wood at fibre saturation point, the point where all free water has been removed from the wood; $k$ is a coefficient relating to the mobility of free water (~0.7); $g$ is the acceleration due to gravity (9.81 m/s) (from S. Wang, Chiu & Lin, 2002).

The $k$ coefficient – originally devised by Sobue (1993) – is an empirical measure of the proportion of free-water that vibrates in phase and, therefore, adds resistance to sound transmissions (cited in X. Wang & Ross, 2001). Preliminary analysis of Equation [7] indicated that there was a problem with it. When applied, Equation [7] succeeded in making MOE independent of fresh moisture content, but MOE also became independent of basic density. This problem had not been previously identified, and may be unavoidable when using these types of adjustments on samples that are close to complete saturation. The effect of fresh moisture content on ultrasonic velocity became less distinct and difficult to predict at high fresh moisture contents (S. Wang, Chiu & Lin, 2003).

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## Conclusions

Acoustic velocity was the most important value in determining the dynamic MOE (i.e. density × acoustic velocity²) in radiata pine. Little variation was found for fresh density. As a result, the assumption of a constant fresh density (i.e. in an 'as alive' condition) did not greatly reduce the accuracy of estimated $E_d$ on trees. Therefore, the immediate focus should be on improving the accuracy of velocity measurements using an advanced signal treatment including time and frequency domains.

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