

Determining the main and interactive effect of age and clone on wood density, microfibril angle, and modulus of elasticity for *Pinus radiata*

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Abstract: Detailed radial measurements of wood properties, taken at breast height, were obtained from control pollinated seedlings and a selection of 13 year old radiata pine (*Pinus radiata* D. Don) clones. Using these data the key objectives of this study were to determine (i) the magnitude of mean clonal variation in modulus of elasticity (MOE) and properties affecting MOE (density and microfibril angle (MFA)) and (ii) whether there is a significant age \times clone interaction for these traits. All wood properties were significantly affected by the main and interactive effects of age and clone. There was a relatively linear increase in both MOE and density with tree age, while MFA declined linearly with tree age. Values of density and MOE diverged between the clonal extremes from age 3 to age 12. After diverging markedly up to age 6, differences in MFA between clonal extremes remained relatively constant to age 12. At age 12, values for density, MFA, and MOE varied between clonal extremes by, respectively, 194 kg·m⁻³ (465–659 kg·m⁻³), 11.3° (9.6–20.9°), and 11.2 GPa (10.4–21.6 GPa). The seedling material had a relatively intermediate ranking, across the age range, for all traits considered.

Résumé : Des mesures radiales détaillées des propriétés du bois ont été prises à hauteur de poitrine sur des semis issus d'une pollinisation contrôlée et sur des clones sélectionnés de pin radiata (*Pinus radiata* D. Don) D. Don âgés de 13 ans. À partir de ces données, les principaux objectifs de cette étude consistaient à déterminer (i) l'ampleur de la variation clonale moyenne du module d'élasticité (MOE) et des propriétés affectant le MOE (densité et angle des microfibrilles (AMF)) et (ii) s'il y a une interaction âge \times clone significative dans le cas de ces traits. Les effets principaux et l'interaction âge \times clone étaient significatifs pour toutes les propriétés du bois. Le MOE et la densité augmentaient de façon relativement linéaire tandis que l'AMF diminuait linéairement en fonction de l'âge d'arbre. Entre 3 et 12 ans, les valeurs de densité et de MOE divergeaient entre les extrêmes clonaux. Après avoir divergé de façon marquée jusqu'à l'âge de 6 ans, les différences d'AMF entre les extrêmes clonaux demeuraient relativement constantes jusqu'à 12 ans. À 12 ans, les valeurs de densité, d'AMF et de MOE variaient entre les extrêmes clonaux de respectivement 194 kg·m⁻³ (465 à 659 kg·m⁻³), 11,3° (9,6 à 20,9°) et 11,2 GPa (10,4 à 21,6 GPa). Le matériel issu des semis avait un classement relativement intermédiaire pour toute la gamme d'âges et tous les traits étudiés.

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Introduction

Advances in tree breeding and changes in silvicultural practice over the last few decades have greatly enhanced growth rates of plantation-grown conifers. These growth gains have led to shorter rotation lengths and, in combination with changes in silviculture, increased the proportion of juvenile wood (Cown 1992; Downes et al. 2000). Juvenile wood (also known as corewood; Burdon et al. 2004) is generally characterized by low-density, thin cell walls, short tracheids with large lumens, high grain angle, and high microfibril angle. As a result, juvenile wood has low strength and stiffness and poor dimensional stability compared with mature wood (Macdonald and Hubert 2002). The

growing recognition that this juvenile wood is of low value has resulted in a recent shift in the way plantations are managed. Rather than focusing solely on maximization of merchantable volume, management strategies are now starting to use genetic stock and implement practices that balance growth rate with wood properties.

In the widely grown plantation softwood radiata pine (*Pinus radiata* D. Don), a useful indicator of wood quality is modulus of elasticity (MOE), which measures the resistance of wood to deformation under an applied load. Although MOE is not an important property for clearwood from pruned logs or pulp, it is used as a threshold criterion in machine stress grading of structural timber (Walker and Nakada 1999) and is also a key property for determining

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quality of laminated veneer lumber. Improving MOE in *P. radiata* therefore contributes to an improved recovery of higher-grade lumber and a higher return at the sawmill. When compared with other internationally traded structural lumber species, plantation-grown *P. radiata* has relatively poor MOE and dimensional stability. Stemwood MOE of *P. radiata* increases with cambial age up to fivefold over the first 30 years (Cave 1968) and the low values of MOE found within the corewood are the most limiting for its utilization in timber-based products (Cown 1992). The widespread adoption of machine stress grading of timber has highlighted both the generally substandard nature of the resource and the financial gains that would be possible if MOE in juvenile wood could be increased sufficiently to reach thresholds for structural grade (Walker and Nakada 1999).

Environment has been shown to have a strong and significant influence on both density (Cown et al. 1991) and MOE (Watt et al. 2009). In New Zealand, national studies using uniform trial series have demonstrated threefold variation in juvenile MOE across different environments for *P. radiata* (Watt et al. 2009). Increases in MOE that occur across this environmental range have been largely attributable to concurrent increases in stem slenderness (height/diameter) and mean minimum air temperature (Watt et al. 2009).

Although MOE varies widely across environments, research shows that there is considerable latitude to manipulate MOE at a given site through silviculture. Increases in stocking have been found to result in higher MOE, within the juvenile core, over a wide range of site types across the operational range in stockings (Lasserre et al. 2005; Waghorn et al. 2007; Zoric 2009). Increases in MOE that occur at higher stockings have been found to be largely mediated through concurrent increases in stem slenderness following closure of the canopy (Lasserre et al. 2005; Roth et al. 2007; Waghorn et al. 2007). Using an extensive national data set, a model of MOE has recently been developed that accounts for 96% of the variance in MOE that occurs across environments and between stockings (Watt and Zoric 2010).

There has also been shown to be significant variation in wood quality including MOE between clones (Cown and Sorensson 2008). Compared with genetic stock of average MOE, deployment of high-MOE clones has been estimated to increase MOE by around 2 GPa (Sorensson et al. 2002). Importantly, research shows that there is no interaction between stocking and clone for MOE at a number of sites (Lasserre et al. 2008), indicating that gains achieved through use of high stockings and improved clonal material may be additive. Given the paucity of long-term clonal trials, there remain some key issues surrounding clones that require clarification.

Little is known about how clonal means, relative to standard genotypes, change with tree age. Although studies have described the interactive effect of age and clone on important properties such as wood density (Cown et al. 2002), little research has described how variation in MOE between clones changes with age. This information is critical for defining the age within the juvenile wood at which structural grade thresholds are reached and the trajectory of increases in MOE over time for clones with superior properties. Assuming the site \times environment interaction for clones to be

negligible or minimal (i.e., assuming clones are selected for low genotype \times environment interaction; Namkoong and Kang 1990), once defined, this information could be readily incorporated into a broader modelling framework. Such a framework would enable managers to identify how deployment of high-MOE clones can be best combined with other silvicultural practices to optimize required end products for specific sites.

Defining how clonal variation in wood properties interacts with age also has important implications for early genetic selection for breeding or commercial production. Little interaction between clones and age would allow rapid identification of clones with superior wood properties enabling faster turnaround time in the screening process. Long-term trials with clones that represent a wide range in wood properties could be used to ascertain the accuracy with which wood properties of superior trees at a young age reflect those found in older material.

Using detailed radial measurements of wood properties obtained from a selection of 13 year old *P. radiata* clones covering a wide range in wood properties, the objectives of this study were to determine (i) the magnitude of mean clonal variation in MOE and properties affecting MOE (density and microfibril angle (MFA)), (ii) whether there is a significant age \times clone interaction for these traits, and (iii) using the means, estimate the minimum age at which screening may be undertaken to identify clones with high MOE.

Methods

Site description

Measurements of wood properties were made on 13 year old *P. radiata* growing in Tarawera Forest Cpt 26/2 (176°42'E, 38°10'S; altitude 250 m above sea level). This forest is very productive with a site index (mean height of tallest 100 stems-ha⁻¹ at age 20) of 32 m and overlays coarse volcanic ash (Taupo rhyolite with Tarawera ash overlay). The region in which this forest grows is relatively warm (mean annual temperature of 13.1 °C; Cliflo database, National Institute of Water and Atmospheric Research). Although it has a high average annual rainfall (2033 mm-year⁻¹; Cliflo database, National Institute of Water and Atmospheric Research), seasonal water deficits do occasionally occur during summer.

Experimental design

Trees were selected from adjoining and replicated genetic trials at age 13. These comprised a clonal trial that included 174 clones and a family trial with control-pollinated seedlings (ID 93/327) with a growth and form rating of 26 (Anonymous 2009a, 2009b). Both experiments were planted into strip-mounds in June 1994 at a spacing of 4.0 m \times 4.0 m (625 stems-ha⁻¹). All trees were access pruned to 3 m at age 6. The live stocking at the time of sampling averaged 600 stems-ha⁻¹ in the seedling experiment and 590 stems-ha⁻¹ in the clonal experiment.

Four seedling trees were selected from the family trial and served as the commercial seedling control. Clones were selected from the population to cover as wide a range as possible in wood density and MOE while minimizing the variation in individual tree diameter (range 289–346 mm).

This approach allowed the identification of changes in wood properties without concomitant reductions in growth rate. Density was assessed within these clones from 5 mm outerwood density cores, while outerwood MOE was estimated acoustically using the Fibre-Gen Director ST300 sonic tool. Using these criteria, a previous assessment identified 13 clones from which two trees per clone were sampled.

Measurements

Measurements of tree diameter at breast height were taken at tree age 13 for all selected trees. Each test tree was cored from the bark to pith at breast height using a power corer and a 12 mm increment borer, producing a minimum of 11 growth rings. Trees were cored at right angles to tree lean to avoid compression wood. Samples were kept moist in plastic wrap and transported to the laboratory where they were immersed in ethanol to prevent fungal attack during air-drying. After gentle drying and conditioning at 20 °C and 40% relative humidity, a standard 2 mm thick radial-longitudinal strip was sawn from each core. These strips were allowed to reequilibrate overnight at 20 °C and 40% relative humidity to an estimated moisture content of 7%–8% before being processed by the SilviScan system. (Henceforth, the density refers to values at 7%–8% moisture content and not basic density.)

Radial profiles of MOE, density, and MFA were estimated from these samples using SilviScan-3 at a step size of 0.025 mm for density and 5 mm for MFA and MOE. This instrument uses X-ray diffraction to estimate MFA and X-ray absorption to estimate density. MOE is calculated from the product of density and the “coefficient of variation of the 002 azimuthal intensity profile” from X-ray diffractometry through the radial cell walls (Evans et al. 1999; Evans 2003, 2006).

Ring boundaries were identified from the radial density profiles and ring level averages for each property were determined. As measurements were incomplete over the last growth ring (tree age 13) and not completely replicated between clones over the first two tree ages (tree ages 1 and 2), these data were not used in the analyses. All values are expressed as a tree age (with time of planting referenced as age 0) and after accounting for the previously mentioned issues cover a tree age range of 3–12 years.

Analyses

All statistical analyses were undertaken using SAS (SAS Institute Inc. 2000). Means for the seedling controls were not used in analyses but were included in graphs for comparative purposes. Relationships between wood properties were examined within each tree age using a combination of linear and nonlinear models. The relationships between density and both MOE and MFA were found to be best described by standard linear functions (of the form $y = a + bx$). The relationship between MOE and MFA was best described by the following exponential decay function:

$$[1] \quad \text{MOE} = a \exp(-b\text{MFA})$$

where a and b are empirically determined parameters.

A mixed-effects model that accounted for the repeated nature of measurements was used to examine the main and interactive effect of clone and age on wood properties. The

model was implemented in SAS using PROC MIXED with the REPEATED statement. Age and clone and their interaction were included in this model as class-level fixed effects.

All dependant variables were log transformed to ensure that residuals for each model met the underlying assumption of normality. Following Littell et al. (2006), a range of covariance structures were tested and the structure that minimized the $-2 \text{ res log likelihood}$, Akaike information Criterion, Bayesian information criterion, and finite population corrected Akaike information criterion was selected. Final covariance structures used for models describing density and MFA were, respectively, compound symmetry and first-order autoregressive (AR(1)). For the MOE model, the covariance structure used a compound symmetry component to model variation between tree means and a first-order autoregressive component to model the within-tree component.

The final model used for density and MFA was as follows:

$$[2] \quad Y_{ijk} = \mu + \alpha_i + \beta_k + (\alpha\beta)_{ik} + e_{ijk}$$

where $\mu + \alpha_i + \beta_k + (\alpha\beta)_{ik}$ is the mean for the clone i at time k , containing effects for clone, time, and the clone \times time interaction, and e_{ijk} is the random error associated with the measurement at time k on the j th ramet that is assigned to clone i . The final model for MOE was similar to eq. 2 but also included a random effect γ_{ij} to account for the j th ramet within the i th clone. Multiple comparisons were undertaken by examining the significance of least square differences of clones for the three traits.

Two different analyses were undertaken at both the tree and clone level to determine the minimum tree age at which superior trait values could be identified. Intraclass correlations (Fisher 1941; Evans et al. 1997) were determined for each wood property by plotting trait values for one of the two ramets within each clone against the other by age. For each relationship, the root mean square error was also determined. Secondly, allocation of the superior clones or trees was determined at annual intervals from tree ages 3–12. Area-weighted values of wood properties were determined for each tree age assuming a circular stem. The means were ranked at tree age 12 at both the clone and the ramet level for MOE, density, and MFA. The six clones and 13 trees with the superior mean area-weighted values for these traits were identified. Using data calculated from previous ages, we then determined the percentage of these trees or clones that were correctly identified from tree ages 3–11.

Results

Relationships between variables

The correlation between MFA and MOE was significant from tree age 4 onwards. After this age, there was an increase in the strength of the relationship with R^2 ranging from 0.64 at age 4 to 0.88 at age 12 (Table 1; Fig. 1). In contrast, the positive linear relationship between density and MOE (Fig. 1) was weak to moderate in strength. The relationship between these two variables was insignificant until age 7 after which moderately strong correlations were generally noted until tree age 12 (Table 1). The relationship between density and MFA was insignificant at all ages examined (Table 1).

Table 1. Relationships between density, microfibril angle (MFA), and modulus of elasticity (MOE) by age.

Tree age (years)	$x = \text{Density, } y = \text{MOE}$	$x = \text{MFA, } y = \text{MOE}$	$x = \text{Density, } y = \text{MFA}$
3	0.04	0.29	0.05
4	0.07	0.64**	0.01
5	0.02	0.59**	0.10
6	0.28	0.76***	0.01
7	0.39*	0.78***	0.03
8	0.49**	0.82***	0.11
9	0.24	0.88***	0.04
10	0.52**	0.80***	0.13
11	0.56**	0.88***	0.30
12	0.59**	0.88***	0.29

Note: Shown are the coefficient of determination (R^2) and the P category. Significance: *** $P = 0.001$, ** $P = 0.01$, and * $P = 0.05$. Values without asterisks are nonsignificant at $P = 0.05$. The relationship between MFA and MOE was fitted using the exponential decay function, described in eq. 1. All other functions were fitted using linear models. All analyses were undertaken using mean clonal values from 13 clones.

Influence of clone and age on wood properties

All wood properties were significantly affected by the main and interactive effects of age and clone (Table 2). Tree age had the strongest influence on all properties examined. There was a linear increase in both density and MOE with age, while MFA declined relatively linearly as age increased (Fig. 2).

The interaction between clone and age was quite marked for all properties studied. This was evident through an increase in the range between lowest and highest trait values with age (Fig. 2), particularly between ages 5 and 6. Differences between clones were significant (at $P = 0.05$) across the entire age range for MFA and density. For MOE, differences became significant at the 5% level after age 5. There was also crossover in rankings between clones for all traits (based on means) and this ranking change was particularly marked at ages less than 6 (Fig. 2).

Variation in wood properties between clones was wide for all traits and increased with tree age. At age 12, values for density, MFA, and MOE varied between clones by, respectively, 194 $\text{kg}\cdot\text{m}^{-3}$ (465–659 $\text{kg}\cdot\text{m}^{-3}$), 11.3° (9.6–20.9°), and 11.2 GPa (10.4–21.6 GPa). The seedling material had a relatively intermediate ranking across the age range for all traits considered (Fig. 2).

The two superior clones exhibited substantially larger mean values for MOE over both seedlings and, in particular, the two clones with the lowest values of MOE. Mean differences between the clonal extremes ranged from 1.4 GPa at age 3 to 9.6 GPa at age 12. Average mean differences of the two superior clones over GF26 seedlings ranged from 1 GPa at age 3 to 5.3 GPa at age 12.

Early identification of superior wood properties

Intraclass correlations were of a similar magnitude for density, MFA, and MOE. Values increased with age, consistently reaching a threshold above 0.80 between 6 and 7 years of age (Table 3). However, consistently low values for standard error were not reached for all of the traits until age 7 (Table 3). From age 7 onwards, intraclass correlations,

Fig. 1. Relationship between (a) density and modulus of elasticity, (b) microfibril angle and modulus of elasticity, and (c) density and microfibril angle. In Fig. 1b, the relationship between microfibril angle and modulus of elasticity was fitted using the exponential decay function to ring-averaged tree ages of 3, 7, and 12. In Figs. 1a and 1c, linear lines are fitted to data for ring-averaged tree ages of 3, 7, and 12. All data shown are the clonal means determined from two trees.

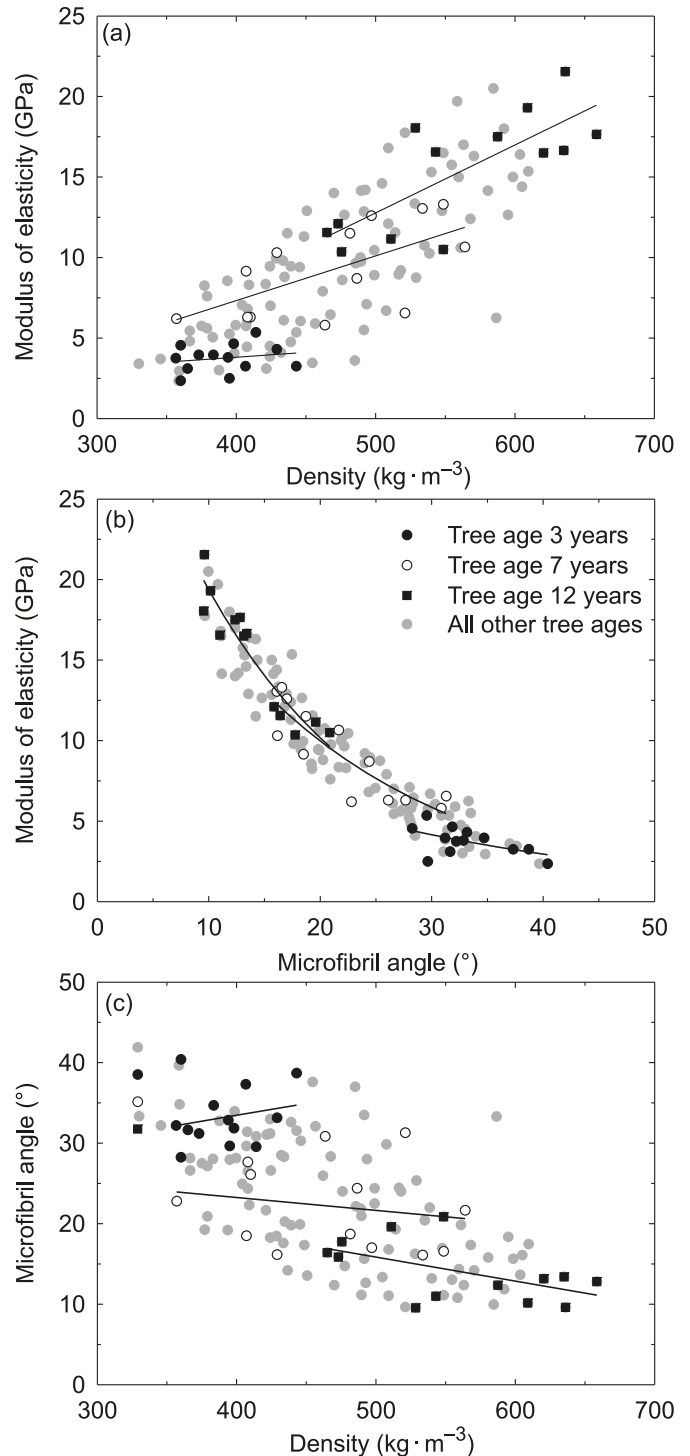


Table 2. Summary of analysis of variance describing the main and interactive fixed effects of clone and tree age on density, microfibril angle (MFA), and modulus of elasticity (MOE).

Term	Density	MFA	MOE
Clone	33.3***	23.4***	17.6***
Age	187***	125***	438***
Clone × age	3.1***	2.0***	2.0***

Note: Shown are *F* values followed by *P* categories. Significance: ****P* = 0.001.

respectively, averaged 0.84, 0.82, and 0.84 for density, MFA, and MOE.

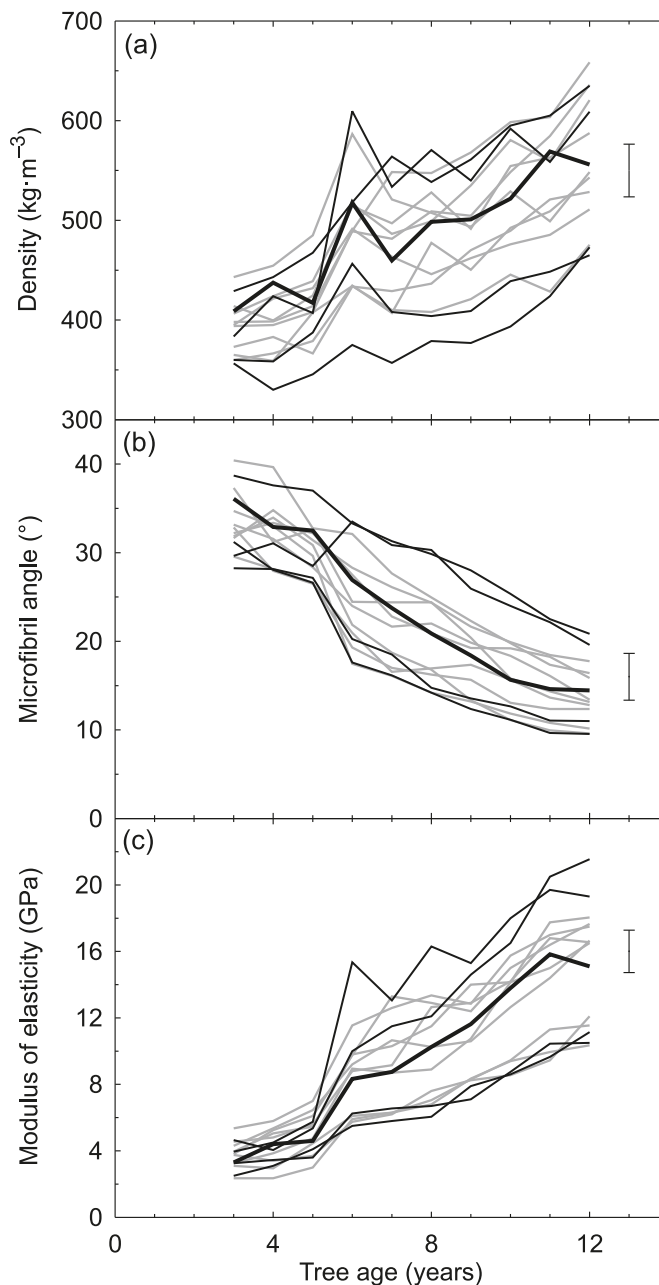
The percentage correct allocation across the age range for the superior 50% of the population at age 12 varied between clone and tree levels. At the clone level, there was a marked increase in correct allocations with age (Table 4). Complete (100%) correct allocation was achieved for density, MFA, and MOE, at the respective ages of 8, 6, and 6. At the tree level, correct allocation of MFA reached a threshold at 92% by age 5 with 100% correct allocation not achieved until age 12. For density and MOE, 100% correct allocation was reached at the respective ages of 9 and 6 for these properties (Table 4).

Discussion

The reductions in rotation age that have occurred over the last few decades (Macalister 1997; New Zealand Forest Owners Association 2004) have resulted in a greater proportion of juvenile wood, with substandard wood properties, in the harvested crop. Numerous studies have shown that one way to improve these juvenile properties is through the use of superior genotypes, including superior clones (Sorensson et al. 2002). Our results extend these findings by demonstrating that any gains from clones selected for wood properties (from means) increase markedly and significantly with tree age (at 1.4 m). This divergence was particularly marked for the most important wood property, MOE, and continued over the entire duration of the age range examined. This is consistent with previous findings for seedling material using age-age genetic correlations (King and Burdon 1991; Matheson et al. 1994; Dungey et al. 2006).

These results have significant implications. It is generally accepted that a threshold for MOE of between 7 and 8 GPa separates structural-grade from non-structural-grade timber (Sorensson et al. 2004). The value of structural-grade timber increases above this threshold to a maximum of 12 GPa, as the timber becomes stiff enough for more valuable end uses. Our results suggest that deployment of clones with high MOE will meet both minimum structural-grade thresholds (8 GPa) and thresholds for higher end uses (with thresholds of 10 and 12 GPa) at earlier ages than seedlings. This should allow a greater proportion of the typically unutilized, and often substantial (Walker and Butterfield 1996), juvenile core to be cut to structural-grade material. Previous research using real lumber grade outturns has shown substantial increases in log value as the diameter of the substandard low-stiffness (less than 7–8 GPa) juvenile core shrinks (Sorensson et al. 2004). As previous research shows that there

Fig. 2. Relationship between tree age and (a) density, (b) microfibril angle, and (c) modulus of elasticity for the two clones with the highest mean values (upper thin black lines), lowest mean values (lower thin black lines), and intermediate modulus of elasticity (grey lines). Also shown for reference are changes in wood properties with age for the seedling material (thick black line). The error bar shown is a least significant difference. Differences between clones greater than this are significant at *P* = 0.05.



is little interaction between site and clone (Lasserre et al. 2008), it is likely that the findings here are applicable over a broader environmental gradient.

Decision support systems will need to account for the relatively complex effect of age on clonal gains found here. Recent research has developed a suitable modelling framework for MOE that could be used to integrate information from clonal trials (Watt and Zoric 2010). This model is sen-

Table 3. Summary of intraclass correlation coefficients followed by root mean square error (in parentheses) for density, microfibril angle (MFA), and modulus of elasticity (MOE) over the range of tree ages represented in the data set.

Age (years)	Density	MFA	MOE
3	0.68 (22)	0.10 (4.9)	0.67 (0.7)
4	0.68 (29)	0.84 (2.1)	0.86 (0.6)
5	0.80 (24)	0.49 (3.2)	0.58 (1.1)
6	0.81 (40)	0.82 (3.5)	0.71 (2.2)
7	0.88 (32)	0.85 (3.0)	0.83 (1.7)
8	0.87 (32)	0.88 (2.8)	0.85 (1.8)
9	0.85 (32)	0.82 (3.0)	0.77 (1.9)
10	0.93 (25)	0.83 (2.8)	0.83 (2.0)
11	0.71 (48)	0.85 (2.4)	0.92 (1.6)
12	0.78 (50)	0.70 (2.9)	0.84 (2.1)

Table 4. Percent correct allocations of clones above the median clone value at age 12 for density and modulus of elasticity (MOE) and below the median clone value at age 12 for microfibril angle (MFA); also shown in parentheses are the percent correct allocations of the superior 50% of trees at age 12 for all three traits.

Tree age (years)	Density	MFA	MOE
12	100 (100)	100 (100)	100 (100)
11	100 (100)	100 (92)	100 (100)
10	100 (100)	100 (92)	100 (100)
9	100 (100)	100 (92)	100 (100)
8	100 (92)	100 (92)	100 (100)
7	83 (85)	100 (92)	100 (100)
6	83 (92)	100 (92)	100 (100)
5	67 (85)	83 (92)	83 (92)
4	83 (85)	83 (77)	83 (92)
3	83 (85)	83 (77)	83 (85)

Note: Percent allocations were undertaken using area-weighted values of each property at each age.

sitive to tree dimensions and accounts for the effect of site, age, and silviculture (stocking and weed competition) on MOE. Using this model, any deviation from the predicted MOE could be interpreted as the genetic effect, given that the effects of site, age, and silviculture are accounted for by the model. Such an approach would allow the rapid identification and assimilation of the genetic effect (additive and nonadditive effects) into a decision support system. Integration of breeding values from the New Zealand *P. radiata* breeding population may provide an alternative means of rapidly defining the additive genetic effect. Development of such a decision support tool could be used by managers to identify, for a given site, the optimal silviculture and genetics required to optimize both structural grade outturn and crop value.

Analyses suggest that the clonal interaction with age was predominantly attributable to divergence in MFA over time between clones representing the extremes in this wood char-

acteristic. Analyses show that for all tree ages greater than 3 years, ring-level MOE was closely coupled to MFA but only weakly to moderately correlated with density. These results concur with previous research that has shown the relationship between density and MOE to be insignificant or weak within *P. radiata* corewood (Walker and Woollons 1998; Burdon et al. 2001; Lasserre et al. 2009). Previous research shows that density does become a more significant determinant of MOE than MFA in outerwood (Cown et al. 1999). In this study, we found an increase in the strength of this correlation with time that suggests that the moderate relationship between density and MOE is likely to transition to a strong relationship as tree age increases above 10 years. The weak and insignificant negative relationship between MFA and density agrees with previous detailed measurements of these two traits within *P. radiata* corewood (Lasserre et al. 2009). The substantial main and interactive effect of clone and age on wood density found here also concurs with previous research (Cown et al. 2002).

Our analyses suggest that measurements of MOE taken from tree age 5 onwards can be used to identify clones with high MOE. This was clearly shown by both the intraclass correlations and the percentage of correct clonal rankings for MOE that both increased markedly above age 5. This threshold agrees with more detailed research by Dungey et al. (2006) who showed that *P. radiata* clones could be successfully selected for high MOE (at breast height) between ages 4 and 8. Our results are less consistent with research on MFA. Heritability estimates, for this trait, at ring 6 were higher than earlier and later ages (rings 3 and 9; P.A. Jefferson, J. Lee, R. Ball, and D.J. Cown, unpublished data). Similarly, individual repeatabilities of 0.71, 0.47, 0.9, and 0.72 were estimated at rings 1, 5, 9, and 15 by Donaldson and Burdon (1995), indicating that early selection for clones would be effective as early as ring 1. However, MFA is arguably more difficult to measure than MOE and it is more efficient to select for MOE, particularly as MOE has been shown to have a higher heritability than its component traits (Dungey et al. 2006).

As MOE is the criterion on which structural grading is based, it is preferable that genetic selection is undertaken directly on this property rather than on its constituents MFA and density. A number of relatively inexpensive methods are available for screening MOE in *P. radiata* clones. SilviScan MOE could be obtained from single X-ray diffraction scans of 30–50 mm long, 5 mm diameter outerwood plugs (cores) scanned at a rate of around 300 samples a day using a tool that was built specifically for precision. Secondly, there is a less precise method based on the removal of small axial samples of outerwood at age 5 on which dynamic MOE can be measured using sonics (Ilic 2003). There are also several different acoustic tools that are able to estimate MOE quickly on standing trees and logs (Lindström et al. 2002; Huang et al. 2003; Wagner et al. 2003; Lasserre et al. 2007). These methods may generally be less precise than SilviScan, although many are likely to be satisfactory in providing relative rankings of average wood properties if sufficient sample sizes are measured (Lindström et al. 2002). In New Zealand, sonic tools are commonly used for this purpose, as SilviScan, run in research mode, has been relatively expensive for ranking the breeding population.

Although MOE strongly affects structural-grade outturn, it should also be noted that timber warp (mainly due to spiral grain) and a high maximum branch size can also result in structural timber downgrade. Maximum branch diameter can be manipulated through genetics (Watt et al. 2000) and markedly declines as final crop stocking increases (Inglis and Cleland 1982; Tomblason et al. 1990). As high final crop stockings are typically used for structural-grade regimes (400–500 stems·ha⁻¹), these stands generally have a low incidence of branches with a diameter greater than the thresholds used in machine stress and visual grading.

Although the findings presented here were reasonably conclusive, the data were subject to some limitations. One of the key limitations of the data was the low replication per clone. Despite this low sample size, the strong intraclass correlations found for all traits, particularly at older ages, do provide evidence of the uniformity of wood properties between the two selected ramets within each clone. It is also worth noting that the range in MOE found here for these clones is likely to underestimate the entire population range, as a large number of the clones selected here had parents with a density well below that of the overall population mean.

In conclusion, this study clearly shows that there is a significant and marked age × clone interaction for MOE. This interaction shows that clonal gains are likely to increase markedly throughout the juvenile wood. Further model development should be undertaken to accurately describe this complex effect. Development of decision support tools that account for the effects of silviculture and genetics will allow growers to simulate how high-MOE clones can be used to modify grade outturn and crop value for a particular site.

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