Genetic variation in wood basic density and pilodyn penetration and their relationships with growth, stems straightness and branch size for *Eucalyptus urophylla* S. T. Blake in Northern Vietnam

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Abstract

Genetic parameters for wood basic density and pilodyn penetration and their relationship with diameter, height, stem straightness and branch size were estimated in two thinned open-pollinated progeny trials of *Eucalyptus urophylla* in northern Vietnam at the age of eight and nine years. The number of families was 127 in one trial and 144 in the other trial, all families were from nine natural provenances and 120 of them were common to both sites. At the time of assessment, each family was represented by from four to eight trees in each trial. Wood basic density, estimated from 5 mm increment cores taken at breast height, averaged 510 kg t^{-1}across the two trials. Estimated narrow sense individual tree heritability ($\hat{h}^2$) for wood basic density was 0.60, and that for pilodyn penetration was 0.42. The estimated coefficient of additive genetic variation (CV_A) for wood basic density was 6.3%. There were no significant differences between provenances for these two traits. The estimated genetic correlation between pilodyn penetration and wood density was -0.86, indicating that pilodyn could be used reliably as an indirect measurement of wood basic density. The estimated genetic correlations among wood basic density and diameter at breast height, height, stem straightness and branch size at each site were weak. Strong estimated genetic correlation between inner wood density and total core density indicated that reliable selection for wood density could be carried out at age three years. Estimated genetic correlations between sites for both wood basic density and pilodyn penetration were strong, indicating little genotype-by-environment interaction for these traits.

Introduction

Most plantations of *Eucalyptus urophylla* S. T. Blake in northern Vietnam are established for pulp wood (Tai, 1994). Therefore, growth traits and wood properties affecting the pulping process need to be addressed in an efficient breeding program in Vietnam. Basic density is one of the most important wood property traits, both for pulpwood and solid wood products (Raymond, 2000). For the pulping industry it affects freight costs, pulp production for a given mill size, chemical and power consumption, and paper quality (Zobel and van Buijtenen, 1989; Zobel and Jett, 1995; Greaves and Borralho, 1996, Geaves et al., 1997a Wei and Borallho, 1999). Density is therefore one of the most studied wood characteristics in eucalypts. It is relatively easy to measure, the measurement cost is low, it can be studied with non-destructive method and the heritability is generally high (Borralho, 1992; Raymond, 2002; Greaves et al., 1996). Generally, density in eucalypts has been reported to be under strong genetic control with individual heritabilities ranging between 0.4 and 0.84 (Borralho et al., 1992; Raymond, 1995; Zobel and Jett, 1995; Greaves et al., 1997b; Wei and Borralho, 1997). Genetic correlations between basic density and growth traits have been weak, but often unfavorable (Borralho et al., 1992; Greaves et al., 1997b; Wei and Borralho, 1997, 1999).

Pilodyn penetration, an indirect method for determining wood basic density, has been effective in assessing large number of trees in eucalypts (Greaves et al., 1996, Wei and Borralho, 1997). Greaves et al. (1996) demonstrated that pilodyn assessment can yield the same amount of gain as direct selection for density, due to its cheaper cost and thereby the ability to measure more trees resulting in higher selection intensity.

Up to now, the knowledge about genetic control of wood density of *E. urophylla* in Vietnam is poorly known. Currently, published information on genetic variation in wood basic density in *E. urophylla* is limited with a few studies conducted in China (Wei and Borralho, 1997; Luo, 2003), Mexico (Ignacio-Sanchez et al., 2005) and South Africa (Darrow and Roeder, 1985).

The aim of this study was to determine how best to integrate selection for wood density into genetic improvement programs for *E. urophylla* in Vietnam. To do this we estimated genetic parameters for wood basic density and pilodyn penetration, the genetic correlations between wood basic density and growth traits, 'age-age' genetic correlation for wood density, and genotype by environment interaction in wood density between two sites in northern Vietnam.

Materials and Methods

Genetic material and locations

The study was based on the two thinned open-pollinated progeny trials of *E. urophylla* established at Van Xuan (1996) and Ba Vi (1997). In each trial, a total of 144 families from randomly selected trees in nine natural provenances from Indonesia, mainly from Flores, Wetar, Pantar and Alor islands (Table 1) were tested. The provenances tested were all from elevations of less than 600 m. Higher-elevation provenances, known to display slower growth from earlier trials in other tropical countries (CABI 2000), were not included.

Table 1

Both trial sites have climatic and soil conditions typical of the areas where *E. urophylla* is planted in northern Vietnam. The soil is degraded ferralitic clay-loam (Chieu and Thuan, 1996) with general loss of topsoil through erosion. Soil depth is 40–70 cm, with low levels of nitrogen, phosphorus and potassium (Chieu and Thuan, 1996). Mean annual rainfall at both sites is in the range 1700 – 1800 mm, with a peak from May to October. The trials were established using row-column designs generated by the computer program Alpha+ (Williams and Matheson, 1994) with 8 replicates, 12 incomplete row blocks and 12 incomplete column blocks in each replicate. Each family was represented in each replicate by a single 4-tree row plot. Further details on trial layout and establishment are given in Table 2.

Table 2

In order to convert the progeny trials to seedling seed orchard to supply seed for plantations, both trials were thinned after the second year measurement, reducing stocking from four trees to one tree per plot. The thinning was based on visual assessment of growth and tree form, generally retaining the largest and straightest tree in each plot with the restriction that within planting rows, retained trees were at least 3 m apart. In Ba Vi, after 5 years an additional thinning was conducted by removing the poorest families and some poor trees from other families, leaving 127 families with 4 to 6 trees per family. There were 120 families in common across the two trials.

Data collection

Measurements and increment cores were collected from all surviving trees in August 2005, at which time the Van Xuan trial was aged 9 years, and Ba Vi 8 years. Diameter at breast height (DBH) and tree height (HT) were measured, stem straightness (STR) and branch size (BRA) were assessed using a five-class relative scoring according to Kha and Hung (1998), where class 3 is acceptable stem straightness and branch size, 1 is a very crooked stem or a tree with very thick branches, and 5 is a very straight stem or a tree with very small branches. Pilodyn penetration (PP) was measured using a 6J Forest Pilodyn, by removing a small section of bark

at 1.3 m and taking two Pilodyn shots on each tree, according to method described by Hansen (2000), the directions for Pilodyn shots were the same for all trees, one in the south and one in the east part of the stem. Five mm pith to bark increment cores were taken at a height of 1.3 m in the east-west orientation from all trees in the two trials, immediately stored in plastic tubes with both ends sealed, and later taken to a freezer. Wood basic density (DEN) was determined using the water displacement method (Olesen, 1971), with two weights for every sample: weight of water displaced by immersion of core, which indicates fresh volume of the sample (w_1); and oven dry weight (w_2). DEN was then calculated as:

$$DEN = \frac{w_2}{w_1} \text{ (g cm}^{-3}\text{)}$$

The method of water displacement is considered as one of the most precise method, especially when working with small samples (Valencia and Vargas, 1997).

In Van Xuan, DEN was measured for whole core density. In Ba Vi, in order to estimate 'age-age' correlation, each increment core was cut into three segments with equal length, numbered 1 to 3 from pith to bark. DEN of each segment was determined as described above, and total core basic density was then calculated as:

$$DEN = \frac{w_{2(1)} + w_{2(2)} + w_{2(3)}}{w_{1(1)} + w_{1(2)} + w_{1(3)}} \text{ (g cm}^{-3}\text{)}$$

Where $w_{1(1)}, w_{1(2)}, w_{1(3)}$ and $w_{2(1)}, w_{2(2)}, w_{2(3)}$ are the weight in water displaced (w_1) and oven dry weight (w_2) of the segment 1, 2 and 3, respectively.

Statistical analysis

Since class frequencies for straightness and branch size were not normally distributed, they were linearized by a normal score transformation (NORTON and GIANOLA, 1981).

The linear mixed-effects model equation for single site analysis was:

$$\mathbf{y} = \mathbf{X}_B\mathbf{b} + \mathbf{X}_M\mathbf{m} + \mathbf{Z}_\mathbf{W}\mathbf{w} + \mathbf{Z}_\mathbf{C}\mathbf{c} + \mathbf{Z}_\mathbf{F}\mathbf{f} + \mathbf{e} \qquad (1)$$

Where **y** is the vector of observations of PP, DEN, DBH, HT, STR or BRA, **b** is the vector of fixed replicate effects, **m** is the vector of fixed provenance effect, **w** is the vector of random row within replicate, **c** is the vector of column within replicate, **f** is the vector of random family effects, and **e** is the vector of random residuals. $\mathbf{X}_B, \mathbf{X}_M, \mathbf{Z}_\mathbf{W}, \mathbf{Z}_\mathbf{C}$ and $\mathbf{Z}_F$ are incidence matrix relating **b**, **m, w, c, f** and **e** to **y**.

The (co)variance of the random terms in the model were assumed to be the following:

$$VAR\begin{bmatrix}\mathbf{y}\\ \mathbf{w}\\ \mathbf{c}\\ \mathbf{f}\\ \mathbf{e}\end{bmatrix} \sim \begin{bmatrix}\mathbf{V} & \mathbf{Z_W W_0} & \mathbf{Z_C C_0} & \mathbf{Z_F G_0} & \mathbf{R_0}\\ \mathbf{W_0 Z_W'} & \mathbf{W_0} & \mathbf{0} & \mathbf{0} & \mathbf{0}\\ \mathbf{C_0 Z_C'} & \mathbf{0} & \mathbf{C_0} & \mathbf{0} & \mathbf{0}\\ \mathbf{G_0 Z_F'} & \mathbf{0} & \mathbf{0} & \mathbf{G_0} & \mathbf{0}\\ \mathbf{R_0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{R_0}\end{bmatrix}$$

where $\mathbf{W_0, C_o, G_0}$ and $\mathbf{R_0}$ are the row, column, family and residual covariance matrices, respectively, and **0** is a null matrix. The phenotypic variance is:

$$\mathbf{V_i} = \mathbf{Z}_{F_i}\mathbf{G_0}\mathbf{Z}'_{F_i} + \mathbf{R_0}$$

Genetic correlations between sites were estimated based on multivariate REML analysis, by treating measurements from different sites as different traits based on model (1) including the term for different sites – replicates, rows and columns. Variances, covariance components and genetic correlations at individual sites were directly estimated from $\mathbf{W_0, C_0, G_0}$ and $\mathbf{R_0}$.

The following linear mixed model was applied in the pooled analysis to estimate pooled heritabilities:

$$\mathbf{y} = \mathbf{X}_S\mathbf{s} + \mathbf{X}_B\mathbf{b} + \mathbf{X}_M\mathbf{m} + \mathbf{Z_W w} + \mathbf{Z_C c} + \mathbf{Z_F f} + \mathbf{Z_I i} + \mathbf{e} \qquad (2)$$

Where **y** is the vector of DEN, PP in both sites, **s, b** and **m** are the vector of fixed site, block within site and provenance effect, respectively; **i** is the vector of the effect of family by site (GEI) interaction, and $\mathbf{Z_I}$ is the incidence matrix for family by site interaction. Before conducting the pooled analysis, data was standardized to the same additive variance by dividing it by the square root of family variance from each site. This eliminates the effect of heterogeneous genetic variance across different sites.

The data analyses were implemented using ASREML software (Gilmour et al., 2001).

The significance of fixed effects was assessed using F-tests.

The coefficient of genetic relationship (*r*) was assumed to be 0.33 for open pollinated families of *E. urophylla* originating from natural stands, because population genetic studies have detected high rates of out-crossing in natural populations of the species (Gaioto et al., 1997). Additive genetic variance (σ_A^2), phenotypic variance (σ_P^2), narrow sense individual tree heritability for single site ($\hat{h}^2$) and across-site ($\hat{h}_p^2$), coefficient of additive variation (CV_A), genetic correlation (r_g) and phenotypic correlation (r_p) between traits were estimated as:

$$\sigma_A^2 = \frac{\sigma_f^2}{r} = 3\sigma_f^2$$

$\sigma_P^2 = \sigma_f^2 + \sigma_e^2$ for single sites, and

$\sigma_P^2 = \sigma_f^2 + \sigma_{fs}^2 + \sigma_e^2$ for pooled sites

$\hat{h}^2 = \frac{\sigma_A^2}{\sigma_f^2 + \sigma_e^2}$ for single sites, and

$\hat{h}_p^2 = \frac{\sigma_A^2}{\sigma_f^2 + \sigma_{fs}^2 + \sigma_e^2}$ for pooled sites

$CV_A = \frac{100\sigma_A}{\overline{X}}$, where $\overline{X}$ is mean value of the trait

$r_g = \frac{\sigma_{A_1 A_2}}{\sigma_{A_1}\sigma_{A_2}}$

$r_p = \frac{\sigma_{P_1 P_2}}{\sigma_{P_1}\sigma_{P_2}}$

where: σ_f^2 is family within provenance variance, σ_{fs}^2 is family by site interaction variance and σ_e^2 is the residual variance. Standard errors of the estimates of heritabilities, genetic and phenotypic correlations were calculated using a standard Taylor series approximation in the ASREML software (Gilmour et al., 2001).

Results

Provenance differences in DEN and PP

Mean values of density and pilodyn penetration are given in Table 1. The values were consistent for the two sites, around 0.51-0.52 g cm^{-3} for density and 16.7 for pilodyn penetration (Table 3). There were no significant differences between provenances either for density or pilodyn penetration, density ranged from 0.50 to 0.53, and pilodyn ranged from 16.0 to 17.2). This indicated that selection of provenances for wood basic density would not be effective.

Table 3

Estimates of heritabilities for DEN and PP

Estimated narrow sense individual tree heritability ($\hat{h}^2$) and estimated coefficients of additive genetic variation (CV_A) for DEN and PP in both trials are listed in Table 4. Heritabilities estimated for DEN were between 0.58 and 0.61, and higher than those for PP, which were

between 0.40 and 0.43. The coefficients of additive genetic variation estimated for DEN were also higher than those for PP.

Table 4

Correlation between PP, DEN and growth traits

Estimated genetic correlations between the wood density traits PP and DEN and the growth and stem form traits DBH, HT, STR and BRA were low with high standard errors, and did not differ significantly from zero (Table 5).

Estimated genetic correlations between DEN and PP were high and negative (-0.86) in both sites, i.e. low density was associated with high pilodyn penetration. Phenotypic correlations between DEN and PP were relatively strong (-0.58 to -0.66), but lower than corresponding genetic correlations.

Table 5

Segment wood basic density at Ba Vi

Segment wood basic density, segment wood heritabilities and correlation between segment density and total core density are presented in Table 6. .

Wood basic density increased from pith to bark. The mean densities of segments 1, 2 and 3 were 0.44 g cm^{-3}, 0.51 g cm^{-3} and 0.56 g cm^{-3} respectively. Heritability was lowest in the segment 1 (0.45) and was 0.60 and 0.55 in segment 2 and 3, respectively. Genetic correlations between the densities in the three segments, and between the segments and total core density were very high (Table 6). The high correlations between segment 1 and total core ($r_g = 0.89$ and $r_p = 0.85$) suggested that selection for wood density can be effective at approximately 3 years.

Table 6

Across-site heritabilities and genetic correlation between sites for DEN and PP

Estimated narrow sense individual tree heritabilities for across-site ($\hat{h}_p^2$) and estimated genetic correlation between sites are presented in Table 7. Across-site heritabilities estimated for DEN and PP were slightly lower than that estimated for the individual sites, and across-site genetic correlations for DEN and PP were strong, at 0.70 for PP and 0.89 for DEN (Table 7).

Table 7

Discussion

Effect of thinning on heritabilities and genetic correlation

The trials used in this study were selectively thinned; therefore heritabilities and genetic correlation estimated could be biased by removing the poorest trees, and the poorest families at Ba Vi, at earlier ages. Selective thinning inflated heritabilities of growth traits in *Pinus radiata* (Matheson and Raymond, 1984). Therefore, the selective thinning would likely have affected the growth and stem form traits. Genetic correlations between DEN and PP and growth and stem form traits were weak and non-significant. The absence of strong genetic correlations between DEN and PP and growth and form traits suggests that selective thinning for growth and stem form would have had little effect on the genetic parameter estimates for density traits.

Provenance variation

The variation in wood density among provenances tested was small and provenances showed no significant difference in wood basic density and pilodyn penetration although the Lewotobi provenance displayed significantly faster growth in these trials (Nguyen Duc Kien et al., submitted). This finding agreed well with the results from Wei and Borralho (1997) in China where no differences in density was found among 5 natural provenances tested at the age of 5 years. However, Darrow *et al*. (1985) detected differences in wood basic density between *E. urophylla* seed sources in provenance trials in South Africa. Generally, the variation in wood density between provenances was large and significantly influenced by provenances were found in other Eucalypt species (Miranda et al., 2001; Raymond, 2002).

Genetic control and relationships between traits

Heritability estimates for DEN were high and corresponded well with results for the same species in China (Wei and Borralho, 1997; Luo, 2003), and in other eucalypt species (Borralho et al., 1992; Raymond, 1995; Zobel and Jett, 1995; Greaves et al., 1997b; Muneri and Raymond, 2000; Raymond et al., 2001; Kube et al., 2001; Arnold et al, 2004; Santos et al., 2004). Heritability estimates for PP were lower than those for DEN. The estimates in this study were lower than that estimated for the same species in China (Wei and Borralho, 1997). Heritability estimated for pilodyn penetration for eucalypt species have not been consistent among studies, the results having ranged between 0.3 and 0.6 (Greaves et al. 1996; MacDonald et al., 1997; Wei and Borralho, 1997; Muneri and Raymond, 2000; Sanhueza et al., 2002). The lower heritability estimated in this study for PP compared to that of DEN

suggested that selection for wood basic density based on PP would not give as high genetic gain as selection based on direct measurement of wood density.

Genetic correlations between PP, DEN and diameter, height, stem straightness and branch size were weak with large standard errors. The poor estimation of these correlations in our study was due at least in part to the reduced numbers of trees available for growth and stem form measurements that was a consequence of the thinning. Nonetheless, other researchers have similarly found weak correlations between density and growth and form traits in the same species (Wei and Borralho, 1997; Ignacio et al., 2005) and other eucalypt species (Borralho et al., 1992; Greaves et al., 1997b; MacDonald et al., 1997; Kube et al., 2001; Sanhueza et al., 2002; Arnold et al., 2004). The weak genetic correlation between wood density and growth suggested that it should be possible to breed to improve both density and growth of *E. urophylla* in northern Vietnam.

Genetic correlation between pilodyn penetration and wood basic density was strong and negative. This agreed well with finding in previous studies in *E. urophylla* (Wei and Borralho, 1997) and other eucalypt species (Greaves et al., 1996). The result indicated that PP was generally reliable as an indirect measure of wood basic density in *E. urophylla*. Kube and Raymond (2002) suggested a two-stage sampling strategy using pilodyn to assess random individual from each family and cores to assess selected individuals in *E. nitens* can deliver up to 70% of the gain from a strategy using cores to assess all trees from each family, at a much lower cost while selection using pilodyn alone resulted in only 29% of potential gains, even when large samples were taken (Kube and Raymond, 2002). The heritabilities found in their study were 0.47 for pilodyn and 0.55 for basic density and the genetic correlation between them was 0.90, comparable to this study. A cost effective approach in selection for wood density in *E. urophylla* could therefore use pilodyn to ranking families and then increment core could be used to determine wood basic density of individuals from the top ranking families based on pilodyn penetration.

Genotype by environment interaction

The strong genetic correlations between sites for both DEN and PP in this study showed that family by site interactions in wood density was relatively small. The lower genetic correlation between sites for PP than for DEN meant there would less accuracy in predicting family rankings across sites using pilodyn than direct density measurements. Results from this study corresponded well with previous study on *E. urophylla* in China that indicated low genotype by environment interaction for PP (Wei and Borralho, 1997).

Implication for optimal age selection

In tropical locations without a prolonged dry season, annual rings are not visible to the naked eye on eucalypt wood samples, owing to more or less continuous growth throughout the year. Therefore, wood cores were divided into segments, corresponding to approximate ages, to give an indication of age-age genetic correlations. Strong genetic correlation between wood density of segment 1 and the whole core implied that high genetic gain could be achieved if the selection for wood density was done at an age of about 3 years.

There are few publications describing age-age genetic correlation for wood density in eucalypts, but reported results agree with our findings, showing strong age-age genetic correlations (Greaves et al., 1997b; Raymond, 2002; Osorio et al., 2003; Luo, 2003). Greaves et al. (1997b) found very strong age-age genetic correlation between age 3 and age 7 (0.93 to 0.95) in *E. nitens*, and the correlations were well described by Lambeth's relationship with logarithm of age ratio. Osorio et al (2003) found the genotypic correlations for wood density between ages 3 years and 6 years for clones of *E. grandis* to be from 0.71 to 0.95. In a review by Raymond (2002), it is suggested that minimum age for wood density evaluation in eucalypts should be 3 years.

Conclusions and implications for tree improvement

Wood basic density reported in this study agreed well with previous published literature on *E. urophylla* (Eldridge et al., 1993; Wei and Borralho, 1997; Luo, 2003). The mean density of *E. urophylla* at age 9 years was 0.51 g cm^{-3} which is suitable for pulp and paper industry. In a review by Dean (1995), it appears that the most suitable range of basic density for pulpwood in eucalypts was 0.47 to 0.55 g cm^{-3} and pulp yield decline sharply when basic density exceeds 0.60 or falls below 0.4. Thus, substantial improvement in wood basic density to about 0.55 g cm^{-3} would likely benefit pulp production in Vietnam.

Wood basic density of *E. urophylla* in two progeny trials in northern Vietnam was under strong genetic control either based on direct measurement on increment cores ($\hat{h}^2 = 0.58 - 0.61$) or indirect measurement of pilodyn penetration ($\hat{h}^2 = 0.40 - 0.43$). Genetic correlations between density, pilodyn penetration and growth traits were not well estimated in this study because of the selective thinning that had been carried out in the trials, reducing population sizes and affecting genetic parameters for growth and form traits. Nonetheless, these correlations appeared to be weak. Strong estimated genetic and phenotypic correlation between pilodyn penetration and wood density from increment cores indicated that

pilodyn penetration can be a useful predictor of wood basic density in this species for ranking families for wood density, but will be less accurate for ranking individuals. The stronger estimated narrow sense individual tree heritabilities of wood density than pilodyn penetration will result in higher genetic gain achieved for selection based on wood density using increment cores than that relying on pilodyn penetration with the same selection intensity. Strong genetic correlation between density of inner wood segments and total core density indicated selection for wood density can be made at age three years. Genotype by environment interaction was small for both wood basic density and pilodyn penetration. Together with earlier results for growth traits (Nguyen Duc Kien et al., submitted), it is suggested that a single breeding population for *E. urophylla* in the northern areas of Vietnam would be an appropriate strategy and a selection index combining growth and wood density using appropriate economic weights is recommended.

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Table 1. Provenance origins and number of families per provenance in the trials

CSIRO Seedlot	Provenance	Lat.	Long.	Alt. (m)	No. of families	
					Ba Vi	Van Xuan
17564	Mandiri, Flores	08°15'S	122°58'E	410	7	11
17565	Lewotobi, Flores	08°32'S	122°48'E	375	32	35
17567	Egon, Flores	08°38'S	122°27'E	450	33	36
17831	N Ilwaki, Wetar	07°52'S	126°27'E	515	14	13
17836	SW Uhak, Wetar	07°39'S	126°29'E	350	17	25
17840	Wai Kui, Alor	08°14'S	124°44'E	540	4	5
17841	Piritumas, Alor	08°19'S	124°31'E	355	8	8
17842	Dalaki Mt, Pantar	08°31'S	124°05'E	440	5	5
17843	Baubilatung,Pantar	08°20'S	124°02'E	285	7	6

Table 2. Site and design details of the progeny trials

Trials	Ba Vi	Van Xuan
Latitude	21°08'N	21°15'N
Longitude	105°28'E	105°15'E
Altitude	60 m	36 m
Soil type	Degraded ferralitic	Degraded ferralitic
Soil depth	40 – 50 cm	50 – 70 cm
Annual rainfall	1700 mm	1800 mm
Rainy season	May - September	April - October
Dry season	October - April	November - March
Mean annual temp. (°C)	23.2	23.1
Mean of maximum daily temperature of hottest month (°C)	31.8	31.2
Mean of minimum daily temperature of coldest month (°C)	14.3	14.7
Site preparation	Ploughed	Ploughed
Planting date	May 1997	May 1996
Fertiliser (kg/ha)	3300 kg cattle manure + 330 kg NPK	3300 kg cattle manure + 330 kg NPK
Design	Row-column design, 8 replicates, 12 rows and 12 column, 4 trees/plot	Row-column design, 8 replicates, 12 rows and 12 column, 4 trees/plot
Spacing	4 m between rows x 1.5 m within rows	4 m between rows x 1.5 m within rows
Number of families	127	144

Table 3. Wood basic density (DEN) and pilodyn penetration (PP) of provenances in the two trials

CSIRO seedlot	Provenance	Ba Vi (8 years)		Van Xuan (9 years)	
		DEN (g/cm^3)	PP	DEN (g/cm^3)	PP
17564	Mandiri, Flores	0.50	17.2	0.51	17.1
17565	Lewotobi, Flores	0.51	16.8	0.51	17.0
17567	Egon, Flores	0.52	16.8	0.52	16.8
17831	N Ilwaki, Wetar	0.52	16.4	0.52	16.8
17836	SW Uhak, Wetar	0.52	16.9	0.51	17.0
17840	Wai Kui, Alor	0.51	16.3	0.50	17.2
17841	Piritumas, Alor	0.53	16.6	0.52	16.8
17842	Dalaki Mt, Pantar	0.52	16.0	0.52	16.5
17843	Baubilatung,Pantar	0.51	16.4	0.51	16.8
Mean		0.51	16.6	0.52	16.8
F probability		ns*	ns	ns	ns

- ns = not significant

Table 4. Estimated narrow sense individual tree heritability ($\hat{h}^2$) and estimated coefficient of additive genetic variation (CV_A) for wood basic density (DEN) and pilodyn penetration (PP) at Ba Vi and Van Xuan, and across-site, and estimated genetic correlations between sites

Traits	Trial	$\hat{h}^2 \pm s.e$	CV_A (%)	$r_g \pm s.e$
PP	**Ba Vi**	0.40 ± 0.12	4.8	
	Van Xuan	0.43 ± 0.10	5.2	
	Across-site ($\hat{h}_p^2$)	0.30 ± 0.09	4.9	0.70 ± 0.18
DEN	**Ba Vi**	0.61 ± 0.13	5.9	
	Van Xuan	0.58 ± 0.11	6.6	
	Across-site ($\hat{h}_p^2$)	0.51 ± 0.09	5.3	0.89 ± 0.12

Table 5. Estimated genetic correlations between DEN and PP and diameter at breast height (DBH), height (HT), stem straightness (STR) and branch size (BRA) at Ba Vi and Van Xuan

Trial	Trait	DBH	HT	STR	BRA	PP	DEN
Ba Vi	**DEN**	0.28 ± 0.25	0.10 ± 0.22	-0.34 ± 0.28	0.06 ± 0.45	-0.86 ± 0.10	
	PP	-0.25 ± 0.27	-0.18 ± 0.24	0.36 ± 0.31	0.16 ± 0.52		-0.86 ± 0.10
Van Xuan	**DEN**	0.27 ± 0.20	0.21 ± 0.24	-0.04 ± 0.19	-0.01 ± 0.23	-0.86 ± 0.07	
	PP	-0.14 ± 0.32	-0.29 ± 0.25	-0.14 ± 0.21	0.06 ± 0.24		-0.86 ± 0.07

Table 6. Estimated narrow sense individual tree heritability ($\hat{h}^2$) of core segment and total core wood basic density (diagonal), estimated genetic (above diagonal) and phenotypic correlations (below diagonal) between wood basic density of core segments and total cores at Ba Vi

Segment	**1**	**2**	**3**	**Total core**
1	**0.45 ± 0.13**	0.83 ± 0.07	0.72 ± 0.13	0.89 ± 0.05
2	0.76 ± 0.02	**0.60 ± 0.13**	0.91 ± 0.07	0.97 ± 0.01
3	0.51 ± 0.03	0.66 ± 0.02	**0.54 ± 0.13**	0.94 ± 0.03
Total core	0.85 ± 0.01	0.91 ± 0.01	0.84 ± 0.01	**0.61 ± 0.13**
Segment density ($g\ cm^{-3}$)	0.44	0.51	0.56	0.51