GENETIC VARIATION IN WOOD BASIC DENSITY AND PILODYN PENETRATION AND THEIR RELATIONSHIPS WITH GROWTH, STEM STRAIGHTNESS, AND BRANCH SIZE FOR *EUCALYPTUS UROPHYLLA* IN NORTHERN VIETNAM*

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ABSTRACT

Genetic parameters for wood basic density and pilodyn penetration and their relationships with diameter, height, stem straightness, and branch size were estimated in two thinned open-pollinated progeny trials of

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Eucalyptus urophylla S. T. Blake in northern Vietnam at the ages of 8 and 9 years. There were 127 families 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 four to eight trees in each trial. Wood basic density, estimated from 5-mm increment cores taken at breast height, averaged 0.51 g/cm^3 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 it 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. The 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 3 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 across these two similar environments.

Keywords: wood basic density; pilodyn penetration; heritability; genetic correlation; genotype by environment interaction; *Eucalyptus urophylla*.

INTRODUCTION

Most plantations of *Eucalyptus urophylla* 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 programme in Vietnam. Basic density is one of the most important wood property traits, for both pulpwood and solid wood products (Raymond 2002). For the pulping industry it affects freight costs, pulp production for a given mill size, chemical and power consumption, and paper quality (Greaves & Borralho 1996; Greaves, Borralho, & Raymond 1997; Zobel & Jett 1995; Zobel & van Buijtenen 1989). 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 non-destructively, and the heritability is generally high (Borralho *et al.* 1992; Raymond 2002). 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; Greaves, Borralho, Raymond, Evans, & Whiteman 1997; Raymond 2002; Wei & Borralho 1997; Zobel & Jett 1995). Genetic correlations between basic density and growth traits have been weak, with reports of both favourable and unfavourable correlations (Borralho *et al.* 1992; Greaves, Borralho, Raymond, Evans, & Whiteman 1997; Ignacio *et al.* 2005; Osorio *et al.* 2003; Wei & Borralho 1997).

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

Until now, there has been a lack of knowledge about genetic control of wood density of *E. urophylla* in Vietnam. Currently, published information on genetic variation in wood basic density in *E. urophylla* is limited to a few studies conducted in China (Luo 2003; Wei & Borralho 1997), Mexico (Ignacio *et al.* 2005), and South Africa (Darrow & Roeder 1983).

The aim of this study was to determine how best to integrate selection for wood density into genetic improvement programmes 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 were tested from randomly selected trees in nine natural provenances from Indonesia, mainly from Flores, Wetar, Pantar, and Alor Islands (Table 1). The provenances tested were all from elevations of less than 600 m. Higher-elevation provenances, known from earlier trials in other tropical countries to display slower growth (CABI 2000), were not included.

Both trial sites had climatic and soil conditions typical of the areas where *E. urophylla* is planted in northern Vietnam. The soil was degraded ferralitic clay-loam (Chieu

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

& Thuan 1996) with general loss of topsoil through erosion. Soil depth was 40–70 cm, with low levels of nitrogen, phosphorus, and potassium (Chieu & Thuan 1996). Mean annual rainfall at both sites was 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 & Matheson 1994) with eight replicates, 12 incomplete row blocks, and 12 incomplete column blocks in each replicate. Each family was represented in each replicate by a single four-tree row plot. Further details on trial layout and establishment are given in Table 2.

In order to convert the progeny trials to seedling seed orchards to supply seed for plantations, both trials were thinned after the second-year measurement, reducing stocking from four trees to one tree per plot, equivalent to a stocking of 416 stems/ha. 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 four to six 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 was 8

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	
Soil depth (cm)	40–50	50–70
Annual rainfall (mm)	1700	1800
Rainy season	May–September	April–October
Dry season	October–April	November–March
Mean annual temperature (°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	
Planting date	May 1997	May 1996
Fertiliser (kg/ha)	3300 kg cattle manure + 330 kg NPK	
Design	Row-column design, 8 replicates, 12 rows, 12 columns, 4 trees/plot	
Spacing	4 m between rows x 1.5 m within rows	
Number of families	127	144

years. Diameter at breast height and tree height were measured; stem straightness and branch size were assessed using a five-class relative score according to Kha & Hung (1998), where Class 3 is acceptable stem straightness and branch size, Class 1 is a very crooked stem or a tree with very thick branches, and Class 5 is a very straight stem or a tree with very small branches. Pilodyn penetration 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 the 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). Density was then calculated as:

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

Water displacement is considered to be one of the most precise methods, especially when working with small samples (Valencia & Vargas 1997).

In Van Xuan, wood basic density was measured for whole core density. In Ba Vi, in order to estimate "age-age" correlation, each increment core was cut into three segments of equal length, numbered 1 to 3 from pith to bark. Density 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 displaced in water (w_1) and oven dry (w_2) of Segments 1, 2, and 3, respectively.

Statistical Analysis

Since class frequencies for straightness and branch size were not normally distributed, they were linearised by a normal score transformation (Norton & Gianola 1981).

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

$$\mathbf{y} = \mathbf{X}_B\mathbf{b} + \mathbf{X}_M\mathbf{m} + \mathbf{Z}_W\mathbf{w} + \mathbf{Z}_C\mathbf{c} + \mathbf{Z}_F\mathbf{f} + \mathbf{e} \quad (1)$$

Where **y** is the vector of observations of pilodyn penetration, wood basic density, diameter at breast height, tree height, stem straightness, or branch size, **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. $\mathbf{X}_B$, $\mathbf{X}_M$, $\mathbf{Z}_W$, $\mathbf{Z}_C$, and $\mathbf{Z}_F$ are incidence matrices relating **b**, **m**, **w**, **c**, **f**, and **e** to **y**.

The (co)variances of the random terms in the model were assumed to be as follows:

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

where $\mathbf{W_0}$, $\mathbf{C_0}$, $\mathbf{G_0}$, and $\mathbf{R_0}$ are the row, column, family, and residual covariance matrices, respectively, and **0** is a null matrix.

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 $\mathbf{W_0}$, $\mathbf{C_0}$, $\mathbf{G_0}$, and $\mathbf{R_0}$.

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

$$\mathbf{y} = \mathbf{X}_S\mathbf{s} + \mathbf{X}_B\mathbf{b} + \mathbf{X}_M\mathbf{m} + \mathbf{Z}_W\mathbf{w} + \mathbf{Z}_C\mathbf{c} + \mathbf{Z}_F\mathbf{f} + \mathbf{Z}_I\mathbf{i} + \mathbf{e} \quad (2)$$

where **y** is the vector of wood density, pilodyn penetration in both sites; **s**, **b**, and **m** are the vectors of fixed site, block within site, and provenance effect, respectively; **i** is the vector of the effect of family-by-site interaction, and $\mathbf{Z_I}$ is the incidence matrix for family-by-site interaction. Before conducting the pooled analysis, data were standardised to the same additive variance by dividing 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^2_A), phenotypic variance (σ^2_P), narrow-sense individual tree heritability for single site ($\hat{h}^2$) and across-site ($\hat{h}^2_p$), coefficient of additive variation (CV_A), genetic correlation ($\hat{r}_g$), and phenotypic correlation ($\hat{r}_p$) between traits were estimated as:

$$\sigma^2_A = \frac{\sigma^2_f}{\mathrm{r}} = 3\sigma^2_f$$

$\sigma^2_P = \sigma^2_f + \sigma^2_e$ for single sites, and

$$\sigma^2_P = \sigma^2_f + \sigma^2_{fs} + \sigma^2_e \text{ for pooled sites}$$

$$\hat{h}^2 = \frac{\sigma^2_A}{\sigma^2_f + \sigma^2_e} \text{ for single sites, and}$$

$$\hat{h}^2_p = \frac{\sigma^2_A}{\sigma^2_f + \sigma^2_{fs} + \sigma^2_e} \text{ for pooled sites}$$

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

$$\hat{r}_g = \frac{\sigma_{A_1A_2}}{\sigma_{A_1}\sigma_{A_2}}$$

$$\hat{r}_p = \frac{\sigma_{P_1P_2}}{\sigma_{P_1}\sigma_{P_2}}$$

where σ^2_f is family within provenance variance, σ^2_{fs} is family-by-site interaction variance, and σ^2_e 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). Log likelihood ratio tests were used to test if the correlations between traits and sites were different from zero.

RESULTS

Provenance Differences in Wood Density and Pilodyn Penetration

Mean values of density and pilodyn penetration are given in Table 3. The values were consistent for the two sites, around 0.51–0.52 g/cm^3 for density and 16.7 for

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
	p-value	ns	ns	ns	ns

ns = not significant

pilodyn penetration. 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.

Estimates of Heritabilities for Wood Density and Pilodyn Penetration

Estimated narrow-sense individual tree heritability ($\hat{h}^2$) and estimated coefficients of additive genetic variation (CV_A) for density and pilodyn penetration in both trials are listed in Table 4. Heritabilities estimated for density were between 0.58 and 0.61, and higher than those for pilodyn penetration, which were between 0.40 and 0.43. The coefficients of additive genetic variation estimated for density were also higher than those for pilodyn penetration.

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	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	0.51 ± 0.09	5.3	0.89 ± 0.12

Correlation Between Pilodyn Penetration, Wood Density, and Growth Traits

Estimated genetic correlations between the wood density traits pilodyn penetration and density, and the growth and stem form traits diameter at breast height, tree height, stem straightness, and branch size, were low with high standard errors, and did not differ significantly from zero (Table 5).

Estimated genetic correlations between density and pilodyn penetration were high and negative (–0.86) in both sites, i.e., low density was associated with high pilodyn penetration and phenotypic correlations between them were relatively strong (–0.58 to –0.66). Both genetic and phenotypic correlations between density and pilodyn penetration were highly significant ($p<0.001$).

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

TABLE 5–Estimated genetic correlations between wood basic density (DEN) and pilodyn penetration (PP) and diameter at breast height (dbh), tree 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

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 Segment 1 (0.45) and was 0.60 and 0.55 in Segments 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 ($\hat{r}_g$ = 0.89 and $\hat{r}_p$ = 0.85) suggested that selection for wood density can be effective at approximately age 3 years.

Across-site Heritabilities and Genetic Correlation Between Sites for Wood Density and Pilodyn Penetration

Across-site heritabilities estimated for density and pilodyn penetration were slightly lower than those estimated for the individual sites, and across-site genetic correlations for density and pilodyn penetration were strong at 0.70 for pilodyn penetration and 0.89 for density, and highly significant (p <0.001).

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 have been biased by removal of the poorest trees, and the poorest families at Ba Vi, at earlier ages. Selective thinning inflated heritabilities of growth traits in *Pinus radiata* D. Don (Matheson & Raymond 1984). Therefore, the selective thinning would likely have affected the growth and stem form traits. Genetic correlations between wood density and pilodyn penetration, and growth and stem form traits, were weak and non-significant. The absence of strong genetic correlations between density and pilodyn penetration 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.

Wood Density and Provenance Variation

Wood basic density reported in this study agreed well with previously published reports on *E. urophylla* (Wei & Borralho 1997). The mean density of *E. urophylla* at age 9 years was 0.51 g/cm^3 which is suitable for pulp and paper manufacture. Dean (1995) indicated that the most suitable range of basic density for pulpwood in eucalypts was 0.47 to 0.55 g/cm^3 and that pulp yield declined sharply when basic density exceeded 0.60 or fell below 0.4. Thus, substantial improvement in wood basic density to about 0.55 g/cm^3 would likely benefit pulp production in Vietnam.

The variation in wood density among provenances tested was small and provenances showed no significant difference in wood basic density or pilodyn penetration, although the Lewotobi provenance displayed significantly faster growth in these trials (Kien *et al*. in prep.). This agreed well with the results of Wei & Borralho (1997) in China who found no differences in density among five natural provenances tested at the age of 5 years. However, Darrow & Roeder (1983) 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 significant differences have been found in other eucalypt species (Miranda *et al*. 2001; Raymond 2002).

Genetic Control and Relationships Between Traits

Heritability estimates for wood basic density were high and corresponded well with results for the same species in China (Luo 2003; Wei & Borralho 1997), and for other eucalypt species (Arnold *et al*. 2004; Borralho *et al*. 1992; ; Greaves, Borralho, Raymond, Evans, & Whiteman 1997; Kube *et al*. 2001; Muneri & Raymond 2000; Santos *et al*. 2004; Zobel & Jett 1995). Heritability estimates for pilodyn penetration were lower than those for density. The estimates in this study were lower than those for the same species in China (Wei & Borralho 1997). Heritability estimated for pilodyn penetration for eucalypt species has not been consistent among studies, ranging between 0.3 and 0.6 (Greaves *et al*. 1996; MacDonald *et al*. 1997; Muneri & Raymond 2000; Sanhueza *et al*. 2002; Wei & Borralho 1997). The lower heritability estimated in this study for pilodyn penetration than for wood density suggested that selection for wood basic density based on pilodyn penetration would not give a genetic gain as high as selection based on direct measurement of wood density.

Genetic correlations between pilodyn penetration, wood density, 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 partly 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 traits in the same species (Ignacio *et al*. 2005; Wei & Borralho 1997) and other eucalypt species (Arnold *et al*. 2004; Borralho *et al*. 1992; Greaves, Borralho, Raymond, Evans, & Whiteman 1997; Kube *et al*. 2001; MacDonald *et al*. 1997; Sanhueza *et al*. 2002). 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 findings in previous studies of *E. urophylla* (Wei & Borralho 1997) and other eucalypt species (Greaves *et al*. 1996). The result indicated that pilodyn penetration was generally reliable as an indirect measure of wood basic density in *E. urophylla*. Kube & Raymond (2002) suggested a two-stage sampling strategy in *E. nitens* using pilodyn to assess random individuals from each family and cores to assess selected individuals. This could deliver up to 70% of the gain from a strategy using cores to assess all trees from each family, and at a much lower cost, but selection using pilodyn alone resulted in only 29% of potential gains, even when large samples were taken (Kube & 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. A cost-effective approach in selection for wood density in *E. urophylla* could therefore be to use pilodyn to rank families and then increment cores 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 density and pilodyn penetration in this study showed that family-by-site interactions in wood density were relatively small. The lower genetic correlation between sites for pilodyn penetration than for density meant there would be less accuracy in predicting family rankings across sites using pilodyn than with direct density measurements. These results corresponded well with a previous study on *E. urophylla* in China that indicated low genotype-by-environment interaction for pilodyn penetration (Wei & Borralho 1997). However, it should be noted that the two trial environments in our study were relatively close and had similar soils and climates.

Implication for Optimal Selection Age

In tropical locations without a prolonged dry season, annual rings are not visible to the naked eye on eucalypt wood samples because of the 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, Borralho, Raymond, Evans, & Whiteman 1997; Luo 2003; Osorio *et al*.; Raymond 2002). Greaves, Borralho, Raymond, Evans, & Whiteman (1997) found very strong age-age genetic correlation between ages 3 and 7 years (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 and 6 years for clones of *E. grandis* to be from 0.71 to 0.95. In a review by Raymond (2002), it was suggested that the minimum age for wood density evaluation in eucalypts should be 3 years. This decision on age of assessment for wood density should take into account tree growth rate and stem size; a minimum age of 3 years would appear acceptable for *E. urophylla* in northern Vietnam, despite the relatively slow growth rates achieved.

CONCLUSIONS, AND IMPLICATIONS FOR TREE IMPROVEMENT

Wood basic density of *E. urophylla* in two progeny trials in northern Vietnam was under strong genetic control according to either 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 in this study could be affected by 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. To improve selection accuracy and genetic gain for wood density from indirect measurement, pilodyn penetration assessment prior to thinning is recommended. 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 3 years. Genotype-by-environment interaction was small for both wood basic density and pilodyn penetration. Together with earlier results for growth traits (Kien *et al*. in prep.), 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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