VARIATION IN PULP WOOD TRAITS BETWEEN EUCALYPT CLONES ACROSS SITES AND IMPLICATIONS FOR DEPLOYMENT STRATEGIES

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LUO JZ, ARNOLD RJ, CAO JG, LU WH, REN SQ, XIE YJ & XU LA. 2012. Variation in pulp wood traits between eucalypt clones across sites and implications for deployment strategies. A total of 20 hybrid eucalypt clones at age 5½ years across four sites in coastal south-west China were assessed for volume and a subset of these for wood basic density and wood mass production. Six of these clones were also assessed for kraft pulp yield. Across the four sites the average tree volume, wood basic density, tree wood mass and pulp yield were 0.119 m^3 $tree^{-1}$, 474 kg m^{-3}, 0.063 tonne $tree^{-1}$ and 49.0% respectively. There were significant differences between both sites and clones for all the key traits studied. The best site for wood mass productivity had average plot wood mass of 0.239 tonne while the poorest site, only 0.128 tonne. Significant clone × site interactions were found for survival, volume $tree^{-1}$, plot volume and plot wood mass. Clone and/or clone × site effects accounted for the major portion of variation for almost all the traits. However, site effects accounted for more variation on plot wood mass, indicating the importance of site selection. On account of the clone × site interactions, adopting a site-specific selection and deployment strategy was estimated to provide 15% greater wood mass yield across the region compared with a generalised selection and deployment strategy.

Keywords: Eucalypt hybrid, site effect, fibre yield, genotype by environment interaction, clonal deployment

LUO JZ, ARNOLD RJ, CAO JG, LU WH, REN SQ, XIE YJ & XU LA. 2012. Variasi ciri-ciri pulpa kayu klon *Eucalyptus* di tapak berlainan serta strategi aplikasinya. Sebanyak 20 hibrid *Eucalyptus* berusia 5½ tahun di empat tapak di pantai barat daya China dinilai untuk isi padu. Sebahagian daripadanya turut dinilai untuk ketumpatan kayu dan penghasilan jisim kayu. Enam daripada klon ini dinilai juga untuk hasil pulpa kraft. Di tapak yang dikaji, purata isi padu pokok, ketumpatan asas kayu, jisim kayu pokok serta hasil pulpa ialah masing-masing 0.119 m^3 $pokok^{-1}$, 474 kg m^{-3}, 0.063 tan metrik $pokok^{-1}$ dan 49.0%. Terdapat perbezaan signifikan antara tapak dan klon untuk semua ciri penting yang dikaji. Tapak yang paling baik untuk penghasilan jisim kayu mempunyai jisim kayu plot sebanyak 0.239 tan metrik berbanding tapak yang paling buruk prestasinya iaitu 0.128 tan metrik sahaja. Hubungan klon × tapak yang signifikan didapati untuk kemandirian, isi padu $pokok^{-1}$, isi padu plot dan jisim kayu plot. Klon dan/atau klon × tapak merangkumi sebahagian besar daripada variasi untuk hampir semua ciri. Bagaimanapun kesan tapak menyebabkan lebih banyak variasi bagi jisim kayu plot. Ini menunjukkan betapa pentingnya pemilihan tapak untuk menambah hasil ladang. Dari segi interaksi klon × tapak, amalan pemilihan serta strategi aplikasi yang berdasarkan tapak dianggarkan dapat memberi peningkatan hasil jisim kayu sebanyak 15% di daerah ini berbanding pemilihan dan strategi aplikasi yang umum.

INTRODUCTION

The area of eucalypt plantations in China is currently estimated to be well over 3 mil ha (ITTO 2011). The overwhelming majority of this resource is managed on relatively short rotations (seven years or less) with the primary objective being profit through fibre production (Chen 2002, Chen et al. 2010). A number of multinational pulp and paper companies operating in China have some of the largest holdings of eucalypt plantations, both by area and by standing volumes, and these are mostly located in warmer coastal regions of southern China, including in provinces of Guangdong, Guangxi, Fujian and Hainan. Lesser areas of eucalypt pulpwood plantations are located in Yunnan, Sichuan, Jiangxi and Hunan provinces.

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In the warmer coastal regions of China, selected hybrid clones of *Eucalyptus grandis, E. urophylla, E. camaldulensis* and/or *E. tereticornis* now account for the vast majority of planting stock for eucalypt pulpwood plantations (Wei 2005). Interest in deploying hybrid eucalypt clones in China developed in the mid- to late 1980s following the introduction and testing of a number of hybrids from Brazil at Dongmen State Forest Farm in southern Guangxi (Li et al. 2003). Since then, a number of organisations in southern China have been actively involved in developing, testing and selecting eucalypt hybrid clones (Turnbull 2007).

Although substantial resources have been devoted to tree improvement over the past 20 years or so in southern China, and many hundreds of eucalypt hybrid genotypes have been produced and included in field trials, the number of clones selected from these and then used commercially on a significant scale is relatively small (Cossalter & Barr 2005, Turnbull 2007). Indeed, a survey of eucalypt nurseries carried out in southern China in 2005 indicated that as few as three clones accounted for more than 60% of the planting stock (Wei 2005). For the 2006 planting season, Turnbull (2007) estimated that this number of clones accounted for as much as 90% of the eucalypt plantation area established, and there has been little change since that time.

Part of the reason for the limited commercial acceptance of greater numbers of hybrid eucalypt clones in southern China is a lack of systematic clonal field tests with subsequent lack of availability of information and data on potential clonal performance across sites. Numerous clonal field trials have been established over the past 20 years or so in this region but only limited results have been reported. Despite the number of field trials established, inconsistencies in trial design and clones tested often make it difficult to compare results and performance across trials.

In order to examine the magnitude and practical importance of genotype by environment interactions with commercial clones across planting sites in coastal south-west China, a range of well-known and candidate commercial clones was established across four field sites in southern Guangxi in May 2003. The objectives for these field trials included: (1) obtaining detailed data on both the growth and wood properties, especially basic density and pulp yields, across sites for such set of clones, (2) examining the magnitude of clone × site interaction between the set clones and its impact on yields, and (3) examining how such data could be used to optimise deployment of clones with respect to matching of clones/varieties to site types.

MATERIALS AND METHODS

Genetic material

This study included a total of 20 clones established across four trial sites in southern China. The details of these clones are provided in Table 1. Two of the trials each included all 20 clones, whilst the other two included only 18 of the 20 clones. Among these clones were some of the most popular commercial clones (i.e. clones most planted as judged by surveys of commercial nurseries).

Field trial sites and trial design

Details on the four trial sites, located in southern Guangxi province are provided in Table 2. The straight line distance between sites ranged from 47 to about 260 km. All four trials were laid out in randomised complete block designs of four to six complete replicates. In each replicate, each clone was represented as a single row of five trees (i.e. five-tree-row plots) with 2 m between trees within rows and 4 m between rows. Previously, all sites were occupied by eucalypt plantations of various species/varieties which were felled (with stumps being removed) prior to establishment. The sites were disc ploughed to a depth of approximately 40 cm and ripped along the planting lines to a depth of 60 cm prior to laying out of each of the trials. Holes of 50 cm depth were hand dug for each tree and 250 g of base fertiliser, fused calcium-magnesium-phosphate (containing 140 g elemental P kg^{-1}), was applied in the base of each hole. At about one month after planting 500 g urea (containing 460 g elemental N kg^{-1}) was applied to each tree and then after two months, 250 g of $N_{15}P_{15}K_5$.

The trial stock comprised clonal rooted stem cuttings and tissue culture plants which averaged 25 cm tall when planted. Blanking (replanting of any dead trees) was carried out regularly during the first three months to provide more than 95% survival in all plots up to the age of six months.

Table 1 Taxonomy of clones included in the four clonal field trials and the number of trials for each clone

Clone code	Taxa (code)	Number of trial site
1	*E. urophylla* × *tereticornis* (U × T)	4
2	*E. urophylla* × *tereticornis* (U × T)	4
3	*E. urophylla* × *camaldulensis* (U × C)	4
4	*E. urophylla* × *urophylla* (U × U)	4
5	*E. grandis* × *tereticornis* (G × T)	4
6	*E. urophylla* × *grandis* (U × G)	4
7	*E. urophylla* × *grandis* (U × G)	4
8	*E. urophylla* × *grandis* (U × G)	4
9	*E. urophylla* × *grandis* (U × G)	4
10	*E. urophylla* × *grandis* (U × G)	4
11	*E. urophylla* × *grandis* (U × G)	4
12	*E. urophylla* × *grandis* (U × G)	4
13	*E. urophylla* × *grandis* (U × G)	4
14	*E. urophylla* × *grandis* (U × G)	4
15	*E. urophylla* × *grandis* (U × G)	4
16	*E. saligna* × *exserta* (S × E)	3
17	*E. urophylla* × *grandis* (U × G)	4
18	*E. urophylla* × *camaldulensis* (U × C)	3
19	*E. urophylla* × *tereticornis* (U × T)	3
20	*E. exserta* × *tereticornis* (E × T)	3
	Taxa	Number of clones
Summary	*E. urophylla* × *grandis* (U × G)	11
	E. urophylla × *tereticornis* (U × T)	5
	E. urophylla × *camaldulensis* (U × C)	5
	Other taxa	4

Table 2 Details of the four clonal field trial sites in southern Guangxi

Site	Latitude (N)	Longitude (E)	Elevation (m asl)	Soil texture	Mean annual temperature (°C)	Mean annual rainfall (mm year^{-1})
Dongmen	22° 22'	107° 51'	130	Clay loam	21.3	1213
Nali	21° 50'	108° 51'	17	Clay loam	22.8	1631
Shankou	21° 35'	109° 42'	27	Sandy	23.2	1713
Tiantang	21° 52'	109° 21'	27	Sandy	22.8	1491

Assessments

Growth and bark

In November and December 2008, at trial age of approximately 5½ years, all surviving trees in all four trials (1526 trees in total) were assessed for the following traits: (1) diameter at breast height (dbh, 1.3 m), measured over bark, (2) total height, measured using hypsometer and (3) bark thickness, measured directly using metal rule after removing a square of bark (approximately 2.5 × 2.5 cm) from each tree at dbh on the south side of the bole.

Basic density

For non-destructive assessment of wood basic density, 5-mm thick bark to bark increment cores were obtained from north to south direction at dbh using hand-powered increment corers. These were collected from the first five trees of each clone at each site deemed 'acceptable', starting from the first replicate and then proceeding to the second replicate and, if necessary, to the third replicate. Acceptable trees were those with dbh within ± 50% of the clone mean and without noticeable defects or branch stubs/knots visible near breast height. Each wood core was placed inside a plastic tube immediately after extraction, and this tube was sealed. The basic density of each sample core was subsequently determined using laboratory methodology described by Ilic et al. (2000).

Pulp yield

Wood samples used for determination of kraft pulp yields were obtained destructively from a limited number of trees and clones—one tree of each of clones 5, 11, 12, 15, 18 and 19 was felled at each site, except at the Nali site where a single tree of each of only five clones were felled (clone 19 was absent from Nali). After felling, two 30-cm long billets were cut from each tree at dbh and at half-tree height. Bark was removed from these billets before they were air dried (for 30 days) and made into wood chips (approximate dimensions of 12 × 12 × 5 mm). To provide a single composite chip sample from each tree, the wood chips from both heights were combined. A subsample of each of these composite samples was then oven dried (to reach constant mass). From this, a 150 g lot was then pulped using laboratory scale kraft pulping equipment according to the following parameters: active alkali concentration 18%, sulphidity 25%, cooking temperature was set to a maximum of 170 °C, cooking time of two hours to reach the maximum temperature and two hours at the maximum temperature, liquor to wood ratio of 5.5:1.0 (litres:kg), volumetric capacity of batch digester at 1.1 litre, and pulping to $KMnO_4$ number of approximately 13.0. Pulp yields were determined after pulp samples were washed, screened (screen hole size 0.1 mm), and air dried.

Data analyses

An index of under bark volume was calculated for each tree assessed using the following equation:

$$V = f \times \pi \times (DBHUB/200)^2 \times (Ht + 3)$$

where V = over bark tree volume (m^3), f = form-factor = 0.4, DBHUB = dbh under bark calculated as dbh over bark minus twice the bark thickness (cm) and Ht = total tree height (m).

Analyses of variance for all traits, except kraft pulp yield, were carried across site based on the following linear model:

$$Y_{ijk} = \mu + S_i + R_{j(i)} + C_k + GE_{i.k} + e_{ijk}$$

where Y_{ijk} = plot mean of clone k in replicate j at site i, μ = overall mean, S_i = effect of site i, $R_{j(i)}$ = effect of replicate j within site i, C_k = effect of clone k, $GE_{i.k}$ = clone × site interaction effect and e_{ijk} = residual error with mean of zero.

Computations of clone means and analyses of variance were carried out using procedures described by Williams et al. (2002). These analyses used the general linear model (GLM) procedure in SAS (SAS/STAT User's Guide, Version 8) and sites and clones were regarded as fixed effects while replicates within sites, as random. Clone means were estimated as least squares means (LSMEANS) from these analyses. The VarComp Procedure in SAS was used to estimate variance components due to the various effects in the model, so the proportion of the total variation due to each effect could be estimated. To examine the effects of survival on comparisons between clones for both plot volume and plot wood mass, the analyses of variance were repeated with plot survival as covariate. Analyses of covariance, including estimation of covariate efficiency factors, were carried out using GLM procedure in SAS. The efficiency of this covariate was evaluated using the difference in the r-squared values obtained for the models with the covariate and without the covariate.

Given the limited sample size for kraft pulp yields (i.e. a single tree of each of five to six clones at each site), statistical analyses could not be conducted for this trait.

RESULTS

Survival, growth and productivity across sites

Analyses of variance across sites at age 5½ years showed significant differences between the four sites for all traits analysed (Table 3). When plot-level survival was included as covariate in the analyses of variance, the survival covariate proved significant ($p < 0.05$) for both plot volume and plot wood mass. However, the overall effect of the covariate was relatively small. For plot volume, the covariate increased the total proportion of variation accounted for by 18% and for plot wood mass the increase was only 4%.

The mean data obtained from the four sites with respect to the traits studied are presented in Table 4. The best overall survival was obtained at Tiantang (84.4%) whilst the poorest, at Dongmen (77.1%), which was the site with the lowest rainfall (Table 2). Despite good survival at Tiantang, average tree volumes there (0.104 m^3 tree-1) and at Shankou (0.097 m^3 $tree^{-1}$) were significantly lower compared with Dongmen and Nali (both averaged 0.138 m^3 $tree^{-1}$). Interestingly, the sites with poorer growth had higher basic density—Shankou had the highest average wood basic density (483 kg m^{-3}) compared with Dongmen (468 kg m^{-3}) and Nali (470 kg m^{-3}). Even so, the higher basic densities at Shankou and Tiantang were not sufficiently high to ameliorate the lower growth at these sites. Shankou and Tiantang were significantly inferior to Dongmen and Nali with respect to average wood mass $tree^{-1}$, with Nali also being superior to even Dongmen for this trait. In terms of the overall productivity (measured by both average plot volume and wood mass) the best site was Nali with 0.593 m^3 and 0.239 tonne $plot^{-1}$ respectively. For wood mass, this site nearly doubled that of the poorest site, Shankou (0.128 tonne $plot^{-1}$). Productivity at Dongmen was 0.513 m^3 and 0.225 tonne $plot^{-1}$ while Tiantang was intermediate at 0.457 m^3 and 0.166 tonne $plot^{-1}$.

For pulp yield, the differences between the four sites were not significant, ranging from 48.7% at Dongmen to 49.1% at Nali (Table 4). Though pulp yield can be used in combination with wood mass estimates to provide quantitative estimates of fibre yield, it seemed inappropriate to do this for the current study as the pulp yields were just based on a single tree sample from just 6 out of the 20 clones at each site.

Table 3 Across site analyses of variance for survival, volume $tree^{-1}$, core basic density, wood mass $tree^{-1}$ and plot wood mass at age 5½ years in the four clonal trials in southern Guangxi

Source of variation	Survival	Volume $tree^{-1}$	Wood basic density	Wood mass $tree^{-1}$	Plot volume	Plot wood mass
Site	*	**	*	**	**	**
Replicate-within-site	**	**	ns	ns	**	ns
Clone	**	**	**	**	**	**
Clone × site	**	**	ns	ns	**	*

ns = not significant, * = significant at $0.01 < p \le 0.05$, ** = significant at $p \le 0.01$

Table 4 Site means for survival, tree volume, core wood basic density, wood mass $tree^{-1}$, plot wood mass and screened kraft pulp yield from the four clonal trials established in southern Guangxi

Site	Survival (%)	Volume $tree^{-1}$ (m^3)	Wood basic density (kg m^{-3})	Wood mass $tree^{-1}$ (tonne)	Plot volume (m^3 $plot^{-1}$)	Plot wood mass (tonne $plot^{-1}$)	Screened kraft pulp yield (%)
Dongmen	77.1 b	0.138 a	468 b	0.066 b	0.513 b	0.225 a	48.7
Nali	82.2 ba	0.138 a	470 b	0.080 a	0.593 a	0.239 a	49.1
Shankou	78.2 b	0.097 b	483 a	0.048 d	0.374 d	0.128 c	49.0
Tiantang	84.4 a	0.104 b	474 ab	0.056 c	0.457 c	0.166 b	49.0
Average	80.5	0.119	474	0.063	0.484	0.190	49.0
LSD	5.3	0.007	11	0.006	0.039	0.033	na[1]

Means for a trait (i.e. means within one column) followed by the same letter are not significantly different as judged by Fisher's least significant difference (LSD) at $p < 0.05$; [1]screened kraft pulp yield was obtained as the mean of just a single tree sample of each of five to six clones at each site, hence the LSD for differences between site means for screened kraft pulp yield could not be obtained (not available)

Differences between clones

The differences between clones across sites were significant and substantial for all of the traits analysed as shown in Tables 3 and 5. The best three clones by survival were 5, 19 and 20 which averaged over 90% and all were hybrids of *E. tereticornis*. In contrast, the clones with the poorest survival across sites were *E. urophylla* × *grandis* or *E. saligna* × *exserta* hybrids (clones 10, 12 and 16), which had below 65% survival. The clones with the best average individual tree volume were 12 and 13, with over 0.150 m^3 $tree^{-1}$ and three times more volume than that of the poorest clone 16 (0.049 m^3 $tree^{-1}$, Table 5). However, clone 16 had the highest wood basic density (523 kg m^{-3}) and clone 13, the lowest (431 kg m^{-3}). In contrast, clone 12 had the fifth highest wood basic density (494 kg m^{-3}). Across sites, clones 1, 12 and 13 presented the highest wood mass $tree^{-1}$, exceeding 0.0890 tonne $tree^{-1}$ and clones 16, 19 and 20 had less than 0.0460 tonne $tree^{-1}$ (Table 5). Generally, the ranking for this trait was closer to individual tree volume than to core basic density. Even within the top 10 clones for highest plot volume and wood mass across sites, there were still considerable differentials in productivity (Table 5). The best clone for plot volume, clone 13 (0.681 m^3 $plot^{-1}$), had over 50% more volume than clone 8 (0.448 m^3 $plot^{-1}$), which was tenth in rank. Similarly, the best clone for plot wood mass, clone 5 with 0.271 tonne $plot^{-1}$, had approximately 50% more productivity than clone 15 with 0.181 tonne $plot^{-1}$. For pulp yield, the absolute magnitude of variation between sites was relatively small; greater variation was observed between some of the six clones evaluated for this trait (Table 6). Across sites, clonal means for pulp yield ranged from 47.6% for clone 19 to 49.8% for clones 12 and 15 (Table 6).

Clone × site interactions and variations between sites

There were significant differences between the performances of clones at the different sites (i.e. clone × site interaction) for survival, average volume $tree^{-1}$, plot volume and plot wood mass but not for core basic density (Table 3). To examine the potential importance of these interactions, the proportions of the total variation across sites attributable to identifiable component effects were quantified for each trait and the results are presented in Table 7. For survival, site effects accounted for a minor part of the total variation (< 2%) but clone and clone × site accounted for 13.4 and 14.5% respectively. In contrast, for volume $tree^{-1}$ it was site and particularly clone effects that contributed the larger portion of the variation (after error) while clone × site interaction accounted for only about 6% of its total variation. For wood basic density, variation between clones was the most important effect (43.9%). Site contributed almost as much as clones for wood mass $tree^{-1}$. Variation between sites for plot wood mass (24.9%) contributed a greater part of the total variation compared with clone × site (15.4%) and clone (8.8%) variations.

To further examine the impact of between site variation, clone–site means were plotted for selected traits for the top 10 clones (as judged by across site means for the trait of interest), as shown in Figure 1. From this it is clear that the best clones overall for volume $tree^{-1}$ consistently ranked among the best at each site, at least across the environmental range represented by these four trial sites. Clone–site means for plot wood mass were plotted for the best clones (Figure 2) and in contrast to volume $tree^{-1}$, results showed that the ranking of individual clones for this trait changed dramatically between study sites.

Deployment options—superior clones

Given that the ranking of clones, as judged by wood mass productivity, changed dramatically between sites, any plantation grower with a large estate dispersed across the region would be wise to evaluate the impact of alternate clonal selection and deployment strategies on their future economic yields. In order to examine such impacts, forecasts of total plantation productivity under alternate selection and deployment scenarios of site-specific selection and deployment and of generalised selection and deployment (i.e. based on average performance across sites), were computed for a notional 100,000 ha plantation estate (Table 8). In the range of environments represented by the trial sites studied here, the site-specific strategy would result in approximately 15% higher wood mass productivity across such an estate compared with a strategy involving selection on overall means across sites and then deployment of

Table 5 Clone means and ranks for survival, tree volume under bark, wood basic density, wood mass tree^{-1}, plot volume and plot wood mass across sites for the four clonal trials in southern Guangxi

Clone	Taxa[1]	Survival (%)	Rank	Volume tree^{-1} (m^3)	Rank	Wood basic density (kg m^{-3})	Rank	Wood mass tree^{-1} (tonne)	Rank	Plot volume (m^3 plot^{-1})	Rank	Plot wood mass (tonne plot^{-1})	Rank
1	U × T	67.3	16	0.124	8	481	9	0.0893	3	0.419	15	0.169	13
2	U × T	85.5	7	0.143	4	506	4	0.0804	7	0.603	3	0.236	3
3	U × C	83.6	11	0.141	5	522	2	0.086	4	0.584	5	0.229	5
4	U × U	88.2	5	0.1	16	483	8	0.0474	17	0.438	11	0.191	8
5	G × T	91.8	2	0.147	3	508	3	0.0848	5	0.657	2	0.271	1
6	U × G	84.5	9	0.123	9	434	19	0.0559	14	0.5	7	0.16	15
7	U × G	86.4	6	0.138	6	466	12	0.0808	6	0.603	4	0.249	2
8	U × G	78.2	15	0.109	12	450	17	0.0572	12	0.448	10	0.176	11
9	U × G	79.1	14	0.115	11	484	7	0.0614	9	0.469	9	0.209	7
10	U × G	62.7	19	0.126	7	451	15	0.0746	8	0.432	13	0.182	9
11	U × G	85.5	10	0.096	17	457	13	0.0539	16	0.405	18	0.127	18
12	U × G	58.2	20	0.154	2	494	6	0.0979	1	0.51	6	0.222	6
13	U × G	79.1	13	0.172	1	431	20	0.0937	2	0.681	1	0.23	4
14	U × G	85.5	8	0.102	15	497	5	0.0566	13	0.437	12	0.144	16
15	U × G	83.6	12	0.103	14	472	11	0.0544	15	0.428	14	0.181	10
16	S × E	63.5	18	0.049	20	523	1	0.0375	20	0.186	20	0.092	20
17	U × G	89.1	4	0.106	13	475	10	0.0592	10	0.47	8	0.173	12
18	U × C	67.3	17	0.121	10	451	16	0.0588	11	0.414	17	0.122	19
19	U × T	91.3	3	0.092	18	449	18	0.0453	18	0.417	16	0.165	14
20	E × T	93.8	1	0.071	19	457	14	0.0395	19	0.328	19	0.14	17
LSD		12.0		0.016		26		0.013		0.089		0.074	

[1]Details of these taxa are provided in Table 1

Table 6 Screened kraft pulp yields (%) of six clones sampled from the four clonal trials in southern Guangxi

Clone	Dongmen	Nali	Shankou	Tiantang	Mean
5	49.0	49.1	48.8	50.6	49.4
11	48.0	48.9	49.9	48.8	48.9
12	50.6	49.3	50.3	49.0	49.8
15	48.8	50.0	48.6	51.5	49.8
18	49.3	48.0	48.8	45.8	48.0
19	46.6	–	47.9	48.4	47.6
Mean	48.7	49.1	49.0	49.0	48.9

The value for each site–clone combination is based on a single tree sample; clone 19 was not included in the trial at Nali

Table 7 Proportion of total variation across sites for different traits attributable to site variation, clone variation and to clone × site interaction at 5½ years for the four clone trials in Guangxi

Source of variation	Survival (%)	Volume tree^{-1} (%)	Wood basic density (%)	Wood mass tree^{-1} (%)	Plot volume (%)	Plot wood mass (%)
Site	1.7	17.2	3.9	32.7	15.1	24.9
Replicate-within-site	1.7	8.8	0.0 ns	0.9 ns	5.0	0.0 ns
Clone	13.4	32.8	43.9	36.4	22.9	8.8
Clone × site	14.5	5.8	1.8 ns	5.6 ns	8.9	15.4
Residual	68.7	35.4	50.4	24.3	48.1	50.9

The proportion of total variation attributable to each effect is expressed as a percentage of the total variation; ns indicates the effect was not significant while other effects were significant at $p \leq 0.05$

the top five clones at all sites (i.e. 1,329,000 cf. 1,154,955 tonne year^{-1}). Across an estate of such magnitude the productivity increase was indeed very substantial, equating to more than 170,000 tonnes of pulpwood per year.

DISCUSSION

Sites

The study found significant differences between the same genetic material planted in the four different locations. These differences for individual tree and plot productivity might be due in part to soil type: Dongmen and Nali with clay soils provided significantly better growth than Shankou and Tiantang with sandy soils. However, this could not be confirmed and more detailed investigations would be required to elucidate the key soil and other environmental variables responsible for differences in productivity between sites represented in this study.

Variation in productivity of eucalypt genotypes across sites in southern China is a common occurrence. It has been reported that tree volume for three-year-old *E. urophylla* more than doubled between the poorest and best site across five sites in Guangdong (Xu et al. 2003). Mo et al. (2003) reported that growth of 27 clones varied significantly between three sites despite having similar climate including rainfall. However, in the present study, neither mean annual rainfall nor mean annual temperature was key determinant in site productivity. For example, Dongmen with the lowest rainfall and mean annual temperature had the highest average tree volume and ranked second best for plot volume and wood mass productivity (Table 4). On the other hand,

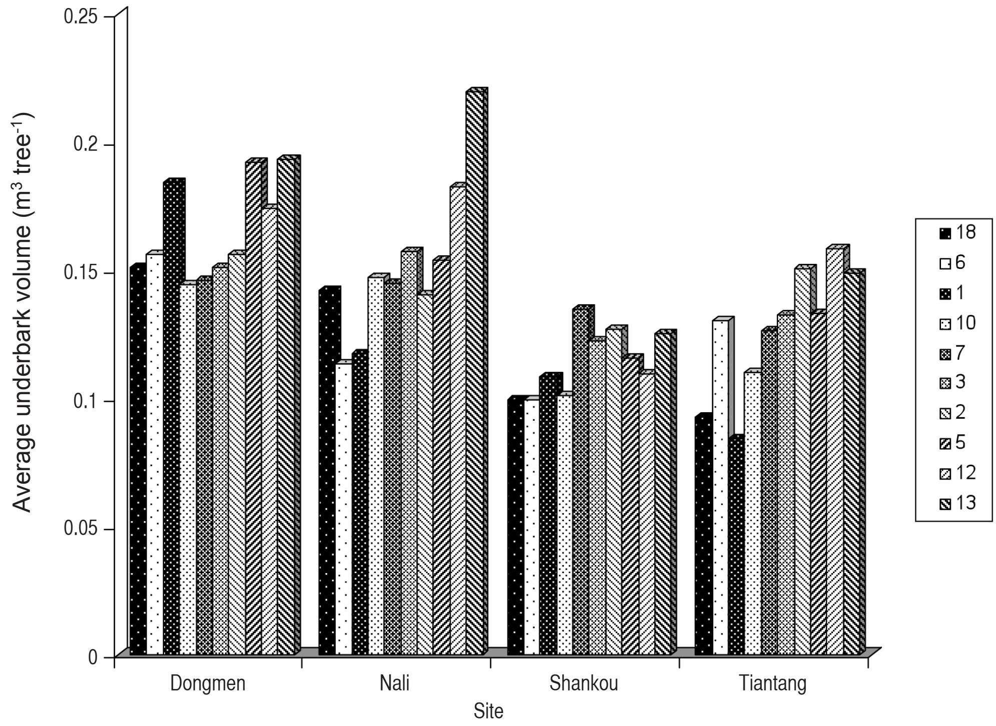

Figure 1 Clone–site means of each of the top 10 clones (judged by averages across sites; details in Table 5) for volume tree^{-1}

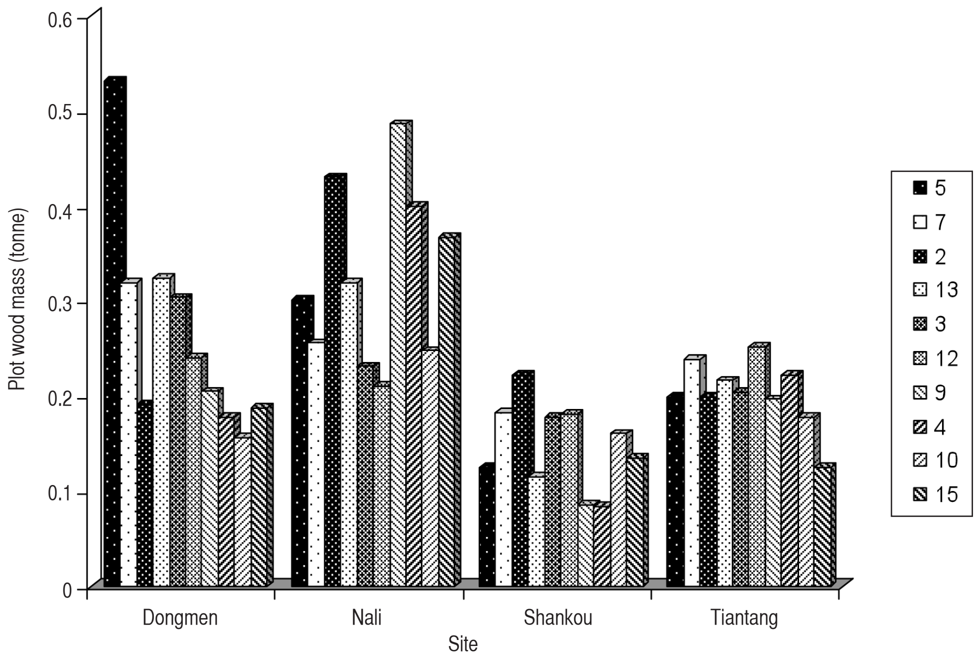

Figure 2 Clone–site means of each of the top 10 clones (judged by averages across sites; details in Table 5) for plot wood mass

Shankou with the highest rainfall and mean annual temperature had the lowest values for all of these traits (Table 4).

The wood mass productivity at the best site, Nali (0.080 tonne tree^{-1}), was nearly double that obtained from the poorest site, Shankou (0.048 tonne tree^{-1}). As all sites received the same silviculture, the growing costs at each of the sites would be approximately equal yet the potential return to growers/investors would vary by far more than just suggested by the differences in individual tree volumes alone. Certainly,

Table 8 Impact of alternate selection and deployment strategies on total productivity of a notional estate.

Strategy	Estate productivity: Volume (m^3 $year^{-1}$)	Estate productivity: Wood mass (tonne $year^{-1}$)
Generalised selection		
Deploy top five clones selected for wood production across sites with selection based on mean wood mass productivity across trial sites	2,851,136	1,154,955
Site specific		
Deploy top five clones at each site category, with selection based on wood mass productivity at representative trial site	2,625,795	1,329,000

Key assumptions for estimates: total plantation area = 100,000 ha; volume $plot^{-1}$ scaled to provide estimates of monoclonal plantation productivity; proportion of estate in each of four site categories (each represented by one of the four trial sites) = 25%; number of clones deployed in equal proportions for each site category = 5

studies in Australia and elsewhere have shown that relatively small increases in site quality can mean large increases in both productivity and profitability (Henson & Vanclay 2004) and the same would apply in China.

The trends observed in wood basic density across the sites in this study may well be due to some environmental variables, e.g. temperature and wood density as reported by Thomas et al. (2007) for eucalypts. Annual temperature and core basic density (0.483 tonne m^{-3}) were highest in Shankou and lowest (0.468 tonne m^{-3}) in Dongmen. Interestingly though, an apparent inverse relationship between average growth and wood basic density between sites is unlikely to indicate a causal relationship. It has been reported that growth rate has little effect on basic density of plantation-grown eucalypt wood (e.g. Downes et al. 2006).

Compared with other studies on kraft pulp yields of plantation-grown eucalypts, the average yields obtained in this study were generally lower than those from subtropical and temperate eucalypts (Downes et al. 1997), yet similar to those reported from China and elsewhere for more tropical eucalypts and their hybrids (Balodis & Clark 2005). Pulp yields averaging 53.3 and 50.1% were obtained from two subtropical Australian sites for eight-year-old *E. dunnii* (Muneri et al. 2007). Balodis and Clark (2005) reported screened kraft pulp yield of 53.2% for *E. dunnii*, 52.6% for *E. globulus*, 49.1% for *E. urophylla* and 50.1% for *E. urophylla* × *grandis* hybrid. Four-year-old *E. urophylla* × *grandis* hybrid clones from Yunnan province had 50.9% kraft pulp yield (Xue & Hu 2007). Some of the differences in pulp yields between the current study and those reported previously for subtropical and temperate eucalypts may be due to age; in eucalypts, kraft pulp yield generally increases from pit to bark so older trees will tend to have a higher yield (Downes et al. 2010).

Clones

The best three clones by survival across sites in this study were 5, 19 and 20 (all hybrids of *E. tereticornis)* and averaged over 90% survival (Table 5). This species is a valuable hybrid parent for southern China due to its combination of good tolerance to drought and typhoon (Bai 1994). In contrast, the clones 10, 12 and 16 (*E. urophylla* × *grandis* or *E. saligna* × *exserta* hybrids) presented the poorest survival data across sites (below 65%). These data were consistent with those of Bai (1994) which reported *E. urophylla*, *E. grandis* and *E. saligna* to be markedly inferior to *E. tereticornis* for drought and typhoon tolerance. Even so, the key factors behind the variation in survival between clones are uncertain. None of the sites experienced severe typhoons up to the 5½ years assessments. Differences in survival may reflect more adaptability and hardiness of the different clones. Perhaps improved early silviculture, such as better outplanting systems, may increase the survival of some clones. Major improvements in seedling quality and outplanting systems provided significant improvement in survival along with improved uniformity and rates of early growth with *Pinus radiata* (Arnold & New 1991). If higher survivals were obtained for all clones in this study, the results for plot volume and wood mass would have been somewhat different as suggested by the significance of plot survival in the covariance analyses.

Only a small variation was observed in pulp yield of the six clones assessed, i.e. ranging from 47.6% for clone 19 to 49.8% for clones 12 and 15 but plot volume varied more than threefold from the poorest (clone 16, 0.186 m^3 $plot^{-1}$) to the best (clone 13, 0.681 m^3 $plot^{-1}$) clone. Nonetheless, the pulp yield variation observed is of major importance as small differences of the magnitudes observed have substantial effects on the operations and profitability of large pulp mills (Downes et al. 1997, Clarke 2009). Such small changes in percentage pulp yield can have major impacts on overall plantation fibre productivity as pulp yield has a multiplying effect with both volume and wood basic density to determine the fibre yield.

Clone × site interaction

For eucalypts, wood property traits have generally been found to show relative stability across small environmental changes compared with growth which can be sensitively affected (Downes et al. 1997, Raymond 2002). Thus, for many wood properties the variation between eucalypt genotypes (e.g. clones) can be much larger than the variation between sites (Raymond 2002). Certainly, the results reported here were consistent with these trends; the variation between sites for pulp yield and wood density amounted to only 0.4% and 0.015 tonne m^{-3} respectively while the variation between clonal averages across sites varied up to 1.8% and 0.092 tonne m^{-3} respectively. The ranges between clones within sites and the general consistency of rankings between sites for both these traits indicate good potential to select clones for superior wood properties, if resources and technology are available to screen sufficient numbers of clones.

Significant genotype by environment interactions (i.e. clone × site interactions) for volume $tree^{-1}$ and for plot wood mass were found across the four sites in this current study. This is similar to results by Mo et al. (2003) for three sites nearby in Guangdong province. The current study indicated that the interaction for volume would not be so important if the trait of interest was just individual tree volume (see Figure 1 and Table 7). This is because the clones that had the best average volume across sites generally ranked among the best clones at each individual site. Similar results was reported for *E. globulus* clones across four sites in Portugal—in these trials some clones showed consistently good growth across all sites (Borralho et al. 1992). In the current study, the proportions of total variation across sites for volume $tree^{-1}$ and for plot volume attributable to the variation between clones were 32.8 and 22.9% respectively while those attributable to clone × site interactions were only 5.8 and 8.9% respectively.

Results for plot wood mass indicated that clone selection (and deployment) should be in line with what Xu et al. (2003) propounded whereby selection of eucalypt genotypes needed to be specific to particular regions/site types. In this study, the clone × site interaction accounted for over 15% of the total variation in plot wood mass across sites while the variation between clones accounted for less than 9% (Table 7).

Although this current study focused on testing and selection of clones, along with quantifying the nature and impacts of extant variation, the results obtained also highlighted the importance of another determinant of plantation productivity and ultimately profitability, namely, site selection. For plot wood mass, variation between sites (24.9% of the total variation) was far greater than that between clones (8.8%) or clone × site interaction (15.4%). This meant that site selection was just as important, or even more, than clone selection in determining wood mass productivity and hence plantation profitability. Accordingly, growers would be wise to invest the same level of resources into assessing and selecting sites as they would into selecting clones.

Deployment

The forecasts of total plantation productivity under alternate selection and deployment strategies for a notional 100,000 ha estate dispersed across the region showed clear advantages for a site-specific strategy (Table 8). The alternative, a generalised selection and deployment strategy, ignores the potential opportunities and consequences of clone × site interactions and will result in a substantially lower yield of wood mass. A previous study by Mo et al.

(2003) did just that—the significant genotype × environment they observed across three sites was ignored in a selection index used to nominate 18 'superior' clones (out of a total of only 27) for use across sites. In contrast, from examining potential impacts of G × E with *E. urophylla* families across five trial sites, Xu et al. (2003) estimated that selection for narrow adaptability combined with regional deployment (i.e. a site or regional specific strategy) could increase volume gains by 25% or more compared with a generalised selection and deployment strategy.

Pursuing a site-specific deployment strategy would incur higher costs because greater numbers of clonal field trials and more complex nursery propagation schedules would be required. However, such investments would seem well justified by the higher wood mass productivity to be obtained from the notional plantation estate evaluated in this study. Interestingly, the site-specific strategy also had an unexpected beneficial consequence in the case of the notional estate in southern Guangxi where not only did it provide a 15% higher wood mass but this was obtained with 8% less volume (Table 8). That is, the total wood mass obtained was higher even though the total volume was lower, providing potential for some reductions in harvesting, handling and/or transport costs.

CONCLUSIONS

This study has clearly shown that both selection of clones and choice of planting sites are very important for optimising the productivity of clonal eucalypt plantations in southern Guangxi. Results from this study would be useful for clonal selection but there was not enough information to reveal which site characteristics had the greatest influences on site productivity within this region. All that could be done was to suggest that rainfall variation was not a key influence on volume productivity. However, the results obtained did indicate that perhaps mean annual temperature of planting sites might have some influence on at least basic density. In addition, this study demonstrated that there would be clear benefits, with respect to productivity of a large eucalypt plantation estate, to pursuing site-specific selection and deployment strategies for commercial clones. Although implementing such a strategy could require significant investments in field trials, for larger growers with plantations spread across site types, the benefits with respect to increased estate yields would be substantial.

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REFERENCES

Arnold RJ & New D. 1991. Improvements in seedling genetic quality and outplanting systems for radiata pine in New Zealand combine for immediate real benefits. In Menzies MI, Parrott GE & Whitehouse LJ (eds) *Efficiency of Stand Establishment Operations—Proceedings of an IUFRO Symposium. 11–15 September 1989, Rotorua. Forest Research Institute Bulletin* 156: 97–101.

Bai J. 1994. Genetic improvement of tropical *Eucalyptus* tree species in China. In Brown AG (ed) *Australian Tree Species Research in China. Proceedings of an International Workshop.* 2–5 November 1992, Zhangzhou. *ACIAR Proceedings* 48: 32–49.

Balodis V & Clark NB. 2005. Pulping and papermaking properties of plantation eucalypts. Pp 244–256 in *Proceedings of China's First International Eucalyptus Pulp and Paper Symposium.* 8–11 September 2005, Haikou.

Borralho NMG, Almeida IM & Cotterill PP. 1992. Genetic control of growth of young *Eucalyptus globulus* clones in Portugal. *Silvae Genetica* 41: 100–105.

Chen S. 2002. Development prospect of cultivating large timber eucalypt. *Eucalypt Science and Technology* 19: 6–10. (In Chinese)

Chen Sx, Wu ZH, Li ZH, Xie YJ, Li TH, Zhou QY & Arnold R. 2010. Selection of species for solid wood production in southern China. *Journal of Tropical Forest Science* 22: 308–316.

Clarke C. 2009. The profitable pulp mill. Paper presented at the Australasian Forest Genetics Conference. 20–22 April 2009, Perth.

Cossalter C & Barr C. 2005. *Fast Growing Plantation Development and Industrial Wood Demand in China's Guangxi Zhuang Autonomous Region.* A report for Guangxi Forestry Bureau and the World Bank. Center for International Forestry Research, Bogor.

Downes GM, Hudson IL, Raymond CA, Dean GH, Michell AJ, Schimleck LS, Evans R & Muneri A. 1997. *Sampling Plantation Eucalypts for Wood and Fibre Properties.* CSIRO Publishing, Melbourne.

Downes GM, Meder RA, & Harwood CE. 2010. A multi-site, multi-species calibration for the prediction of cellulose content in eucalypt woodmeal. *Journal of Near Infrared Spectroscopy* 18: 381–387.

Downes GM, Worledge D, Schimleck L, Harwood C, French J & Beadle C. 2006. The effect of growth rate and irrigation on the basic density and kraft pulp yield of *Eucalyptus globulus* and *E. nitens*. *New Zealand Journal of Forestry* 51: 13–22.

Henson M & Vanclay JK. 2004. The value of good sites and good genotypes: an analysis of *Eucalyptus dunnii* plantations in NSW. Paper presented at the IUFRO Conferences, The Economics and Management of High Productivity Plantations. 27–30 September 2004, Lugo.

Ilic J, Boland D, Mcdonald M, Downes G & Blakemore P. 2000. *Wood Density Phase 1—State of Knowledge.* National Carbon Accounting System: Technical Report No. 18. Australian Greenhouse Office Press, Canberra.

ITTO (International Tropical Timber Organization). 2011. Report from China. *ITTO Tropical Timber Market Report* 16: 12–13.

Li H, Shen W, Wang G & Pegg RE. 2003. Performance at Dongmen, Guangxi of *Eucalyptus grandis* from improved and unimproved sources. Pp 89–93 in Turnbull JW (ed) *Eucalypts in Asia. Proceedings of a Symposium.* 7–11 April 2003, Zhanjiang. ACIAR Proceedings No. 111.

Mo X, Peng S, Long T, Chen W & Yang X. 2003. Important traits and combined evaluation of eucalypt clones. Pp 102–109 in Wei RP & Xu D (eds) *Eucalypt Plantations: Research, Management and Development. Proceedings of an International Symposium.* 1–6 September 2002, Guangzhou. World Scientific, Singapore.

Muneri A, Daido T, Henson M et al. 2007. Variation in pulpwood quality of superior *Eucalyptus dunnii* families grown in NSW. *Appita Journal* 60: 74–77.

Raymond CA. 2002. Genetics of *Eucalyptus* wood properties. *Annals of Forest Science* 59: 525–531.

Thomas DS, Montagu KD & Conroy JP. 2007. Temperature effects on wood anatomy, wood density, photosynthesis and biomass partitioning of *Eucalyptus grandis* seedlings. *Tree Physiology* 27: 251–260.

Turnbull JW. 2007. *Development of Sustainable Forestry Plantations in China: A Review.* ACIAR Impact Assessment Series Report No. 45. ACIAR, Canberra

Wei RP. 2005 Genetic diversity and sustainable productivity of eucalypt plantations in China. Pp 19–27 in Wang H (ed) *Changing Patterns: Tree Introduction and Phytogeography.* China Forestry Publishing House, Beijing. (In Chinese)

Williams ER, Matheson AC & Harwood CE. 2002. *Experimental Design and Analysis for Use in Tree Improvement.* Second edition. CSIRO, Melbourne.

Xu J, Li G, Lu Z, Bai J, Lu G & Wang S. 2003. Progeny test of open-pollinated families of *Eucalyptus urophylla* on multiple sites. Pp 101–106 in Turnbull JW (ed) *Eucalypts in Asia. Proceedings of a Symposium.* 7–11 April 2003, Zhanjiang. ACIAR Proceedings No. 111.

Xue B & Hu D. 2007. Superior eucalypt clone selection and their pulp and paper property study in southern Yunnan high altitude area. *Eucalypt Science and Technology* 24: 1–6. (In Chinese)