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Original article

Effects of site on fibre, kraft pulp and handsheet properties of *Eucalyptus globulus*

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Abstract –
• Eight-year old trees from two *Eucalyptus globulus* Labill. clones planted across three different sites in Tasmania, Australia, were sampled for wood and kraft pulp/handsheet properties.
• Site had a significant effect on all measured properties. Compared with the poor site (Parkham) the wood from the good site (West Ridgley) had on average 11% lower wood density. The poor site had also greater microfibril angles, shorter fibres at lower pulp yields.
• The handsheets produced with pulp from the poor site resulted in comparatively higher bulkiness, lower burst, lower tear and tensile indices, lower zero span tensile strength, but higher opacity, higher light scattering and higher surface roughness. Significant height effects were found with all wood properties, and also with tear index, zero span tensile strength and opacity.
• Discriminant analysis showed that for 76 out of 100 handsheets the raw material source, i.e. growth site, could be predicted correctly using a set of handsheet properties with tear index and bulk index being most prominent.
• This is unique evidence that site conditions are strongly reflected in handsheet properties produced from *Eucalyptus* pulp.

eucalypt / wood quality / fibre length / pulp / paper

Résumé – Effet du site sur les propriétés des fibres, de la pâte et des feuilles d'essai *d'Eucalyptus globulus*.
• Nous avons échantillonné des arbres de huit ans de deux clones d'*Eucalyptus globulus* Labill., sur trois sites différents de Tasmanie en Australie, pour analyser les propriétés du bois et les propriétés papetières.
• Le site a un effet significatif sur toutes les propriétés. Sur le meilleur site (West Ridgley), le bois a une densité inférieure de 11 % à celle obtenue sur le site le plus pauvre. Ce dernier (Parkham) présente un angle des microfibrilles plus important, des fibres plus courtes et un rendement en pâte plus faible.
• Les feuilles fabriquées avec de la pâte du site pauvre conduisent à une main plus importante, un éclatement, une déchirure et des indices de traction moindres, une résistance à la traction à la mâchoire jointive plus faible, mais une opacité plus forte, une diffusion à la lumière et une rugosité de surface plus importantes.
• Des effets significatifs de la hauteur ont été mis en évidence pour toutes les propriétés du bois mais aussi pour l'index de déchirement, pour la résistance à la traction à la mâchoire jointive et pour l'opacité. L'analyse discriminante a montré que pour 76 feuilles sur 100, l'origine de la matière première, c'est-à-dire le site de production, pouvait être prédite correctement en utilisant un jeu de propriétés des feuilles, l'indice de déchirement et la main étant les plus évidents.
• Cela montre de manière originale que les conditions stationnelles sont reflétées dans les propriétés de feuilles de papiers produites avec de la pâte mécanique.

***Eucalyptus* / qualité du bois / longueur des fibres / angle des microfibrilles / pâte kraft / papier**

1. INTRODUCTION

Wood of plantation grown *Eucalyptus globulus* Labill. (Tasmanian blue gum) is largely used as a fibre source in the pulping industry. Fast growth and good tree form, together with adequate wood properties such as density, fibre geometry and chemical composition, pulp yield and handsheet properties, make this species commercially important (Cöpür et al., 2005; Muneri and Balodis, 1997; Turner et al., 1983; Vermaas, 2000). *E. globulus* has a limited natural occurrence in Tasmania (mainly south of Hobart) and Victoria, Australia, but has been extensively planted in many other countries. It prefers cool temperatures with higher rainfall (1000 mm and above) and does not resist extensive drought periods (Cremer, 1990). Factors influencing growth and properties of *E. globulus* are therefore mostly associated with the water availability, i.e. rainfall (Santiago and Neto, 2007). Other variables such as altitude, temperature and soil type, with possible effects on pulp and paper quality, have not been adequately addressed (Vermaas, 2000).

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Table I. Site location, basic tree data, climate and site quality index SQI [1]; Standard deviations are in brackets.

	Sample sites		
Parameter	Parkham	Woolnorth	West Ridgley
Latitude/longitude	41° 26' S /146° 37' E	40° 49' S / 144° 53' E	41° 08 'S / 145° 48' E
Altitude (m)	185	60	200
Tree species		*Eucalyptus globulus* Labill.	
Tree age (years)		8	
Planted / sampled	16 Aug. 90/26 Aug. 98	8 Aug. 90/25 Aug. 98	2 Aug. 90/27 Aug. 98
Total tree height (m)	13.1 (1.3)	16.3 (1.5)	20.6 (1.5)
Merchantable tree height (m)	6.7 (1.3)	10.2 (0.8)	13.3 (1.4)
Diameter at breast height (cm)	16.3 (3.0)	19.4 (3.0)	20.7 (1.6)
Annual total rainfall (mm)	800–1000	1000–1200	1200–1400
Annual mean temperature (°C)	12.6	12.2	11.4
Soil type	Sandy loam, clay subsoil	Yellow podzol	Kraznozem
General site quality	poor	medium	good
Site quality index SQI (m)	16.9	23.4	26.7
Initial spacing (m^2)		3×3	
Fertiliser history		100 g/m^2 soon after trial establishment	

The extent to which site factors determine wood quality, including pulp and papermaking performance, has economic importance. Pereira et al. (1995) concluded that influences of genetic, silvicultural and environmental factors on fibre yield and quality of *E. globulus* are minor. Therefore, managing for fast growth can be pursued without undue concern over negative influences on wood properties. Turner et al. (1983) found that pulp qualities of *E. globulus* are dependent on genotype, tree age and the area from which the samples were taken. In Williams et al. (1995) kraft pulp yields differed significantly between sites. Downes et al. (2006) also showed no effect of growth rate on either kraft pulp yield or basic density. Due to limited availability of handsheet data, the substantial amount of variation made it difficult to make an assessment of possible growth site effects.

The competitive pulp and paper markets of today are focusing on the control of wood and pulp quality. The prediction of pulp/paper quality from wood properties used to be limited by the ability to select and measure the appropriate fibre properties. In recent years, new emerging technologies have allowed rapid and efficient characterisation of wood samples (e.g. Downes and Drew, 2007; Downes et al., 1997; Evans, 1994; Evans et al., 1995; 1996; Fardim and Duran, 2005; Muneri and Balodis, 1997; Schimleck et al., 2006). These new evaluation techniques are especially useful for measuring the large variation of wood properties within and among trees, clones, families, provenances, species and genera. Data are important as many wood traits are under strong genetic control or can be affected by silvicultural practices, allowing the potential for selective breeding and management programs with knowledge of end product quality requirements (Borralho et al., 1992; Hamilton et al., 2007).

This study compares wood, kraft pulp and handsheet properties of *E. globulus* grown on sites with contrasting productivity, and it supplements an earlier work that has focused entirely on effects of wood characteristics on pulp and handsheet properties (Wimmer et al., 2002). In this work, it is hypothesised that productivity differences prevalent on different growth sites are expressed not only in the measured wood properties, but also in properties obtained from wood pulp and formed handsheets. It is further hypothesised that the sites can be identified with significance through specific handsheet properties produced from beaten pulp.

2. MATERIALS AND METHODS

Eight-year old *Eucalyptus globulus* clones, planted across three different sites were sampled for wood, pulp and handsheet properties ($4 \times 3 = 12$ trees). Two clones were selected from a clonal trial established by North Forest Products (now Gunns Ltd.), they were comparable in terms of tree size, and have been selected on the basis of contrasting basic density. Trees were planted in 1990 with initial spacing of 3×3 m^2. Both clones were propagated through open-rooted tissue culture. Basic site characteristics are given in Table I. Site productivity was calculated using an earlier version of the ProMod software (Battaglia and Sands, 1997; Sands et al., 1999) a model that refers to a site's ability to grow trees. The calculated Site Quality Index (SQI) is the height of the plantation usually at age fifteen years for *Eucalyptus globulus*. The inputs required by ProMod were latitude, longitude, altitude, slope and aspect of the sites and a classification of soil depth, texture, stoniness, drainage and a rating of the site fertility. ProMod has been developed and validated on the basis of data from *E. globulus* plots in Tasmania (Battaglia and Sands, 1997). The Parkham site had the lowest SQI, poor soil fertility and lowest annual rainfall. West Ridgley had the highest SQI with fertile soils and higher annual rainfall; SQI of the third site Woolnorth was medium.

From each of the twelve trees, stem disks were cut from six relative heights at 0, 10, 30, 50 and 70%, and breast height. The results from the individual heights were grouped into three categories representing the lower (0%, breast height and 10%), medium (30%) and higher stem region (50%, 70%). Disks were taken from each height for wood property measurement, and sufficient other disks were taken at each height for pulping. The wood samples from each tree height (n = 68) were chipped in a laboratory chipper and air-dried. Three hundred gram (o.d. equivalent) sub-samples of air-dry chips were kraft pulped in a three-litre Haato 12 autoclave air pulping digester and associated equipment. Up to four separate cooks were required to obtain pulp with the target kappa number of 18 (determined according to AS/NZ 1301.201) determined. A liquor/wood ratio of 3:5.1 L/kg was used with a temperature cycle consisting of a nominal 90 min from ambient to 170 °C and 90 min at 170 °C. Cooked chips were washed, disintegrated, spun dry, crumbed and weighed before total yield was recorded. Handsheets were prepared from each pulp sample in accordance with AS/NZS 1301.203. Pulp freeness was measured according to AS/NZS 1301.206. In total, 204 samples were processed.

After drying overnight under controlled temperature and humidity, handsheets were tested for bulk, burst, tear and tensile index, tensile energy absorption index (TEA), opacity, light scattering coefficient, surface roughness, and air permeability as per AS/NZS 1301.208. Bending stiffness followed AS/NZS 1301.453s and Zero-span testing was done according to AS/NZS 1301.459rp.

Length-weighted fibre length was measured with a Kajaani FS200 fibre analyser on unrefined pulp according to TAPPI T271 pm-91. Samples were also run through the SilviScan-2 system as described by Evans et al. (1995; 1996). From extracted and air-dried samples wood density and microfibril angles (MFAs) were determined and weighted by the cross-sectional area at each measured tree height (Downes et al., 1997; Evans, 1994; Evans et al., 1995). Dry wood consumption (*WC* in m^3/t), which is the volume of wood required to produce a tonne (dry) of pulp, was calculated according to Borralho et al. (1993). *WC* can be estimated as the inverse of the product of wood density (kg dry wood / m^3) and pulp yield (kg dry pulp/kg dry wood):

$$WC = \frac{1000}{Density \times Pulpyield}. \tag{1}$$

Statistical analysis

An ANOVA model was used to test for site, clone and height effects, written in the form

$$y = \mu + \alpha_i + \beta_j + \gamma_k + (\alpha\beta)_{ij} + (\alpha\gamma)_{ik} + (\beta\gamma)_{jk} + \varepsilon_{ijk} \tag{2}$$

with the grand mean μ, the treatment effects α_i, β_j, γ_k, reflecting changes in the response due to sites, clones, tree height and interactions $(\alpha\beta)_{ij}$, $(\alpha\gamma)_{ik}$, $(\beta\gamma)_{jk}$, and ε_{ijk} as the error term. The model was re-calculated for each wood, pulp and handsheet parameter. As handsheets were produced with unbeaten and beaten pulp the shown handsheet property models were computed with beaten pulp data only, as these models were stronger but not different to those using unbeaten pulp data. All statistical analyses were carried out with SPSS for Windows, Release 15.0.

The reported data are unique because wood, pulp and handsheet properties were processed on identical trees, at several heights. This experimental design was extremely laborious and time consuming, which was the reason why the number of trees was kept to twelve, with four trees coming from each site. Despite only using 12 trees, analysis revealed strong models and consistent results with the chosen effects.

3. RESULTS

Tree growth varied considerably between sites with West Ridgley providing the tallest trees with the greatest diameter while Parkham had the smallest. This is also reflected in the SQI that was calculated for each site (Tab. I). The clones planted on each site did not significantly differ from each other in terms of height and diameter.

3.1. Wood characteristics and pulp yield

Clear trends are seen with the wood characteristics and pulp yield (Fig. 1). Density dropped on average by 11% from the poorest to the best site, though no difference existed between the poor and medium one. The highest wood density drop was 14% and took place at the higher stem section. Wood density was also higher at the higher stem sections (Fig. 1a). Clear increases along with improving site quality were seen with fibre length with the best site (West Ridgley) exhibiting 24% longer fibres than Parkham (Fig. 1b). MFA decreased with increasing site quality (–15%); the smallest angles were registered at West Ridgley (not shown). Pulp yield rose from the poor to the good site up to 10% (equals 3% pulp yield), the mid stem section showed the highest pulp yield (Fig. 1c). Interestingly, wood consumption was lowest at the medium site, and highest at West Ridgley (up by 15%). The higher stem section showed also lower wood consumption, meaning less volume of wood is required to produce a tonne of pulp (Fig. 1d).

As the clones were chosen for contrasting wood density, the density of the high-density clone was in effect 15% greater (not shown). The high-density clone also had a 15% higher MFA, slightly lower pulp yield (1%), and a 12% lower wood consumption. Fibre length did not differ significantly.

3.2. Handsheet properties

Two different trends were found: (1) tear index, tensile index, zero span tensile strength, and burst index tended to increase with improving site quality, while (2) bulk index, opacity, light scattering, surface roughness decreased with higher site qualities (selection of properties is shown in Fig. 2). Although there were significant differences between sites, bending stiffness and air permeance showed no clear trends. TEA and pulp freeness did not show significant effects at all; meaning site, clone, and tree height were not significant sources of variance. As tree height was a significant effect for all wood parameters, among the handsheet properties only tear index, zero span tensile strength and opacity showed significance. The other handsheet parameters proved to be statistically independent from tree height. Handsheet properties also differed between the high-density and the low-density clones. The higher-density clone exhibited at all sites higher bulkiness, lower burst, lower tensile index, but higher opacity, higher light scattering, higher surface roughness and higher air permeance (not shown).

3.3. Site discriminant analysis

Two discriminant functions were calculated to demonstrate how properties measured with handsheets are indicative for the

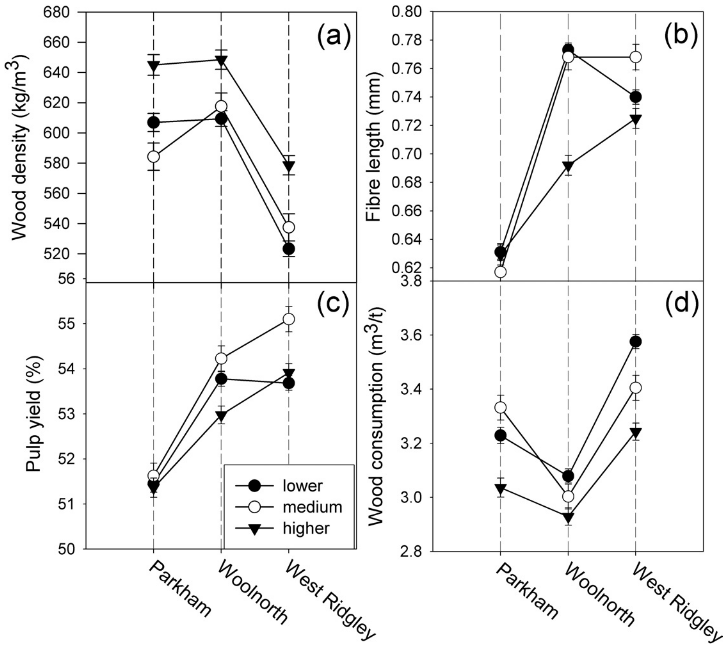

Figure 1. Site × tree height interactions of wood density (a), fibre length (b), pulp yield (c) and wood consumption (d); three height categories: lower (0–10% rel.height), medium (30% rel.height), higher (50–70% rel.height).

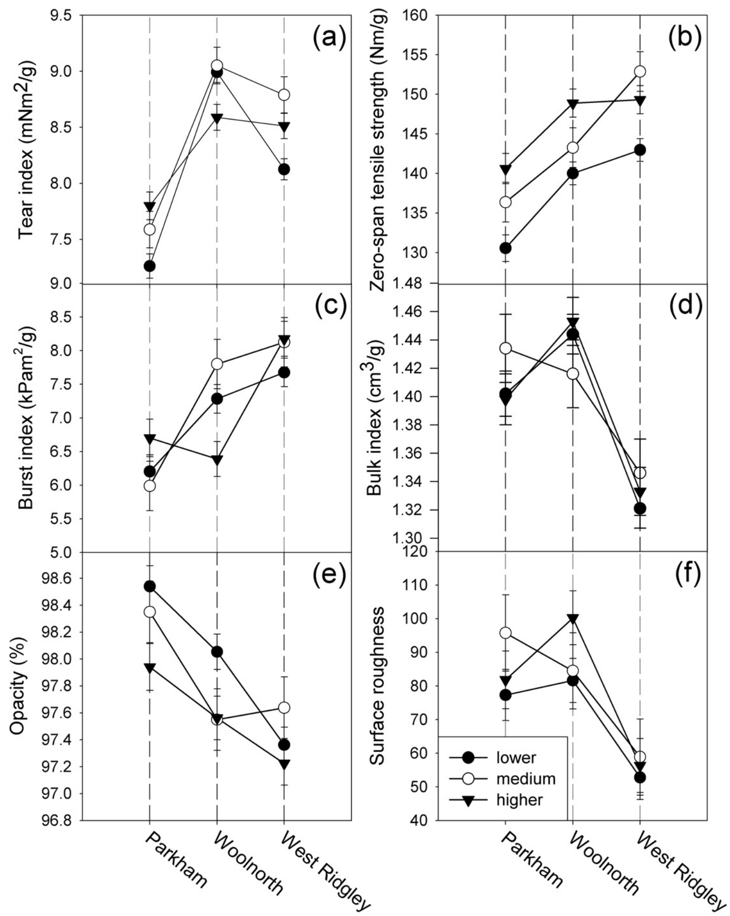

Figure 2. Site × tree height interactions of tear index (a) zero-span tensile strength (b), burst index (c), bulk index (d), opacity (e) and surface roughness (f); three height categories: lower (0–10% rel.height), medium (30% rel.height), higher (50–70%rel.height).

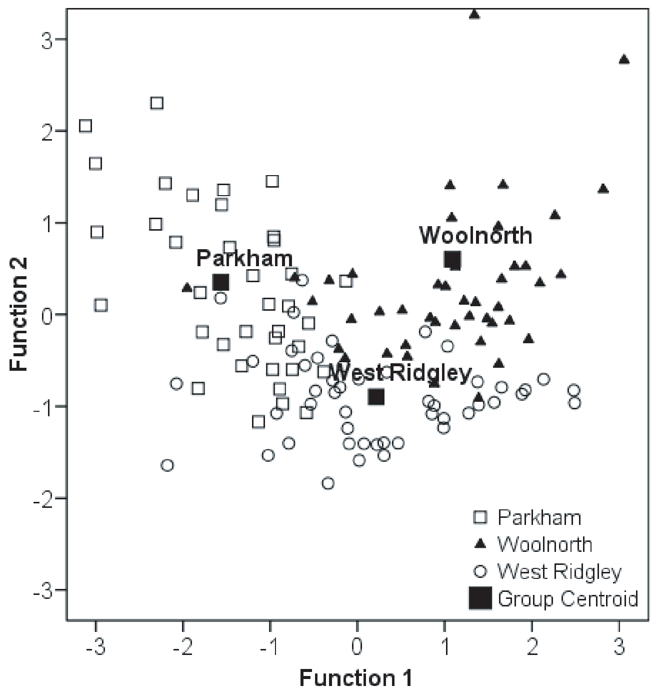

Figure 3. Site discriminant plot using the two functions (standardized), function 1 = –0.83 bulk +0.93 tear index –0.75 light scattering +1.34 permeance, function 2 = 2.39 bulk –0.21 tear index –0.58 light scattering –1.18 permeance. Calculated values of the three sites and site means are shown.

growth sites (Fig. 3). Bulk, tear index, light scattering coefficient, and air permeance were found best to discriminate sites. Function 1, explaining 72%, provided the greatest overall discrimination between the groups. Tear index was the strongest contributor to function 1, while function 2 was loaded with the entire set of parameters in equal measure, with bulk index being strongest. While function 1 separates all three sites, function 2 discriminates the good West Ridgley site from the two others (Fig. 3).

Through cross-validation it was shown to what extent the discriminant functions are in the position to identify the sites through handsheet properties. In cross-validation each case was classified by the functions derived from all cases other than that case and overall, 76% of cross-validated grouped cases could be correctly classified. Therefore, it can be concluded that with knowledge of selected handsheet properties, the original growth sites could be identified with high probability (Tab. II). Rate of retrieval was best at Parkham (78%), the medium site Woolnorth (71%) as well as the good West Ridgley site (69%) were ranked equally high.

Finally, a Pearson product moment correlation was performed between the two calculated discriminant functions and the wood properties. Function 1 correlated strongest with fibre length ($r = 0.68$) and MFA ($r = -0.43$), while function 2 correlated best with wood density ($r = 0.60$).

Table II. Cross-validation of the discriminant functions to identify growth sites through handsheet properties. Each case was classified by the functions derived from all cases other than that case. Overall, 76% of cross-validated grouped cases could be classified correctly.

	Predicted sites		
Actual sites	Parkham	Woolnorth	West Ridgley
Parkham	**78**	3	19
Woolnorth	8	**71**	21
West Ridgley	14	17	**69**

4. DISCUSSION

Compared with the poor site the wood from the good site at West Ridgley had on average 11% lower wood density. The poor site had also greater MFA, shorter fibres at lower pulp yields. Further, significant height effects were found for all wood properties, which are consistent with previously reported findings (e.g. Jorge et al., 2000; Kibblewhite and Riddell, 2000; Phillips, 1988). Miranda and Pereira (2001; 2002) found for *E. globulus* that wood density did not vary significantly with tree height; however, there was evidence for strong site effects.

In this study, a significant lower pulp yield was found together with shorter fibres at the low-quality growth site. Leal et al. (2003) determined site and clonal effects for a number of vessel characteristics of *E. globulus*: The dryer site was associated with lower vessel proportion and consequently also denser wood. Downes et al. (2006) showed that varying water availability (via irrigation) caused significant effects on growth density and pulp yield, with the more water stressed treatments having higher density and lower growth and pulp yield. Within treatments no effect of growth rate on density or pulp yield was evident.

Handsheets produced with pulp from the poor site resulted in higher bulkiness, lower burst, lower tear and tensile indices, lower zero span tensile strength, but higher opacity, higher light scattering and higher surface roughness. Little et al. (2003) stated for *Eucalpytus* that if wood density rises above 300 kg/m^3, there is a decline in paper strength in terms of tensile, burst and folding endurance. In our study we found significant height effects only with tear index, zero span tensile strength and opacity suggesting that the within-tree variability for these properties is less pronounced. This evidence was also reported by Raymond et al. (1998) who looked at pulp yield only and found little variation with tree height, for the species *E. globulus* and *E. nitens*.

Through a discriminant analysis it was shown that for 76 out of 100 handsheets the raw material source, i.e. growth site, could be predicted correctly using a set of four handsheet properties with tear index and bulk index being most prominent. This is unique evidence that site conditions are strongly reflected in handsheet properties produced from beaten pulp. Fibre length and wood density were the wood characteristics that correlated best with the two discriminant functions. Earlier results have shown that fibre length had strong, direct effects on the tear index in the first place, while wood density was a strong predictor for most of the handsheet properties (Wimmer et al., 2002). It seems that the combination fibre length – wood density is a strong determinant for most of the handsheet properties.

Depending on the end product, pulp with adequate strength, high brightness for bleached grades, high refining rate and good machine runnability are commonly preferred. Wood with high pulp yield and low extractive content is also favoured (Phillips, 1988). Our results emphasise the value of understanding site effects in improving plantation productivity for pulp wood. Wood production of plantations can be correlated with soil type, mean annual rainfall (Hingston and Galbraith, 1998) and may include also quality criteria to optimally grow pulpwood. The good site at West Ridgley had the highest pulp yield, lowest density and best productivity, delivering the strongest paper. For printing and writing paper, however, good optical properties are required, including high brightness and opacity, good formation, surface compressibility and surface strength. Light scattering coefficient and opacity were highest at Parkham, i.e. the site with the lowest productivity showing merchantable tree height half of that at West Ridgley.

Actual pulp yield differed between the good and the poor site by 3%. Beadle et al. (1996) has shown with 8-year old *E. globulus* and *E. nitens* that pulp yield decreases with increasing altitude and the difference within provenances did not exceed 3.4%. Megown et al. (2000) found average differences in pulp yield of 3% between poor and good sites, whereas site differences in an *E. globulus* study by Raymond et al. (2001) did not exceed 2.3%. From these results it can be concluded that site selection might give the potential of improving pulp yield by about 3%.

Because several of the measured wood parameters are highly heritable, the potential for improvements through site selection compared with genetic gains needs consideration. Genetic differences, which exist between provenances of the same *Eucalyptus* species, may vary greatly in terms of growth on particular sites, and also in terms of wood, pulp and paper properties. Examples for wood density should demonstrate the large differences obtained in open-pollinated progeny trial studies. For *E. globulus* Borralho et al. (1993) reported a genetic gain of 47% for *E. regnans,* while Raymond et al. (1998) reported 3.5%wood density. The latter study also reports a genetic gain for fibre length as high as 6.8%. Other studies reported a density gain in a clonal trial of 8% (Zhang et al., 2003). With the data obtained in this study it can be concluded that gains in various paper properties can be expected from different sites (Henson and Vanclay, 2004).

5. CONCLUSIONS

In this study, we have shown with a limited number of trees planted on three sites that the environmental and physical conditions prevalent at these sites affect the properties of the end product. The potential of improving pulp yield as a function of site is in the order of 3%. Therefore, substantial gains can be expected for *Eucalyptus globulus* with site selection, which should further improve when combined with genetics. The obtained results reemphasise the importance of good land as well as good planting material in industrial plantations. Relatively small increases in site index may cause large increases in production and profitability. Understanding relationships between site, growth and product variation should enhance the value of decision-support software that predicts growth variation as a function of site and climate.

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