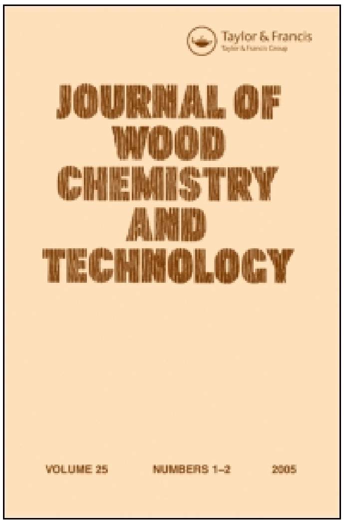

Journal of Wood Chemistry and Technology
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713597282

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To cite this Article Ramírez, Mauricio , Rodríguez, Jaime , Balocchi, Claudio , Peredo, Miguel , Elissetche, Juan Pedro , Mendonça, Regis and Valenzuela, Sofia(2009) 'Chemical Composition and Wood Anatomy of *Eucalyptus globulus* Clones: Variations and Relationships with Pulpability and Handsheet Properties', Journal of Wood Chemistry and Technology, 29: 1, 43 — 58

To link to this Article: DOI: 10.1080/02773810802607559

URL: http://dx.doi.org/10.1080/02773810802607559

Journal of Wood Chemistry and Technology, 29: 43–58, 2009
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ISSN: 0277-3813 print / 1532-2319 online
DOI: 10.1080/02773810802607559

Chemical Composition and Wood Anatomy of *Eucalyptus globulus* Clones: Variations and Relationships with Pulpability and Handsheet Properties

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Abstract: Variation and relationships among dasometric parameters, chemical composition, wood anatomy, pulpability (efficacy of kraft delignification), and handsheet properties were studied in fourteen 7-year-old *Eucalyptus globulus* clones grown in a clonal trial in the Bio-Bio Region, Chile. Three ramets per clone were sampled and all properties were measured for each tree. Results showed variations among clones for parameters associated with wood anatomy, chemical composition, pulpability, and handsheet properties, which are the basis for the improvement of these traits through clonal selection. However, our findings showed that tree size can negatively affect other traits such as basic density and other related parameters as wood consumption, tear index, specific bulk, and Gurley air resistance. Wood density and chemical composition were the most important parameters correlated with pulpability and handsheet properties. Therefore, future efforts in tree improvement should be focused on wood properties such as density, lignin, holocellulose, and α-cellulose contents.

Keywords: *Eucalyptus globulus*, handsheet, kraft pulping, pulpability, wood anatomy

INTRODUCTION

The main species currently grown for short-fiber pulp in Chile is *Eucalyptus globulus* Labill., which is extensively used for pulping due to its fast growth, high pulp yield, and good fiber and handsheet properties.[1–3] The economical

We thank the following institutions and people for their financial and technical support: Project FONDEF DO3I1103, Bosques Arauco S.A., Bioforest S.A., CONICYT, Laboratory of Wood Anatomy (Bio-Bio University), Mr. Alex Opazo, and Mrs. Helga Contreras.

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value of an *E. globulus* pulp-wood stand is determined by stem volume and by the pulp quality derived from the wood. The major determinants of pulp-wood quality are properties of the fibers forming the paper, including fiber dimensions (cross-section), mechanical properties (tensile strength, compressibility, and stiffness), and chemical composition. These are determined by the characteristics of the original fibers in the wood, and modified during the pulping process and subsequent paper manufacturing.[4] In this way, the improvement of wood contributes to a reduction of the manufacturing costs for pulp and paper companies by giving better digestibility, higher pulp yield, and stronger paper.[5] However, in most countries, tree breeding programs have historically been based on selection by the growth rate and tree form, not considering the wood properties.

At this time, with increasing recognition of the economic importance of wood properties, the incorporation of these traits into breeding programs is becoming a priority; mainly because wood properties directly influence the type and quality of pulps and papers that can be produced.[6] In this context, one of the main research objectives related with these subjects is the use of biotechnological tools to identify and select the best trees (clones) for the pulp and paper industry.

To successfully improve wood quality through biotechnology and genetic improvement, the variation and correlations between wood and properties of the final products must be known. Currently, there is little knowledge regarding these variations and relationships among these properties in clones of *E. globulus* grown in Chile. This study presents the results of a clonal trial evaluation from the stand to the pulp mill industry, including tree characteristics; chemical, physical, and anatomical properties of wood; pulpability; and handsheet properties.

The specific objectives are: (i) To quantify the variation of chemical composition, wood anatomy, pulpability, and handsheet properties in 7-year-old *E. globulus* clones, (ii) To determine the relationship among tree growth, pulpability, and handsheet properties of individual trees, and (iii) To evaluate the effects of wood anatomy, chemical, and physical properties on pulpability and handsheet properties.

METHODS AND MATERIALS

Clonal Trial Description, Selection of Trees, and Samples Preparation

During January 2006, samples were collected from forty-two 7-year-old *E. globulus* trees (corresponding to 14 genotypes/clones, 3 ramets each) growing in a clonal trial established in the Bio-Bio Region of Chile (37°21′ S; 73°20′ W). This area has a sub-humid and temperate climate, with maritime influence, and four dry months per year. The mean annual rainfall is near to 1380 mm; the annual average temperature is 12.6°C, varying between 5.0°C and 22.8°C. The prevailing topography is hilly, but there are flat sectors. Soils of the trial area are classified as Merilupo.[7] These soils are deep marine sediments with loamy red clays in the surface and dark red clays in depth. The soils are well structured, allowing good root development in depth, and good soil water holding capacity.

The clonal trial was established in November 1998, using single tree plots and ten replications. Trees were planted at 3.0 × 1.7 m spacing with a management according to the operational practices for eucalypts plantations in Chile.

For wood anatomy and chemical analysis, two increment cores per tree were sampled at breast height (BH). Trees were harvested for biometric parameters measurements, including: diameter at breast height (DBH), total height (TH), commercial height (CH, height to minimum commercial diameter of 8 cm, with bark), wood volume (WV), and bark volume (BV).

Sample for pulping, chemical, and physical analysis were obtained from five logs of one-meter length at the commercial length of each tree, which were chipped and screened. A representative sub-sample (approximately 30 kg) of green wood chips from each tree was sent to the laboratory for further analysis.

Wood Anatomy, Microscopic Images, and Morphology Measurements

One radial increment core of 12 mm (bark to bark) was taken from each tree at BH. For fiber and vessel measurements, sampling was carried out along the radius from pith to bark at 10, 50, and 90% of the total radius. At each percentage of the radial distance, one block of 1 cm length was taken. From each block, transversal microsections of 30 μm thickness were obtained using a sliding microtome (MICROM, HM 325). Samples were stained with Safranin, dehydrated in alcohol and mounted in Canadian Balsam, on glass slides.

From each sample, microscopic images of the cross-sections were collected using a Zeiss Microscope (Axiolab) connected to a personal computer and images were stored in a digital format for image analysis (Polaroid DMC1). The radial and tangential cell wall thickness and lumen diameters of 40 randomly selected fibers with a total magnification of 100× were measured by the image processing software Wincell 5.1 (Regent Instrument Inc., Canada) calibrated with a stage micrometer. Additionally, the number of vessels elements was determined with a total magnification of 10× by counting those present within a field (approximately 2 mm^2) and expressed as the number of vessels per square millimeter. Out of a total of 5 to 10 vessels, those with the largest and smallest individual diameter were measured using a 40× magnification.

With the data obtained, the radial and tangential fiber cell wall thickness, lumen diameters, number of vessels per mm^2 (vessel frequency), and percentage of the total area covered by vessels (vessel coverage) were calculated.

Physical Properties, Analysis of Wood Chips

Before pulping, moisture content and basic density of wood chips from each tree were determined. Moisture content was calculated as the difference between green and oven dried weight, divided by green weight. Basic density was measured using oven dried weight and green saturated volume, determined by a water immersion method.[3]

Kraft Pulping of Wood Chips

All pulping was carried out in a MK Systems digester, equipped with a cylindrical reactor of 10 L capacity, with forced liquor circulation. The digester was heated with an electric heating device. The wood charge was 950 g (dry weight basis) of wood chips. The cooking was done according to the following conditions: 4:1 liquor-to-wood ratio, 30% sulfidity, and 16% active alkali as Na_2O. The maximum pulping temperature was 165°C. Heating time required to reach this temperature was 120 min and cooking time at maximal temperature was variable in order to reach pulps with Kappa number 15 ± 1. Cooked wood chips were disintegrated by vigorous agitation in water and the resulting pulp screened in a Valley flat screen (0.2 mm slots). The screened pulp was centrifuged, giving a pulp consistency of approximately 30%. A sample of this pulp was used for moisture determination and screened pulp yield was calculated based on initial wood and final pulp dry weights. Kraft pulps were analyzed according to Tappi and Scan standards for Kappa number, T236 cm-85; and viscosity, Scan-C 15:62.

A minimum of two pulpings with a Kappa number 15 ± 1 were obtained for each tree. Pulp yields at Kappa number 15 were interpolated from the Kappa number-pulp yield relationship of the laboratory pulps.

Chemical Properties of Increment Cores and Wood Chips Analysis

The chemical analysis of increment cores included ethanol/toluene-soluble extractives, lignin (Klason), holocellulose, and alpha cellulose contents. The ethanol/toluene-soluble extractives were analyzed according to Tappi standard T204 cm-97. Extracted samples were treated with 72% (w/w) sulfuric acid at 30°C (300 mg of sample and 3 mL of sulfuric acid) for 1 h, then, 84 mL of deionized water were added to give an acid concentration of 4.2%, and the resulting suspension was heated at 120°C for 1 h. The final suspension was filtered through a porous glass filter (number 3). Solids were dried at

105 ± 1°C to constant weight and used to determine insoluble lignin. Soluble lignin was determined by measuring the absorbance at 205 nm in the filtrates.

Holocellulose was prepared by weighting 250 mg of extractives-free milled wood in a 50 mL round-bottom flask, adding 5 mL of deionized water, 2 mL of glacial acetic acid, and 5 mL of sodium chlorite 80%. The flask was sealed with a glass cap and immersed in a water bath at 90°C for 1 h. After this period of time, 2 mL of glacial acetic acid and 5 mL of sodium chlorite 80% were added to the flask and the reaction was carried out for another hour at 90°C. The reaction was stopped by immersing the flask in a water bath at 10°C. Solids were filtered through a porous glass filter number 2, washed with 500 mL of deionized water, dried at 105°C until constant weight and determined as holocellulose.

Alpha-cellulose samples were prepared according to Browing,[8] weighting 100 mg (dry weight) of holocellulose in a 25 mL flask kept at room temperature for 30 min to reach equilibrium moisture content. Then, 8 mL of sodium hydroxide 17.5% w/v were added; the slurry was homogenized and allowed to react for 30 min at room temperature. Finally, 8 mL of deionized water were added and mixed for one minute and let it stand for 29 min (1 h of total reaction time). Solids were filtered using a porous glass filter, washed with 150 mL of deionized water, followed by washing with 20 ml of acetic acid 1.0 M, for 5 min. The neutralized sample was washed with 300 mL of deionized water. The final insoluble residue (alpha-cellulose) was dried at 105°C to constant weight. The difference between the initial and final weight was used to calculate the alpha-cellulose content.

Ethanol/toluene-soluble extractives, soluble and insoluble lignin contents were determined in wood chip samples obtained from whole trees (in triplicates). The values of the chemical composition corresponded to the mean of triplicates for each sample, deviation from the mean being lower or equal to 3%.

Papermaking and Evaluation of Handsheets

Screened unbleached pulps were refined in a PFI mill according to T248 cm-00 and handsheets were prepared following the T205 sp-95 method. Opacity, refining energy, specific bulk, Gurley air resistance, and strength properties of these handsheets were measured according to T519 om-02, cm-00, T411 om-97, T460 om-02, T494 om-01, T414 om-98, and T403 om-97, for opacity, refining energy, specific bulk, Gurley air resistance, and tensile, tear, and burst indexes, respectively.

Statistical Analysis

To quantify the variation in the chemical composition, wood anatomy, pulpability, and handsheets properties in the 7-year-old *E. globulus* clones, descriptive parameters of variability were calculated for each one of the properties measured. The clone effect on each trait was evaluated by variance analysis (ANOVA) using a simple randomly design. The experimental unit was the tree, with three replicates per clone.

On the other hand, to determine growth rate effect on pulpability and handsheet properties, simple regression analysis was carried out. The effect of wood anatomy, chemical, and physical properties on pulpability and handsheet properties was evaluated by mean Pearson correlation coefficients, considering its sign and significance. Statistical analysis was performed with Statistica V7.0.

RESULTS AND DISCUSSION

Variability of Dasometric Parameters in *E. globulus* Clones

Total height, DBH, and stem volume were statistically different among the clones studied, with values between 16.1–22.7 m, 12.5–21.1 cm, and 0.064–0.282 m^3, respectively (Table 1). This variability is the basis for genetic improvement of productivity (volume of wood per hectare) based on clonal selection.

By increasing growth, production cost is reduced, compared with unimproved plantations because more volume per hectare is obtained. There are additional benefits due to the use of uniform clones, which facilitate the forest operations[9] and could reduce the total plantation area required to obtain a defined wood production.

Variability of Wood Anatomy in *E. globulus* Clones

The size and structure of anatomical elements that influence wood properties in *E. globulus* and its variation can be used to improve the quality of final products.[10,11] In this context, the main result obtained from the wood

Table 1. Variation of dasometric characteristics in fourteen *E. globulus* clones

Property	Average	Std. dev.	Minimum	Maximum	p-value*
Total height (m)	20.6	1.0	16.1	22.7	0.031
DBH (cm)	16.1	1.6	12.5	21.1	0.010
Stem volume (m^3)	0.148	0.039	0.064	0.282	0.008
Bark volume (m^3)	0.026	0.006	0.010	0.054	0.237
Bark content (%)	15.2	1.36	9.6	20.8	0.668

*Variables with p-value < 0.05 differ significantly among clones.

Table 2. Wood anatomy variation of *E. globulus* clones

Property	Average	Std. dev.	Minimum	Maximum	p-value*
Vessel frequency (number mm^{-2})	8.0	0.6	5.9	9.6	0.201
Vessel coverage (%)	10.8	1.7	6.7	15.9	0.003
Fiber wall thickness (μm)	3.2	0.4	1.1	4.0	0.291
Lumen diameter (μm)	12.9	1.5	4.2	15.8	0.107
Fiber diameter (μm)	19.2	2.2	6.3	23.0	0.117

*Variables with p-value < 0.05 differ significantly among clones.

anatomy evaluation was the significant difference found on vessel coverage (Table 2).

During the papermaking process, high vessel coverage facilitates the penetration of pulping liquor into wood and increases bulk. On the other side, surface quality of the paper is lowered, because vessel elements may pick out from the paper surface during the printing process, leaving ink-free spots on the printed page.[12–16]

The vessel frequency variation found among the clones studied was similar to those described by Hudson et al.,[17,18] who measured at 20% height on 7-year-old trees, and similar to the ones obtained by Leitch[15] at 15% of the total height on 4-year-old *E. globulus* trees; and to those presented by Leal et al.[16] for twenty-seven *E. globulus* clones of 7 years old. Values for vessel coverage reported by Leitch[15] and Leal et al.[16] were between 8–12%, similar to the range obtained in this study. The results of this study show an important variation on vessel coverage among the clones analyzed (Table 2), which differ from those presented by Leal et al.[16] who have pointed out that vessel coverage remained rather constant for all clones.

Eucalypt fibers are spindle shaped cells with abundant bordered pits and are correctly called fiber-tracheids.[19] For fiber wall thickness, results showed that it remains constant for all trees across clones (Table 2). This result is consistent with the conclusion reported by Miranda et al.[2] Also, fiber dimensions measured on this study are similar to those reported by Bamber [19] and Miranda and Pereira.[2]

Variability of Chemical Composition in *E. globulus* Clones

The chemical composition in *E. globulus* wood is relevant for pulp production because it is related with kraft pulp yield.[20] In this study, important differences were found for all variables analyzed on increment cores, but not on wood chips of whole trees, where only the klason lignin content showed differences among clones (Table 3).

Table 3. Variation of chemical composition in wood chips and increment cores of *E. globulus* clones

Sample	Property	Average	Std. dev.	Minimum	Maximum	p-value*
Increment cores	Extractives (%)	1.8	0.3	1.3	2.5	<.001
	Holocellulose (%)	74.5	1.7	71.2	78.6	<.001
	Alpha-cellulose (%)	62.6	1.9	59.4	67.7	<.001
	Total Lignin (%)	26.6	1.0	24.4	28.6	<.001
Whole tree wood chips	Extractives (%)	0.5	0.1	0.3	0.7	.320
	Total Lignin (%)	25.4	1.3	28.8	27.8	.027

*Variables with p-value < 0.05 differ significantly among clones.

The sampling methodology and chemical determination protocols normally vary among different authors; consequently, direct comparison of results is often not possible.[2,21]These arguments could explain our differences with some values reported in the literature. However, if compared with those obtained by Miranda and Pereira,[2,22] for increment cores and discs taken at breast height in the same species and age, our values are within the range reported by these authors.

Extractives and lignin have generally been found to correlate negatively with pulp yield, whereas the carbohydrate fraction, as α-cellulose correlates positively with pulp yield. Holocellulose (cellulose plus hemicelluloses) generally gives a weak positive correlation with pulp yield.[20]

Variability of Pulpability in *E. globulus* Clones

Pulp yield per unit of plantation area will depend on volume production as well as on wood properties as wood density and pulp yield. Then, to improve pulp production, growth should be an important selection criterion; however, wood properties are also important. For instance, wood density and pulp yield can strongly affect fiber production per unit area. According to our results, important and significant differences were found among clones for all the variables evaluated (Table 4).

The basic density obtained for *E. globulus* clones (Table 4) was similar to the average value of 8-year-old *E. globulus* (490 kg m^{-3}) described by Kibblewhite et al.[1], lower than the one measured by Miranda and Pereira[11] in four provenances of 9-year-old *E. globulus* at three sites (504 to 572 kg m^{-3}), and similar to those reported by Downes et al.[23] for 10 families of 9-year-old *E. globulus* (409 to 601 kg m^{-3}). The basic densities of the clones studied are within the 400 to 600 kg m^{-3} range considered acceptable for commercial pulpwoods. High-density woods, when associated with tylosis or extractives, can be more difficult to impregnate with cooking liquors, leading to uneven

Table 4. Pulp ability and fiber productivity variation of *E. globulus* clones

Property	Average	Std. dev.	Minimum	Maximum	p-value*
Basic density of wood chips (kg m^{-3})	491	22	442	549	<.001
Pulp yield at Kappa 15 (%)	53.4	1.5	49.9	56.9	<.001
Specific consumption (m^3 ADt^{-1})	3.82	0.24	3.33	4.29	<.001
Fiber productivity (ADt ha^{-1})	75.8	17.3	30.3	137.7	.033

*Variables with p-value < 0.05 differ significantly among clones. ADt: air dry ton.

delignification of woodchips, but some paper companies accept wood with higher densities for fine paper production, for example up to 650 kg m^{-3} in Australia and up to 700 kg m^{-3} in Japan.[24]

The variation in pulp yield was higher than the one measured from whole tree in 6-year-old *E. globulus* plantations (Wallis et al.[20]) who found a range from 45.7 to 50% at kappa number 15, and similar to the ones obtained by Miranda and Pereira[2] from increment cores taken at breast height of 7-year-old *E. globulus* (46.8–53.3%), but lower than the average values presented by Miranda and Pereira[11,22] for 2-, 3-, 6-, and 9-year-old *E. globulus*, at different kappa numbers from 13.2 to 17.5.

Specific consumption of wood is an important trait for the pulp industry and it is obtained by combining the information on wood density with pulp yield in order to obtain an estimated pulp production per cubic meter of wood (m^3 ADt^{-1}). The results of this study showed that there is a large variation among clones for this trait, ranging from 3.33 to 4.29 m^3 ADt^{-1} (Table 4). At the pulp mill industry, this parameter is important to optimize the use of the digester, which is limited by volume capacity. If wood-specific consumption is combined with volume production per tree or hectare, cellulose productivity is obtained (ADt ha^{-1}). Generally, the variation in pulp production will be enhanced due to large differences in growth among clones. According to our results, values were from 30.3 to 137.7 (ADt ha^{-1}), confirming the importance of growth.

Variability of Handsheet Properties in *E. globulus* Clones

Knowing the physical-mechanical and optical properties of pulp, is important because the majority of customers of pulp and paper mills require consistent quality, with specified minimum standards for the products they are purchasing.[9] In this study important handsheet properties from unbleached

Table 5. Variation of physical-mechanical and optical properties of handsheets*

Property	Average	Std. dev.	Minimum	Maximum	p-value**
PFI revolutions	1,064	350	300	2,000	<0.001
Tensile index (Nm g^{-1})	90.0	8.5	68	107	<0.001
Tear index (mNm^2 g^{-1})	7.8	0.5	5.9	9.0	0.590
Burst index (kPa m^2 g^{-1})	5.6	0.8	3.8	7.7	0.002
Specific bulk (cm^3 g^{-1})	1.4	0.1	1.3	1.7	<0.001
Opacity (%)	96.4	0.4	94.9	98.0	0.865
Gurley air resistance (s 100 mL^{-1})	15.8	6.0	4.0	41.9	0.003

*Pulps refined to 30 °SR.

**Variable with p-value < 0.05 differ significantly among clones.

kraft pulps were determined, and they showed a wide range of variation for all variables studied among clones, except for tear index and opacity (Table 5).

Refining is one of the most important activities (evaluated between 300 to 2000 PFI revolutions) in a paper manufacturing facility, because it modifies the fiber properties and consequently affects almost all the properties of the final-end products. This measurement is important not only in terms of production costs, measured through the energy consumption, but also because it leads to a certain decline in properties such as handsheet opacity, porosity, and bulk. On the other hand, when refining levels increase, tensile index improves. Tensile index is an important parameter used by paper makers; a tensile index of around 70 Nm g^{-1} can be considered "standard" for many of the final-end applications of *Eucalyptus* market pulps in Europe.

From the final-end uses of pulps, the combination of low sheet density and high porosity pulps make them well suited for production of certain types of special papers, such as decorative laminates, cast-coated paper, photographic paper, cigarette paper, and parchment. On the other hand, pulps with high tensile strength, high opacity, and low porosity should make them well suited for the important market segment of uncoated and coated wood-free printing and writing papers. Finally, pulps with low porosity and high strength should also be well suited for some specialty end-uses such as security and label papers. According to our results (Table 5), differences among clones for properties such as tensile and tear strength, specific bulk, porosity, and refining energy were found. This variability represents large gains in quality that can be achieved by selecting the best clones.

Tree Growth: Its Effects on Pulpability and Handsheet Properties

To improve pulp production in forest plantations (tons of pulp per ha), growth differences between clones is an important selection criterion; however, to successfully improve wood quality through genetics and biotechnology, the

Table 6. Regression models using wood volume as independent variable explaining variance in basic density, pulp yield, and handsheet properties (n = 42). The statistical significance of the regression model is shown (p) together with the proportion of variance explained (r^2)

Property	Intercept	Wood volume coefficient	r^2	p-value
Basic density of wood chips (kg m^{-3})	520.4	−192.40	0.19	.004
Pulp yield at Kappa 15 (%)	54.0	−4.33	0.02	.392
Wood consumption (m^3 ADt^{-1})	3.5	4.83	0.14	.013
PFI revolutions	993.5	474.27	0.00	.721
Tensile index (Nm g^{-1})	84.0	40.45	0.04	.182
Tear index (mNm^2 g^{-1})	8.6	−5.99	0.10	.044
Burst index (kPa m^2 g^{-1})	5.0	3.77	0.04	.194
Specific bulk (cm^3 g^{-1})	1.5	−0.68	0.14	.015
Opacity (%)	96.4	0.02	0.00	.995
Gurley air resistance (s 100 mL^{-1})	6.1	65.74	0.19	.003

effect of tree growth on pulp production and pulp quality handsheet properties must be known. Among these properties, we found that tree growth has a significant negative effect on basic density, specific bulk, and tear index, but has a positive effect on wood consumption and Gurley air resistance (Table 6).

As pulpwood, younger and low density eucalypts are to be preferred to older denser woods on most grounds: lower chemical consumption during pulping, higher pulp yields, superior black liquors leading to easier chemical recovery, minimal extractives problems, and higher bonding strength.[12] In this way, *E. globulus* combines fast growth under appropriate conditions, with good tree form and excellent wood quality for pulp production. In Chile, the usual stand management for pulp is based on plantations with rotation ages ranging from 7 to 12 years. Planting density is approximately 1660 plants ha^{-1} and the expected growth rates of these plantations are between 16 to 25 m^3 ha^{-1} $year^{-1}$. According to Miranda and Pereira,[22] in intensive plantations, maximizing the volume production and decreasing the rotation age have no detrimental effects on wood quality. Consequently, they conclude that intensively grown trees and short rotations may be used for pulping without losing raw material quality. However, our results (Table 6) show that tree size (measured as wood volume) can affect negatively basic density and other parameters that are directly influenced by basic density, such as wood consumption, tear index, specific bulk, and Gurley air resistance; parameters that were not measured by Miranda and Pereira.[22] In this context we conclude that wood quality of raw material for pulping is affected by growth rate. Similar conclusions were presented by Beadle et al.[25] who found that continuous irrigation or drought cycles have a marked effect on growth, wood fiber, and pulp properties of *E. globulus* and *E.*

nitens. However, more work needs to be done to assess these effects in other sites, stand densities, genetic material, and cultural practices.

Effects of Wood Anatomy, Chemical Composition, and Basic Density on the Behavior of Pulpability and Handsheet Properties

Wood fiber morphology and wood chemistry are important traits because they determine key paper qualities such as strength, opacity, porosity, and bulk.[26] In this context, one of the objectives of this study was to evaluate the effect of wood anatomy, chemical, and physical properties on pulp production, pulp quality, and handsheet properties (Table 7).

The optimum level for each pulp and paper property depends on the target quality of the final-end products, consequently what combination of traits should be breed, will depend on the final-end product. According to our results (Table 7), except for the correlation between opacity and fiber wall thickness and fiber diameter, there was no correlation between wood anatomy measured in increment cores taken at breast height, and pulpability and handsheet properties of the whole tree. In this context, O'Neill et al.[27] have pointed out that the relationships between wood anatomy and handsheet properties could be improved if fiber cross-section is measured using a technique in which pulp fibers are dried and rewetted, embedded and sectioned, and then examined by optical microscopy for image analysis. Fiber length and coarseness must be included, because they are very important traits for pulp and paper; however, these cell parameters have not been implemented in most tree improvement programs, due to the cost and time of measurements.[28]

On the other hand, significant relationships were found between chemical composition measured in increment cores and pulpability of the whole tree (Table 7). Holocellulose and α-cellulose contents have a positive correlation with pulpability (basic density and pulp yield), and negative effect on specific consumption of wood, whereas for lignin content the opposite could be observed. Extractive content did not have any significant relationship with the parameters measured. These results are in line with previous works reported for *E. globulus* by Wallis et al.[20] and Miranda and Pereira,[2] excepting that these authors found a significant negative relationship between extractive content and pulp yield.

In whole tree woodchips, basic density and lignin content have significant correlations with pulpability and handsheet properties (Table 7). High densities produce bulkier, more porous sheets with lower tensile and burst index and high tear index. Lower density woods mainly produce denser sheets with high tensile strength. These results agree with those reported by Wimmer et al.,[29] who studied the relationship between whole tree properties, and pulp and handsheet properties in *E. globulus* clones and found that wood density was a strong

Table 7. Correlation coefficients among wood anatomy, chemical composition, basic density, pulp ability and handsheet properties. Values presented were significant at 5% level

	Increment cores								Woodchips		
Property	Vessel frequency (number mm^{-2})	Vessel coverage (%)	Fiber wall thickness (μm)	Fiber diameter (μm)	Extractives (%)	Holocellulose (%)	α-cellulose (%)	Lignin (%)	Basic density (kg m^{-3})	Extractives (%)	Lignin (%)
Basic density (kg m^{-3})	n.s.	n.s.	n.s.	n.s.	n.s.	0.52	0.53	−0.50	—	n.s.	−0.54
Pulp yield at Kappa 15 (%)	n.s.	n.s.	n.s.	n.s.	n.s.	0.50	0.58	−0.68	0.45	n.s.	−0.39
Wood consumption (m^3 o.d.t^{-1})	n.s.	n.s.	n.s.	n.s.	n.s.	−0.59	−0.61	0.65	−0.91	n.s.	0.55
PFI revolutions	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Tensile index (Nm g^{-1})	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	−0.43	n.s.	0.36
Tear index (mNm^2 g^{-1})	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	0.38	n.s.	n.s.
Burst index (kPa m^2 g^{-1})	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	−0.36	n.s.	0.36
Specific bulk (cm^3 g^{-1})	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	0.49	−0.32	0.66	n.s.	−0.48
Opacity (%)	n.s.	n.s.	−0.43	−0.48	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Gurley air resistance (s 100 ml^{-1})	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	−0.42	n.s.	−0.62	n.s.	0.52

n.s.: non significant.

predictor of most handsheet properties. These results for the same species were later confirmed by Downes et al.,[23] who concluded that kraft pulp handsheet properties can be explained primarily by density, and suggest that the inclusion of wood anatomical data describing vessel and fiber properties could improve these relationships.

CONCLUSIONS

The variations found among *E. globulus* clones, for important parameters associated with wood anatomy, chemical composition, pulpability, and handsheet properties, is the basis for the improvement of these traits through clonal selection.

Most tree improvement programs have traditionally focused on growth as criteria for tree selection. This work shows that tree size (measured as stem volume) can negatively affect other traits as basic density and other related parameters such as specific wood consumption, tear index, specific bulk, and Gurley air resistance. Therefore, it is possible to conclude that wood quality of *E. globulus* clones as raw material for pulping is affected by growth rate. However, more work needs to be done to assess these effects in other sites, stand densities, genetic material, and cultural practices.

The low values of correlation coefficients found between wood anatomy measured in increment cores and pulp ability and handsheet properties of the whole tree, suggest that the use of increment cores as a non-destructive method to evaluate these types of relationships is limited, and also suggests that more work is needed to confirm these findings, in particular the anatomical data measured on pulp.

Wood density and chemical composition were the most important parameters correlated with pulpability and handsheet properties. For this reason, future efforts in tree improvement should be focused on wood properties such as wood density, lignin, holocellulose, and α-cellulose contents.

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