Interrelationships between kraft handsheet, and wood fibre and chemical properties for the trees and logs of 29 *Eucalyptus fastigata* and 29 *E. nitens*

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SUMMARY

Interrelationships between kraft handsheet, and wood-fibre and chemical properties of 15/16-year-old *Eucalyptus fastigata* and *E. nitens* were estimated for 29 individual trees per species, as well as for 5.5 m log-height portions of nine-tree subsets.

Kraft pulp qualities of individual-trees of *E. fastigata* and *E. nitens* (and logs) can be effectively predicted by glucose content and wood-microstructure characteristics (fibre perimeter, wall thickness, fibre length, and microfibril angle (MFA)). Also, fibre perimeter and wall thickness can be replaced in the predictive models by fibre coarseness and wood basic density. The inclusion of coarseness (with wood density) ensures fibre number per unit mass is taken into account.

Predictions of handsheet density, tensile index, stretch and T.E.A. index were consistent, and moderate to high (R^2 = 0.57 to 0.91). The separate influences of fibre perimeter and wall thickness, versus fibre coarseness and wood density, were quantified and explained by the different within-tree property distributions of *E. fastigata* and *E. nitens*.

Keywords

Individual-trees, logs, kraft pulp, wood density, fibre coarseness, microfibril angle, fibre dimensions, fibre length, wood chemistry, interrelationships

There is a need to be able to describe the performance properties of products made from individual trees (genotypes), as opposed to bulked samples from several trees (*1*). In manufacturing quality papers and pulps, fibre quality and chemistry are the important descriptors. More specifically, these wood microstructure and chemical descriptors are fibre dimensions, microfibril angle, and glucose or lignin content, which in turn determine the important compound wood properties of density and reaction wood (*1-3*).

Wood, kraft fibre and handsheet properties, including density, vessel-free density, fibre dimensions, microfibril angle and chemical properties, have been reported elsewhere for 29 trees each of 15/16-year-old *Eucalyptus fastigata* and *E. nitens* (*4-7*). A sub-set of nine trees of each species was additionally sampled by 5.5 m log/height positions. In this paper, interrelationships of individual-tree (and log) kraft handsheet properties with wood physical and chemical properties have been quantified for the same 29-tree samples of each of *E. fastigata* and *E. nitens*. In a comparable study of two sets of 25 individual trees of *Pinus radiata*, relationships among handsheet, wood and chemical properties have also been recently reported (*8*).

Handsheet apparent density (or bulk) has proved to be an important determinant of individual-tree kraft pulp quality, and a base against which all other handsheet properties can be compared (*2,3*). Hence, it is important if handsheet density can be related to wood microstructure through fibre dimensions, microfibril angle and chemistry (*1*). This will allow standing trees to be characterised by their fibre quality and chemistry, and ultimate end-use potential (*2,3*). More importantly, it could help bridge the gap between the gene and the product, and ultimately allow the development of early screening procedures for young trees, seedlings and plantlets. Despite the requirement that individual-tree kraft handsheet properties be compared against apparent density, we also need to understand relationships between individual handsheet properties and important wood microstructure and chemical properties.

EXPERIMENTAL

Sample origin

Samples of 29 trees of both *E. fastigata* and *E. nitens* were obtained from provenance/progeny trials in Kaingaroa Forest, in the central North Island of New Zealand. In each species, 20 trees were processed in the first year (aged 15 years) and the remaining nine trees were processed in the following year (aged 16 years) (*4-7*). The trees included in each of the 20- and 9-tree samples were selected to cover the range of wood density at each site, excluding suppressed trees. Additional site information is presented elsewhere (*4*).

Pith-to-bark strips were cut at time of felling from 5 cm-thick discs from each tree at nominal heights of 0, 1.4, 5.5, 11, 16.5, 22 and 27.5 m, one radial strip per disc. A 1.4 m long billet was removed from the base of each tree for assessment of solid wood properties (*9*). Density, cross-sectional fibre dimensions and microfibril angle were determined within each strip using SilviScan technology. All remaining logs of each tree were chipped for pulping by kraft (*6,7*) and cold soda mechanical (*10-12*) processes. Logs were mostly 5.5 m long, except for the toplogs which were taken to 100 mm s.e.d., length from 4 to 7 m, and the lowest log chipped which was 4.1 m long. For both species, the logs of the 20- and 9-tree samples were numbered from 1 to 5, starting from above the 1.4 m height disc. Each log was chipped separately in a commercial chipper and the chips passed through a 40 mm-diameter overs screen and retained on a 10 mm-diameter screen. For the 9-tree subsets, individual-log chips were collected at the chipper outfall and sampled. For both the 20- and 9-tree samples all the chips from the logs of each tree were bulked and well-mixed before individual-tree chip samples were taken (*6,7*).

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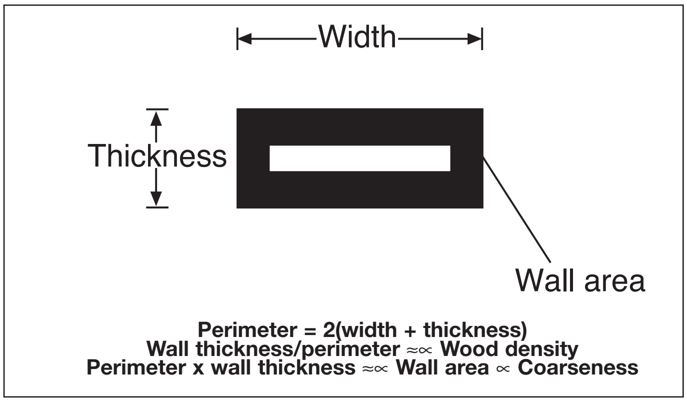

Fig. 1 Wood-fibre cross-section dimensions. Note: The longest (width) and shortest (thickness) dimension of a fibre can be either the radial or tangential dimension depending on its within ring position in the radial strip (*14,15*).

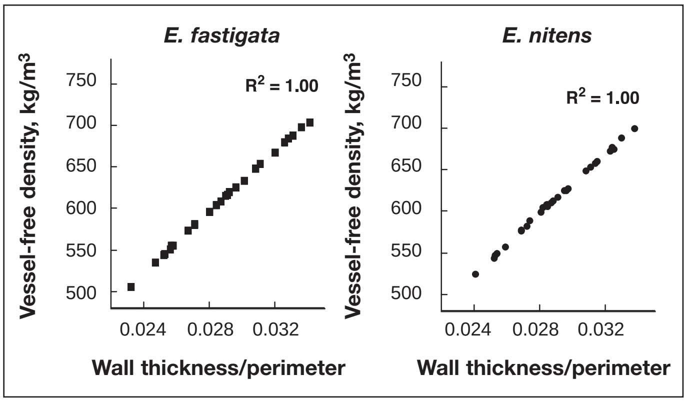

Fig. 2 Area-weighted whole-tree vessel-free density versus wall thickness/perimeter (T_w/P ratio) for 29 trees each of *E. fastigata* and *E. nitens*.

Chemical analyses

300 g o.d. chip samples were collected for chemical analyses prior to pulping. Chips were air-dried for three days prior to grinding (20 mesh). Samples were then extracted in a Soxtec extractor with dichloromethane, with a boiling time of 30 minutes and rinsing time of 60 minutes. Extractives were vacuum dried overnight and moisture contents were determined on separate samples. The dichloromethane-extracted samples were further ground to 40 mesh for analysis of lignin and carbohydrates. After acid hydrolysis, these were analysed following Tappi T222 om-88 for lignin, Tappi um250 for acid soluble lignin, and the method of Pettersen and Schwandt (*13*) for carbohydrates. Reported Klason lignin values could include some non-lignin polyphenolic substances, not extracted by dichloromethane (Appita P11s-78, J.A. Lloyd unpublished).

Pulping

Kraft pulps at Kappa number 20±2 were prepared from each chip sample by varying the H-factor at constant alkali charge (*6,7*). Pulps were prepared in 2.0 L pressurised reactors with 300 g o.d. chip charges. Pulps were disintegrated with a propeller stirrer and screened through a 0.25 mm slotted flat screen. After dewatering and fluffing, Kappa number was determined.

Handsheet preparation and evaluation

Handsheets were prepared and pulp physical evaluations made in accordance with AS/NZS 1301 standard procedures. The load applied during pulp refining with the PFI mill was 1.77 N/mm. Pulps were refined at 10% stock concentration for 500, 1000, 2000 and 4000 rev.

Wood-fibre properties

Transverse fibre dimensions and microfibril angle were determined on SilviScan 2 using image analysis, and X-ray densitometry and X-ray diffractometry (*14,15*). A single pith-to-bark radial strip was cut from each disc, then solvent-exchanged in ethanol and dried, and a thin pith-to-bark strip (2 mm wide by 7 mm high) was cut from each dried strip. All SilviScan samples were conditioned to 20°C and 40% RH. Wood density, and fibre radial and tangential diameters were measured at 50 µm intervals along the strip. Fibre coarseness, outer perimeter (from radial and tangential diameters) and average wall thickness were generated from these primary measures (Fig. 1). Estimates of vessel-free density were calculated from the vessel proportions in each strip, also determined using SilviScan 2 (*16*). The sample point values for each property along the radial strip were weighted by annulus areas to calculate 'disc' values. Individual-tree and individual-log mean wood and fibre properties were then calculated for each tree (or log) by interpolation and volume weighting of the appropriate 'disc' values.

Terminology

Chip basic density, kg/m³	D_c
Wood density (air-dry), kg/m³	D_{ss}
Vessel-free density, kg/m³	D_v
Microfibril angle, °	MFA
Fibre perimeter, µm	P
Fibre wall thickness, µm	T_w
Fibre coarseness, µg/m	C

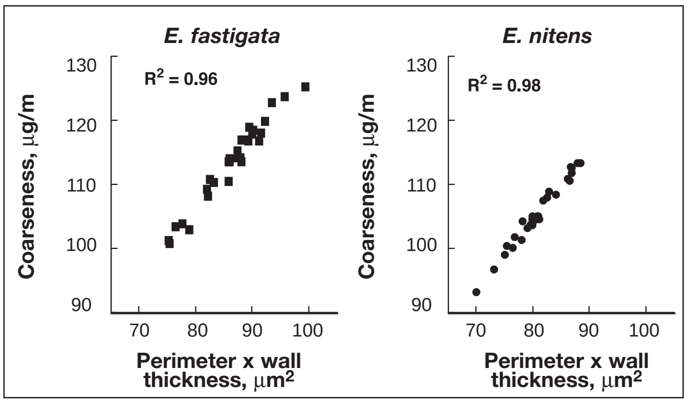

Fig. 3 Area-weighted, whole-tree wood-fibre coarseness versus perimeter by wall thickness (P by T_w product) for 29 trees each of *E. fastigata* and *E. nitens*.

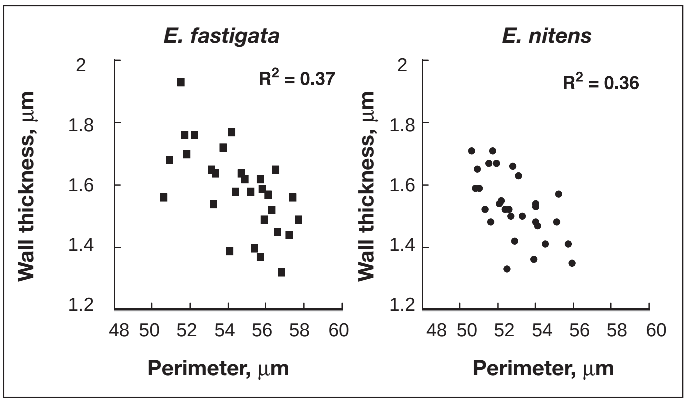

Fig. 4 Individual-tree weighted mean fibre wall thickness versus fibre perimeter for 29 trees of each of E. fastigata and *E. nitens.*

Fibre perimeter by wall thickness PxT_w
Fibre perimeter/wall thickness P/T_w
Kraft fibre length-weighted-length, mm L
Glucose, g/100g Gu
Klason + acid soluble lignin, g/100g Lg

Statistical analyses

Pearson correlation coefficients were first calculated among the wood fibre and wood chemistry variables. Combinations of wood properties were then used to predict lightly refined (500 rev PFI mill) kraft handsheet properties, using multiple linear regression models. The regression models used included no interaction or curvilinear terms. In this investigation, the data set consisted of trees that were chosen only to cover a range of wood densities. Consequently some of the predictor variables are correlated, which increases the size of coefficient standard errors, and results in changes to the coefficients for the model solutions when the pool of predictors used in the model is altered. All results presented in the tables were for 5 predictor variable combinations. Model solutions were calculated using the SAS REG procedure. The tests of significance used were type III tests.

RESULTS AND DISCUSSION

The selection of all sample trees of both *E. fastigata* and *E. nitens* to cover the range of wood density ensured high levels of among-tree variation for wood density, and indirectly for fibre perimeter, wall thickness and coarseness (*2,3*). For both species, individual-tree vessel-free density is strongly related to the wall thickness /perimeter ratio (R^2 = 1.00) (Fig. 2) while fibre coarseness is directly related to wall area or the product of perimeter by wall thickness (R^2 = 0.96 and 0.98), (Fig. 3). Thus, the wood characteristics, density and fibre coarseness, may be substituted for the wood microstructure characteristics, fibre perimeter and wall thickness, as predictors of handsheet properties. With SilviScan technology, estimates of fibre coarseness and wall thickness are derived from measured values for density and fibre radial and tangential diameters (*14,15*). Individual-tree microfibril angle (MFA), chip glucose and lignin contents, and kraft fibre length are the remaining variables used in the prediction of individual-tree kraft handsheet properties.

Overall means of whole-tree values for selected wood-fibre and kraft handsheet properties, area-weighted where appropriate, for 29 trees each of *E. fastigata* and *E. nitens*, are listed with their coefficients of variance and ranges in Table 1. Means for the 9-tree subsets that were sampled by log/height classes are shown in Table 2. Further information on these and other variables for these *E. fastigata* and *E. nitens* individual trees, and their interrelationships one with another, are reported elsewhere (*4-7*).

Table 1
Overall means of area-weighted (where appropriate) whole-tree values and their coefficients of variation and ranges, for wood, fibre, chemical and handsheet properties of 29 trees each of *E. fastigata* and *E. nitens*.

Property	*E. fastigata*			*E. nitens*		
	Mean	C.V. (%)	Range	Mean	C.V. (%)	Range
D_{ss}, kg/m^3	589	9.0	489-695	583	7.4	495-659
D_V, kg/m^3	619	9.9	507-765	618	7.5	525-700
C, µg/m	114	5.8	101-125	106	4.7	93.3-114
P, µm	54.5	3.7	50.6-57.7	52.8	2.9	50.6-55.9
T_w, µm	1.59	8.7	1.32-1.93	1.54	6.8	1.33-1.71
MFA, °	15	9.5	12.6-17.7	13.4	9.6	11.9-17.3
L, mm	0.85	4.9	0.76-0.92	0.86	5.3	0.78-0.95
Gu, g/100g	41.5	4.9	37.8-45.8	42.9	3.0	40.5-46.6
Lg, g/100g	30.5	3.0	28.7-31.8	27.5	2.7	25.1-29.0
Sheet density, kg/m^3	708	5.7	636-776	679	3.9	634-736
Air resist., $\log_e$(s/100 mL)	2.6	30.5	1.19-4.09	1.99	31.5	0.79-3.25
Tensile index, Nm/g	101.8	10.2	84.8-122.9	100.8	8.2	81.3-116.3
Stretch, %	2.86	9.5	2.48-3.41	2.57	9.8	2.10-3.11
T.E.A. index, J/kg	1966	18.3	1447-2663	1715	15.9	1295-2205
Light scat. Coeff., m^2/kg	31.8	3.5	30.0-34.9	32	4.8	28.6-35.2

Table 2
Overall means of area-weighted (where appropriate) log values and their coefficients of variation and ranges for wood, fibre, chemical and handsheet properties of 9-tree subsets (chipped and pulped by log/height classes) of *E. fastigata* and *E. nitens*.

Property	*E. fastigata*			*E. nitens*		
	Mean	C.V. (%)	Range	Mean	C.V. (%)	Range
D_{ss}, kg/m^3	593	9.0	502-679	578	9.8	471-681
D_V, kg/m^3	622	9.2	524-716	617	9.9	495-729
C, µg/m	114	7.2	96-126	104	6.4	89-117
P, µm	54.4	3.3	51.3-57.1	52.5	4.4	48.3-58.2
T_w, µm	1.59	9.0	1.31-1.83	1.52	8.6	1.31-1.75
MFA, °	14.6	10.5	12.5-18.9	13.3	9.9	11.3-16.5
L, mm	0.86	6.0	0.76-0.94	0.92	7.1	0.78-1.04
Gu, g/100g	42.9	3.6	39.7-45.9	42	5.0	36.7-46.4
Lg, g/100 g	30.5	3.6	28.3-32.6	27.4	3.1	25.3-28.9
Sheet density, kg/m^3	692	5.2	638-765	673	5.1	622-732
Air resist., $\log_e$(s/100 ml)	2.46	25.7	1.65-3.76	1.79	45.3	0.47-3.28
Tensile index, Nm/g	93.3	10.4	80.3-117.2	97.8	9.3	82.2-112.6
Stretch, %	2.65	8.3	2.16-3.04	2.57	12.6	2.05-3.40
T.E.A. index, J/kg	1686	16.2	1165-2271	1665	20.0	1120-2329
Light scat. Coeff., m^2/kg	32.6	3.1	30.9-36.1	33.4	3.9	31.1-36.9

Wood property interrelationships among 29 individual trees of *E. fastigata* and *E. nitens*

The interrelationships among eight wood, fibre and chemical properties are indicated by the correlation coefficients shown for each species in Tables 3 and 4. These correlation matrices indicate the levels of independence among the eight selected predictor variables, fibre perimeter, wall thickness, length, coarseness, and MFA, wood density and vessel-free density, and chip glucose and lignin contents. Some points of note follow:

1. Wood density and vessel-free density are strongly correlated one with another (R^2 = 0.98) in both species. Correlations are also similar between these two density variables and other variables of note (Tables 3,4), so vessel-free density is used (in place of density) in the analyses of this paper as it takes account of vessel content among and within trees. Vessel proportions in the *E. fastigata* (4.9%) and *E. nitens* (5.7%)

29-tree data sets are similar and, hence, correlations of other properties with density and vessel-free density are similar (Tables 3,4).

2. Fibre wall thickness and perimeter are moderately correlated (R^2 = 0.36) (P <0.001) in both species, and so are fibre coarseness and vessel-free wood density (R^2 = 0.38 to 0.50), Tables 3, 4 and Figures 4, 5.
3. The three remaining variables, MFA, fibre length and glucose content, are poorly correlated one with another, and with fibre wall thickness and perimeter (or coarseness or vessel-free density) (R^2 <0.3).
4. Glucose and lignin content show a low (R^2 = 0.26 to 0.39) but significant (P <0.01) level of association, (Tables 3,4). There is a clear species difference for lignin content and a not-so-clear difference in glucose content (Fig. 6) (*4,6*). Furthermore, the relatively high coefficient of determination (R^2 = 0.38) for the 29 *E. nitens* individual-tree data is clearly influenced by a few isolated high and low lignin values.

Kraft handsheet property prediction for 29 individual trees of *E. fastigata* and *E. nitens*

Eucalypt kraft pulps are known to combine the most important pulp and paper properties in a particularly favourable way (*17*). They give good strength and formation with excellent bulk (or sheet density), porosity and optical properties. Hence, the important individual-tree kraft handsheet properties that are considered here are apparent sheet density, the log of air resistance, tensile index, stretch, T.E.A. index and light scattering coefficient.

Handsheet density (or bulk) is considered to be an important determinant of

Table 3
Correlation coefficient matrix (r) between wood, fibre and chemical properties for 29 *E. fastigata* trees. Levels of significance are indicated by the bracketed P-values.

	D_{ss}	D_v	C	T_w	P	MFA	L	Gu	Lg
D_{ss}	1								
D_v	0.99	1							
	<0.0001								
C	0.61	0.62	1						
	(0.0004)	(0.0003)							
T_w	0.95	0.96	0.81	1					
	<0.0001	(<0.0001)	(<0.0001)						
P	-0.81	-0.81	-0.04	-0.62	1				
	(0.0001)	(<0.0001)	(0.83)	(0.0003)					
MFA	-0.56	-0.58	-0.47	-0.59	0.39	1			
	(0.0015)	(0.001)	(0.011)	(0.0007)	(0.035)				
L	0.39	0.41	0.27	0.39	-0.33	-0.37	1		
	(0.035)	(0.029)	(0.16)	(0.036)	((0.082)	(0.047)			
Gu	0.25	0.23	0.29	0.27	-0.06	-0.39	0.41	1	
	(0.20)	(0.24)	(0.13)	(0.16)	(0.76)	(0.034)	(0.026)		
Lg	-0.24	-0.24	-0.28	-0.28	0.10	0.57	-0.40	-0.51	1
	(0.22)	(0.21)	(0.14)	(0.15)	(0.62)	(0.0013)	(0.031)	(0.0044)	

Table 4
Correlation coefficient matrix (r) between wood, fibre and chemical properties for 29 *E. nitens* trees. Levels of significance are indicated by the bracketed P-values.

	D_{ss}	D_v	C	T_w	P	MFA	L	Gu	Lg
D_{ss}	1								
Dv	0.99	1							
	(<0.0001)								
C	0.74	0.71	1						
	(<0.0001)	(<0.0001)							
Tw	0.98	0.97	0.86	1					
	(<0.0001)	(<0.0001)	(<0.0001)						
P	-0.74	-0.78	-0.11	-0.60	1				
	(<0.0001)	(<0.0001)	(0.57)	(0.0006)					
MFA	-0.11	-0.14	-0.14	-0.14	0.12	1			
	(0.58)	(0.48)	(0.48)	(0.48)	(0.55)				
L	0.02	0.05	0.05	0.02	-0.13	-0.33	1		
	(0.92)	(0.79)	(0.79)	(0.93)	(0.51)	(0.079)			
Gu	0.09	0.10	0.10	0.09	-0.11	-0.34	0.55	1	
	(0.64)	(0.61)	(0.61)	(0.64)	(0.58)	(0.071)	(0.0022)		
Lg	-0.34	-0.33	-0.33	-0.36	0.13	0.67	-0.54	-0.62	1
	(0.068)	(0.085)	(0.085)	(0.056)	(0.51)	(0.051)	(0.0026)	(0.0003)	

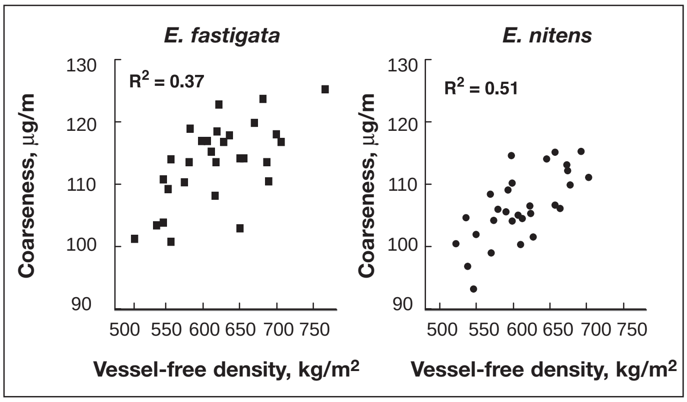

Fig. 5 Individual-tree weighted mean fibre coarseness versus vessel-free density for 29 trees of each of *E. fastigata* and *E. nitens.*

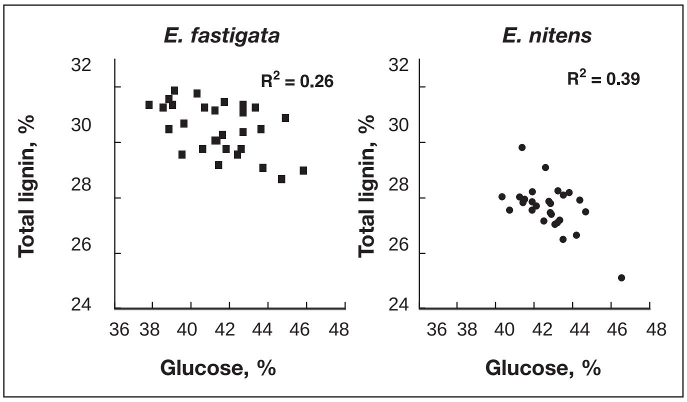

Fig. 6 Individual-tree glucose versus lignin content for 29 trees of each of *E. fastigata* and *E. nitens.*

individual-tree kraft pulp quality, and a base against which all other handsheet properties can be compared (*2,3*). Hence, it is fortunate that individual-tree handsheet density (and other properties) is predictable by wood microstructure properties, including fibre dimensions, microfibril angle and chemistry. In this paper, two sets of five predictor variables, including wood-fibre perimeter and wall thickness (or density and coarseness), MFA and glucose content, and kraft fibre length are related to handsheet properties for both *E. fastigata* and *E. nitens* (Tables 5-8).

Precision of handsheet property prediction is consistently reduced when lignin content (Klason plus acid-soluble) is substituted for glucose content in the five-variable prediction models (unreported). Also, the effect of lignin is consistently non-significant (0.05 level) when included with glucose in extended six-variable prediction models. Glucose and lignin content are correlated one to another to a moderate extent only (Tables 3,4, Fig. 6).

Individual-tree handsheet density and porosity prediction

Handsheet density (or bulk) is best predicted by wall thickness, glucose and MFA for *E. fastigata* (R^2 = 0.84), and by wall thickness, length-weighted fibre length, glucose and MFA for *E. nitens* (R^2 = 0.87) (Tables 5,6). The influences of both wall thickness and glucose content are highly significant ($p<0.01$), with sheet density decreasing (and bulk increasing) with increasing wall thickness and glucose content. Sheet density also increases significantly with increasing MFA, indicated by positive MFA coefficients (Tables 5,6). The laws of physics suggest that fibre collapse would decrease with increasing MFA. Hence, the increase in sheet density with increasing MFA may be explained by other fibre influences such as increased flexibility and conformability. In addition, our (unpublished) X-ray diffraction data indicate that there is an inverse correlation between MFA and the proportion of S2 microfibrillar material in the wood cell wall. The degree to which this relationship holds after the pulping process remains to be tested. The influences of fibre perimeter and length on sheet density are small and non-significant (except for length in the *E. nitens* tree-set (P = 0.04)). Perhaps the significant effect of length on the *E. nitens* prediction model is related to the very different fibre length distributions within the *E. nitens* and *E. fastigata* trees (*7*). This effect is also indicated by the wide range of mean log fibre lengths for the *E. nitens* 9-tree sub-set (Table 2).

It is noteworthy that wall thickness is the principal variable in predicting sheet density. By itself wall thickness accounts for 70 and 54 per cent respectively of the tree variation in sheet density for *E. fastigata* and *E. nitens* (unreported). Corresponding coefficients of determination (R^2) for wall thickness plus glucose content are respectively 0.78 and 0.77. With the inclusion of MFA in the prediction models, these values of R^2 for *E. fastigata* and *E. nitens* are increased respectively to 0.81 and 0.82.

The prediction of handsheet porosity (log of Gurley air resistance), which is related to fibre packing arrangements in paper webs, follows the trend of handsheet density although the effect of glucose is markedly diminished (Tables 5,6). The signs (±) for the regression coefficients of the fibre predictor variables are consistent for sheet density and the log of air resistance, for both species. For the log of air resistance, wall thickness is again the dominant predictor, followed by MFA

Table 5
Regression model statistics for the prediction of kraft handsheet properties (at 500 PFI mill rev.) from 29 individual trees of *E. fastigata*: parameter estimates using wood glucose content (Gu), fibre perimeter (P), wall thickness (Tw), length (L) and MFA as predictor variables.

Predictor	Handsheet property prediction					
	Density (kg/m^3)	Air resistance ($\log_e$ s/100ml)	Tensile index (Nm/g)	Stretch (%)	T.E.A. index (J/kg)	Light scattering coefficient (m^2/kg)
Tw (µm)	-159 **	-3.73 **	-59.0 **	-1.30 **	-1979 **	-0.436
P (µm)	3.82	0.0352	-0.0790	-0.0193	-18.7	-0.400 **
L (mm)	126	0.259	27.6 **	-0.274	797	-12.1 **
Gu (g/100g)	-5.68 **	-0.0437	0.556 *	-0.0229	-34.4 *	0.281 **
MFA (°)	6.53 *	0.131 *	0.893	0.0571 *	63.8 *	-0.0586
Intercept	783	6.23	176	6.30	5925	53.7
R^2	0.84	0.84	0.79	0.79	0.85	0.62
RMSE	17.6	0.348	5.17	0.138	153	0.761

* Significant at the 0.05 level. ** Significant at the 0.01 level.

Table 6
General linear model statistics for the prediction of kraft handsheet properties (at 500 PFI mill rev.) from 29 individual trees of *E. nitens:* parameter estimates as for Table 5.

Predictor	Handsheet property prediction					
	Density (kg/m^3)	Air resistance ($\log_e$ s/100ml)	Tensile index (Nm/g)	Stretch (%)	T.E.A. index (J/kg)	Light scattering coefficient (m^2/kg)
Tw (µm)	-176 **	-4.47 **	-60.0 **	-1.42 **	-1924 **	1.37
P (µm)	0.741	0.0297	-0.0119	-0.0196	-12.9	-0.176
L (mm)	-159 *	-4.62 **	-15.7	-0.653	-930	7.46
Gu (g/100g)	-6.06 **	-0.106 *	-1.29	-0.0362	-43.4	0.190
MFA (°)	4.51 *	0.0788	-0.0130	0.0864 **	59.0 *	0.124
Intercept	1247	14.8	263	6.73	7225	22.8
R^2	0.87	0.86	0.64	0.66	0.78	0.16
RMSE	11.4	0.288	5.46	0.161	141	1.57

* Significant at the 0.05 level. ** Significant at the 0.01 level.

(although not significant for *E. nitens*), with glucose content non-significant for *E. fastigata*, and barely significant ($p < 0.05$) for *E. nitens*. The influence of fibre length is not significant for *E. fastigata* but highly significant ($p < 0.01$) for *E. nitens*, also in agreement with the prediction of handsheet density.

Table 7
Regression model statistics for the prediction of kraft handsheet properties (at 500 PFI mill rev.) from 29 individual trees of *E. fastigata*: parameter estimates using wood glucose content (Gu), fibre coarseness (C), vessel-free density (Dv), length (L) and MFA as predictor variables.

Predictor	Handsheet property prediction					
	Density (kg/m³)	Air resistance (log_e s/100ml)	Tensile index (Nm/g)	Stretch (%)	T.E.A. index (J/kg)	Light scattering coefficient (m²/kg)
Dv (kg/m³)	-0.443 **	-0.00805 **	-0.100 **	-0.00138 *	-2.60 **	0.0162 **
C (µg/m)	-0.124	-0.0160	-0.399 *	-0.0139 *	-18.1 **	-0.0950 **
L (mm)	128	0.358	80.6 **	-0.224	870	-11.6 **
Gu (g/100g)	-5.68 **	-0.0447	-1.143 *	-0.0235	-35.3 *	0.271 **
MFA (°)	6.60 *	0.131 *	0.990	0.0564 *	63.1 *	-0.0664
Intercept	1024	8.99	185	5.61	5418	32.2
R^2	0.84	0.84	0.78	0.79	0.85	0.61
RMSE	17.5	0.347	5.23	0.137	153	0.769

* Significant at the 0.05 level. ** Significant at the 0.01 level.

Table 8
Regression model statistics for the prediction of kraft handsheet properties (at 500 PFI mill rev.) from 29 individual trees of *E. nitens*: parameter estimates as for Table 7.

Predictor	Handsheet property prediction					
	Density (kg/m³)	Air resistance (log_e s/100ml)	Tensile index (Nm/g)	Stretch (%)	T.E.A. index (J/kg)	Light scattering coefficient (m²/kg)
Dv (kg/m³)	-0.322 **	-0.00872 **	-0.100 **	-0.00145	-2.63 **	-0.00321
C (µg/m)	-1.08	-0.0249	-0.423	-0.0155	-17.0 *	-0.0133
L (mm)	-153 *	-4.49 **	-13.1	-0.575	-835	-1.79
Gu (g/100g)	-6.12 **	-0.107 *	-1.32	-0.0368	-44.4	-0.0171
MFA (°)	4.68 *	0.0825	0.0476	0.0882 **	61.2 *	-0.145
Intercept	1324	17.4	275	5.98	6938	17.8
R^2	0.87	0.86	0.64	0.66	0.78	0.20
RMSE	11.5	0.282	5.44	0.160	140	0.561

* Significant at the 0.05 level. ** Significant at the 0.01 level.

Prediction of individual-tree handsheet stress/strain relationships

Wall thickness continues to be the dominant predictor variable for handsheet tensile index, stretch and T.E.A. index, with highly significant effects ($p < 0.01$) for both *E. fastigata* and *E. nitens* (Tables 5,6). MFA is the other predictor variable of note, with significant effects on stretch and T.E.A. index, where web extensibility increases with increasing MFA. The absence of an MFA effect on tensile index of the two eucalypts is noteworthy, since MFA has a highly significant ($p < 0.01$) and negative effect in radiata pine individual-tree pulps with much longer fibres (*8*). The significant effects of fibre length and glucose content on tensile index in *E. fastigata* are unexplained. Tensile index is normally expected to be essentially unchanged by fibre length (*6,7*). The coefficients of determination (R^2) for prediction of tensile index for *E. fastigata* are 0.66 for wall thickness alone, 0.77 for wall thickness plus glucose, and 0.78 when wall thickness, glucose and length are included in the model. Tensile index prediction by length alone has an $R^2 = 0.02$.

The percentage total variation explained in each dataset with the handsheet property prediction models is consistently lower for tensile index, stretch and T.E.A. index compared to those for density and the log of air resistance (Tables 5-8). This is explained by higher analytical error being incurred during tensile testing with high proportions of individual test strips being rejected for failing close to a clamp. Corresponding predictions for burst index (R^2) are consistently high at 0.84 for *E. fastigata* and 0.86 for *E. nitens* (unreported).

Substitution of predictor variables 'fibre wall thickness and perimeter' by 'fibre coarseness and wood density'

Fibre wall thickness has highly significant effects on handsheet density and stress/strain properties, for both *E. fastigata* and *E. nitens*, while the effects of perimeter were not significant (Tables 5,6) probably because of its low variation among trees within a species (Table 1). The situation could be very different if the analyses were made across species with very different mean fibre perimeters such as *E. globulus*, *E. maidenii* and *E. nitens* (or *E. fastigata*) (*18*).

When fibre wall thickness and perimeter are replaced by wood density and fibre coarseness in the prediction models, overall predictions are essentially unchanged for handsheet density, the log of air resistance, tensile index, stretch and T.E.A. index (Tables 5,6 and 7,8). Features of interest are:

1. Wood density by itself, or the wall thickness/perimeter ratio (T_w/P) (Fig. 2), is as effective as wall thickness in the prediction of handsheet density and log air resistance for both *E. fastigata* and *E. nitens*.
2. Both wood density and fibre coarseness are required in the prediction of handsheet tensile index, stretch and T.E.A. index for each species as the inclusion of coarseness along with

density ensures fibre number per unit mass is taken into account.

Prediction of individual-tree handsheet light scattering coefficient

Handsheet light scattering coefficient is an indicator of the optical properties of a pulp. It is particularly relevant in the assessment of eucalypt kraft pulps, which are used as a component of papermaking furnishes to enhance the opacity and formation properties of many wood-free grades (*17*). The prediction of handsheet light scattering coefficient is moderate (R^2 = ~0.6) for *E. fastigata* (Tables 5,7) and very poor for *E. nitens* (R^2 = ~0.2) (Tables 6,8). This situation is reversed when pulps are derived separately from all log height classes of each species (Tables 9,10). The inconsistencies remain unexplained and light scattering coefficient is not considered further in this paper. Perhaps the inconsistent predictions of handsheet light scattering coefficient can be related to changes in fibre wall thickness and coarseness brought about by kraft pulping (*19*).

Kraft handsheet property prediction for the logs from 9-tree subsets of *E. fastigata* (31 logs) and *E. nitens* (39 logs)

For the 29 trees of *E. fastigata* and *E. nitens*, a subset of nine trees from each species was processed one year later, aged 16 years (*6,7*). These trees were selected, as for the first 20, to cover the range of densities of trees at each site, and were crosscut into mostly 5.5 m logs, which were chipped and pulped separately. Separate log-level wood, chemical and fibre properties were determined and kraft pulp quality determinations were made for each of a total of 31 logs of *E. fastigata* and 39 logs of *E. nitens*. Individual-tree and log-height variation is therefore confounded amongst the logs of each species. It is important to understand that in these log-level regressions, there is the same amount of tree-to-tree variation as in the individual-tree-level data, plus the considerable systematic variation in wood fibre properties that is found from the base to the top of the tree. This systematic difference with log height is somewhat different in its characteristics in each species (*4,7*).

Levels of association among the five predictor variables of the two species sets of logs (compared to those among 29 individual trees) are reduced for wall thickness and perimeter but increase marginally for most other variable-pair combinations (unreported data). For wall thickness and perimeter, correlation coefficients (r) changed from -0.62 to -0.38 for *E. fastigata*, and from -0.60 to -0.51 for *E. nitens*.

Handsheet density and log air resistance prediction models are generally similar for the *E. fastigata* individual-trees and logs (Tables 5, 9). Regression coefficients for these properties are of the same sign and similar magnitudes. The main differences between the individual-tree and log models are the lowered levels of significance for MFA and glucose content (sheet density only) in the log models. Coefficients of determination are not greatly different for the tree and log models at respectively 0.84 and 0.79 for sheet density, and 0.84 and 0.88 for the log of air resistance. Corresponding prediction models for tensile index, stretch and T.E.A. index are generally similar for the *E. fastigata* individual-tree and log-level data sets with some minor

Table 9
Regression model statistics for the prediction of kraft handsheet properties (at 500 PFI mill rev.) from the 31 logs of the nine individual trees of the *E. fastigata* 9-tree sub-set: parameter estimates as for Table 5.

Predictor	Handsheet property prediction					
	Density (kg/m^3)	Air resistance ($\log_e$ s/100ml)	Tensile index (Nm/g)	Stretch (%)	T.E.A. index (J/kg)	Light scattering coefficient (m^2/kg)
Tw (µm)	-163 **	-3.22 **	-43.0 **	-1.04 **	-1423 **	0.307
P (µm)	2.45	0.039	1.09	-0.0536 *	-18.6	-0.2516
L (mm)	21.3	1.74	72.5 *	0.683	1640	-6.18
Gu (g/100g)	-5.78	-0.115 *	-3.11 *	-0.00822	-52.3	0.221
MFA (°)	4.66	0.0724	-1.03	0.0443	14.9	0.156
Intercept	980	7.84	188	6.35	5589	37.5
R^2	0.79	0.88	0.74	0.57	0.69	0.24
RMSE	18.3	0.243	5.45	0.149	160	0.98

*Significant at the 0.05 level. ** Significant at the 0.01 level.

Table 10
Regression model statistics for the prediction of kraft handsheet properties (at 500 PFI mill rev.) from the 39 logs of the nine individual trees of the *E. nitens* 9-tree sub-set: parameter estimates as for Table 5.

Predictor	Handsheet property prediction					
	Density (kg/m^3)	Air resistance ($\log_e$ s/100ml)	Tensile index (Nm/g)	Stretch (%)	T.E.A. index (J/kg)	Light scattering coefficient (m^2/kg)
Tw (µm)	-160 **	-4.33 **	-54.2 **	-1.54 **	-1879 **	-2.93
P (µm)	3.88 **	0.0829 **	0.449	-0.0203	-7.37	-0.478 **
L (mm)	-89.1 *	-1.76	33.1 **	0.113	317	5.24
Gu (g/100g)	-0.431	-0.0191	-1.36 **	0.0121	-6.71	-0.0667
MFA (°)	7.54 **	0.108 *	0.312	0.143 **	102 **	0.134
Intercept	712	5.01	179	3.46	3552	59.1
R^2	0.89	0.91	0.88	0.82	0.87	0.55
RMSE	12.3	0.256	3.35	0.147	129	0.942

* Significant at the 0.05 level. ** Significant at the 0.01 level.

exceptions as follows: (Tables 5,9):

1. For tensile index the effect of glucose content is significant, with a positive coefficient for individual trees (Table 5), and significant with a negative coefficient for logs (Table 9). It is suggested that these glucose-content-related differences are probably associated with a level of carbohydrate degradation in the 20 individual-tree chemical analysis samples (*6*).
2. Prediction-variable coefficients are generally similar for the two stretch models, with the perimeter effect becoming significant (0.05 level) and MFA non-significant (although close, P = 0.07) in the log-level model.
3. Except for MFA, the prediction-variable coefficients are similar for the two T.E.A. index models. The non-significant MFA and glucose content effects on the log-level compared to the individual-tree models can be related to the different influences of these predictive variables on handsheet tensile index and stretch. For the logs, increasing MFA increases handsheet stretch (p = 0.07) and decreases tensile index (p = 0.24), resulting in only a minimal and non-significant net influence on T.E.A. index.
4. Tensile index, stretch and T.E.A. index model predictions (R^2) were reduced for log-level versus individual-tree regressions for *E. fastigata* as follows: tensile index 0.79 to 0.74, stretch 0.79 to 0.57, and T.E.A. index 0.85 to 0.69 (Tables 5,9).

For *E. nitens* (Tables 6,10) the log-level prediction model for handsheet density was quite different, with the perimeter effect being highly significant (0.01 level), in contrast to being consistently non-significant for other handsheet properties (Tables 5-9). The significant effects of MFA and length were retained, and the glucose effect was greatly diminished. The signs of the predictor-variable coefficients were the same for both tree and log models although the magnitudes of the perimeter and glucose coefficients were substantially different. Similar but not identical trends were shown for the handsheet air resistance prediction models.

The emergence of fibre perimeter as a highly significant handsheet density prediction variable for *E. nitens* logs (Table 10) may be explained by the higher among-log variation in perimeter compared to that in *E. fastigata* (Tables 1,2). For *E. nitens*, fibre perimeter decreases rapidly with tree-height above ground whereas wall thickness increases (*4,7*). Hence, the extent of fibre collapse (P/Tw) decreases and wood density increases with increasing tree-height. By contrast, in *E. fastigata* both fibre collapse and wood density remain generally unchanged with increasing tree-height. For *E. fastigata*, fibre perimeter and wall thickness decrease proportionately one with another with increasing tree-height (*4,7*).

The large effect of fibre perimeter on handsheet density and the log of air resistance are absent in the corresponding stress-strain property prediction models. For the *E. nitens* individual-tree and log-level data sets, the influence of fibre perimeter is small and non-significant (0.05 level) in the prediction of handsheet tensile index, stretch and T.E.A. index (Table 10). Features of note for tensile index prediction are the highly significant effects of fibre length and glucose content of the log-level compared to the individual-tree model. These increased influences of length and glucose content may be explained by the wide range of mean log values (Tables 1,2). Handsheet stretch and T.E.A. index prediction models are generally similar for the logs and individual-trees of *E. nitens*. Handsheet property predictions are particularly strong for log-level data of *E. nitens*, with coefficients of determination (R^2) ranging from 0.82 for stretch to 0.91 for log of air resistance (Table 10).

Comparable models are obtained when mean-log fibre coarseness and wood density are substituted for fibre perimeter and wall thickness (unreported), as discussed earlier for the individual-tree *E. fastigata* and *E. nitens* data-sets (Tables 5-8). For these two pairs of variables, wood density (like wall thickness) is the main predictor of handsheet density and the log of air resistance. In contrast, wood density and coarseness, in combination, are important predictors ($p < 0.05$ or 0.01) of tensile index, stretch and T.E.A. index in *E. nitens* log-level models. On the other hand, for the corresponding *E. fastigata* data set, the tensile index model is strongly influenced by density (but not coarseness) whereas stretch and T.E.A. index models are strongly influenced by coarseness (but not density) ($p < 0.01$).

CONCLUSIONS

Kraft handsheet properties of individual whole-tree pulps (minimally refined at 500 PFI mill rev.) of *Eucalyptus fastigata* and *E. nitens* can be predicted from their wood microstructure and chemical properties, fibre perimeter and wall thickness, fibre length, glucose content and MFA. Levels of prediction are high for sheet density, log of air resistance and burst index (R^2 >0.8), and tensile index, stretch, and T.E.A. index ($R^2 \approx 0.7$).

When a subset of nine trees per species was divided into 5.5 m log-height portions (logs) and these pulped separately, high predictabilities of handsheet properties for logs were maintained or improved. In contrast, predictions of handsheet light scattering coefficient were poor to moderate, and inconsistent for the species, individual-tree and individual-log data sets. Similar predictions of kraft pulp properties were obtained when density and fibre coarseness were used in place of the wood microstructure characteristics, fibre perimeter and wall thickness. Furthermore, lignin can be substituted for glucose as a predictor although levels of prediction were marginally lower.

Fibre wall thickness was the principal predictor for sheet density, log of air resistance, tensile index, stretch and T.E.A. index for the individual-tree pulps of each species. Glucose content and MFA were also significant predictor variables for handsheet density (which is determined by fibre properties and their packing arrangements and configurations in paper webs). Handsheet density decreases with increasing wall thickness and glucose content but increases with increasing MFA. The positive MFA effect may be explained by fibre flexibility or conformability influences rather than by fibre collapse. MFA also has a strong influence on stretch and T.E.A. index but not tensile index. The expected decrease in tensile index with increasing MFA was absent in all four data sets. Hence, it is concluded that any negative effect of increasing MFA on handsheet tensile index is confined to long softwood fibres such as radiata pine, but not short eucalypt fibres.

The range of wood microstructure and chemical predictor variables is markedly increased when logs of each tree are pulped separately. Fibre perimeter becomes a highly significant predictor of sheet density and the log of air resistance for *E. nitens* but not for *E. fastigata* logs. This is explained partly by the high among-log variation in perimeter compared to that among individual-trees of *E. nitens*. An additional and confounding factor for *E. nitens* is that fibre perimeter decreases with increasing tree-height whereas both fibre wall thickness and wood density increase. For *E. fastigata*, on the other hand, wood density remains unchanged with increasing tree-height, and fibre perimeter and wall thickness decrease proportionately one with another.

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