Kraft pulp fibre property prediction from wood properties in eleven radiata pine clones

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SUMMARY

Patterns of variation in density, tracheid cross-section dimensions and kraft pulp fibre dimensions have been estimated in a series of eleven 16-year-old radiata pine clones. The aims were to compare wood and pulp fibre measurements and to estimate the efficiency of sampling at breast height (BH: 1.4 metre) for prediction of whole tree wood and kraft pulp fibre properties. Radial sections were examined from six heights in twenty-four trees, representing the eleven clones. Density and tracheid cross-section dimensions were measured at a radial resolution of 50 µm using SilviScan-1, a combined image analyser and scanning microdensitometer. Fibre length distributions of the kraft pulps were measured using the Kajaani FS200, and the cross-section dimensions of dried, unrefined fibres were obtained by image analysis of thin sections. Correlations between BH wood properties and whole-tree estimates were very strong, but there was no significant correlation between tracheid perimeter and wall thickness. It is concluded that tracheid cross-section dimensions may be independently selected in tree improvement programs and that BH sampling is reliable for radiata pine clones.

Increasing worldwide competition for pulp and paper markets is focusing attention on the measurement and control of wood and pulp quality. Methods for the rapid characterization of these raw materials will enable the development of efficient breeding and silvicultural strategies. In the long term, major improvements in the level and consistency of many fibre properties are possible. In the shorter term, quality assessment of pulpwood and market pulps will allow forest managers and manufacturers to match their resources with changing product specifications and to identify new products and new markets.

Any generally useful pulpwood assessment strategy must be convenient, cheap and rapid, and must be able to cope with hundreds or thousands of trees. Routine assessment requires that (a) sampling is non-destructive, (b) sample size is small, (c) sampling rate is high, (d) measurement rate is high, (e) sample properties reflect those of the whole resource and (f) resource properties control product properties. Coring at breast height (BH: 1.4m) with a motorized increment corer generally satisfies requirements (a), (b) and (c); it is now possible for a skilled operator to collect 150 12 mm cores in one day. Cores are removed by the operator standing on the ground and the trees are not significantly damaged by the procedure. SilviScan (*1,2*) satisfies requirement (d) by assessing many thousands of cores per year. This report addresses requirement (e) for a series of 24 radiata pine trees and an associated report (*3*) addresses requirement (f) for the same trees.

EXPERIMENTAL

Two trees from each of ten clones and four trees from another clone were selected to cover a wide range of BH wood density and tracheid length. Radial sections for microstructure analysis were cut from discs at BH and five other heights at intervals of approximately 5.5 m. Although, the radial sections were not taken with an increment corer, they will be referred to as cores in this report. Each tree was also whole tree chipped and representative samples were kraft pulped to 30 Kappa number. Full papermaking and testing was done to establish relationships between fibre properties and paper properties (*3*). The cross-section dimensions of unrefined pulp fibres prepared from dried handsheets were measured by image analysis of embedded sections (*4*). Pulp fibre length distribution and coarseness were measured with a Kajaani FS200 fibre analyser on unrefined pulp according to TAPPI T271 pm-91.

The air dried wood samples were cut radially on a twin blade saw to 2 mm tangentially by 7 mm longitudinally, extracted and polished using methods described elsewhere (*1,2*). Radial profiles and distributions of density and tracheid cross-section dimensions were measured for each core using SilviScan-1. Unweighted and area weighted results were produced for each height in each tree. Within-tree and within-clone average properties were estimated from volume weighted data. It was assumed that the properties varied linearly with height between the sampling points. Whole tree volumes were estimated from the cross-section area versus height curves extrapolated to zero area at the top of each tree. Air dry tree masses were similarly estimated from area weighted densities and whole tree volumes.

RESULTS AND DISCUSSION

Wood and tracheid properties from increment cores

Whole tree estimates, unweighted BH and area weighted BH properties are summarized in Table A1 (all Tables in the Appendix are identified by the letter A), where clone 7 represents a composite of four trees. Figure 1 shows the relationships between whole tree average tracheid coarseness and wood density and between tracheid wall thickness and perimeter. These are equivalent means of displaying the results. One coordinate system can be readily converted to the other using the simple model of a rectangular tracheid cross-section with constant cell wall density (2) The transverse aspect ratio of the tracheids (radial diameter : tangential diameter) is represented in Figure 1 by the diameter of the symbols. Large symbols represent large aspect ratios. The lack of cor-

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relation between tracheid perimeter and wall thickness shows that there is considerable scope in breeding programs for selective manipulation of these important wood characteristics. Although environmental factors influenced growth rate, they had little effect on the cross-section dimensions of the tracheids. Genetic control of tracheid dimensions was considerably greater than environmental control within this site (*5*).

Relationships between breast height and whole tree properties

The most common non-destructive techniques for wood property evaluation involve BH core sampling. It is essential therefore that the relationships between BH properties and whole tree properties are strong. Table 2 shows that this is the case for all properties measured with SilviScan-1. Coefficients of determination for unweighted BH properties ranged from 0.827 for tracheid tangential diameter to 0.942 for radial diameter. Area weighting of the BH data improved r^2 but had little or no effect on SE. Use of average clone properties further improved r^2, but again with little improvement in SE. Although the cross-section aspect ratio (radial diameter / tangential diameter) is unlikely to be directly relevant to pulp and paper manufacture, it was also strongly predicted from BH data. Note that the coefficients of determination for relationships between BH and whole tree properties are overestimated here because the BH properties contribute to the estimate of whole tree properties (autocorrelation).

For the detailed prediction of paper structure and properties, it may be necessary to estimate, from core samples, distributions as well as means of whole tree wood properties. Knowledge of distributions will allow a choice of different wood property weightings for each paper property. The relationships between the distributions of properties in BH cores and in whole trees vary with property type. Figure 2 shows the distributions in tracheid perimeter for whole trees (estimated from cores at all sampled heights) and for unweighted BH cores from clones 1 and 9. The perimeters at BH tend to lie to the low side of those

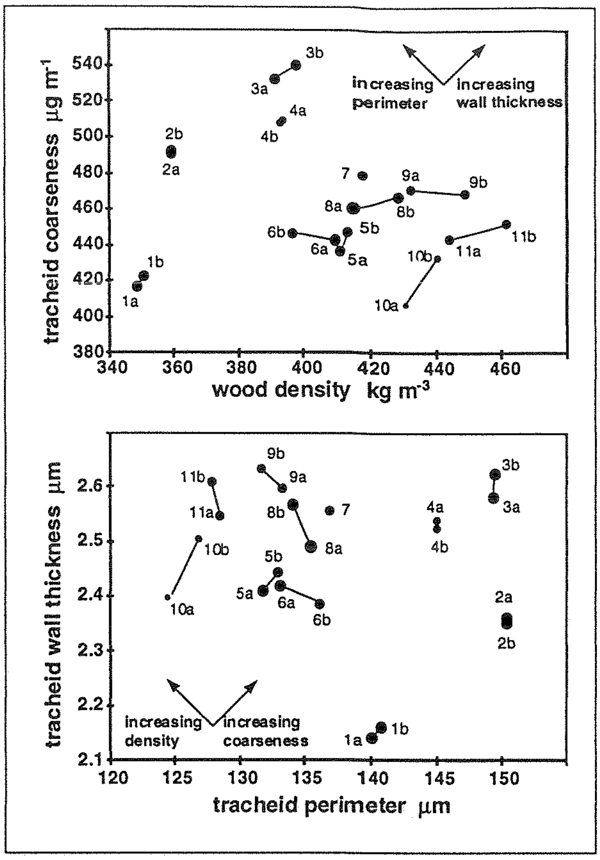

Fig. 1 Relationship between whole tree tracheid coarseness and whole tree density, and between whole tree tracheid wall thickness and whole tree tracheid perimeter as estimated by SilviScan-1 on samples taken from six heights within each tree. Symbol size is proportional to (radial diameter/tangential diameter-1).

Table 2
Prediction of whole tree properties from unweighted and area weighted breast height properties

Property	Trees				Clones			
	Unweighted		Weighted		Unweighted		Weighted	
	r^2	SE	r^2	SE	r^2	SE	r^2	SE
density	0.856	11.5	0.837	12.3	0.906	9.4	0.867	11.2
coarseness	0.911	10.2	0.913	10.2	0.915	10.2	0.923	9.7
wall thickness	0.831	0.054	0.816	0.056	0.862	0.049	0.841	0.052
perimeter	0.905	2.34	0.918	2.18	0.926	2.11	0.943	1.85
radial diameter	0.942	0.56	0.924	0.64	0.968	0.42	0.952	0.52
tangential diameter	0.827	0.67	0.898	0.52	0.836	0.67	0.925	0.45
aspect ratio	0.777	0.017	0.868	0.013	0.788	0.017	0.932	0.010

Table 3
Intraclass correlation coefficients r_I and their significance levels *P* for a range of properties

Property	r_I whole tree	*P*	r_I unwtd BH	*P*	r_I area wtd BH	*P*
density	0.954	< 0.00001	0.848	< 0.001	0.933	< 0.00001
coarseness	0.964	< 0.00001	0.936	< 0.00001	0.937	< 0.00001
wall thickness	0.930	< 0.00001	0.839	< 0.001	0.937	< 0.00001
perimeter	0.985	< 0.00001	0.931	< 0.00001	0.927	< 0.00001
radial diameter	0.988	< 0.00001	0.946	< 0.00001	0.938	< 0.00001
tangential diameter	0.974	< 0.00001	0.898	< 0.0001	0.884	< 0.0001
radial:tangential diam.	0.951	< 0.00001	0.761	< 0.01	0.871	< 0.001
volume	0.388	ns				
mass	0.012	ns				

Table 4
Intraclass correlation coefficients r_i and their significance P for whole tree property distribution widths estimated from cores

Distribution width (percentiles)		r_i	P
density	75 – 25	0.926	< 0.00001
coarseness	75 – 25	0.828	< 0.001
perimeter	75 – 25	0.845	< 0.001
wall thickness	75 – 25	0.600	< 0.05
density	90 – 10	0.835	< 0.001
coarseness	90 – 10	0.681	< 0.05
perimeter	90 – 10	0.920	< 0.0001
wall thickness	90 – 10	0.784	< 0.01

in the whole tree. The results for tracheid wall thickness are given in Figure 3. In this case, the distributions at BH are very similar to those in the whole tree.

Variation within and between clones

Although diameter growth varied considerably between trees of a clone, tracheid properties varied little. Intraclass correlation coefficients are 'a measure of fraternal resemblance' (*6*). Table 3 lists the intraclass correlation coefficients, r_i, for whole trees, unweighted BH cores and area-weighted BH cores. The correlation is extremely high—in most cases with significance levels better than 0.00001 (0.001%). Even the aspect ratio (radial diameter/tangential diameter) appears to be under strong genetic control. The range for these trees was 1.08–1.22 with a highly significant intraclass correlation coefficient (r_i) of 0.951. The 95% confidence limits for r_i were 0.824 and 0.987. The high intraclass correlation coefficients for the measurements on wood properties are not only an indication of the similarity of trees within a clone but also show that sampling and measurement variances were relatively small.

Intraclass correlations for whole tree volume and mass were not significant. There are, however more efficient means of measuring tree volume, and the low r_i values for volume and mass using increment cores may not adequately reflect the true variability of these properties. It is of considerable practical significance that differences in growth rate, as indicated by tree volume, do not have a marked effect on the tracheid properties. The (more costly) assessment of wood properties in a clonal population should require far fewer samples than for the estimation of wood production rate.

The stability of frequency distributions of properties within trees of the same clone is illustrated in Figure 4. These results are similar to those for all the clones examined in this study; the similarity in the property distributions for two trees within a clone is remarkable. Two measures of distribution width are given in Table 4 (25th to 75th percentile and 10th to 90th percentile). They exhibit strong intraclass correlations, providing further evidence both of the stability of within clone wood property variation and of the measurement techniques.

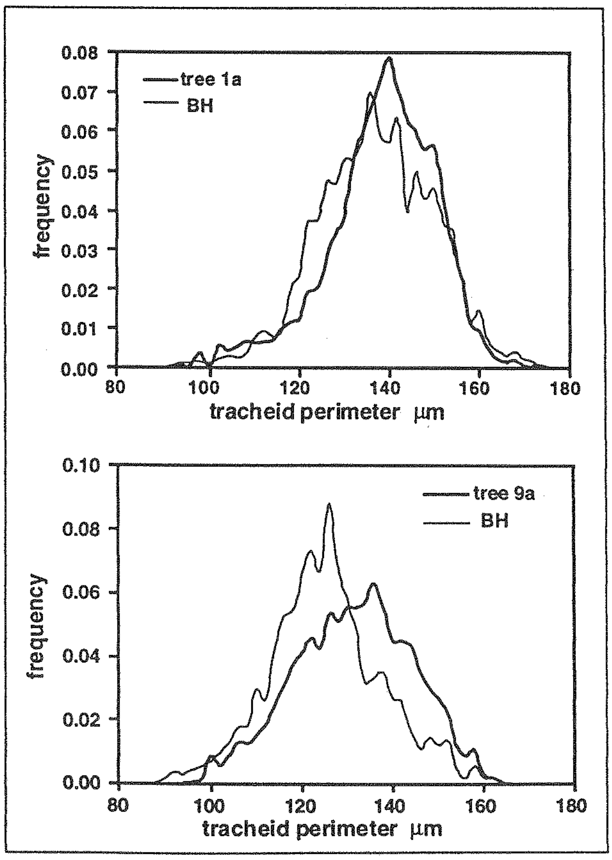

Fig. 2 Comparison of estimated whole tree and BH tracheid perimeter distributions for a tree from each of clones 1 and 9.

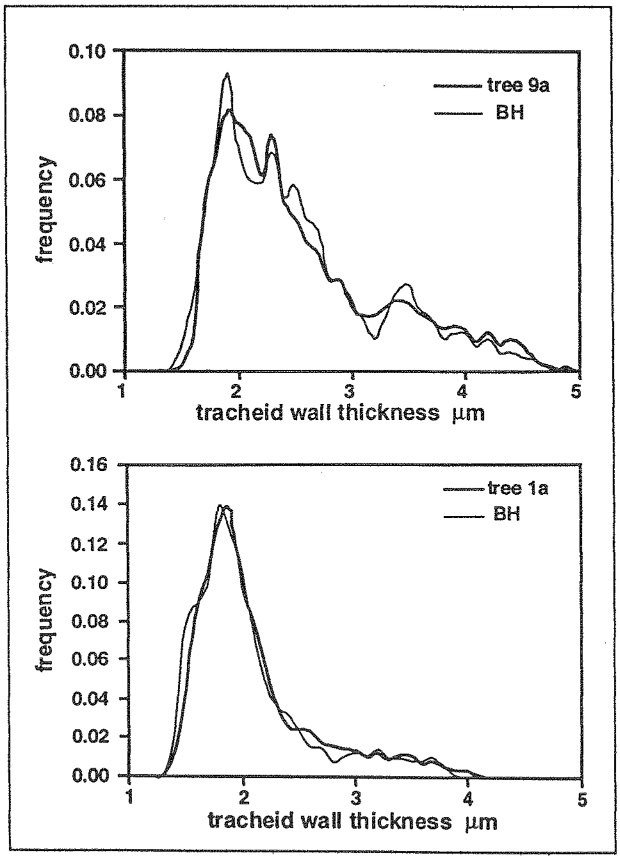

Fig. 3 Comparison of estimated whole tree and BH tracheid wall thickness distributions for a tree from each of clones 1 and 9.

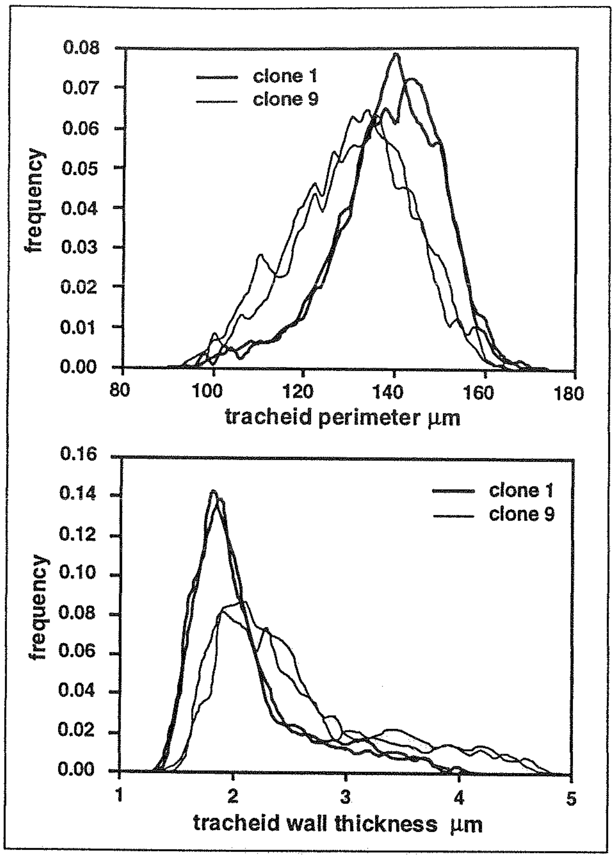

Fig. 4 Comparison of estimated whole tree and BH tracheid perimeter and wall thickness distributions for two trees in each of clones 1 and 9.

Prediction of wood and kraft pulp fibre properties from increment core data

A summary of wood and kraft pulp fibre properties is given in Table A5. Relationships between selected properties are summarized in Tables A6-A9 for individual trees and clones. Included in the Tables are the standard errors and their percentages based on the means and ranges of predicted properties.

Table 10 shows the intraclass correlation results for wood density and selected kraft pulp properties. The values of r_i are moderate to high with two notable exceptions. Tracheid length at BH and fibre wall thickness. These appear to be excessively variable between trees of the same clone. For tracheid length, this may result from high local variability near the sampling point, and for fibre wall thickness the pulping process may have increased the variability of cell wall structure. Both problems are under investigation. Other properties exhibiting relatively weak correlations were kraft pulp yield and length-weighted pulp fibre length, which were significant only at the 90% and 95% confidence levels with r_i values of 0.528 and 0.682. The average basic density of the trees/clones as estimated from discs and whole tree chips was generally very strongly correlated with the corresponding density estimated from cores. Unweighted BH data explained 85.6% of chip basic variance (Table A7) and the combined data from all sample heights accounted for 98.5% of the variance in clone average density (Table A6). Standard errors were 11.3 kg.m^{-3} and 3.4 kg.m^{-3} respectively. At the other end of the scale, unrefined dried pulp fibre wall thickness was poorly correlated with tracheid wall

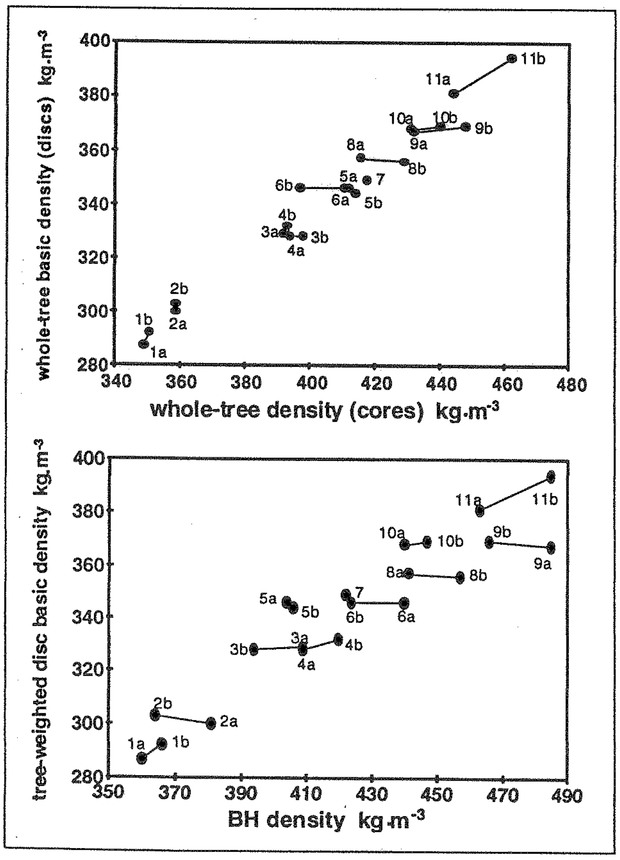

Fig. 5 Comparison of whole tree density measured on discs with whole tree estimates from cores at all heights and from a single BH core.

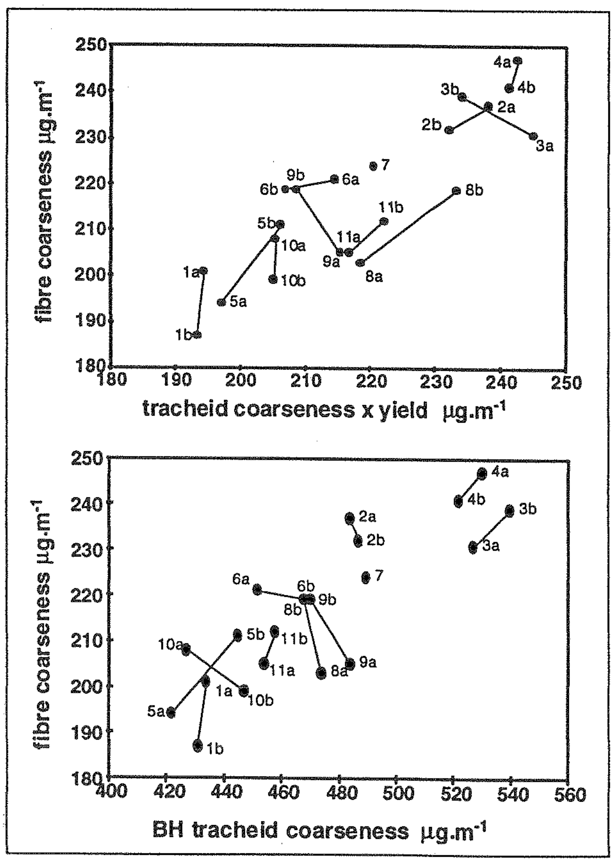

Fig. 6 Comparison of whole tree pulp fibre coarseness with whole tree estimates of tracheid coarseness from cores at all heights and from a single BH core.

Table 10
Intraclass correlation coefficients r_i and their significance levels P for a range of wood and kraft pulp properties

Wood and pulp fibre	r_i	P
wood basic density	0.988	< 0.00001
chip basic density	0.961	< 0.00001
kraft pulp yield	0.528	< 0.1
tracheid length at BH	0.098	ns
length weighted length	0.682	< 0.05
coarseness	0.800	< 0.01
width	0.834	< 0.001
thickness	0.545	< 0.01
perimeter	0.887	< 0.0001
wall area	0.792	< 0.01
wall thickness	0.336	ns

thickness for reasons which are currently being sought.

Pulp fibre coarseness was moderately well predicted by whole tree tracheid coarseness, as were fibre wall area and the product of fibre width and thickness (fibre area). The data in Table A6 show that the prediction of fibre coarseness and fibre wall area could be improved by correcting the tracheid coarseness for pulp yield (fibre wall material is lost during pulping). Applying the yield correction to pulp fibre coarseness was slightly more effective than applying it to tracheid coarseness. At BH, however, correction for yield was less effective and occasionally detrimental (Tables A7 and A8). Yield values relate to whole trees. Corrections at BH should therefore be made using yield data at BH (not available for this study). The strongest correlations between core properties and pulp fibre properties were obtained for tracheid and fibre perimeter. Unweighted BH tracheid perimeter accounted for 84.4% of pulp fibre perimeter as measured by the minimum bounding rectangle perimeter. When all heights were used to estimate clone averages (Table A6), this value rose to 92.9%. The range in SE was only 1.2 – 1.8 µm for all regressions of fibre perimeter on tracheid perimeter. Whole tree density is well predicted by chip density, but not as strongly as by the density of cores at six heights (Table A9).

The interdependence of some wood and pulp fibre properties is presented in Table A9. Fibre wall area and fibre area (width times thickness) explain 69.6% and 63.5% of variance in fibre coarseness. Averaging within clones increases these figures to 75.9% and 71.2%. The regression of fibre width/thickness on density was included in view of their common relationship to collapse potential. The clone-average r^2 (0.738) was comparable with that for most other relationships listed in Tables A6–A8.

Figures 5–8 illustrate a selection of relationships from Tables A6 and A8. The data are well distributed over the various ranges of properties. Pairs of trees within each clone are joined by a line to give a visual indication of the within-clone variation relative to the total variation.

Fibre collapse resistance

Over the range of properties exhibited by these clones, strong linear relationships exist between various geometric measures of collapse resistance – Runkel ratio, Luce's shape factor (7), wood density, and the ratio of fibre wall thickness T_W to perimeter P. If the separated fibres are assumed to be circular in cross-section (the actual geometry will not alter our conclusions), Runkel's ratio, R, and Luce's shape factor, L, are defined by:

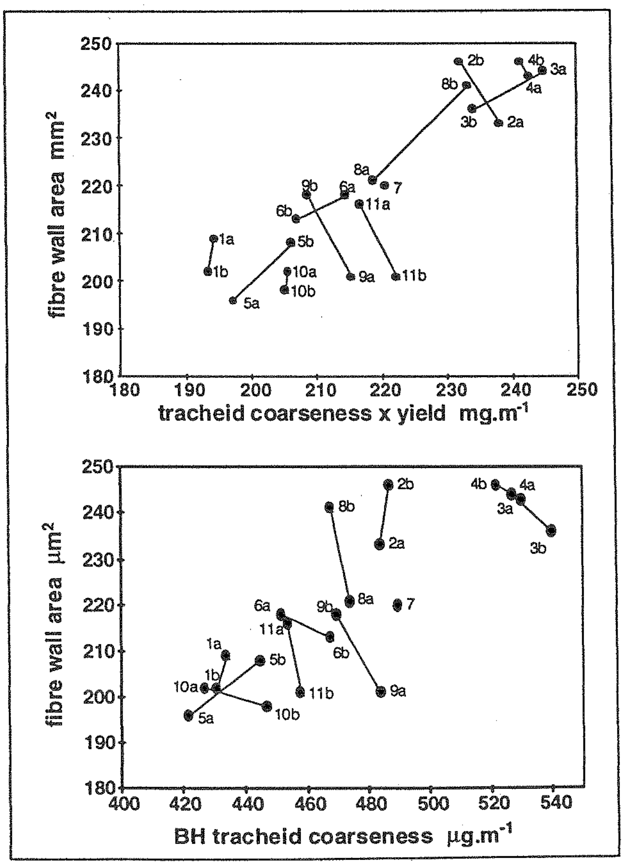

Fig. 7 Comparison of whole tree pulp fibre wall area with whole tree estimates of tracheid coarseness from cores at all heights and with a single BH core.

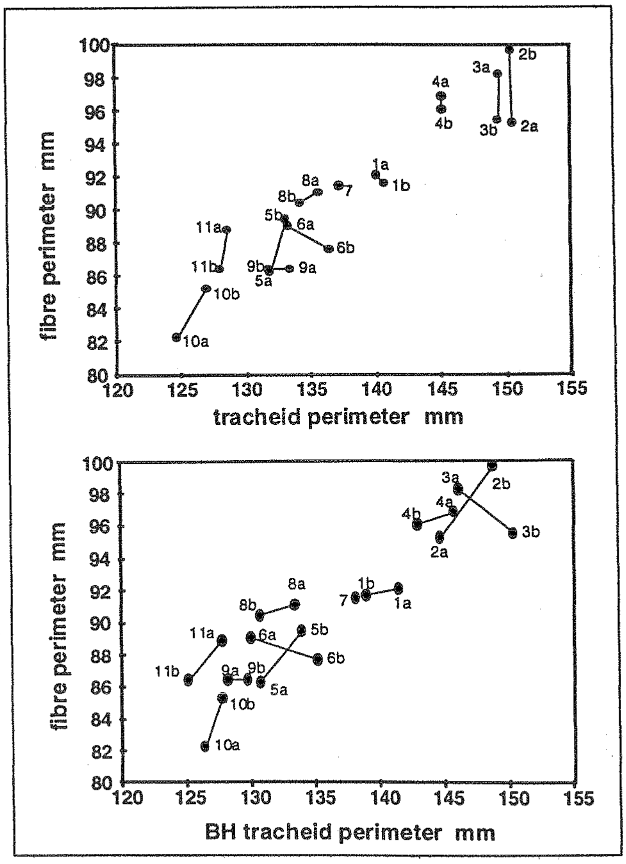

Fig. 8 Comparison of whole tree pulp fibre perimeter with whole tree estimates of tracheid perimeter from cores at all heights and with a single BH core.

Runkel ratio = double wall thickness / lumen diameter

$$R = 2T_w / (P/\pi - 2T_w)$$
$$= (2\pi T_w / P)/(1 - 2\pi T_w / P)$$

Luce shape factor = (fibre dia² – lumen dia²)/(fibre dia² + lumen dia²):

$$L = [(P/\pi)^2 - (P/\pi - 2T_w)^2] / [(P/\pi)^2 + (P/\pi - 2T_w)^2]$$
$$= (2\pi T_w / P)(1 - \pi T_w / P) / [1-(2\pi T_w/P)(1 - \pi T_w/P)]$$

For circular tracheid cross-sections, wood density at the single fibre level can be defined as

$$D = 4\pi D_w (T_w/P)(1 - \pi T_w / P).$$

Only the constants change if a space-filling square cross-section is assumed:

$$D = 16D_w (T_w/P)(1 - 4T_w/P)$$

where D_w is the cell wall density (≈contant). For these clones $T_w / P << 1$ and the expressions may be simplified:

$$D \approx 4\pi D_w T_w/P \quad (\text{or } 16D_w T_w/ P)$$
$$R \approx 2\pi T_w / P$$
$$L \approx 2\pi T_w/P$$

The constants 4π and 2π and 16 result from the assumed shape of the fibre cross-sections. In summary:

$$D \propto R \propto L \propto T_w/ P$$

When wall thickness is much less than fibre perimeter, as is the case for the clones in this study, these quantities should be very strongly and linearly correlated with each other. Linear correlation coefficients for combinations of density and three geometric measures of collapse resistance were calculated for our series of clones. These are given in Table 11. Wall thickness is estimated by SilviScan-1 using measured perimeter and density. The three quantities are therefore not independent. If wall thickness had been measured by an independent method, the correlations in Table 11 would have been weaker. The coefficients deviate from unity because of slight curvature in the relationships and deviations from the assumed fibre geometry.

The strong correlation between shape factor and basic density of eucalypts has previously been discussed by Higgins et al (7). Over a limited range, wood density should be as efficient an indicator of fibre collapse resistance as is any of these geometric ratios. For this series of radiata pine samples, inclusion of density in regression equations automatically accounts for most (>99%) of the variation due to fibre collapse resistance as defined by ratios of fibre cross-section dimensions. Conversely, if one of these geometric measures is used in regression analysis, it is unnecessary to add density. Any additional effects of fibre wall thickness or fibre perimeter beyond those accounted for by density, cannot simply be attributed to collapse resistance. This argument relies on the premise that ratios of cross-section dimensions alone are adequate indicators of relative collapse resistance. The effects of cross-section dimensions may not scale linearly, as implied by such ratios and we have yet to consider the influence of other fibre characteristics. Absolute fibre dimensions, fibre chemistry, and microfibril angle should also be used for the prediction of the structure and properties of paper.

Finally, cross-section geometry affects paper structure and properties even if all fibres collapse completely. Note that cross-section thickness:width ratio of a thin walled collapsed fibre is $4T_w / P$, which has the same form as the above measures of collapse resistance. A decrease in this ratio would increase fibre packing efficiency and relative bonded area. The perimeter and wall thickness in this case are for pulp fibres.

Table 11
Correlation between various calculated measures of collapse resistance for the eleven clones

	Runkel	Luce	T_w/P	density
Runkel	1.00000			
Luce	0.99998	1.00000		
T_w/P	0.99994	0.99999	1.00000	
density	0.99845	0.99844	0.99841	1.00000

CONCLUSIONS

- Trees within a clone are very similar in their wood and tracheid properties, regardless of differences in growth rate. Correlations between BH properties and whole tree properties are strong for radiata pine, giving confidence in this long established, non-destructive and convenient sampling technique.
- Important kraft fibre properties such as perimeter and coarseness, as well as wood density, can be efficiently predicted from the properties of wood measured on increment cores taken at BH.
- According to the tracheid model used in this study, wood density in these clones is equivalent to the ratio of tracheid wall thickness to perimeter as well as to established measures of collapse resistance such as Runkel's ratio and Luce's shape factor.
- Pulp fibre wall thickness is not well predicted from tracheid wall thickness, and tracheid length at BH does not predict kraft pulp fibre length in the whole tree. Furthermore neither pulp fibre wall thickness nor BH tracheid length is stable for trees within a clone, as judged by intraclass correlation. Resolution of these problems should considerably improve the prediction of paper properties.

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APPENDIX

Table A1
Whole tree (Tree), unweighted breast height (UBH) and area-weighted breast height (WBH) properties for eleven radiata pine clones. Whole tree properties were estimated using the weighted properties at all sampled heights. The tree labels a and b in this report correspond with labels 1 and 2 in reference (3).

Clone	Density $kg.m^{-3}$			Coarseness $\mu g.m^{-1}$			Wall thickness μm			Tan. diameter μm			Rad. diameter μm			Perimeter μm			$Vol.m^3$	Mass,kg
	Tree	UBH	WBH	Tree	UBH	WBH	Tree	UBH	WBH	Tree	UBH	WBH	Tree	UBH	WBH	Tree	UBH	WBH	Tree	Tree
1a	349	349	360	417	404	434	2.14	2.10	2.21	32.0	31.2	31.8	38.1	37.9	39.0	140.2	138.2	141.6	1.24	432
1b	351	356	366	423	407	431	2.16	2.13	2.23	32.0	30.9	31.4	38.4	37.5	38.1	140.8	136.8	139.0	1.30	457
2a	359	363	381	492	454	484	2.36	2.28	2.42	34.3	32.6	32.9	40.9	39.0	39.5	150.4	143.2	144.8	1.14	408
2b	359	346	364	493	456	487	2.35	2.22	2.36	34.2	33.4	33.7	41.0	40.3	40.7	150.4	147.4	148.8	1.41	505
3a	392	393	409	533	505	527	2.58	2.52	2.63	33.9	33.1	33.3	40.8	39.7	39.8	149.4	145.6	146.2	1.05	411
3b	398	381	394	541	510	540	2.62	2.48	2.60	33.9	33.5	33.9	40.8	40.4	41.3	149.4	147.8	150.4	0.92	367
4a	394	397	409	508	502	530	2.53	2.53	2.64	34.2	33.5	33.9	38.4	38.3	39.0	145.2	143.6	145.8	1.34	527
4b	393	406	420	506	489	522	2.52	2.53	2.66	34.2	33.0	33.4	38.3	37.2	38.1	145.0	140.4	143.0	0.88	346
5a	412	395	404	437	401	422	2.41	2.25	2.34	30.0	29.3	29.7	35.9	35.1	35.7	131.8	128.8	130.8	0.90	372
5b	414	403	406	448	422	445	2.44	2.33	2.40	30.5	29.8	30.5	36.1	35.6	36.5	133.2	130.8	134.0	0.97	401
6a	411	437	440	442	434	452	2.42	2.48	2.54	30.2	28.9	29.2	36.4	35.0	35.8	133.2	127.8	130.0	1.11	454
6b	397	399	424	447	439	468	2.38	2.37	2.54	31.3	31.0	31.2	36.9	36.3	36.4	136.4	134.6	135.2	0.93	369
7	418	407	422	479	460	490	2.55	2.46	2.59	31.9	32.6	32.1	36.7	36.4	37.1	137.2	138.0	138.2	1.21	532
8a	416	416	441	460	441	474	2.49	2.43	2.61	30.6	29.7	29.9	37.2	36.5	36.8	135.6	132.4	133.4	1.01	419
8b	429	437	457	467	452	468	2.56	2.53	2.64	30.4	29.3	29.2	36.7	36.4	36.2	134.2	131.4	130.8	1.25	535
9a	432	453	485	471	442	484	2.59	2.57	2.80	30.9	29.3	29.6	35.8	33.9	34.5	133.4	126.4	128.2	0.74	318
9b	448	435	466	469	432	470	2.63	2.48	2.69	30.5	29.6	29.9	35.4	34.6	35.0	131.8	128.4	129.8	0.71	319
10a	431	416	440	407	400	427	2.39	2.32	2.48	30.0	30.0	30.3	32.3	32.7	32.9	124.6	125.4	126.4	0.64	276
10b	440	430	447	433	420	447	2.50	2.42	2.56	30.2	29.9	30.1	33.2	33.2	33.8	126.8	126.2	127.8	1.01	443
11a	444	439	463	444	424	454	2.54	2.47	2.64	29.8	29.1	29.5	34.6	34.0	34.4	128.8	126.2	127.8	1.06	471
11b	462	467	485	452	441	458	2.61	2.61	2.72	29.6	28.3	28.3	34.4	34.2	34.3	128.0	125.0	125.2	0.94	434

Table A5
Selected wood and kraft pulp fibre properties

Clone	Chip basic density kg.m^{-3}	Wood basic density * kg.m^{-3}	Kraft pulp yield %	Length-wtd length mm	Coarseness µg.m^{-1}	Fibre width µm	Fibre thickness µm	Fibre wall area µm^2	Fibre wall thickness µm	Fibre perimeter† µm
1a	298	287	46.6	2.32	201	34.8	11.2	209	2.95	92.0
1b	310	292	45.7	2.29	187	35.2	10.6	202	2.82	91.6
2a	326	300	48.4	2.66	237	35.5	12.1	233	3.16	95.2
2b	315	303	47.1	2.53	232	37.8	12.0	246	3.13	99.6
3a	351	329	46.0	2.54	231	35.8	13.3	244	3.17	98.2
3b	344	328	43.3	2.52	239	35.6	12.1	236	3.22	95.4
4a	342	328	47.8	2.60	247	36.0	12.4	243	3.28	96.8
4b	348	332	47.7	2.65	241	35.7	12.3	246	3.43	96.0
5a	353	346	45.1	2.25	194	31.9	11.2	196	3.02	86.2
5b	356	344	46.1	2.32	211	33.6	11.1	208	3.00	89.4
6a	358	346	48.5	2.46	221	32.9	11.6	218	3.35	89.0
6b	352	346	46.3	2.56	219	32.1	11.7	213	3.29	87.6
7	356	349	46.1	2.64	224	33.6	12.1	220	3.18	91.4
8a	372	357	47.5	2.28	203	33.8	11.7	221	3.16	91.0
8b	384	356	50.0	2.49	219	32.3	12.9	241	3.66	90.4
9a	393	367	45.7	2.52	205	31.8	11.4	201	3.11	86.4
9b	386	369	44.5	2.51	219	31.3	11.9	218	3.42	86.4
10a	388	368	50.5	2.57	208	29.4	11.7	202	3.33	82.2
10b	371	369	47.4	2.40	199	31.2	11.4	198	3.12	85.2
11a	417	381	48.8	2.31	205	32.6	11.8	216	3.26	88.8
11b	418	394	49.2	2.36	212	31.4	11.8	201	2.99	86.4

* estimated from densities of discs from all heights
† perimeter of minimum bounding rectangle

Table A9
Interdependence of selected wood and pulp fibre properties.
r^2 is the adjusted coefficient of determination, and SE the standard error. Units, means, and ranges are those of the dependent variable.

Area weighted BH (independent)	Wood and pulp (dependent)	Units	r^2		SE		Mean	Range	% SE / mean		% SE / range	
			Tree	Clone	Tree	Clone			Tree	Clone	Tree	Clone
chip basic density	tree basic density (discs)	kg.m^{-3}	0.919	0.943	7.8	6.6	343	107	2.3	1.9	7.3	6.2
chip basic density	fibre width / thickness		0.584	0.738	0.14	0.10	3.03	0.98	4.6	3.2	14.1	9.9
fibre wall area	fibre coarseness	µg.m^{-1}	0.696	0.759	8.6	7.4	218	60	4.0	3.4	14.4	12.4
fibre width thickness	fibre coarseness	µg.m^{-1}	0.635	0.712	9.4	8.1	218	60	4.3	3.7	15.7	13.5

Table A6

Dependence of selected wood and pulp fibre properties on whole tree properties as estimated from all sample heights.
r^2 is the adjusted coefficient of determination, and SE the standard error. Units, means, and ranges are those of the dependent variable.

Whole tree estimate (independent)	Wood and pulp (dependent)	Units	r^2		SE		Mean	Range	% SE / mean		% SE / range	
			Tree	Clone	Tree	Clone			Tree	Clone	Tree	Clone
density	tree basic density (discs)	kg.m^{-3}	0.967	0.985	4.9	3.4	343	107	1.4	1.0	4.6	3.2
density	chip basic density	kg.m^{-3}	0.875	0.916	10.6	8.7	359	120	2.9	2.4	8.8	7.3
coarseness	fibre coarseness	μg.m^{-1}	0.677	0.761	8.9	7.4	218	60	4.1	3.4	14.8	12.3
coarseness × yield	fibre coarseness	μg.m^{-1}	0.732	0.805	8.1	6.7	218	60	3.7	3.1	13.5	11.1
coarseness	fibre coarseness / yield	μg.m^{-1}	0.787	0.853	17.6	14.2	464	143	3.8	3.1	12.3	9.9
coarseness	fibre wall area	μm^2	0.627	0.723	9.9	8.2	220	50	4.5	3.7	19.9	16.5
coarseness × yield	fibre wall area	μm^2	0.755	0.855	8.1	6.0	220	50	3.7	2.7	16.1	11.9
coarseness	fibre width × thickness	μm^2	0.731	0.794	17.9	15.5	401	127	4.5	3.9	14.1	12.2
coarseness × yield	fibre width × thickness	μm^2	0.722	0.790	18.2	16.0	401	127	4.5	3.9	14.3	12.3
perimeter	fibre perimeter	μm	0.875	0.929	1.6	1.2	90.8	17.4	1.7	1.3	8.9	6.7
wall thickness	fibre wall thickness	μm	0.191	0.291	0.16	0.12	3.19	0.84	5.0	3.8	18.9	14.5

Table A7

Dependence of selected wood and pulp fibre properties on whole tree properties as estimated from unweighted breast height cores.
r^2 is the adjusted coefficient of determination, and SE the standard error. Units, means, and ranges are those of the dependent variable.

Unweighted BH cores (independent)	Wood and pulp (dependent)	Units	r^2		SE		Mean	Range	% SE / mean		% SE / range	
			Tree	Clone	Tree	Clone			Tree	Clone	Tree	Clone
density	tree basic density (discs)	kg.m^{-3}	0.863	0.931	10.1	7.3	343	107	2.9	2.1	9.4	6.8
density	chip basic density	kg.m^{-3}	0.856	0.915	11.3	8.8	359	120	3.2	2.5	9.4	7.3
coarseness	fibre coarseness	μg.m^{-1}	0.736	0.816	8.0	6.5	218	60	3.7	3.0	13.4	10.8
coarseness × yield	fibre coarseness	μg.m^{-1}	0.681	0.743	8.8	7.7	218	60	4.1	3.5	14.7	12.8
coarseness	fibre wall area	μm^2	0.642	0.757	9.7	7.7	220	50	4.4	3.5	19.5	15.5
coarseness × yield	fibre wall area	μm^2	0.660	0.769	9.5	7.5	220	50	4.3	3.4	19.0	15.1
coarseness	fibre width × thickness	μm^2	0.720	0.780	18.3	16.0	401	127	4.6	4.0	14.4	12.6
coarseness × yield	fibre width × thickness	μm^2	0.626	0.658	21.2	20.0	401	127	5.3	5.0	16.7	15.7
perimeter	fibre perimeter	μm	0.844	0.909	1.7	1.3	90.8	17.4	1.9	1.4	10.0	7.5
wall thickness	fibre wall thickness	μm	0.248	0.491	0.15	0.10	3.19	0.84	4.8	3.2	18.2	12.3

Table A8

Dependence of and selected wood and pulp fibre properties on whole tree properties as estimated from area weighted breast height cores.
r^2 is the adjusted coefficient of determination, and SE the standard error. Units, means, and ranges are those of the dependent variable.

Unweighted BH cores (independent)	Wood and pulp (dependent)	Units	r^2		SE		Mean	Range	% SE / mean		% SE / range	
			Tree	Clone	Tree	Clone			Tree	Clone	Tree	Clone
density	tree basic density (discs)	kg.m^{-3}	0.865	0.888	10.0	9.3	343	107	2.9	2.7	9.3	8.7
density	chip basic density	kg.m^{-3}	0.890	0.909	9.9	9.1	359	120	2.8	2.5	8.3	7.6
coarseness	fibre coarseness	μg.m^{-1}	0.716	0.819	8.3	6.4	218	60	3.8	3.0	13.9	10.7
coarseness yield	fibre coarseness	μg.m^{-1}	0.707	0.773	8.5	7.2	218	60	3.9	3.3	14.1	12.0
coarseness	fibre wall area	μm^2	0.603	0.727	10.3	8.2	220	50	4.7	3.7	20.5	16.4
coarseness yield	fibre wall area	μm^2	0.665	0.768	9.4	7.5	220	50	4.3	3.4	18.8	15.1
coarseness	fibre width thickness	μm^2	0.668	0.742	19.9	17.3	401	127	5.0	4.3	15.7	13.7
coarseness yield	fibre width thickness	μm^2	0.620	0.646	21.3	20.3	401	127	5.3	5.1	16.8	16.0
perimeter	fibre perimeter	μm	0.839	0.899	1.8	1.4	90.8	17.4	1.9	1.5	10.1	7.9
wall thickness	fibre wall thickness	μm	0.256	0.505	0.15	0.10	3.19	0.84	4.8	3.2	18.1	12.1