Clonal variation in wood, chemical, and kraft fibre and handsheet properties of slabwood and toplogs in 27-year-old *radiata pine*

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SUMMARY

Broad sense heritabilities of kraft pulp handsheet properties were high for both toplog and slabwood pulps from 27- and 28-year-old clonal ramets. Heritabilities were moderate to high for kraft fibre length and cross-section dimensions. Heritabilities were moderate for glucose content and pulp yield. Heritabilities for whole-tree wood density and tracheid dimensions were very high, and moderate for whole-tree microfibril angle.

When toplogs, 'midlogs and toplogs', and slabwood were compared, 'midlogs and toplogs' had chip density and fibre length values that were intermediate between the low toplog values and high slabwoodvalues. Toplog and 'midlog and toplog' handsheet values were very similar, and very different from slabwood handsheet properties. There was a large amount of clonal variation for a given wood type in all properties. The range of clonal variation for a given wood type was similar in magnitude to differences between wood types for wood density, glucose content, pulp yield, handsheet density, tensile index, and tear index. Segregation of wood chips from monoclonal blocks could realise differentiation of kraft pulp properties to a similar extent as the current practice of segregation on wood type.

Keywords

Clonal variation, heritability, slabwood, toplogs, fibre properties, handsheet properties

Tested clones and families of radiata pine are being planted increasingly by some large forestry companies in New Zealand as a means of realising greatest possible genetic gains and of increasing uniformity in resulting stands and harvested wood. Early clonal tests, that formed precursors of this trend to clonal forestry, have also provided suitable material for studies relating solid wood and pulp and paper end-product characteristics to the morphology, microstructure, chemical constituents and fibre quality of individual trees and clones (*1,2,3,4*).

There was a need in these studies to be able to describe individual trees, non-destructively and relatively cheaply, for their tracheid dimensions, microfibril angle and wood density. SilviScan2, an automated wood structure analyser, can measure these characteristics on a strip, machined from a breast-height 12 mm increment core or from discs cut at any level, and this development has been a major step forward in such research (*5,6,7,8*).

Extensive multidisciplinary studies have been undertaken at Forest Research since 1993 to determine the technical requirements for different end products of radiata pine. This research has quantified tree-to-tree variation within stands and between and within clones in characteristics of different end products and developed predictive relationships linking stem morphology, wood and chemical properties with characteristics and value of various end products. By studying at least two trees per clone, relative magnitudes of genotypic and environmental effects were quantified to evaluate the level of genetic control of the character, as well as possible gain from clonal selection in clonal tests. Variance components from 'between clone' and 'between trees within clones' were estimated in most studies and used to estimate broad-sense heritability. The results, summarised in 1997 (*9*), were from two trees of ten 16-year-old clones and later from 4 trees of 27-28-year-old clones, both grown in Kaingaroa Forest. These involved over 90 different traits, including properties of tree morphology, wood, kraft and thermomechanical pulp and paper, and various types of sawn timber and veneers.

The study reported here involves the kraft pulping of 2 trees each of the second set of ten 27-28-year-old clones, of which basal logs were processed for sawn timber (*5*) and veneers (*10*). The slabwood and toplogs of these clones were separately chipped and kraft pulped. In this paper, clonal variation and heritabilities of kraft pulping, fibre and handsheet properties, and of SilviScan-measured tracheid dimensions, density and microfibril angle are reported, for both slabwood and toplogs.

EXPERIMENTAL

Tree selection

The trees selected for these studies were required to show a range of qualities, typical as far as possible of the genetically unimproved crop being currently harvested. Matching stems were needed for application of two sawing methods and two peeling methods (*10,11*). A unique early clonal test, planted in a single-tree plot, incomplete-block design in 1968 in Kaingaroa Forest, New Zealand (altitude 420 m, lat. 38°17´S, long. 176°47´E), provided the material for these studies. 216 clones were propagated in 1966 by rooted cuttings taken from plantation trees aged 6 and 7 years from seed, which were selected non-intensively for vigour and freedom from forking, and subsequently culled to the higher wood-density half of the population. 46 of the originally-planted 216 clones had at least 4 well-grown trees in 1995 and from these, 10 clones were selected for a range of the 4 traits: diameter at breast height (DBH), wood density, branch diameter and internode length (*4*). Clone mean DBH varied from 33 to 62 cm, internode index from 0 to 60%, branch index from 33 to 65 mm, outerwood density from 350 to 460 kg/m^3.

The trial was planted at 1,370 stems per ha, waste thinned to 700 stems/ha at age 7 years and again at 13 years to a stocking of 350 stems/ha. All trees were pruned, first to 2 m at age 4 and then to 4 m at age 6 years. Early growth of the clonal cuttings showed some signs of physiological ageing, such as reduced diameter growth, lighter branching and better stem form than seedlings.

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Log processing

Two trees of these 10 clones were felled at age 27 years (Tree-set 27) and from each tree 3 to 5 logs were used for the sawn timber study. The logs sawn were the butt log of 4 m and the 2nd log of 4.9m as well as 1 to 3 additional selected logs of 4.9 m from above the 2nd log. Most commonly the uppermost sawn log was from the 5th or 6th actual log height class, but the uppermost sawn log ranged from the 3rd log for a small tree to the 7th log for a large tree. The remaining toplogs above the uppermost sawn log and the slabwood residues from the 1st, 2nd, and 3rd or 4th logs were kraft pulped separately, by individual trees. A further 2 trees of each clone were felled the following year and their basal logs, whose total length varied considerably between trees and clones, were used for the peeling and slicing study (*10*). The remaining toplogs of each tree (Tree-set 28) were chipped, and pulped by kraft and TMP processes (*11*).

The two sets of 20 individual-trees, 2 trees per clone, were felled and cross-cut into logs, the toplogs from which were chipped and pulped, one at age 27 years (Tree-set 27) and the other one year later at age 28 years (Tree-set28). Toplog specifications for Tree-set 27 and Tree-set 28 were very different (Table 1). The wood used for toplog chips for Tree-set 28 begins on average at 19 m, which is 6.3 m lower down the tree than the average height of 25.3 m for Tree-set 27. The large difference between tree-sets in the height at which the first toplog starts, is reflected in the much larger average diameters and higher numbers of large-end growth layers for Tree-set 28. The uppermost toplog material for Tree-set 28 starts 1.2 m lower than Tree-set 27. Because of these factors and the extra year of growth there is a major difference between the toplogs of each Tree-set in average number of growth layers at the small-end of the uppermost toplog.

For Tree-set 27 only, individual-tree slabwood samples were obtained from 3 of the 4 basal logs of 20 trees (2 trees per clone). For trees where the 3rd log was sawn in the sawing study, the 1st, 2nd and 3rd log slabwood was chipped, and for trees where the 3rd log was not sawn, the 1st, 2nd, and 4th log slabwood was chipped. All slabs of length ≥3.7 m were included in each slabwood sample.

Each individual tree's toplog samples were chipped in a commercial chipper and the chips well mixed with a front-end loader. Bulk samples (5 kg o.d.) were taken for kraft pulping. Each sample was passed through a Williams round-hole screen, with accept chips passing through the 32 mm hole screen and retained on the 9 mm hole screen. Slabwood from each tree was chipped and mixed similarly. Chips of each tree of Tree-set 28 were thermomechanically pulped in the Forest Research pilot plant (*11*).

Disc sampling

For each of the 20 trees of Tree-set 27, 50 mm thick discs were taken from the lower ends of the butt-log and of each of the sawlogs. Also, a disc was taken from the top of the uppermost sawlog. Since there were from 3 to 7 logs below the start of the toplogs for each tree, between 4 and 8 discs were taken. From each disc a radial strip was cut for SilviScan analysis of density, tracheid cross-sectional dimensions and microfibril angle. No Silviscan sampling was undertaken for the trees of Tree-set 28.

Chip density

Chip basic density was determined in accordance with AS/NZS 1301.001s-79, except that the fresh chips were not given the specified soaking period.

Chemical analyses

Samples of chips were air dried, ground and extracted with dichloromethane and then further ground for analysis of lignin and carbohydrates by the methods of TAPPI T222 om-88 for lignin, TAPPI um 250 for acid-soluble lignin, and Pettersen and Schwandt (*12*) for carbohydrates.

Wood tracheid and pulp fibre dimensions

A single radial pith-to-bark strip was cut from each disc from each tree and analysed by SilviScan for transverse wood tracheid dimensions, density and microfibril angle, using respectively, image analysis, X-ray densitometry and diffraction at 50 μm intervals along the strip (*5,6,7,8*). Tracheid coarseness, outer perimeter (from radial and tangential diameters) and average wall thickness were generated from these primary measures. Individual-tree wood and tracheid properties for slabwood and toplogs were calculated by interpolation and extrapolation of the results obtained from all sampling heights.

Pulping and handsheet preparation and evaluation

Kraft pulps of target Kappa number 30±2 were prepared from each chip sample by varying the H-factor at constant alkali charge. The pulping conditions were:

16% effective alkali as Na_2O, sulfidity 30.0%, 4:1 liquor-to-wood ratio, 90 minutes to maximum temperature. A minimum of three pulps were prepared for each of the 40 toplog and 20 slabwood individual-tree chip samples. Pulp yield at 30 Kappa number was determined by interpolation of results for the 3 pulps prepared.

Cross-sectional pulp-fibre dimensions of thickness and width of the minimum bounding rectangle, wall area and wall thickness were measured using image processing procedures described previously (*13*). The ratio, width/thickness, is an indicator of the level of collapse of a

Table 1
Comparison of means and ranges of toplog descriptors for Tree-set 27 and Tree-set 28.

Tree-set statistics for 20 tree sets	Starting height of first toplog (m)	Large-end diameter for the first toplog (mm)	Large-end number of growth rings of first toplog	Height of last (uppermost) toplog small end (m)	Small-end diameter for the uppermost toplog (mm)	Small-end number of growth rings for the uppermost toplog
Tree-set 27:						
Mean	25.3	192	9.8	31.1	127	5.6
Range	18.1-33.4	170-220	7-14	21.8-38.3	75-170	4-8
Tree-set 28:						
Mean	19.0	315	16.8	29.9	208	10.2
Range	10.0-25-0	250-400	14-20	22.8-35.9	130-305	7-13

dried and rewetted fibre. Measurements were made on dried and rewetted fibres reconstituted from handsheets. Individual-tree length weighted average kraft fibre length was determined with a Kajaani FS 200 instrument, following TAPPI T271 pm-91.

Handsheets were prepared and pulp physical evaluations made in accordance with AS/NZS standard procedures. The load applied during pulp refining with the PFI mill was 3.4 N/mm. Pulps were refined at 10% stock concentration for 500, 1000, 2000 and 4000 rev.

Statistical analyses

Individual–tree values for all tree, wood property, pulp, kraft fibre and handsheet characteristics were subjected to analysis of variance according to the model:

$$Y_{ij} = \mu + \alpha_i + \varepsilon_{(i)j}$$

where:
Y_{ij} = phenotypic value of the jth ramet of genotype i,
μ = trait mean
α_i = phenotypic value of the ith genotype
$\varepsilon_{(i)j}$ = variance among trees within genotype i

Variance components were estimated for all traits using the SAS procedure VARCOMP. The method used to estimate variance components was Restricted Maximum Likelihood. Broad sense heritability, H^2, for each trait was calculated as:

$$H^2 = \sigma^2_G \,/(\sigma^2_G + \sigma^2_e)$$

where,
σ^2_G = variance among clones,
σ^2_e = variance between trees within clones (environmental and measurement error variance)

RESULTS AND DISCUSSION

Comparison of clone means and heritabilities of whole-tree wood tracheid properties

Mean values over all clones of Tree-set 27 for volume-weighted whole-tree wood tracheid properties measured by SilviScan are shown in Table 2. The clone mean ranges shown in Table 2 are the minimum and maximum out of the 10 clone mean values calculated.

Heritabilities calculated from this study have large confidence limits because there were only 10 clones with two ramets per clone. Because of this, for comparison, clone means and broad-sense heritabilities of ten 16-year-old clones from a past study (2) are shown in Table 3. For the study on 16-year-old trees whole-trees were chipped for kraft pulping and handsheet property determinations.

The whole-tree wood properties of the 27-year-old trees (Table 2) contrast with the 16-year-old trees (Table 3) as follows:

- Wood density (air-dried extracted), tracheid wall thickness and coarseness are larger for the older 27-year-old trees though there was some overlap of clone ranges for wood density, wall thickness and for coarseness.
- Mean tangential and radial diameters, and perimeter were very similar for both sets of clones with a very large overlap in values.
- Microfibril angle (MFA) mean values and clonal ranges cannot be directly compared; for the 27-year-old trees whole-tree volume weighted MFA was measured by SilviScan using X-ray diffraction on strips cut from each disk, while for the 16-year-old trees, MFA was determined by a microscopic method.

The differences between overall means and ranges for whole-tree wood properties of these two sets of clones are mainly attributable to age, but sites were in different parts of Kaingaroa Forest, with the 16-year-old clones grown at an altitude of 560 m versus 420 m for the 27-year-old clones. The 16-year-old clones were selected additionally for a range of tracheid length.

For both sets of clones broad-sense heritabilities of air-dried wood density and tracheid cross-sectional dimensions were very high. For Tree-set 27 (Table 2) heritabilities were between 0.96 and 0.98, and for the 16-year-old clones (Table 3), between 0.88 and 0.94. These high heri-

Table 2
Means, clone mean ranges, variance components and broad-sense heritabilities for Tree-set 27 for whole-tree volume-weighted means of SilviScan wood properties.

	Mean	Clone means range	Var(clone)	Var(error)	H^2
Wood density, a.d. (kg/m³)	501	445-562	1537	68	0.96
Tracheid radial diameter (µm)	35.5	32.4-38.9	4.331	0.073	0.98
Tracheid tangential diameter (µm)	30.5	29.0-33.1	1.446	0.044	0.97
Tracheid coarseness (µg/m)	523	441-581	2619	95	0.96
Tracheid wall thickness (µm)	2.96	2.53-3.36	0.0672	0.0031	0.96
Tracheid perimeter (µm)	132	123-141	31.74	0.66	0.98
Tracheid specific surface area (m²/g)	263	235-300	415	14	0.97
Tracheid microfibril angle (°)	15.7	13.3-18.3	1.64	1.04	0.61

Table 3
Means, clone mean ranges, variance components and broad-sense heritabilities for ten 16-year-old clones for whole-tree volume-weighted means of SilviScan wood properties.

	Mean	Clone means range	Var(clone)	Var(error)	H^2
Wood density, a.d. (kg/m_)	423	363-476	1453	104	0.93
Tracheid radial diameter (µm)	36.9	33.4-40.6	5.826	0.387	0.94
Tracheid tangential diameter (µm)	31.1	28.9-33.7	3.078	0.406	0.88
Tracheid coarseness (µg/m)	471	433-534	1243	84	0.94
Tracheid wall thickness (µm)	2.54	2.22-2.75	0.0259	0.0017	0.94
Tracheid perimeter (µm)	136	127-148	65.76	5.18	0.93
Tracheid microfibril angle (°)	28.6	22.5-34.2	6.21	5.97	0.51

tabilities in part reflect selection of the clones in both studies for a range of outerwood density. Both sets of clones had similar between-clone variance for wood density. The radial diameter, tangential diameter, and perimeter error variances (between trees within clone and measurement error) were much smaller for Tree-set 27 than they were for the 16-year-old clones. Broad sense heritabilities of microfibril angle were lower and similar for both sets of clones.

Comparison of clone means and heritability of wood chip sample, kraft pulp, and handsheet properties

Means over all clones, ranges of clone means, variances between and within clones and broad sense heritabilities of wood chip sample properties, pulp yield, pulp fibre measurements, and handsheet properties for Tree-set 27 and Tree-set 28 are shown in Table 4. In the following text, tables, and figures, Tree-set 28 toplogs are identified as 'midlogs and toplogs' wood type to emphasise the position, on average 6.3 m lower down the trees, from which the wood was cut. The overall-clone means clearly indicate differences between these three wood types since toplogs and slabwood of Tree set 27 and the 'midwood and toplog' samples of Tree-set 28 are from two sets of 2 trees of each of the same ten clones. Heritabilities and clone means of the ten 16-year-old clones (2) are shown for comparison in Table 5. Comparisons of clone means and heritabilities between the whole-tree material of the 16-year-old clones and the three wood types of this study confound differences in tree age, clones selected, site and wood type. These illustrate the large range in properties possible with different clones and the same wood type, as well as suggesting possible differences between pulps from young whole-trees versus toplogs and slabwood of older trees.

Figures 1-6 show, for each clone, the individual-tree values (and thus the variability within clones) of chip density, glucose, fibre length, apparent sheet density, tensile index and tear index for toplog (t) and slabwood (s) of the 27-year-old material and for the 28-year-old 'midlog and toplog' (m) wood type.

For chip basic density there is a large range in clone means with overlap between ranges of clone means for all three wood types (Table 4, Fig. 1). The toplogs of Tree-set 27 have the lowest clone mean chip basic density and their slabwood has the highest density. The Tree-set 28 'midlogs and toplogs' have a chip basic density between the toplogs and slabwood of Tree-set 27, slightly closer to the toplogs. The overall mean chip density for the 16-year-old trees is lower than for Tree set 27 toplogs, but with a large overlap in clone mean ranges (Tables 4 and 5). Heritabilities for chip basic density are high for all three wood types of this study (Table 4, Fig. 1). The heritability of 0.79 for Tree-set 27 toplogs is lower than for 'midlogs and toplogs' (0.91) and slabwood (0.90), and whole-tree air-dry density (0.93). Comparison of variance components indicate that the lower heritability of Tree-set 27 toplog material is caused by a combination of lower between-clone variation and higher error (between-tree, within-clone) variance. The higher error variance for the toplog material could relate to variability between clones and trees within clones in the height from which toplogs were taken. For each wood type, the differences between the two ramets of each clone are small (Fig. 1) yet there is tremendous variation within a wood type amongst clones. The differences in density between wood types are also clearly shown.

Overall means for DCM extractives contents for toplogs and slabwood (Tree-set 27) are both low (Table 4) indicating these wood types have included much of the heartwood formed in the inner rings. Extractives for 'midwood and toplog' of Tree-set 28 (Table 4) and of the 16-year-old clones (Table 5) are both higher, indicating more heartwood has been included because the midwood material from further down the tree has more inner growth rings (Table 1). Heritabilities of extractives were moderate for young trees (Table 5) and toplogs, but low for 'toplogs and midwood' and slabwood, possibly reflecting variation in allocation of wood material into these wood types.

Lignin contents are similar for the three wood types in this study (Table 4) though there is a very large overlap in ranges of clone means. The 10 clones of the 16-year-old trees had higher mean lignin content and also a much larger range of clone means (Table 5) than the 10 clones in this study. Heritability values are moderate (0.31 to 0.44), as were those of the 16-year-old set of clones (Table 5). For glucose content, overall means were highest for slabwood, with 'midlogs and toplogs' slightly higher than toplogs (Fig. 2, Table 4). Heritabilities of glucose content were moderate to high for all three wood types in this study (0.59 to 0.71), and were also similar for the 16-year-old set of clones (Table 5).

Overall means for pulp yield at 30 Kappa number were highest for slabwood, lowest for toplogs, and intermediate for 'midlogs and toplogs'. Heritability of pulp yield was moderate for the three wood types in this study and the 16-year-old clones, with values slightly less than heritability of glucose content (Tables 3 and 4). The clone mean ranges in glucose content and pulp yield overlapped widely for the three wood types (Fig. 2, Table 4).

Kraft pulp fibre length overall means were highest for slabwood, lowest for toplogs, and intermediate for 'midlogs and toplogs' (Fig. 3, Table 4). This property is strongly influenced by wood type, with no overlap in the clone mean range for slabwood and 'midlogs and toplogs', and only a small overlap for 'midlogs and toplogs' with toplogs (Fig. 3). This indicates that large increases in toplog fibre length (approximately 0.3 mm) would be obtained if the highest sawlog were pulped. Heritability of fibre length (Table 4) was low for toplogs (0.31) and moderate to high for 'midlogs and toplogs' (0.58) and slabwood (0.65). Comparison of variance components between wood types indicates that a combination of low between-clone variance and high error variance for the toplogs explains its low heritability. Overall means and clone mean ranges for fibre length for the ten 16-year-old clones (Table 5) were similar to the toplogs, and heritability was high (0.68).

Fibre perimeter differences between wood-type means were small, with considerable overlap between wood-type clone mean ranges. Clone means for slabwood are much higher for wall area and wall thickness compared to the other two wood types (Table 4). Fibre collapse is low for slabwood, high for toplogs, and intermediate for 'midlogs and toplogs'. For the toplogs the between-clone variance component has been calculated as zero (by the REML variance components method) for fibre wall area and wall thickness, indicating the between-clone variance is lower than expected, given the size of the error variance. For these two kraft fibre cross-section measurements, calculated heritability is zero. For 'midlogs and toplog', heritabilities of kraft fibre dimensions range from low to high. Heritabilities are moderate to high for the slabwood fibre perimeter, wall area, wall thickness, and collapse. Heritabilities are moderate to high for most of these characteristics of the 16-year-old clones (Table 5).

For all handsheet properties the overall means and ranges of clone means are very

Table 4

Means, clone mean ranges, variance components and broad-sense heritabilities.

Wood type	Tree-set 27 toplogs					Tree-set 28 midlogs and toplogs					Tree-set 27 slabwood				
	Mean	Range	Var(clone)	Var(error)	H^2	Mean	Range	Var(clone)	Var(error)	H^2	Mean	Range	Var(clone)	Var(error)	H^2
Wood chip sample properties															
Chip basic density (kg/m^3)	378	344-416	562	146	0.79	405	349-440	896	85	0.91	441	408-493	950	110	0.90
Dichloromethane extractives (%)	0.78	0.48-1.10	0.041	0.029	0.58	1.38	1.06-1.71	0.000	0.111	0.00	0.49	0.34-0.72	0.002	0.027	0.08
Total lignin content (%)	28.0	27.2-29.0	0.19	0.41	0.31	27.9	27.1-29.2	0.23	0.21	0.51	28.1	26.5-28.9	0.45	0.57	0.44
Arabanose content (%)	1.79	1.55-1.90	0.0089	0.0068	0.57	1.59	1.49-1.69	0.0015	0.0068	0.18	1.31	1.22-1.42	0.0032	0.0020	0.61
Galactose content (%)	2.72	2.30-3.16	0.015	0.161	0.08	2.86	2.35-3.76	0.148	0.062	0.70	2.27	1.87-3.09	0.036	0.189	0.16
Glucose content (%)	41.2	39.5-42.2	0.56	0.27	0.67	41.9	39.5-44.4	1.51	0.62	0.71	43.8	42.4-45.6	0.57	0.39	0.59
Xylose content (%)	7.14	6.70-7.67	0.055	0.062	0.47	6.31	5.86-6.81	0.028	0.063	0.31	5.12	4.65-5.55	0.052	0.025	0.68
Mannose content (%)	10.3	9.8-11.0	0.110	0.150	0.42	10.8	10.2-11.8	0.254	0.073	0.78	10.8	10.2-11.9	0.197	0.055	0.78
Ash content (%)	0.34	0.29-0.42	0.00085	0.00142	0.37	0.30	0.25-0.34	0.00038	0.00131	0.22	0.28	0.21-0.37	0.00068	0.00193	0.26
Kraft pulp yield at 30 Kappa number (%)	46.9	44.0-51.0	2.01	2.40	0.46	47.6	45.0-50.0	1.16	0.95	0.55	49.8	47.5-52.5	1.72	1.70	0.50
Kraft pulp fibre properties															
Fibre length (mm)	2.40	2.17-2.62	0.0074	0.0163	0.31	2.68	2.43-2.89	0.0157	0.0114	0.58	3.11	2.93-3.32	0.0126	0.0068	0.65
Fibre perimeter (µm)	87.7	84.0-90.2	2.5	3.2	0.45	88.6	84.5-93.7	3.5	5.7	0.38	90.1	84.9-96.4	12.2	4.0	0.75
Fibre wall area (µm^2)	219	188-233	0	173	0.00	225	196-251	150	142	0.51	272	226-303	519	281	0.65
Fibre wall thickness (µm)	3.32	2.84-3.45	0.0000	0.0326	0.00	3.37	3.05-3.58	0.0266	0.0043	0.86	4.25	3.69-4.72	0.0890	0.0541	0.62
Fibre width/thickness	3.03	2.83-3.25	0.0174	0.0078	0.69	2.73	2.38-3.12	0.0531	0.0112	0.83	2.55	2.25-2.81	0.0282	0.0203	0.58
Handsheet properties at 500 rev PFI															
Apparent sheet density (kg/m^3)	679	642-726	696	367	0.65	660	622-707	1120	152	0.88	586	540-640	841	287	0.75
Tensile index (N.m/g)	83.0	72.0-95.5	43.3	13.1	0.77	84.1	72.0-99.5	75.0	10.4	0.88	60.4	49.0-73.0	47.6	18.2	0.72
Stretch (%)	2.35	2.06-2.72	0.031	0.027	0.54	2.31	1.92-2.83	0.065	0.011	0.85	1.71	1.37-2.24	0.058	0.017	0.78
T.E.A. index (J/kg)	1350	1067-1679	41964	16832	0.71	1333	968-1808	73975	10064	0.88	716	452-1123	35446	10768	0.77
Tensile stiffness index (kN.m/g)	9.64	9.01-10.32	0.101	0.076	0.57	9.59	8.97-10.43	0.169	0.044	0.79	8.61	8.00-9.09	0.118	0.119	0.50
Handsheet properties at 1000 rev PFI															
Logarithm tear index (lne(mN.m^2/g))	1.01	0.91-1.10	0.0041	0.0016	0.73	1.06	0.94-1.17	0.0064	0.0014	0.82	1.29	1.18-1.44	0.0073	0.0016	0.82
Handsheet properties at 4000 rev PFI															
Apparent sheet density (kg/m^3)	750	719-788	423	193	0.69	734	699-774	694	163	0.81	674	639-708	465	89	0.84
Tensile index (N.m/g)	109	102-117	13.5	9.3	0.59	113	103-122	27.8	8.6	0.76	92.8	82.5-99.5	29.1	12.5	0.70
Stretch (%)	2.86	2.75-3.09	0.0039	0.0157	0.20	2.91	2.80-3.14	0.0076	0.0093	0.45	2.53	2.32-2.86	0.0228	0.0067	0.77
T.E.A. index (J/kg)	2114	1976-2361	10858	16068	0.40	2203	1937-2463	21280	10523	0.67	1591	1347-1923	28555	10576	0.73
Tensile stiffness index (kN.m/g)	10.9	10.2-11.3	0.013	0.135	0.09	10.9	10.2-11.6	0.118	0.067	0.64	10.1	9.6-10.4	0.074	0.045	0.62
Logarithm tear index (ln_e(mN.m^2/g))	0.93	0.84-1.00	0.00261	0.00134	0.66	0.97	0.87-1.05	0.00367	0.00098	0.79	1.12	1.03-1.24	0.00390	0.00072	0.84

Table 5
Means, clone mean ranges, variance components and broad-sense heritabilities for whole-tree properties of ten 16-year-old clones, 2 ramets per clone (2,7,9).

Property	Mean	Clone means range	Var(clone)	Var(error)	H^2
Wood chip sample properties					
Chip basic density (kg/m³)	359	298-418	1025	42	0.96
Dichloromethane extractives (%)	1.45	0.88-2.83	0.123	0.111	0.52
Total lignin content (%)	28.5	25.1-31.2	0.93	0.82	0.53
Arabanose content (%)	1.47	1.29-1.63	0.0053	0.0017	0.76
Galactose content (%)	2.66	2.11-3.88	0.101	0.054	0.65
Glucose content (%)	42.7	40.3-45.3	0.58	0.47	0.55
Xylose content (%)	5.41	4.66-6.35	0.168	0.00	1.00
Mannose content (%)	9.67	8.62-10.67	0.138	0.00	1.00
Kraft pulp yield at 30 Kappa number (%)	47.1	44.7-49.0	1.82	1.66	0.53
Kraft pulp fibre properties					
Fibre length (mm)	2.45	2.25-2.66	0.0119	0.0054	0.68
Fibre perimeter (µm)	90.8	83.8-97.4	21.68	2.68	0.89
Fibre wall area (µm²)	219	200-245	261	72	0.79
Fibre wall thickness (µm)	3.19	2.89-3.41	0.0130	0.0255	0.34
Fibre width/thickness	3.05	2.79-3.45	0.0290	0.0270	0.52
Handsheet properties at 500 rev PFI					
Apparent sheet density (kg/m³)	690	665-730	492	104	0.83
Tensile index (N.m/g)	85.1	75.1-96.6	31.6	4.5	0.87
Stretch (%)	2.62	2.40-3.06	0.041	0.029	0.70

* Microscopic method used (2), not SilviScan MFA as measured in Table 2.

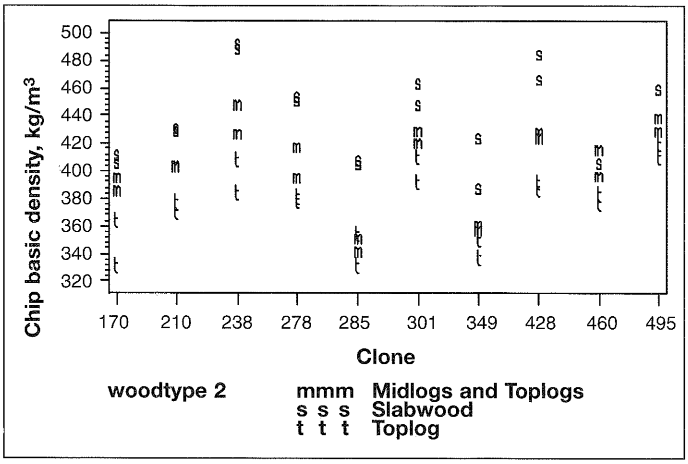

Fig. 1 **Chip basic density of individual trees and clones for each wood type.**

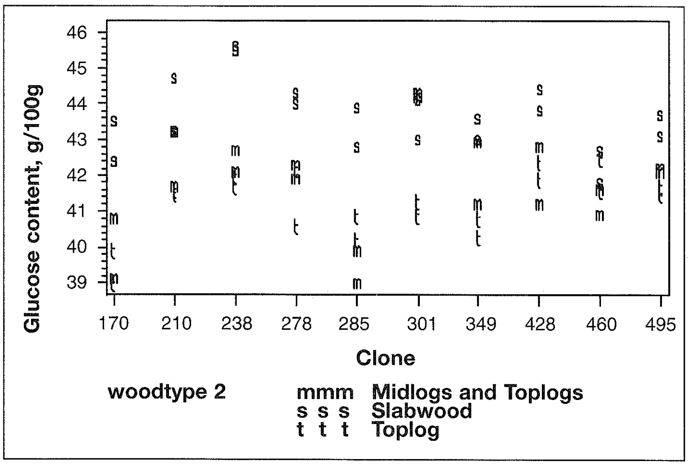

Fig. 2 **Wood chip sample glucose content of individual trees and clones for each wood type.**

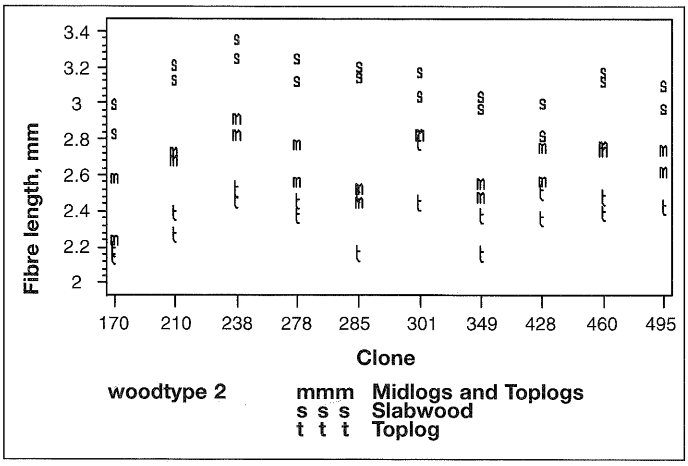

Fig. 3 **Kraft fibre length of individual trees and clones for each wood type.**

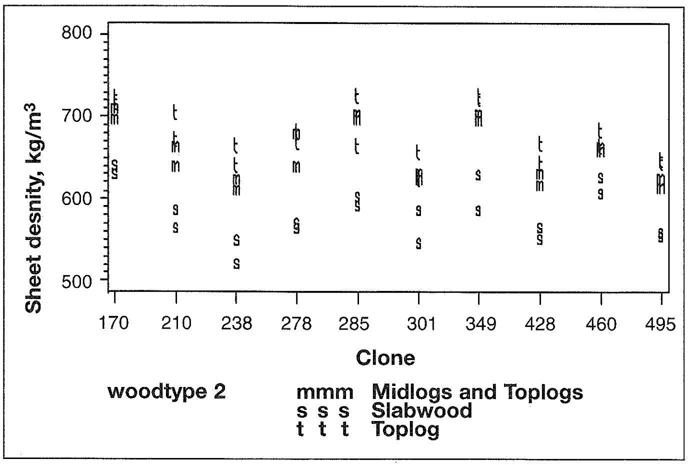

Fig. 4 **Handsheet apparent sheet density of individual trees and clones for each wood type.**

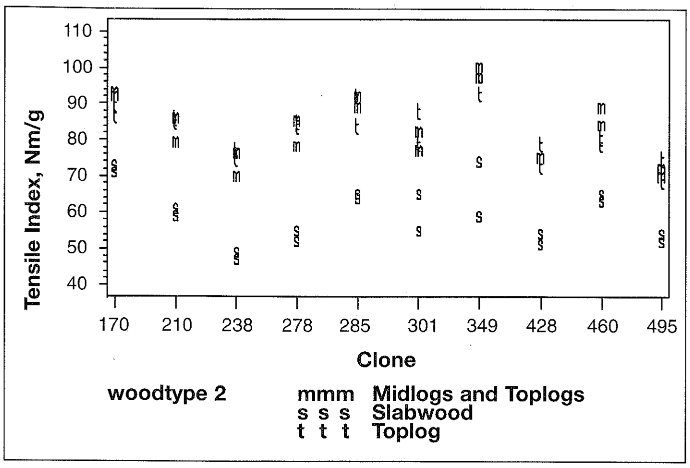

Fig. 5 Handsheet tensile index of individual trees and clones for each wood type.

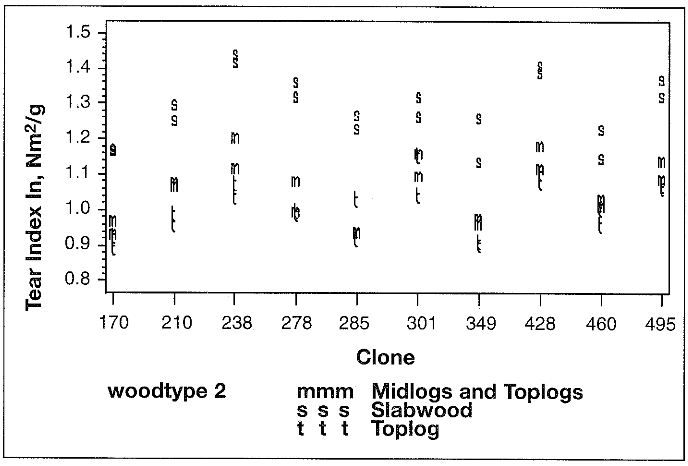

Fig. 6 Handsheet tear index of individual trees and clones for each wood type.

similar for Tree-set 27 toplogs and Tree-set 28 'midlogs and toplogs' for both lightly- and highly-refined pulps. There are consistent differences between wood types with 'midlogs and toplogs' handsheet properties slightly on the slabwood side of those of toplogs, but differences are small and there is a lot of overlap in clone mean ranges for these two wood types. The relatively small differences between 'toplogs' and 'midlogs and toplogs' in apparent sheet density, tensile index and tear index (Fig. 4, 5, 6) are surprising given the large differences between these two wood types in chip basic density and fibre length (Fig. 1, 2). The longer fibres of 'midlogs and toplogs' have resulted in slightly higher tear index than toplogs (Fig. 6). Overall means for handsheet properties of slabwood are completely different from those of toplogs and 'midlogs and toplogs' (Table 4, Fig. 4, 5, 6), with only small overlap between slabwood and 'midlogs and toplogs'.

Heritabilities are very high to high for almost all handsheet properties at low and high refining levels (Table 4). Low to moderate heritabilities were obtained for stretch of 'toplogs' and 'midlogs and toplogs' at the high refining level. The heritabilities of handsheet properties for the 16-year-old clones (Table 5) were also high. Clone means and ranges for handsheet properties for the 16-year-old clones were similar to the toplogs in this study.

CONCLUSIONS

Whole-tree wood density and tracheid dimensions of the 270year-old and earlier-studied 16-year-old clones showed very high broad-sense heritabilities. Clonal forestry could therefore be used to produce clones that cover a remarkably wide range of fibre dimensions, and with low variation between trees of each clone. The high heritability and high clonal variability of wood density, tracheid coarseness and kraft fibre length would enable the improvement of radiata pine pulp for reinforcement of printing and writing grades.

The moderate broad-sense heritability of glucose content and kraft pulp yield indicate that tree-breeders could probably improve kraft pulp yield by selective breeding, thus improving the economics of the kraft pulp production process. The moderate broad-sense heritabilities and the high between-clone variance found in these traits show that clonal forestry could also substantially lift kraft pulp yield.

Toplogs and slabwood are residues from the log processing industries and represent about 50% of total harvested volume. This study found very large differences between clones and high heritabilities, for both toplog and slabwood-derived chips / kraft pulps in chip basic density, kraft fibre length, and kraft sheet density, tensile index, stretch, TEA index, and tear index, indicating that these end-product characteristics could be substantially improved by clonal selection.

Segregation of wood types to optimise allocation of wood resources for different products has been practiced by pulp and paper companies in New Zealand for at least two decades. The differences in kraft pulp properties between clones of a given wood type are of approximately the same size as differences between the wood types. Therefore, for a given wood type (whole-trees, toplogs or slabwood), segregation of wood from monoclonal blocks could realise differentiation of kraft pulp properties to a similar extent as segregation on wood type alone. With segregation of chips by both wood type and monoclonal block, very wide differentiation of wood resources for kraft pulp properties would be possible. This extended range of fibre types could lead to new product uses for radiata pine kraft pulp.

REFERENCES

(*1*) Uprichard, J.M., Kimberley, M.O., Foster, S. and Shelbourne, C.J.A. – Thermomechanical pulping studies on ten *Pinus radiata* clones: the effects of wood quality and papermaking properties, *Proc. TAPPI Intl Pan Pacific Conference,* San Diego, p.83 (1994).

(*2*) Kibblewhite R.P. and Uprichard J.M. – Kraft pulp qualities of eleven radiata pine clones, *Appita J.* **49**(4):243 (1995).

(*3*) Kibblewhite, R.P. and Shelbourne, C.J.A. – Genetic selection of trees with designer fibres for different paper and pulp grades, *Trans 11th Fundamental Research Symposium 'Fundamentals of Papermaking Materials'*, Cambridge, p 439 (1997).

(*4*) Beauregard, R., Gazo, R., Kimberley, M.O. and Shelbourne, C.J.A. – Clonal variation in the quality of radiata pine random width boards, *Wood Pap. Sci.* **3**(3):222 (1999).

(*5*) Evans, R. – Rapid measurement of the transverse dimensions of tracheids in radial wood sections from *Pinus radiata, Holzforschung* **48**(2):168 (1994).

(*6*) Evans, R., Downes, G.M., Menz, D.N.J. and Stringer, S.L. – Rapid measurement of variation in tracheid transverse dimensions in a radiata pine tree, *Appita J.* **48**(2):134 (1995).

(*7*) Evans, R., Kibblewhite, R.P. and Stringer, S. – Kraft property prediction from wood properties of eleven radiata pine clones, *Appita J.* **50**(1):25 (1997).

(*8*) Evans, R. and Ilic, J. – Rapid prediction of wood stiffness from microfibril angle and density, *Forest Prod. J.* **51**(3):53 (2001).

(*9*) Shelbourne, C.J.A. – Genetics of adding value to the end-products of radiata pine, In Burdon, R.D. and Moore, J.M. (ed.) **IUFRO 97 Genetics of *Radiata Pine*,** *Proc. NZFRI-IUFRO Conference,* Rotorua, New Zealand, p.129 (1997).

(*10*) Harding, O.V. and Orange, R.P. – Unpublished data (1998).

(*11*) Jones, T.J. – Tracheid properties control TMP and PRMP pulp properties, *Proc. Intl Mechanical Pulping Conference,* Houston, p.97 (1999).

(*12*) Pettersen, R. and Schwandt, V. – Wood sugar analysis by anion chromatography, *J. Wood Chem. Tech.* **11**(4):297 (1988).

(*13*) Kibblewhite, R.P. and Bailey, D.G. – Measurement of fibre cross-section dimensions using image processing, *Appita J.* **41**(4):297 (1988).

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