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ORIGINAL ARTICLE

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Examination of within-tree variations and the heights representing whole-tree values of derived wood properties for quasi-non-destructive breeding of *Eucalyptus camaldulensis* and *Eucalyptus globulus* as quality pulpwood

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Abstract Within-tree variations of derived wood properties of Runkel ratio, Luce's shape factor, slenderness ratio, and solids factor were examined for *Eucalyptus camaldulensis* and *Eucalyptus globulus* trees and the tendency difference in the within-tree variations between individuals and between species, in both radial and axial directions by statistical data analysis. These properties are important for quality breeding of pulpwood. In both species, within-tree variations were generally observed as higher values in the upper and outer parts compared with other parts of the trunk for Runkel ratio and Luce's shape factor. In *E. camaldulensis*, within-tree variations were observed as higher values in the upper and outer parts compared with other parts of the trunk for slenderness ratio and solids factor. In *E. globulus*, within-tree variations were observed as higher values in the outer parts compared with other parts for slenderness ratio and solids factor. However, significant difference of tendency was observed in radial variation between individuals of *E. globulus* for Runkel ratio and in both radial and axial variations between species for solids factor. Furthermore, within-tree variations of derived wood properties were analyzed to determine a sampling height in the trunk which can be used to represent whole-tree values. Representative heights of derived wood properties from two trees were found to be 2.8 m in *E. camaldulensis* (except for Runkel ratio and Luce's shape factor) and 1.8 m in *E. globules* (except for Runkel ratio), regardless of differences in tree height (growth rate) and in tendency of within-tree variation of derived wood properties.

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Introduction

The genus *Eucalyptus* is a widely planted species for pulp production in many plantation sites. The breeding programs of trees aim to improve growth, pulp yield, and strength for the pulp production, because elite tree selection contributes to reduction of pulp costs in plantations with short-term rotations.[1] The increment core method is a quasi-non-destructive sampling method, and is effective and efficient in the practical quality breeding program because a core can be easily removed from the trunk using an automatic drill without cutting the tree down.[2] However, using this indirect selection method, clear relationships between wood and pulp properties are needed for the prediction of whole-tree properties of interest.

Derived wood properties, such as Runkel ratio, Luce's shape factor, slenderness ratio, and solids factor, have been recognized as important traits for pulp and paper properties in *Eucalyptus*.[3–6] For example, Runkel ratio is related to paper conformability[3,5] and pulp yield,[6] and Luce's shape factor and slenderness ratio are related to paper sheet density and to pulp digestability, respectively.[6] These suggest derived wood properties could be used as selection indices for quality breeding.

The use of increment core method depends on how well the core-sampling position represents the whole tree. To determine the core-sampling position accurately, an examination of within-tree variations of derived wood properties is required. Within-tree variations of derived wood properties, such as Runkel ratio and slenderness ratio in *Eucalyptus* have been reported previously.[7–11] However, little has been presented on within-tree variations of derived wood properties including Luce's shape factor and solids factor, which significantly correlate to breaking length of paper in *Eucalyptus*.[6] Furthermore, the tendency difference of within-tree variation of wood properties were little exam-

Table 1. Sample tree height and diameter at breast height (DBH)

Specimen	Tree height (m)	DBH (cm)
Eucalyptus camaldulensis No. 1	15.2	18.8
Eucalyptus camaldulensis No. 2	18.1	23.5
Eucalyptus globulus No. 1	19.9	24.4
Eucalyptus globulus No. 2	30.0	23.8

ined either between individuals or between species by a quantitative manner using statistical data analysis.

Moreover, the most appropriate core-sampling position is reported for Runkel ratio in *Eucalyptus*,[12] but not for Luce's shape factor and solids factor on a whole-tree basis.

In this study, we investigated the within-tree variations of derived wood properties in *Eucalyptus camaldulensis* and *Eucalyptus globulus* trees and examined the tendency differences in within-tree variations of derived wood properties between individuals and between species, in both radial and axial directions by statistical data analysis.

Furthermore, we investigated the use of a representative height in the trunk to indicate whole-tree values of derived wood properties for core-sampling and the influence of the tendency difference in within-tree variations of derived wood properties between individuals and between species as part of achieving a quality breeding program for pulpwood.

Materials and methods

Materials

Two trees each of 14-year-old *Eucalyptus camaldulensis* and *Eucalyptus globulus* were obtained from Manjimup in Western Australia (annual average temperature: 15.5°C, annual rainfall: 1000 mm) for this study. The two sample trees were selected in each species as No. 1 and No. 2 trees, possessing average and superior growth characteristics, respectively (Table 1).

Discs (6 cm thick) were cut at 1-m intervals from 0.3 m above the ground up to the height with a diameter of 8 cm. Two 2-cm wide strips were removed from the center of each disc. One strip was cut into 2 (radial) × 2 (tangential) × 6 cm (longitudinal) wood blocks from pith to bark. These blocks were fixed with ethanol/water and utilized for the fiber morphology determination for calculating the derived wood properties.

Determination of wood properties

Cross sections (15 μm thick) were microtomed from block samples and stained with safranin and mounted in Bioleit (Ohken Shoji, Tokyo, Japan). The cross-sectional images were captured by personal computer and converted to digital format using an image scanner CanoScan 2700F (Canon, Tokyo, Japan) for the image analysis. Fiber morphology was measured: radial and tangential diameters, lumen radial and tangential diameters, cell area, lumen area, cell perimeter, and lumen perimeter. Fiber diameter, fiber lumen diameter, and fiber wall thickness were calculated as follows:

Fiber diameter (μm) =
(radial diameter + tangential diameter)/2
Fiber lumen diameter (μm) =
(radial lumen diameter + tangential lumen diameter)/2
Fiber wall thickness (μm) =
2 × (cell area − lumen area)/(cell perimeter + lumen parameter)

Here, fiber wall thickness was calculated as the height of the trapezoid according to Yoshinaga et al.,[13] because each whole fiber wall area was regarded as the trapezoid. Under these measuring conditions, a dimension of one pixel on the computer corresponded to 0.15 μm of real dimension.

The cell morphologies of 50 randomly selected fibers were measured by image-processing software, NIH Image 1.62 (National Institute of Health, Bethesda, MD, USA). The cell length of 50 fibers, macerated from small sticks (ca 1 × 1 × 10 mm) with Schultz's solution,[14,15] was measured by a digitizer (Oscon, Gradimate SQ-3000, Tokyo, Japan) coupled to an Olympus CH light microscope (Olympus, Tokyo, Japan).

The derived wood properties of Runkel ratio,[16] Luce's shap factor,[17] slenderness ratio,[9] and solids factor[18] were calculated from measurements of the fiber morphology:

Runkel ratio =
fiber wall thickness × 2/fiber lumen diameter
Luce's shape factor =
(fiber diameter^2 − fiber lumen diameter^2)/
(fiber diameter^2 + fiber lumen diameter^2)
Slenderness ratio = fiber length/fiber diameter
Solids factor =
(fiber diameter^2 − fiber lumen diameter^2) × fiber length

Tendency difference of within-tree variations for derived wood properties between individuals and between species

The tendency difference of within-tree variations of derived wood properties was examined between individuals and between species for both radial and axial directions by statistical data analysis. The linear regression line was created for radial variation at a given distance from pith and for axial variation at a given height above the ground using SigmaPlot 8.0 statistical software (SPSS, Chicago, IL, USA). The slopes for one individual and for one species were grouped as one sample and utilized for the examination of tendency difference of within-tree variations of derived wood properties between individuals and between species, respectively, in both radial and axial directions by the Moses test of extreme reactions[19] using SPSS 11.0J (SPSS). All samples were used without data trimming.

Table 2. Derived wood properties

Traits	*Eucalyptus camaldulensis*		*Eucalyptus globulus*	
	No. 1 (n = 33)	No. 2 (n = 44)	No. 1 (n = 56)	No. 2 (n = 93)
Runkel ratio	0.50 ± 0.12	0.50 ± 0.10	0.54 ± 0.12	0.67 ± 0.24
Luce's shape factor	0.37 ± 0.06	0.37 ± 0.05	0.39 ± 0.06	0.44 ± 0.10
Slenderness ratio	56.6 ± 5.2	50.5 ± 5.3	59.9 ± 7.0	57.7 ± 6.3
Solids factor (μm^3) × 10^3	51.2 ± 8.2	48.6 ± 9.0	96.3 ± 29.1	97.6 ± 41.0

Results are given as average ± standard deviation

Whole-tree and whole-disc values of derived wood properties

The whole-tree and whole-disc values of derived wood properties were determined, as reported previously,[20] in the following manner. The unmeasured parts between two axially adjacent measured parts were considered to hold the average values of the measured parts because selected parts were measured in the trunk and uneven growth was observed for some directions. Other unmeasured parts were considered the same as values in radially adjacent measured parts or the calculated parts described above. Additionally, each measured or calculated part was hypothesized to possess the same quality as its concentric circled section. From these, whole-tree and whole-disc values were determined as weighted values by wood volume. Whole-disc values at 0.8, 1.8, and 2.8 m above the ground were calculated as the average of two adjacent measured-disc values.

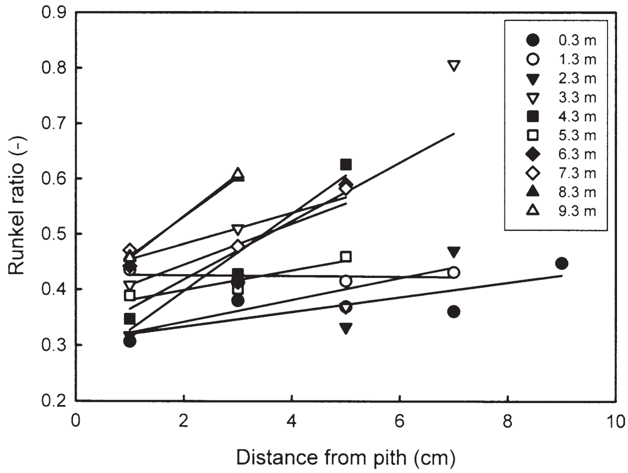

Fig. 1. Plots of linear regression lines at given heights above ground for Runkel ratio against distances from pith in *Eucalyptus camaldulensis* tree No. 1

Results and discussion

The derived wood properties are summarized in Table 2. The linear regression lines at given heights above the ground were plotted for Runkel ratio against a distance from pith in *Eucalyptus camaldulensis* No. 1 (Fig. 1). The slopes of regression lines in the radial and axial directions are summarized in Tables 3 and 4, respectively. The slopes for one individual and for one species were grouped as one sample and utilized for the examination of tendency difference in within-tree variations of derived wood properties between individuals and between species, in both radial and axial directions by the Moses test of extreme reactions. The results are summarized in Table 5. The Moses test is a nonparametric analysis for two independent samples and is used in experimental studies where it is assumed that the treatment variable will affect subjects in either a positive or negative way, creating a polarizing effect.[19] In the comparison of the tendency difference of within-tree variation, it often happens that one is normally distributed and the other is polarized at some extreme. In such a case, it is possible both samples have the same central tendency and might not be found to be significantly different by some tests which emphasize difference in central tendency. The Moses test focuses on the differences in extreme tendencies in the tails of the distribution. If the possibility associated with the Moses test is less than the desired significance level (in this study 0.05), then the two samples do not differ.

Within-tree variation of Runkel ratio

Within-tree variations of Runkel ratio in *E. camaldulensis* and *Eucalyptus globulus* are shown in Figs. 2 and 3, respectively.

In *E. camaldulensis*, both No. 1 and No. 2 trees had a high Runkel ratio in the upper and outer parts of the trunk. There was a trend for Runkel ratio to increase from pith to bark in the radial direction, and from bottom to top in the axial direction, except in the upper parts of tree No. 2. Similarly, in *E. globulus*, both trees had a high Runkel ratio in the upper and outer parts of the trunk, but the trend of within-tree variation was different between individuals. In particular, the upper and outer parts in tree No. 2 showed higher Runkel ratio compared with the other parts. In *E. globulus* No. 1, a relatively uniform trend of increasing Runkel ratio was observed from pith to bark in the radial direction, with a weak trend of increasing Runkel ratio from bottom to top in the axial direction. On the other hand, in *E. globulus* No. 2, a trend of increasing Runkel ratio was only observed from pith to bark in the lower parts of the trunk in the radial direction, but no clear trend was observed in the

Table 3. Slopes of linear regression lines for radial variation at given heights above the ground

Sample	Height above the ground (m)	Runkel ratio	Luce's shape factor	Slenderness ratio	Solids factor (μm^3)
Eucalyptus camaldulensis No. 1	0.3	0.0131	0.0082	0.8200	2.5850
	1.3	−0.0007	−0.0005	−0.5600	1.2550
	2.3	0.0196	0.0141	0.3150	1.3400
	3.3	0.0528	0.0275	0.9200	3.7700
	4.3	0.0698	0.0425	1.7750	5.0000
	5.3	0.0178	0.0128	1.0000	2.8750
	6.3	0.0370	0.0198	2.3000	4.1000
	7.3	0.0280	0.0155	1.7500	4.5500
	8.3	0.0715	0.0415	8.9000	12.6000
	9.3	0.0755	0.0415	3.6000	3.5500
E. camaldulensis No. 2	0.3	0.0106	0.0067	0.8125	2.8536
	1.3	0.0039	0.0020	0.3200	2.2186
	2.3	0.0043	0.0005	1.1200	1.6100
	3.3	0.0036	0.0032	2.0750	4.1000
	4.3	−0.0019	−0.0011	2.2100	3.4350
	5.3	0.0141	0.0085	1.3850	4.2750
	6.3	−0.0127	−0.0077	2.7100	2.3550
	7.3	0.0108	0.0055	3.4000	4.3500
	8.3	−0.0324	−0.0211	−0.4000	0.1625
	9.3	−0.0837	−0.0473	1.3250	0.4250
	10.3	−0.0210	−0.0130	1.2000	2.3500
	11.3	−0.0210	−0.0130	1.2000	2.3500
Eucalyptus globulus No. 1	0.3	0.0389	0.0211	0.7157	3.1679
	1.3	0.0006	0.0008	0.2929	9.9957
	2.3	0.0183	0.0115	1.7300	8.8150
	3.3	−0.0209	−0.0132	0.4350	9.6200
	4.3	0.0174	0.0123	2.2500	13.3950
	5.3	−0.0050	−0.0025	1.5300	8.5250
	6.3	−0.0161	−0.0083	1.7800	13.0350
	7.3	−0.0051	−0.0025	−0.9750	7.5600
	8.3	0.0157	0.0095	1.5200	9.5300
	9.3	0.0292	0.0155	0.6000	9.9000
	10.3	−0.0392	−0.0208	−1.0500	11.8500
	11.3	−0.0188	−0.0095	1.7750	23.9000
	12.3	0.0375	0.0235	2.4000	25.7500
	13.3	−0.0260	−0.0120	−3.6500	22.7500
E. globulus No. 2	0.3	0.0236	0.0140	1.7518	9.7304
	1.3	0.0262	0.0145	0.8429	11.1000
	2.3	0.0590	0.0296	2.2500	14.1500
	3.3	0.0475	0.0221	1.9750	14.2800
	4.3	0.0542	0.0269	1.6800	12.4800
	5.3	0.0461	0.0262	1.7350	16.6100
	6.3	0.0270	0.0170	2.2200	14.0550
	7.3	0.0440	0.0217	1.0000	15.9450
	8.3	0.0354	0.0191	3.1850	11.9550
	9.3	0.0606	0.0314	1.3200	13.5600
	10.3	0.0059	0.0018	1.6850	18.3800
	11.3	0.0076	0.0030	1.0700	19.1050
	12.3	−0.0399	−0.0196	1.3950	15.7100
	13.3	0.0185	0.0101	2.2850	18.6200
	14.3	−0.0155	−0.0068	0.5150	15.0750
	15.3	−0.0355	−0.0124	1.2600	15.1400
	16.3	0.0041	0.0038	1.2600	11.9800
	17.3	−0.0532	−0.0260	2.2000	23.5000
	18.3	−0.1493	−0.0632	1.1500	13.1750
	19.3	−0.0238	−0.0097	2.6500	19.0000
	20.3	−0.0175	−0.0092	4.0750	14.7250
	21.3	−0.1025	−0.0420	2.0000	23.8500
	22.3	−0.0400	−0.0140	4.7000	23.2500

upper parts. The trend of increasing Runkel ratio was also observed from bottom to top in inner parts of the trunk in the axial direction, but the variation was small in outer parts. From these observations, significant difference between individuals was recognized in the radial variation of *E. globulus* (Table 5). Consequently, for both species, the upper and outer parts had higher Runkel ratios compared with other parts.

In the radial direction, the trend of increasing Runkel ratio from pith to bark was reported for *Eucalyptus*

Table 4. Slopes of linear regression lines for axial variation at given distances from pith

Sample	Distance from pith (cm)	Runkel ratio	Luce's shape factor	Slenderness ratio	Solids factor (μm^3)
Eucalyptus camaldulensis No. 1	1	0.0148	0.0099	0.1473	−0.2709
	3	0.0207	0.0116	1.4618	0.9061
	5	0.0358	0.0220	1.1560	2.1940
	7	0.1378	0.0756	3.0600	1.1800
E. camaldulensis No. 2	1	0.0195	0.0108	0.8175	0.8175
	3	0.0146	0.0088	1.1497	1.1497
	5	0.0151	0.0096	1.2467	1.2445
	7	0.0218	0.0132	2.7571	2.7571
	9	−0.0295	−0.0210	−1.3000	−1.3000
	11	−0.0100	−0.0010	−8.7000	−8.7000
Eucalyptus globulus No. 1	1	0.0124	0.0075	0.7613	0.2782
	3	0.0101	0.0062	−0.0029	2.7974
	5	0.0156	0.0100	−0.4483	4.1937
	7	0.0133	0.0079	−0.0200	2.8833
	9	0.0143	0.0080	1.8100	5.7200
	11	−0.3760	−0.1780	−9.2000	8.0000
E. globulus No. 2	1	0.0261	0.0130	0.4314	0.6905
	3	0.0143	0.0081	0.2661	2.8036
	5	0.0170	0.0101	0.3731	3.7557
	7	0.0219	0.0127	0.2037	3.8495
	9	0.0153	0.0096	0.1413	6.8551
	11	0.0210	0.0100	−5.2000	−27.5000

Table 5. Significance of statistical differences of tendency in within-tree variations of derived wood properties between individuals and between species by the Moses test ($P < 0.05$)

Trait	Runkel ratio	Luce's shape factor	Slenderness ratio	Solids factor
Radial difference between individuals of *Eucalyptus camaldulensis*	NS (0.059)	NS (0.059)	NS (1.000)	NS (0.571)
Radial difference between individuals of *Eucalyptus globulus*	Significant (0.011)	NS (0.102)	NS (0.362)	NS (1.000)
Radial diffrence between species	NS (0.690)	NS (0.865)	NS (0.521)	Significant (0.000)
Axial difference between individuals of *E. camaldulensis*	NS (0.452)	NS (0.262)	NS (0.667)	NS (0.452)
Axial difference between individuals of *E. globulus*	NS (0.121)	NS (0.273)	NS (1.000)	NS (0.773)
Axial diffrence between species	NS (0.805)	NS (0.805)	NS (0.805)	Significant (0.001)

P values are shown in parentheses
NS, not significant

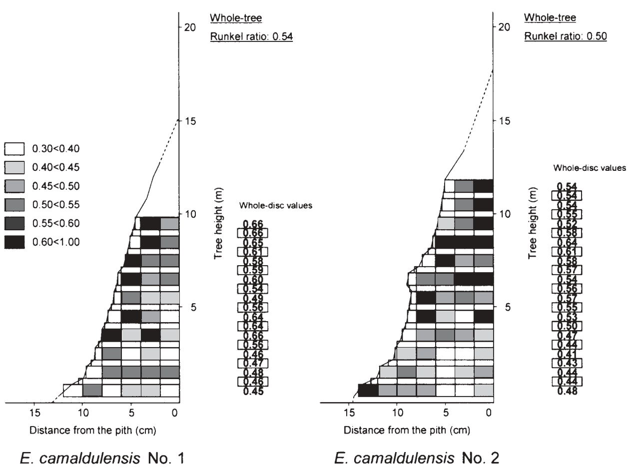

Fig. 2. Within-tree variation of Runkel ratio in *E. camaldulensis*. *Unboxed* and *boxed digits* represent whole-disc values at given heights

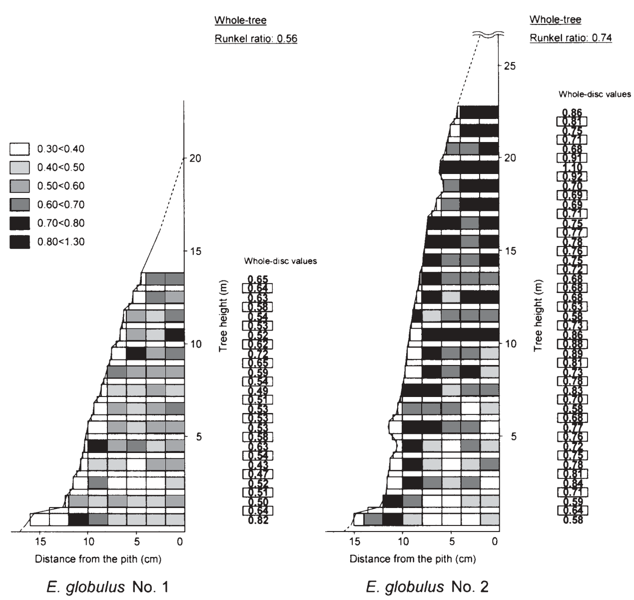

Fig. 3. Within-tree variation of Runkel ratio in *Eucalyptus globulus*

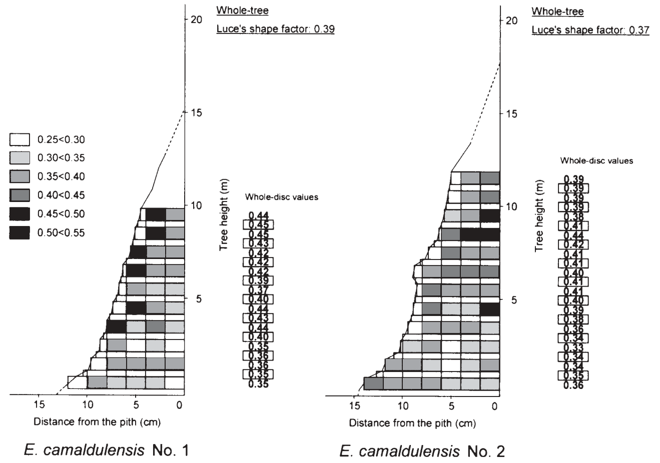

Fig. 4. Within-tree variation of Luce's shape factor in *E. camaldulensis*

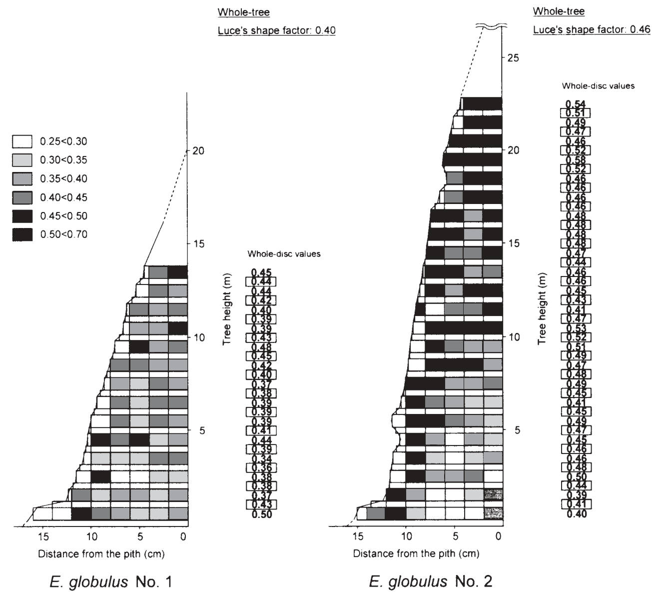

Fig. 5. Within-tree variation of Luce's shape factor in *E. globulus*

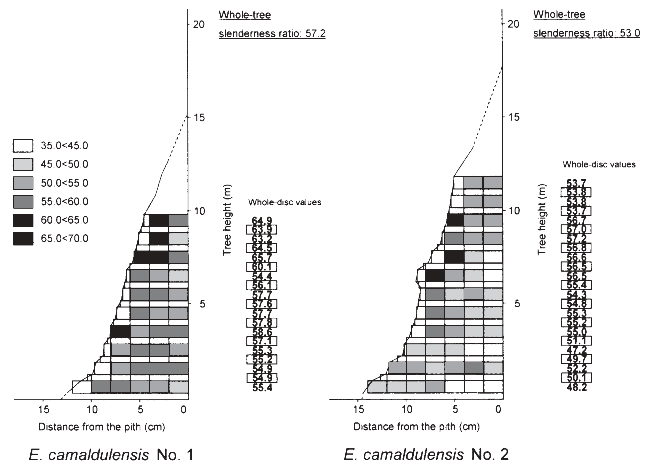

Fig. 6. Within-tree variation of slenderness ratio in *E. camaldulensis*

pilularis[7] and *Eucalyptus grandis*.[8,9] We observed a similar trend of increasing Runkel ratio in this study, which was not affected by the growth rate difference. The trend of within-tree variation of Runkel ratio in both species was very similar to that of wall thickness, as reported previously.[19] This is probably due to fiber wall thickness which had a higher proportional increase than lumen diameter. Within-tree variation of Runkel ratio is considered to be largely affected by only fiber wall thickness, although Runkel ratio is derived from fiber wall thickness and lumen diameter.

In making paper using hardwood, a Runkel ratio less than 1.0 is desirable to obtain good conformability and fiber to fiber contact in paper.[5] From this aspect, the Runkel ratio in both species is adequate for making paper.

Ona et al.[6] reported that Runkel ratio significantly related to pulp yield (positively) and to digestibility (negatively) in *E. camaldulensis*. The results obtained suggest the upper and outer parts of the trunk will have higher pulp yield and better digestibility than other parts in *E. camaldulensis*.

Within-tree variation of Luce's shape factor

Within-tree variations of Luce's shape factor in *E. camaldulensis* and *E. globulus* are shown in Figs. 4 and 5, respectively.

Both *E. camaldulensis* and *E. globulus* had high Luce's shape factor in the upper and outer parts of the trunk. In *E. camaldulensis*, there was a weak trend of increasing Luce's shape factor from pith to bark in the radial direction, and from bottom to top in the axial direction, except in the upper parts of tree No. 2. In *E. globulus,* a trend of increasing Luce's shape factor from pith to bark in the radial direction was observed in the lower parts of the trunk, but no clear trend was observed in the upper parts. The trend of increasing Luce's shape factor was in the axial direction for the inner parts of the trunk, but the variation was small in outer parts.

The general trend of within-tree variation of Luce's shape factor in both species was similar to that observed for Runkel ratio. Similar to Runkel ratio, the trend of within-tree variation of Luce's shape factor may be associated with that of wall thickness, because both the fiber diameter and the fiber lumen diameter are used to obtain the cross-sectional fiber wall area in the equation for Luce's shape factor.[17]

Within-tree variation of slenderness ratio

Within-tree variations of slenderness ratio in *E. camaldulensis* and *E. globulus* are shown in Figs. 6 and 7, respectively.

In *E. camaldulensis*, both No. 1 and No. 2 trees had higher slenderness ratios in the upper and outer parts compared with other parts of the trunk. In particular, the upper parts in tree No. 1 showed high values compared with the

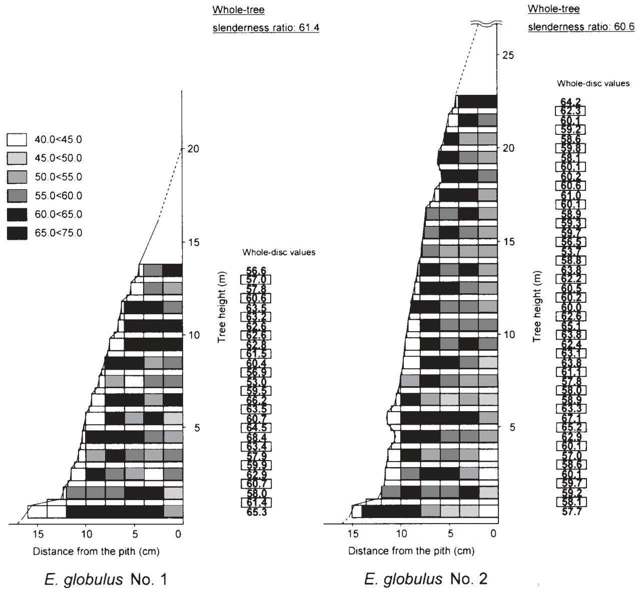

Fig. 7. Within-tree variation of slenderness ratio in *E. globulus*

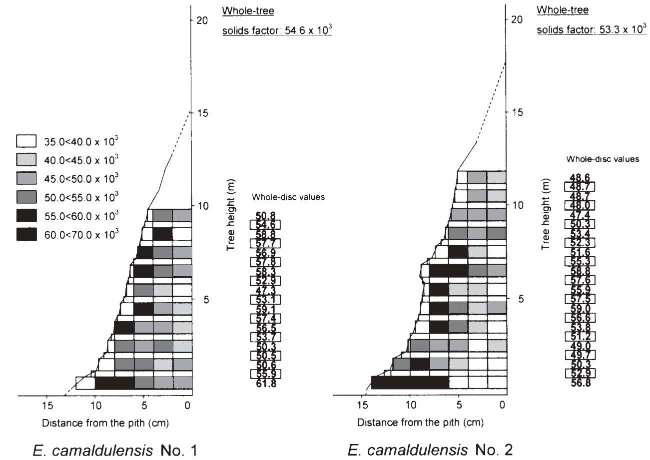

Fig. 8. Within-tree variation of solids factor in *E. camaldulensis*

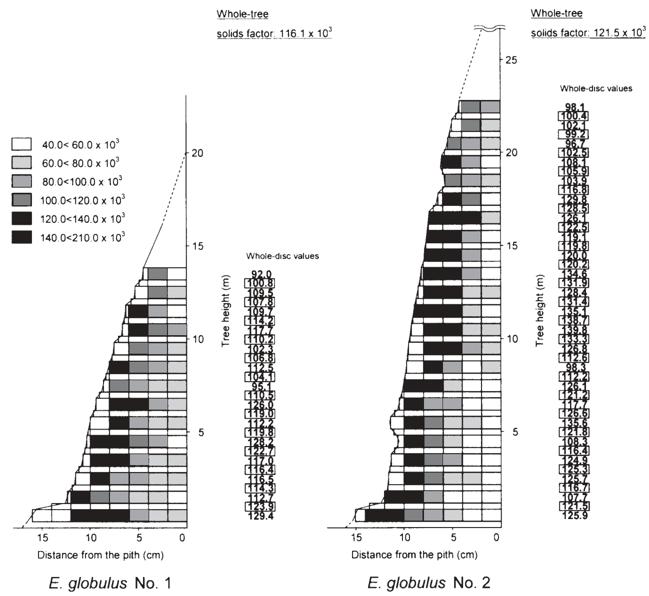

Fig. 9. Within-tree variation of solids factor in *E. globulus*

other parts. There was a trend of increasing slenderness ratio from pith to bark in the radial direction, and from bottom to top in the axial direction. Tree-to-tree variation was small (Table 5). In contrast, the *E. globulus* trees had high slenderness ratios only in the outer parts of the trunk. The parts at about 5.0 m above the ground showed a higher slenderness ratio, especially compared with the other parts of the trunk. No clear trend in the radial direction was observed for tree No. 1, but a trend of increasing slenderness ratio was observed from pith to bark for tree No. 2. No clear trend in the axial direction was observed for tree No. 1, but a relatively weak trend from bottom to top was evident for tree No. 2.

In the radial direction, the trend of increasing slenderness ratio from pith to bark was reported for *E. grandis*.[8,9] Similar trends were observed in our samples. This suggests the increase in fiber length is not associated with a proportional increase in fiber diameter, and fibers near the pith possess a proportionally larger diameter than those found in the outer parts of the trunk, as reported for *E. grandis*.[8]

Within-tree variation of solids factor

Within-tree variation of the solids factor in *E. camaldulensis* and *E. globulus* are shown in Figs. 8 and 9, respectively.

Both *E. camaldulensis* trees had a high solids factor in the upper and outer parts of the trunk, although the inner parts of tree No. 2 showed lower values than tree No. 1. A trend of increasing solids factor was observed from pith to bark in the radial direction, and from bottom to top in the axial direction. Tree-to-tree variation was small (Table 5). Compared with this, both *E. globulus* trees had a high solids factor only in the outer parts of the trunk. A trend of increasing solids factor was observed from pith to bark in the radial direction, although a relatively uniform trend of increasing solids factor from bottom to top was observed in the axial direction. Tree-to-tree variation was also small in *E. globulus* (Table 5). Consequently, significant difference between species was observed for the solids factor (Table 5).

High negative relationship between the solids factor and the breaking length of paper in *E. camaldulensis* was obtained by Ona et al.[6] From this, the upper and outer parts of the trunk in *E. camaldulensis* would have lower breaking length of paper than other parts.

The most appropriate height for sampling increment cores

To determine the whole-tree value of each derived wood property, a representative height was examined below 3.3 m above the ground for sampling an increment core using an

Table 6. Whole-tree and whole-disc values of derived wood properties at given heights with their deviations from whole-tree values in *Eucalyptus camaldulensis*

Traits	Height above the ground (m)	No. 1		No. 2	
		Whole-disc value	Deviation from whole-tree value (%)	Whole-disc value	Deviation from whole-tree value (%)
Runkel ratio	3.3	0.66	22.2	0.47	−6.0
	2.8	0.56	3.6	0.44	−12.0
	2.3	0.46	−14.8	0.41	−18.0
	1.8	0.47	−13.0	0.43	−14.0
	1.3	0.48	−11.1	0.44	−12.0
	0.8	0.46	−14.8	0.44	−12.0
	0.3	0.45	−16.7	0.48	−4.0
	Whole-tree value	0.54	–	0.50	–
Luce's shape factor	3.3	0.44	12.8	0.36	−2.8
	2.8	0.40	2.5	0.34	−8.1
	2.3	0.35	−10.3	0.33	−12.1
	1.8	0.36	−7.7	0.34	−8.8
	1.3	0.36	−7.7	0.34	−8.1
	0.8	0.35	−10.3	0.35	−5.4
	0.3	0.35	−10.3	0.36	−2.8
	Whole-tree value	0.39	–	0.37	–
Slenderness ratio	3.3	58.6	2.4	55.0	3.8
	2.8	57.1	−0.2	51.1	−3.6
	2.3	55.3	−3.3	47.2	−10.9
	1.8	55.2	−3.5	49.7	−6.2
	1.3	54.9	−4.0	52.2	−1.5
	0.8	54.9	−4.0	50.1	−5.5
	0.3	55.4	−3.1	48.2	−9.1
	Whole-tree value	57.2	–	53.0	–
Solids factor (μm^3) $\times 10^3$	3.3	56.5	3.5	53.8	0.9
	2.8	53.7	−1.6	51.2	−3.9
	2.3	50.3	−7.9	49.0	−8.1
	1.8	50.5	−7.5	49.7	−6.8
	1.3	50.9	−6.8	50.3	−5.6
	0.8	55.9	2.4	52.9	−0.8
	0.3	61.8	13.2	56.8	6.6
	Whole-tree value	54.6	–	53.3	–

automatic drill as part of a test for practical quality breeding.[20] The representative height is defined as the height with the whole-disc value within the whole-tree value ±5%. This is done in consideration of the analytical deviation of wood following our previous report.[21] The whole-disc values of derived wood properties at heights below 3.3m in *E. camaldulensis* and *E. globulus* are summarized in Tables 6 and 7, respectively.

Common representative heights between individuals are as follows: in *E. camaldulensis*, Runkel ratio: none; Luce's shape factor: none; slenderness ratio: 1.3, 2.8, 3.3m; solids factor: 0.8, 2.8, 3.3m; in *E. globulus*, Runkel ratio: none; Luce's shape factor: 1.8m; slenderness ratio: 0.8, 1.8–2.8m; solids factor: 1.8–3.3m. Consequently, the most appropriate height to sample an increment core is 2.8m above the ground for *E. camaldulensis* (except for Runkel ratio and Luce's shape factor), and 1.8m above ground for *E. globulus* (except for Runkel ratio). No representative height for Runkel ratio was obtained for either species, probably because of the large difference between whole-tree and whole-disc values resulting from relatively small or unclear within-tree variation. The representative heights were not reflected by the differences in tree height (growth rate) for all derived wood properties and by the difference of tendency in within-tree variations of derived wood properties, especially in the case of the solids factor.

Hudson et al.[12] reported that the representative height (whole-tree value ±5%) as percentage of tree height was 10% (1.5m) and 20% (3.0m) in *E. globulus* for Runkel ratio, and 5% (0.7m) in *Eucalyptus nitens* in the same way. However, no representative height for Runkel ratio was obtained in our samples. Previous results obtained using the same sample trees showed the representative height for fiber morphology was 2.8m above the ground for *E. camaldulensis*, and 1.8m above the ground for *E. globulus*.[22] Including the present results, the representative heights to sample an increment core are 2.8m and 1.8m, for *E. camaldulensis* and *E. globulus*, respectively. However, it should be mentioned that these heights may cause errors for Runkel ratio and Luce's shape factor.

These results suggest that using a single increment core, sampled at the most appropriate height, it is possible to estimate whole-tree values of fiber morphology and derived wood properties. These measurements and determinations could be used in *Eucalyptus* tree breeding to improve the pulpwood quality.

Table 7. Whole-tree and whole-disc values of derived wood properties at given heights with their deviations from whole-tree values in *Eucalyptus globulus*

Traits	Height above the ground (m)	No. 1		No. 2	
		Whole-disc value	Deviation from whole-tree value (%)	Whole-disc value	Deviation from whole-tree value (%)
Runkel ratio	3.3	0.43	−23.2	0.78	5.4
	2.8	0.47	−19.1	0.81	9.5
	2.3	0.52	−7.1	0.84	13.5
	1.8	0.51	−8.9	0.71	−4.1
	1.3	0.50	−10.7	0.59	−20.3
	0.8	0.64	14.3	0.64	−13.5
	0.3	0.82	46.4	0.58	−21.6
	Whole-tree value	0.56	–	0.74	–
Luce's shape factor	3.3	0.34	−15.0	0.46	0.0
	2.8	0.36	−10.0	0.48	4.3
	2.3	0.38	−5.0	0.50	8.7
	1.8	0.38	−5.0	0.44	−4.3
	1.3	0.37	−7.5	0.39	−15.2
	0.8	0.43	7.5	0.41	−10.9
	0.3	0.50	25.0	0.40	−13.0
	Whole-tree value	0.40	–	0.46	–
Slenderness ratio	3.3	57.9	−5.7	57.0	−5.9
	2.8	59.9	−2.4	58.6	−3.3
	2.3	62.9	−2.4	60.1	−0.8
	1.8	60.7	−1.1	59.7	−1.5
	1.3	58.0	−5.5	59.2	−2.3
	0.8	61.4	0.0	58.1	−4.1
	0.3	65.3	6.4	57.7	−4.8
	Whole-tree value	61.4	–	60.6	–
Solids factor (μm^3) $\times 10^3$	3.3	117.0	0.8	124.9	2.8
	2.8	116.4	0.3	125.3	3.1
	2.3	116.5	0.3	125.7	3.5
	1.8	114.3	−1.6	116.7	−4.0
	1.3	112.7	−2.9	107.7	−11.4
	0.8	123.9	6.7	121.5	0.0
	0.3	129.4	11.5	125.9	3.6
	Whole-tree value	116.1	–	121.5	–

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