Indian Journal of Natural Products and Resources,
Vol. 5(4), December 2014, pp. 338-344

Variation of sapwood and heartwood content in half-sib progenies of *Eucalyptus tereticornis* Sm.

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Received 06 September 2013; Accepted 19 September 2014

Thirty six progenies of *Eucalyptus tereticornis* Sm. from seven geographical locations were evaluated for sapwood and heartwood content variation at Punjab Agricultural University, Ludhiana. The maximum wood and heartwood diameter were recorded in genotype 142, whereas, maximum heartwood content was in genotype 4. The heartwood stopped within the tree at 55 to 65 % of total height. Heartwood was present in all trees attaining the 12 m height but at the 14 m height, only seven trees showed heartwood. Sapwood radial growth was lowest at the base and showed maximum variability between trees from 4.29 to 8.61 cm of the pooled mean of sapwood at different height levels. Heartwood taper was higher than tree taper in the lower part of the stem but slightly lower than the upper part of the stem. The mean heartwood content was 53.3 % of the total tree volume at breast height. Heartwood dimensions from wood diameters were estimated by using a linear model. The heartwood diameter was positively correlated with radial tree growth and showed a good linear regression with a high coefficient of determination (R^2 = 0.80) to the wood diameter, whereas, sapwood width was independent on the diameter.

Keywords: *Eucalyptus tereticornis,* Heartwood, Taper, Linear model, Frequency distribution.

IPC code; Int. cl. (2014.01)–A61K 36/00

Introduction

Commercial *Eucalyptus* plantations are important global assets providing wood and fibre products to the modern societies and offer a wide range of social, environmental and economic benefits. The wood of *E. tereticornis* Sm. is an important source of paper making fibres in the pulp industry, combining quality pulp and paper properties with fast tree growth and short rotations[1]. The stem quality for pulping is negatively influenced by its proportion of heartwood since heartwood has a number of detrimental impacts, mostly resulting from its higher content of extractives and, to a lesser extent, from the loss of between-cell permeability[2]. In comparison to sapwood, heartwood results in lower pulp yields, higher chemical consumption, decreased pulp brightness, as well as equipment corrosion and is associated with the occurrence of stickies in the paper sheet[3-4].

The proportion of sapwood and heartwood in a tree varies genetically with genera, species and provenances and with factors such as silviculture, growing conditions, site and tree age[5-7]. In *Eucalyptus*, heartwood formation starts at an early age of 3 to 5 years and at harvest for pulping it represents a substantial part of the tree stem[8]. Heartwood development is linked to tree size, and even-aged trees that grow more in diameter and height have more heartwood content in the stem[9-11].

Such a species with multifarious uses has gained only limited research attention especially with inference to tree improvement. As the species is of immense importance but limited systematic work has been done on evaluation and identification of potential genetic resources. However, a lots of study has been carried out in other species of *Eucalyptus* by several workers, thus the present study has been carried out to select the potential open pollinated families by assessing the existing variability in wood properties so that the same can be used in future improvement and plantation programme and to evaluate genotypic influence on heartwood content and development within and between trees of *E. tereticornis* as one of the important quality factors to evaluate the timber potential of this species.

Materials and Methods

The study was conducted at main experimental area of Punjab Agricultural University Ludhiana

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(30°58´N latitude, 75°44´E longitude and 247 m Altitude) with an average annual rainfall of 604.88 mm. The progeny trial consisting 96 half sib progenies raised by open-pollinated seeds of 95 plus trees and one bulk seed mixed population during July, 1999 (22.5-year-old) was used for the study are shown in Table 1. The one parent from the best progenies was identified on the basis of their superiority for growth and stem quality since 2012. The selected genotypes (coded by 4, 7, 26, 40, 55, 57, 58, 59, 62, 63, 67, 71, 76, 77, 79, 80, 81, 82, 84, 98, 99, 101, 104, 109, 110, 116, 127, 128, 129, 130, 137, 138, 139, 142, 143 and control) were marked with paint and used for collecting wood samples for carrying out further investigation.

The trees were bucked and stem discs with 5 cm thickness were taken at different height levels: 2, 4, 6, 8, 10, 12 and 14 m from the base. The surface of the stem discs was smoothed by sanding. In all cases, the heartwood was clearly distinguished from colour difference. Dimensions of total over-bark stem cross-section, bark, total wood, heartwood and sapwood were measured. Total wood and heartwood diameters were calculated by considering their areas as circles and sapwood radial width and bark thickness considering a circular cross-section for stem and heartwood[8]. Total wood and heartwood content (%) were calculated as per the procedure used by Langat and Kariuki[12]. The tree wood volume and the heartwood volume were calculated by sections corresponding to the different height levels of sampling. The sapwood volume was calculated by difference. A simple regression model (response variable = $\beta 0 + \beta 1$ independent variable + ε) was used to study the correlations between heartwood diameter and wood diameter. Statistical analysis was performed by Sigma plot for windows version 11.0 (2013 Systat Software) and the 0.05 level was used in significance tests.

Results and Discussion

Wood and bark content

The average values of total wood diameter, heartwood diameter, bark thickness, total wood content and heartwood content with respect to total cross sectional area of the stem are presented in Table 2. An inference of data showed that maximum wood diameter was recorded in genotype 142 and minimum value in genotype 129. Similarly, wood content exhibited genotypic variability with the

Table 1—Details of seed sources of selected genotypes of *Eucalyptus tereticornis* Sm.

S. No.	Provenance/sources	Plus tree No.	Code No.
1	Australian Tree Seed Center	17753/BVG1822	4
2	-do-	1775/BVG1813	7
3	-do-	13547/JD1043	26
4	-do-	19010	40
5	-do-	16547/JD1574	55
6	-do-	16547/JD1572	57
7	-do-	16547/JD1569	58
8	-do-	16547/JD1568	59
9	-do-	16645/JD1562	62
10	-do-	16645/JD1569	63
11	Sita Nandi Sanctuary, Chhattisgarh, India	Code no. 1	67
12	-do-	Code no. 2	71
13	OUAT, Bhubaneswar, India	QUAT, ET 4	76
14	-do-	QUAT, ET 5	77
15	-do-	QUAT, ET7	79
16	-do-	QUAT, ET 8	80
17	-do-	QUAT, ET 10	81
18	-do-	QUAT, ET 17	82
19	-do-	QUAT, ET 50	84
20	University of Calcutta, West Bengal, India	CU-4	90
21	-do-	CU-16	98
22	Haryana Agricultural University, India	HS-1	99
23	Haryana Agricultural University, India	HS-3	101
24	-do-	HS-6	104
25	Tamil Nadu Agricultural University, India	FC&RI, MTP/ET-5	109
26	-do-	FC&RI, MTP/ET-6	110
27	PAU, Ludhiana, India	L-42/98	116
28	-do-	L-59/98	127
29	-do-	L-60/98	128
30	-do-	L-61/98	129
31	-do-	L-64/98	130
32	-do-	L-75/98	137
33	-do-	L-76/98	138
34	-do-	L-79/98	139
35	-do-	L-81/98	141
36	-do-	L-82/98	142
37	-do-	L-83/98	143
38	-do-	Bulk seed mixed general population	Control

maximum wood content of 86.37 % in genotype 142 and minimum was 73.00 % in genotype 129 with the mean of 81.00 %. The average bark thickness varied from 5.29 mm (genotype 62) to 9.14 mm (genotype 57). The present study revealed that the formation of bark is directly influenced by genotype.

Maximum heartwood was recorded in genotype 4 (37.86 % of the total cross sectional area) followed by genotype 142, 57, 90 and 128, and minimum value in genotype 7 (13.50 %), whereas, maximum pooled value of heartwood diameter of a tree was recorded in genotype 142 and minimum value in 129. The study showed that heartwood content over total wood area is not only dependent on heartwood diameter but also on ratio of heartwood to wood diameter. Several studies on heartwood variation of *Eucalyptus* species have been made for *E. camaldulensis* Dehnhardt[13], *E. tereticornis*[14], *E. marginata* Sm. and *E. maculata* Hook.[15], *E. delegatensis* F. Muell. ex R.T. Baker and *E. dalrympleana* Maiden[5], *E. grandis* W. Hill[7],

Table 2—Variation in different wood traits in *Eucalyptus tereticornis* Sm. genotypes

Genotypes	Wood diam. (cm)	Heartwood diam. (cm)	Wood content (%)	Bark thickness (mm)	Heartwood (%)
4	16.79	11.29	84.52	7.14	37.86
7	13.77	5.54	84.18	6.00	13.50
26	12.30	6.10	76.80	7.76	19.23
40	14.06	8.14	85.31	5.71	27.37
55	10.27	5.34	76.43	6.71	20.87
57	19.00	12.17	82.60	9.14	31.94
58	13.21	6.67	80.37	7.07	20.37
59	12.53	6.21	77.60	7.93	18.94
62	10.73	6.07	81.9	5.29	25.79
63	14.43	8.21	83.21	6.50	26.55
67	11.04	6.33	78.02	6.79	24.69
71	12.16	6.99	82.01	6.07	25.66
76	11.86	5.83	80.18	6.36	18.87
77	11.26	6.03	80.19	5.86	21.42
79	11.89	5.74	78.36	6.86	17.95
80	11.69	5.84	81.32	5.64	19.50
81	14.64	7.96	83.04	6.50	23.84
82	14.21	8.06	84.21	5.93	26.30
84	12.16	7.87	74.78	8.32	29.99
90	15.69	9.53	85.74	6.14	30.91
98	14.61	6.00	84.01	6.36	15.06
99	11.19	5.50	77.55	6.93	18.56
101	16.86	10.54	83.43	6.71	29.90
104	14.83	7.50	81.64	7.14	20.10
109	13.87	8.37	81.28	7.07	27.27
110	11.83	5.99	74.77	8.29	19.38
116	13.74	8.61	76.87	8.82	29.33
127	13.43	6.94	83.34	6.29	21.90
128	15.00	9.43	81.22	6.85	30.37
129	9.99	4.61	73.00	7.57	15.15
130	14.00	7.97	80.67	7.36	26.56
137	15.36	8.37	83.55	7.14	24.29
138	15.11	8.07	79.79	8.07	21.64
139	12.17	5.23	79.54	6.93	16.01
141	16.99	8.83	84.58	7.29	22.44
142	19.44	12.61	86.37	7.36	34.81
143	17.54	9.69	80.40	7.86	25.36
Control	14.21	6.01	85.14	5.64	15.19

E. globulus Labill.[11], *E. grandis* × *E. urophylla* S.T. Blake[1] and proportion of heartwood was shown to vary substantially between species[16].

Heartwood and sapwood variation along the stem

The vertical profile of the total wood, heartwood and sapwood area within the stem cross sectional area are shown in Fig 1. With respect to pooled mean of all genotypes, total wood and heartwood content decreased with the height levels from the base upwards. The heartwood stopped within the tree at 55 % to 65 % of total height. Heartwood was present in all trees attaining on the 12 m height but at the 14 m height, only seven trees showed heartwood (genotype 4, 57, 81, 137, 141, 142 and 143). At the base of 2 m from the ground level the heartwood area was almost higher than sapwood area and decreased afterwards. The data revealed that heartwood was approximately 50 % at the base (2 m) and at the height 8 m, it was on an average 30 % and at 14 m height, the heartwood was almost absent for 10-year-old *E. tereticornis* trees.

Recently, Miranda *et al*[11] also reported high values of heartwood proportion at breast height, between 68 and 78 % for 18-year-old *E. globulus* trees and data are also available for younger *E. globulus* trees i.e. 52-54 % in 12-year-old[10], 43 % in 9-year-old[8] and 29-61 % in 8-year-old trees[17]. However, these studies indicated that it is not only affected by age but also tree dimensions, particularly tree diameters that are the main factors responsible for heartwood development. This is in agreement with similar results obtained for other *Eucalyptus* species, i.e. *E. grandis*[7] and for other species, i.e. *Tectona grandis* L. f.[18], *Pinus contorta* Douglas ex Loudon[19] *Juglans nigra* L.[20], *Pinus pinaster*Aiton[21], *Acacia melanoxylon* R. Br.[22].

The proportion of heartwood in the stem cross-section also decreased within the tree from base to the top (Fig. 2). At the 2 m height, the heartwood proportion among the trees ranged 26-65 % of the total sectional area and decreased with a constant rate to the 8 m tree height where it ranged 11-38 % from that point upwards the decrease was higher and at 14 m of height heartwood represented 0.43-15.5 % of the cross sectional area.

The pooled values of area of the sapwood in the cross section remained stable in the lower part of the stem with only a slight decrease until 8 m of tree height, after which it decreased steadily and sharply in the upper part (Fig. 1). The average, mean value of sapwood represented 58 % at the base (2 m height) and 64, 70, 75, 81, 89 and 95 %, respectively, at 4, 6, 8, 10, 12 and 14 m of tree height (Fig. 2). Sapwood radial growth was lowest at the base and showed maximum variability between trees from 4.29 to 8.61 cm of the pooled mean of sapwood of different height levels. This is consistent with what has been reported for most of *Eucalyptus* species[5]. Similar significant differences for heartwood content among the 18 provenances of *E. grandis* were reported by Langat and Kariuki[12] in Kenya which ranged from 29.5 to 61.5 %.

The vertical heartwood shape accompanied the stem shape. Heartwood taper was higher than tree taper at the lower part of the stem but slight lower than the upper part of the stem. Stem taper, total wood taper and heartwood taper were similar with an average of 7.8 mm/m at the 30 % of tree height (6 to 8 m height level). At the upper part of the tree, the stem and heartwood taper increases, especially after approximately 50 % of tree height level, with a significantly higher tonicity for the heartwood (Table 3). A similar result was reported by Knapic *et al*[22].

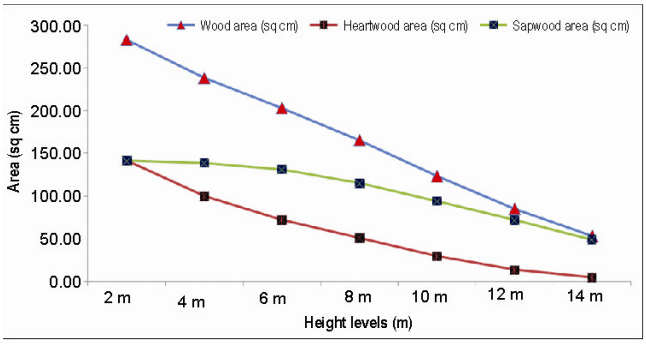

Fig. 1—Relationship among total wood area, heartwood area, sapwood area and height in *Eucalyptus tereticornis* Sm.

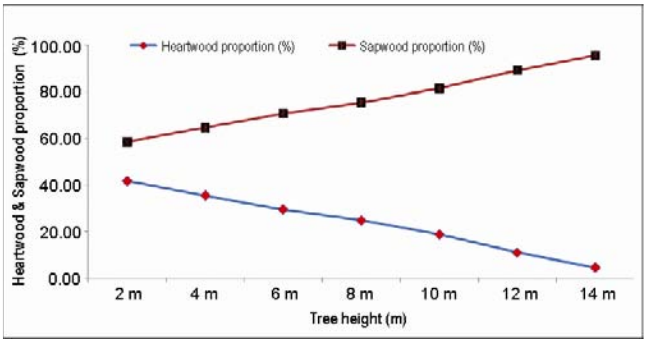

Fig. 2—Pooled mean of heartwood area (%) and sapwood area (%) in the cross section at the different tree height levels of all genotypes in *Eucalyptus tereticornis* Sm.

Heartwood and sapwood volume

The average tree wood volume accumulation along the stem is shown in Fig 3. Volume increases rapidly with tree height in the lower part of the stem, after which the accumulation of wood volume decreases. Heartwood volume increased with height level up to ~30 %, after which accumulation of heartwood volume decreased. Sapwood volume rapidly increased with height level. Heartwood represented a substantial part of the trees, corresponding on average to 53.3 % of the total tree volume at breast height. For the pulping, the volume of heartwood is significant; corresponding to approximately one third of the stem volume in *E. globulus* at the harvesting age[8].

The heartwood followed closely the stem wood profile circularly in the cross-section (Fig 3). This was especially notorious in the bottom part of the trees, where form was irregular and the heartwood followed the external circumference of the buttresses, allowing for a rather constant sapwood width around the section. An enlargement of heartwood from base to some point in the lower part of the stem was not found, contrary to what has been reported for some species or trees, i.e. in maritime pine[23-24] or *Pinus sylvestris* L.[25].

Table 3—Variation of tree, wood and heartwood taper in *Eucalyptus tereticornis* Sm. along the stem height

Tree height (m)	Taper, total diam. (mm/m)	Taper, wood diam. (mm/m)	Taper, heartwood diam. (mm/m)
2-4	9.3	7.9	10.7
4-6	7.1	6.8	8.7
6-8	7.9	7.8	7.8
8-10	9.9	9.9	9.5
10-12	10.1	10.9	10.4
12-14	10.2	11.2	9.2

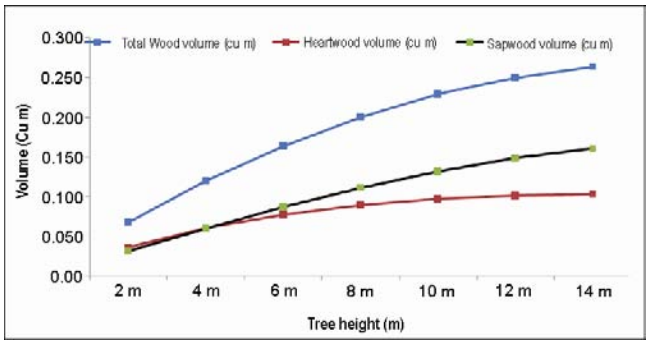

Fig. 3—Variation in total volume, heartwood and sapwood volumes in *Eucalyptus tereticornis* Sm. along the height

Influence of tree growth on heartwood and sapwood

The variation of heartwood diameter with radial diameter for all the trees is shown in Fig. 4(a). There is a positive correlation between these two variables, corresponding to the following linear model as used by Knapic *et al*[22], where $D_{heartwood}$ and D_{wood} are, respectively, the diameter of heartwood and the wood diameter:

$D_{Heartwood} = 0.756 \times D_{wood} - 2.891$ Where; ($R^2 = 0.799$, $P < 0.001$)

This model estimate that heartwood start to be formed for total wood diameter above 3.28 cm ($D_{heartwood} = 0$) and that over this diameter heartwood formation absorbs 75.6 % of the radial wood formation ($D_{heartwod}/D_{wood} = 0.756$). The heartwood diameter was positively correlated with the total diameter (Fig. 4a) and larger trees had larger heartwoods.

Estimation of heartwood diameter based on over bark stem diameter was also using the following linear regression; D_{total} is the stem over-bark diameter: $D_{Heartwood} = 0.742 \times D_{total} - 3.728$ where; (R^2 0.807, $P < 0.001$).

This model estimate that heartwood start to be formed for tree stem over-bark diameter above 5.02 cm ($D_{heartwood} = 0$) and that over this diameter heartwood formation absorbs 74.2 % of the radial wood formation ($D_{heartwod}/D_{wood} = 0.742$). The heartwood proportion in the stem cross section increased with the tree radial size as increased wood diameter as shown in Fig. 4(b). Lower R^2 values (coefficient of determination) showed randomness in observed data that indicates difference between observed values and model predicted values are larger and biased. Previous works with *E. globules* have reported a linear regression of heartwood height with total stem height[9].

The sapwood width was independent on the diameter of all trees and at different height levels

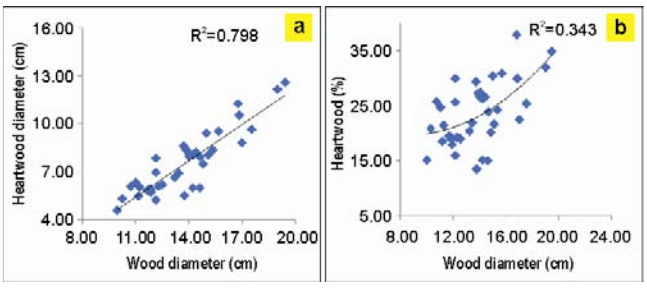

Fig. 4 (a)—Variation of heartwood diameter with total wood diameter; (b) Variation of heartwood proportion with the corresponding wood diameter in *Eucalyptus tereticornis* Sm.

where, heartwood was present (Fig. 5). Estimation of heartwood dimensions from external wood diameters (either over or under bark) was possible using a linear model. This is an aspect of practical importance since the inner heartwood core is the priority of the saw milling industry. The use of heartwood dimension models makes it possible to estimate its content within a log and therefore its potential value. Similar heartwood dimensional models have been reported for maritime pine in France, Spain and Portugal[21, 23, 24, 26], and for other pine species such as Scots pine[25] and *P. canariensis* Spreng.[27]. Similar to the current findings, a strong positive relationship between wood diameter and heartwood diameter was observed in an even aged population of *A. melanoxylon*[22], *E. globulus*[8, 28].

Frequency distribution of genotypes

Considerable variation has been recorded for tree diameter and heartwood diameter. Tree diameter varied from 11.50 to 20.91 cm, with maximum number of trees (n = 12) in the diameter class 14.52-16.02 cm (Fig. 6a). Heartwood diameter varied from 4.61-12.61 cm, with 36.84 % of the trees falling in the diameter class 4.61-6.11 cm (Fig. 6 b). Only

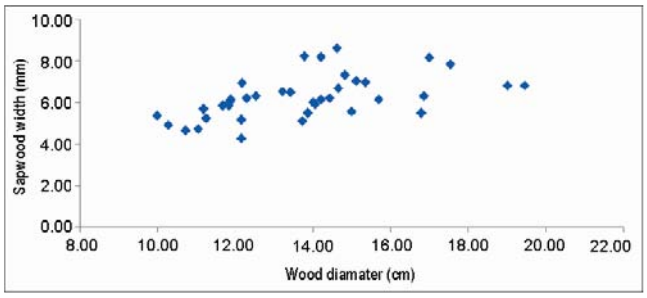

Fig. 5—Sapwood width and total wood diameter measured on all cross-sections along tree height where heartwood was present in *Eucalyptus tereticornis* Sm.

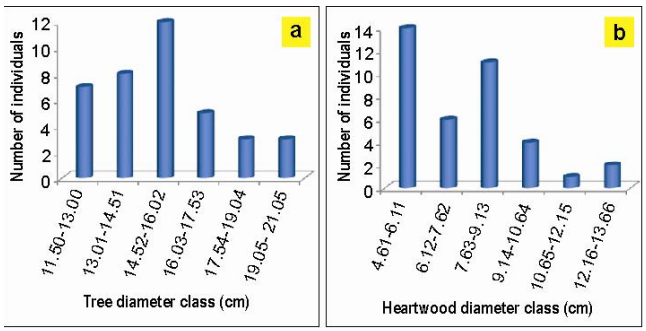

Fig. 6—(a). Frequency distribution of genotypes with tree diameter; b. Frequency distribution of genotypes with heartwood diameter in *Eucalyptus tereticornis* Sm.

10.52 % of the trees had heartwood diameter >10.00 cm. The results are in accordance with the results reported by Kumar *et al*[29].

Conclusion

The present study revealed that when the trees are harvested for the pole and solid wood products, genotypes 4, 142, 57, 90 and 128 could be selected because of high proportion of heartwood and when the tree is harvested for pulp, genotypes 7, 98, 129, control and 139 could be selected due to high proportion of sapwood. The heartwood content in the tree is positively related with tree size, genotypes and the factors that will result into a faster tree growth. Through the results it can be concluded that genotypes showed a wide range of variability in total wood, heartwood and sapwood content so that the genus provides ample scope for genetic improvement. The variation can be exploited for the selection of different wood traits variability. However, individuals need to be analyzed for different wood chemical properties before recommending their deployment in plantations programmes. The coppice from the stumps of best genotypes selected from the study will be used for cloning and further testing for multiplicative studies from multiple sites.

Acknowledgements

The authors would like to express their gratitude to Avtar Singh (Sr. Silviculturist-cum-Head), Department of Forestry and Natural Resources, Punjab Agricultural University, Ludhiana, Punjab for providing facilities and funds for the successful completion of the study.

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