WOOD DENSITY AND HEARTWOOD PROPORTION IN *EUCALYPTUS* TREES FROM INTENSIVELY-MANAGED SHORT-ROTATION PLANTATIONS IN KERALA, INDIA

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PILLAI PKC, PANDALAI RC, DHAMODARAN TK & SANKARAN KV. 2013. Wood density and heartwood proportion in *Eucalyptus* trees from intensively-managed short-rotation plantations in Kerala, India. We analysed the impact of nitrogen fertilisation and weed management on wood density and heartwood proportion in *Eucalyptus tereticornis* and *E. grandis* trees from 6.5-year-old experimental plantations in Kerala, India. Wood samples taken from 0.20 m, breast height, 50, 75 and 100% of the merchantable bole length of trees were used in the analysis. Addition of nitrogen significantly improved productivity in *E. tereticornis* (15–28 m^3 ha^{-1} $year^{-1}$) and *E. grandis* (44–72 m^3 ha^{-1} $year^{-1}$) plantations. Likewise, weed management had significant effect on productivity of *E. tereticornis* plantation (8–19 m^3 ha^{-1} $year^{-1}$). In terms of heartwood proportion in trees, treatment effect was significant only in *E. grandis* plantation added with nitrogen. However, axial variation was significantly different for wood density and heartwood proportion of trees in nitrogen input plots in *E. tereticornis* plantation. Significant axial variation was found only in proportion of heartwood in weed management plots. In *E. grandis*, axial variation was significant only in heartwood proportion in both experimental plots. Density varied from pith to periphery in both species.

Keywords: Nitrogen input, weed management, *Eucalyptus tereticornis, Eucalyptus grandis*

PILLAI PKC, PANDALAI RC, DHAMODARAN TK & SANKARAN KV. 2013. Ketumpatan kayu dan kandungan kayu teras dalam pokok *Eucalyptus* yang ditanam di ladang pusingan pendek yang diurus secara intensif di Kerala, India. Kami mengkaji kesan baja nitrogen dan pengurusan rumpai terhadap ketumpatan kayu serta kandungan kayu teras dalam pokok *Eucalyptus tereticornis* dan *E. grandis* yang berusia 6.5 tahun di ladang eksperimen di Kerala, India. Sampel kayu daripada kedudukan 0.20 m, diameter aras dada serta 50%, 75% and 100% batang boleh niaga diguna dalam analisis ini. Penambahan nitrogen meningkatkan dengan signifikan produktiviti ladang *E. tereticornis* (15–28 m^3 ha^{-1} $tahun^{-1}$) dan *E. grandis* (44–72 m^3 ha^{-1} $tahun^{-1}$). Pengurusan rumpai juga memberi kesan signifikan terhadap produktiviti ladang *E. tereticornis* (8–19 m^3 ha^{-1} $tahun^{-1}$). Dari segi kandungan kayu teras, rawatan hanya berkesan di ladang *E. grandis* yang ditambah nitrogen. Bagaimanapun, variasi aksial berbeza dengan signifikan dalam ketumpatan kayu dan kandungan kayu teras di plot *E. tereticornis* yang ditambah nitrogen. Variasi aksial yang signifikan hanya dicerap dalam kandungan teras kayu di ladang yang menjalani pengurusan rumpai. Bagi *E. grandis*, variasi aksial hanya signifikan dalam kandungan kayu teras di kedua-dua plot eksperimen. Ketumpatan berbeza dari empulur ke pingir kedua-dua spesies.

INTRODUCTION

The adaptability of *Eucalyptus* to diverse soil and climatic conditions has led to worldwide establishment of large-scale short rotation plantations. Many countries in the tropics and subtropics including India are now committed to developing *Eucalyptus* plantations to meet the ever increasing demand for raw material by the pulp and paper industry. In the State of Kerala, India, *Eucalyptus tereticornis* and *E. grandis* are the main species planted. *Eucalyptus tereticornis* is grown at low altitude (< 500 m asl) and *E. grandis*, at high altitude (500–2000 m asl) areas. However, these plantations are low in productivity (< 10 m^3 ha^{-1} $year^{-1}$) compared with *Eucalyptus* plantations in other countries (Jayaraman & Krishnankutty 1990). Poor productivity of plantations is generally ascribed to poor nutrient status of

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soil, use of low quality planting stock and lack of weed control (Sankaran et al. 2008). With silvicultural interventions, average productivity of *Eucalyptus* plantations in Brazil ranges from 20 to 60 m^3 ha^{-1} $year^{-1}$ (Gonçalves et al. 2004, Rockwood et al. 2008).

In 1998–2005, an investigation was conducted in Kerala to improve the productivity of *E. tereticornis* and *E. grandis* plantations through intensive silvicultural practices such as weed management and nutrient input. These management practices were aimed at accelerated growth of trees and higher productivity. However, the effect of high input management practices on the properties of pulpwood was not investigated. Wood density is probably the most widely used factor to characterise wood quality because it is correlated to many physical and technological properties.

Information on the heartwood development in *E. tereticornis* and *E. grandis* grown in intensively-managed plantations is rather sparse. The extractive content of heartwood, which usually increases steadily from pith to periphery of the heartwood, influences wood density. Accumulation of extractives that accompanies heartwood formation causes higher chemical consumption, lower pulp yield and brightness. The present study was aimed at evaluating effects of silvicultural interventions such as nitrogen fertilisation and weed management on productivity as well as selected physical properties, namely, wood density and heartwood proportion in *E. tereticornis* and *E. grandis*.

MATERIALS AND METHODS

One experimental plantation each of *E. tereticornis* and *E. grandis* was established in 1998 in Kerala to evaluate the impact of different silvicultural practices on productivity. Seeds of select provenances of *Eucalyptus* were procured from the Tree Seed Centre, CSIRO, Canberra, Australia. The *E. tereticornis* plantation was raised at Punnala in the Kollam District, a low land region along the foothills of Western Ghats and the *E. grandis* plantation at Surianelli in Idukki District, a highland region in the Western Ghats. Climate of both the study areas is tropical warm humid with the south-west monsoon from early June till September and the north-east monsoon from October till November. Mean annual temperature is 27 °C (range 20–42 °C) and relative humidity between 64% (February–March) and 93% (June–July). Characteristics of the study sites are given in Table 1.

The effect of nitrogen input on productivity of *E. tereticornis* and *E. grandis* was evaluated on single factor basis at each plantation. Different dosages of nitrogen applied in the field were determined based on a previous

Table 1 Site characteristics of the study area

Site feature	Study area	
	Punnala (*Eucaluptus tereticornis*)	Surianelli (*Eucalyptus grandis*)
Latitude (N)	9° 6'	10° 2'
Longitude (E)	76° 54'	77° 10'
Altitude (m asl)	150	1280
Mean annual rainfall (mm)	2000	3000
Soil texture	Sandy loam to clay loam	Medium clay to sandy loam
pH	5.1	4.8
Total C (mg g^{-1})	43.6	40.9
Total N (mg g^{-1})	2.89	2.49

study conducted by the Kerala Forest Research Institute (Balagopalan et al. 1998). The field trial was on a randomised block design with four replicates in each treatment. The plot size was 20 m × 20 m with trees planted in 2 m × 2 m spacing. Treatments of nitrogen (N) input (as urea) were zero N input (N_0), 18 kg N ha^{-1} (N_{18}), 60 kg N ha^{-1} (N_{60}), 187 kg N ha^{-1} (N_{187}) and 375 kg N ha^{-1} (N_{375}). Phosphorus (63 kg P ha^{-1}) as super phosphate was added to each N dosage. The treatments were continued in the first and second year of planting. In the fourth year half the dosage was applied.

In the weed management, periodic weeding treatment was carried out in four replicate plots by manually slashing the weeds to ground level on three occasions each year (March/April, July/August, November/December). Weeds were retained in another four replicate plots as no-weeding treatment. The N input and weed management plots received an initial dose of fertiliser (NPK) during the establishment stage (42.4 kg N ha^{-1}, 18.5 kg P ha^{-1} and 23 kg potassium (K) ha^{-1}, plus trace elements).

Productivity of the *Eucalyptus* was evaluated at the age of 6.5 years by measuring diameter at breast height (dbh) and height of trees. Stem volume (v) was calculated using the equation $v = \frac{1}{3}\pi r^2 h$, where r = radius at ground level (projected from dbh) and h = height of tree. Stand volume was calculated as the sum of stem volumes, expressed as per ha and productivity was calculated by dividing stand volume with plantation age.

Wood sampling

Productivity of nitrogen input plots was the highest in 187 kg N ha^{-1} treatment. Hence, physical properties of the wood were evaluated from trees sampled from this treatment and from the lowest level N input treatment (18 kg N ha^{-1}). Samples were also collected from plots with N_0 treatment for comparison. Healthy trees were selected at random from the above treatment plots and harvested at the age of 6.5 years. Similarly, sampling was carried out from each replicate plot from periodically weeded and non-weeded plots. In total, 20 trees each from the *E. tereticornis* (N_0: n = 4, N_{18}: n = 4, N_{187}: n = 4 representing nitrogen input and no-weeding treatments, periodic weeding treatment: n = 4 representing weed management) and *E. grandis* plantations were used for the analysis of wood properties. Growth characteristics of sampled tress are given in Table 2.

Two cross-sectional discs of 25-mm thickness were cut from five height levels, i.e. from tree base (20 cm above ground), dbh and 50, 75 and 100% of merchantable bole length of each harvested tree to study axial variation (base to top) in wood density

Table 2 Dendrometrical characteristics of sampled trees

Experiment	Treatment	Species			
		E. tereticornis		*E. grandis*	
		Height (m)	Dbh (cm)	Height (m)	Dbh (cm)
N input	N_0	15.99 a ± 2.03	10.8 a ± 0.7	19.13 a ± 2.10	12.0 a ± 1.3
	N_{18}	17.79 b ± 0.59	12.6 b ± 0.8	22.65 b ± 0.78	14.8 b ± 1.8
	N_{187}	19.94 c ± 1.79	14.7 c ± 1.2	24.13 c ± 2.09	18.0 c ± 1.3
Weed management	NoW	12.85 a ± 2.76	9.8 a ± 2.3	21.00 a ± 1.41	15.0 a ± 1.0
	CW	19.70 b ± 2.50	13.4 b ± 3.1	22.08 a ± 0.91	18.4 a ± 2.1

Values are means with standard deviations; N_0 = no fertiliser added, N_{18} = 18 kg N ha^{-1}, N_{187} = 187 kg N ha^{-1}; NoW = no weeding, CW = periodically weeding; values with same letter in a column for each experiment indicate non-significant differences and heartwood proportion. One disc at each height level was used for the estimation of heartwood proportion. The area of disc covered by heartwood was determined by colour difference after water impregnation with an image analysis system. To estimate the heartwood proportion, the area covered by heartwood and total area of the disc were calculated using the average of four radii of the disc and the heartwood taken at right angles to each other (Miranda et al. 2009).

Using the second disc, wedges were cut from pith outwards on both opposite radii to determine axial variation in wood density. Wood blocks (10 mm × 10 mm × 25 mm) representing inner (25% from the distance from pith), middle (50%) and outer (75%) radial positions from the diametrical segment of each disc was removed from pith outwards on both radii to determine radial variation (pith to periphery) in wood density. Basic density of wood was measured on oven-dry weight to green volume basis. Wood volume was measured by water displacement method (Olesen 1971). To determine axial variation of wood density, mean values were determined for each height level as the arithmetic mean of all measured radial positions. Mean values were subjected to Student's *t*-test.

RESULTS AND DISCUSSION

Site management and plantation productivity

Nitrogen input significantly ($p \leq 0.01$) improved productivity of *E. tereticornis* (15–28 m^3 ha^{-1} $year^{-1}$) and *E. grandis* (44–72 m^3 ha^{-1} $year^{-1}$) plantations (Table 3). Between the N treatments in *E. tereticornis,* highest productivity was obtained in the N_{187} treatment (91% increase over control), followed by N_{375} (79%), N_{18} (57%) and N_{60} (38%). Responses of N treatments for *E. grandis* plantation were in the order N_{187}, N_{60}, N_{375} and N_{18} with 67, 40, 29 and 28% increase in productivity over N_0 treatment. Improved productivity of *Eucalyptus* plantations in response to nitrogen treatment has been reported in other countries (Cromer et al. 2002, Gonçalves et al. 2004, Xu et al. 2004).

Periodic weeding enhanced the productivity of *E. tereticornis* plantation significantly ($p \leq 0.01$). The productivity in plots with weeding treatment doubled compared with plots without (Table 3). However, in the *E. grandis* plantation, effect of weed management was not significant as in *E. tereticornis. Eucalyptus grandis* developed a closed canopy early in the

Table 3 Productivity (m^3 ha^{-1} $year^{-1}$) of *Eucalyptus* plantations at the age of 6.5 years

Experiment	Treatment	Species	
		E. tereticornis	*E. grandis*
N input	N_0	14.50 a ± 2.11	44.18 a ± 10.96
	N_{18}	22.76 bc ± 4.45	56.70 b ± 13.75
	N_{60}	20.06 ab ± 3.02	61.67 bc ± 6.64
	N_{187}	27.67 bcd ± 5.09	71.71 c ± 1.34
	N_{375}	25.91 bcd ± 4.25	56.84 b ± 6.53
Weed management	NoW	8.41 a ± 4.99	37.90 a ± 9.18
	CW	18.75 b ± 2.84	43.64 a ± 6.44

Values are means with standard deviations; N_0 = no fertiliser added (control), N_{18} = 18 kg N ha^{-1}, N_{60} = 60 kg N ha^{-1}, N_{187} = 187 kg N ha^{-1}, N_{375} = 375 kg N ha^{-1}; NoW = no weeding, CW = periodically weeding; values with same letter in a column for each experiment indicate non-significant differences rotation (by 2 years) and shading effectively suppressed weed growth. In contrast, *E. tereticornis* developed a sparse crown cover, which allowed greater light penetration and promoted weed growth. Weeds compete with trees for site resources and adversely affect growth. Enhanced productivity of *Eucalyptus* plantations as a result of proper weed management has been reported in South Africa (Little et al. 2003). Result of the present study indicated that weed control alone can improve productivity of *E. tereticornis* significantly (Table 3).

Wood properties

Wood density

Wood density values of *E. tereticornis* in N_0, N_{18} and N_{187} treatments were in the range of 570–607, 597–624 and 574–611 kg m^{-3} respectively along the axial direction of the stem (Table 4a). The same parameters for *E. grandis* varied from 425–476, 434–468 and 430–501 kg m^{-3} respectively (Table 4b). Wood density was lowest at dbh. Wood density of *E. tereticornis* in the nitrogen input plots was significantly different ($p \leq 0.05$) along the axial direction. However, this trend was not observed in *E. grandis.* In the no-weeding and weeding treatments, wood density of *E. tereticornis* along the axial direction ranged from 554–603 and 620–645 kg m^{-3} respectively (Table 4a). In *E. grandis*, wood density values were 454–494 and 396–508 kg m^{-3} in the respective weeding treatments (Table 4b). Wood density did not show any significant axial variation in *E. tereticornis* as well as *E. grandis* in the weed management experiment. However, there was a slight decrease towards dbh and a smooth increase upwards with slight variations in both species. Similar results were recorded by Gominho et al. (2001) and Shashikala et al. (2009).

Several studies from India indicated decreased wood density in *E. tereticornis* with tree height (Sharma & Sharma 2003, Shukla et al. 2004). Radial variation of wood density was significant ($p \leq 0.01$) in both species and treatments in the present study. Significant radial variation of wood density was also found in *E. camaldulensis* (Veenin et al. 2005).

Nitrogen input and weed management did not alter wood density in both species compared with controls. This is in conformity with results obtained for *Eucalyptus* sp. elsewhere (DeBell et al. 2001, Little et al. 2003, Jaakkola et al. 2006). On the contrary, nutrient addition in Norway spruce plantations improved growth but decreased wood density (Cao et al. 2008).

Heartwood proportion

Within-tree variations of heartwood in different treatments are given in Tables 4a and b. Within the tree, heartwood proportion of *E. tereticornis* at each height level decreased from base to top in the N input as well as weed management plots (Table 4a). Similar trend in *E. globulus* and the hybrid urograndis were reported earlier from Portugal and Brazil (Gominho & Pereira 2000, Gominho et al. 2001, Morais & Pereira 2007). However, results from this study showed an increase in proportion of heartwood from base to dbh but a decline towards the top in *E. grandis* in both experiments (Table 4b). Similar to our findings, a study of *E. grandis* provenances in Kenya showed that heartwood proportion decreased with height and maximum heartwood was at dbh (Sidhu & Rishi 1997).

In the weed management treatment in *E. tereticornis*, heartwood proportion from top to base was between 24 and 51% in weeding treatment and 16 and 46% in no-weeding treatment (Table 4a). The heartwood proportion of *E. grandis* ranged from 22–54% and 19–57% in the respective treatments (Table 4b). Significant ($p \leq 0.01$) within-tree variation was found in heartwood proportion in both species in the two experiments. Effect of nitrogen input on heartwood proportion of *E. grandis* was significant ($p \leq 0.05$) and high dosage N input in *E. grandis* resulted in higher heartwood proportion due to increased radial growth. This indicated that growth rate influenced the heartwood formation. Similar results were reported in

Table 4a Mean wood density and heartwood proportion of *E. tereticornis*

Property	Experiment	Treatment	Base	Dbh	50%	75%	100%
Basic density (kg m^{-3})	N input	N_0	582.5 ab (46)	570.2 a (43.4)	596.3 cd (43.2)	607.0 cd (42.1)	592.6 bc (36.4)
		N_{18}	624.2 d (23.1)	597.0 a (18.3)	619.3 bc (49.5)	603.4 abc (25.1)	603.1 ab (30.8)
		N_{187}	609.1 bc (26.4)	573.7 a (15.3)	587.4 a (30)	610.8 bc (44.9)	605.8 b (12.7)
	Weed management	NoW	603.4 a (66.6)	562.2 a (84.4)	553.5 a (38.3)	579.6 a (74.7)	584.5 a (78.1)
		CW	637.8 a (55.4)	620.3 a (68.3)	645.1 a (60.3)	632.2 a (41.1)	623.9 a (52.1)
Heartwood proportion (%)	N input	N_0	49.8 c (10.9)	33.6 d (8.9)	25.8 c 99.2)	17.0 d (1.4)	9.4 a (1.4)
		N_{18}	59.4d (3.8)	44.0 c (12.1)	29.9 b (3.1)	20.7 a (7.2)	17.0 a (7.3)
		N_{187}	53.7 d (11.6)	47.3 d (13.1)	32.4 c (8.8)	23.9 b (7.6)	15.7 a (7.3)
	Weed management	NoW	46.1 d (5.7)	40.6 c (8.4)	34.5 b (7.2)	34.0 b (6.1)	16.4 a (3.9)
		CW	50.7 d (10.3)	42.0 c (7.8)	38.8 c (12)	31.7 b (9.8)	23.7 a (9.8)

Table 4b Mean wood density and heartwood proportion of *E. grandis*

Property	Experiment	Treatment	Base	Dbh	50%	75%	100%
Basic density (kg m^{-3})	N input	N_0	437.2 a (61.6)	425.0a (33.6)	448.0a (42.1)	475.6a (41.8)	465.4 a (72.9)
		N_{18}	454.0 a (44.2)	433.9a (33.1)	466.3a (41.9)	468.4a (49.1)	466.0 a (28.2)
		N_{187}	500.9 a (21.7)	445.4a (13.4)	463.1a (38.3)	450.0a (17.7)	429.7 a (45.9)
	Weed management	NoW	466.2 a (98)	453.8 a (30)	453.2 a (32)	487.8 a (54.9)	493.5 a (72.9)
		CW	508.4 a (47.5)	453.8 a (19.3)	396.4 a (111.6)	428.5 a (10.8)	457.8 a (18.4)
Heartwood proportion (%)	N input	N_0	40.8 a (8.2)	41.0 a (10.9)	35.1 a (6.8)	32.4 a (8.9)	16.6 a (9)
		N_{18}	51.8 b (4.4)	53.0 b(2.8)	38.9 ab (7.3)	43.6 b (5.3)	23.5 b (13.2)
		N_{187}	58.9 c (3.2)	60.1 c(2.2)	41.1 ab (3.1)	32.4 a (9.1)	20.0 ab(4.4)
	Weed management	NoW	46.8 cd (5.1)	54.0 d (3.7)	31.9 b (8.7)	41.5 c (8.5)	21.8 a (5.6)
		CW	55.4 c (5.1)	57.4 c (6.1)	35.1 b (6.3)	35.1 b (3.5)	19.2 a (5.5)

Values in parentheses are standard deviations; N_0 = no fertiliser added (control), N_{18} = 18 kg N ha^{-1}, N_{60} = 60 kg N ha^{-1}, N_{187} = 187 kg N ha^{-1}, N_{375} = 375 kg N ha^{-1}; NoW = no weeding, CW = periodically weeding; values with same letter in a column for each experiment indicate non-significant differences; base, dbh, 50%, 75% and 100% = positions of wood sampling from the trees

E. globulus in Portugal whereby wide spacing influenced heartwood proportion and enhanced tree growth (Miranda et al. 2009).

CONCLUSIONS

Results of the study showed that *E. tereticornis* and *E. grandis* exhibited within-tree variations in wood density and heartwood proportion irrespective of treatments. The increase in proportion of heartwood was significant only in *E. grandis* with N input. It is also clear that wood properties such as basic density and proportion of heartwood of *Eucalyptus* trees are not substantially affected by silvicultural practices. However, the treatments improved productivity of *Eucalyptus*.

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