Within-Tree and Tree-Age Variation of Selected Anatomical Properties of the Wood of Ugandan-Grown *Eucalyptus grandis*

O. E. Sseremba
P. Mugabi
A. Y. Banana

Abstract

The challenges of utilizing *Eucalyptus grandis* thinnings prompted a study into its anatomical properties with the aim of identifying its potential based on the within-tree axial and tree-age variation. Fiber length, fiber diameter, vessel length, vessel diameter, vessel average, ray height, and ray frequency at 3, 6, 9, and 12 years were studied. Axial sample portions at 25, 50, and 75 percent of tree height were collected from western Uganda and prepared for maceration, microtomy, and microscopy. Analysis of variance and Tukey's test were used to obtain axial and tree-age variation. Fiber length (819 to 1,077 µm) decreased axially in higher tree ages of 6, 9, and 12 years and increased with tree age. Fiber diameter (10 to 13.4 µm) varied inconsistently axially and decreased with tree age. Vessel length had no consistent axial pattern but decreased with tree age (338 to 548 µm). Vessel diameter showed higher values at 75 percent and increased with tree age (93 to 138 µm). Vessel average did not vary axially but decreased with tree age (8 to 11 vessels per mm^2). Ray height did not vary axially but increased with tree age (107 to 278 µm). Ray frequency decreased with tree age (8 to 10 rays per mm^2). *E. grandis* trees at the ages of 3, 6, 9, and 12 years have anatomical properties suitable for production of strong pulps although with a modest proportion of fines. Comparative research on cloned *E. grandis* varieties and their implied industrial potential would be appropriate to improve utilization of this fast-growing tree species.

Studies that improve the availability of knowledge on the anatomy of wood are important for sustainable management of forests and their utilization (Naji et al. 2011). The desired properties of wood material used in wood product production industries, such as the pulping industry, depend greatly on the anatomical properties of wood (Zbonak et al. 2007). The fast-growing economy of Uganda, estimated at 7.2 percent per annum (Uganda Bureau of Statistics 2014), has fostered a construction boom that has increased the demand for wood and its related products. In the struggle to satisfy the high demand for wood products, the wood supply fraction of the market has increased the preference for faster-growing tree species, such as *Eucalyptus grandis* W. Hill ex Maiden 1862, over traditional and indigenous tree species that have longer rotations. *E. grandis* is the most traded and one of the most grown multipurpose wood species in Uganda, dominating over 43 percent of the market share (World Wide Fund 2012). Given the good growth results of *E. grandis* in Uganda (Saw Log Production Grant Scheme [SPGS] 2010), it is important to study its properties, specifically the anatomical properties at the different ages of tree growth, in order to support its sustainable production and efficient utilization. Most important to note is that the utilization of *E. grandis* in Uganda is limited to timber, poles, and fuelwood, yet there could be potential to venture into other products, such as wood pulp, if more knowledge about the characterization of its wood quality is made available. This dilemma has skewed the wood products market in Uganda toward a huge demand for trees between the ages of 2 and 14 years, mainly as poles and timber, although knowledge on their general wood quality and specific anatomical

The authors are, respectively, Lecturer, Senior Lecturer, and Professor Dept. of Forestry, Biodiversity and Tourism, College of Agric. and Environ. Sci., Makerere Univ., Kampala, Uganda (sserembaowen@gmail.com [corresponding author], pkmugabi@gmail.com, abwoli.banana@gmail.com). This paper was received for publication in October 2015. Article no. 14-00070.

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properties is limited. Moreover, the thinnings from *E. grandis* plantations are not optimally utilized because their value added is limited; therefore, tree farmers do not get optimal value for the wood thinnings (SPGS 2010), probably owing to limited knowledge of the quality of wood of the thinnings at the specific thinning ages. In-depth research to provide more knowledge on the specific anatomical properties at such juvenile wood tree ages of *E. grandis* could be a basis for improved, optimal, and diversified utilization of the tree species. Given that Uganda does not have any wood pulp industries, obtaining such knowledge on the wood quality of trees at the ages of 3 to 12 years would support the development of the wood pulp industry so as to diversify the utilization of *E. grandis* thinnings.

E. grandis is a hardwood tree species with a diverse range of anatomical features that can be characterized as vessel frequency, solitary vessel percentage, vessel diameter, vessel member length, fiber length and diameter, libriform fiber length, ray frequency, and ray height (Chang-ming and Xin-ying 1994). This study specifically characterized the fiber length and diameter, vessel length and diameter, ray height, vessel average, and ray frequency. For clarity in this article, we use the term ''vessel length'' to mean the length of a single vessel element. In order to guide rotation-specific utilization, the variation of these anatomical features with tree age was studied as well at the ages of 3, 6, 9, and 12 years. This choice of tree ages was based on the real demand for trees between the ages of 2 and 14 years and the inefficient and suboptimal utilization of trees in that age range and because this is the only stock available to satisfy the high demand for wood in Uganda (SPGS 2010).

Malan (1990) emphasized the existence and importance of the variations of the anatomical properties of *E. grandis* within species and site of growth and with age of the tree. The fact that different species show different relationships between anatomical features at different tree ages justifies the importance of knowing the specific anatomical features at a specified tree age in order to guide utilization (Zhu et al. 2008). In some species of the *Eucalyptus*, there exists known relationships. For example, Pisuttipiched (2004) noted that there was a direct relationship between fiber dimensions and tree age of *E. camaldulensis* up to a particular age limit beyond which there are no changes. Several other authors have researched and observed radial patterns of variation in more genera and clones of eucalyptus. These include Ramírez et al. (2008) on *E. globulus* and Quilhó et al. (2000) on clones of *E. grandis* × *E. urophylla*. Much as Malan (1990) described the variation of the anatomy of *E. grandis* grown in South Africa, his emphasis detailed the correlation and prediction among anatomical features, especially in the radial positions. There are limited studies and hence limited literature on the axial variation of anatomical properties of *E. grandis* both within a tree and among trees of different ages. It is thus important to identify and document the anatomical features and biometry at the different ages of growth and their within-tree axial variations of the wood of *E. grandis*.

Studying the anatomy of *E. grandis* grown in Uganda is important because there are several afforestation programs in the country that have suffered challenges related to utilization, probably because some of its properties are not well documented. Specifically, the anatomical properties of *E. grandis* and their variations with age are not known. Further, the implications of the specific anatomical properties at the specific ages of tree growth are not documented to aid efficient utilization of Ugandan-grown *E. grandis*. For example, knowing the fiber length of a tree at a certain age will guide the design of processing technology, such as saw kerf size, that efficiently processes the wood with those specific properties and nature of fibers at that tree age. On the other hand, the availability of information on a property such as fiber length could support the establishment of wood pulp industries, especially if the study finds it desirable for pulp and paper production. In practice, the available thinnings are not effectively and efficiently utilized owing to the similar challenges of unknown properties that would aid their utilization, as noted by Harrison and Windhorst (2010). Studies that provide information on the properties of wood at different tree ages will guide the choice of processing technology and the avenue of utilization and provide a basis for structural designs, as suggested by Zziwa et al. (2009).

As part solution to the utilization challenges of *E. grandis* wood in Uganda, a study was conducted with the general objective of identifying the anatomical properties of *E. grandis* grown in Uganda and their within-tree axial and tree-age variations. Specifically, the study was conducted to (1) assess the within-tree axial variations of fiber length, fiber diameter, vessel length, vessel diameter, vessel frequency, ray height, and ray frequency at ages 3, 6, 9, and 12 years; (2) assess the variation of the selected properties of *E. grandis* at ages of 3, 6, 9, and 12 years; and (3) identify the potential uses of *E. grandis* at ages 3, 6, 9, and 12 years based on the anatomical properties obtained. Obtaining such knowledge of the anatomical properties of *E. grandis,* such as the fiber length of trees at different ages for Ugandan-grown trees, could be used to accurately estimate the optimal harvesting age for specific products, in turn supporting the appropriate choice of processing technology. In addition, such information could further aid the establishment of wood processing factories that target wood at the different times of the thinning regimes rather than waiting on the perceived maturity of the trees.

Methodology

Study area

The study was carried out on *E. grandis* plantations in Kabarole district in western Uganda. The region is known not only for excellent yield of *E. grandis* but also for the availability of stands at different tree ages that were a prerequisite for this study. Such prevalence of stands with trees at the different ages of growth was the basis for the choice of the study area. Kabarole district lies on the slopes and ranges of Mountain Rwenzori, bordered by the districts of Kasese in the south, Kamwenge in the southeast, Kyenjojo in the east, and Bundibugyo in the north and west. Kabarole lies between 00°15″N and 10°00″N and between 300°00″E and 310°15″E. It lies at an altitude of 1,300 to 1,800 m above sea level. The climatic conditions of the area are generally wet with temperatures ranging from 20°C to 30°C and a bimodal rainfall pattern ranging from 1,200 to 1,500 mm per annum. Geologically, the area has black loams (volcanic), while a few places have red sandy clay loams occasionally aligned by soft laterites (Rucker 2005).

Sampling

A locality with all the desired tree age stands was identified at Kaswa village in Busoro subcounty, Kabarole district of western Uganda. Three trees of good bole were identified from each tree-age stand in a localized site of the plantation. The heights and diameters at 1.3 m were taken and recorded for further processing and specimen preparation. Three circular discs 15 cm in height were obtained from each tree at the 25, 50, and 75 percent levels of tree height for specimen preparation.

Specimen preparation

Each disc was quarter sawn to obtain a scantling with a cross-section surface 0.04 m long and 0.02 m wide from each quarter. This gave a total of four scantlings from each disc that were further cut into 0.02-m^2 cubes and prepared for maceration and microtomy.

Maceration and microtomy

Macerated samples were obtained by further sectioning to obtain smaller samples of approximately 0.004 by 0.004 by 0.01 m manually using a hacksaw from the 0.02-m^2 scantling for maceration. These were immersed in a solution that contained 10 percent 0.3 M hydrogen peroxide, 50 percent glacial acetic acid, and 40 percent water. The suspended wood material was left for 3 days with constant monitoring, shaken, and stirred to acquire a milky suspension with visible tissue strings. The solutions were rinsed with distilled water and placed on slides for microscopy.

Staining was done using a solution of Sudan IV and propylene to increase color contrast for better identification during microscopy. Microtomy samples were prepared by boiling the 0.02-m^2 cubes in glycerin for 3 hours to soften and were sectioned in the radial, tangential, and axial dimensions using a sliding microtome. The sections were mounted and stained with Safranin to enhance microscopy assessment.

Microscopy and data recording

Using a BA 212 biological light microscope, calibration was done using the standard eyepiece calibrator to obtain a view-field dimension of 0.12 m^2 that was used to measure the features observed from the slides of the macerated samples. Using slides with macerated material, length and diameter dimensions of 10 randomly viewed vessels and fibers were taken at a magnification of ×10. The diameters of fibers and vessels were measured at the midportion of their length. Each measurement was repeated three times and averaged to improve the accuracy of the record. Using slides with wood sections, ray height was measured at a magnification of ×10. All vessels and rays viewed in each section were counted and expressed as a ratio of the view-field calibration of 0.12 m^2 to obtain vessel frequency and ray frequency per unit area.

Data analysis

The measurements from the maceration observations were recorded and analyzed using STATA version 12 and MINITAB version 14 computer software packages to obtain mean estimates of fiber length, fiber diameter, vessel length, vessel diameter, vessel frequency, ray height, and ray frequency within and among trees at the ages of 3, 6, 9, and 12 years. Analysis of variance was done, and the critical difference among each of the means was obtained using Tukey's test to separate the means at the different tree ages and within the tree height levels. Analysis and iterative comparison of data from previous authors was done to obtain the potential uses of the wood of *E. grandis* at the different tree ages based on the properties obtained.

Results

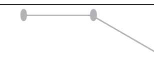
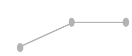
Within-tree variation of anatomical properties of *E. grandis*

Fiber length and diameter.—Within-tree fiber length of *E. grandis* varies from 819 to 1,077 μm and generally decreases from 25 to 75 percent of tree height level (Table 1). This pattern is significant among the older trees at 6, 9, and 12 years. However, this pattern is not significant among the 3-year-old trees. Generally, longer fibers are identified at 25 percent of tree height than at 75 percent of tree height. Fiber diameter did not show any consistent observable patterns, especially in the 9-year-old trees (Fig. 1). Nevertheless, there were more observations of a pattern in the 6- and 12-year-old trees, showing a higher fiber diameter at the 25 percent portion, the lowest at the 50 percent portion, and then higher at the 75 percent portion.

Vessel length, diameter, and average.—The axial variation of the vessel length of *E. grandis* did not show a consistent pattern, with values ranging from 374 to 548 μm (Table 1). However, the absolute values of the vessel length portray lower values at the 25 percent portion, highest values at the 50 percent tree level, and lower values at 75 percent of tree height. Uniquely, the vessel length of the 9-year-old trees did not show statistical significance depicting uniform lengths of vessels at all the tree height levels. On the other hand, the 3-year-old trees portrayed the most vivid and clear variation among the three height levels compared with the other age groups. The diameter of vessels did not show a conspicuous pattern, but there is a general observation that the 75 percent portion of the tree had vessels with larger diameter estimates within 93 to 138 μm (Table 1). Consequently, for nearly all tree ages, the vessel diameter at 50 percent tree level is not significantly different from that at 75 percent of the tree height, leaving the 25 percent portion of the trees with more significantly different estimates of vessel diameter. However, this does not apply to the 9-year-old trees, which did not show any variation in vessel diameter. The within-tree axial variation in vessel average was not significant for all tree ages. The absolute number of vessels per unit area was higher at 75 percent of the tree height than that at 25 percent of the tree height, within the range of 11 to 18 vessels per mm^2 (Table 1).

Ray height and frequency.—Ray height was generally inconsistent in all age groups, with estimates in the range of 107 to 278 μm (Table 1). However, the 3- and 12-year-old trees showed distinct and clear variation within the tree levels compared with those in the 6- and 9-year-old trees. Moreover, the 9-year-old trees did not show any variation of ray height from 25 to 75 percent of tree height. Considering that three of the four age groups showed absolute figures that depict an increase in ray height at 75 percent of the tree, a generalized weak pattern can be deduced that ray height increases from 25 to 75 percent of tree height. The number of rays per square millimeter was also similar without any

Table 1.—Within-tree anatomical property estimates and pattern impressions.[a]

Property	Age (yr)	Mean values at tree height levels (n = 300): 25%	50%	75%	Within-row 1-way ANOVA: Signifi-cance	P	F at α = 0.05	Three-point pattern axial var. summary (25%–50%–75%)
Fiber length (µm)	3	819.6 ± 166.69[s]	835.7 ± 155.04[s]	685.0 ± 115.97[d]	S	0.000	94.42	
	6	1,000.0 ± 116.8[d]	928.8 ± 113.37[s]	936.8 ± 136.51[s]	S	0.000	30.33	
	9	1,013.6 ± 112.9[d]	937.6 ± 105.3[d]	868.4 ± 152.1[d]	S	0.000	101.06	
	12	1,077.2 ± 79.4[d]	972.0 ± 108.9[d]	862.4 ± 109.6[d]	S	0.000	344.19	
Fiber diameter (µm)	3	11.2 ± 3.255[s]	13.4 ± 3.928[d]	11.2 ± 3.255[s]	S	0.000	40.86	
	6	11.0 ± 2.003[d]	10.0 ± 0.000[d]	11.6 ± 2.336[d]	S	0.000	62.08	
	9	11.2 ± 2.139[s]	11.2 ± 3.255[s]	11.6 ± 2.336[s]	NS	0.098	2.33	
	12	11.8 ± 2.404[d]	10.6 ± 1.628[d]	12.4 ± 2.502[d]	S	0.000	51.47	
Vessel length (µm)	3	373.6 ± 114.2[d]	450.0 ± 125.2[d]	338.0 ± 112.5[d]	S	0.000	71.24	
	6	500.80 ± 84.18[s]	508.0 ± 85.79[s]	438.8 ± 95.92[d]	S	0.000	55.08	
	9	534.4 ± 132.8[s]	548.0 ± 109.3[s]	529.2 ± 87.7[s]	NS	0.103	2.28	
	12	417.2 ± 107.8[d]	471.2 ± 124.9[s]	455.6 ± 116.5[s]	S	0.000	17.04	
Vessel diameter (µm)	3	93.50 ± 32.48[d]	99.53 ± 24.39[s]	97.77 ± 21.93[s]	S	0.018	4.06	
	6	106.07 ± 16.86[s]	113.93 ± 18.5[d]	109.10 ± 16.55[s]	S	0.000	15.74	
	9	107.03 ± 20.06[s]	109.33 ± 15.04[s]	107.07 ± 18.12[s]	NS	0.196	1.63	
	12	123.50 ± 30.99[d]	135.93 ± 35.65[s]	137.57 ± 36.44[s]	S	0.000	14.96	
Ray height (µm)	3	253.70 ± 67.1[d]	206.60 ± 47.96[d]	268.20 ± 76.59[d]	S	0.000	73.68	
	6	218.60 ± 67.81[d]	243.72 ± 46.06[s]	238.77 ± 65.79[s]	S	0.000	14.42	
	9	107.03 ± 20.06[s]	109.33 ± 15.04[s]	107.07 ± 18.12[s]	NS	0.196	1.63	
	12	278.40 ± 54.03[d]	242.40 ± 48.66[d]	208.10 ± 53.22[d]	S	0.000	136.97	
Vessel average (per mm^2)	3	16.032 ± 2.681[s]	15.617 ± 2.948[s]	18.167 ± 3.676[s]	NS	0.117	2.29	
	6	12.378 ± 2.261[s]	11.640 ± 2.306[s]	13.180 ± 2.932[s]	NS	0.338	1.12	
	9	12.833 ± 1.329[s]	11.801 ± 0.889[s]	12.487 ± 2.345[s]	NS	0.305	1.23	
	12	11.365 ± 1.471[s]	11.270 ± 0.969[s]	11.980 ± 1.707[s]	NS	0.421	0.89	
Ray frequency (per mm^2)	3	10.133 ± 1.593[s]	9.775 ± 0.802[s]	9.567 ± 0.722[s]	NS	0.458	0.8	
	6	10.200 ± 1.7[s]	9.750 ± 0.649[s]	10.042 ± 0.997[s]	NS	0.650	0.44	
	9	8.925 ± 1.086[s]	9.283 ± 1.11[s]	9.758 ± 1.18[s]	NS	0.207	1.65	
	12	8.942 ± 1.12[s]	9.450 ± 1.03 [s]	9.275 ± 1.15[s]	NS	0.656	0.43	

[a] The letters "d" (different) and "s" (same) indicate Tukey's mean separation statistic after 1-way analysis of variance (ANOVA) within a row. S = significant; NS = not significant.

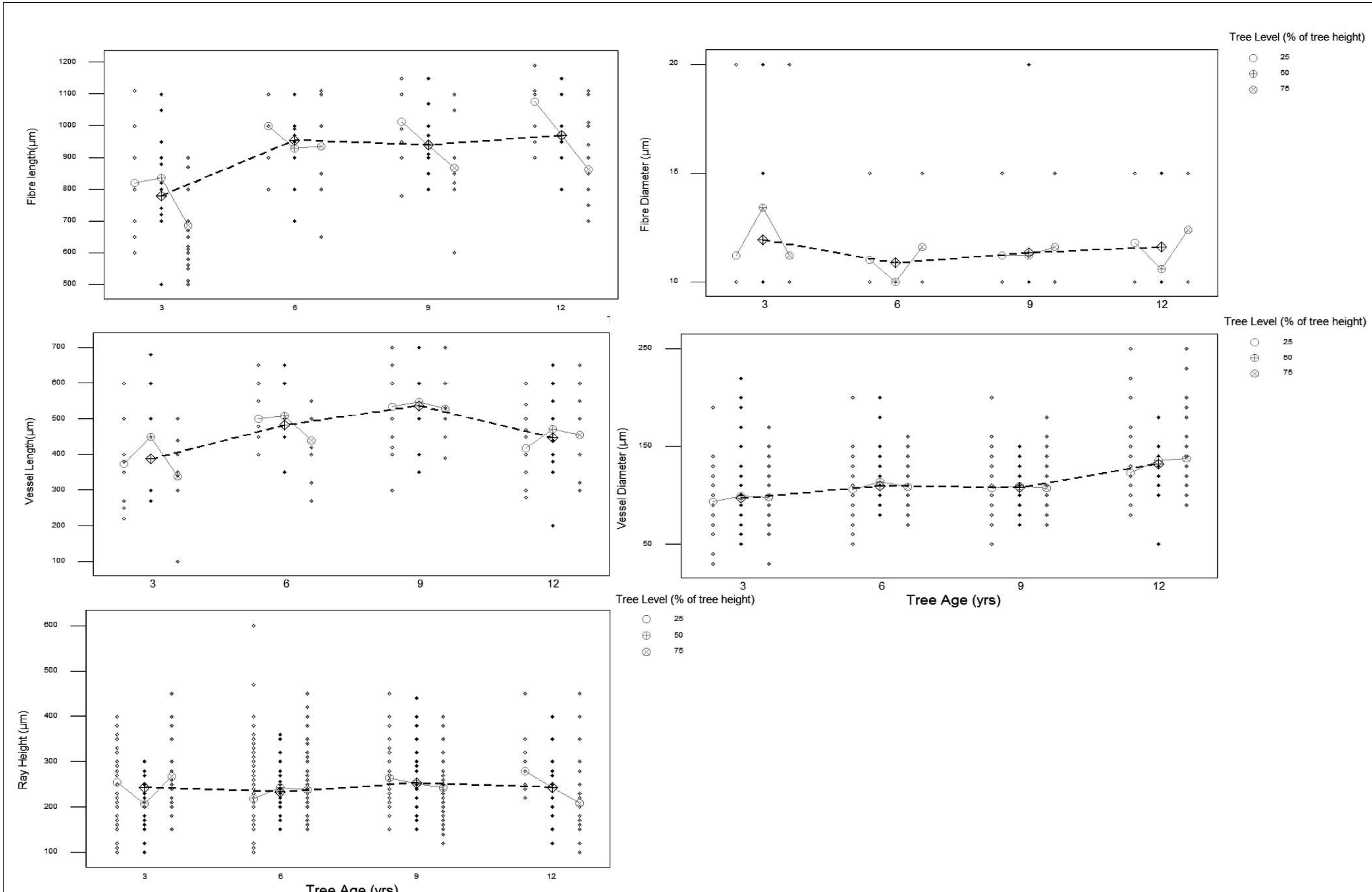


Figure 1.—Within-tree variation of E. grandis *anatomical properties. Dashed lines show the general trend of property variation with age.*

significant difference in all the tree height levels of all the age groups, with a range of 8 to 10 rays per mm^2 (Table 1).

Variation of anatomical properties of *E. grandis* with tree age

Fiber length and diameter.—The fiber length of *E. grandis* varies significantly with a progressive increase with tree age. However, Tukey's separation of means indicates that the 9- and 12-year-old fiber lengths are similar (Table 2). The fiber diameter follows a similar pattern, where there is a significant difference in the wood of trees at 3 and 6 years, while those of 9 and 12 years are not significantly different, with a general increase from 3 to 12 years (Fig. 2). Most important to note is the huge range of the absolute values for the fiber diameter of the 12-year-old trees compared with the other tree ages, which showed hardly any observed dispersion (Fig. 2).

Vessel length, diameter, and average.—The vessel length of *E. grandis* varies significantly among all tree ages. There is also a notable drop in vessel length after 9 years. Nevertheless, there is a general rise in vessel length with tree age. Vessel diameter is observed to have a sharp rise from the 3-year-old trees to the 6-year-old trees. The 6-year-old tree stand was observed to have the highest vessel diameter with a gentle drop toward the 9- and 12-year-old trees. There is a significant reduction in the number of vessels with increasing tree age (Table 2), with the highest estimate of 16 vessels per mm^2 at 3 years to the lowest of 11 vessels per mm^2 at 12 years.

Ray height and frequency.—The height of the rays increased significantly with tree age in an estimated range of 242 to 970 μm. Notable, too, is the sharp significant rise of ray heights from the 3-year-old trees to the 6-year-old trees (Fig. 2). The frequency of rays takes on a gradual reducing trend with nonsignificant estimates ranging from 9 to 10 rays per mm^2.

Potential uses of Ugandan-grown *E. grandis* based on their anatomical properties

A comparison of the Ugandan-grown anatomical wood properties with values of industrial fiber estimates from other studies in the industry was done so as to describe the potential of Ugandan-grown *E. grandis* wood (Table 3). Following the remarks and comments (Table 3) on each comparison of anatomical properties of this study with the desired industrial estimates, it was observed that *E. grandis* grown in Uganda has generally good-quality wood at the four tree ages.

Discussion

Within-tree variation of anatomical properties of *E. grandis*

Fiber length and diameter.—For all the tree ages studied, the fiber length of *E. grandis* is higher at 25 percent of tree height and lower at 75 percent. This trend of variation in fiber length is in agreement with the findings of Quilhó et al. (2006). This variation was more significant in the 9- and 12-year-old trees. The fiber length of the 3-year-old trees shows similarity at 25 and 50 percent of tree height, and it decreases at 75 percent of tree height. Considering that the estimates of fiber length in all axial positions of all the trees at all the ages are above the critical length of 250 μm, as noted by Pirralho et al. (2014), they are all desirable for pulping and papermaking.

Although there is no dominant and conspicuous pattern in axial variation of fiber diameter, there is a general increase from 25 to 75 percent of the tree, an observation that is in agreement with the earlier study of Malan (1991). The diameter of fibers of *E. grandis* varies more from 25 to 75 percent of the tree in the 6- and 12-year-old stands. This increment could be explained by the increase in proportion of juvenile wood in the sections that are above 75 percent of tree height, which often have larger lumens that in effect provide wider diameters of the fibers. The trend of increasing fiber diameter is in agreement with the findings of Taylor (1973) and Bhat et al. (1990). Subsequently, this could probably imply that the wood in the crown parts of *E. grandis* will undergo more machining and seasoning defects, such as wash-boarding, warping, and collapse.

Vessel length, diameter, and average.—The most common pattern of variation of vessel length is the increase from the 25 percent portion of the tree to the 50 percent portion and a slight fall toward the 75 percent portion. Greater vessel length at the upper parts of the tree is in line with the findings of Ohshima et al. (2005). This might imply that there would be more porosity and have implications on dimension stability during processing. The increased porosity could be a result of more surface area provided by the greater lengths and thus the presence of more pits. The diameter of vessels does not show a consistent pattern from 25 to 75 percent of tree height, similar to the findings of Rao et al. (2002) on studies of *E. tereticornis*. For all age-groups, the average number of vessels per unit area did not vary from 25 to 75 percent of tree height. This non-significance was also observed by Naji et al. (2011), although it was in contrast to earlier observations of Leitch (2001). This consistency for vessel average within the tree

Table 2.—Estimates of biometry variation with tree age.[a]

Property	n	Mean estimates ± SD at each tree age				Row statistic (α = 0.05)
		3 yr	6 yr	9 yr	12 yr	
Fiber length	360	780.10 ± 162.11*	955.20 ± 126.60*	969.87 ± 138.36^{NS}	970.53 ± 133.16^{NS}	$P = 0.000, F = 355.62$
Fiber diameter	360	11.944 ± 3.645*	10.867 ± 1.894*	11.333 ± 2.626^{NS}	11.600 ± 2.334^{NS}	$P = 0.000, F = 25.47$
Vessel length	360	387.20 ± 126.27*	482.53 ± 93.98*	537.20 ± 111.63*	448.00 ± 118.68*	$P = 0.000, F = 277.21$
Vessel diameter	360	96.933 ± 26.743*	482.53 ± 93.98*	107.81 ± 17.87*	132.33 ± 34.98*	$P = 0.000, F = 309.77$
Ray height	360	242.83 ± 70.04*	955.20 ± 126.60*	939.87 ± 138.36*	970.53 ± 133.16*	$P = 0.000, F = 14.77$
Vessel average	143	16.605 ± 3.243*	12.399 ± 2.527*	12.373 ± 1.650*	11.538 ± 1.412*	$P = 0.000, F = 34.8$
Ray frequency	143	9.825 ± 1.104*	9.997 ± 1.178^{NS}	9.322 ± 1.147^{NS}	9.222 ± 1.347^{NS}	$P = 0.016, F = 3.58$

[a] * = significantly different; NS = not significantly different (within-row Tukey mean separator indicator).

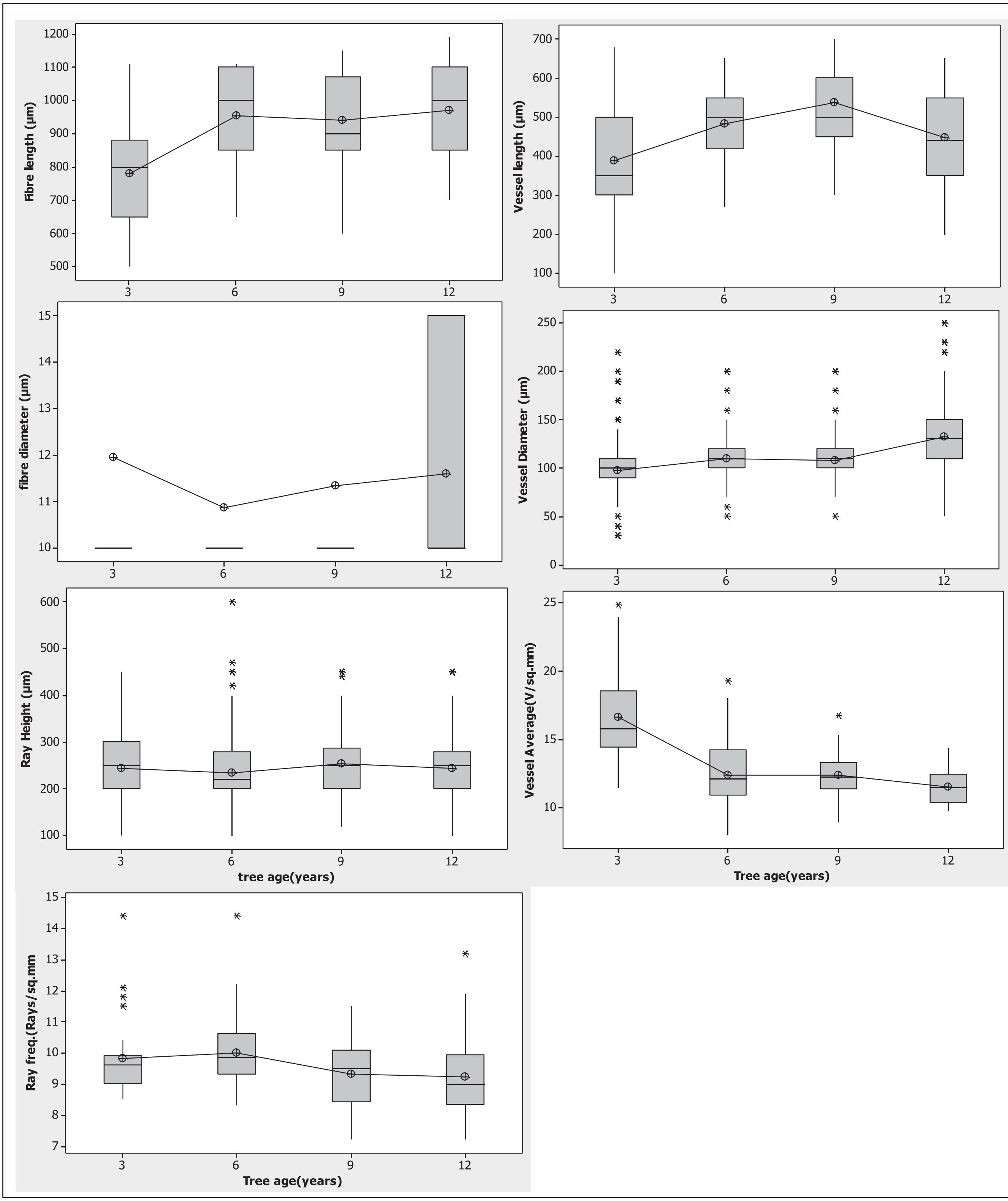


Figure 2.—Variation of E. grandis *anatomical properties with tree age. Confidence intervals, whiskers, and outliers (asterisks) are shown.*

suggests that *E. grandis* has an even distribution of vessels from the bottom to the top of the tree. Generally, the within-tree axial variations of vessel length, diameter, and average number of vessels per unit area of *E. grandis* suggest that the wood at 75 percent of tree height is more porous owing to the larger sizes of the vessels and their frequency and hence having implications on pressure treatment, dimension stability, and seasoning defects, such as splitting. Such a

Table 3.—Potential uses of Ugandan-grown E. grandis *at 3, 6, 9, and 12 years based on their anatomical properties.*

Property	Age (yr)	Estimate by this study	Estimated range by this study	Industrial estimate and source	Remarks and comments
Fiber length (μm)	3	780.10	780–939	700–1,300 (Pirralho et al. 2014)	Generally higher than 250 μm, and therefore fit for pulp production pulp. Increased folding endurance for pulp and tearing strength at 6, 9, and 12 yr. All tree ages are suitable for good strength pulp production.
	6	955.20		600–1,100 (Foelkel 2009)	
	9	970.53			
	12	939.87			
Fiber diameter (μm)	3	11.600	11–12	16–17 (Pirralho et al. 2014)	Low external midfiber diameter. Lower taper and increased pulp mat formation. Fit for pulp production pulp.
	6	11.333			
	9	10.867			
	12	11.944			
Vessel length (μm)	3	387.20	386–537	218–273	Generally higher vessel length and therefore lower-quality pulp yield because longer and larger vessels yield high volumes of fines in the pulp, which lowers the grade.
	6	482.53			
	9	448.00			
	12	537.20			
Vessel diameter (μm)	3	96.933	97–132	72–80	Generally higher vessel length and therefore lower-quality pulp yield because longer and larger vessels yield high volumes of fines in the pulp, which lowers the grade.
	6	109.70			
	9	132.33			
	12	107.81			
Ray height (μm)	3	242.83	234–353	148–143	Very low ray proportions imply reduced fibers and better pulping yields.
	6	233.70			
	9	242.97			
	12	252.89			
Vessel average (per mm^2)	3	16.605	11–17	11–18	Lower number of vessels per unit area supports lower nonstructural fiber content and higher pulp yield. Trees older than 6 yr are more desired.
	6	12.399			
	9	12.373			
	12	11.538			
Ray frequency (per mm^2)	3	9.825	9–10	9–11	The lower figure for ray frequency contributes to a lower volume of parenchyma and better pulp yield.
	6	9.997			
	9	9.322			
	12	9.222			

condition calls for the provision of the deserved care and choice of processing technology.

Ray height and frequency.—The ray height of *E. grandis* is observed to have no significant variation and no consistent pattern along the height of the tree. This limited variation in axial ray height was also observed by Gryc et al. (2008) in a study of similar hardwood species. In addition, the variation in the frequency of rays at all levels of tree height was not significant. The limited variation of ray biometry was also observed by Quilhó et al. (2000). Such uniformity of ray properties in Ugandan-grown *E. grandis* would imply that the utilization properties of the wood that are based on characteristics of rays, such as shear strength, cleavage resistance strength, and the volume of pulp-content fines, are likely to be consistent within and among trees of different ages.

Variation of anatomical properties with age

Fiber length and diameter.—The fiber length of *E. grandis* increases with tree age significantly for the 3- and 6-year-old tree stands. However, both the 9- and the 12-year-old stands have similar fiber length. The general increase in fiber length with tree age of *E. grandis* is in agreement with the earlier findings of Bhat et al. (1987). The range of 780 to 970 μm obtained for fiber lengths across all ages suggests that the fibers of all tree ages are reliable and conducive for pulp production. Moreover, the increment of fiber length with tree age is an indication of increased pulp properties, namely, pulp burst strength, folding endurance, tearing strength, and tensile strength (Pirralho et al. 2014). Much as Foelkel (2009) gives optimal fiber length for pulp production to be at the age of 7 to 10 years, Ugandan-grown *E. grandis* obtains the required fiber length at 3 years and hence is conducive for pulp production. Subsequently, the fiber length of *E. grandis* at 3 years is desirable for paper production because it falls within the desired range as reported by other authors (Oluwafemi and Sotannde 2007). This is characteristic of fast-growing tropical trees, with the very high mean annual increment benefiting from the relatively high annual rainfall estimates that probably support the rapid development of long fibers. The fiber diameter of the 12-year-old trees has a range that conspicuously differs from the other tree ages. This could probably be attributed to the uniformity of the fibers at a particular tree age that was observed during the experimentation process.

Fiber diameter generally decreased with tree age and is observed to have statistically similar values for trees that are 9 and 12 years of age. Decreasing fiber diameter with tree age was also observed by Rao et al. (2002) in other *Eucalyptus* species. The higher values of fiber diameter at younger tree ages are a reflection of juvenile tree cells that are characterized by larger cell vacuoles that demonstrate higher fiber diameters. On the other hand, following the increasing fiber length with tree age, from laboratory observation, the longer fibers tended to be visually slimmer, hence the smaller diameter with greater tree ages. Moreover, the phenomenon of the Poisson ratio could explain this occurrence; that is, when geometrical bodies are elongated in the longitudinal dimension, they tend to be constrained in the radial planes, resulting in the reduction of fiber diameter with increasing fiber length and tree age. In effect, when the cells elongate, they often get smaller in diameter in the process of formation.

Vessel length, diameter, and average.—The vessel length and diameter of *E. grandis* increased with tree age from 3 to 6 to 9 years and then decreased in the 12-year-old trees, and these variations are statistically significant. This occurrence is similar to the findings of Kurjatko et al. (2006) for related hardwood tree species. The increase in vessel length could be attributed to the increased physiological demands of larger-crowned trees at the older tree ages, as highlighted by Mencuccini et al. (2005). The increase in vessel length with tree age could imply increased permeability as a parameter for pressure impregnation. However, the argument of Foelkel (2009) puts *E. grandis* at a disadvantage in pulping because it has higher values for vessel length, vessel diameter, and frequency that cause the presence of the undesirable fines. The vessel average of *E. grandis* generally decreased with tree age. This is probably attributed to a reduction in growth rates that is expected as the tree grows older. Following the anatomical discourse that relates wood permeability to impregnation as being determined by vessel frequency, there is a possibility that the wood of *E. grandis* at the age of 12 years will offer more resistance to impregnation than at younger ages. The observation that vessel frequency decreases with tree age is a positive attribute in pulp production because pulp fines are decreased. Pulp fines are known to decrease the grade of pulps. Therefore, Ugandan-grown *E. grandis* wood could have pulps with lower fines from older trees (9 and 12 yr old).

Ray height and frequency.—The general trend of the increasing height of rays with age of *E. grandis* agrees with the findings of Saravanan et al. (2013) and Toong et al. (2014) for related commercial timbers. Further, such trends of ray characteristics could imply an increase of fuzzy grain owing to lower structural stiffness on machining along the grain for the older trees as a result of larger areas provided for by the lumens of opened rays when cleaved open by machines. The decreased number of rays as the tree grows older could be explained by the decreased physiological demands of trees at older tree ages and the presence of fewer portions of juvenile wood. Older trees have lower growth rates and hence a reduced need for rays that transport nutrients in the radial direction, as opposed to higher juvenile wood proportions with higher physiological demands at younger tree ages that would demand the presence of larger rays. Subsequently, such lower values of ray frequency give less movement during processing and seasoning, especially in the axial dimension of wood among the older trees.

Potential uses of Ugandan-grown *E. grandis* based on tree age and anatomical properties

E. grandis wood grown in Uganda showed properties that give an indication of the potential of producing good-grade pulps. With specific reference to fiber length, as a predictor of quality pulps, *E. grandis* grown in Uganda was found to have comparable lengths as noted earlier by Foelkel (2009) and later by Pirralho et al. (2014). Noticeable is the availability of desired lengths of fibers, even at 3 years of tree age for plantations that have been subjected to fertilizer application and minimal tending. Such fiber lengths at 3 years of tree age are more common in clonal varieties of *Eucalyptus* than in the pure stands. This could imply that with more focused tending and silviculture, the quality of fibers and eventually pulps would be appropriate for paper production.

Conclusions and Recommendations

Conclusions

Within-tree axial variation showed that the fiber length and diameter of *E. grandis* vary significantly. Whereas fiber length decreases with tree height, fiber diameter does not show a consistent pattern. Vessel length and diameter and ray height have inconsistent patterns, with significant variations from 25 to 75 percent of tree height, with the exception of the 9-year-old trees, which do not show significant variation. Vessel average and ray frequency equally did not show significant variation with tree height.

The variation of *E. grandis* properties with tree age showed that fiber length increases with tree age in the range of 780 to 970 μm, while fiber diameter decreases with tree age in the range of 12 to 11 μm. Both vessel length and vessel diameter increase with tree age in the ranges of 387 to 532 μm and 97 to 132 μm, respectively, while vessel average decreases with tree age in the range of 16 to 11 vessels per mm^2. Ray height increases with tree age in the range of 242 to 970 μm, while ray frequency decreases with tree age in the range of 9 to 10 rays per mm^2.

The fiber length and fiber diameter of *E. grandis* at the ages of 3, 6, 9, and 12 years grown in Uganda have the potential for production of paper pulps with high tensile and tear strength, formation, and burst characteristics. Based on the observed vessel and ray characteristics and variations, the 6-year-old tree rotation would best suit moderate pulp properties with lower fines and a higher quality per unit of pulp because most vessel characteristics are on the high side compared with industrial estimates for related tree species. Generally, based on wood anatomical properties, the wood of Ugandan-grown *E. grandis* is capable of producing good-strength pulps but with moderate volumes of fines.

Recommendations

Much as the development of hybrid clonal *Eucalyptus* species plantations in Uganda is still low in terms of acreage, the potential is high. Therefore, there is a need to conduct similar anatomical studies on the properties of *E. grandis* clonal varieties at different ages of tree growth. This will probably aid future optimal utilization of the newly introduced *Eucalyptus* clones in Uganda's private-sector tree farming. Further, economic evaluation of harvesting time and rotation ages of *E. grandis* needs to be studied to support the findings of this study with economic and financial viability at harvesting.

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