The effect of moisture availability on wood density and vessel characteristics of *Eucalyptus grandis* in the warm temperate region of South Africa

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Abstract

Productivity of forest plantations in South Africa is highly dependant on soil moisture availability. Soil moisture availability is often limited and evaporative demand is high. *Eucalyptus grandis*, planted extensively in South Africa, is highly intolerant of adverse conditions, and performs poorly when planted on shallow soils and/or on dry sites.

A study was conducted to assess the effect of moisture availability on the wood density and vessel characteristics of *E. grandis* grown in the warm temperate regions of South Africa. Gamma-ray densitometry and image analysis techniques were used. This study compared cores taken at breast height from compartments representing varying levels of moisture availability. Different levels of moisture availability were achieved using combinations of mean annual precipitation (MAP) and estimated soil water storage (SWS).

Preliminary results indicated a strong relationship between MAP and mean vessel percentage. Significant negative correlations were found between site index (SI) and other properties: mean density, mean vessel frequency, mean vessel percentage. Mean wood density, in some instances, showed a trend of decline with increasing water availability. Vessel frequency declined significantly with MAP at medium and high SWS levels. Relationships between water availability and wood properties are expected to become clearer and more robust as the study progresses.

KEYWORDS: *Eucalyptus grandis*, moisture availability, wood density, vessel diameter, vessel frequency, vessel percentage

Introduction

Plantation yield has conventionally been measured solely by stem volume production. More recently, focus has been on increasing fibre production, accelerating tree growth through improved silvicultural and management techniques and reducing rotation length thereby minimizing timber costs and maximizing returns on investments (Bhat *et al.*, 1990; Malan, 1991; Malan, 1995; Downes *et al.*, 2002). For this reason, information on the basic wood properties of young trees and the effect of growth rate on these properties is required.

Water and nutrient interactions are widely recognised as key factors in determining forest productivity (Stoneman *et al.*, 1996; Louw and Scholes, 2002; Whitehead and Beadle, 2004). The pattern of response of trees to change is recorded in their wood structure. The variation of wood properties over time is a net result of a complex web of interactions (Downes *et al.*, 2002). It is useful to know how trees respond, either directly or indirectly, to various individual contributing factors that result from varying environmental conditions. The impact of a change in environment can seldom be related directly to a single measurable factor in the total complex and subtle interrelationships usually exist between environmental factors (Malan, 1988a; Downes *et al*., 2002).

Eucalyptus species, predominantly the Australian *Eucalyptus grandis* Hill ex Maiden, have been planted extensively in South Africa since the beginning of this century (Taylor, 1973; Malan and Arbuthnot, 1995; February *et al*., 1995). Eucalypt plantations in South Africa occur over a range of soils and biophysical environments. The productivity of many of the sites, however, is below their potential and growth rates vary widely within a relatively small geographic region (Louw, 1999).

The particular importance of water availability in this study is pertinent to South African conditions where water is frequently limiting to growth and influences wood properties. *E. grandis* is highly intolerant of adverse conditions, and shows poor growth when planted on shallow soils and/or on dry sites (Boden, 1991). The growth rate and health of plantations is highly dependant on soil moisture availability which is often limited and evaporative demand is high (Roberts, 1994). Tree water status is a function of the balance between water absorption by roots and transpirational water loss, both of which are dependant on a variety of organismic variables and environmental inputs (Borchert, 1999).

Favorable environmental conditions lead to higher growth of eucalypt plantations by increasing both the rates of supply of resources, and the efficiency of resource use (Whitehead and Beadle, 2004). The optimum MAP and MAT for *E. grandis* is ≥ 900 mm and ≥ 16 ºC respectively (Schulze, 1997).Various authors have illustrated significant effects of the environment on wood properties of *E. grandis* (Boden, 1991; February *et al*., 1995; Clarke *et al*., 1999; Pierce and Verryn, 2000).

The wood density of eucalypt pulp wood is widely regarded as possibly one of the most influential factors controlling the strength and several other characteristics of the paper sheet (Malan, 1991; Malan and Arbuthnot, 1995). The wood density of a stem can be described as a gross measurement of its internal anatomy and is not a single wood property but represents a combination of characteristics. Basic density does not automatically correlate with fibre cell wall dimensions because density also measures vessels and parenchyma, which have thinner walls and wider lumens and reduce density. In mature *E. grandis*, density increases rapidly from pith to bark, especially in the zone of juvenile wood (Taylor, 1973; Malan, 1988b) but in young fast grown trees, such steep gradients do not exist.

For many hardwoods, vessel elements are a major problem in paper-making. Ideally, when hardwood trees are developed to become a raw material for pulp and paper, vessels should be few and small and easy to separate from the fiber material (Lundqvist, 2002). Increased vessel volume may have an adverse effect on surface quality as a result of ‘vessel picking’ (Haygreen and Bowyer, 1989). For many genera and species, diameter and vessel element length decrease while vessel frequency increases with decreasing water availability (Carlquist, 1975; Bamber, 1982; Malan, 1991; February *et al*., 1995). One of the most important of these variables in angiosperm wood is probably vessel diameter, because hydraulic conductivity is proportional to the vessel radius raised to the fourth power (Zimmerman, 1983). This means that even a slight increase in vessel radius is equivalent to an enormous increase in ability to transport sap. In general, vessel diameter increases with increasing distance from the pith while vessel frequency declines (Malan, 1991).

The current study explored the use of rapid screening tools to characterize the properties of wood in compartments of *Eucalyptus grandis* grown in the warm temperate region of South Africa. Varying levels of moisture availability were represented by using combinations of mean annual precipitation (MAP) and estimated soil water storage (SWS). The approach used in this study involved the non-destructive extraction of core samples taken at breast height; analyses of strips cut from the cores included the use of microscopy and image analysis and gamma-ray densitometry. In this paper, the relationships among density and vessel characteristics with moisture availability are examined.

Material and methods

Experimental design

Broad level macro-zones defined in a site classification system developed by the Institute for Commercial Forestry Research (ICFR) (Smith *et al*., 2005) were used as a foundation for the experimental design. In this system, forestry growing areas are classified into three broad level macro-zones based on mean annual temperature (MAT) – cold, warm and sub-tropical zones. These macro-zones are further subdivided into three mean annual precipitation (MAP) and MAT classes. Soil water storage (SWS) formed part of the last level of this classification system which considered geological groupings in terms of soil properties. Soil water storage (SWS) is expressed as the total water available for growth.

Only the warm temperate macro-zone has been selected for discussion in this paper. Combinations of MAP and SWS were compared in a two-factor factorial design: three compartments per cell were sampled. The South African Atlas of Agrohydrology and –Climatology (Schulze, 1997) was used to extract MAT and MAP values for the *E. grandis* resource in South Africa, and estimates of SWS were obtained from the ICFR (C. Smith, pers. comm.[1]). Compartments were grouped within cells of the experimental design in terms of dry, moist and wet MAP, and low, medium and high SWS with the intention of capturing the variability of the bioclimate in each compartment and region. Table 1 illustrates thresholds for MAP and SWS, and the location of compartments in the experimental matrix. The thresholds for dry, moist and wet values for MAP that were chosen are the thresholds that correspond to the average temperature range for that region. The experimental matrix was not completely populated at the time of compiling this article and sampling is ongoing. Two disks or two pith to bark cores were taken at breast height (1.3 m above ground) from five trees per compartment, one for density evaluation and the other for anatomical characteristics.

Table 1. Experimental design with ranges for mean annual precipitation (MAP) and soil water storage (SWS). Compartments were grouped within cells in terms of MAP x SWS combinations.

MAP (mm) SWS (mm)	DRY 600-875 mm	MOIST 876-975 mm	WET 976-3500 mm
LOW (72-151 mm)	B14 K8 A5	F9 M6	H75a W80a D22
MEDIUM (152-230 mm)		A3 A26 D05	A53d C4 D105
HIGH (231-309 mm)		A4 F031	A35c E17

The location and age of compartments and description of each compartment in terms of MAT, MAP, SWS, age, site index at a base age five years (SI_5)and number of stems per ha (SPH) is provided in Table 2.

Table 2. Compartment and plantation names, location and age of compartments, and description of site characteristics

Compartment name	Plantation name	Long.	Lat.	MAT (°C)	MAP (mm)	SWS (mm)	Age (yrs)	SI_5	SPH
A5	Harding	29°50'	30°41'	17	811	91	9.8	17.7	1369
B14	Mooiplaas	31°12'	28°33'	17	866	100	9.8	21.8	1752
K8	Highflats	30°8'	30°17'	17	792	100	10.5	21.1	1465
F9	Riverdale	30°11'	29°55'	17	927	136	10.9	27.9	1242
M6	Baynesfield	30°21'	29°45'	17	891	136	15.3	15.3	1111
A26	Windyhill	30°34'	29°30'	17	961	187	12.5	21.7	1083
A3	Windyhill	30°32'	29°29'	17	880	187	11.9	19.7	1274
D05	Mountain Home	30°16'	29°34'	17	1020	187	8.0	20.1	1561
A4	Mooiplaas	31°16'	28°32'	17	948	309	9.9	17.2	1401
F031	Ntonjaneni	31°17'	28°31'	17	901	260	7.6	19.5	1146
D22	Glenbain	30°4'	29°57'	16	919	160	7.5	19.6	1624
H75a	Clan	30°21'	29°23'	18	1106	136	10.3	24.3	1369
W80a	Clan	30°26'	29°18'	17	1071	136	11.0	23.2	1274
A53d	Windyhill	30°33'	29°31'	18	1051	187	5.6	22.5	1306
C4	Mooiplaas	31°12'	28°35'	17	996	187	7.4	21.9	1401
D105	Ntonjaneni	31°18'	28°36'	17	1079	136	11.2	20.4	1338
A35c	Mooiplaas	31°15'	28°32'	16	980	309	10.8	21.8	1433
E17	Shafton	30°14'	29°26'	16	1067	257	12.6	19.8	1401

Site index

The quality of site can be described by site index, an indicator of the growth rate of trees in a compartment. Site indices were derived by calculating the mean height of 20% of the tallest trees in each stand using a base age of five years. Sample plots (10 m in radius) were selected from each compartment and enumerated by measuring diameter at breast height (DBH) and total tree height using a Vertex III. Site index at a base age five was

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calculated using Modified Schumacher-difference form (Coetzee, 1994 *in* Pienaar and Kotze, 1998) (Equation 1).

$$SI_5 = \beta_3 * HD_1 * \exp[\beta_1(AGE_1 - AGE_2) + \beta_2 (1/AGE_1 - 1/AGE_2)]$$

Equation 1

Where: β_1, β_2 and β_3 = parameter estimates
AGE1 and AGE2 = compartment age at sampling and at base age five, respectively
HD1 = average dominant height of 20% tallest trees measured

Vessel characteristics

Radial strips, 2.5 mm thick, were obtained from samples taken at breast height samples. Strips were softened by soaking in water. Thereafter, the strips were cut with a sledge microtome to obtain a 20-25 µm thick section. Sections were mounted in ethanol on a glass slide, covered with a cover-slip, and examined using a Leica fluorescent microscope. Anatomical measurements were performed every 0.5 mm, from bark to pith using an image analysis system (Leica QWin). An algorithm, developed using the image analysis software, enabled the automatic separation of vessels from the fibres and parenchyma in each image acquired. Anatomical characteristics measured included: vessel diameter, vessel frequency (the number of vessels per unit area), and vessel percentage (the percentage area occupied by vessels per unit area).

Wood air-dry density

Another core sample or a 2-cm radial block obtained from disc was stored at 23ºC and 50% relative humidity to achieve an equilibrium moisture content of about 10%. Strips of uniform thickness were cut along the radius using a twin-blade saw. The sample dimensions were 12 mm in the longitudinal direction, 2.5 mm in the tangential direction and length was determined by the radius of the core/disc. Strips were scanned at 0.5 mm intervals, from bark to pith, using a gamma-ray densitometer to determine the density profile. Use of a gamma-ray densitometer was considered to be an accurate and reliable technique for determining the density of wood (Malan and Marais, 1991).

Statistical analyses

Results were analysed using univariate analysis of variance using the General Linear Models procedure, and Bivariate Correlations procedure conducted in SPSS, version 9.01 (SPSS Inc., Chicago, USA). Fisher's least significant difference (LSD) procedures, using SPSS, were conducted on main effects and interactions between MAP and SWS. Pearson's correlation coefficient was used to assess linear relationships, if any, between variables.

Disc maps were constructed in order to illustrate the radial distribution of vessel diameter and wood density. These were plotted and compared for each cell. The diameter of each map was scaled down and represents the actual mean tree diameter per cell.

Results and discussion

Preliminary correlations (Table 3) are based on means of compartments sampled (five trees per compartment). MAP and mean vessel percentage were found to have a strong negative correlation (r=-0.77). As would be expected, vessel frequency and vessel diameter were also negatively correlated, i.e.: fewer vessels per unit area when vessels are larger in diameter. Significant negative correlations were also found between site index (SI) and other properties: mean density, mean vessel frequency, mean vessel percentage. This suggests that areas with higher site index have lower density wood with fewer vessels. This is in agreement with other studies (Megown *et al.* 1998; Clarke, 1999) where recognisable trends towards decreasing density with an increase in site index were found. Density is a strong predictor for paper properties (DuPlooy, 1980; Malan, 1991, and Malan and Arbuthnot, 1995). High density wood has adverse effects on pulp strength.

MAT, SWS, age and number of stems per hectare (SPH) were not significantly correlated with any of the wood properties measured. MAT represents the very broadest of indices of the environmental status of a location. A drawback of MAT is that it integrates diurnal, monthly and seasonal patterns of minimum and maximum temperature (Schulze, 1997). With regards to the data presented in this paper, MAT is only being used as a good first approximation to describe a broad temperature range within the design. Relationships between SWS and wood properties are expected to emerge once sampling in the low SWS cells is completed since interactions between growth and plant water status are affected by soil factors which influence water retention and water availability (Landsberg and Gower, 1997). Similarly, significant relationships between individual environmental variables and wood properties are anticipated.

Table 3. Correlation matrix comparing site characteristics with wood properties of compartment means (n = 18) (* = significant correlation at $p < 0.05$ (2-tailed) and ** = significant correlation at $p < 0.01$) (2-tailed)

		MAT	MAP	SWS	SI	Age	SPH	Mean density	Mean vessel diameter	Mean vessel frequency	Mean vessel %
MAT	Pearson Correlation	1	.175	-.366	.251	-.228	-.266	-.321	-.163	.124	.001
	p-value		.488	.135	.315	.363	.286	.194	.518	.624	.998
MAP	Pearson Correlation	.175	1	.264	.339	-.090	-.085	-.300	-.104	-.374	**-.767(**)**
	p-value	.488		.290	.169	.721	.739	.227	.683	.126	.000
SWS	Pearson Correlation	-.366	.264	1	-.193	-.099	-.131	-.015	-.094	.058	.039
	p-value	.135	.290		.444	.695	.604	.952	.712	.820	.877
SI	Pearson Correlation	.251	.339	-.193	1	-.213	.032	**-.544(*)**	.232	**-.505(*)**	**-.491(*)**
	p-value	.315	.169	.444		.395	.900	.020	.355	.032	.038
Age	Pearson Correlation	-.228	-.090	-.099	-.213	1	-.401	.237	.020	.044	-.054
	p-value	.363	.721	.695	.395		.099	.344	.936	.862	.832
SPH	Pearson Correlation	-.266	-.085	-.131	.032	-.401	1	.056	.250	-.271	-.075
	p-value	.286	.739	.604	.900	.099		.825	.318	.276	.768
Mean density	Pearson Correlation	-.321	-.300	-.015	**-.544(*)**	.237	.056	1	-.124	.244	.157
	p-value	.194	.227	.952	.020	.344	.825		.623	.329	.534
Mean vessel diameter	Pearson Correlation	-.163	-.104	-.094	.232	.020	.250	-.124	1	**-.803(**)**	.215
	p-value	.518	.683	.712	.355	.936	.318	.623		.000	.391
Mean vessel frequency	Pearson Correlation	.124	-.374	.058	**-.505(*)**	.044	-.271	.244	**-.803(**)**	1	.371
	p-value	.624	.126	.820	.032	.862	.276	.329	.000		.129
Mean vessel %	Pearson Correlation	.001	**-.767(**)**	.039	**-.491(*)**	-.054	-.075	.157	.215	.371	1
	p-value	.998	.000	.877	.038	.832	.768	.534	.391	.129	

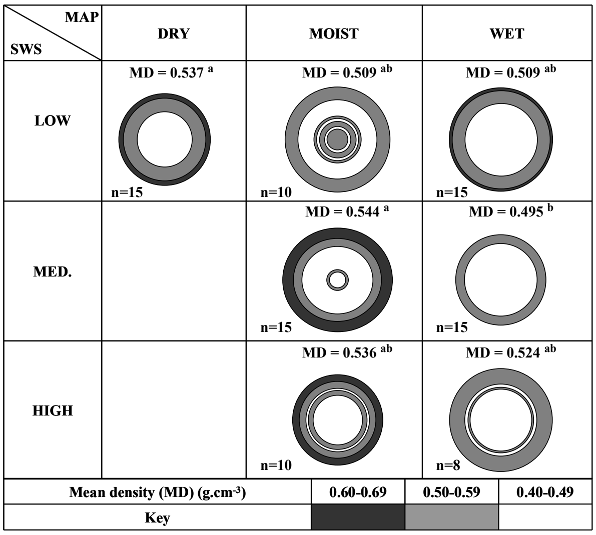

Figure 1. Maps of radial distribution of wood density across different levels of MAP and SWS. The number of trees sampled is indicated in each cell. Superscripted letters next to mean values per cell indicate significant differences ($p \leq 0.05$)

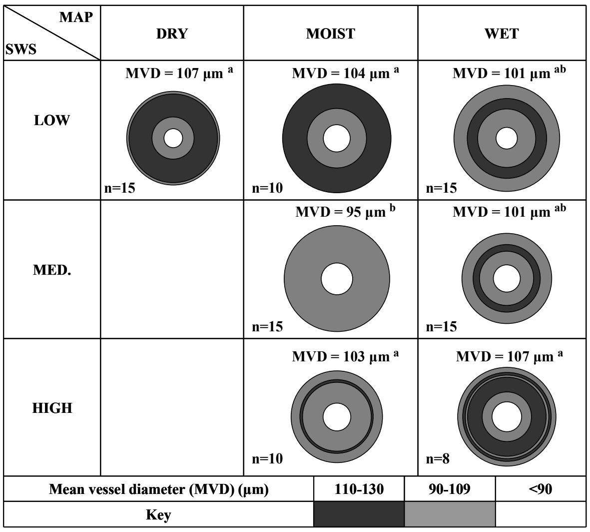

Figure 2. Maps of radial distribution of vessel diameter across different levels of MAP and SWS. The number of trees sampled is indicated in each cell. Superscripted letters next to mean values per cell indicate significant differences ($p \leq 0.05$)

The diameter at breast height and radial patterns of distribution of mean density and vessel diameter across ranges of MAP and SWS in the warm temperate region is illustrated in Figures 1 and 2 respectively. Generally, density in *E. grandis* increases with increasing distance from the pith (Taylor, 1973; Malan, 1988b; Bhat, 1990, Malan, 1993). Density declined with increasing MAP at each level of soil water storage. However, this trend was not significant at the high SWS levels (Figure 1).

Density ranged from 0.4 $g.cm^{-3}$ closer to the pith to 0.7 $g.cm^{-3}$ near the bark, and vessel diameter ranged between 60-130 µm from pith to bark. A comparison of patterns of mean density and mean vessel diameter distribution in Figures 1 and 2 revealed a trend of higher density areas corresponding with smaller vessel diameters and vice versa; however, this trend did not apply to areas closer to the pith.

The mean vessel diameters showed a narrow range of variation among cells of MAP and SWS (Figure 2). Although the moist x medium cell did have a significantly lower mean vessel diameter compared to four out of six cells compared, the pattern of vessel diameter distribution from bark to pith for this cell corresponded with the lower mean. The weighted mean vessel diameter and the pattern of vessel diameter distribution were similar for cells in the low x dry cell and the wet x high cell. This was not expected since larger vessel diameters are usually associated with higher water availability (Carlquist, 1975; Malan, 1991; February, 1995; Searson, 2004). Reasons for this will be explored once sampling has been completed, and vessel characteristics will be related to rainfall experienced during the period of growth of each compartment as opposed to relating measurements to long term means.

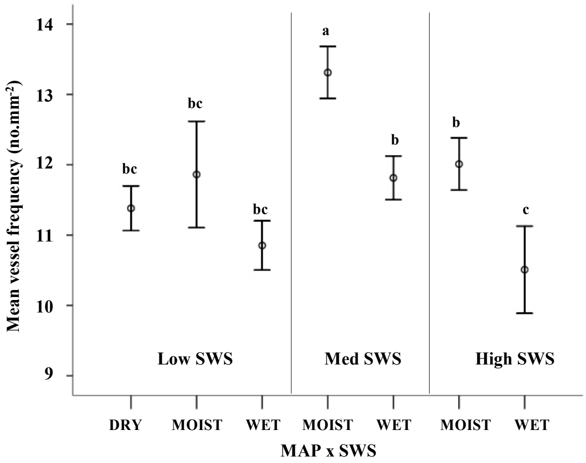

Figure 3. Mean vessel frequency is compared at each MAPxSWS level. Letters above the bars indicate differences at $p \leq 0.05$. Error bar is equal to one standard error.

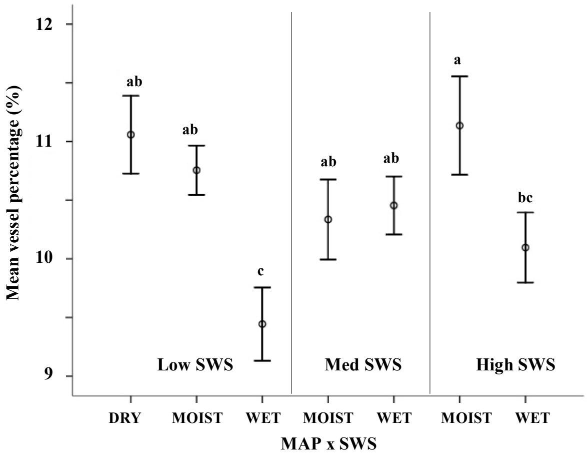

Figure 4. Mean vessel percentage is compared at each MAPxSWS level Letters above the bars indicate differences at $p \leq 0.05$. Error bar is equal to one standard error.

At low SWS, vessel frequency was not influenced by MAP (Figure 3). However, at medium and high SWS levels vessel frequency declined significantly with MAP. Mean vessel diameter of *E. grandis* seedlings is significantly reduced by water limitation (February, 1995; Searson *et* al., 2004). February (1995) did not find any significant correlations between vessel frequency and water availability.

Vessel percentage showed a strong correlation with MAP (Table 3). This correlation is illustrated in Figure 4 where a significant decline in mean vessel percentage with increasing MAP was found at low and high SWS (Figure 4).

Conclusions and future outcomes

The effect of moisture as a major factor in controlling wood properties has been a prominent topic reported in numerous studies during the past decades (Malan, 1991; February, 1995; Downes *et al.*; 1999; Searson *et* al., 2004). Preliminary results from this study indicated a strong relationship between MAP and vessel percentage, and density showed a trend of decline with increasing water availability. Site index had a significant impact on wood density and vessel characteristics. However, the term site index is a composite expression of the effects of interacting site variables on wood properties. The relationships between water availability and wood properties are expected to become clearer and more robust as more compartments are included in the experimental design.

The presented results shown were from only a portion of the study sites. This work is part of a broader study in which more detailed comparisons will be made between wood properties of *E. grandis* grown in the subtropical and warm temperate forestry growing regions in South Africa in an attempt to quantify and model the interactive effects of specific environmental variables. Aspects of fibre characteristics, such as cell wall thickness, fibre diameter and fibre lumen diameter will be assessed in conjunction with the use of near infra-red spectroscopy which will be used to predict chemical wood properties from solid wood strips. Variables of interest such as mean minimum and maximum temperature, median temperature and rainfall, seasonality, drought-breaking rainfall, etc. will be explored in greater detail when assessing measurements conducted on the pith to bark cores. An additional outcome of this study also aims to add new knowledge to the question of annual rings in *E. grandis*, grown in South Africa, through the analysis of vessel and fibre characteristics.

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