Eur. J. Wood Prod.
DOI 10.1007/s00107-016-1016-3

ORIGINAL

Variation in physical and mechanical properties from three drought tolerant *Eucalyptus* species grown on the dry west coast of Southern Africa

C. B. Wessels[1] · P. L. Crafford[1] · B. Du Toit[1] · T. Grahn[2] · M. Johansson[3] · S. O. Lundqvist[2] · H. Säll[3] · T. Seifert[1]

Received: 18 November 2014

Abstract Southern Africa, and specifically its western parts is dominated by low rainfall areas, and it is expected that the rainfall in most of these parts will in future decrease further due to climate change. Woodlots of fast-growing, non-invasive tree species can provide the opportunity to produce wood and release the pressure on natural woodlands, while creating much needed income to inhabitants. Over the last two decades several trials of *Eucalyptus* species that could potentially withstand arid conditions were established on the South African west coast. The three most promising genotypes according to their volume growth were selected among 46 pure and hybrid species from two 20-year-old trials for further evaluation. These included 10 *Eucalyptus grandis* × *Eucalyptus camaldulensis* hybrid trees, 9 *Eucalyptus gomphocephala* trees, and 9 *Eucalyptus cladocalyx* trees for a total of 28 trees. The objective of the study reported here was to investigate the within-tree and between species variability of selected physical and processing properties determining the suitability of these three species for lumber production. The density, microfibril angle, spiral grain angle, MOE, MOR, radial and tangential shrinkage, twist, bow, splitting, and collapse were measured in a radial and longitudinal gradient. Valuable insights were gained which could provide decision support for planting, processing and further research on these species when grown in arid conditions. The *E. grandis* × *camaldulensis* hybrid was inferior in terms of most relevant properties to the other two species evaluated. The main shortcoming of both *E. gomphocephala* and *E. cladocalyx* was the high levels of twist in lumber.

✉ C. B. Wessels
cbw@sun.ac.za

[1] Department of Forest and Wood Science, Stellenbosch University, Private Bag X1, Matieland 7600, South Africa

[2] Innventia AB, Box 5604, SE-114 86 Stockholm, Sweden

[3] School of Engineering, Linnaeus University (Lnu), 351 95 Växjö, Sweden

1 Introduction

Half of the countries of the world lie partly or entirely in arid and semi-arid zones. These zones, together with their sub-humid margins, or the so-called dry lands, cover a total area of about 45 million km^2 or one-third of the total land area of the world (FAO 1989). In Africa, the dry forests and woodlands cover 54 % of the continent's land area and support some 64 % of its population through the provision of a wide range of environmental goods and services (CIFOR 2011). Southern Africa, and specifically its western parts is dominated by low rainfall areas, and it is expected that the rainfall in most of these parts will in future decrease further due to climate change. At the same time the region has one of the fastest growing populations in the world and as such faces the challenge of increasing food requirements. This challenge has inevitably resulted in large forested areas being cleared in the Southern African Development Community (SADC) region (FANR 2011). The major causes of deforestation are attributed to agricultural expansion and fuelwood requirements, generally triggered by population increase and ongoing land reforms in some countries. The relatively limited access and high cost of electricity and fossil fuels in rural areas where over 70 % of the people reside, worsen the situation. According to a risk analysis of the SADC countries, fuelwood and charcoal demands for domestic use are amongst the major drivers of forest destruction (FANR 2011).

Published online: 20 February 2016

Woodlots of fast-growing, non-invasive tree species in these areas can provide the opportunity to restore woodlands, can produce more wood on a smaller area, and can also provide much needed income to inhabitants of these parts. Over the last 20 years several experiments were established in the dry climates of the South African west coast (Ellis 1995; Ellis and Van Laar 1999; Van Wyk et al. 2001; Von Doderer and Kleynhans 2010). New drought tolerant *Eucalyptus* hybrids were successfully developed and the best genotypes had mean annual increments in the range of 8–12 m^3 ha^{-1} $year^{-1}$ in areas where the precipitation varied between 300 and 400 mm per annum. Apart from fuelwood, one of the products that might be viable from these trees is sawn timber that can be used by the local population or sold as a cash generating source.

Unfortunately there is a dearth of information on the wood quality and processing properties of most eucalypts which were grown on arid sites. Commercial forestry is mostly practiced in areas with a medium to high growth rate and research studies also focus on these areas. Hence it is difficult to make informed planting and processing choices in arid zones where the aim is to produce end-products with commercial value.

The end-use of sawn timber products determines to a large degree which properties will be important. Or, seen from a different perspective, the properties of the timber determine which products and markets are options for a specific wood resource. Many *Eucalyptus* species pose serious processing challenges. Some have very high shrinkage coefficients and are collapse-prone, which might cause difficulties in certain applications (Chafe 1990; Malan 1993; Vermaas and Bariska 1994; Ilic 1999). Another problem that is frequently encountered in timber from *Eucalyptus* species and which often makes the profitable processing of this species challenging is splitting due to growth stresses (Jacobs 1955; Malan 1984, 2003). Other important properties that are often required from sawn timber include dimensional stability, strength, stiffness, hardness, durability, and machinability. Density and microfibril angle are basic properties that are frequently related to some of these desirable characteristics in wood and are therefore very often measured in wood quality studies.

Trees from a 20-year-old field trial from two sites on the dry west coast area of South Africa were recently evaluated for growth characteristics. The three most promising genotypes were selected, according to their volume growth, among 46 pure and hybrid species for further evaluation. These included *Eucalyptus grandis* × *Eucalyptus camaldulensis* hybrid, *Eucalyptus gomphocephala,* and *Eucalyptus cladocalyx*. The objective of the study reported here was to investigate the within-tree and between species variability of selected physical and processing properties determining the suitability of these three species grown on arid sites for lumber production. This information can be used in making planting and processing decisions. It will also be useful for informing tree breeders and silviculturists to identify which properties need improvement through breeding selection or forest management strategies.

2 Background

The hybrid of *E. grandis* and *E. camaldulensis* was developed in South Africa primarily in order to obtain the high growth rate of *E. grandis* and the tolerance to drought and cold conditions of *E. camaldulensis* (Malan 1993). It is one of the main Eucalypt hybrids used commercially (Potts and Dungey 2004). Malan (1993) evaluated wood and pole properties of 5-year-old trees from this hybrid from six sites in South Africa. These sites were located in medium to high rainfall forestry areas. The air-dry density of the hybrid's wood varied between 550 and 650 kg/m^3 and density increased slightly from pith to bark. Malan (1993) found no relationship between wood density and volume growth. Radial shrinkage to oven-dry moisture content was 4.7 % and tangential shrinkage 9.7 %. Strong site effects were detected indicating that fast-growing trees from good sites shrink less than slow-growing trees. As with most hybrids which were developed over the last few decades, there were not much wood property and processing research results available for this hybrid.

Eucalyptus gomphocephala or Tuart occurs naturally in a narrow belt along the coastal plains north and south of Perth in Western Australia. It produces hard, dense, durable wood that is relatively termite-resistant and in the past has been used for keelsons, stern posts, bridge supports, shafts and wheelwright work (Boland et al. 2006). Cookson (2004) found that *E. gomphocephala* had high natural durability in Australia and may be expected to have a service life of 15–25 years in ground contact. Banks et al. (1976) tested clear wood samples from South African grown *E. gomphocephala* trees and reported a mean modulus of rupture (MOR) value of 136 MPa and mean modulus of elasticity (MOE) of 18.3 GPa. Stern-Cohen and Fahn (1964) found that the MFA of *E. gomphocephala* grown in arid conditions in Israel varied between 2.5° and 16.1°. Ferrari (1995) investigated the variation of properties at different heights in Italian grown *E. gomphocephala* and found that density increased and collapse decreased with height. Although *E. gomphocephala* was also planted in several low rainfall areas outside of Australia such as Spain, Italy, Israel and South Africa (Le Roux, 1975), no other reports on its wood properties and processing could be found.

Eucalyptus cladocalyx or sugar gum is native to a fairly small coastal area in Southern Australia (Boland et al. 2006). Of the three species investigated in this study, the most research literature was available on *E. cladocalyx*. The wood of *E. cladocalyx* in Australia has been described as of moderate strength and in the past has been used for furniture, flooring, panelling, firewood, poles, posts, general construction and railway sleepers (Boland et al. 2006). Reporting on a number of natural durability trials at different sites in Australia, Cookson (2004) found that *E. cladocalyx* was in the class of highest natural durability and may be expected to have a service life of 25 years or more in ground contact. Based on results from a South African study, Vermaak (1979), however, recommend that *E. cladocalyx* should not be planted for use as pole material in the Northern regions of the country due to attack of heartwood by termites. The mean basic density of 27-year-old plantation grown *E. cladocalyx* in Australia has been reported as 752 kg/m^3 and the shrinkage without reconditioning from green to 12 % moisture content as 8.5 % in the tangential direction and 3.4 % in the radial direction (Blakemore 2004). Similar density was found for South African grown *E. cladocalyx* (Munalula and Meincken 2009). Banks et al. (1976) tested clear wood samples from South African grown *E. cladocalyx* trees and reported a mean modulus of rupture (MOR) value of 140 MPa and mean modulus of elasticity (MOE) of 18.4 GPa. Ozarska (2009) found that 40-year-old Australian plantation grown *E. cladocalyx* trees had very similar density, MOE and MOR properties to that of old-growth trees. Washusen et al. (1996) as quoted in Blakemore et al. (2003) obtained good appearance grade sawn timber recoveries from large diameter *E. cladocalyx*. Blakemore et al. (2003), however, reported low appearance grade sawn product recovery from 29-year-old trees at the felling age but recommended *E. cladocalyx* as the species with the best potential for high grade solid wood product in the lower rainfall areas of Australia. The main defects in that study which caused the low recovery values included decay and knots.

3 Materials and methods

3.1 Sampling

Twenty-eight, 20-year-old trees were obtained from two trial sites on the west coast of South Africa. Pampoenvlei is about 50 km north of Cape Town. It is a flat dune area with mean annual precipitation of 400 mm (Ellis and van Laar 1999; Van Wyk et al. 2001). The arid conditions of this site are somewhat ameliorated by cool sea mists and an underground water table approximately 2–3 m from the surface in the winter months. Chemfos is an even drier site, situated further from the coast, close to Hopetown about 80 km north of Cape Town, also on deep sandy soil with a mean annual precipitation of 319 mm. The sample included nine *E. gomphocephala* trees (five from Pampoenvlei and four from Chemfos), nine *E. cladocalyx* trees (four from Pampoenvlei and five from Chemfos), and ten *E. grandis* × *camaldulensis* trees (five from Pampoenvlei and five from Chemfos). It must be emphasized that the annual mean rainfall on the trial sites is at the lower limit or below the lower limit of the rainfall ranges in the areas in Australia where these species occur naturally (FAO 2014). Sample trees were selected to cover the range of diameters available at the sites. Only trees with acceptable stem form for saw logs were selected. The *E. gomphocephala* trees generally had poor stem form and even selected trees sometimes had severe sweep. Data for the different trees can be seen in Table 1. Further information on the sampled trees can be found in Phiri et al. (2015) who modelled tree biomass using the same data set.

Trees were felled and bolts of 60 cm length were removed from four heights along the stem of each tree in sampling procedures similar to that developed by Lundqvist et al. (2013). Bolts were removed from breast height, 25 % of total tree height, 60 % of total tree height, and at the top of the tree where the diameter was 7 cm. A saw log of 1.5 m length was removed above breast height. After felling, the bolts were closed in plastic bags and stored in a cold room to avoid any moisture losses. Test specimens for the different tests were later prepared from these bolts.

3.2 Density and microfibril angle

A disc was removed from each bolt and radial strips were cut from the pith to the bark in the north to south direction. Water was replaced by ethanol in three stages before the strips were dried to equilibrium moisture content. These

Table 1 Diameter at breast height (DBH) and height data for the 28 sample trees

		E. cladocalyx	*E. gomphocephala*	*E. grandis* × *camaldulensis*
	n	9	9	10
DBH (cm)	Mean	29.4	26.4	27.2
	Min	21.5	20.4	16.1
	Max	37.1	32.6	36.5
Height (m)	Mean	15.3	15.6	15.5
	Min	13.0	11.5	12.3
	Max	18.1	19.4	17.7

radial strips were scanned by the Silviscan instrument of Innventia, Sweden, to determine the density and microfibril angle in 2 mm increments from pith to bark in the north–south direction.

3.3 Grain spirality (grain angle)

Spiral grain angle was determined across the diameter of discs obtained from billets at all four heights. The scribe method, as described by Säll (2002), was used to determine the grain angle at roughly 15 mm increments from the pith to bark in the north–south direction. For each radial position there was thus two grain angle values—one on the south and one on the north side of a disc. Most specimens were not suitable for testing due to the presence of knots which could not be avoided during sample cutting. A positive angle indicates left handed spiral grain and negative angles indicate right-handed spiral grain.

3.4 Shrinkage

A wedge, extending from pith to bark, was prepared from each bolt, to determine radial and tangential shrinkage from moisture content above fibre saturation point to air dry (Fig. 1). Two radial lines were drawn from pith to bark and steel pins were used to mark the pith, 1/3rd radius, 2/3rd radius and bark on each line. Radial and tangential distances were measured for the wet wedges and then later for wedges dried to equilibrium moisture content at a relative humidity of 65 % and 20 °C.

3.5 MOE and MOR

Test specimens of 20 × 20 × 300 mm^3 were prepared for bending tests of small clear specimens of wood. Specimens were cut parallel to the pith and each specimen was numbered according to its radial position. MOE and MOR was determined according to the centre-point method in BS 373:1957 (2008). By far most specimens were not suitable for testing due to the presence of many small knots which could not be avoided during sample cutting. In order to obtain a reasonable number of test specimens, pin-sized knots at the ends (lengthwise) of test specimens, where they have limited influence on the flexural properties, were allowed. The grain angle at the centre of each test specimen was recorded on both sides over a length of 62 mm and the mean angle per specimen was used for analysis.

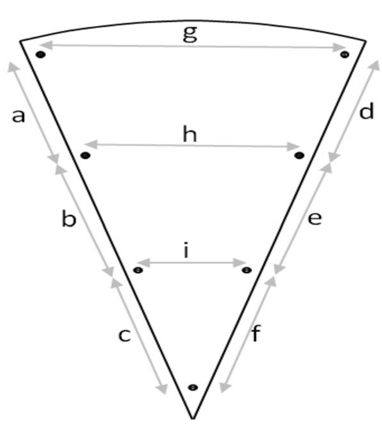

Fig. 1 Wedge for shrinkage analysis with measurement points indicated

3.6 Sawing and drying

The 1.5 m long saw logs were cut into slabs of 28 mm thick in the north–south direction (Fig. 2). These boards were stacked indoors in a controlled environment where the relative humidity was 65 % and temperature was 20 °C and left for several months until equilibrium moisture content was reached. After drying, most boards had a thickness of slightly above 25 mm.

3.7 Warp

Because the boards were of different widths, the measurements to determine warp was performed on a custom made apparatus where a board rests on three index pins (Fig. 3). The warp measurements were done at a width of 135 mm and a length of 1500 mm. In other words, although boards were of different widths, the warp measurements were performed as if each board was sawn into 25 × 135 × 1500 mm^3 dimensions. Twist and bow were calculated from these measurements according to the SANS 1783:1 (2009) standard.

3.8 Splitting

Splits after drying of the boards were measured. Splits mostly occurred at the two ends of the boards. The length and width of each split was measured and for each board the total split length was calculated.

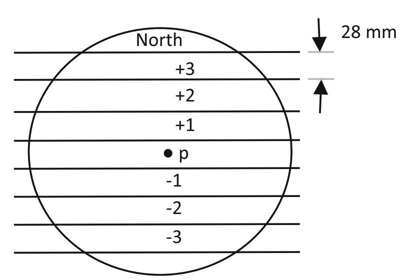

Fig. 2 Saw logs were cut into 28 mm thick boards and marked according to their radial position from the pith

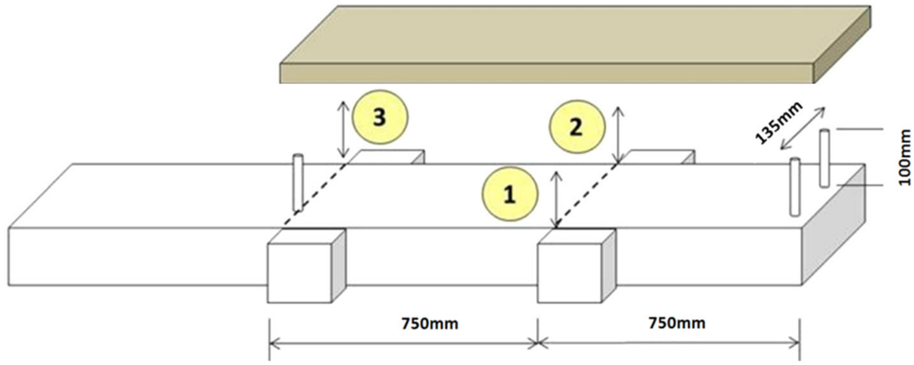

Fig. 3 Measurement jig for warp where a board rests on three index pins. The measurement locations are indicated as numbers 1–3

3.9 Collapse

Distortion, flattening and crushing of wood cells is defined as collapse. In severe cases collapse usually shows up as grooves or corrugations on the surface of boards. Collapse was visually assessed and each board was graded into one of four classes based on the percentage of surface area affected.

3.10 Statistical analysis

In the statistical analysis, three-way cross-classification analysis of variance (ANOVA) was done using species, height, and radial position as factors using the Statistica software (http://www.statsoft.com). The effect of these factors were analysed on all the measured properties. If the three-way interaction was significant it was interpreted, otherwise the significant two-way interactions or main effects were interpreted. If enough data was not available for a three-way ANOVA, successive two-way ANOVAs were performed.

4 Results and discussion

The trees at both trial sites of all three genotypes were healthy and no signs of any serious pest or disease were observed. *Eucalyptus gomphocephala* and *Eucalyptus cladocalyx* have been introduced to South Africa more than a century ago and are generally healthy where planted in South Africa. *Eucalyptus grandis* × *camaldulensis* in South Africa is currently threatened by the Eucalyptus gall wasp (*Leptocybe invasa*) which cause galls on the leaves and stems resulting in stunted and gnarled looking trees (Roux et al. 2012). The Eucalypt Snout Beetle, *Gonipterus scutellatus* is also present in the Western Cape Province, but it causes limited damage because it is under effective biological control by the parasitoids wasp, *Anaphes nitens* (Tribe 2005).

4.1 Density

Density, as determined with the Silviscan device from pith to bark, was evaluated up to a 70 mm radius (140 mm diameter) and for the first three sample heights. Data from discs having a radius larger than 70 mm were not included in order to enable performance of a three-way ANOVA. Analysis of variation of density showed that species, radial position, and height within the stem had a highly significant influence (Table 2). The interactions between species and radial position and species and height were also highly significant (Fig. 4a, b).

The mean density of the *E. grandis X camaldulensis* hybrid was much lower than the two other species and stayed fairly constant over the radius between 580 and 720 kg/m^3 except very close to the pith where the mean density dropped to approximately 500 kg/m^3 (Fig. 4a). This is roughly in agreement with Malan's (1993) results. The density gradient of the hybrid was also lower over both the radius and the height of the tree than those of the other two species. The mean density of *E. gomphocephala* was slightly higher at similar distances from the pith and heights than that of *E. cladocalyx*. The mean density of *E. gomphocephala* increases from 800 kg/m^3 at the pith to around 900 kg/m^3 after 50 mm radius. The *E. cladocalyx* mean density decreased from the pith to 730 kg/m^3 before increasing again to 870 kg/m^3 after 50 mm radius. As is evident from the confidence intervals, there were fairly high variations in density between trees at similar positions from the pith (Fig. 4a).

The mean density of *E. grandis* × *camaldulensis* and *E. gomphocephala* increased with stem height. The decreasing density with height for *E. cladocalyx* illustrated in Fig. 4b was not significant. In a study by Ferrari (1995) on *Eucalyptus* species grown in Italy which included *E. grandis, E. camaldulensis* and *E. gomphocephala,* density was found to increase with height. Increasing density with height, from breast height upwards, has also been found in other studies on *E. grandis* (Taylor 1973; Bhat et al. 1990; Githiomi and Kariuki 2010).

Table 2 Three-way analysis of variance for density measured by Silviscan (kg/m^3)

Source of variation	SS	df	MS	F	p
Intercept	**1.266E + 09**	**1**	**1.267E + 09**	**152618.7**	**0.0000**
Species	**1.972E + 07**	**2**	**9.858E + 06**	**1187.9**	**0.0000**
Radial position	**1.617E + 06**	**34**	**4.754E + 04**	**5.7**	**0.0000**
Height	**8.420E + 04**	**2**	**4.210E + 04**	**5.1**	**0.0063**
Species × radial position	**1.085E + 06**	**68**	**1.595E + 04**	**1.9**	**0.0000**
Species × height	**2.709E + 05**	**4**	**6.773E + 04**	**8.2**	**0.0000**
Radial position × height	5.098E + 05	68	7.497E + 03	0.9	0.6980
Species × radial position × height	9.385E + 05	136	6.900E + 03	0.8	0.9187
Error	1.641E + 07	1977	8.299E + 03		

Significant factors at the 5 % level are bold

4.2 Microfibril angle

Analysis of variation of MFA showed that species, radial position, height and the interaction between species and height had a highly significant influence (Table 3). Figure 4c, d shows the variation of MFA over different radial positions and heights for the three species.

In a review on MFA measurement and variation by Donaldson (2008), it was mentioned that hardwood MFA angles are typically between 15° and 20° near the pith which was consistent with the current results (Fig. 4c). Barring the position right at the pith, the mean MFA at all positions for *E. cladocalyx* was lower than that of *E. grandis × camaldulensis,* which was again lower than that of *E. gomphocephala*. The general trend for MFA of all the species was to decrease from the pith outwards (Fig. 4c) which is consistent with other results on the *Eucalyptus* species (i.e. Stuart and Evans 1994; Evans et al. 2000; French et al. 2000, Lima et al. 2004). The trends between the species in the longitudinal direction were very similar: a sharp decrease in mean MFA from breast height to 25 % of total height and then a moderate decrease towards 60 % of total height (Fig. 4d). Evans et al. (2000) found that the MFA of *E. nitens* decreased with stem height up to about 30–50 % of the total height whereupon it increased again towards the top of the tree. The trends in MFA results obtained here generally agree with unpublished data of other Silviscan studies on eucalypt species performed at the Innventia laboratory. As is evident from the confidence intervals, there were fairly high variation in MFA between trees at similar positions from the pith (Fig. 4c).

A very relevant study was that of Wimmer et al. (2002) who found that for *E. nitens* trees grown under different water availability regimes, trees subjected to drought had smaller MFA angles with less fluctuations in MFA compared to irrigated trees. If the same would apply to the species studied here, it would mean that the arid growth conditions may actually result in better MFA properties than higher rainfall areas. This, however, would need to be verified in another research study as no trees from comparative sites with higher rainfall were available.

The only other study on MFA on any of the species investigated here that the authors are aware of was by Stern-Cohen and Fahn (1964) who found that the MFA of *E. gomphocephala* varied between 2.5° and 16.1°.

4.3 Grain spirality (grain angle)

Successive two-way ANOVA‘s were performed with species, distance from pith, and height as factors. The main effects and two-way interactions were in both cases highly significant and therefore the interactions were interpreted (Fig. 4e, f).

The mean spiral grain angle at different heights and radial positions was mostly negative meaning it formed a right handed spiral in the tree. This is similar to results found on other eucalypt species (Thinley et al. 2005). The grain angle of the hybrid *E. grandis × camaldulensis* was less than that of the other two species at nearly all positions in the stem (Fig. 4e, f). When the limit for useful timber utilization is set at a maximum allowable spiral grain of ±4° (as mentioned in Säll 2002), it can be seen that this limit is substantially exceeded by *E. cladocalyx* at diameters bigger than 60 mm and for *E. gomphocephala* at breast height.

The patterns of variation between the species were very different. The grain angle of both *E. gomphocephala* and *E. cladocalyx* increased sharply from the pith to 50 mm radius. After that, however, *E. gomphocephala*’s grain angle decreased outwards whereas that of *E. cladocalyx* kept on increasing towards the bark. Height-wise *E. grandis × camaldulensis* and *E. cladocalyx* showed the same pattern whereas *E. gomphocephala’s* grain angle decreased consistently from breast height upwards.

There was large within- and between tree variation in grain angle. Both visual examination and measured grain angle results for all three species showed that the grain was often interlocked. In other words the grain angle changed

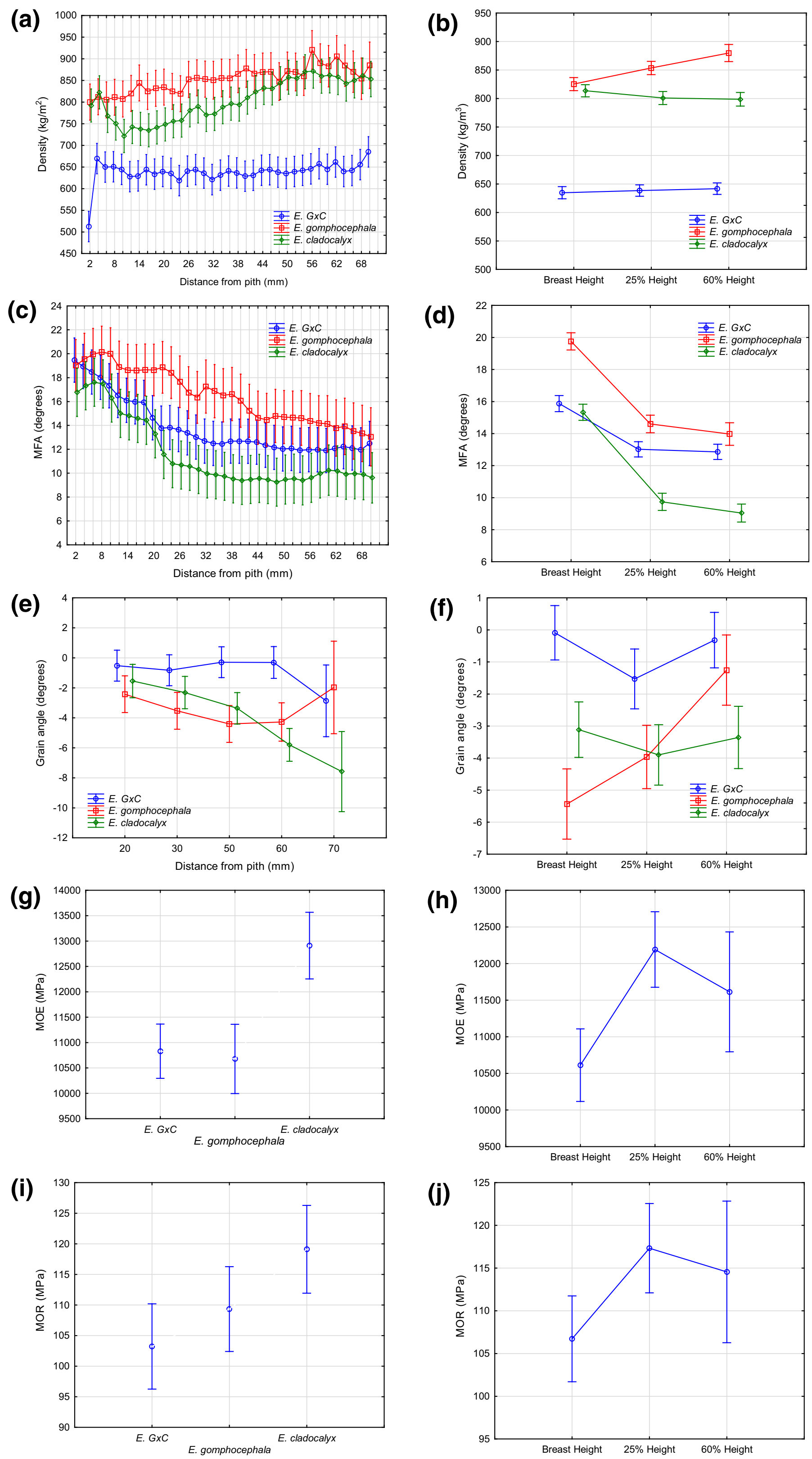

Fig. 4 Variation in density, MFA, grain angle, MOE and MOR over different radial positions, heights and species. Means and the 95 % confidence intervals are indicated

from positive to negative or vice versa in subsequent growth seasons. Of the 569 grain angle measurements, there was a total of 158 times where a change in grain direction occurred between subsequent radial measurements (positive to negative or vice versa)—roughly equally spread between the species. Both the *E. gomphocephala*

Table 3 Three-way analysis of variance for microfibril angle (MFA) measured by Silviscan

Source of variation	SS	df	MS	F	p
Intercept	**411902**	**1**	**411902**	**22429**	**0.0000**
Species	**7455**	**2**	**3728**	**203**	**0.0000**
Radial position	**12525**	**34**	**368**	**20**	**0.0000**
Height	**11566**	**2**	**5783**	**315**	**0.0000**
Species × radial position	952	68	14	1	0.9243
Species × height	**976**	**4**	**244**	**13**	**0.0000**
Radial position × height	823	68	12	1	0.9856
Species × radial position × height	1038	136	8	0	1.0000
Error	36308	1977	18		

Significant factors at the 5 % level are bold

Table 4 Pearson correlations between properties of clear wood bending specimens

	Grain angle	Density	MFA	MOR	MOE
Grain angle	1.000				
Density	0.317**	1.000			
MFA	0.174	−0.200*	1.000		
MOR	−0.352**	0.486***	−0.474***	1.000	
MOE	−0.307**	0.513***	−0.585***	0.927***	1.000

"*", "**", "***" indicate significance at the 0.1, 0.05, and 0.001 levels, respectively

and *E. cladocalyx* also showed wavy grain, which was extreme in the case of *E. gomphocephala*.

4.4 MOE and MOR

There were not enough suitable specimens without knots to perform three-way cross-classification ANOVA's for MOE and MOR. Successive two-way ANOVA's were performed with species, radial position, and height as factors. The main effects, species and height, were highly significant for both MOE and MOR (Fig. 4g, j). The radial position or distance from the pith, and interactions did not have a significant influence on either the MOE or MOR of the clear bending specimens.

A Pearson correlation matrix of measured properties of the bending specimens that could possibly influence the MOE and MOR can be seen in Table 4. A multiple regression model was developed for predicting MOE with grain angle, density and MFA as independent variables (Fig. 5). Take note that the grain angle was measured on the mechanically tested specimens and is not to be confused with the spiral grain measurements determined from disc samples. All the variables were highly significant and the model had a coefficient of determination of 0.65. The mean grain angle over all the specimens was 3.8° with high variation between specimens (standard deviation of 2.3 mm).

The clear wood MOE of *E. cladocalyx* was significantly higher than that of the other two species (Fig. 4g). It was

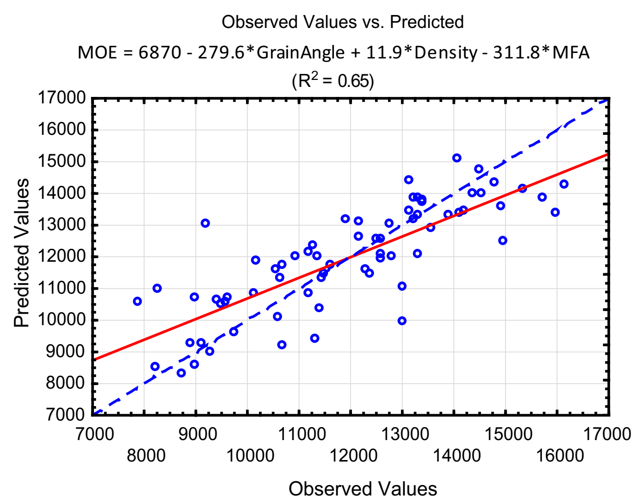

Fig. 5 Predicted vs. observed values for a multiple regression model to predict MOE with independent variables density, MFA and grain angle. The model (*solid line*) and 1:1 relationship (*broken line*) are indicated

quite surprising that *E. gomphocephala*, which had the highest density, had the lowest mean stiffness of the species. This was probably due to the high MFA and grain angles present in this species. In terms of height, the lowest mean MOE was at breast height—probably again a result of the high MFA angles found for all the species at breast height (Fig. 4d).

The correlation between MOE and density (r = 0.513) and MOE and MFA (r = 0.585) as seen in Table 4, was rather low compared to results from studies on clear wood samples of other species (i.e. Foslie 1971, Evans and Ilic 2001). One possibility for this low correlation was the fact that there were often severe grain angles present in the samples. Another explanation might be that MFA and density was measured on a disc taken 300 mm away from the central point of the specimen used for the test of MOE. The multiple regression model with density, MFA and grain angle as independent variables explained 65 % of the variability in MOE (Fig. 5)—which was much better than the individual correlations but still lower than expected. The degree of determination of the model could be improved to 75 % by removing four outliers identified using Cook leverage values and a Bonferroni outlier test. The relatively low coefficient of determination is difficult to explain but might be due to the wavy and interlocking grain of the samples, which sometimes changed angles within the samples. Some specimens had small areas of high grain angle even when the mean grain angle per sample might have been fairly low. Another interesting observation from the correlation matrix in Table 4 was that the correlation between MOE and MOR of 0.927 was higher compared to other studies on clear wood specimens (i.e. Foslie 1971, Yang and Evans 2003).

4.5 Radial and tangential shrinkage

Three-way cross-classification ANOVA's with species, radial position, and height as the main effects were performed for both radial and tangential shrinkage. The three-way interactions were not significant for neither radial nor tangential shrinkage. For both tangential and radial shrinkage, the species-height and species-radial position two-way interactions were highly significant (see Fig. 6 for tangential shrinkage variation). In the case of tangential shrinkage, the height-radial position interaction was significant at the 0.05-level, but for radial shrinkage this interaction was not significant at all.

The mean tangential shrinkage of *E. grandis* × *camaldulensis* was higher than the other two species at all the heights and radial positions (Fig. 6). Malan (1993) found tangential shrinkage of this hybrid at the base of the stem to be 9.7 %, which was slightly higher than the mean at breast height for this study here. The shrinkage values for the hybrid showed large within-tree variation both radially and longitudinally, which could cause problems in certain applications, i.e. where different pieces of wood are glued together or with flooring. The tangential shrinkage of the other two species was much more even around the 6–7 % level except for *E. cladocalyx* at the pith which was somewhat higher than 6 %. It is interesting to note that the shrinkage of *E. cladocalyx* from this study was significantly lower than that found by Blakemore (2004) on 27-year-old Australian, plantation grown trees.

4.6 Warp and split measurement results

There was only one sawlog removed from each tree—1.5 m long and just above breast height. The only factors to consider in the ANOVA were therefore the species and the radial position from the pith.

Twist was significantly influenced by species but not by the radial position from the pith or the interaction between species and position (Fig. 7a). Take note that board lengths were 1.5 m and twist was measured at 135 mm width. The twist of both *E. cladocalyx* and *E. gomphocephala* was relatively high. The SANS 1783-3 (2010) standard allows a maximum twist for appearance grade timber of the sample widths of 4.7 mm whereas the mean twist of these two species was both more than 8 mm. In the processing of timber to secondary products it is often necessary to plane products to get straight faces and edges and high levels of twist result in high wood losses. Drying practices can reduce twist (to a degree). It will also help to reduce planing losses if products are of a relatively narrow width—a factor to consider when comparing product choices for this resource. The high levels of twist of *E. cladocalyx* and *E. gomphocephala* were almost certainly a result of the high grain angles, caused by spiral grain, of these two species. The much lower twist of *E.*

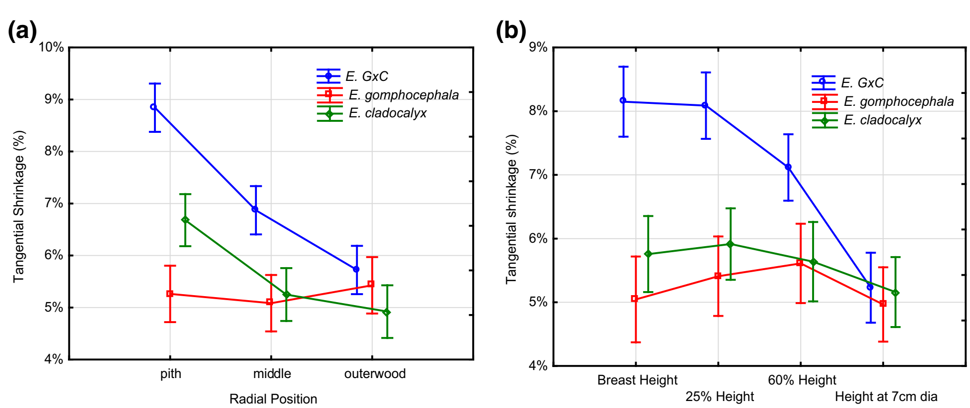

Fig. 6 Means and 95 % confidence intervals for tangential shrinkage of the different species at various radial positions (**a**) and heights (**b**)

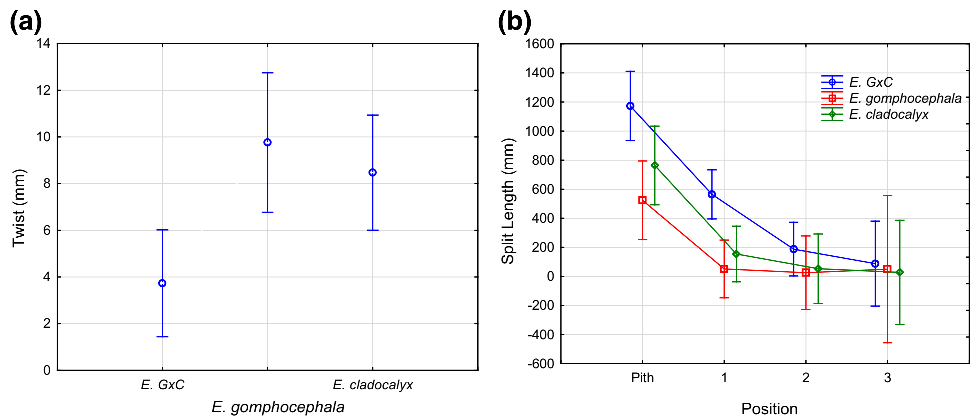

Fig. 7 Mean twist (**a**) and split length (**b**) and 95 % confidence intervals for 1.5 m long boards

grandis × *camaldulensis* was probably partly a result of the lower grain angle as well as the high levels of splitting that occurred and which masked some of the twist. Research by Famiri et al. (2011) showed that girdling of standing trees might be a potential method of reducing distortions in lumber from *E. gomphocephala*.

Neither species nor radial position was a significant factor influencing bow. The mean bow for all the specimens was 2.6 mm over 1.5 m long which was fairly low compared to the allowable bow for appearance grade lumber of 7.5 mm (SANS 1783-3:2010).

The total split length was significantly influenced by both species and radial position, but not by the interaction between these two effects (Fig. 7b). The splitting levels for the *E. grandis* × *camaldulensis* hybrid were extremely high—especially on the pith boards. The mean split length on the hybrid pith board was nearly 1.2 m of a total board length of 1.5 m. Splitting of the hybrid boards was of such a magnitude that many solid wood applications will not be options for this resource. The *E. cladocalyx* splitting levels were lower than the hybrid, and *E. gomphocephala* boards had the least splitting.

Most of the splitting appeared directly after sawing of the logs, which indicated that it was due to growth stresses. Many *Eucalyptus* species are well known for its high levels of growth stresses present (Jacobs 1955; Malan 1984, 2003). It is hypothesized that the relatively lower splitting observed for *E. cladocalyx* and *E. gomphocephala* boards might be due to the wavy and interlocked grain present in these two species. These phenomena probably break the typical splitting planes of the wood and stop propagation of a new split when grain angles diverge from each other within the split. *E. gomphocephala,* which had very high grain angles at the pith and at breast height, and also had (from visual observation) severe wavy grain, and interlocked grain, had by far the lowest mean splitting of pith boards. Different sawing patterns might result in lower levels of splitting for the *E. grandis* × *camaldulensis* hybrid boards, although there will be a limit to the ameliorating potential of this strategy as splitting already affected most of the logs before sawing took place.

4.7 Collapse

Collapse was based on a visual assessment of surface area affected on each board. Results for the three species can be seen in Table 5. The hybrid *E. grandis* × *camaldulensis* was most affected by collapse as more than half of all the boards showed some degree of collapse. *E. gomphocephala* was not affected by collapse at all and *E. cladocalyx* had limited area where collapse was visible. Collapse can be minimised and even recovered, to a degree, using suitable drying and steaming practices. However, for appearance grade products collapse is usually removed and results in lower value recovery.

5 Conclusion

5.1 *E. grandis* × *camaldulensis*

The wood properties of this hybrid were in general markedly different to the other two species. In appearance the heartwood was of a pink to light red colour compared to the other two species which were light yellowish-brown. The spiral grain angle was relatively low and subsequently the

Table 5 Percentage of boards from each species falling in one of four collapse classes based on surface area affected

Species	n	Surface area affected by collapse			
		0 (%)	0–15 (%)	15–30 (%)	≥30 (%)
E. GxC	49	43	22	18	16
E. gomphocephala	30	100	0	0	0
E. cladocalyx	34	82	12	6	0

twist of boards was also much lower than the other two species. The density of the hybrid was significantly lower at all locations within the tree than *E. gomphocephala* and *E. cladocalyx*. In terms of shrinkage and collapse the hybrid performed poorly compared to the other two species. The main shortcoming of the *E. grandis* × *camaldulensis* hybrid as a resource for lumber is the high levels of splitting around the pith. Alternative sawing and drying methods might be able to improve some of the properties such as splitting and collapse. However, as a resource for high value solid wood products this hybrid was inferior in terms of most relevant properties to the other two species evaluated.

Future research should in the first place focus on strategies to improve the splitting behaviour of the *E. grandis* × *camaldulensis*. Sawing methods and tree breeding selection criteria might be options to investigate as possible solutions to the splitting problem.

5.2 *E. gomphocephala*

Eucalyptus gomphocephala had the highest mean density of the three species. However, it also had the highest mean MFA as well as the highest mean grain angles close to the pith. This resulted in this species having the lowest mean MOE of the three species evaluated in this study. The MOE was still sufficient for most applications such as structural or appearance grade lumber, but might put the lumber at a disadvantage against high value species typically used for decking or flooring. Probably the main shortcoming of this species was the high spiral grain angles found at breast height, which resulted in extremely high levels of twist. Stem form, which was not measured in this study, was also very poor and should be a focus area where silvicultural intervention (planting density and thinning) and tree breeding might be utilized for improving the straightness of boles.

Eucalyptus gomphocephala is a species that performed well, in terms of growth, on very dry sites. The very high density of its wood might make this a good species to use for multiple end-product processing where products which can gain advantage of high density, such as chips for biofuel, is one of the end-products together with lumber. If the tree is used solely for lumber production, the poor stem form and high levels of twist might result in very low yields of useable final product.

For this species, in terms of wood properties and processing, future research should focus on reducing the levels of twist of boards. The spiral grain angles at the lower part of the stem (breast height) is most probably the main reason for the twist and it might be possible to utilise tree breeding selection strategies to reduce grain angles. Research on other species indicated that spiral grain angle is under genetic control—although there might also be environmental factors involved (Säll 2002). Lower grain angles will also improve the MOE of the wood. Drying practices together with sawing methods should also be investigated for reducing twist in boards.

5.3 *E. cladocalyx*

Eucalyptus cladocalyx had relatively high density (slightly lower than *E. gomphocephala*), and the lowest MFA of all three species. The result was that despite relatively high grain angles, it had very high MOE and MOR values. *E. cladocalyx* performed similar to or slightly worse than *E. gomphocephala* in terms of shrinkage, splitting and collapse. As with *E. gomphocephala,* the main challenge of this species will be the high levels of twist in boards—although twist was slightly lower than that of *E. gomphocephala*. The fact that stem form was much better than *E. gomphocephala*, gives this species a big advantage in terms of product yield potential.

Further research should thus also focus on factors which could reduce the levels of twist in boards. In terms of processing, sawing wide slabs which can be dried under restraint (weight) and then reworked into narrow, high value products such as decking, might be one option to investigate. Tree breeding can, in the longer term, be used to reduce spiral grain angles of this species.

According to literature, one of the strengths of both *E. cladocalyx* and *E. gomphocephala* is the durability of the heartwood—both species were described as highly durable in Australian studies (Cookson 2004). In a South African study on utility poles, however, the heartwood of *E. cladocalyx* was found to be susceptible to termite attacks in the northern parts of the country (Vermaak 1979). It is probable that the highest value lumber products from these species might be heartwood lumber for external use such as decking, balustrades, garden furniture or external structures not permanently in ground contact. The durability and heartwood/sapwood ratios for South African grown *E. cladocalyx* and *E. gomphocephala* should be verified in the different areas of the country.

This study provided data on the within-tree variation of wood properties relevant for solid lumber production from three drought-resistant species grown on the arid west coast of South Africa. As far as the authors are aware of this was the most comprehensive study for any of these species in terms of the within-tree variation data of wood properties measured. Some data, such as MFA, had never been measured and reported on before for two of the species. The knowledge gained in the study can be used for planting, end-product and processing decision support as well as choices for further research in this field.

Acknowledgments Our appreciation to the following persons who helped with field work and measurements during this study: Mark February, Anna Clarin, Wilmour Hendrikse, Emile Kitenge, Robert Mupamba, Lars Olson, and Nils-Olaf Petersen. We gratefully acknowledge funding for the study by the Swedish International Development Agency (SIDA) and co-funding by Research Institutes of Sweden (RISE).

References

Banks CH, Otto KP, Van Vuuren WFJ (1976) The mechanical properties of timbers with particular reference to those grown in the Republic of South Africa. South African Forestry Research Institute. Bulletin 48:1–88

Bhat KM, Bhat KK, Dhamodaran TK (1990) Wood density and fiber length of *Eucalyptus grandis* grown in Kerala India. Wood Fiber Sci 22(1):54–61

Blakemore P (2004) Density and shrinkage of four low-rainfall plantation-grown eucalypts. Aust For 67(3):152–155

Blakemore P, Waugh G, Northway R, Washusen R (2003) High value, solid wood products from low rainfall (450–650 mm/year) farm forestry. A report for the RIRDC/Land and Water Australia/FWPRDC Joint Venture Agroforestry Program. Publication No. 03/022. Project No. PN 99.2002

Boland DJ, Brooker MIH, Chippendale GM, Hall N, Hyland BPM, Johnson RD, Kleinig DA, McDonald MW, Turner JD (2006) Forest trees of Australia. CSIRO Publishing, Collingwood

BS 373:1957 (2008) British Standard. Methods of testing small clear specimens of timber

Chafe SC (1990) Effect of brief presteaming on shrinkage, collapse and other wood-water relationships in *Eucalyptus regnans* E Muell. Wood Sci Technol 24:311–326

CIFOR (2011) Centre for International Forestry Research webpage. http://www.cifor.org/events/dry-forests.html. Accessed 15 Nov 2011

Cookson LJ (2004) The in-ground natural durability of Australian timbers. Report project PN04.1004. Forest and Wood Products Research and Development Corporation. Australian Government. p 12

Donaldson L (2008) Microfibril angle: measurement, variation and relationships—a review. IAWA J 29(4):345–386

Ellis F (1995) Drought resistance of *Eucalyptus* species/provenances on sandy soils along the dry South African Cape West Coast: a case study. In: Schulte A and D Ruhiyat (eds) Proceedings of International Congress of Tropical Forest Ecosystems. Third conference on forest soils. Balikpapan, Indonesia, pp 106–114

Ellis F, Van Laar A (1999) Nutrient levels of three *eucalyptus* species provenances, measured over four seasons in a trial along the sandy, dry, Cape west coast of South Africa. South Afr For J 184:33–40

Evans R, Ilic J (2001) Rapid prediction of wood stiffness from microfibril angle and density. For Prod J 51(3):53–57

Evans R, Stringer S, Kibblewhite RP (2000) Variation of microfibril angle, density and fibre orientation in twenty-nine *Eucalyptus nitens* trees. Appita J 53(5):450–457

Famiri A, Kabouchi B, Baillères H, El Abid A, El Alami S, Hakam A (2011) Effect of standing trees girdling on the fissurations propagation and sawing distortions for two eucalyptus species: *E. grandis* and *E. gomphocephala*. Phys Chem News 59:65–72

FANR (2011) SADC Food Agriculture and Natural resources webpage http://www.sadc.int/fanr/naturalresources/forestry/management.php. Accessed 5 Oct 2011

FAO (1989) Arid zone forestry: a guide for field technicians. http://www.fao.org/docrep/t0122e/t0122e00.htm#Contents. Accessed 21 Oct 2014

FAO (2014) Food and agriculture organization ecocrop database. Webpage http://ecocrop.fao.org/ecocrop/srv/en/home. Accessed 13 Oct 2014

Ferrari G (1995) Variation in *Eucalyptus* sp. wood properties with tree height. Econ Mont Linea Ecol 27(5):53–58 **(in Italian)**

Foslie M (1971) Strength properties of Norway spruce. Part 3—strength properties of small defect free specimens. Report No 42. Norwegian Institute of Wood Technology (in Norwegian)

French J, Conn AB, Batchelor WJ, Parker IH (2000) The effect of fibril angle on some handsheet mechanical properties. Appita J 53:210–217

Githiomi JK, Kariuki JG (2010) Wood basic density of *Eucalyptus grandis* from plantations in central rift valley, Kenya: variation with age, height level and between sapwood and heartwood. J Trop For Sci 22(3):281–286

Ilic J (1999) Shrinkage-related degrade and its association with some physical properties in *Eucalyptus* regnans F Muell. Wood Sci Technol 33:425–437

Jacobs MR (1955) Growth habits of the Eucalypts. Commonwealth Forestry and Timber Bureau, Canberra

Le Roux PJ (1975) Afforestation in low rainfall areas. S Afr For J 93:1–6

Lima JT, Breese MC, Cahalan CM (2004) Variation in microfibril angle in *Eucalyptus* clones. Holzforschung 58:160–166

Lundqvist SO, Grahn T, Olsson L (2013) Properties of materials from birch—variations and relationships. Part 1: growth, wood density and biomass. Innventia Report No 390

Malan FS (1984) Studies on the phenotypic variation in growth stress intensity and its association with tree and wood properties of South African grown *Eucalyptus grandis* (Hill ex Maiden). Dissertation, University of Stellenbosch

Malan FS (1993) The wood properties and qualities of three South African-grown Eucalypt hybrids. S Afr For J 167:35–44

Malan FS (2003) The wood quality of the South African timber resource for high-value solid wood products and its role in sustainable forestry. South Afr For J 198:53–62

Munalula F, Meincken M (2009) An evaluation of South African fuelwood with regards to calorific value and environmental impact. Biomass Bioenergy 3(3):415–420

Ozarska B (2009) Engineering properties of selected young plantation-grown Australian hardwoods for furniture. For Prod J 59(7–8):27–30

Phiri D, Ackerman PA, Wessels CB, Johansson M, Säll H, Lundqvist S-O, du Toit B, Seifert T (2015) Biomass equations for selected drought tolerant eucalypts in South Africa. South For. doi:10.2989/20702620.2015.1055542

Potts BM, Dungey HS (2004) Interspecific hybridization of *Eucalyptus*: key issues for breeders and geneticists. New For 27(2):115–138

Roux J, Hurley BP, Wingfield MJ (2012) Diseases and pests of eucalypts, pines and wattle. In: Bredenkamp B, Upfold SJ (eds) S Afr For Handb, 5th edn. Published by the Southern African Institute of Forestry, Menlo Park, pp 303–335

Säll H (2002) Spiral grain in Norway spruce. Acta Wexionesia No. 22/2002. ISBN: 91-7636-356-2. Dissertation, Växjö University

SANS 1783-1 (2009) South African National Standard. Sawn softwood timber. Part 1: General requirements

SANS 1783-3 (2010) South African National Standard. Sawn softwood timber. Part 3: Industrial timber

Stern-Cohen S, Fahn A (1964) Structure and variation of the wood fibres of *Eucalyptus gomphocephala* along and across the stem. La Yaaran 14(4):132–133

Stuart S, Evans R (1994) X-ray diffraction estimation of the microfibril angle variation in eucalypt wood. Appita J 48:197–200

Taylor FW (1973) Variation in anatomical properties of South African grown *Eucalyptus grandis*. Appita 27:171–178

Thinley C, Palmer G, Vanclay JK, Henson M (2005) Spiral and interlocking grain in *Eucalyptus dunnii*. Holz Roh-Werkst 63:372–379

Tribe GD (2005) The present status of *Anaphes nitens* (Hymenoptera: Mymaridae), an egg parasitoid of the Eucalyptus snout beetle Gonipterus scutellatus, in the Western Cape Province of South Africa. South Afr For J 203(1):49–54

Van Wyk G, Van Laar A, Theron JM (2001) Yield potential of selected *Eucalyptus* genetic stock on the sandy soils of the South African Cape west coast. South Afr For J 191(1):9–19

Vermaak GS (1979) Service tests of telephone poles of ten *Eucalyptus* and Three Pinus species. S Afr For J 109(1):26–31

Vermaas HF, Bariska M (1994) Collapse during low temperature drying of *Eucalyptus grandis W. Hill* and Pinus silvestris L. In: Proceedings IUFRO Wood Drying Conference, Rotorua, New Zealand 141–150

Von Doderer CCC, Kleynhans TE (2010) Financial viability of agroforestry for bioelectricity generation on various farm types in the Western Cape South Africa. Agrekon 49(2):168–194

Washusen R, Waugh G, Hudson I (1996) Wood products from low-rainfall farm forestry. Forest and Wood product Research and Development Corporation. Project report PN 007.96

Wimmer R, Downes M, Evans R (2002) Temporal variation of microfibril angle in *Eucalyptus nitens* grown in different irrigation regimes. Tree Physiol 22:449–457

Yang JL, Evans R (2003) Prediction of MOE of eucalypt wood from microfibril angle and density. Holz Roh Werkst 61(6):449–452