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Evaluation of Growth and Wood Traits in *E. camaldulensis* and Interspecific Eucalypt Hybrid Clones Raised at Three Diverse Sites in Southern India

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Abstract

Twenty-five *Eucalyptus* clones (14 *E. camaldulensis* - EC and 11 interspecific eucalypt hybrid clones - EH) grown in three contrasting sites were evaluated for the growth and few wood traits at 4 years of age. The stability, genotype-site interaction and suitability of these clones for pulp and solid wood industry sectors were studied. Growth of eucalypt clones was significantly higher at site 1 with higher rainfall, but wood density did not differ significantly from lower rainfall sites. Kraft pulp yield (KPY) decreased from sites 1 to 3 based on moisture availability, but not between two groups of clones. Volumetric shrinkage (VS) was significantly higher in EC clones at site 3 with lowest rainfall, but there was no specific trend at other two sites with maximum (site 1) and intermediate (site 2) rainfall. The mechanical traits modulus of rupture (MOR) and modulus of elasticity (MOE) were at par in sites 1 and 2, but significantly lower at the driest site 3. The growth rate had a significant positive correlation with KPY, MOR and MOE and a negative correlation with VS, but no significant impact on wood density in both groups of clones. Genotype×environment interaction (G×E) was evident in most traits due to the difference in response of clones to moisture availability. Since wood density was negatively correlated to KPY, it has to be kept at an optimum level for the profitability of pulp industry. There was no significant difference between EC and EH clones for most traits except VS at site 3. Stability of clones varied across sites in different traits, and hence clones may be selected for deployment at each site by screening for growth, followed by wood density, considering the relationship of growth and density with other traits required by pulp and solid wood industry sectors.

Key Words: *Eucalyptus* clones, growth, wood traits, density, pulp yield

Introduction

Eucalyptus is planted worldwide as an important source of raw material for pulp industry, due to its fast growth and potential to produce wood biomass in short rotations. Breeding programs and clonal forestry have helped to increase wood productivity and pulp yield in the last three decades (Rezende et al. 2014). *E. camaldulensis* is the ma-

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jor eucalypt species planted in India due to its adaptability to harsh climatic conditions (Varghese et al. 2017), while interspecific hybrids of *E. grandis*, *E. urophylla*, *E. pellita* and *E. camaldulensis* are the major planted eucalypt taxa in many countries (Luo et al. 2012). Interspecific hybrids are widely grown in high rainfall regions with well drained fertile soils due the high productivity and pulp yield that are important for the profitability of the pulp industry (Lee et al. 2001; Prasetyo et al. 2018; Listyanto et al. 2020). Deployment of *E. camaldulensis* clones has helped to increase the wood yield in farmlands in India in short rotations of three to four years. While pulp industry is the major consumer of *Eucalyptus* wood, consumption by the solid wood and veneer industry sectors has also increased recently (Wu et al. 2006) due to the shortage of traditional timber from natural forests. The wood traits required for pulp and timber industry are quite different (Raymond 2002) and it is necessary to understand how these traits differ between the clones and stability of the traits across sites. To meet the increasing requirement of pulp wood, plantations are being extended to marginal sites with low rainfall (Lee et al. 2001). For successful establishment in diverse sites, it is necessary to identify the genotypes that match different site conditions. Pure species and interspecific hybrid clones may perform differently in diverse edaphic and climatic conditions. Expanding plantations to arid sites also requires careful selection of clones that can withstand long dry spells.

Interspecific hybrids of *E. camaldulensis* with other species like *E. urophylla*, *E. pellita* and *E. grandis* that generally grow in high rainfall locations can combine the drought tolerance of *E. camaldulensis* and wood traits of the other species (Prasetyo et al. 2017). Rapid increase in hybrid clone deployment was reported in several countries due to the recognition that hybrids have improved growth and wood traits compared to the parent species (Assis 2000). The physical wood properties of eight- to ten-year-old *Eucalyptus* species (Shukla and Rajput 1983; Kamala et al. 1995) and four-year-old *E. camaldulensis* clones (Kothiyal 2006) were evaluated in India, but information on the wood traits of eucalypt hybrids is very limited. Raymond (2002) emphasised the need for prioritising the wood traits to be incorporated in breeding programs for different end products. Breeding programs in India have considered pulp traits of *E. camaldulensis* clones and seedlots (Varghese et al. 2008), but not the traits that are of significance to the solid wood industry (Raymond 2002) like volumetric shrinkage, modulus of rupture and modulus of elasticity (Sharma et al. 2005). For planning a robust plantation program for industrial wood supply, it is necessary to clearly define the traits required by each industry.

To cope with changing environments, plants resort to phenotypic plasticity, which determines the stability of the genotypes in different environments (Hanson 1970). Growth rate is the most important trait often assessed for industrial wood production, especially for solid wood, as large diameter logs are desirable for better recovery of sawn wood (Lundqvist et al. 2017). Genotype×site interaction was evaluated for growth and pulp yield in *E. camaldulensis* in India (Varghese et al. 2017), but the physical parameters of wood were not well evaluated, though it is reported that the pattern of variation in the traits can differ across sites (Muneri and Raymond 2002). If clones suitable to both the pulp and solid wood industry can be developed (Prasetyo et al. 2017), it would help in capturing greater value for the wood produced from a unit area and providing higher income to the farmers. While lot of emphasis is given for enhancing wood production by breeding and deploying high yielding clones for pulp industry, it is also necessary to consider the traits required by the solid wood industry, and develop the clones desired for multiple end uses (Raymond 2002). Testing clones in diverse sites covering different edaphic and climatic conditions is a prerequisite for identifying stable and adaptable genotypes suitable for growth and wood traits required by the pulp and solid wood industry. A study was therefore undertaken to evaluate pure *E. camaldulensis* and interspecific eucalypt hybrid clones grown across three diverse sites that differ in maximum temperature, duration of dry spell and total annual rainfall. This study aims to assess the growth and wood traits of pure *E. camaldulensis* and interspecific eucalypt hybrid clones to identify stable as well as site-specific clones with different desired traits suitable for the pulp and paper as well as solid wood-based industry sectors.

Materials and Methods

Study sites and experimental design

Twenty-five Eucalyptus clones (14 *E. camaldulensis* and 11 *Eucalyptus* hybrids) were evaluated at three diverse sites (Fig. 1, 2, Site 1: KOY-Andhra Pradesh, Site 2: KOV – Tamil Nadu and Site 3: MBN – Telangana) located in southern India (mean annual rainfall decreasing from sites 1 to 3). Details of the test locations are given in Table 1. The interspecific hybrids comprised of ten *E. camadulensis*× *E. urophylla* clones (Clones 1-10) and one *E. urograndis* (*E. urophylla*× *E. grandis*) clone (Clone 25). Pure *E. camaldulensis* clones (EC) included 10 selections from progeny trials (Clones 11-20) of imported natural seed lots, and four commercial EC clones (Clones 21-24). Clone trials were established in randomised complete block design (RCBD) with five replications of three trees per replication at a spacing of 3 m between rows and 1.5 m within row (375 trees per site in 0.17 ha).

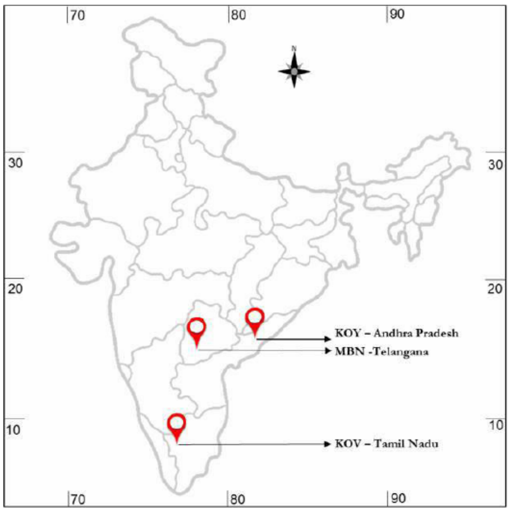

Fig. 1. Map showing location of study sites in India.

Sample collection and property evaluation

The trials were evaluated for growth (diameter at breast height – DBH) and wood traits at four years. While all the trees (15 trees per clone) were evaluated for DBH, increment core samples (5 mm diameter) were extracted at

(a) (b) (c)

Fig. 2. Field trials. (a) KOY- Andhra Pradesh, (b) KOV-Tamil Nadu, (c) MBN-Telangana.

Table 1. Description of field trial sites

Site parameters	Trial site		
	Site 1: KOY	Site 2: KOV	Site 3: MBN
Latitude (N)	17°12'	11°19'	16°44'
Longitude (E)	81°41'	77°56'	77°59'
Altitude (m)	90	426	498
Mean Annual Rainfall (mm)	925	760	613
Mean daily maximum temperature of hottest month (°C)	42	35.4	42
Mean daily minimum temperature of coldest month (°C)	17.6	19.7	15.6
Dry season (consecutive months with mean monthly rainfall <40 mm	5	4	7
Soil texture	Loam	Loam	Sandy loam

breast height from three trees of each clone at each site (one tree each from three replications − nine trees from three sites of each clone), for estimating the pulp yield from powdered wood meal using NIRS calibration curve developed for *Eucalyptus* species (Ramadevi et al. 2010). After extracting the core samples, bottom billets of about 1 m length (lower part from breast height) were obtained from the same trees (total 225 trees-75 trees from each site). The billets were converted into wood specimens of different sizes described in Indian standards (Anon 1986). The wood specimens were tested to evaluate the basic wood density, volumetric shrinkage and two static bending parameters, namely flexural strength (modulus of rupture-MOR) and flexural stiffness (modulus of elasticity-MOE). The testing procedures are given briefly as follows (Anon 1986; Shukla et al. 2022):

Equilibrium moisture content (EMC)

Wood specimens of the size 20×20×25 mm^3 were selected from the tested specimens immediately after completion of mechanical tests. All the specimens were weighed initially with an accuracy of 0.001 g. The final weight was taken after drying in a well-ventilated oven at 103±2°C for 24-48 h when variation between last two readings did not exceed 0.002 g. The EMC of the test samples was computed as follows:

$$EMC=((W_1-W_0)/W_0)\times 100 \quad (1)$$

where W_1=weight of wood specimen at test (g) and W_0=oven-dry weight of specimen (g).

Wood density

The specimen size was 20×20 mm in cross-section and 60 mm in length. The specimens were weighed correctly to 0.001g and dimensions were measured correctly to 0.01 mm using a digital caliper. Volume of each specimen was determined by multiplying the dimensions. The density (kg/m^3) of wood specimen was calculated using the following equation:

$$Density=W/V \quad (2)$$

where W is the weight (kg) of specimen and V is the volume at test condition (m^3).

Volumetric shrinkage

Test specimens for radial and tangential shrinkage were 20×20 mm^2 in cross section and 60 mm in length. Dimensions of the specimen were measured correct to 0.01 mm by means of a digital caliper. The specimens were allowed to dry in an oven at 103±2°C until an approximately constant weight is reached. After oven-drying, the specimen volume was determined again. The volumetric shrinkage (VS) from initial condition to oven-dry condition is computed using following equation:

$$VS(\%)=((V_1-V_0)/V_1)\times 100 \quad (3)$$

where V_1=volume in initial condition (mm^3) and V_0= volume in oven dry condition (mm^3).

Flexural properties

The flexural *parameters* were evaluated according to the procedure given in Indian standards IS: 1708 (Anon. 1986) using a 50 kN computerized universal testing machine (AG-50, Shimadzu, Japan). The wood specimens were kept in an airy room for conditioning at temperature 24±5°C and relative humidity 70±5% for more than three months. The size of specimens was 20×20×300 mm^3 with a span length of 280 mm. Rate of loading was kept constant at 1.0 mm/min and load was applied on tangential surface of each test specimen. Two flexural parameters (MOR and MOE) were computed using following equations:

$$MOR=(3\times P_m\times l)/(2\times b\times h^2) \quad (4a)$$

$$MOE=(P\times l^3)/(4\times D\times b\times h^3) \quad (4b)$$

where P=load at the limit of proportionality (kN); P_m=maximum load (kN), l=span of the test specimen (mm), b=breadth of the test specimen (mm), h=depth of the test specimen (mm) and D=deflection at the limit of proportionality (mm).

Data analysis

The data were subjected to analysis of variance (ANOVA) using the statistical package R (R core Team 2022), followed by post hoc Tukey HSD test of the mean value of each clone from the three sites for each trait using the package "Agricolae" (de Mendiburu 2019). The variation in each trait across the sites was represented as box plots using the package ggplot2 (Wickham 2016). The stability of the clones was determined by developing a linear regression value for each trait against the site mean values of all the clones using the following regression model (Malan and Verryn 1996):

$$Y = a + bX \quad (5)$$

where: Y is the mean value of the clone for a particular trait, a is the Y-intercept, b is the regression coefficient, X is the mean value of the site for a particular trait.

The clones with regression coefficient close to 1 (>0.5 and <1.5) were considered to have average stability across the three sites. Clones with regression coefficient above 1 were sensitive to the changes in the environment (higher values showing below average stability) and those with values less than 1 (above average stability) were less sensitive to the site variation (Malan and Verryn 1996). The regression value of each clone was plotted against the mean value of the clone across the three sites to depict the stability of the clone for each trait assuming that the site's environmental conditions affect the tree's characteristics at regression coefficient intervals of 0.5. The clone×site interaction was studied in three selected clones − Clone 1 (the most productive, stable hybrid), Clone 25 (*E. urograndis* - a high productivity hybrid clone, with low growth stability), and Clone 24 (a commercial EC clone with stable growth) by plotting the mean values of the three clones at each site. Phenotypic correlation between the mean values of each trait for all the three sites was estimated for the pure *E. ca-*

Table 2. Comparison of mean values of different Eucalyptus taxa at three locations based on analysis of variance

Location 1 - KOV

Taxa	Ht (m)	DBH (cm)	BD (kg m^{-3})	PY (%)	VS (%)	MOR (MPa)	MOE (GPa)
EC-Commercial clone	10.2	7.7	610.8	46.3	6.2	83.5	7.2
EC×EU Hybrid clone	9.9	9.0	612.9	47.9	7.2	81.5	7.4
EC-Native seed clone	9.9	7.7	619.4	44.7	5.8	85.9	7.9
E. urograndis clone	9.8	7.5	609.9	46.6	6.0	100.3	9.6
p	0.138	0.995	0.389	<0.001	<0.001	0.158	0.007
SE	0.308	0.351	8.29	0.383	0.2399	3.5	0.282

Location 2 - KOY

Taxa	Ht (m)	DBH (cm)	BD (kg m^{-3})	PY (%)	VS (%)	MOR (MPa)	MOE (GPa)
EC-Commercial clone	11.8	9.4	600.3	47.2	6.9	84.1	8.6
EC×EU Hybrid clone	13.2	9.9	583.8	47.0	6.0	79.8	7.9
EC-Native seed clone	12.0	10.5	585.5	49.1	5.9	73.7	6.9
E. urograndis clone	14.0	12.3	625.7	47.2	6.8	86.7	9.2
p	0.003	<0.001	0.188	<0.001	<0.001	<0.001	<0.001
SE	0.410	0.348	11.760	0.264	1.843	2.830	0.281

Location 3 - MBN

Taxa	Ht (m)	DBH (cm)	BD (kg m^{-3})	PY (%)	VS (%)	MOR (MPa)	MOE (GPa)
EC-Commercial clone	9.55	7.21	602.24	43.93	711.29	77.31	7.20
EC×EU Hybrid clone	9.68	7.61	606.72	43.01	713.05	63.08	5.60
EC-Native seed clone	9.29	8.27	636.49	46.19	731.17	52.99	4.61
E. urograndis clone	9.17	7.21	587.29	44.53	684.26	74.89	7.21
p	0.313	0.122	<0.001	<0.001	<0.001	<0.001	<0.001
SE	0.394	0.369	9.570	0.302	0.275	2.139	0.255

maldulensis and interspecific hybrid clones separately to compare the changes in traits across the two groups of taxa.

Results and Discussion

Variation across sites

The mean value of different wood traits of many genotypes at a site can be used as a biological estimate of the site quality index (Malan and Verryn 1996). The mean values of DBH in clones of the different taxa: EC, *E. camaldulensis*×*E. urophylla* hybrids and *E. urograndis* in the three sites are given in Table 2. The *E. urograndis* clone had significantly higher DBH than EC and other hybrids at KOY but not in the other sites. The trees at the high rainfall KOY site had significantly higher DBH than the other two sites with lower comparable values. The hybrids showed greater variance in growth than EC clones at the KOY site (Fig. 3a), though many clones were in the lower quartile in both the groups. At the medium rainfall KOV site, the variation was comparatively low in both hybrids and EC, whereas EC clones showed greater variance at the dry MBN site. The growth response to site conditions can vary in different taxa as reported by Rubilar et al. (2020) in a study of 30 genotypes across two contrasting sites with low and high irrigation treatments. They reported greater growth with irrigation in most taxa, but less difference in *E. nitens*×*globulus* hybrids compared to *E. nitens* and *E. globulus* genotypes.

Wood density and shrinkage are two important traits that determine the suitability of wood for different end uses like solid wood products (Wu et al. 2006) and pulp and paper (Wimmer et al. 2002). The mean basic density of hybrid and pure EC clones was lower at the KOY site (590 kg/m^3), but not significantly less than the mean value of the two drier locations (605-625 kg/m^3). The density variation among clones was similar in EC and hybrids at KOY, but there was no specific trend at the other two sites (Fig. 3b). The *E. urograndis* clone had significantly lower density than other taxa at the low rainfall MBN site whereas it was comparable at the other sites (Table 2). Litsyanto et al. (2020) reported lower wood density with better growth in eucalypts, whereas this trend was not very significant in the current study. Wood density in eucalypts is influenced by many factors such as site conditions, the species, growth rate, provenance and age of the stand (Muneri and Raymond 2000). The absolute kraft pulp yield (KPY) was 4-5% higher in the moist KOY site than MBN (Fig. 3c). At the medium rainfall KOV site, both groups had intermediate KPY (45%) and exhibited similar variance pattern. This observation is in line with the trend reported in other studies (Downes et al. 2006; Gardner et al. 2007). Ramadevi et al. (2018) also reported 5-6% difference in pulp yield between dry and moist sites in four-year-old *E. camaldulensis* clones.

There was no specific trend in the variation in volumetric shrinkage in two groups of clones (Fig. 3d). Average VS value was high in EC clones (8.5%) at the dry MBN site, while it was comparable at the other two sites (5.9 to 6.2%). The hybrids had a similar trend of significantly lower VS at KOY (5.9%), but higher and comparable values were ob-

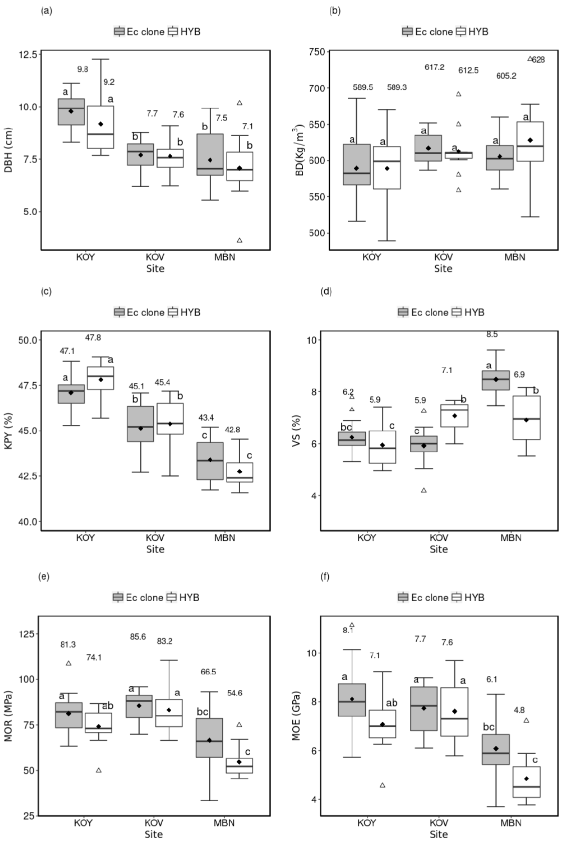

Fig. 3. Variation in (a) DBH and wood traits, (b) basic density, (c) Kraft pulp yield, (d) volumetric shrinkage, (e) modulus of rupture and (f) modulus of elasticity in *E. camaldulensis* (Ec) and hybrid (HYB) clones across three sites. Mean values with the same letter do not differ significantly (◆Mean value, △Outliers).

served at the other dry sites (6.9 to 7.1%). Shrinkage is known to vary between sites in eucalypts (Yang et al. 2002). Litsyanto et al. (2020) reported higher shrinkage in sites with good growth, whereas in the current study, the VS values were significantly higher in EC clones with poor growth at the dry MBN site.

The static bending parameters such as MOR values were significantly lower at the arid MBN site than the other two sites (Fig. 3e).The MOE also followed a similar trend as MOR with low values (Fig. 3f) at the dry site (MBN). In general, MOE values were observed to be less in both hybrids and EC at MBN and higher and comparable at the other locations. Hein et al. (2010) reported significant difference in MOE between *E. urophylla*×*E. grandis* hybrid clones tested at three sites with similar rainfall in Brazil, but no significant variation was seen across the sites.

Stability of clones

The performance of each genotype can be assessed against the average expression of many genotypes at a site, and the regression of each genotypic value against the mean value of the genotype in different sites can be used to compare the phenotypic expression in diverse environments, which indicates its stability (Finlay and Wilkinson 1963). Regression coefficient around 1 indicates average stability of the genotype across sites, and values above 1 indicate below average stability. Values below 1 indicate above average stability, but no response to changes in environment (Malan and Verryn 1996).

For growth (DBH), 8 clones (32%) had regression coefficient values ranging from 0.5 to 1 (Fig. 4a) of which three were hybrids (3, 5 and 7). Stability was comparatively less in the most productive (hybrid clone 2 - that had the highest mean DBH across the three sites) and the least productive (hybrid clone 9 - with lowest mean DBH) clones. Among the commercial clones, only clone 24 had regression coefficient close to 1, but lower mean DBH than the other commercial clones. Four hybrids (1, 4, 6 and 10), and two EC clones (20 and 22) were insensitive to the site conditions whereas 11 clones (44%) had low stability which included four hybrids (2, 8, 9 and 25). The *E. urograndis* clone (clone 25) had high overall growth but least stability across sites. Low stability observed in many clones (regression value more than 1) is due to the better performance in the good site (Souza et al. 2019) and sensitivity to changes in environment as observed in a study of 31 clones in South Africa by Malan and Verryn (1996). Olivera et al. (2020) also observed variation in performance of 109 eucalypt clones across sites in Brazil requiring selection of site-specific clones for high genetic gain at each site.

Wood density values in hybrids may vary depending on effect of heterosis, complementarity or diversity of alleles (Madhibha et al. 2013). Chen et al. (2018) reported intermediate wood density values in *E. urophylla*×*E. tereticornis* hybrids compared to the parent species, which is mostly due to the complimentary expression of the trait in the hybrids. In the present study four clones were very stable (16%) for wood density (Fig. 4b) of which two were hybrids (clones 6 and 25). Seven clones were not responsive (28%) to site differences, but 14 clones (56%) had low stability, with regression coefficients up to 3, of which six were hybrids. A similar classification of *Eucalyptus* clones with average, low and high stability in wood density was done by Malan and Verryn (1996) in South Africa. Lima et al.

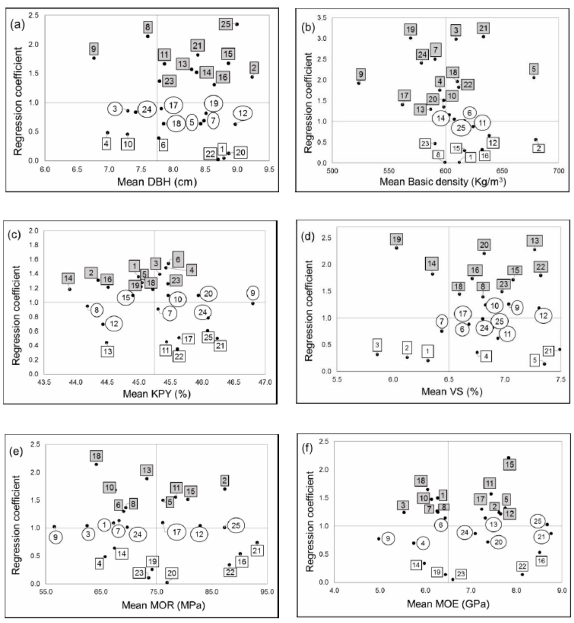

Fig. 4. Regression coefficients of growth. (a) mean DBH and mean wood traits, (b) basic density, (c) Kraft pulp yield, (d) volumetric shrinkage, (e) MOR, (f) MOE in 25 Eucalyptus clones across three sites. Shaded boxes indicate clones with low stability, circles indicate clones with average stability and open boxes indicate clones with above average stability (Hybrids: 1 to 10 & 25, EC clones: 11 to 24).

(2000) reported a lower range in regression coefficients (0.3 to 1.93) in wood density in 26 *Eucalyptus* hybrid clones tested across four sites in Brazil.

For KPY, four hybrids (clones 7, 8, 9 and 10) and four EC clones (12, 15, 20 and 24) showed average stability (32%) across sites, whereas six hybrids (clones 1-6) and five EC (14, 16, 18, 19 and 23) clones had low stability (44%) and six EC clones were not responsive (24%) to site differences (Fig. 4c). Souza et al. (2020) reported a similar trend of variation in stability in pulp yield in pure and interspecific eucalypt hybrids across five sites in Brazil, with some clones being fairly stable and others showing variation across sites. However, Luo et al. (2012) found pulp yield to be fairly stable across four sites with similar rainfall in China, but greater variance among *Eucalyptus* hybrid clones than across sites.

Variation in volumetric shrinkage across sites was more in the EC clones (only four clones had average stability) due to the higher shrinkage at the dry MBN site. Hybrid clones showed comparatively less variation across site (Fig. 4d) with five clones (clones 1-5) not responding to site, and five being fairly stable across site (clones 6, 7, 9, 10 and 25) and one hybrid clone (8) having regression coefficient around 1.5. Malan and Verryn (1996) also found a similar trend of many *E. grandis* clones being not sensitive to site for shrinkage, and a few clones being sensitive. The dry MBN site was not suitable for growing clones for solid wood production due to higher shrinkage than the other sites. Prasetyo et al. (2018) reported lower shrinkage in *E. grandis* compared to other eucalypt species of higher wood density. Similarly, Litsyanto et al. (2020) observed that interspecific hybrids of *E. grandis* with species like *E. camaldulensis* and *E. urophylla* had greater shrinkage than the parent *E. grandis*. Hence, it may be noted that the volumetric shrinkage in *Eucalyptus* hybrids would vary depending on the parent species used for hybridisation. For MOR (Fig. 4e), 11 EC clones were either insensitive or sensitive to the site. Among hybrids, five were stable and five had low stability, and one (clone 4) was not sensitive to site. For MOE (Fig. 4f) the eleven hybrid clones were either stable or unstable across sites, whereas nine EC clones were either stable or not responsive to site changes. Similar variation between clones was reported in various eucalypt species and interspecific hybrids (Andrea et al. 2010; Prasetyo et al. 2018). Regression coefficients were generally significant in clones that showed below average and above average stability compared to the stable clones. The regression coefficients also depend on the range of the values; they were comparatively less in KPY since the range of absolute KPY values was low.

Genotype×environment interaction

Evaluation of genotypes in diverse climatic conditions, especially with differences in length of dry season would help in identifying the productive capacity (Oliveira et al. 2018) and the response to different environments (Pupin et al. 2018). G×E could vary between genotypes and traits depending on the genetic control of the trait (Razafimahatratra et al. 2016) and site factors (Gonçalves et al. 2004). Comparison of three clones – two hybrids and one EC clone – Clone 1: a very productive hybrid with low growth sensitivity to site differences, Clone 25 (*E. urograndis*): a highly productive hybrid clone with low growth stability, and EC clone 24: the most stable EC clone for growth, re-

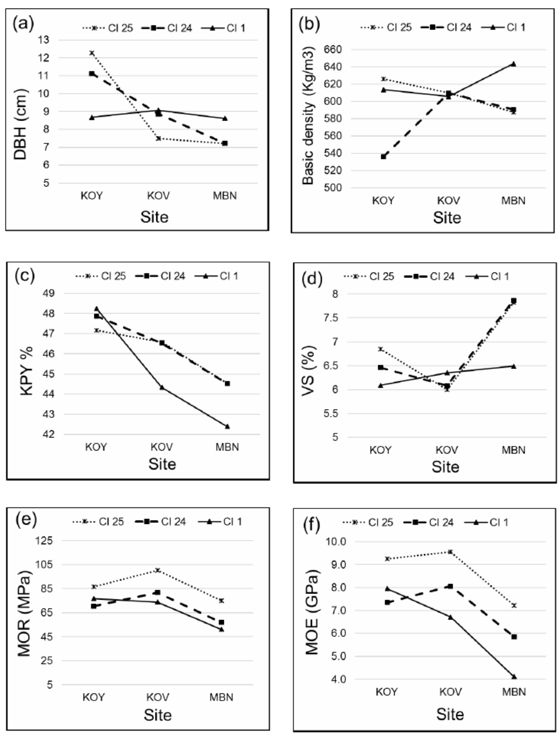

Fig. 5. Mean growth (a) DBH, and wood traits: (b) basic density, (c) kraft pulp yield, (d) volumetric shrinkage, (e) MOR, (f) MOE of three eucalypt clones across three diverse sites.

vealed different patterns of response for each trait. The two hybrids showed different growth response at the high productivity site (KOY). The *E. urograndis* clone (clone 25) showed highest growth among all clones at KOY but significantly lower growth at the other two sites (Fig. 5a). The hybrid clone 1 had more or less uniform growth at all three sites whereas EC 24 was very sensitive to the site conditions with DBH reducing steadily from KOY to KOV and MBN, in response to the length of the dry season. Lundqvist et al. (2017) reported low growth sensitivity with site variation in a eucalypt hybrid clone (*E. grandis*×*E. camaldulensis*) compared to other pure species in South Africa in line with the trend observed in hybrid clone 1 in the present study.

Wood density of the clones showed varying trends across the sites (Fig. 5b). The hybrids (clones 1 and 25) showed a similar decreasing trend between KOY and KOV, but their response to the MBN site was quite different. While clone 25 showed a decreasing trend at the dry MBN site, in line with the observation by Lindqvist et al. (2017), clone 1 had significantly higher wood density at MBN, a trend similar to that reported by Hein et al. (2010). Clone EC 24 had comparatively lower wood density at KOY but higher values on par with clone 25 at other two sites. Chaix et al. (2011) observed higher variance in wood traits of *E. urophylla*×*E. pellita* hybrids than *E. urophylla*×*E. grandis* hybrids tested at a high rainfall site in Congo. Lima et al. (2000) reported significant difference in clone×site interaction in Eucalyptus hybrid clones in Brazil. Wood density is reported to increase in eucalypts with temperature, and decrease with mean annual rainfall (Muneri et al. 2007; Drew et al. 2017). Difference in ranking among clones between sites that differ in temperature and rainfall indicates complex G×E interaction for this trait (Oliveira et al. 2020).

Kraft pulp yield (KPY) followed a consistently decreasing trend with decreasing moisture availability in all the clones (Fig. 5c). Higher pulp yield in sites with better growth is reported in many studies (Downes et al. 2006; Gardner et al. 2007). Souza et al. (2020) recommended identifying a cluster of clones with higher pulp yield than the mean of all clones for each site to reduce the impact of interaction with site. Volumetric shrinkage in EC 24 and clone 25 followed a very similar trend, with significantly high value at MBN and low value at KOV (Fig. 5d). Shrinkage in hybrid clone 1 was more or less at par at the three sites with a slight increasing trend from KOY to MBN. Litsyanto et al. (2020) reported variation in shrinkage among different eucalypt species, with low shrinkage in *E. saligna* than other species like *E. dunii* and *E. pilularis*, and lower shrinkage in *E. grandis* than its hybrids with species like *E. camaldulensis* and *E. urophylla*.

The hybrid clone 25 had higher MOR values than the other two clones at all sites (Fig. 5e), but all the clones followed the same trend across sites with low values at the MBN site. MOE also had a similar trend but the values decreased drastically from KOY to KOV and MBN in response to decrease in moisture availability at the site (Fig. 5f). Hein et al (2010) however found no significant difference in MOE between sites in six-year-old clones of *E. grandis*×*E. urophylla* in Brazil, though there was significant difference between clones for growth and wood traits.

Correlation between traits

Diameter growth at breast height was associated with a

Table 3. Phenotypic correlation between traits in Hybrids (above diagonal) and EC clones (below diagonal)

	DBH	BD	PY	VS	MOR	MOE
DBH		0.25	0.34	-0.45**	0.35*	0.43*
BD	0.08		-0.43*	0.05	0.19	0.20
PY	0.54***	-0.19		-0.26	0.40*	0.44*
VS	-0.23	0.21	-0.56***		0.04	0.04
MOR	0.40**	0.41**	0.35*	-0.30		0.96***
MOE	0.48**	0.31*	0.43**	-0.30	0.91***	

***$p<0.001$, **$p<0.01$, *$p<0.05$.

significant increase in PY across the three sites (Table 3) in *E. camaldulensis* (r=0.54***) but not in the hybrids (r=0.34). Diameter had no significant impact on wood density in both taxa, but a significant positive impact on MOR and MOE in both taxa (r=0.35* to 0.48**). Volumetric shrinkage decreased with increase in DBH only in the hybrids (r=-0.45**). Wood density had a significant negative relationship with PY in the hybrids (r=-0.43*) but not in EC (r=-0.19). The relationship between wood density and cellulose content is reported to vary with species. While Stackpole (2011) observed a negative relationship (r=-0.31) in *E. globulus*, a positive trend (r=0.36) was seen in *E. nitens* (Hamilton et al. 2009) and very low correlation (r=0.09) was reported in *E. urophylla* (Denis et al. 2013). Basic density had a significant positive relation with MOR and MOE in EC clones (r= 0.41*, 0.31*) in the present study but no significant impact on volumetric shrinkage. Chen et al. (2018) reported a positive relationship of growth with cellulose content and wood density in *E. urophylla*×*E. tereticornis* hybrids. Wu et al. (2006) reported a weak positive correlation between wood density and total shrinkage in *E. urophylla*, *E. grandis* and their hybrids, but higher correlation of wood density with tangential and radial shrinkage. Talgatti et al. (2018) reported a significant positive relationship between wood density and static bending properties MOR and MOE in Eucalyptus hybrids. Pulp yield was negatively correlated with volumetric shrinkage in EC (r=-0.56**) but not in the hybrids (r=-0.26), and positively correlated with MOR and MOE in both taxa (r=0.35* to 0.44*). The relationship between pulp yield, wood density and shrinkage are likely to vary with the taxa and location as they are complex traits which may be influenced by anatomical changes in the wood (Wu et al. 2006) based on the response of the taxon to the site effects. Boosting the growth rate by growing in good sites with higher moisture availability improves the traits desirable for both pulp (KPY) and solid wood (density, VS, MOR and MOE) industry sectors. Basic density has to be kept at an optimum level since it is negatively correlated with KPY (particularly in hybrids), but has a positive impact on MOR and MOE in EC though not quite significant in *E. hybrids*.

Selection of clones for pulp and solid wood uses

Interspecific *Eucalyptus* hybrids are preferred over the parent species (Wu et al. 2011) by companies in Brazil, China and Indonesia due to the benefits of higher growth, drought tolerance, wood density, pulp and fibre traits, but its use in structural purposes is restricted (Carvalho et al. 2004), due to the fact that many eucalypts are prone to shrinkage and warping. Shrinkage properties that affect the dimensional stability of plantation grown eucalypt wood is considered to be influenced by density, but it is also controlled by the anatomical traits like cell wall proportion and lumen dimensions (Wu et al. 2006), which can vary in different species and interspecific hybrids (Lundqvist et al. 2017). Pulpwood breeders aim to maximise cellulose production, which is best achieved if the wood density is between 500-550 kg/m^3 (Marco de Lima et al. 2019), but higher wood density is expected to give better static bending properties (Talgatti et al. 2018). Pulpwood breeding in *Eucalyptus* aims to save the total pulp cost by improving wood density, growth, and pulp yield (Greaves et al. 1997). Chen et al. (2018) however reported a positive correlation of growth with wood density and cellulose content, enabling improvement of both the traits simultaneously with growth, in interspecific hybrids between *E. urophylla* and *E. tereticornis*, in sites with higher rainfall and lower mean temperature (Weng et al. 2014) than the locations in the current study. Wood density in *Eucalyptus* hybrids is reported to be intermediate to the parents and could vary depending on the parents used for hybridisation (Prasetyo et al. 2018). This trend is not quite evident in the present study as the wood density of the parent species (*E. camaldulensis* and *E. urophylla*) used for hybridisation is not very different (Marchesan et al. 2020) and the sites had lower rainfall and higher temperature than the other studies compared here. Hence, the strength parameters are also not drastically different between *E. camaldulensis* and the hybrids in the present study. Interspecific eucalypt hybrids of low density may be quite acceptable as pulpwood but not for solid wood due to the low strength properties (Lundqvist et al. 2017). In the present study, the *E. urograndis* hybrid (clone 25) had comparable wood density as the hybrid clone 1 at two sites but lower density at the dry MBN site. Since there is no consistency in the ranking of the top clones at each site, stability of the clones can be used to refine the selection process and deploy a composite group of clones (Rezende et al. 2019) best suited to each site for different end uses.

Conclusion

This study clearly shows different response of clones in growth and wood traits at the three sites. There are only a few clones that show stability across the sites for more than one trait, and hence it would be necessary to select clones specific to each site. Clones 5, 7, 12 and 19 have average growth stability across the sites, whereas clones 1, 20 and 22 are not impacted by the site with fairly uniform yield across sites. The *E. urograndis* clone 25 is promising in the high productivity site but not at the other sites with lower rainfall. The clones varied in stability of wood density, with clones 6, 11 and 25 having average stability, but hybrid clones 2 (above average stability) and 5 (low stability) had higher density. Since there is no significant correlation between growth and wood density, it may be possible to select for growth and then screen for the wood density. From KPY point of view, stable clones 9, 20 and 24 and clones 21 and 25 that are not sensitive to site can be considered. But the site effect is very evident, as the two dry sites have lower KPY. Since wood density has a negative correlation with pulp yield, it is critical to ensure that wood density does not exceed the desired optimum level. Though several clones showed fair stability in shrinkage, very dry sites with long dry spells are not desirable for both pulp and solid wood industry sectors as KPY, MOR and MOE are low, and shrinkage is high. Moisture availability is a major factor that influences the growth and wood traits of *Eucalyptus* clones, and supplementary irrigation is necessary in low rainfall areas with long dry periods. This study reveals that site selection is important for managing growth and wood traits of *Eucalyptus* clones to match the different end uses. Improving growth rate in productive clones will certainly benefit both the pulp and solid wood industry alike due to the positive correlation of growth with pulp yield, MOR and MOE and negative correlation with volumetric shrinkage.

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