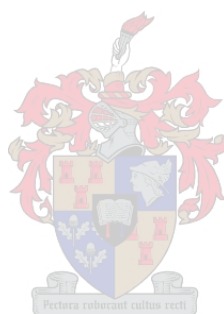# Production potential of Eucalypt woodlots for bio-energy in the Winelands region of the Western Cape

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at the Faculty of AgriSciences

University of Stellenbosch

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Figure 3.5 The top photo illustrates the growth of *E. cladocalyx* at the Coetzenburg site, while the bottom photo illustrates the growth of *E. gomphocephala* at this same site. As the picture illustrates the survival of both species were excellent at this site and the growth similar, as opposed to the Darling site (**Figure 3.4**).

Figure 3.6 Map illustrating the origin of the provenances of *E. cladocalyx* in South Australia (*Google Earth,* 2010)

Figure 3.7 Map illustrating the origin of *E. gomphocephala* provenances in Western Australia (*Google Earth,* 2010)

Table 3.5 Specific families of *E. cladocalyx* at Coetzenburg and Darling sites

Provenance	Seedlot no.	Family	Local Reference
		E. cladocalyx	
Kersbrook SPA	20595	365	A1
Wirrabara SF	20268	JSL3078	B1
		JSL3087	B2
		JSL3088	B3
		JSL3082	B4
		JSL3091	B5
		JSL3084	B6
		JSL3090	B7
		JSL3081	B8
Wilmington	20388	SC14	C1
		SC13	C2
		SC12	C3
		SC15	C4
		SC3	C5
		SC2	C6
		SC11	C7
		SC16	C8
		SC10	C9
		SC4	C10
Cowell	20411	SC27	D1
		SC21	D2
		SC30	D3
		SC23	D4
		SC28	D5
Wirrabara SF	20389	SC56	E1
		SC51	E2
		SC52	E3
		SC57	E4
		SC55	E5
		SC49	E6
Marble Range	19349	GJM2766	F1
		GJM2762	F2
		GJM2760	F3
		GJM2768	F4
		GJM2765	F5
Flinders Chase NP	20267	JSL3053	G1
		JSL3044	G2
			G3
		JSL3055	G4
			G5
		JSL3049	G6
		JSL3048	G7
		JSL3046	G8
		JSL3056	G9
		JSL3052	G10
		JSL3050	G11
Wirrabara SF	20414	SC46	H1
		SC42	H2
		SC43	H3
		SC45	H4
		SC44	H5
		SC47	H6
	LOCAL	CONTROL	I1

Table 3.6 Specific families of *E. gomphocephala* at Coetzenburg and Darling sites

Provenance	Seedlot no.	Family	Local Reference
Darling *E. gomphocephala*			
Harvey	19417	MM1515	1A
		MM1518	1B
		MM1513	1C
		MM1519	1D
		MM1516	1E
		MM1520	1F
		MM1522	1G
		MM1517	1H
		MM1521	1I
		MM1514	1J
Ludlow SF	17675	MM001107	3B
		MM001106	3C
		MM001115	3F
	LOCAL	CONTROL	4A
Yalgorup SF	1763	MM001101	5D
		MM001103	5G
		MM001096	5H
Coetzenburg *E. gomphocephala*			
Harvey	19417	MM1515	1A
		MM1518	1B
		MM1513	1C
		MM1519	1D
		MM1516	1E
		MM1520	1F
		MM1522	1G
		MM1517	1H
		MM1521	1I
		MM1514	1J
Ludlow SF	17675	MM001111	3A
		MM001107	3B
		MM001106	3C
		MM001115	3F
	LOCAL	CONTROL	4A
Yalgorup SF	17673	MM001101	5D
		MM001104	5F
		MM001103	5G
		MM001096	5H

3.3 Volume Estimation

Tree growth has been estimated by collecting the diameter and height of the trees on the sites that form part of this study. The stocking as well as the survival rate of the trees were calculated. These parameters were then used to estimate the volume and hence the growth potential of the stand.

3.2.1 Measurements procedure:

The important characteristics that can be used to make estimate additional properties of trees are tree height and the diameter at breast height (dbh). When faced with trees with irregular form, trees that forked below breast height were considered as two trees, and a fork above breast height was considered as one tree (*Fuwape et al.,* 2001; *Ravindranath & Ostwald,* 2008). In cases of multiple stem leaders, all stems were measured and heights were measured for all tree stems from which a dbh measurement was taken (*Ravindranath & Ostwald,* 2008).

The biomass estimation was done on the families with the largest volumes.. The groups with the highest mean dbh were core-sampled for wood density properties. Within the group, the whole diameter class range was sampled to get a good idea of variation between the dbh classes, although large differences in eucalyptus species are not common (*Illic et al.*, 2000). This method was used on the assumption that more knowledge about the families with the largest volume potential would be beneficial, because they would be more likely to be used further in the region.

The equipment used to take aforementioned measurements:

- DBH tapes : to measure the diameter at breast height of each tree
- Vertex Hypsometer: to measure the tree height

- Relascope: to measure Pressler's height
- Increment corer (20mm): to retrieve increment cores for the density estimation of the families with the top mean dbh.

3.2.2 Volume estimation

The study includes five different Eucalyptus taxa. This required specific equations and variables for each of these genotypes, which are presented in **Table 3.7**. The Schumacher and Hall equation was used to estimate the volume of *E. cladocalyx*.

$$ln\,V = b_0 + b_1\,ln(dbh + f) + b_2\,ln\,H \qquad \text{Equation (3.1)}$$

ln	=	Natural logarithm to the base *e*
V	=	stem volume (m^3, under-bark) usually to 50mm top diameter
dbh	=	breast height diameter (cm, over-bark)
f	=	correction factor

The Demaerschalk equation was used to estimate the volume of *E. dunnii, E. grandis, E. grandis x urophylla and E. grandis x camaldulensis* as used in *Pienaar and Kotze* (2001).

$$V_t = \left(\frac{\pi}{40000}\right) \cdot \left(\frac{\beta_0}{\beta_1 + 1}\right) \cdot dbh^2 \cdot ht \qquad \text{Equation (3.2)}$$

V_t	= tree volume
dbh	=diameter at breast height (m)
ht	= tree height (m)

Table 3.7 Specific volume equations used for different species and the coeffecients used in these equations (after Bredenkamp, 2000)

Genotype	Equation	β_0	β_1	β_2	f	Reference
E. cladocalyx	Schumacher and Hall	-10.3985	1.9970	0.9589	0	Bredenkamp, 1994
E. gomphocephala	Form height					This study[1]

[1] The form height that will be used in the volume estimation was derived from samples taken as part of this study

E. gomphocephala is not a very widely used taxon commercially, especially in South Africa, thus not as much research is available on this genotype as a commercially used species and there is no published volume estimation equation for this taxon. For this reason, a rarely used volume equation based on the height, dbh and height at half dbh was used to produce an estimate of the volume of *E. gomphocephala*.

Form height is a simple method of approximating volume of a taxon in the absence of more sophisticated volume equation. The form height was estimated by measuring the height at which the diameter is half of dbh. This height is known as the form height or Pressler's height. The form height was then used as a variable, along with basal area to estimate volume using **Equation 3.3**. Pressler's height is typically recorded to scale in relation to the diameter at breast height and thus cannot be read directly from the Relascope, some conversion is necessary. It was also necessary to note the band count that was used as well as the measurement system, i.e. CP metric or standard because the conversion method differs with different scales (*Zöhrer*, 1980).

$$v = (f h_1) \times g \qquad\qquad \text{Equation (3.3)}$$

where: $\qquad\qquad f = $ Form quotient

$\qquad\qquad\qquad h_1 = $ Pressler's height

The form quotient (f) is derived as follows:

$$f = \left(\frac{fh}{d}\right) \times \left(\frac{d}{h}\right) \qquad\qquad \text{Equation (3.4)}$$

Where:

fh/d= the relative form height (dimensionless; determined with relascope)

d= diameter at breast height (cm)

h = tree height (m)

A minimum of 30 trees measurement was required at each site; 50 trees at the Coetzenburg site and 48 trees at the Darling site were actually measured. Trees with good form and relatively straight stems were chosen for measurement based on the assumption that the trees with less uniform stems will have the same amount of volume as straighter stems, just with different spatial distribution. The trees with the more uniform stems were easier to accurately measure than the less uniform trees. The sample trees were distributed across the diameter class range in the stand to get a more accurate estimate of the form at different dbh intervals. With the Relascope, the dbh, Pressler's height and height to the stem base of tree was determined in scale. The form height was then calculated using the **Equation 3.4**, keeping in mind the scale that was used to find Pressler's height. The volume was then estimated using **Equation 3.3**. The form height was calculated per tree and weighted mean per site was used in **Equation 3.4** to estimate the tree volume of *E. gomphocephala*.

The volume that is obtained with Pressler's method is an estimate of tree volume, not utilizable volume as the other formulae estimates. Thus, an estimate as to the utilizable percentage of volume had to be estimated in order to have a meaningful comparison between *E. cladocalyx* and *E. gomphocephala*. The utilizable volume is affected by age, dbh and thin-end diameter. The specific utilizable percentage (P) model that was used is based on the relationship between thin-end diameter and the dbh of *E. grandis* and *E. saligna* trees (Equation 3.5). The model is completely dependent on the units of measurement, as it is dimensionless (*Nel,* 1990). The bark of the tree also has to be considered when estimating utilizable volume. The average, 0.13, from *Dovey* (2009) was used to estimate the proportion of volume that bark contributes to the utilizable volume. The bark ratio and the P- value from Equation 3.5 (*Nel*, 1990) together constitute the utilizable percentage of the full tree volume. The trees that were sampled to calculate form height were used to produce a site specific P-value average.

$$P = e^{(-(DT/DBH)/b)^c} \qquad \text{(Nel, 1990)} \qquad \text{Equation (3.5)}$$

$P =$ percentage of tree volume from base of tree to specified thin-end diameter

$DT =$ thin-end diameter of dbh class (*cm*)

$dbh =$ diameter at breast height (*cm*)

$b = 0.7902$

$c = 4.5619$

The volume per hectare at experimental sites was determined by computing the volume per tree in a plot using appropriate volume equations, and the per plot volumes was then expressed on a per hectare basis. At Coetzenburg and Darling sites, all surviving trees were measured per plot. The volumes at

35

age 6 years of the Coetzenburg and Darling sites were compared on a site, provenance and family level.

At the Backsberg site, the determination of utilisable volume of the taxa can be very misleading due to the young age of the trees. A better description of the amount of biomass on such a site is the biomass index (**Equation 3.6**) (*Allan and Carlson*, 1998; *Viero et al.,* 2000). This gives a more accurate indication of the amount of biomass on the site when many of the trees are still smaller than breast height. Only the inner 12 trees per plot (3×4) were measured at the Backsberg plot so as to minimize the effects of competition.

$$BI = d^2 \times h$$ Equation (3.6)

Where:

BI $\quad$ = Biomass index (cm^3)

d $\quad$ = diameter at breast height (cm)

h $\quad$ = height (cm)

Site index is a method of identifying potential present and future productivity (*Avery and Burkhart,* 1994). Height growth is a reliable indicator when producing potential yield estimates. Site index is based on the top-height at a specific reference age and normally an essential predictor variable when estimating growth and yield parameters. The definition of top height is the mean height of the 20% of trees with largest dbh (*Coetzee,* 1999).

To contextualise the growth response of the taxa at the three trial sites, these data were compared to a set of growth curves across a range of site indices for *E. grandis,* covering the range in top heights that was measured at the respective trial sites (where necessary, top heights were adjusted to the base

age if they were measured at a different age). The contextualisation was done because of the growth of *E. grandis* has been well documented and reliable equations for predicting growth of the genotype have been published (*Coetzee*, 1999) for a range of site indices.

The equation used to estimate the Site Index of this site if planted to a crop of E. grandis (*Coetzee*, 1999) follows:

$$\ln(SI) = \ln(THT) + 0.271(5 - Age) - 1.908(0.2 - Age^{-1})$$ Equation (3.7)

Where:

SI	= Site Index
ln	= Natural logarithm
Age	= Stand age (years)
THT	= Top Height (m)

3.4 Biomass estimation

Biomass is estimated as the product of utilisable woody volume and wood density. The utilisable percentage of the trees is a good estimate of the amount of wood that would be harvested for bioenergy with the current suggested motor-manual harvesting system (*von Doderer,* 2010).

The dbh and height data is used to create dbh classes, which the stand was subsequently divided into. Sample trees were chosen to represent the whole population of stand and thus individuals were chosen across all dbh classes. Only the specific families with the highest mean dbh were chosen to sample for wood density in this situation. The three families within a genotype with the largest mean dbh from each site were sampled. Five density cores were sampled from plots across the site and across the dbh spectrum that existed

with the chosen families. Because of the low survival of individuals of *E. cladocalyx* at the Darling site, the three top volume producing families were slightly different to that of the families with the largest mean dbh. For this reason, and because there was little variation in wood density between families, the mean wood density per site was used, instead of specific families having specific wood densities. The specific variances are discussed in Chapter 4 of this thesis.

The wood density of core samples (taken at breast height) was determined by the displacement theory (*Snowdon et al.*, 2002; *Illic et al.,* 2000). A known volume of water is put in a beaker; the sample is submerged in the beaker and the volume of the water displaced is then equal to the volume of the sample. Cores were submerged in water at least a half an hour before weighing the cores to ensure saturation before wood density estimation. The container with water was put on the scale, zeroed, the sampled submerged in the water, the displaced mass of water was recorded and related to volume. The cores were dried at a standard 70°C, that remained as constant as possible. Dry weight was measured after 72 hours, then at regular intervals, until there was no longer any fluctuation in the weight of the cores.

The total standing volume (m^3 ha^{-1}) of top producing families were estimated, multiplied with the estimated wood density and finally inflated to a mass per unit area basis so that the biomass estimate could be expressed in tons per hectare (*Verwijst and Telenius, 1999; Ravindranath & Ostwald* , 2008).

3.4 Statistical Analysis

The survival was analysed on a plot level as this was the unit that all other calculations and analyses were done on. From the raw data it was clear that the site that was the most affected by survival would be the Darling site.

Firstly the relationship between mean dbh and survival was investigated at a taxon level at each site. Thus the effect that survival had on each family or taxa per site was done. This was done by regressing the variables against one another and interpreting the results of the Spearman test (*Corder and Foreman,* 2009).

The survival data was analysed using ANOVA and the residuals was then checked for normality. They did not have normal distribution, and thus a non-parametric test was done. There was no need to transform the data, because of the use of the non-parametric test that is explained further on in this chapter.

The statistics investigated the differences in growth on different levels therefore an Analysis of Variance (ANOVA) was an appropriate test to ascertain if there were significant differences between sites and taxa. In order to carry out an ANOVA, a test for homogeneity of variances was done. Populations with homogenous variances can be analysed with ANOVA, however, populations with heterogeneous variances would have to undergo another transformation before being analysed (*Clewer and Scarisbrick*, 2006). The Cochran's test for heteroscedacity was used in this study.

Least Square Means (LS means) Tests were done to verify significant (p<0.05) results in ANOVA. Significant differences suggested in the ANOVA and LS means test were investigated using either Bonferroni or Duncan tests. If the difference between variables were not large enough, the intervals of the Bonferroni test would not be able to pick them up, and thus the Duncan test would be done.

The distribution of the data residuals was then investigated. If the residuals were not normally distributed, one of two non- parametric tests were done; namely the Mann- Whitney U or the Kruskal-Wallis. The Mann-Whitney U test was used if there were two independent variables, when the differences between sites were being done (*Clewer and Scarisbrick,* 2006). Non-parametric tests were used when data residuals were not normally distributed. The test ranks the data and does analysis on the ranks and not the specific data. Another method of non-parametric test is the Bootstrap method, where the data is multiplied to such a level that its distribution is similar to the *t*- distribution. Analysis is then done on this multiplied data. This non-parametric test would verify the outcome of the ANOVA and suggest significant differences between variables at the 5% significance level (p<0.05). If multiple variables were being analysed, for instance investigating the differences between families, the Kruskal- Wallis non-parametric test was used. This test would also verify the outcome of the ANOVA and suggest significant differences at the 5% significance level (p<0.05). The non-parametric test was also accompanied by a Box and whiskers graph that visually shows the nature and variations that occur in the data.

Mann-Whitney U test

The Mann-Whitney U test is a non-parametric test for testing whether two independent samples were drawn from the same probability distribution and is very similar to a normal parametric two-sample *t*-test (*Corder and Foreman*, 2009; *Conover*, 1980).

Kruskal-Wallis one- way analysis of variance

The Kruskal-Wallis non-parametric method is for testing for the equality of population means among different group and is identical to the analysis of variance, except the data itself is replaced by its rank. The test is used to investigate non-normally distributed data involving 3 or more groups. The test does not assume normality, it does however assume identically- shaped scaled distribution for the groups involved, except for the differences in group medians (*Corder and Foreman*, 2009).

Analysis of Variance (ANOVA)

The analysis of variance is a selection of statistical models in which variances are partitioned into different groups according to different explanatory variables. It is used to test for differences among at least three groups (*Keppel and Wickens,* 2004). Interactions were first tested by means of a two-way ANOVA on normally distributed data. If there was no interaction, the main effects were investigated.

Bootstrap test

This test estimates properties of population variance by sampling from an approximate distribution. In the case of a set of observations from an independent and identically distributed population, this test can be implemented by constructing a number of re-samples of the observed dataset, each of which is obtained by random sampling with replacement from the original dataset (*Chernick,* 1999).

Cochran's test

This is a non-parametric statistical test of whether *k* treatments have identical effects. In the analysis of two-way randomized block designs where the response variables can have only two possible outcomes (*Conover,* 1980).

3.5 Insect infestation assessment

Infestation of insects could possibly have a large role in determining whether the tree species are suitable for this region. Because of the history of the Eucalyptus in South Africa it is highly unlikely that any pest or insect will cause fatality in the species yet, but it should be monitored.

A crude visual assessment as to the infestation levels on the different sites was done.

To assess *Thaumastocoris peregrinus* infestation level a numerical scale based on a visual physical assessment of trees in a stand was used. The assessment levels are available in **Table 3.8**.

Table 3.8 Assessment of infestation levels and their visual description (*Nadel, 2009*)

Level	Description
0	Leaves are green with no noticeable feeding damage.
1	Low infestation with noticeable signs of feeding damage on the leaves (Photo A) (**Figure 3.8**)
3	Small egg clusters (B) and/or a few adults present on the *Eucalyptus* leaves
5	Infestation with large numbers adults present of the leaf surface (Photo C) and / or numerous large egg clusters (Photo D) (**Figure 3.8**)
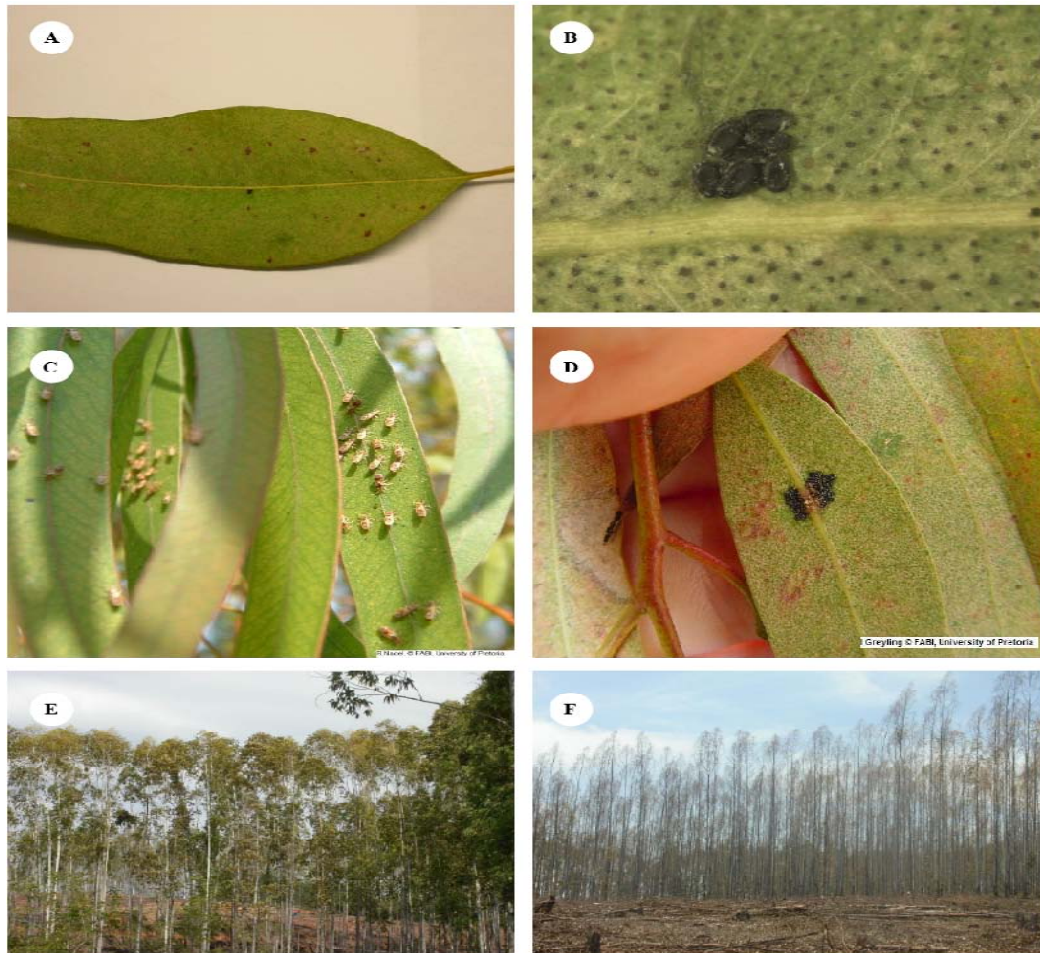
Photos: © FABI, University of Pretoria

A. Minor damage on leaf; B. Small egg cluster; C. *Thaumastocoris* infestation; D. Large egg clusters; E. infestation on *Eucalyptus*; F. very severe infestation on *Eucalyptus*

Figure 3.8. Photographic description of infestation levels in Eucalypts, correlates with **Table 3.8.** Images are courtesy of TPCP, FABI and the University of Pretoria (*Nadel*, 2009)

Levels 2 and 4 are for cases when it is difficult to determine between two levels of infestation, for example one would use level 4 when it is worse than level 3 but not quite level 5.

The assessment of the sites should preferentially be done in a drier and wetter season as there seems to be a fluctuation in infestation levels between seasons. Assessments were done in the morning on the side of the

compartment that is exposed to the most sun. All measurement trees were assessed for infestation of *Thaumastocoris* and presence of *Gonipterus*.

The assessment of the presence of *Gonipterus scutellatus* (**Figure 3.9**) is done by assessing the presence of beetles on the trees. These beetles also feed on the tips of the trees, the damage is clearly visible and so can be visually assessed.

Figure 3.9 Some damage caused by *Gonipterus scuttelatus* on *eucalypt* leaves.

3.6 Specific Objectives and hypotheses

For the purpose of focussing our investigations, the following hypotheses were formulated:

Hypothesis 1: Volume production potential differs significantly between eucalypt species tested and trial sites.

Hypothesis 2: A single family within a species will not grow optimally across the major climatic zones of the study area.

Hypothesis 3: The maximum biomass production potential of species will differ significantly across the climatic range.

Hypothesis 4: Commercially available taxa have the potential to be more productive than *E. cladocalyx* in the sub-humid zone of the Greater Boland Region.

Chapter 4: Results

The focus of the Darling and Coetzenburg sites was to investigate which families of the commonly grown *E. cladocalyx* (selected from 9 provenances) and *E. gomphocephala* (selected from 4 provenances) are most suited to the study region. The experiments are almost identical, thus facilitating comparison of most families across sites types. Tree survival and stand volume data are compared at the site, species, provenance and family level. Furthermore, the stem wood biomass of the top volume producers of each genotype per site were estimated and compared with each other.

4.1.1 Survival

The survival data was collected when dbh and height were measured at the site. An initial investigation into the correlation between mean dbh and survival at the two sites revealed that only *E. cladocalyx* at the Darling site showed a significant ($p < 0.05$) positive correlation between survival and mean tree diameter. The general trend displays an increase in mean diameter of the remaining trees in the presence of some mortality, although only significantly so in *E.cladocalyx* at the Darling site (**Figure 4.1**).

The distribution of the residuals of the analysis of variance was found to be skewed, thus the Mann-Whitney, non-parametric test was done, which is described in greater detail in Chapter 3.
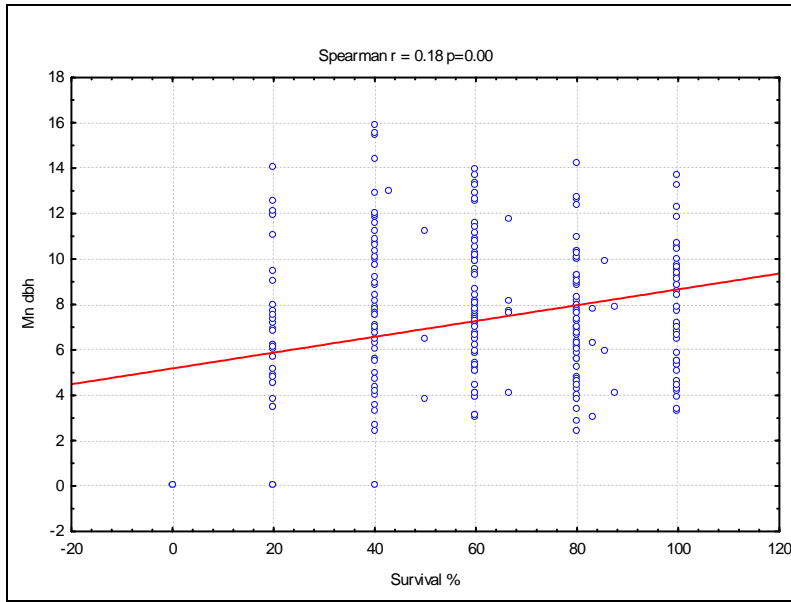
Figure 4.1 The only significant relationship between mean dbh and survival of *E. cladocalyx* at the Darling site

Table 4.1 Statistically significant results of survival percentage between site, genotypes and families at the Darling and Coetzenburg site

Mean volume Relationships	Non-parametric Test (p-value)
Comparison of interaction between site and species	
Site × Genotype	<0.001*
Comparison of genotypes between sites	
Darling	<0.001*
Coetzenburg	0.00012*
Comparison between families of genotypes	
E. cladocalyx- Coetzenburg	0.0127*
E. cladocalyx- Darling	<0.001*
E. gomphocephala- Coetzenburg	<0.001*
E. gomphocephala- Darling	0.0016*

Table 4.2 The mean survival at the Darling and Coetzenburg sites at 6 years of age.

Taxa	Coetzenburg (%)	Darling (%)
E. gomphocephala	90[a]	80[b]
E. cladocalyx	90[a]	58[c]
Mean survival (%)	90	64

Basic statistics indicate a significant interaction between survival and site (**Table 4.1** and **4.2**). Coetzenburg (90%) has a higher overall survival percentage than Darling (64%), with both *E. cladocalyx* and *E.gomphocephala* having low levels of mortality. At Darling however, *E. cladocalyx* had only a 58% survival, while *E.gomphocephala* had a survival of 80%. Furthermore **Table 4.1** and **4.2** indicate that there was a significant difference in the survival between the genotypes at both the Coetzenburg and Darling sites (*p*<0.05*)*. The higher overall survival percentage at the Coetzenburg site for both taxa suggests that they are more suited to the wetter site than the drier Darling site. Another important result of this section is that *E. gomphocephala* has a good survival percentage at both Darling and Coetzenburg site.

The survival rates of families between different taxa and sites are significant (**Table 4.2**). **Figures 4.2** and **4.3** visually show the variation in survival between families at Darling and Coetzenburg. At Coetzenburg, the survival is not very different between *E. gomphocephala* and *E. cladocalyx*, with low numbers of families being significantly different to each other (**Figure 4.2**). At Darling, however, the survival rate between *E.cladocalyx* and *E. gomphocephala* is apparent, with *E. gomphocephala* having a higher survival percentage than that of *E. cladocalyx.* The better site conditions at Coetzenburg lend to a higher survival rate across the board, while *E. gomphocephala* has a high survival rate at Coetzenburg as well as Darling
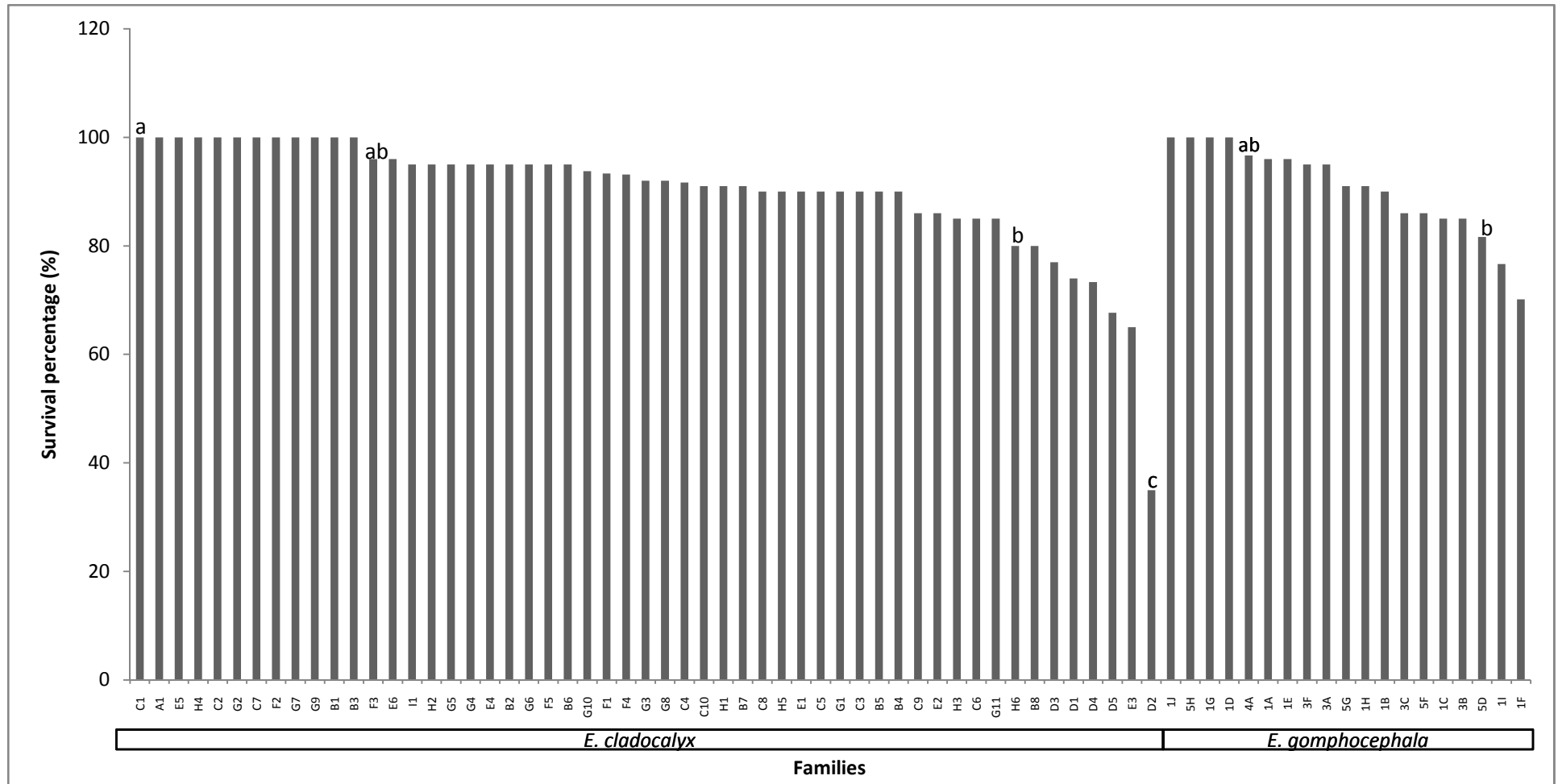
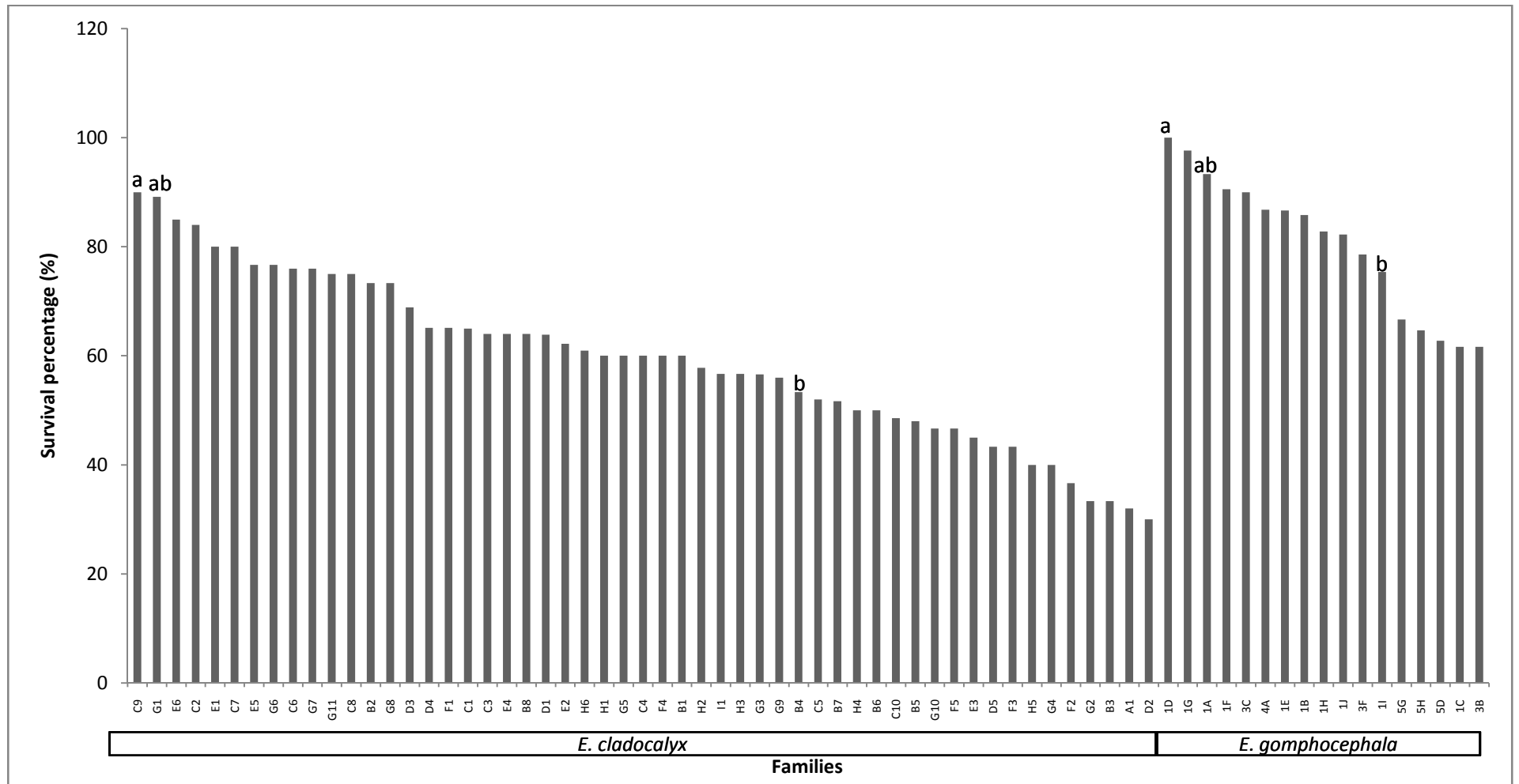**Figure 4.2** The survival of families at the Coetzenburg site. Letters on bars indicate significance of *p*<0.05

Figure 4.3 Survival percentages of families at the Darling site. Lettering on bars indicate significance of $p<0.05$
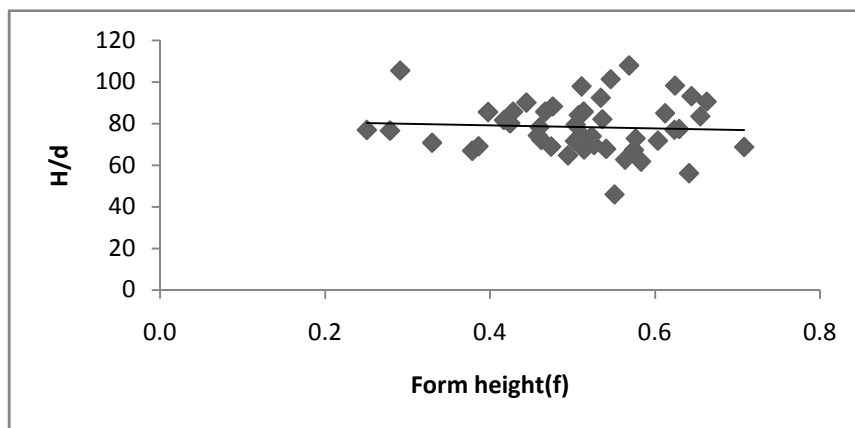
4.1.2 Form Height and Utilizable volume percentage

4.1.2.1 Form Height

The mean weighted form height per site of *E. gomphocephala* was used to estimate the stem volume of this taxon, due to lack of a published volume equation. Traditionally it was thought that the relationship between form height and h/d is an exponential one (FAO, 1979). This was not true for this study that was done on *E. gomphocephala* on the Darling and Coetzenburg sites. **Figures 4.4 and 4.5** illustrates the relationship between form height and h/d on the sites that have been sampled. A good percentage of the population was sampled (30% of the individuals in the stand) and the majority of the form heights fell within the 0.4-0.6 range. The trend lines do not have significant r-squared values which would indicate correlation (FAO, 1979; *Clewer and Scarisbrick,* 2006).

The mean weighted average is more accurate than the mean because it takes into account the higher frequency form heights and can thus give a better description of the average. The weighted mean form factors were found to be 0.514 and 0.512 at the Darling and Coetzenburg sites respectively, which correlates with the literature (FAO, 1979). The form of *E. gomphocephala* is not affected by site as the variance between the form factors between the sites was negligible.
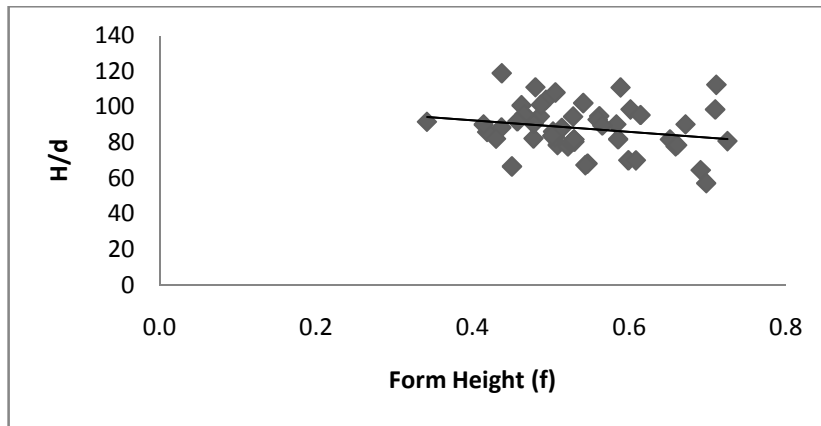
Figure 4.4 The relationship between form height and ratio h/d at the Darling site

Figure 4.5 The relationship between form height and ratio h/d at the Coetzenburg site

4.1.2.2 Utilizable volume percentage

An average utilizable percentage of stems was calculated using the sample trees that were used for the determination of form height per site for *E. gomphocephala*, to estimate utilizable volume. The utilizable stem volume was different per site and was estimated to be 75% at Coetzenburg and 80% at the Darling site, based on sample tree data. These values are in line with work done in Eucalyptus South Africa by *Dovey* (2009) and a range of

species in Europe that indicate that the percentage of full tree volume lost in bark and tree tops range from approximately 13-25% (*Eder and Hoang,* 2003).

4.1.3 Yield

The yield at the Coetzenburg and Darling sites were calculated to a utilizable plot volume per hectare (m^3 ha^{-1}) at age six years and analysed on this level. Yield is the variable used to compare the growth between the different sites, provenances and families because it takes into account the diameter and height growth of trees as well as the stocking (and hence, survival). The statistical differences between site, provenance and families per site are shown in **Table 4.3**. The yield was statistically compared using ANOVAs, where it was normally distributed, to analyse estimated volume differences and interactions between families, provenances and sites. An analysis where survival was used as a covariate was deemed to be unnecessary because there is no evidence in the site commentary to suggest that any outside influence caused mortality of trees at either of these sites. It was thus assumed that mortality was treatment related and we analysed growth responses without further adjustment for survival percentages.

There is an interaction between site and species in terms of volume yield, which in indicates that site has an effect on the yield of the species (**Table 4.3** and **Figure 4.6**). Estimated volume at a site level indicates that Coetzenburg has a greater yield than Darling, with mean volumes of 41.7 m^3 ha^{-1} and 13.6 m^3 ha^{-1} respectively (**Table 4.4**).

The difference in yield between species is also evident in **Table 4.3** and **Figure 4.6.** The yield of *E. cladocalyx* differs between the Coetzenburg and Darling sites, with the mean estimated volume of *E.cladocalyx* at Coetzenburg being 42.2 m^3 ha^{-1}, as opposed to 9.8 m^3 ha^{-1} at Darling (**Table**

4.3 and **Figure 4.6**). The difference in yield of *E. gomphocephala* between the sites is also evident due to the mean estimated volume at Coetzenburg being an approximate 40.4 m^3 ha^{-1}, as opposed to the 24.9 m^3 ha^{-1} at Darling (**Table 4.3** and **Figure 4.6**).
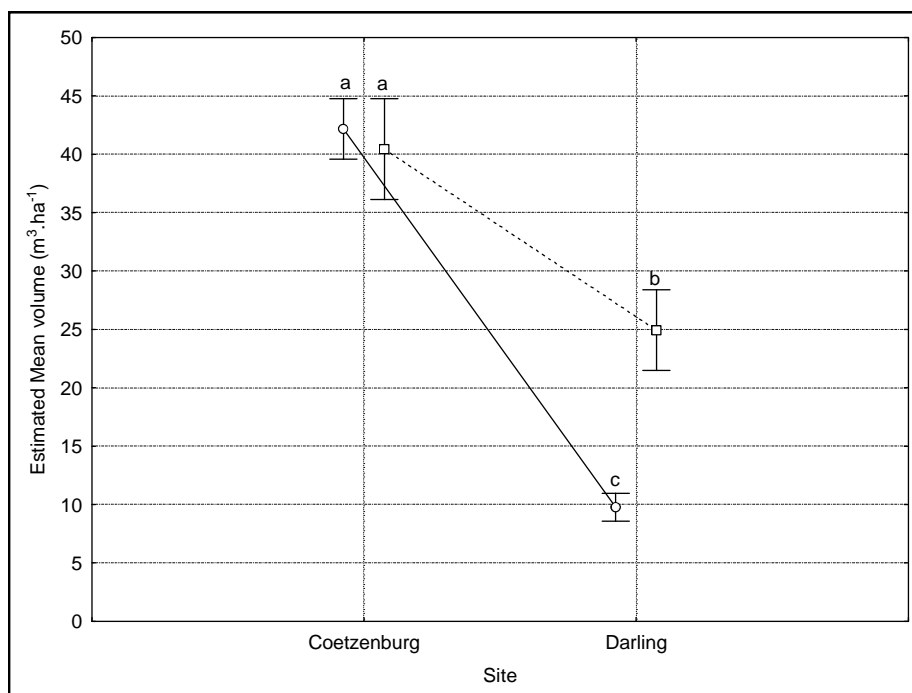
■ *- E. gomphocephala* ■ *E. cladocalyx*

Figure 4.6 The statistical relationship between site and species of weighted mean utilizable volume at Darling and Coetzenburg sites

Table 4.3 Mean utilizable volumes per species at the Darling and Coetzenburg sites at 6 years of age. Values with the same superscript letter are not significantly different at *p*<0.05.

Taxa	Coetzenburg (m^3 ha^{-1})	Darling (m^3 ha^{-1})
E. gomphocephala	40.4[a]	24.9[b]
E. cladocalyx	42.2[a]	9.8[c]
Mean survival (m^3 ha^{-1})	41.7	13.6

Table 4.4 Statistically significant differences between sites, species, provenances and families at Darling and Coetzenburg sites at 6 years of age

Comparison of interaction between site and species (Refer to Table 4.3)			
Source of variation	**Df**	**MS**	***p***
Intercept	1	476493.2	<0.001*
Site	1	79455.8	<0.001*
Taxa	1	6246.7	<0.001*
Site×Species	1	9878.6	<0.001*
Error	738	290.4	
Comparison of interaction between site and provenance (Refer to Table 4.5)			
E. cladocalyx			
Source of variation	**Df**	**MS**	***p***
Intercept	1	122665.0	<0.001*
Site	1	51619.9	<0.001*
Provenance	6	5822.7	<0.001*
Site*Provenance	6	2810.0	<0.001*
Error	542	183.8	
E. gomphocephala			
Source of variation	**Df**	**MS**	***p***
Intercept	1	84907.17	<0.001*
Site	1	5746.94	<0.001*
Provenance	3	929.75	0.051761
Site×Provenance	3	175.16	0.685663
Error	167	353.27	
Main effects of *E. gomphocephala* provenances between sites			
Darling			
Source variation	**Df**	**MS**	***p***
Intercept	1	29309.90	<0.001*
Provenance	3	277.69	0.441764
Error	97	306.90	
Coetzenburg			
Source of variation	**Df**	**MS**	***p***
Intercept	1	72098.43	<0.001*
Provenance	3	596.45	0.216753
Error	81	393.57	
Comparison of interaction between site and families (Refer to Figure 4.7 and Figure 4.8)			
Source of variation	**Df**	**MS**	***p***
Intercept	1	548902.9	<0.001*
Site	1	145177.8	<0.001*
Family	69	966.7	<0.001*
Site×Family	69	556.7	<0.001*
Error	602	211.6	

*-indicates significant differences ($p<0.05$)

E. cladocalyx is the only species that displays significant site-provenance interactions (**Table 4.4 and Table 4.5**). This indicates that the yield of *E. cladocalyx* provenances is not consistent across sites. There is no significant interaction between site and provenance in *E.gomphocephala*. Thus, provenances of *E. gomphocephala* are ranked similarly in terms of volume growth of provenances on both experimental sites. There are, however, significant differences between the yield at the sites between the provenances **(Table 4.4 and Table 4.5)**.

The top two mean volume producing provenances are different between species at the different sites, although the lower producing provenances have similar rankings (**Table 4.5**). At the Darling site, the top producing provenance is Flinders Chase for *E.cladocalyx* and Harvey for the *E. gomphocephala.* The top producing provenance at the Coetzenburg site is Kersbrook SPA for the *E. cladocalyx*. The control proved to produce the largest yield for the *E. gomphocephala* at the Coetzenburg site, though it does not yield significantly larger yields than the second ranking, Harvey provenance (**Table 4.5)***.*

Table 4.5 Differences in volume production between provenances at the Darling and Coetzenburg sites. Values with the same superscript letter are not significantly different at $p<0.05$.

| E. gomphocephala		
Site	**Provenance**	**Mean volume ($m^3 ha^{-1}$)**
Coetzenburg	Control	47.5^a
Coetzenburg	Harvey	43.4^a
Coetzenburg	Yalgorup SF	30.9^a
Coetzenburg	Ludlow SF	29.6^a
Darling	Harvey	27.1^b
Darling	Control	23.0^{bc}
Darling	Ludlow SF	21.5^c
Darling	Yalgorup SF	19.6^c
E. cladocalyx		
Site	**Provenance**	**Mean volume ($m^3 ha^{-1}$)**
Coetzenburg	Kersbrook SPA	78.3^a
Coetzenburg	Flinders Chase NP	57.5^b
Coetzenburg	Wirrabara SF	45.6^c
Coetzenburg	Wilmington	37.0^{de}
Coetzenburg	Control	35.7^e
Coetzenburg	Marble Range	26.3^e
Darling	Flinders Chase NP	12.7^f
Darling	Kersbrook SPA	12.3^{fg}
Coetzenburg	Cowell	11.8^{fg}
Darling	Wirrabara SF	10.4^{fg}
Darling	Wilmington	9.7^{fg}
Darling	Control	7.8^{fg}
Darling	Marble Range	4.8^g
Darling	Cowell	4.4^g

The interaction between utilizable volume and families of the two species at both Coetzenburg and Darling sites is evident from the statistical analysis performed ($p<0.05$) (**Table 4.4**). **Figure 4.7 and 4.8** further illustrate the difference in yield of the species between the different sites. A large variation in estimated volume per family exist on both sites with the largest variation being amongst *E. cladocalyx* families. **Figure 4.7** visually displays the differences that occur between the different families, at the Darling site. The top performing families of *E. gomphocephala*, and the site as a whole, at Darling are 1G,1C, 1A, , while the top producing *E.cladocalyx* families are H6, B1 and G1 (**Figure 4.7**). The ability of *E. gomphocephala* to outgrow *E.*

cladocalyx at Darling is apparent in **Figure 4.7** and when looking at the differences in the top producing families at the sites (**Table 4.5**). At the Coetzenburg site, the top producing families of *E. cladocalyx,* and the site as a whole, are; A1, G2, and G9, and those from *E. gomphocephala* are 1A, 1J and 1D (**Figure 4.8**).The better site quality of Coetzenburg is also visible in the overall higher volume yield of the top producing families as well as the presence of *E. cladocalyx* in top five producers **(Figure 4.8 and Table 4.6)**. At Coetzenburg, *E. cladocalyx* had the top producing families and produced the largest mean volume, although not significantly different from the yield of *E. gomphocephala* at the same site (**Table 4.6**).

The potential bioenergy of the top producing families were estimated after multiplication with the calorific value of 18.4 MJ kg^{-1} obtained by Munalula and Meincken (2009)(**Table 4.6**). The mean estimated potential energy at six years of age at the Coetzenburg site was 767 GJ ha^{-1} which is larger than the estimated mean potential energy at the Darling site (3012 GJ ha^{-1}).

Table 4.6 Estimated and mean volume, biomass and bioenergy yield of the three most productive families of each species at Darling and Coetzenburg sites at six years of age. Values with the same superscript letter in any single column are not significantly different at $p<0.05$. Site means are not included in significance tests

Site	Species	Family	Mean volume (m^3ha^{-1})	Survival %	Density ($kg\ m^{-3}$)	Mean Biomass ($t\ ha^{-1}$)	Bioenergy Estimate ($GJ\ ha^{-1}$)
Coetzenburg	*E. cladocalyx*	A1	78.3[a]	100	620	48.5[a]	892
Coetzenburg	*E. cladocalyx*	G2	76.5[a]	100	620	47.4[a]	872
Coetzenburg	*E. cladocalyx*	G9	74.1[a]	100	620	45.9[ab]	844
Coetzenburg	*E. gomphocephala*	1A	58.4[ab]	96	620	36.2[ab]	666
Coetzenburg	*E. gomphocephala*	1J	56.9[ab]	100	620	35.3[ab]	649
Coetzenburg	*E. gomphocephala*	1D	55.3[ab]	100	620	34.3[b]	631
Coetzenburg Mean Values			**67.3**	**99**	**620**	**41.7**	**767**
Darling	*E. gomphocephala*	1G	36.2[bc]	98	588	21.3[bc]	392
Darling	*E. gomphocephala*	1C	33.2[bc]	62	588	19.5[bc]	359
Darling	*E. gomphocephala*	1A	32.8[bc]	93	588	19.3[bc]	355
Darling	*E. cladocalyx*	H6	21.5[c]	61	588	12.7[bc]	234
Darling	*E. cladocalyx*	B7	19.4[c]	52	588	11.4[bc]	210
Darling	*E. cladocalyx*	G1	18.5[c]	89	588	10.9[bc]	201
Darling Mean Values			**27.9**	**78**	**588**	**16.4**	**302**
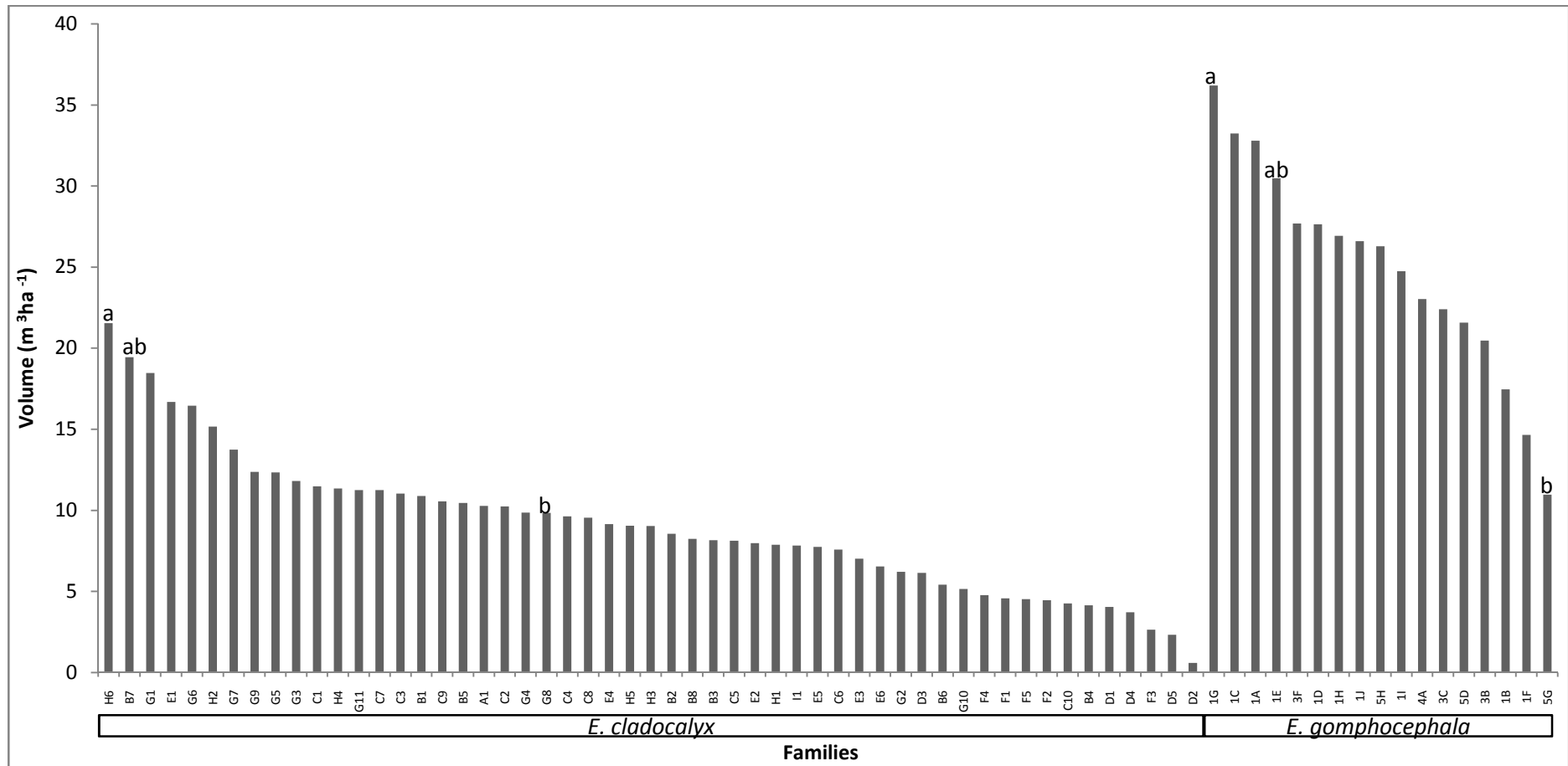
Figure 4.7 Mean volumes of all families at Darling site at six years. Bars with different letters indicate significant differences at *p*<0.05.
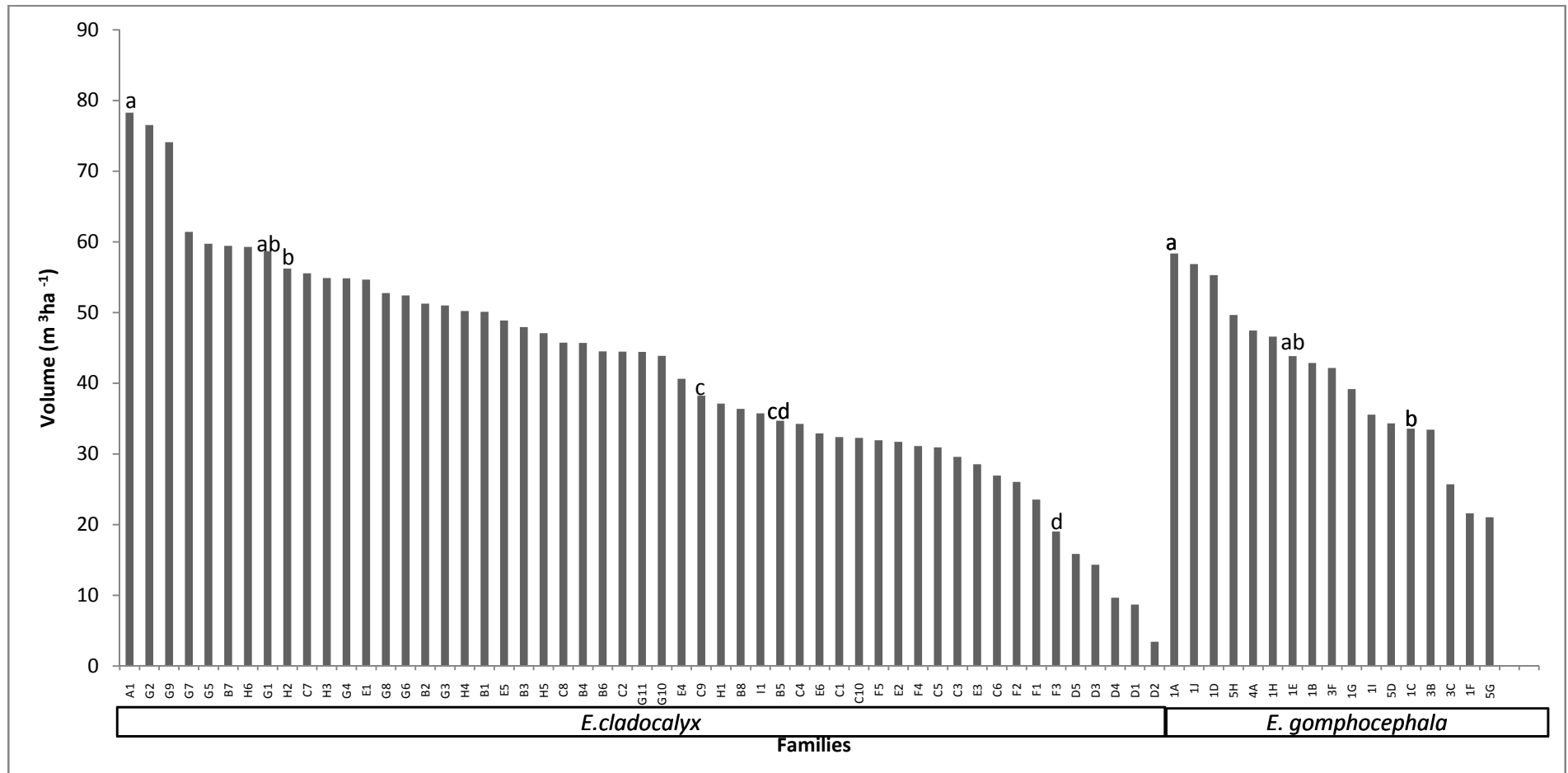
Figure 4.8 Mean volumes of all families at Coetzenburg site at six years. Bars with different letters indicate significant differences at *p*<0.05

4.1.4 Stem wood biomass potential

Stem wood biomass provides an indication of the mass of wood that is readily available at a site and is determined by multiplying the volume of the stand by the wood density. A rough estimate of stem wood biomass was done for the top three volume producing families of each species per site at six years of age; the estimated biomass for a total of 12families was calculated.

4.1.4.1 Wood density estimation

Statistical analyses of the variance in wood density between species and sites are presented in **Table 4.7.** The mean wood density of the drier Darling site (588 kg m^{-3}) was lower than at the wetter Coetzenburg site (620 kg m^{-3}).The wood density of the top performing families were significantly different between sites but not between species within sites. These estimates are comparable with wood densities of fast growing tree species recorded in the literature, ranging from 430 - 660 kg m^{-3} (*Illic et al.,* 2000; *Clark,* 2001; *Dovey, 2009*). A site specific mean wood density was used to estimate woody biomass due to the variance in wood density between densities of families and taxa being very small within sites (**Table 4.7**). The distribution of the densities at the site level was skewed and thus a non-parametric test had to be used when analysing the densities on a site level.

Table 4.7 Tests of significance for wood density amongst the families selected for biomass estimation (i.e. the best volume producers) at Coetzenburg and Darling sites.

Density between sites			
	Coetzenburg	**Darling**	**Non-parametric test (*p*-value)**
Mean density (kg m^{-3})	619.9	587.528	0.001714*
Differences in Wood Density of families at Coetzenburg site				
Source of variation	**Df**	**MS**	**F**	***p***
Intercept	1	11.53	1.5213	<0.001*
Family	5	0.00107	1.42	0.2543
Error	24	0.00076		
Differences in Wood density of families at Darling site				
Intercept	1	11.76	5138.001	<0.001*
Family	5	0.00304	1.328	0.2792
Error	30	0.00229		

* statistically significant results of $p<0.05$

The top three families of each taxon at the two sites were used to estimate the potential above ground stem wood biomass at the sites (**Table 4.6**). The mean volume of the top producers at Coetzenburg was 76.3 m^3 ha^{-1} with no significant difference between families from different species. The mean volume of *E. cladocalyx* top producers at Darling was 19.8 m^3 ha^{-1} and that of *E. gomphocephala*, 34.1 m^3 ha^{-1}. The differences in volume of the top three families per genotype per site are shown in **Table 4.6**.

4.1.4.2 Stem wood biomass estimation

There is a significant interaction between estimated stem wood biomass of the top producers ($p<0.05$), family ($p<0.05$) and site (**Table 4.8**). **Table 4.6** indicates the differences in estimated mean stem wood biomass across site and families and **Figure 4.9** depicts this significant site by species interaction. The Coetzenburg site has a significantly higher estimated mean stem wood biomass than Darling, yielding 41.3 tha^{-1} and 15 8 t ha^{-1} respectively (**Figure 4.9**). Unlike Darling, at Coetzenburg there is no

significant difference between the biomass yields of top producing families within *E. cladocalyx* and *E. gomphocephala* (**Table 4.5**). The significant differences of stand volume on the site, species and family levels are carried through to significant differences between top stem wood biomass producing families (**Table 4.7** and **Table 4.8**).

Table 4.8 Results of ANOVA on biomass yield at six years of age between sites, species and families at Darling and Coetzenburg site.

Comparison of interaction between site and species			
Source of variation	**Df**	**MS**	**p**
Intercept	1	53353.16	<0.001*
Site	1	10583.84	<0.001*
Species	1	55.78	0.548
Site×Species	1	1710.40	0.0014*
Error	62	153.00	
Comparison of yield of families within species (Table 4.6)			
Source of variation	**Df**	**MS**	**p**
Intercept	1	53353.16	<0.001*
Family	11	1123.53	<0.001*
Error	54	174.73	

* statistically significant results of $p<0.05$

From **Figure 4.9** it is clear, in terms of stem wood biomass production, *E. gomphocephala* performed well at both sites. It is also clear that *E. cladocalyx* is not well suited to the dry, sandy site at Darling, but produces comparatively greater quantities of stem wood biomass at the wetter Coetzenburg site. This relationship is mirrored in the survival trends of the genotypes across the sites. Coetzenburg enjoys higher survival percentages across the board when compared to Darling, where *E. gomphocephala* had fairly good survival rates while the *E. cladocalyx* survival rate at the same site was dismally low. The relationship between estimated volume and stem wood biomass is quantified in **Table 4.6** and it is clear that the top volume producers are also the top stem wood biomass producers
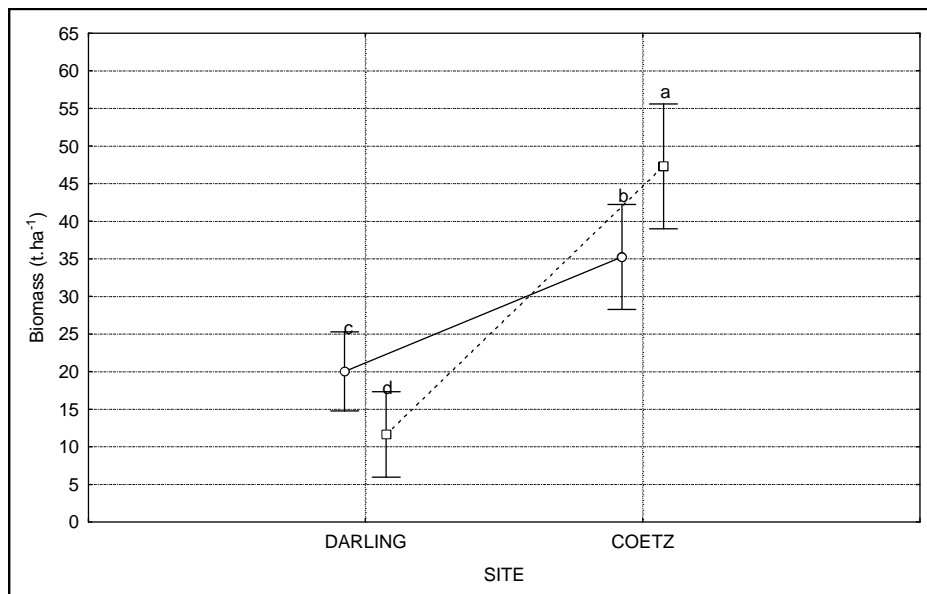
E. gomphocephala   *E. cladocalyx*

Figure 4.9 Weighted means of utilizable stem wood biomass (t ha^{-1}) at six years of age for the three best-performing families of *E.cladocalyx* and *E. gomphocephala*, planted across the Darling and Coetzenburg trial sites. Means with the same letter code are not significantly different at *p*<0.05.

4.1.4.3 Estimation of total biomass and bioenergy at site

It is possible to estimate the total above ground tree biomass, by means of average ratios of leaves, branches and bark to stem wood biomass, from previous intensive and in depth allometric studies, such as work done by Dovey (2009). The South African based work of *Dovey* (2009) suggests that the "branch plus bark": "stem wood" ratio is approximately 0.25 for eucalypts between 6 and 12 years across the commercial forestry region of South Africa and is in line with international findings for eucalypts in the same age class (*Hassal and Associates*, 1998; *Montagu et al.,* 2005; *Pérez et al.,* 2006).

On the basis of survival percentage and stem wood biomass production at the Coetzenburg and Darling sites, it appears that *E. gomphocephala* is

better suited than *E. cladocalyx* to the drier site and that both genotypes are well suited to the wetter site, although the top families of *E. cladocalyx* outperforms those of *E. gomphocephala* (**Figure 4.7** and **Figure 4.8**).

The potential Bioenergy available from the top producing families are also estimated in **Table 4.6** using the average calorific content of 18.4 MJ kg^{-1} (*Munalula and Meincken*, 2009).

4.2 Backsberg

The Backsberg site is focussed on investigating possible alternative fast growing tree species that could rival the productivity of the commonly used *E. cladocalyx* and *E. gomphocephala* genotypes in the study region. Four genotypes were tested against *E. cladocalyx*, including commercially used hybrids; *E. grandis × camaldulensis* and *E. grandis × urophylla* and species; *E. dunnii* and *E. grandis*. The survival, biomass index and insect infestation of these genotypes were investigated.

4.2.1 Survival and Mean Height

Backsberg enjoys a favourable survival percentage, the least favourable being that of *E. cladocalyx*, having a 78% survival rate. The other genotypes all have very good survival rates, the highest being *E. grandis* with 98%, followed by *E. grandis × camaldulensis, E. grandis × urophylla, E. dunnii* and the aforementioned *E. cladocalyx* (**Table 4.9**). The taxon that will be most suited to this site would thus depend largely on the potential biomass index as well as the susceptibility to pest infestation, as the taxa have comparable survival percentages.

The mean height differs quite substantially between taxa at the Backsberg site. The *E. grandis x camaldulensis* and *E. grandis x urophylla* being the tallest with similar mean heights, *E. grandis* in the middle of the range and the lowest being *E. dunnii* and *E. cladocalyx* (**Table 4.9**).

Table 4.9 Growth attributes of taxa at Backsberg site at age two years. Values with the same superscript letter in any single column are not significantly different at *p*<0.05.

Taxa	Survival (%)	Mean height(m)	Mean Biomass Index (m^3 ha^{-1})	Top height (m)	Estimated peak MAI* ($m^3ha^{-1}yr^{-1}$)
E. g × c[1]	96 [ab]	4.85	0.47 [a]	7.8	17.89
E. g × u[2]	95 [ab]	4.73	0.41 [a]	7.79	17.82
E. grandis	97[a]	3.33	0.20 [ab]	5.46	12.50
E. dunnii	92 [b]	2.67	0.09 [b]	3.96	9.07
E. clad[3]	83 [c]	2.33	0.05 [b]	3.78	8.65

Mean annual increment at ten years

[1]*- E. grandis × camaldulensis*

[2]*- E. grandis × urophylla*

[3]*- E. cladocalyx*

4.2.2 Yield

The mean volumes can be misleading, due to the young age of the trees at this site (most volume and taper functions calculate utilizable timber which can give erroneous results in small trees), and there being no prior research available on the growth trends of these taxa in the study region, save *E. cladocalyx*. Thus, to have some indication of growth for the genotypes at the Backsberg site, an estimate of the trees' biomass index was used, instead of the estimated volume, and the height growth was compared to the growth of *E. grandis*. The growth of *E. grandis* has been well documented and relatively reliable equations for predicting growth, using top height as a growth indicator, of this species have been published (*Coetzee*, 1999). According to *Coetzee* (1999), with a top height of 5.46 m at two years of age,

the Backsberg site has a Site Index (base age 5) of 11. With this information, paired with the stocking data (1667 stems ha^{-1}), predictions of yield can be made. The biomass index gives an indication of the relative production potential of each taxon at the site, while the top height and Site Index of *E. grandis* can give insight as to the potential volume production of each taxon on the site.

There are significant differences between the estimated biomass indices of the taxa ($p<0.05$), at age two at Backsberg (**Table 4.9**). The best performing taxon is *E. grandis × camaldulensis* with an estimated mean biomass index of 0.47 m^3 ha^{-1} at two years of age. The *E. grandis × urophylla*, the second highest biomass index at two years, followed by *E.grandis*, *E. dunnii* and *E. cladocalyx* (**Table 4.9**).

The estimated top height of *E. grandis* on a site with a Site Index of 11, at six years of age is 12.04m. The estimated mean annual increment (MAI) of this site, having a stocking of 1667 stems per hectare, is 12.5 m^3 ha^{-1} yr^{-1}, culminating after ten years of age according to *Coetzee* (1999). The relationship between the top heights of the different genotypes at this site currently can be translated into a prediction of potential volume increment prediction (**Table 4.9**). The potential MAI difference between the hybrids may change as time continues, but they are potentially still the best growers at six years of age, yielding approximately 18 m^3 ha^{-1} year^{-1}, followed by *E. grandis* (12.5 m^3 ha^{-1} year^{-1}) and *E. dunnii* and *E. cladocalyx* bringing up the rear with 9 m^3 ha^{-1} year^{-1}. This, however, is a prediction and only time will tell if these volume increments can be reached by these taxa.

4.2.3 Abiotic Risks

The experimental design at Backsberg affords a good opportunity to assess the possible infestation of known pests in commercial forestry regions to that of the study region. It could give a good indication as to what to expect if commercially produced and used species were to be planted in the study region as a source of biomass.

The taxa were assessed for the presence of pests by means of non-parametric tests as stipulated in Chapter 3, due to the non- normal distribution of data residuals. The two main pests identified in other experimental sites in the study area are *Thaumastocoris peregrinus* and *Gonipterus scutellatus* and so at this point they are the known threats in the area. The infestation level of *Thaumastocoris peregrinus* is assessed by the amount of feeding damage, egg clusters and adults on the tree, while the *Gonipterus scuttelatus* presence is marked by the visual signs of feeding, larvae tracks and adult beetles.

Certain taxa are significantly more susceptible to *T. peregrinus* than others ($p<0.001$), the most susceptible genotype being *E. grandis x camaldulensis*, with the least susceptible being *E. cladocalyx* (**Figure 4.10**). In general the hybrids were more susceptible to *T. peregrinus* than the seedlings. The estimated infestation by pests did not seem to be that high at the time of visual assessment. However, there were plots were the lower tree crown foliage had died and fallen off the tree due to *T. peregrinus*, thus reducing of photosynthetic capacity. The defoliation was observed mainly in the hybrids; *E. grandis x camaldulensis, E. grandis x urophylla* and in a singular *E. grandis* plot. This defoliation was most prevalent in the *E. grandis x camaldulensis* plots.
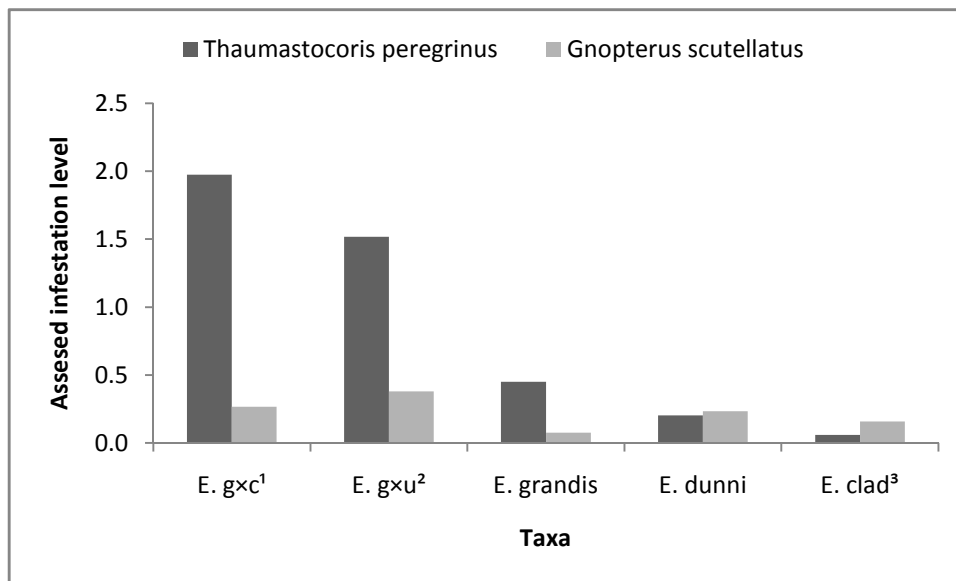
Figure 4.10 Infestation levels of *Thaumastocoris peregrinus* and *Gonipterus scutellatus* on the taxa at Backsberg trial site at age two years. (Refer to Table 3.8 and Figure 3.6 for description of infestation level scores).

[1] = *E. grandis x camaldulensis*

[2] = *E. grandis x urophylla*

[3] = *E. cladocalyx*

In terms of *Gonipterus scuttellatus*, the presence of the pest was noted and used to get an idea of the taxa that are most susceptible to this pest. There was a significant difference in presence of the pest between the taxa ($p<0.001$). The most susceptible taxon being *E. grandis x urophylla* followed by *E. grandis x camaldulensis, E. dunnii,* and *E. cladocalyx*, with the least susceptible taxon being *E. grandis*. The general trend for presence of *G. scutellus*, aside from the preference for specific taxa, more damage by these pests could be seen in the larger, more mature trees than the smaller ones (visual observations).

Chapter 5: Discussion

5.1 Survival

5.1.1 Coetzenburg and Darling

Survival at Darling was significantly less than at Coetzenburg, especially in the case of *E. cladocalyx* (58% survival at Darling)*.* The poor survival along with the fact that no external sources of death were recorded in the trial notes, suggests that *E. cladocalyx* is not as well suited for the drier conditions of the Darling site. The *E. gomphocephala* at the same site presented a more positive survival rate (80%). At the Coetzenburg site, the overall survival of *E. cladocalyx and E. gomphocephala* were excellent with survival rates of 90%.

Of the families present at the Coetzenburg site, 49% have a survival percentage higher than 95% and the 97% of the total amount of families has survival rate of 70% and above. At the Darling site, 43% of families have survival percentages higher than 70%, and only 3% have survival percentages above 95%.The fact that *E. gomphocephala* has a good survival percentage at both sites shows that it can survive in both the wetter and drier sites, but has a higher chance of survival in the wetter regions of the study area. Whereas, the poor survival percentages of *E. cladocalyx* at the Darling site and the excellent survival percentages at the Coetzenburg site, indicate that *E. cladocalyx*, in terms of survival, is better suited to the wetter sites in the study area.

5.1.2 Backsberg

The Backsberg site enjoyed a favourable survival percentage, with the lowest survival rate being 78% (*E. cladocalyx*) and the other 4 taxa having a survival rate of 90% and above, with the highest being 98% (*E. grandis*). The hybrid taxa (*E. grandis×camaldulensis* and *E. grandis×urophylla*) did enjoy a higher rate of survival than the seedlings, which is not unique to this experiment (*Smith et al.,* 2005). The weak performance of *E. cladocalyx*, the traditionally planted taxon in the study region (ARC, 2009; *van Wyk et al,* 2001), and the excellent performance of the cloned plant material (*E. grandis×camaldulensis* and *E. grandis×urophylla*) that originates from the commercial forestry region, which has a vastly different climate than that of the study region, are points of interest. The poor survival of E. cladocalyx could possibly be ascribed (at least in part) to the poorer seedling quality of this taxon at time of planting. *E. cladocalyx* was not raised in a commercial nursery while all other taxa in this trial were sources from very well managed commercial nurseries of multinational forestry companies.

5.1.3 Survival versus Mean dbh

The commonly observed relationship between mean dbh and survival in plantations is that decreasing survival (leading to lower stocking levels) will facilitate an increase in mean dbh. The decreased survival will provide more space, nutrients and sunlight for the remaining trees to grow on the plots with lower survival. However, this was not so in the correlations done of mean dbh and survival percentages in this study. In fact, the opposite was found to be true, although only significantly so in *E. cladocalyx* at the Darling site. The relationships between survival and mean dbh could indicate that some families with extreme mortality produced low volume yields and small diameters, probably due to genetic incompatibility with the site, i.e. off- site planting. This is evident when comparing the top producing families between the sites (**Figure 5.1**). The only family that was well-suited to both sites was

1A of species *E. gomphocephala*. The difference in estimated yield of this family between the two sites is evident; 38.4 m^3 ha^{-1} with 93% survival at Darling compared with 96% survival and estimated yield of 52 m^3 ha^{-1} at Coetzenburg (**Figure 4.3 and 4.4**). The difference in performance of these top producing families at the different sites suggest that some families' poor performance was due to incompatibility with the site, rather than the issue of survival and mean dbh. This genetic incompatibility could also have added to the relationship of mean dbh being so different from the expected. Survival should not be equated with volume production because when assessing survival, live trees with no measurable dbh were also included, even though they were not contributing to the volume of the plot.

The only top producing family that had similar yield at both sites were *E. gomphocephala* 1G and 1C. These families were amongst the least productive at Coetzenburg, but the most productive at the Darling site. This suggests that this might be the maximum productivity of these families and, consequently, they should be planted at the Darling site, as there are other families that outperform them at the Coetzenburg site. In all the other families, the yield at the Coetzenburg site surpassed that of the yield at the Darling site (**Figure 4.3 and 4.4**). In family A1, the low survival (30%) could explain the difference in yield between the Darling and Coetzenburg sites. G2 had one of the lowest yields at the Darling site (6 m^3 ha^{-1}), while the mean volume for this same family at Coetzenburg is 77 m^3 ha^{-1}, which is a substantial (71 m^3 ha^{-1}) difference in volume yield. This substantial difference in yield coupled with the low survival rate at Darling (32%), indicates that this family is not well suited to the dry climates, but will prosper in sub-humid sites.

5.2 Stand density

The common trend between stand density and yield is that the higher the stand density, the higher the utilizable volume production, the higher the mean annual increment (*Coetzee,* 1999; *Smith et al.,* 2006). Stand density in this scenario refers to the number of trees or stems per hectare of land on a site. The time that it takes to achieve culmination MAI is also shorter on sites that are more densely stocked (*Smith et al.,* 2006). The decreased time to culmination MAI and also the difference in utilisable volume between the stocking is more pronounced on the sites with higher productivity. On lower productivity sites, the difference between lower and higher stand densities is not as apparent, with intermediate stocking being optimal (*Smith et al.,* 2006). This is applicable in plantations for pulp production, with the culmination MAI taking approximately 10 years to be achieved on the lower productivity sites (*Smith et al.,* 2006). It must be stated that the lower productivity sites in the commercial forestry areas are akin to the better sites in the specific study region. The estimated time to culmination MAI in work done in the study region was 10 years at a low stand density (900 stems ha^{-1}) (after Van Wyk et al., 2001). Comparable sites in the commercial forestry region indicate the possibility of culmination MAI being reached at 12 years at sites with stocking of 1667- 2222 stems ha^{-1} and SI 13 (*Smith et al.,* 2006). A biomass estimation exercise was done in Australia on a 3 year old Eucalyptus stand. The site was sandy and had 304mm rainfall annually through the course of the experiment, which mirrors the very low productivity sites in the study region. The trial plots were established at different positions in slope, which would change natural water availability, and stem densities varying from 500 stems ha^{-1} to 4000 stems ha^{-1}. At all positions on the slope (water availability) it was found that increased stand density equates to increased yield. The highest yielding site was always the 4000 stems ha^{-1} treatment, even though at some sites the 500 stems ha^{-1} had the largest trees (*Sochacki et al.,* 2007).

The optimum stand density would depend on the purpose of growing the trees and the economic viability of the stand. The end use of the tree would determine the stand density in that there might be minimum and maximum diameter requirements for whatever technology is being used during harvesting and utilization. If the size stipulations are very lenient, as with biomass production, it might be more prudent to have areas planted with very high stem density for a shorter period of time. This option could also be more attractive as the economic returns will be reaped sooner rather than later for the same amount of biomass. This is evident in **Figure 5.1**, the more densely the site is stocked, the higher the yield. A preliminary economic analysis on using biomass from trees for electricity production in the Greater Boland Region suggest that on medium (comparable with Coetzenburg site) and low productivity (comparable with the Darling site) sites a stocking of 1750 stems ha^{-1} and 1500 stems ha^{-1} respectively, produce positive returns (*von Doderer and Kleynhans,* 2009). The fresh wood, i.e. standing timber that hasn't been dried, biomass estimates were 18 t ha^{-1} a^{-1} at the medium site with 1750 stems ha^{-1}and 9 t ha $^{-1}$ a^{-1} at the lower productivity site with 1500 stems ha^{-1} (*von Doderer and Kleynhans,* 2009) with rotation ages being 7 and 10 years respectively. In terms of this study, an intermediate stocking, of approximately 1600 stems ha^{-1}, may be an economically viable option, although studies done to estimate the maximum stem density on a site should be done to potentially shorten the rotation period.

5.3 Yield

5.3.1 Coetzenburg and Darling

The mean volume production per site differed quite substantially between the Darling and Coetzenburg sites, with a yield of 13.6 m^3 ha^{-1} and 41.7 m^3 ha^{-1} respectively (**Table 4.3**) *E. cladocalyx* performed better at Coetzenburg (42.2 m^3 ha^{-1}) than at Darling (9.8 m^3 ha^{-1}) (**Table 4.3**). The lower yield in conjunction with the lower survival rate of *E. cladocalyx* at Darling, suggests *E. cladocalyx* is better suited to the wetter regions of the study area i.e. the Coetzenburg site, while *E. gomphocephala* grows well at the Darling site. There are also differences in top performing provenances and families at the the Coetzenburg and Darling sites, which all resounds the suitability of *E. gomphocephala* and *E. cladocalyx* at the sites.

The MAI of the top producing families per species are 11.2 and 4.65 m^3 ha^{-1} a^{-1} at Coetzenburg and Darling respectively at 6 years of age from estimates in **Table 4.6**. These MAI's are in line with the estimated volume growth MAI at intermediately stocked, low productivity sites in the commercial forestry region at their culmination MAI (*Smith et al.,* 2005; *Boreham and Pallet,* 2009). The time to culmination for these low productivity sites, do differ with stocking, but range from 8-13 years (*Smith et al.,* 2005). Other studies that have been done in the study region estimate MAI of 8.6 m^3 ha^{-1} $annum^{-1}$ at 10 years of age for the drier end of the spectrum (*van Wyk et al.,* 2001).

Because of the lack of annual measurement data, specific current annual increment (CAI) and MAI curves could not be created for the Darling and Coetzenburg sites. In order to obtain an idea of the expected maximum growth rate and potential age where MAI culminates, the current MAI values obtained on both sites are compared to known MAI curves for other

Eucalypts (*van Wyk et al.,* 2001; *Coetzee,* 1999). The MAI development of a stand of *E. grandis* with SI=13, planted at respectively 1000 and 1600 stems ha^{-1} (Coetzee, 1999) is plotted alongside the point data MAI of the Darling and Coetzenburg sites (**Figure 5.1**). **Figure 5.1** also shows the MAI development of the best performers at the Pampoenvlei trial site, situated near Darling on the Western Cape coastal plain (*Van Wyk et al.,* 2001). This is done to estimate the magnitude and timing of the potential peak MAI that could be realised on the sites of higher and lower productivity.
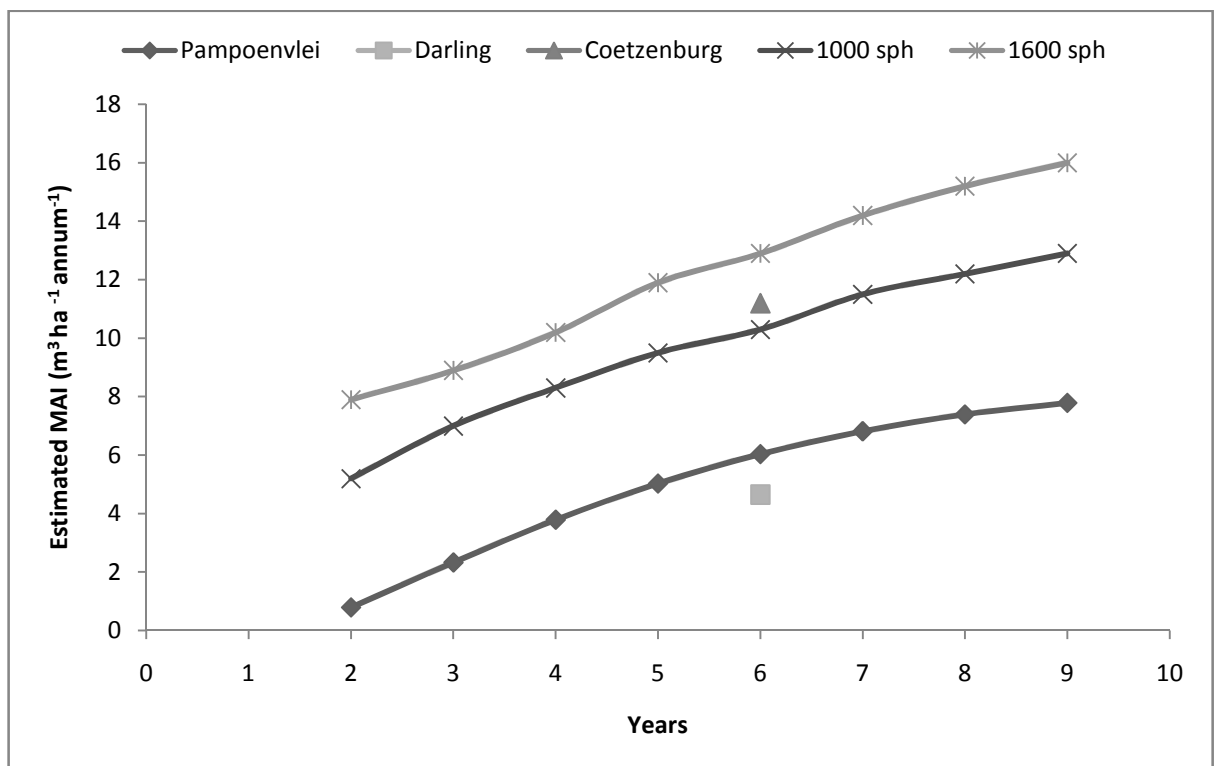
Figure 5.1. Estimated development of MAI of *E. grandis* with SI 13 for stem densities of 1000 stems ha^{-1}, 1600 stems ha^{-1} (after Coetzee, 1999), and of the top producers at the Pampoenvlei trial (after van Wyk et al., 2001). The point data represents MAI of the top producers at the Darling and Coetzenburg sites at 6 years of age.

The MAI of *E. gomphocephala*, from studies done in Morocco, can vary from 7 m^3.ha^{-1} annum^{-1} in semi-arid areas, but can yield between 21-44 m^3. ha^{-1}

annum^{-1} on highly productive, irrigated sites in Morocco (*van Wyk et al.,*2001). The MAI of the top producing families at the Darling and Coetzenburg site fall within this range. The MAI of Coetzenburg at 6 years with SI 13 is comparable to the yield of *E. grandis* at 1000 stems ha^{-1}, which has fewer stems per hectare, than at the Coetzenburg site. The MAI of Darling is much lower than the SI 13 at stem density of 1000 stems ha^{-1}, but is more comparable to the MAI curve of the Pampoenvlei trial. This is not unexpected due to the climatic and environmental similarities between the sites. This illustrates the low production potential of the Darling site due to its low yield when compared to a site with similar Site Index and stem density in the commercial forestry regions of South Africa.

5.3.2 Backsberg

The comparison of volume yield of these sites might be very misleading in that the hybrid taxa outperform the seedlings by far, but this is typical of the growth trends of hybrid taxa; they have rapid initial growth. Therefore, a biomass index was used as an indication of growth. The survival at this site indicates that there is not a crippling amount of mortality on the site. Thus, the low-yielding taxa *(E. dunnii* and *E. cladocalyx)* do not have high mortality; they are only growing slower than the hybrid taxa and *E. grandis*. Consequently, an estimation of biomass was deemed more appropriate than using volume equations, taking into account the stocking of per plot of the different taxa.

The top biomass yielding taxon was *E. grandis×camaldulensis* followed closely by *E. grandis×urophylla* with *E. grandis* having intermediate yields while *E. dunnii* and *E. cladocalyx* achieved low yields (Table 4.6). It must be reiterated that the yield of these taxa could change in the years to come and might present a totally different scenario when the hybrids lose their initial growth vigour (*Smith et al.,* 2006).

5.4 Biomass production

5.4.1 Wood density for biomass estimation

Biomass was estimated using estimates of wood density. The interesting finding is that the density of the cores were not very different from each other across families or taxa, thus a mean density was used per site. The densities obtained are conservative compared to density studies of *E. gomphocephala (800* kg m^{-3}*)* and *E. cladocalyx (700* kg m^{-3}*)* (*Illic et al.,* 2000; *Hassal and Associates,* 1998) in its natural habitat, but was consistent with the density range of fast growing Eucalyptus plantation trees, 430kg/m^3 -660kg/m^3 (*Illic et al.,* 2000; *Clark,* 2001; *Dovey,* 2009). Furthermore, the densities were higher on the wetter site than on the drier site, which is contrary to what some literature sources suggests for eucalypts (*Miranda et al.,* 2001; *Thomas et al.,* 2004; *Montagu et al.,* 2005). Site and interaction of provenance with site was not found to be a significant factor of density variation (*Miranda et al.,* 2001) the variation could be attributed more to the age of the trees. There are no consistent correlations between growth rates and wood density (*Thomas et al.,* 2004), although some literature suggest that faster growing trees have higher densities than the slower growing trees (*Ferreira,* 1970; *Leclercq,* 1977; *Malan,* 1993; *MacFarlane and Adams,* 1998; *Wilkins and Singh*, 2008). This could offer part of the explanation for the confounding wood density values between the wetter and drier site in this study. Furthermore, studies have also found that increased temperature and elevation could have an increasing effect on the wood density (*Thomas et al.,*

2004). In this study the temperature would not have such a large effect, but the elevation could have. The literature, however, agrees that there are many environmental factors that have an effect on wood density and therefore is complex (*Montagu et al.,* 2005; *Miranda et al.,* 2001; *Thomas et al.,* 2004; *Wilkins and Singh,* 2008*).* The individuals that were sampled could also have attributed to the differing mean density between sites. Only the families with the largest mean dbh were sampled. Although this sampling method is statistically sound, it could have led to a different result than if a general sample of the whole stand was taken.

5.4.2 Estimated biomass at Coetzenburg and Darling sites

Table 4.6 presents the top producing families per species, their total estimated volume and stem wood biomass as well as the survival percentage. These essentially would be the best species and families to plant at wetter and drier sites in the study area from the species in this study. The only species that had the same family in the top producers at both sites was *E. gomphocephala;* namely the 1A family.

Biomass estimation is the best way of ascertaining the suitability of families for energy production because it takes into account both key factors, namely volume and density. It is important to note that the biomass estimates (**Table 4.6** and **Figure 4.9**) are that of the stem wood biomass. Literature suggests that the branches and leaves ratio: stem wood is approximately 0.25-0.3 for fast growing commercial eucalypt species in South Africa (*Dovey, 2009; Hassal and Associates*, 1998; *Montagu et al.,* 2005; *Pérez et al.,* 2006). The current mean stem wood biomass of the three top producing families are 41.7 t ha^{-1} and 16.4 t ha^{-1} at Coetzenburg and Darling respectively (**Table 4.6**). Taking the leaves and branches into account, Coetzenburg could additionally gain approximately 10.4t ha^{-1} and Darling 4.1 t ha^{-1} in biomass (when using the 0.25 bark and branches ratio: stem wood). This is an

estimated potential of the above ground available biomass at this site. This study is in no form advocating the removal of all above-ground plant material from the site. These branches and leaves provide nutrients to the site and thus the portion of this biomass that may be removed from the site is site specific (it should be restricted to well-buffered sites).

Biomass at a dry, Australian site at three years of age (*Sochaki et al.,* 2007) ranged from 11.8-13.5 t ha^{-1}, which is comparable with the values found at the Darling site, with its estimated mean total above ground biomass, including branches and leaves, being 20.5 t ha^{-1} at six years of age. The top producers at the sites had an utilizable biomass yield of 2.7 and 6.9 t ha^{-1} a^{-1} at the Darling and Coetzenburg sites respectively. This is in the lower end of the estimated range of biomass production for the Cape Winelands Municipality, which is 2-18 t ha^{-1} annum^{-1} (*von Doderer and Kleynhans,*2009), and the aforementioned study in Australia (*Sochaki et al.,*2007).

5.5 Biotic Risks

The Backsberg site was quite useful in assessing the potential biotic risks that the hybrid commercial taxa face in the study region. The pests that were spotted at experimental sites were *Thaumastocoris peregrinus* and *Gonipterus scutellatus*. Thus a visual assessment was done to gain a better understanding of which taxa are more susceptible to infestation by these pests.

The susceptibility to pests of the commercially used hybrids in this region is a cause for concern. The presence of *T. peregrinus* is the most concerning because there is no known control for this pest as of yet. It is also of great concern that the two most productive taxa at the moment seem to be the most susceptible to the pests.

5.6 Discussion of results by hypothesis

Hypothesis 1 investigates the growth potential of families across the climatic range in the study area. Statistical tests suggests that there is no statistically significant difference in the potential growth of families between *E. gomphocephala* at the Darling site ($p<0.05$) (**Table 4.4**), while there are significant differences between families of the *E. cladocalyx* taxon at both sites ($p<0.05$) (**Table 4.4**). The variances of the yield of families are visible in **Figure 4.7** and **Figure 4.8.** The pronounced differences in yield are also very apparent. The families with the highest productivity are presented in **Table 4.6**, with the only common family across the sites being 1A from *E. gomphocephala*. The hypothesis is not to be accepted for all but the single case of family 1A that was among the top three producers for the *E. gomphocephala* taxon at both sites.

Hypothesis 2 investigates the differences in suitability of different species and provenances to be planted in different regions of the study area. The statistical analyses suggest that there is a significant interaction between estimated stem wood volume and sites ($p<0.05$) (**Table 4.4**). The difference in stem wood volume between sites is illustrated in **Table 4.3** and **Figure 4.**6. This hypothesis cannot be accepted because there are statistically significant differences in stem wood volume production between sites and taxa.

Hypothesis 3 investigates the estimation of stem wood biomass available to harvest across a climatic gradient i.e. the difference in biomass production potential between families on the Coetzenburg and Darling sites. There is a significant difference interaction between stem wood biomass production and site (**Table 4.5**), which suggests that there will be a difference in biomass between the sites. **Figure 4.9** aptly describes the relationship between estimated stem wood biomass in Coetzenburg and Darling, while **Table 4.6** visually shows the differences between stem wood biomass of the top

performing families per species at the two sites. Estimated stem wood biomass differs significantly between the two sites, as well as between the species and families (**Table 4.8** and **Figure 4.9**). There is not enough evidence to reject hypothesis 3. It is accepted because there is in fact a significant difference ($p<0.05$) between the estimated stem wood biomass between the Coetzenburg and Darling sites.

Hypothesis 4 investigates whether commercially available taxa have the potential to be more productive than *E. cladocalyx* in the study area. At the Backsberg site, it was found the *E. grandis* had the highest survival rate and *E. cladocalyx* had the lowest (**Table 4.9**). The estimated biomass index at this site, indicated that the hybrid taxa are the best volume producers at this site to date, specifically *E. grandisxcamaldulensis*. The Biomass Index at this site still indicates a large variation in growth between the clones and the other taxa, with the least productive of all being *E. cladocalyx* (**Table 4.9**). The better survival and higher biomass index of taxa other than *E. cladocalyx* provide enough evidence not to reject the hypothesis. Hypothesis 4 (stating that commercially used taxa have the potential to be more productive than the local stalwart *E. cladocalyx* in the study region) is thus accepted. It must, however, be noted that in terms of pest infestation, *E. cladocalyx* is of the less susceptible taxa, which is a very important aspect to consider (**Figure 4.10)**.

Chapter 6: Conclusions and Recommendations

The results show that even when only taking climatic data into account, there is a variation in species that are suitable for the different regions in the study area as well as the growth potentials between sites. Maximum biomass production potential at the dry and sub humid site was approximately 2.7 and 6.9 t ha^{-1} a^{-1}.

E. cladocalyx displayed superior biomass potential to *E. gomphocephala* on the wetter Coetzenburg site. At the drier, Darling site, *E. gomphocephala* out-performed the *E. cladocalyx* planted on this site. The volume and biomass production of *E. gomphocephala* at the Darling site was however, noticeably lower than the Coetzenburg site.

The best performing families are of similar provenances across the Darling and Coetzenburg sites. On the drier site the Flinders Chase NP (12.7 m^3 ha^{-1}) and Kersbrook SPA (12.3 m^3 ha^{-1}) proved to have the largest volume potential of *E. cladocalyx*, while the best performing *E. gomphocephala* provenances, Harvey (27.1 m^3 ha^{-1}) and Control (23.0 m^3 ha^{-1}), produced the largest potential volume on this site. Similarly, at the wetter site the *E. cladocalyx* provenances Kersbrook SPA (78.3 m^3 ha^{-1}) and Flinders Chase NP (57.5 m^{3}ha^{-1}) had superior volume potential. In terms of *E. gomphocephala*, the top producing provenance was the Control (47.5 m^3 ha^{-1}) followed closely by the Harvey (43.4 m^3 ha^{-1}) provenance. This superior volume production translates into superior biomass potential too.

The differing densities of the sites (588 versus 620 kg m^{-3}) are also a point of interest. The fact that the wetter site had the higher wood density, was

contrary to some findings, but that might be because the Coetzenburg site has a faster growth rate.

The survival and mean dbh correlation was also contrary to what was expected, with the survival increasing with mean dbh. A possible explanation for this trend is the poor survival of some of the families displayed, especially in *E.cladocalyx* at the Darling site, is the off-site planting of some of the families, thus the survival was so low and this correlation became apparent.

The hybrids have displayed excellent growth potential in the area thus far. The predicted MAI at ten years indicates that there is not a large difference between the estimated volume of these taxa, *E. grandis × camaldulensis* (17.89 m^3 $ha^{-1}a^{-1}$) and *E. grandis × urophylla* (17.82 m^3 $ha^{-1}a^{-1}$). The wood density and susceptibility to pest infestation need to be assessed in future to ascertain the more suitable of the two taxa. The superior growth of the hybrids is a positive result, because of their mass production in the industry as well as their lower risk of becoming invasive in the water scarce study region, because most hybrids are sterile. Further research into the effect of irrigation with effluent water could broaden the range of taxa that could be used in this biomass production scenario.

The insects that infest these hybrids could be a big problem and should be taken into consideration when species are chosen to be planted. The good survival percentage paired with the significantly larger biomass index yield of *E. grandis × camaldulensis* makes it the best suited taxa for this site, in terms of biomass potential. The second best performing taxa, namely, *E. grandis × urophylla*, yields volume that is significantly larger to *E. grandis*, but has the added demerit of being a susceptible host to *Thaumastocoris* , which is a defoliator and could lead to mortality (*Jacobs and Neser,* 2005). Thus, it would not be recommended to plant the hybrids in this region, despite its yield potential, if it is so susceptible to infestation of this pest, given that there

are no commercially available control measures. *E. grandis* has a lower estimated MAI (12.5 m^3 ha^{-1}a^{-1}) and superior survival percentage (97%) to *E. grandis✕ camaldulensis* (96%) and *E. grandis✕urophylla* (95%)*,* but an apparent higher pest tolerance . Studies show that there has been sightings of *Thaumastocauris* on *E.grandis* (*Jacobs and Neser,* 2005; *Noack and Coviella,* 2006), but few signs of stress were observed even if there were signs of heavy infestation during this study. Thus, if the infestation persists on the hybrid taxa, *E.grandis* might be the best option in the region, because of its comparable volume production and apparent resistance to infestation by *Thaumastocoris*.

The inclusion of the results of parallel studies investigating the potential growth of alternative species of indigenous and exotic trees should also be compared with the results of this study to broaden the range of species that could be planted as a biomass source on sub-optimal land in the study region.

Planting trees on low-productivity sites can be an effective method of crop diversification for farmers in the region and be economically lucrative, albeit not to such an extent as major cash crops like vineyards or fruit orchards. The current growth potential on the dry site is 6.95 m^{3}ha^{-1}a^{-1} and is 11.2 m^3.ha^{-1}a^{-1} on the wet site, while projected potential growth at ten years is approximately 13 and 8 m^3 ha^{-1}a^{-1} at the wet and dry sites respectively. Thus, studies such as this one, through which the understanding into suitable species' growth potential is bettered, becomes important.

The site and family differences in volume and biomass estimation were followed through in the estimated bioenergy production. The top bioenergy producing family was at the Coetzenburg site of the *E. cladocalyx* species (892 GJ ha^{-1}) as opposed to the top performing *E. gomphocephala* family (392 GJ ha^{-1}) at the Darling site. Estimated mean bioenergy at the

Coetzenburg site (767 GJ ha^{-1}) was, as expected, larger than that at the Darling site (302 GJ ha^{-1}).

Recommendations for further study

Further allometric studies should be done to ascertain the more accurate biomass equations for the climatic conditions of the greater Boland region. In conjunction with this, studies to ascertain the nature of nutrient pools in these sites, as well as sites that are typical of the Greater Boland region, should be done to determine the portion of trees that should remain on site for reasons of nutritional sustainability. These equations should also address the issue of using an appropriate upper stem diameter (depending on the harvesting system) which could be altered to estimate the utilisable volume in different scenarios. Studies that can provide more concrete recommendations on stem density, rotation length and coppicing capacity of these low productivity sites would be very helpful in the extrapolation and planning of bioenergy woodlots in the region.

7. References

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