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

Ilse Botman

Thesis presented in partial fulfilment of the requirements for the degree of Master of Science in Forestry

at the Faculty of AgriSciences

University of Stellenbosch

Supervisor: Dr Ben du Toit

March 2010

Declaration

By submitting this dissertation electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the owner of the copyright thereof (unless to the extent explicitly otherwise stated) and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

March 2010

Summary

The purpose of the study was to investigate the potential tree taxa that could be grown as a source of biomass in the Cape Winelands region. The trials comprises of two different aspects. The first being the estimation of potential volume, density and biomass of a pair of six year-old stands of *E. gomphocephala* and *E. cladocalyx* families at two climatically different sites within the study region. The second part of the study was the early growth assessment of alternative taxa that could be planted in the region compared to the regional mainstay *E. cladocalyx*.

The volume of families was estimated using appropriate volume equations and using the form height were none were available. The best volume yield varied from 4.6 to 11.2 m^3 $ha^{-1}a^{-1}$, at the dry and sub-humid sites, respectively. Wood density, estimated from non-destructive samples at both sites, varied from 620 (sub-humid) to 588 kg m^{-3} (dry site). The estimated biomass production rate of the top producing families yielded 2.7 and 6.9 t $ha^{-1}a^{-1}$ at the dry and sub-humid sites, respectively. In terms of estimated biomass and survival, *E. gomphocephala* was more suited to the dry site, while *E. cladocalyx* displayed superior yield than *E. gomphocephala* on the sub-humid site, but not significantly so.

Early growth assessment of the trial of alternative taxa found that the hybrid *E. grandis* × *camldulensis* and *E. grandis* × *urophylla* had superior biomass indices, but were more susceptible to infestation by *Thaumastocoris peregrinus* and *Gonipterus scuttelatus*.

Opsomming

Die doel van hierdie studie was om potensiële boom taksa vir gebruik as ’n bron van biomassa in die Kaapse Wynlandstreek te ondersoek. Die proewe behels twee aspekte: eerstens die beraming van die potensiële volume, digtheid en biomassa van sesjaaroue opstande met families van *E. gomphocephala* en *E. cladocalyx* by twee klimatologies verskillende groeiplekke in die studiegebied; tweedens die beoordeling van die vroeë groei van alternatiewe taksa wat in die streek geplant kan word in vergelyking met die streek se historiese staatmaker-spesie *E. cladocalyx*.

Die volume van die families is beraam deur gebruik te maak van toepaslike volumevergelykings, en met behulp van ’n vormfaktor waar vergelykings nie beskikbaar was nie. Die volume aanwas by die droë en sub-humiede groeiplekke was onderskeidelik 4.6 en 11.2 $m^3 ha^{-1} j^{-1}$. Houtdigtheid is beraam deur nie-destruktiewe monsters uit die opstand te neem. Gemiddelde digthede het variëer van 588 (sub-humied) tot 620 kg m^{-3} (droë groeiplek). Die beraamde biomassaproduksie van die top-families beloop onderskeidelik 2.7 en 6.9 t $ha^{-1} j^{-1}$ vir die droë en sub-humiede groeiplekke. In terme van beraamde biomassa en oorlewing, is *E. gomphocephala* meer geskik vir droër groeiplekke , terwyl *E. cladocalyx* by die sub-humiede groeiplek ’n hoër opbrengs as *E. gomphocephala* getoon het, hoewel nie betekenisvol nie.

Beramings van die vroeë groei by die proef met alternatiewe taksa het getoon dat die basters *E. grandis × camldulensis* en *E. grandis × urophylla* hoër biomassa-indekse het, maar meer vatbaar is vir besmetting deur *Thaumastocoris peregrinus* en *Gonipterus scuttelatus*.

Acknowledgements

I would like to acknowledge:

1. My supervisor, Dr. Ben du Toit for his continuous support and assistance.

2. Fellow students, colleagues and staff of the Department of Forest and Wood Sciences for their help with data collection, sharing of their abundant knowledge as well as encouragement.

3. Mr Michael Back for allowing trial sites on his property.

4. The Centre for Renewable and Sustainable Energy Studies for financial support.

5. The University of Stellenbosch for the facilities and specifically the staff of Department of Forest and Wood Sciences for sharing their knowledge.

6. My family and friends for the constant support and encouragement.

7. God Almighty, without whom none of this would be possible.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

Dbh- diameter at breast height, 1.3m from the ground
E_p- Estimated Evaporation
GHG- Green House Gases
IPCC- International Panel on Climate Change
LCA- Life cycle analysis
MAE- Mean Annual Evaporation
MAE$_p$- A-pan evaporation
MAP- Mean Annual Precipitation
m.a.s.l- metres above sea level
MAT- Mean Annual Temperature
Max. Temp- Maximum Temperature
Min. Temp- Minimum Temperature
sph- Stems per hectare
UNFCC- United Nations Forum on Climate Change

Chapter 1: Introduction

1.1 Background

Green house Gasses (GHG) are believed to be the largest contributor to the climate changes that have systematically been taking place (*Blignaut et al.,* 2005). There are a few GHG that are partially responsible for these namely N_2O and CH_4, but the main contributor to GHG world-wide is CO_2. The emission of CO_2 is mainly due to the combustion of coal that supplies 70% of South Africa's energy (*Blignaut et al.,* 2005). Industrial processes are the largest consumer of electricity in the country (44.2%), followed by services (26.2%), residential demands (16%), mining (8%) and the agricultural sector (5%) (*Blignaut et al.*, 2005). However, the largest emitter of GHG in South Africa is the transport sector, and thus it is in this sector where the major mitigation projects are geared (*Department of Minerals and Energy*, 2007).

Carbon footprint is a measurable amount of carbon that is emitted to the atmosphere by a certain organization or individual. This encapsulates everything that we do, from the fossil fuel burnt to provide electricity, fuel consumption, to the products that we purchase. To maintain a balance between carbon sequestration and carbon emissions, calculations can be made to determine a finite amount of carbon emissions for each individual, based on the amount of CO_2 the earth can sequester. When this finite share is exceeded the effects of CO_2 and other GHG will become detrimental to the environment. Currently, the emission of GHG exceeds the amount that the earth can sequester. To counteract this, the concept of decreasing carbon footprints becomes important. If all organizations and every individual are willing to reduce the amount of carbon they emit from the earth, there will be a decrease in the effects of global warming. As will be discussed in more detail later, forestry could play a larger role in the energy industry as a whole. Not only is woody vegetation and it's biomass an alternative source of energy, it can also replace the use of steel and iron, the production of which demands a large portion of the energy consumed by the industrial sector in South Africa (*Blignaut et al.,* 2005).

South Africa has a carbon use intensity that is 240 % more than the average usage world-wide, the highest of all developing countries considered, such as China, Brazil, Nigeria and Argentina, which are all of comparable development stages to South Africa (*Blignaut et al.*, 2005). **Figure 1.1** illustrates the demand of various sources of energy. Currently renewable resources supply only 8% of the required residential energy consumption, while this sector uses 16% of the total available energy in South Africa. If renewable energy is made more available to this sector (and other sectors strongly reliant on electricity), it could contribute to the reduction of CO_2 emissions in South Africa. The Department of Minerals and Energy investigation in 2003, found the transport sector most damaging to the environment. Therefore, the national mitigation strategy focuses mainly on the use of agricultural crops to produce 10 000 GWh of energy annually by 2013 (*Department of Minerals and Energy,* 2007). This could be achieved by enforcing a mandatory blend of bioethanol or biodiesel with fuel sources. The main crops that are considered are sugar cane and sugar beet as a source of a bioethanol blend and sunflower, canola and soya beans as a source of biofuel (*Department Minerals and Energy,* 2007). Maize, although a good producer of biofuel, is not considered in the strategy because of the effect the competition might have on food security (*Department Minerals and Energy,* 2007). The strategy also doesn’t outline any steps to return carbon deposits to the earth. Biomass from trees are a desirable source of energy as it is comparable to other sources of biomass (i.e. bagasse and wheat), having good intrinsic material properties such as moisture content, ash content and calorific values (*McKendry,* 2002). The downfall of the wood as a source of bioenergy is the area it requires to produce an economically viable yield (*McKendry,* 2002). This is where trees could become very useful, because they can be used on marginal land, could possibly be used as a source of electricity and sequester large amounts of carbon (*Marland and Schlamadinger, 1997; Cook & Beyea*, 2000).

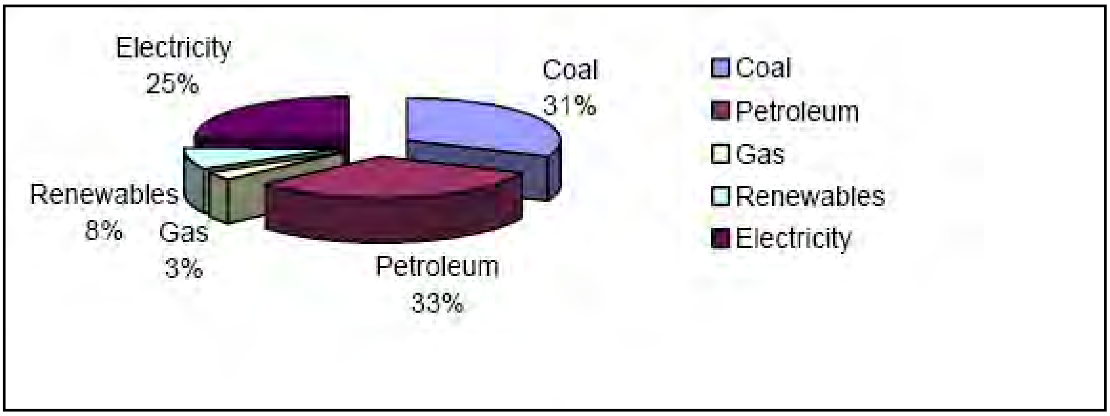


Figure 1.1. Share of final demand for energy by fuel type in 1998 (*Blignaut et al*, 2005)

1.2 Bioenergy from forest plantations

Bio-energy is the energy that is produced using biomass. Approximately 14% (50 exajoules) of the world's energy use is obtained from a bio-energy source (*Schlamadinger & Marland,* 1996)*,* of which 38% is used in developing countries. Trees can possibly reduce carbon from the atmosphere in four basic ways (*Schlamadinger & Marland,* 1996):

- The storage of carbon in the biosphere
- The storage of carbon in forest products
- The replacing of fossil fuels by bio fuels
- The use of wood as a product instead of other products that cost more carbon to produce.

The combustion of fossil fuels has been found to be the primary producers of atmospheric CO_2. The basic concept of various trees and plants reducing the CO_2 in the atmosphere is that the solar energy is thus stored in the plant as carbohydrates, the building blocks of woody biomass (*McKendry,* 2002).

The woody biomass in-turn is used as a form of biomass for fuel to replace or off set fossil fuels (*Schlamdinger & Marland,* 1996). In order to efficiently use biomass as a likely alternative for energy production, a life cycle and the role that the biomass (trees) plays in the environment must be understood in order to manipulate the situation for biomass production. Typically, a Life cycle analysis (LCA) is done on a proposed biomass production scenario before implementation. The LCA takes into account all carbon that is released and gained during the process of producing the biomass, from fertiliser application at planting, to the emissions caused by harvesting equipment. Life Cycle Analyses are typically done with intricate and data intensive models predicting the mitigation effects of specific biomass production scenarios could have, such as GORCAM (*Schlamadinger and Marland,* 1999) and CO_2Fix (*Masera*, 2001; *Mohren and Goldwijk,* 1990). These models can also be modified for area specific studies, like CAMfor (*Richards and Evans*, 2000; *Masera,* 2001).

Biomass plantations are deemed an important potential source of biomass in many studies (*Cook and Beyea*, 2000; *Matthews*, 2001; *Berndes*, 2002; *Cannell*, 2003; *Niu and Duiker*, 2003). Apart from dedicated biomass plantations, the residues from forest plantations and associated industries are also considered to be a possible biomass source. Biomass plantations are also less likely to infringe on food security due to the product not having a dual purpose as a food source, like maize; and the possibility of the biomass plantations being planted on low productivity sites which will not interfere with the cultivation of food crops. The planting of trees on degraded land is also one of the mitigation strategies of the IPCC (Intergovernmental Panel on Climate Change) (*Nabuurs et al,* 2007), furthermore the UNFCC (United Nations Forum on Climate Change) has attached a monetary value to the carbon that is stored in the soil, this may make the choice of trees as a bio-energy crop an even more attractive option to farmers wishing to diversify their crops. The carbon mitigation importance is increased with a coppicing rotation crop because the tree is harvested thus removing the carbon, but the stumps and roots can still potentially store carbon in the soil.

Literature suggests large variations of estimates for mitigation potential of forests (*Marland and Schlamadinger, 1997; Cook & Beyea*, 2000; *Matthews*, 2001; Berndes, 2002; *Cannell*, 2003; *Niu and Duiker*, 2003; *Nabuurs et al,* 2007). Potential oven- dry biomass yield over 25 years, can be in the vicinity of 10-25 t ha $^{-1}$ yr^{-1}, which translates to 5-12 t C ha $^{-1}$yr^{-1} of carbon storage (*Matthews*, 2001) in a seedling rotation plus 2 coppice rotations, which is not uncommon practice in the forestry industry. In Australia, average estimated potential atmospheric carbon sequestration from plantations ranges from 13 t ha^{-1} yr^{-1} for *Pinus radiata* to 15.8 t ha^{-1} yr^{-1} for Eucalyptus (*Fung et al.,* 2002).

Planting biomass crops commercially increases the water usage, reducing available water. South Africa is already a water scarce country, and adding to the water usage demands will lead to a more severe water shortage even if rain fed crops are used (*Berndes*, 2002). Predictions suggest that the water scarcity problem will continue to increase with the effects of global warming and economic growth (*Berndes*, 2002). Thus, it is imperative to use all water resources that are available in the most efficient manner.

There are instances worldwide, where effluent and waste water have been used to irrigate woody crops (*Al-Jamal et al*, 2002; *Berndes,* 2002; *Guo and Sims,* 2003; *Sudmeyer and Goodreid,* 2007). The use of this effluent water to irrigate Eucalyptus trees may also open the scope to species that could viably be planted in the region. Scenarios where trees have been used in a phyto-remediation capacity, or grown in saline conditions have also proven to be successful (*Berndes*, 2002; *Sudmeyer and Goodreid,* 2007). The trees will use the saline or polluted, and otherwise unusable, water source and then produce a product that is environmentally friendly and can be used as a bio fuel.

1.3 Justification of study

The aim of this study is to assess the possibility of facilitating short rotation tree crops on sites with low agricultural production potential in the Winelands region of the Greater Boland Region. Currently, 107 662 ha of the Winelands region is used for woodlots and exotic plantations (*van Wyk et al.,* 2001) and potentially an additional 106 000 ha is suited for woodlots (*von Doderer and Kleynhans,* 2009).This publication is in no way advocating that the entire available area be planted for biomass, it is an estimate as to the amount of area that is potentially available for afforestation.

Bioenergy crops need to be planted on sites where tree taxa are well adapted to site conditions to be highly efficient and effective (*Schlamadinger & Marland, 1996*). This is the core purpose-to find a source of woody biomass that will efficiently use the space and site conditions that are available. Having these woodlots could be beneficial in this following ways: The woodlots could not only serve as a source of bio-fuel for energy on farms and surrounds, but also reduce the carbon footprint of farms. The reduction of carbon footprint could be beneficial when trying to export products to developed countries that are constantly scrutinized for their CO_2 use under the stipulations of the Kyoto protocol. The trees are to be planted in a woodlot manner and will be a dedicated biomass crop. In the selection of woody species suitable for biofuels, species were sought that: (a) are fast growing under prevailing climatic conditions; (b) not aggressively invasive in the landscape, biologically or aesthetically; (c) have good coppicing ability, for easy and rapid regeneration and increased carbon sequestration; and (d) have an acceptable density and calorific value . A genus of trees that fit this description well would be Eucalyptus and various taxa of this genus. Taxa are defined as taxonomic units which are phylogenetically related and have characters in common, which differentiate the group from other taxa. In this study the taxon unit could be referring to a species, provenance, hybrid or clone, thus the blanket term taxon is used (*Ride et al.*, 1999). Parallel studies investigating the difference in growth rate between fast growing indigenous species is underway, but quantifiable results will not be available for a number of years.

Historically, *E. cladocalyx* (Sugar gum) and to a lesser extent *E. gomphocephala* (Tuart tree) (*van Wyk et al.,*2001) has been planted extensively on farmland in the Greater Boland Region, partly for its beneficial effects on apiaries, but also as a generally well adapted all-purpose farmyard tree. Since that time, other species and hybrids have been developed in South Africa and abroad. Many of these taxa are untested in the Greater Boland Region.

1.4 Study objectives

The main objective was to assess the suitability of various tree crops that can be planted as woodlots for bioenergy in the study region. This was done by investigating the growth potential of several taxa in existing trials that are suited to grow in this region. The main focus of this study was: a) assess biomass production potential of specific families from provenances of historically planted taxa, namely; *E. gomphocephala* and *E. cladocalyx*; and b) an investigation into other taxa that may be suitable but were not historically planted in this region as well as investigating possible threats to the these species.

Growth data from existing trials of fast growing Eucalyptus were analysed. These trials were situated on a wet and dry site to represent conditions prevailing across the study region. The differences in growth were analysed at different levels of specificity. An estimate of biomass production potential was made using selected density determinations and stand volumes. Furthermore, an investigation into alternative Eucalyptus taxa, aside from the traditional *E. cladocalyx* and *E. gomphocephala,* that could be planted in the study region was done. The specific objectives are as follows:

1. Investigate the differences in suitability of different taxa to be planted in different regions of the study area.

2. Estimate growth potential across climatic range in the study area and estimation of volume at 6 years of age.

3. Estimation of biomass available to harvest across a climatic gradient.

4. Taxa that are not historically planted in the study region are being assessed against the region's stalwart *E. cladocalyx* in a species trial. The taxa involved are as follows: *E. grandis* × *urophylla, E. grandis* × *camaldulensis, E. grandis, E. dunnii and E. cladocalyx.*

The first part of this study is a species trial that is extended to yield more information on the biomass production potential of the taxa involved. There is not much literature on plantation forestry for the *Eucalyptus spp.* in the Greater Boland Region. This is because the climate differs greatly from the main commercial forestry regions in South Africa. Thus, a lot of literature from Australia and the Mediterranean region of Europe are cited. The second part of study compares growth of regional stalwart Eucalyptus taxa with commercially used taxa.

The key concepts around which the study revolves are: site species matching, the measuring and estimation of growth in species trials, biomass estimation and background knowledge on possible insects and pests that are common in commercial forestry.

A more detailed description of specific hypotheses set is discussed in the materials and methods section of this thesis.

Chapter 2: Literature review

Plantation or woodlots designed to supply biomass for purposes of bioenergy generation usually have the following characteristics:a) Fast-growing species are usually planted at high stand densities on short rotations with the aim of maximising biomass production, but with little emphasis on individual tree size (commonly small diameters) and have harvesting systems that are designed to utilize all aboveground biomass from the stand, but other variations exist (e.g. removal of woody biomass or removal of stem wood only). In specific cases, it may even include harvesting of the coarse root biomass. Bioenergy generation sometimes utilise solid pieces of wood/branches as feeder material, however, most commonly biomass is chipped and compacted to briquettes or pellets for greater efficiency of energy extraction (*Di Giacomo and Taglieri,* 2009; *Strehler,* 2000; *Serup et al.,* 2002).

Currently there are few published studies investigating tree species that would be suitable for biomass production in this winter rainfall, drier region of the Greater Boland Region (*van Wyk et al.*, 2001; *von Doderer & Kleynhans, 2009*). The general recommendation of *Poynton* (1979) was also used to find potentially suitable species. Early results of three experiments that have recently been planted to supplement the existing body of knowledge are located at Darling, Coetzenburg and Backsberg and are presented in chapter 4 of this thesis.

2.1 Measurement and estimation of stand growth from trial data

Bio-energy production from woody fuels will be governed mainly by the quantity of utilisable volume produced per hectare, the wood density and the calorific value of the biomass. Other factors such as piece size, uniformity, moisture content, tree height, survival, diameter at breast height (dbh) and stocking are important parameters and indicative of tree growth (*Darrow,* 1994; *Darrow,* 1997; *Dunlop et al.,* 2002). Where trees are too young to have dbh and thus volume estimations, the heights of the trees is the only indicator of growth (*Darrow, 1997*).These parameters make it possible to assess and compare the growth characteristics on different sites.

Volume production is an indicator of growth potential. Tree height and dbh measurements are necessary to estimate the under-bark volume of a stand of trees. Equations to estimate biomass are often site and species specific. These equations are obtained from the correlations of many allometric relationships from extensive allometric studies. This however, was outside the scope of the present study. Stands grown for biomass production has some similarities with short-rotation pulpwood stands, e.g. comparable stand densities and harvesting systems. For this reason, volume equations developed for commercial pulpwood stands could be used in this study. A top-end diameter of 50 mm was used which does not differ much from some of the top-end diameters used in biomass equation studies, e.g. the top-end diameter of 40 mm was considered acceptable for biomass production in New Zealand (*Senelwa and Sims,* 1998; *Madgwick et al.,* 1991*)*. The 50 mm upper diameter that was used in the volume equations is also appropriate for suggested existing harvesting technology (*von Doderer and Kleynhans,* 2009), although most bioenergy crops advocate whole tree harvesting (*Madgwick et al.,* 1991). Volumes of standing trees were thus estimated using standard equations that have been formulated based on extensive detailed measurement of the under-bark volumes of logs of many trees, with a top- end diameter of 50 mm. A commonly used equation in South Africa is the Schumacher and Hall equation (*Bredenkamp,* 2000).

These equations, however, only estimate stem volume and not utilisable volume, because the equations make allowances only for the stump left in the ground, but not wastage or irregularities and imperfections with boles of trees. The equations only provide an estimate of total under-bark volume to a specified diameter (*Bredenkamp, 2000)*. In order to broaden the use of these equations, taper has been used to get an estimate of under-bark volume at any diameter. Taper is the relationship between height and diameter- as the height increases, the diameter decreases (*Bredenkamp, 2000*). Taper thus gives an indication of the stem profile and so allows for the estimation of volume at any height or diameter (*Bredenkamp, 2000*). The equations that have regression coefficients based on South African research uses the simpler taper equation, the Demaerschalk's function, to account for stem form with the result being more accurate volume estimations. Each taxon differs in growth rate and stem form, thus has a specific form factor as well as regression coefficient to estimate volume.

It is a very laborious task to collect enough information to calculate coefficients for species, thus the work has been done mainly on commercially important species and specific taxa in that species. Some of the taxa that form part of this study are not deemed as commercially important and thus no taxa specific, applicable form factors and regression co-efficient are available (e.g. *E. gomphocephala*). In such cases alternative methods of volume determination need to be used, such as, the determination of volume without volume equations with use of an upper-stem diameter (*Finlayson,* 2009*; Zöhrer, 1980*). The inclusion of a measurement of upper stem diameter can increase the accuracy of volume equations as it provides a good idea of the trees stem form. Pressler's method (1865) also known as the '*Richthöhenmethode*', uses upper diameter to increase accuracy by utilising reference height at which the diameter is half of that found at dbh (*Finlayson,* 2009*; Zöhrer,* 1980). Pressler deduced that this measurement results in a good estimation of stem form and thus the volume of the stem.

Practically, Pressler's diameter and height is measured with a Relascope. This measurement is expressed as a factor in relation to dbh (*Finlayson,* 2009; *Zöhrer*, 1980). The Bitterlich relascope can be read on different scales, namely 25m, 33m or 50m scale. The factors of each of the scales are different and so it seems to be best to use a constant scale throughout measurements in order to avoid confusion and incorrect calculations (*Finlayson,* 2009; *Zöhrer*, 1980).

With additional stocking data, it is possible to make estimate the wood mass production on a specific site on an area basis i.e. t ha^{-1} year^{-1} (*Darrow, 1997*). The difference in mass estimation between sites will thus provide an indication to the difference in growth potentials on comparative sites.

2.2 Investigating alternative species for planting in the Greater Boland Region

The climate of the commercial forestry region in South Africa differs significantly from the climate in the Greater Boland Region. Thus commercially important species are not necessarily suitable for to the conditions in the study region. The study region has a Mediterranean climate with cool, wet winters and hot, dry summers. The annual rainfall ranges from 792 mm at Coetzenburg, the wettest site to 596 mm at Darling, the driest site. Backsberg has the highest mean annual temperature (MAT) of 23.5 °C while both Coetzenburg and Darling have a mean annual temperature of 18 ºC. The study region is also relatively free of snow and frost the main concern is the drought period of summer. The climate of the study region is discussed in detail in Chapter 3. This begs the question: which species, that are both fast growing and drought resistant, could be suited to the study region?

Species and provenance trials are not widespread and plentiful in the Greater Boland Region as a whole, much less so in the semi-arid region in which the study area falls. The suitability of growing eucalypts in a short-rotation, wood lot scenario has also not been as widely investigated as in the summer rainfall region of South Africa. There have, however, been studies in the Southern Cape, testing eucalypts for short rotation (14 year-18 year) saw timber (*Gardner et al.,* 2003). Some of the taxa that were tested were *E. globulus, E. nitens, E. saligna × urophylla, E. grandis × nitens, E. grandis × saligna* (*Gardner et al.,* 2003). The Southern Cape with its consistent rainfall distribution is, however, not climatically comparable to the Greater Boland Region. The key study in region for Eucalypts as a commercial crop in the Greater Boland Region is the work done at Pampoenvlei (*van Wyk et al.,* 2001). In this study, known drought hardy taxa of the fast growing eucalypts were tested. A recent study investigating the feasibility of using woody biomass sources to generate electricity in the study region also named potentially suitable species of fast growing trees and made specific mention of Eucalyptus taxa (*von Doderer and Kleynhans,* 2009). Many of the taxa that were potentially useful were evaluated by *van Wyk et al.* (2001) namely; *E. grandis × camaldulensis, E. grandis, E. cladocalyx* and *E. gomphocephala* (**Table 2.1**).

The difference in growth between unimproved seedlings and genetically improved material should be considered when assessing growth as both types of material will be present in the experiment. A trial was done in the Kwa-Zulu Natal Midlands and formed part of a study of the interaction of fertilisation, weed control and the effect of tree improvement on the growth of improved *E. macarthurii* and *E. grandis* seedlings (*van den Berg and Little, 2005)*. It was found that the improved seedlings had a significantly higher basal area than those of the unimproved seedlings and had better form and survival (*van den Berg and Little, 2005)*. New (unimproved) species and provenances should thus be evaluated with the potential for genetic improvement in mind.

The main criteria for the selection process were the climatic factors (Mean annual temperature (MAT), Mean annual precipitation (MAP), rainfall and altitude), hardiness towards drought and the usefulness of its timber for fuel wood (i.e. density and energy content).

Many *Eucalyptus* taxa are well known as fast growing, and commonly grown in commercial plantations, namely; *E. grandis, E. nitens, E.smithii, E. dunnii, E. grandis* × *camaldulensis* and *E. grandis* × *urophylla*. Some eucalypts are more invasive than others, specific to this study, the species *E. cladocalyx, E. grandis* and *E. gomphocephala* were classified as a having a high potential to become invasive (Agricultural Research Council, 2009). This experiment in no way advocates that these taxa be planted on every piece of non- used land, because of their invasive capabilities. They should be planted and tended responsibly and be confined to demarcated areas away from water courses. The use of the commercial hybrid clones counter the problem of potential invasiveness because many of the hybrids are sterile. This could be a way of harnessing these useful, fast growing species in a manner that is also environmentally sound.

This study focuses on the growth of the drought hardy eucalypts and in no way claims that there are no other suitable, fast growing species that may be suitable in the study region. Interestingly, the growth of *Acacia mearnsii* and *A. decurrens* were found not to be competitive with the growth of the eucalypts in trials done in the Southern Cape (*Gardner et al.,* 2003).There is however a parallel study being done, testing other tree species as well as indigenous tree species and comparing the growth to that of the eucalypts. Results from this study will only become available in a number of years.

Table 2.1 Climatic constraints of potentially suitable *Eucalyptus* taxa for the Greater Boland Region.

Species	**MAT range (°C)**	**Mean max. temp (°C)**	**Mean min. temp (°C)**	**Rainfall range in Southern Africa (mm.a^{-1})**	**Altitude (m.a.s.l.)**	**Drought hardiness***	**Traditional uses**
E. cladocalyx	18-20	30	8	400-700	0-600	Moderate	Poles
E. gomphocephala	17-20	29	7	300-1400	0-400	High	Fence posts
E. dunnii	15-19	29	8	800-950	900-1350	Very high	Pulp,saw timber
E. grandis	16.5-21.5	32	5	830-930	<1000	Moderate	Pulp, structural timber
E. grandis× camaldulensis	18.5-22	32	5	830-930	<1000	High	Pulp
E. grandis × urophylla	17.5-22	32	5	920-1000	<1000	High	Pulp

Sources: FAO, 1979; *Poynton*, 1979; *van Wyk, et al., 2001*; *Swain and Gardner*, 2003; *von Doderer & Kleynhans*, 2009.

*Indicates class of ability to withstand drought, based on rainfall requirements

Most taxa in **Table 2.1** can potentially fit into the designated climatic silvicultural zone, Bw4, as prescribed by *Poynton* (1979); sub-humid (B), predominantly winter rainfall (w) and virtually frost free (4). Some of these taxa were also tested in the Pampoenvlei trial (*van Wyk et al., 2001*) and proved to have potential on the dry, sandy site. The Pampoenvlei trial, however, is a much drier than the Coetzenburg and Backsberg site and is more comparable to the Darling site as discussed in Chapter 3. Thus, some taxa might grow better on the sub-humid sites than the semi-arid sites and this still had to be tested.

2.3 Biomass and potential energy estimation:

Biomass in the scope of this study refers to the above ground matter namely; the stem, leaves, branches and bark of the tree, the parts of the tree that can be used for energy production with comparative ease. There are studies that include root systems as biomass (*Bouillet et al.,* 2002; *Gonçalves et al.,* 2004; *Stape et al.,* 2004; *Laclau et al.,* 2008), but falls outside the scope of this study. In order to estimate the amount of energy that is available on a certain area, an estimation of the amount of biomass is critical (*Verwijst and Telenius*, 1999). This estimation can be done in a number of ways, broadly grouped into non-destructive and destructive methods, the more accurate being the destructive method (*Verwijst and Telenius,* 1999).

Destructive methods are very time consuming and are not widely used in a commercial scenario, but the accuracy makes it widely used in the research environment. These methods include harvesting sample trees, physically measuring the biomass and its energy content and then using these values to extrapolate to a larger area. Sample trees of these destructive methods should be carefully chosen and be a true representation of the population which characteristics are being studied *(Kumar & Pratt, 1996; Nùñez-Reguiera et al., 2001; Pèrez et al., 2006)*.

Allometry is the empirically- based description of the proportional change of one character in relation to another (*Medhurst et al., 1999*). This method is used to draw conclusions about biomass and other characteristics of the trees by using factors that are easily measurable such as dbh, height and taking samples of branches and leaves of trees. These methods have been used to extrapolate the estimated biomass across largely homogenous regions (*Hassal & Associates, 1998; Montagu et al., 2005; Pérez et al., 2006*) to give an idea of the carbon stock that is available.

Non- destructive methods of biomass estimation are a compromise between a required level of accuracy, the demand of the procedure as well as existing knowledge of the biological reality of the situation. Estimations using this method are obtained by measuring key indicators such as height, spacing and diameters of trees and then further more using appropriate volume equations and wood density data to produce biomass estimates (*Verwijst and Telenius,* 1999).

Wood density is the ratio of mass of oven dry wood to its green volume and can be estimated in two main sample methods: by means of discs or increment cores (*Illic et al.,* 2000). The discs can be taken if it is possible to do a destructive study on trees. Discs are usually taken at various intervals across the entire height of the tree and the density is then determined in the laboratory. Discs are taken at different intervals to assess and account for the difference in density across the length of the tree. Wood density does, however, increase from pith to bark of the tree. Density of annual rings also seems to be affected by rainfall due to a decrease in wood density with an increase in growth rate (*Illic et al.,* 2000). In Eucalypts, however, literature has shown that unlike the softwoods, density remains fairly constant with an increase in height (*Illic et al.*, 2000). Using cores for wood density estimation is a non- destructive method of density estimation. The increment cores are taken at dbh and for increased accuracy, cores can be taken at different heights along the stem to get a better idea of transition in density.

The last step for bioenergy estimation would be a calorific value. The literature suggests that the calorific values of fast-growing eucalypts fall within a narrow range (*Munalula and Meincken*, 2009). An estimated calorific value of 18.4 KJ kg^{-1} (*Munalula and Meincken,* 2009) was thus used to estimate the energy content of the top biomass producing families of the different species at the Darling and Coetzenburg sites. This calorific value was determined in an energy study for *E. cladocalyx* grown in the Boland Region and corroborates with other calorific studies (*Munalula and Meincken*, 2009; *Pérez et al*., 2006; *Pérez et al.,* 2008; *Reddy,* 1994).

Biomass is in essence the volume of wood or plant material multiplied by its density (*Hassall and Associates*, 1998; *Ravindranath and Ostwald,* 2008). The contribution of leaves, fine and medium roots decrease in relation to increasing stem wood biomass, while the portion of biomass present in branches and coarse roots is larger in young trees (*Misra et al.,* 1998). The general trend of increased biomass allocation to stem wood increases with tree size and age (*Madgwick et al.,* 1991; *Cromer et al.,* 1993; *Misra et al.,*1998). The biomass of roots are not being taken into account in this study and the biomass of the branches and leaves can be estimated to be approximately one third of the biomass of the stem as the focus is available above ground biomass in mature trees (*Hassal and Associates*, 1998; *Montagu et al.,*2005; *Pérez et al.,* 2006). Similar work by *Dovey* (2009) suggests an average bark: stem wood ratio of 0.13 and a branches: stem wood ratio of 0.2 for 6 to 12 year old eucalypts in a South African context, which corroborates with work done on the branch and leaves: stem wood ratio's worldwide. The latter work was done on a wider age range of mature trees, with some stands being as old as 40 years. Thus it can be estimated that the portion of branches, leaves and bark amount to a fraction of between 0.25 and 0.30 of the stem wood. The stem wood: branch and bark ratio was done in the commercial forest region of South Africa with eucalypt stands being 6 years and older, thus the ratio of stem wood biomass to branches and bark at the experiment sites should be similar to this value, as they are planted in a similar fashion and are similar in age. When sampling the trees for biomass estimation, it is important to sample trees from all the dbh classes in the stand. The general consensus in the literature about wood density sampling is that all the dbh classes at the site should be sampled (*Montagu et al.,* 2005; *Illic et al.,* 2000). Wood density within a taxon is dependant mainly on environmental factors like rainfall and differs more from the pith to bark than base to apex of the tree in *Eucalyptus* (*Illic et al.,* 2000). Literature suggests that the average oven-dry density of fast growing *Eucalyptus* wood ranges between 430 and 660 kg m^{-3} (*Illic et al.,*2002; *Clark,* 2001; *Pérez et al.,* 2006; *Dovey,* 2009) with the general trend of higher densities on drier sites (*Montagu et al.,* 2005).

2.4 Potential abiotic risks

The study region is free of frost, snow and wind risk. Fire is always a risk, but good management practices can minimise risks. The nature of some taxa present in this trial make it highly unlikely that they would have disease because most of the *Eucalypts* taxa that form part of this study have not been in present in South Africa long enough for disease causing agents to have grown accustomed to them (and they were imported with comparatively few diseases). In this regard, *E. cladocalyx* and *E. grandis* have a higher risk of disease as they are more commonly used commercial taxa. There are many pests that commercial forestry *Eucalyptus* species are susceptible to, but because of the Mediterranean climate of the study region, many of them are not of high risk (*Smith, Wingfield and Pertini*, 1996). There are, however, two pests that are potentially problematic in the region:

Gonipterus scutellatus

This pest (a snout beetle) is a leaf feeder and a major defoliator of host *Eucalyptus* (*Govender and Wingfield*, 2005). The pest is indigenous to Australia but occurs worldwide and was introduced into South Africa in the early 21st century. The larvae of the pest feed on the leaves of the trees, leaving tell-tale brown 'tracks', while the adults feed on older leaves and the green bark of twigs (*Atkinson,*1999). This pest can cause reduction in growth, coppicing, stunting of tree growth and possibly mortality. Females lay eggs in batches on the surfaces of young leaves. The eggs are covered by capsules formed by excrement (*FAO,* 2007).

Thaumastocoris peregrinus

This pest has wide range of taxon of *Eucalyptus spp.* namely; *E. viminalis, E. camaldulensis, E. grandis, E. terecticornis, E. smithii, E. grandis* × *camaldulensis* and *E. grandis* × *urophylla* (*Jacobs & Neser,* 2005; *Noack &*

Coviella, 2006; *FAO*, 2007; *Agricultural Research Council,* 2009). The pest is of Australian origin and the specific taxon that is found in South Africa originates in the region of Sydney. *Thaumastocoris peregrinus* is a sap sucking insect and is of commercial importance in South Africa (*Jacobs & Neser,* 2005; *Carpintero & Dellope,* 2006). It reduces the photosynthetic ability of trees resulting in stunted growth or mortality in severely infested trees (*Jacobs & Neser,* 2005; *Noack & Coviella,* 2006; *FAO,* 2007). The presence of *Thaumastocoris peregrinus* has been confirmed all over the country from Tzaneen to Cape Town.

Chapter 3: Materials and methods

3.1 Site descriptions

The Greater Boland Region is situated in the south of Western Cape Province, South Africa, the only province that has a Mediterranean climate. The region is a hub of agricultural activity, mainly with food crops, thus only marginal land is available for forestry projects. **Figure 3.1** indicates the main agricultural regions, the potential available land for forestry as well as the location of the experimental sites discussed in this study. This area is very widely used for agricultural purposes (**Table 3.1**) and so the degraded sites and grasslands are the only possible available land for woodlots, apart from the marginal tracts of land that form part of the cultivated land (**Table 3.2**).

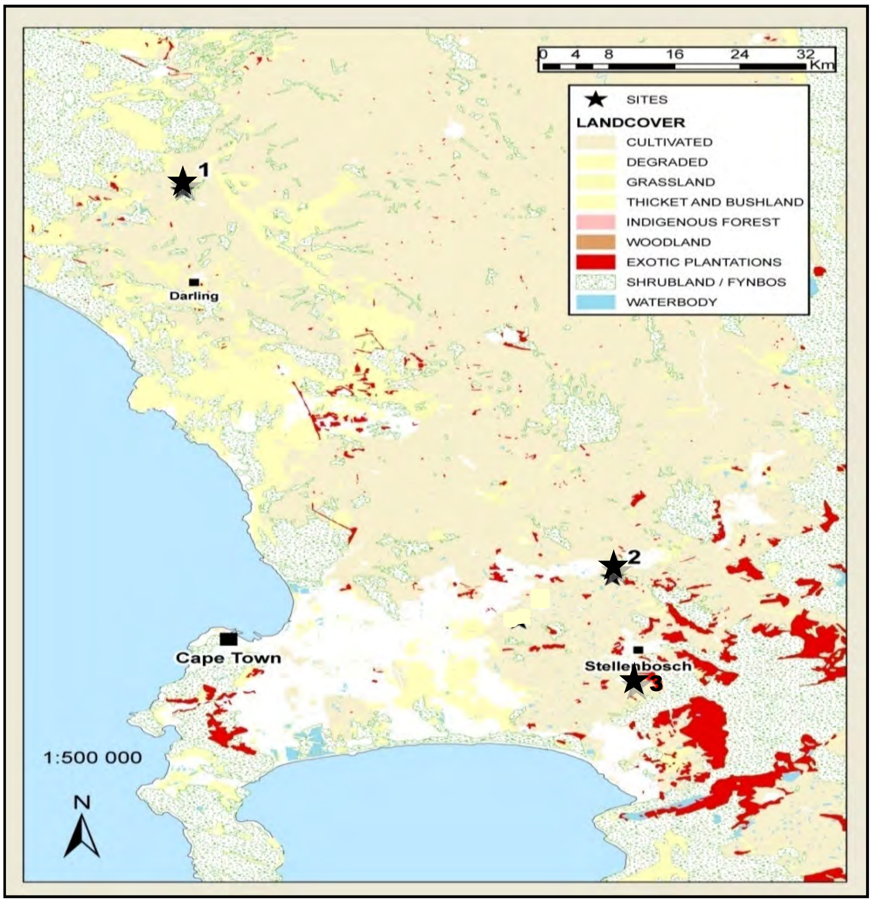


Figure 3.1 Map indicating main agricultural region, experimental sites and land type covers of the Greater Boland Region.

Table 3.1 Site names and climatic description of site numbers in Figure 3.1

Site Number	Site Name	Climatic description
1	Darling	Semi-arid
2	Backsberg	Sub-humid
3	Coetzenburg	Sub-humid

Table 3.2 Area allocated to various land uses in the Western Cape(Agricultural Research Council, 2008).

Land use	Area (ha)
Cultivated	2 256 270
Degraded	305 578
Grassland	120 878
Thicket and Bush land	653 527
Indigenous Forest	62 430
Woodland	2
Exotic Plantations	107 661
Scrubland/Fynbos	9 199 979
Water body	47 376

The three study sites (**Table 3.1**) can be categorised according to climate and water availability as follows: semi-arid, sub-humid (**Table 3.3)**. The climate on all three sites is strongly seasonal, with the duration of the dry summer being a key factor in determining tree stress. For this reason, the moisture growing season was calculated according to the FAO (1978) technique, i.e. the period where precipitation > 0.3 times potential evaporation. The mean annual values for potential evaporation from a class A pan (MAE_p) and precipitation (MAP) as well as the mean monthly values for rainfall (P) and the value ($0.3 * E_p$) of the three sites are depicted in the **Figure 3.2** (A to C). The period where $P > 0.3 * E_p$ is defined as the moisture growing season (FAO, 1978; *Schulze et al.,* 1997). There is a marked difference in water supply and atmospheric evaporative demand between the sites. Darling has the highest evaporation and lowest rainfall, while Backsberg has the highest rainfall and lowest evaporation. The moisture growing season appears to start slightly earlier at Coetzenburg than at Backsberg, but the duration is fairly similar. The moisture growing season at Darling is shorter than the other two sites and the moisture stress is greater in summer. Darling is the warmer site, having the highest minimum temperature, while the maximum temperatures are very similar across all sites.

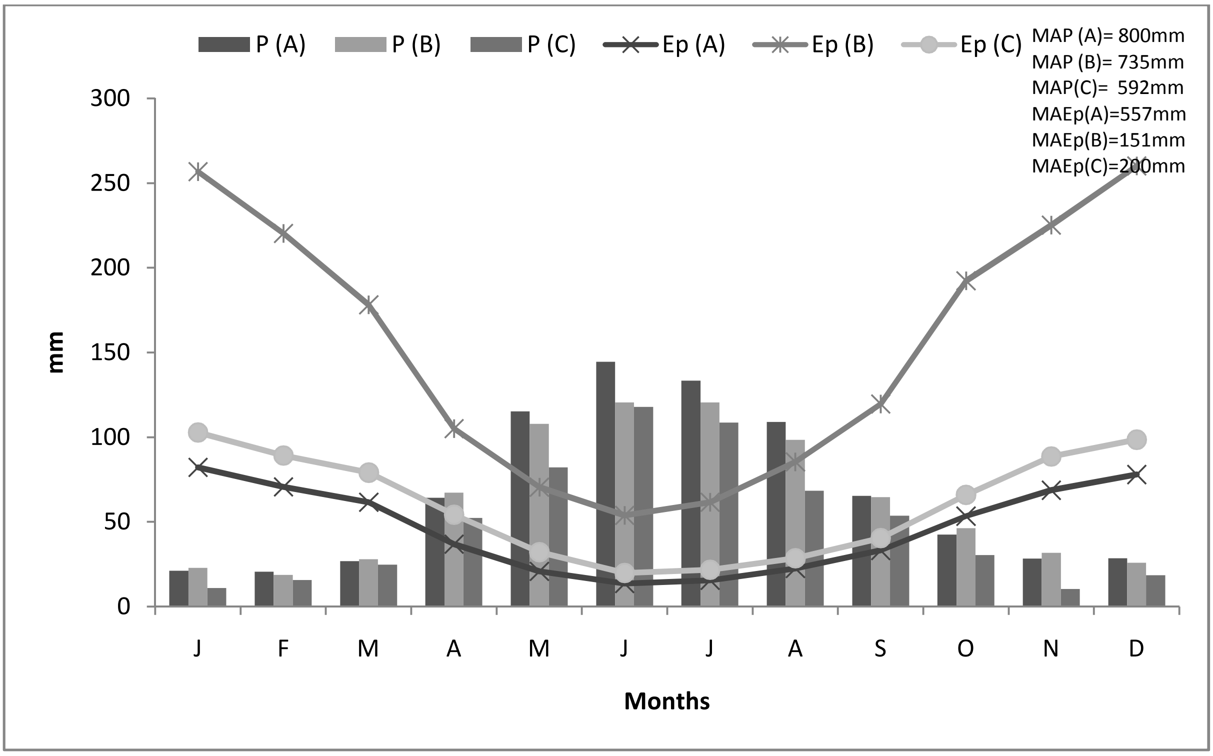


Figure 3.2 Average monthly precipitation (P) and Potential evaporation (Ep) at the three study sites: Backsberg (A), Coetzenburg (B) and Darling (C).

Table 3.3 Climatic information of the experimental sites

Climatic information	Backsberg	Coetzenburg	Darling
Mean Annual Rainfall (mm)	800	735	592
Mean Annual Temperature (°C)	17.5	17.3	18
Mean maximum of warmest month (°C)	28	28	29
Mean maximum of coldest month (°C)	6	8	8
Mean Annual Min Temperature (°C)	11	12	12
Altitude (m.a.s.l.)	220	250	70
Co- ordinates	33°50’09.28’’S 18º55’15.04’’E	33°57’07.69’’S 18°52’38.58’’E	33°16’08.20’’S 18°27’25.66’’E

3.1.1 Site descriptions and trial design sites

The Coetzenburg site is situated in Stellenbosch and is a sub-humid mountain site. The site is planted with provenances of *E cladocalyx* and *E. gomphocephala*. The Darling site is located up the West coast of South Africa. It is the site that the represents the semi-arid region of the Western Cape Provnce. Backsberg is near Klapmuts just outside of Stellenbosch. The experimental design and climatic details of the sites are in **Tables 3.4** and **3.3.**

Table 3.4 Experimental design of the three trial sites

	Backsberg	**Coetzenburg**		**Darling**	
		E. cladocalyx	*E. gomphocephala*	*E. cladocalyx*	*E. gomphocephala*
Experimental Design	Latin square	Randomised Block	Randomised Block	Randomised Block	Randomised Block
Replications	5	5	5	6	6
Plots	25	268	96	290	108
Plot size	30 trees	4 trees/plot	4 trees/plot	5 trees/plot	5 trees/plot
Espacement	2m×3m (1667 sph)	2m×3.5m (1428 sph)	2m×3.5m (1428 sph)	2m×5m (1000 sph)	2m×5m (1000 sph)
Area (ha)	1.35	0.753	0.269	1.64	0.54
Date planted	5th July 2007	24-26 June 2003	26-27 June 2003	10-12 June 2003	13th June 2003

At the Backsberg site, square plots of 5×6 treelines were used, but only the inner 12 trees (4×3) were measured, thus leaving a surround of one line of trees around each plot. The plots at Coetzenberg and Darling are line plots consisting of 4 or 5 trees per plot without surround rows. The dbh and height of each tree was taken at each of the sites. Photos of these sites are shown in **Figures 3.3**, **3.4 and 3.5**. The specific information of families and provenances of the taxa at Coetzenburg and Darling are given in **Tables 3.5** and **3.6** and **Figure 3.5. Figures 3.6** and **3.7** shows that the *E. cladocalyx* provenances are from Southern Australia origin, while all but one provenance of *E. gomphocephala* is of West Australian origin.

Figure 3.3 Growth differences between taxa at the Backsberg site. The top picture displays the difference in growth between *E. cladocalyx* on the right in the foreground and the hybrids *E. grandis* × *urophylla* and *E. grandis* × *camaldulensis* on the right and left, respectively in the background. The leaf discolouration in bottom picture, illustrates the effects of a seasonal sulphur deficiency most probably caused by the waterlogging of soil in winter.

Figure 3.4 Differences in families' growth at the Darling site. The top picture illustrates the difference in potential growth on the site with *E. gomphocephala* on the left and *E. cladocalyx* on the right of the picture. The bottom picture illustrates the poor survival and growth of some of the *E. cladocalyx* at the site as well as the harsh site conditions these trees are growing on

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).

$$v = (fh_1) \times g \qquad \text{Equation (3.3)}$$

where: f = Form quotient

h_1 = Pressler's height

The form quotient (f) is derived as follows:

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

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.

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

$P = \text{percentage of tree volume from base of tree to specified thin-end diameter}$

$DT = \text{thin-end diameter of dbh class } (cm)$

$dbh = \text{diameter at breast height } (cm)$

$b = 0.7902$

$c = 4.5619$

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 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.

$$BI = d^2 \times h \qquad \text{Equation (3.6)}$$

Where:

$\mathrm{BI} = \text{Biomass index } (\mathrm{cm}^3)$

$d = \textit{diameter at breast height(cm)}$

$h = \textit{height (cm)}$

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:

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

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 70ºC, 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

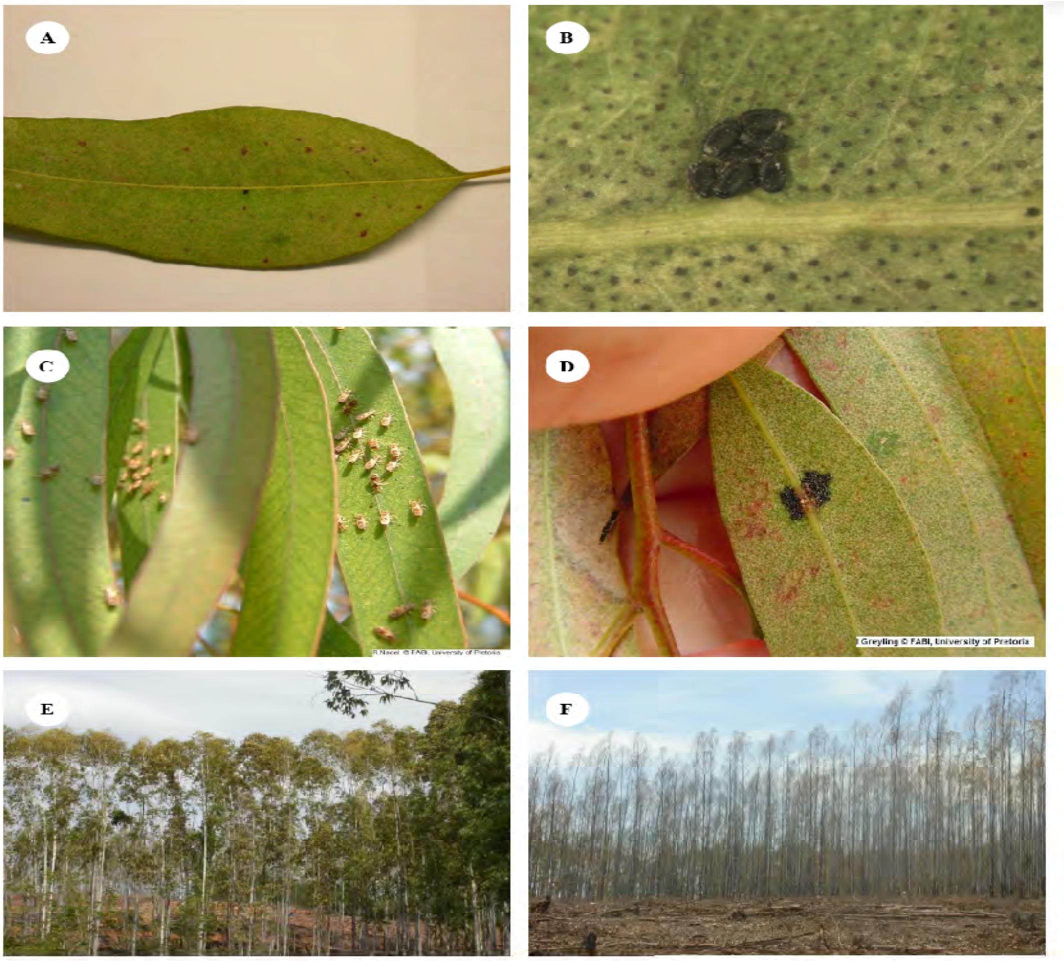
Infestation of insects could possibly have a large role in determining whether the tree species are suitable for this region. Because of the history of the Eucalyptus in South Africa it is highly unlikely that any pest or insect will cause fatality in the species yet, but it should be monitored.

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.

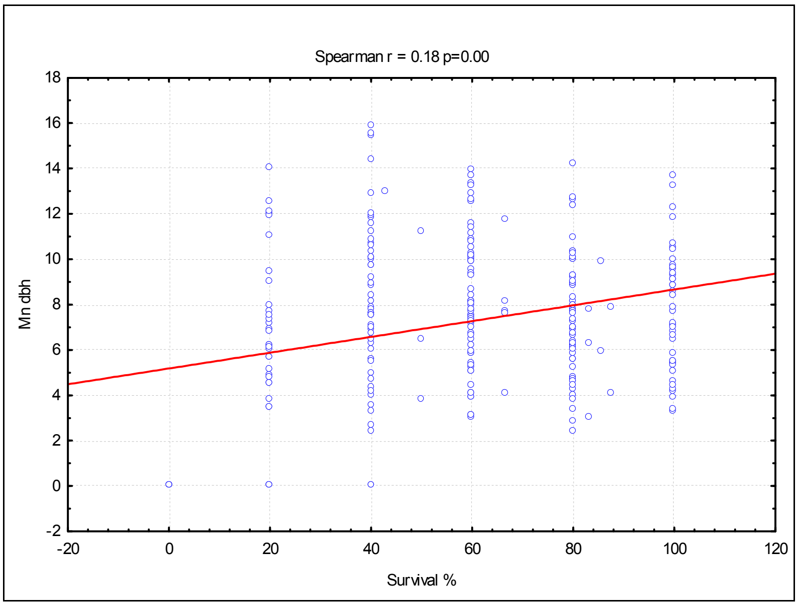


Figure 4.1 The only significant relationship between mean dbh and survival of *E. cladocalyx* at the Darling site

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

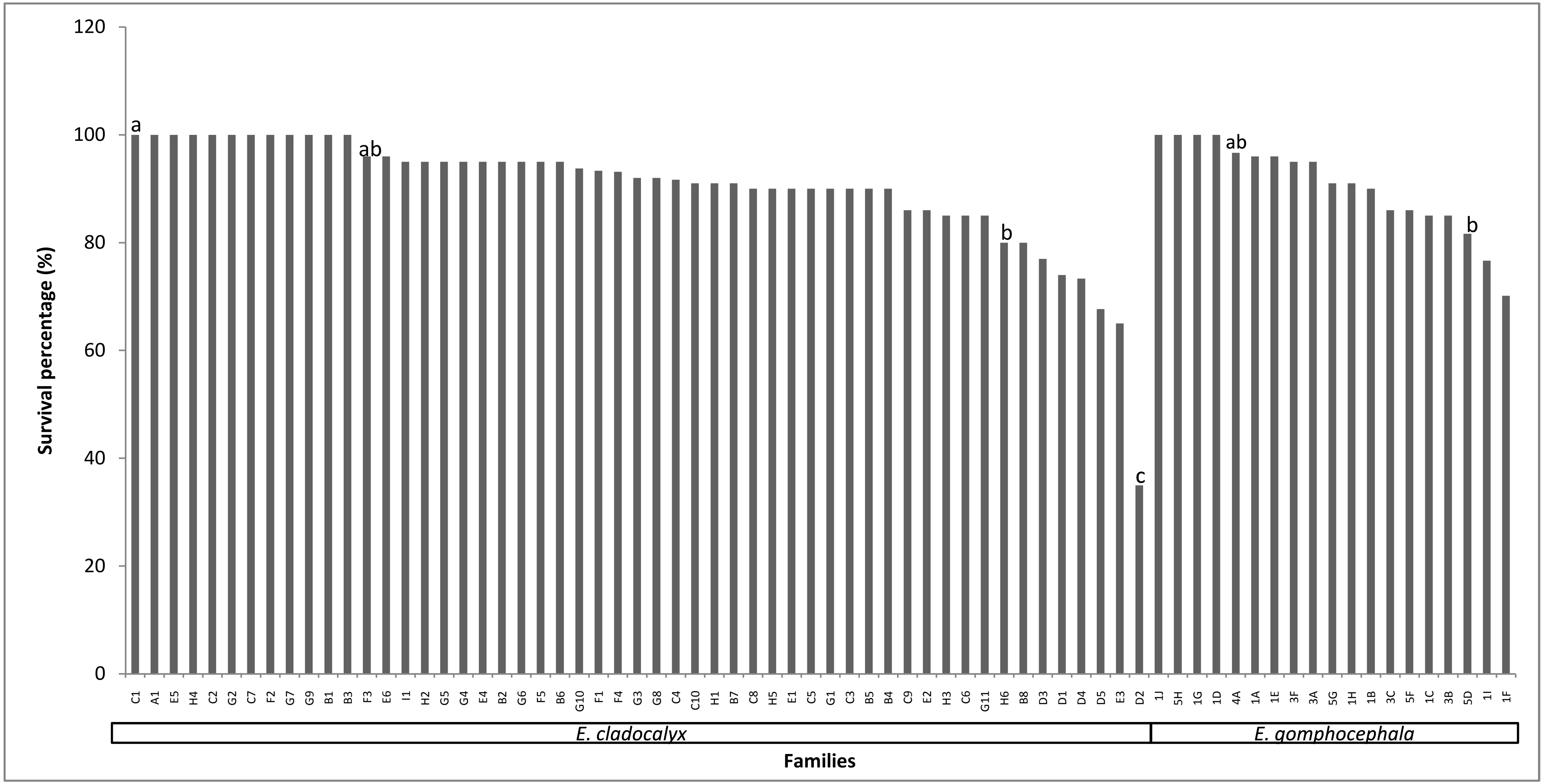


Figure 4.2 The survival of families at the Coetzenburg site. Letters on bars indicate significance of $p<0.05$

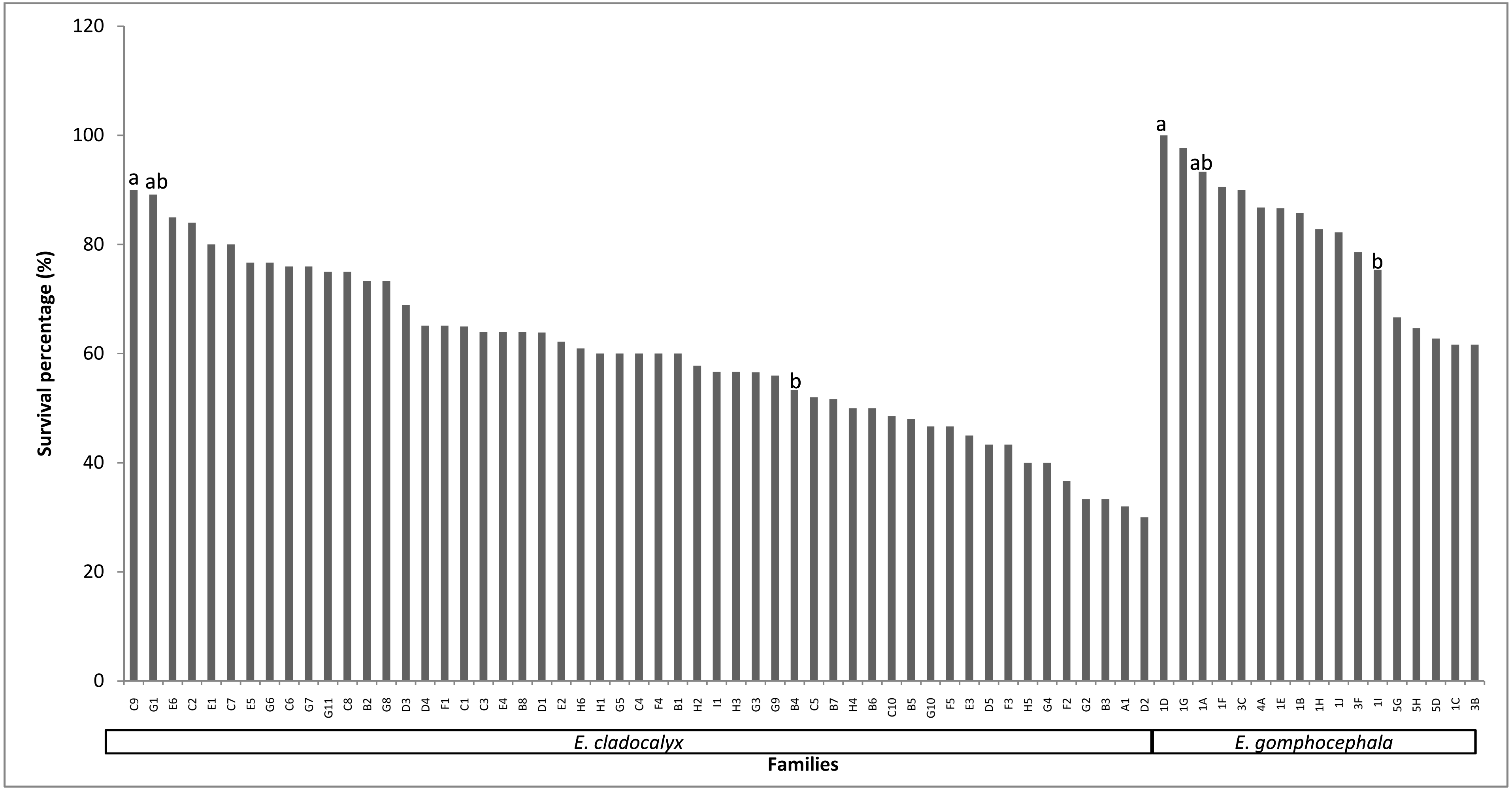


Figure 4.3 Survival percentages of families at the Darling site. Lettering on bars indicate significance of $p<0.05$

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.

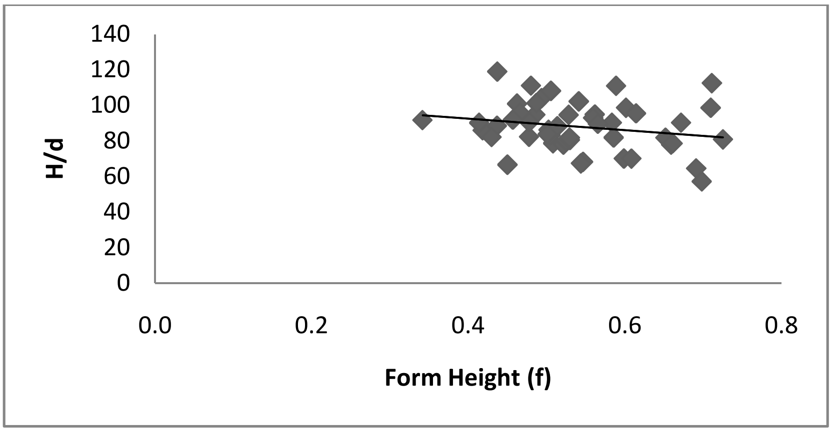


Figure 4.4 The relationship between form height and ratio h/d at the Darling site

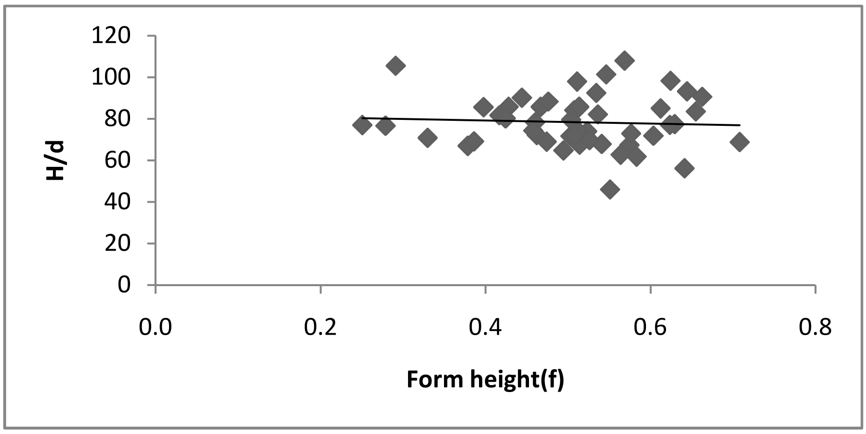


Figure 4.5 The relationship between form height and ratio h/d at the Coetzenburg site

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).

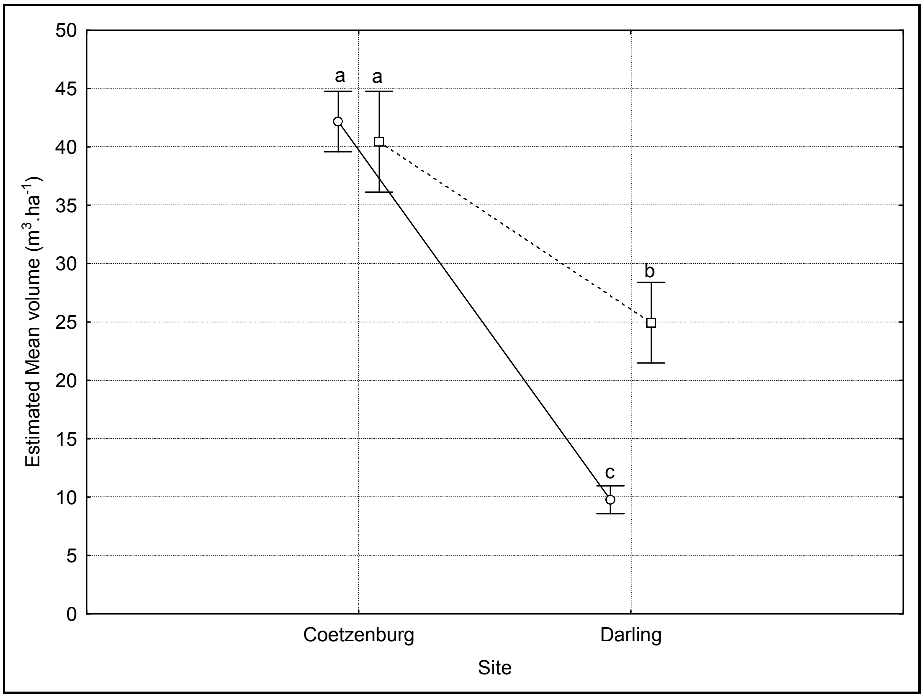
4.1.3 Yield

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**

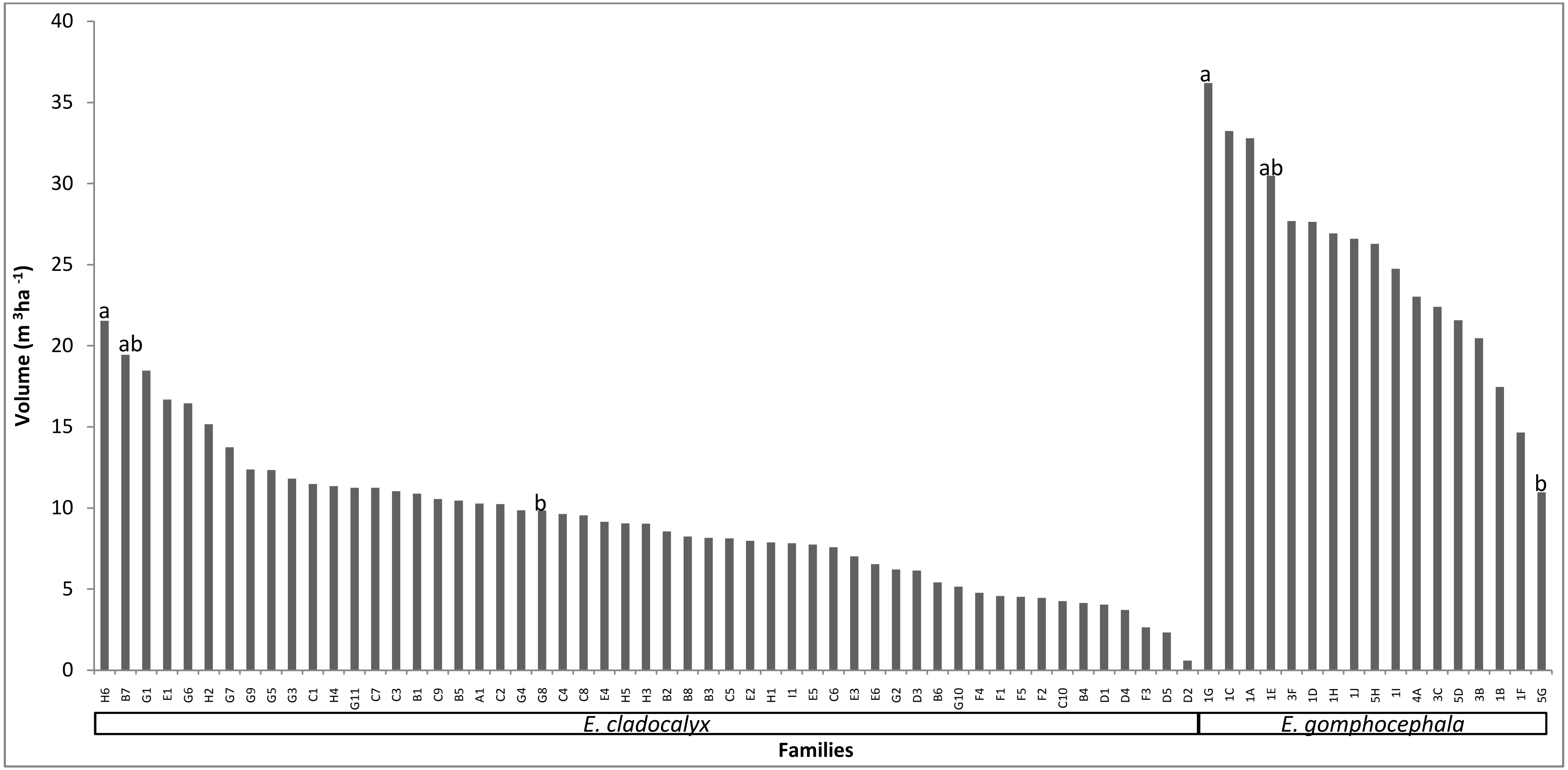


Figure 4.7 Mean volumes of all families at Darling site at six years. Bars with different letters indicate significant differences at $p<0.05$.

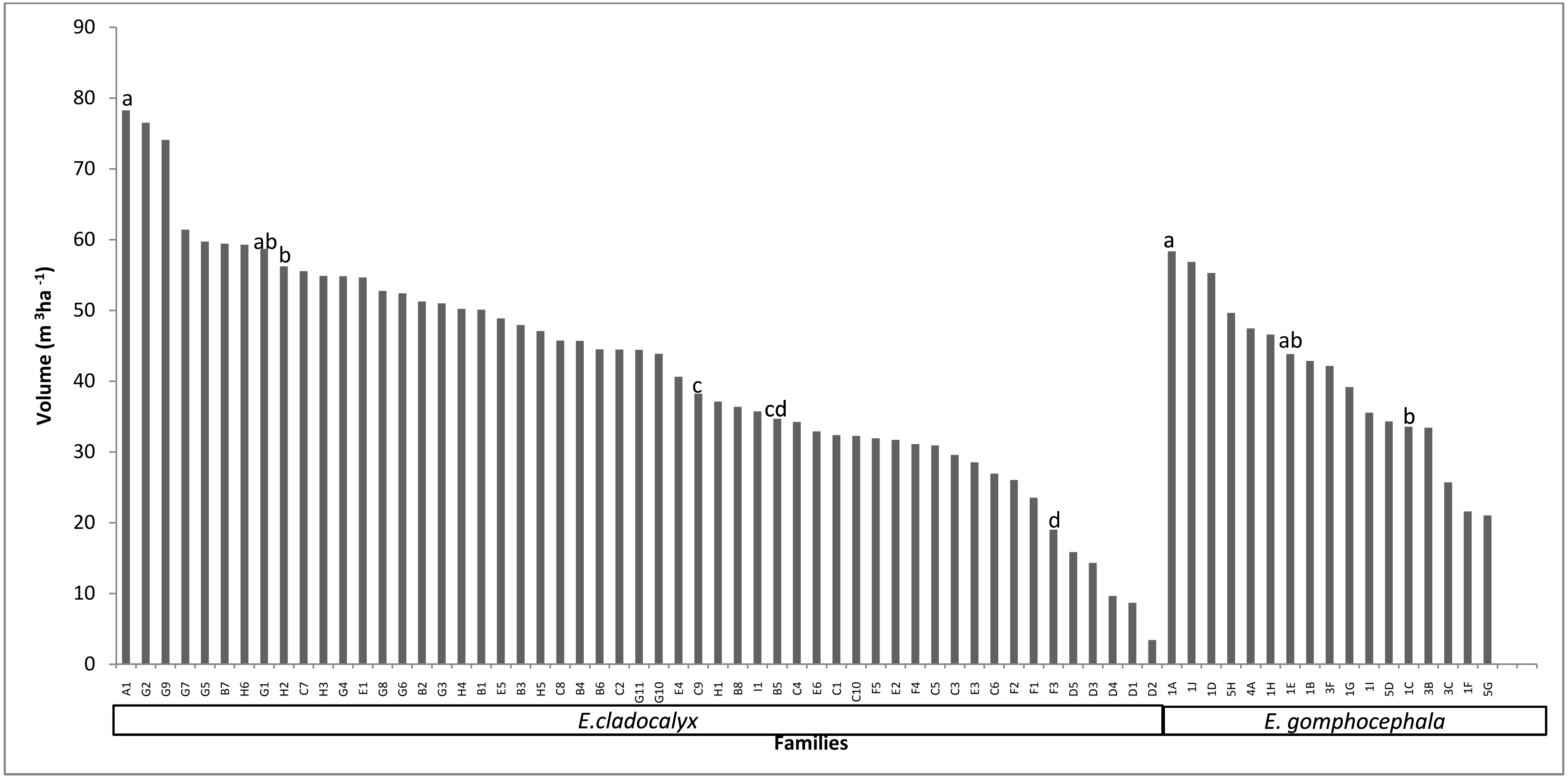


Figure 4.8 Mean volumes of all families at Coetzenburg site at six years. Bars with different letters indicate significant differences at $p<0.05$

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

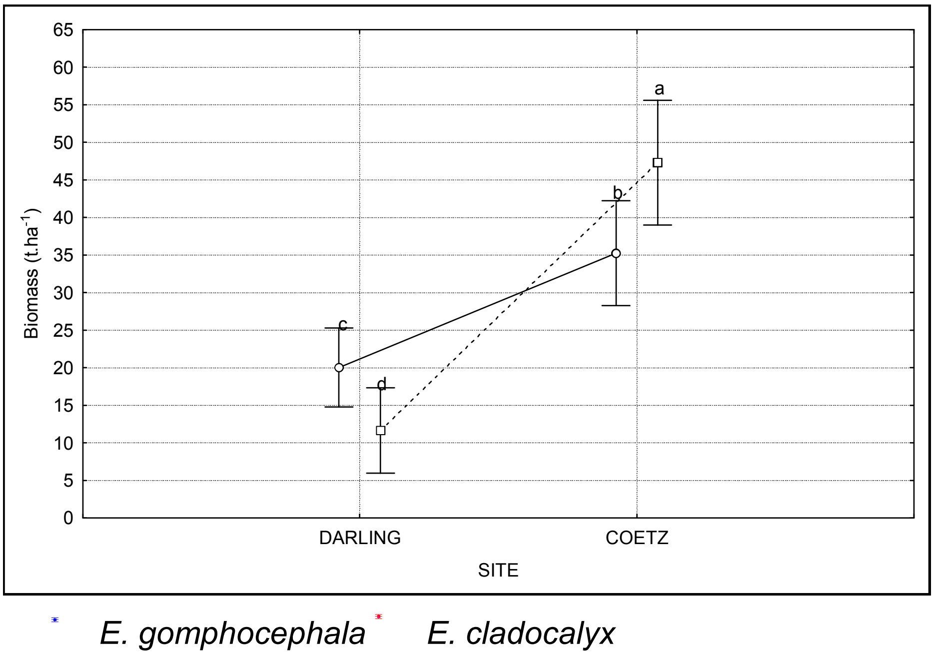


Figure 4.9 Weighted means of utilizable stem wood biomass (t ha^{-1}) at six years of age for the three best-performing families of *E.cladocalyx* and *E. gomphocephala*, planted across the Darling and Coetzenburg trial sites. Means with the same letter code are not significantly different at *p*<0.05.

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^{3}ha^{-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* × *camaldulensis, E. grandis* × *urophylla* and in a singular *E. grandis* plot. This defoliation was most prevalent in the *E. grandis x camaldulensis* plots.

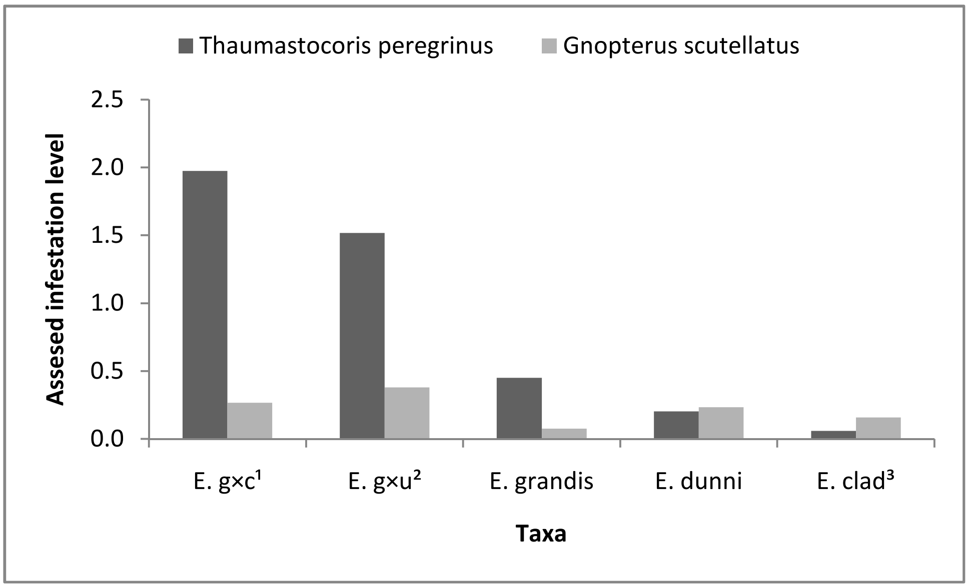


Figure 4.10 Infestation levels of *Thaumastocoris peregrinus* and *Gonipterus scutellatus* on the taxa at Backsberg trial site at age two years. (Refer to Table 3.8 and Figure 3.6 for description of infestation level scores).

[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 × 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.

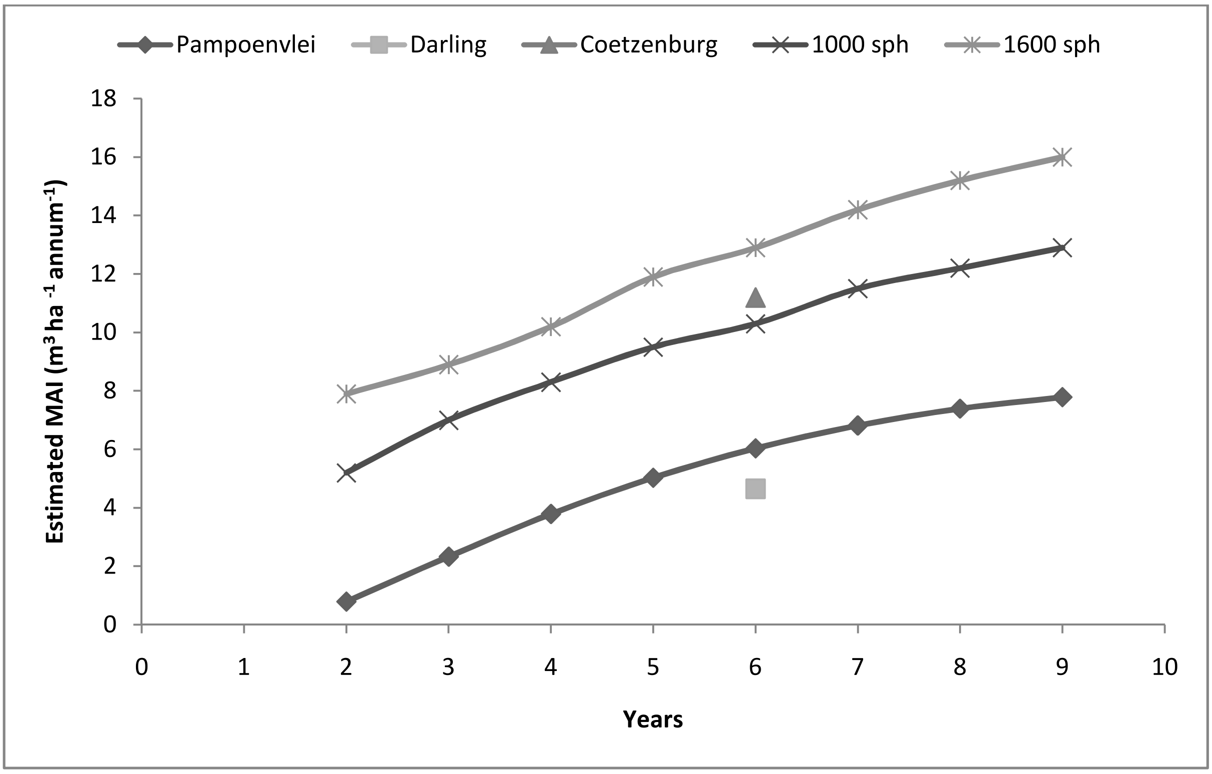


Figure 5.1. Estimated development of MAI of *E. grandis* with SI 13 for stem densities of 1000 stems ha^{-1}, 1600 stems ha^{-1} (after Coetzee, 1999), and of the top producers at the Pampoenvlei trial (after van Wyk et al., 2001). The point data represents MAI of the top producers at the Darling and Coetzenburg sites at 6 years of age.

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

1. Allan, R., Carlson, C. 1998. **Report on trial SP69/03: An investigation into the re-establishment of severely burnt sites.** *ICFR Bulletin 10/98. Pietermaritzberg: Institute for Commercial Forestry Research.*

2. Al-Jamal, M.S., Sammis, T.W., Mexal, J.G., Picchionni, G.A., Zachritz, W.U.2002. **A growth-irrigation scheduling model for waste water use in forest production.** *Agricultural Water Management 56(1): 57-79*

3. Atkinson, P.R. 1999.***Eucalyptus* snout beetle, *Gonipterus scutellatus* Gyll. And its control in South Africa through biological, cultural and chemical means.** *ICFR Bulletin 01/1999. Pietermaritzberg: Institute for Commercial Forestry Research.*

4. Agricultural Research Council. 2009. **South African Plant Invader Atlas News**. *No. 12, ARC- Plant Protection Research Institute.*

5. Avery, T. E., Burkhart, H.E. 1994. **Forest Measurements**. *pg:278-287, McGraw-Hill, Inc.*

6. Berndes, G., 2002, **Bio-energy and water- the implications of large-scale bio-energy production for water use and supply**, *Global Environmental Change 12(4): 253-271*

7. Blignaut, J.N., Chitinga-Mabungu, M.R. and Mabungu, R.M. 2005. **Constructing a greenhouse gas emissions database using energy balances: The case of South Africa 1998**. *Journal of Energy in Southern Africa 16(3):105-116*

8. Boreham, G. R., Pallet, R.N.2009. **The influence of tree improvement and cultural practices on the productivity of *Eucalyptus* plantations**

in temperate South Africa. *Southern Forests 71(2): 85-93, Menlo Park: South African Institute of Forestry*

9. Bouillet, J.P., Laclau, J.P., Arnoud, M., M'Bou, A.T., Saint- André, L., Jourdan, C. 2002. **Changes with age in the spatial distribution of roots of Eucalyptus clone in Congo, impacts on water and nutritional uptake.** *Forest Ecology and Management 171(1-2):43-57*

10. Bredenkamp, B.V. 2000. **Volume and mass of logs and standing trees**. *South African Forestry Handbook Volume 2:167-174, South African Institute of Forestry*

11. Cannell, N.G.R. 2003. **Carbon sequestration and biomass energy offset: theoretical, potential and achievable capacities globally, in Europe and the UK.** *Biomass and Bioenergy 24 (2): 97-116*

12. Carpintero, D.L., Dellope, P.M. 2006. **A new species of *Thaumastocoris* from Argentina.** *Zootaxa 1228:61-68*

13. Chernick, M.R. 1999. **Bootstrap Methods: A practitioner's guide**. *Wiley Series in Probability and Statistics. Wiley and Sons, New York, USA.*

14. Cherry, M., Hingston, A., Battaglia, M., Beadle, C.1998. **Calibrating the LI-COR LAI-2000 for estimating Leaf Area Index in eucalypt plantations**. *Tasforests 10: 75-83*

15. Clark, M.B. 2001. **Longitudinal density variation in irrigated hardwoods.** *Appita 54:49-53*

16. Clewer, A.G, Scarisbrick, D.H.2006. **Practical Statistics and Experimental Design for Plant and Crop Sciences**.*pg: 67-71, 213-225, 293-306. John Wiley and Son LTD, New York.*

17. Coetzee, J. 1999. **Growth prediction for short rotation *Eucalyptus grandis* crops.** *ICFR Bulletin 09/99. Pietermaritzberg: Institute for Commercial Forestry Research.*

18. Coetzee, J., Naicker, S., 1999. **Tree volume and taper equation for *Eucalyptus dunnii.*** *ICFR Bulletin Series 07/1999. Pietermaritzberg: Institute for Commercial Forestry Research.*

19. Cook, J. and Beyea, J., 2000. **Bioenergy in the United States: Progress and Possibilities.** *Biomass and Bioenergy 18(6): 441-455.*

20. Conover, W.J. 1980. **Practical Non-parametric Statistics (3rd Edition).** *John Wiley and Sons, New York, USA.*

21. Corder, G.W., Foreman, D.I. 2009. **Non-parametrics for Non-statisticians: A Step-by-Step Approach**. *Wiley and Sons, New York, USA*

22. Cromer, R.N., Cameron, D.M., Rance, S.J., Ryan, P.A., Brown, M. 1993. **Response to nutrients in *Eucalyptus grandis.* 1. Biomass accumulation.** *Forest Ecology and Management 62 (1-4): 211-230*

23. Darrow, W. K.,1994. **Species trials of cold tolerant eucalyptus in the summer rainfall zone of South Africa,** *ICFR Bulletin 10/94. Pietermaritzberg: Institute for Commercial Forestry Research.*

24. Darrow, W.K., 1997. **Eucalypt site-species trials in Zululand: results at four years of age.** *ICFR Bulletin 3/97 26pp. Pietermaritzberg: Institute for Commercial Forestry Research.*

25. Deblonde, G., Penner, M., Royer, A. 1994. **Measuring Leaf area index with the LI-COR LAI-2000 in Pine stands**. *Ecology 75(5):1507-1511*

26. Department of Minerals and Energy, 2007. **Biofuels Industrial Strategy of Republic of South Africa.**
27. Di Giacomo, G., Taglieri, L. 2009. **Renewable energy benefits with conversion of woody residues to pellets.** *Energy (34): 724-731*

28. Dovey, S.B, 2009.**Estimating biomass and macronutrient content of some commercially important plantation species in South Africa.** *Southern Forests: a Journal of Forest Science 71(3):245-251, Menlo Park: South African Institute of Forestry.*

29. Dunlop, R.W., Goodricke, T.G., de Leur, D.T., 1997. **Five year results from an Australian Acacia species trial at Piet Retief, South Africa.***ICFR Bulletin 01/2002, Pietermaritzberg: Institute for Commercial Forestry Research.*

30. Eder, W., Hoang, D.P. 2003. **Vorläufige Referenztafeln für die Forsteinrichtung**. Pg 4-53, *Forschungsantalt für Waldökologie und Forstwirtschaft Rheinland-Pfalz, Trippstadt, Landesforsten Rheinlad Pfalz.*

31. FAO .1978. **Report on the agro-ecological zones project, volume 1: Methodology and results for Africa**, *World Soil Resources Report 48, Food and Agricultural Organisation of the United Nations, Rome*

32. FAO.1979. **Eucalyptus for planting**, *pg 355-510. Food and Agriculture Organisation of the United Nations, Rome*

33. FAO, 2007.**Forest Health an Biosecurity Working Papers: Overview of forest pests South Africa,** *Working Paper FBS/30E, Food and Agriculture Organisation of the United Nations, Rome*

34. Ferreira, M. 1970. **Variation in the basic density of the wood of *Eucalyptus alba* and *Eucalyptus saligna.*** *IPEF (1):83-96*

35. Finlayson, W. 2009. **The Relascope: with standard metric scale and wide scale.** *Instruction Manual, Spiegel-Relascope, Feinmechanische Optische, Salzburg, Austria*

36. Fung, P.Y.H., Kirschbaum, M.U.F., Raison, R.J., Stucley, C**.** 2002. **The potential for bioenergy production from Australian forests, it's contribution to national greenhouse gas targets and recent developments in conversion processes**. *Biomass and Bioenergy 22 (2): 223-236*

37. Fuwape, JA, Onyekwelu, JC, Adekunle, VAJ, 2001, **Biomass equations and estimations for *Gmelina arborea* and *Nuclea diderrichii* stands in Akure forest reserve***, Biomass and Bioenergy 21(6): 401-405*

38. Gardner, R., Swain, T., and Norris, C. 2003. **Eucalypt species and Provenance trials in the Southern Cape: Results at four years of age**. *ICFR Bulletin 11/2003, Pietermaritzberg: Institute for Commercial Forestry Research*

39. Gonçalves, J.L.M., Stape, J.L., Laclau, J.P., Smethurst, P., Gava, J.L. 2004. **Silvicultural effects on the productivity and wood quality of eucalypt plantations.** *Forest Ecology and Management 193(1-2): 45-61*

40. Google Earth, 2010. *US Department of State Geographer, Europa Technologies*

41. Govender, P., Wingfield, M.J. 2005.**Entomological research in Mediterranean forest ecosystems in South Africa.** *Entomological research in Mediterranean Forest Ecosystems: 43-52, Editions Quae*

42. Guo, L.B., Sims, R.E. 2003. **Soil response to eucalypt tree planting and meatworks effluent irrigation in short rotation forest regimes in New Zealand**. *Bioresource Technology 87(3): 341-347.*

43. Hassal and Associates, 1998. **Carbon sequestration in low rainfall areas: the measurement of plantation trees in Victoria,** *Environment Australia: Biodiversity group*

44. Illic, J., Boland, D., McDonald, M., Downer, G., Blakemore, P. 2000. **Wood density Phase 1- State of knowledge.** *National Carbon Accounting System- Technical Report no. 18, Australian Greenhouse Office.*

45. Jacobs, D.H., Neser, S. 2005. ***Thaumastocoris australicus* Kirkaldy (Heteroptera: Thaumastocridae): a new insect arrival in South Africa, damaging to *Eucalyptus* trees**. *South African Journal of Science 101: 233-236, Academy of Science South Africa (ASSAf)*

46. Keppel, G., Wickens, T.D. 2004. **Design and analysis: A researcher's handbook (4th Edition).** *Pearson-Prentice-Hall, Upper Saddle River, New Jersey, USA*

47. Kumar, J.V. and Pratt, B.C. 1996. **Determination of calorific values of some renewable fuels,** *Thermochimica Acta 279(1-2): 111-120*

48. Laclau, J.P., Bouillet, J.P., Gonçalves, J.L.M., Silva, E.V., Jourdan, C., Gunha, M.C.S., Moreira, M.R., Saint- André, Z., Maquére, V., Nouvellon, Ranger, J. 2008.**Mixed species plantations of *A. mangium* and *E. grandis* in Brazil 1 Growth dynamics and above ground net primary production.** *Forest Ecology and Management 255(1-3): 375-391*

49. Leclercq, A. 1977. **Relations between growth, structure and wood density of beech timber.** *Bulletin des Recherches Agronomiques de Gembloux 12 (4): 321-330*

50. MacFarlane, C., Adams, M.A. 1998. δ**13C of wood in growth-rings indicates cambial activity of drought stressed trees of *Eucalyptus globulus***. *Functional Ecology 12(4): 655-664*

51. Madgwick, H.A.I., Frederick, D.J., Thompson Tew, D. 1991. **Biomass relationships in stands of *Eucalyptus* species.** *Bioresource Technology 37(1): 85-91*

52. Malan, F.S. 1993. **The wood properties and qualities of 3 South African grown eucalypt hybrids.***South African Forestry Journal (167):35-44*

53. Masera, O.R., 2001. **Carbon sequestration dynamics in forestry projects: The CO2FIX V.2 model approach**, *Simposio Internanional Medición y Monitoreo de la Captura de Carbono en Ecosistemas Forestales 18 al 20 de Octubre.*

54. Marland, G, Schlamadinger, B.1995. **Biomass fuels and forest management strategies: How we calculate GHG emissions and benefits.** *Energy 20(11): 1131-1140*

55. Marland, G., Schlamadinger, B. 1997. **Forests for Carbon sequestration or fossil fuel substitution? A sensitivity analysis.** *Biomass and Bioenergy 13(6): 389-397*

56. Matthews, R.W. 2001.**Modelling of energy and carbon budgets of wood fuel coppice systems.** *Biomass and Bioenergy 21(1): 1-19*

57. McKendry, P.2002. **Energy production from biomass (part 1): Overview of biomass.** *Bioresource Technology 83(1):37-46*

58. Medhurst, J.L., Battaglia, M., Cherry, M.L., Hunt, M.A., White, D.A., Beadle, C.L., .1999. **Allometric relationships for *Eucalyptus nitens (Deane and Maiden)* Maiden plantations.** *Trees-Structure and Function 14(2): 91-101, Springer, Berlin/Heidelberg*

59. Miranda, I., Almeida, H.H., Pereira, H. 2001. **Provenance and site variation of wood density in *E. globulus* at harvest and it's relation to a non-destructive, early assessment.** *Forest Ecology and Management 149(1-3):235-240*

60. Misra, R.K., Turnbull, C.R.A., Cromer, R.N., Gibbons, A.K., LaSala, A.V., 1998. **Below-and above ground growth on *Eucalyptus nitens* in young plantation.I. Biomass.** *Forest Ecology and Management 106(2-3): 283-293*

61. Mohren, G.M.J., Goldewijk, K. 1990. **CO_2fix : A dynamic model of the CO_2 fixation in Forest stands**, Rapport 624

62. Montagu, K.D., Düttner, K., Barton, C.V.M., Cowie, A.L.2005. **Developing general allometric relationships for regional estimates of Carbon sequestration: an example using *eucalyptus pilularis* from seven contrasting sites.** *Forest Ecology and Management 204(1): 113-129*

63. Munalula, F., Meincken, M. 2009.**An evaluation of South African fuelwood with regards to calorific value and environmental impact.** *Biomass and Bioenergy 33(3):415-420*

64. Nabuurs, G.J., O. Masera, K. Andraska, P. Benitez-Ponce, R. Boer, M. Dutschke, E. Elsiddig, J. Ford-Robertson, P. Frumhoff, T. Karjalainea, O. Krankina, W.A Kurz, M. Matsumoto, W. Oyhantcabal, N.H. Ravindranath, M.J. Sanz Sanchez, X. Zhang.*2007:* **Forestry. In Climate Changes 2007: Mitigation. Contribution of Working Group III to the fourth assessment report on the Intergovernmental Panel on Climate Change [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)].** *Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.*

65. Nadel, R. 2009. **Forestry and Agricuture Biotechnology Institute***, Personal Communication, University of Pretoria*

66. Nel, J.H. 1990. **'n Model vir die beraming van blokklsopbrengste vir *Eucalyptus grandis×saligna.*** *Management of Eucalyptus grandis in South Africa: 197- 203, Proceedings of a Symposium arranged by the Forest Mensuration and Modelling Working Group in collaboration with the South African Institute of Forestry and the Eucalyptus grandis Reseach Network*

67. Niu, X., Duiker, S.W.2003. **Carbon sequestration potential by afforestation of marginal agricultural land in Mid-Western US.** *Forest Ecology and Management 223 (1-3): 415-427*

68. Noack, A.E. and Coviella, L.E. 2006. **Scientific Note: *Thaumastocoris austrilicus* Kirkaldy (Hemiptera Thaumastocoridae): First record of this invasive pest of *Eucalyptus* in the Americas.** *Gen. Appl. Ent.35: 13-14.*

69. Nùñez-Reguiera, Rodriguez-Añon, J.A., Proupin-Castiñeiras, J., Vilanova-Diz, A., Montero-Santoveña, N. 2001. **Determination of calorific values of forest waste biomass by static bomb calorimetry,** *Thermochimica Acta (1-2): 23-31*

70. Pèrez, S., Renedo, C.J., Ortiz, A., Mañana, M., Siliò, D. 2006. **Energy evaluation of the *Eucalyptus globulus* and the *Eucalyptus nitens* in North of Spain (Cantabria),** *Thermochimica Acta 451(1-2): 57-64*

71. Pèrez, S., Renedo, C.J., Ortiz, A., Mañana, M. 2008. **Energy potential of waste from 10 forest species in North of Spain(Cantabria).***Bioresource Technology 38 (5):6339-6345*

72. Pienaar, B., Kotze, H. 2001. **Growth and yield functions.** *Unpublished Report. Pietermaritzberg: Mensuration and Modelling Consortium*

73. Poynton, R.J., 1979, **Characteristics and uses of trees and shrubs**.*Report to the Southern African Regional Commission for Conservation and Utilization of the Soil (SARCCUS) on tree planting in southern Africa, Bulletin 39, Department of Forestry, Republic of South Africa,*

74. Ravindranath, NH, Ostwald, 2008, **Carbon Inventory Methods: Handbook for Greenhouse Gas Inventory, Carbon Mitigation and Roundwood Production Projects**, *Dorcrecht*: *Springer Science: 113-127*

75. Reddy, B.,S. 2008. **Biomass Energy for India: An Overview.** *Energy Conserv. Mgmt. 35(4):341-361*

76. Richards, G., Evans, D. 2000.**Carbon accounting model for forests (CAMfor) user manual: version 3.35.** *National Carbon Accounting System, Technical Report N0.26. Canberra, Australia Green House Office.*

77. Ride, W.D.L., Cogger, H.G., Duplus, C., Kraus, O., Minelli, A., Thompson, F.C., Tubbs. 1999. **The International code of zoological nomenclature online**. *The International Trust for Zoological Nomenclature 1999, The Natural History Museum, London. http://www.iczn/index.jsp .Accesed December 14, 2009*

78. Schlamadinger, B. and Marland, G., 1996, **The Role of Forest and Bioenergy Strategies in the Global Carbon Cycle,** *Biomass and Bioenergy 10(5-6): 275-300*

79. Schlamadinger, B., Marland, G.1999. **The Kyoto protocol could make a difference for optimal forest-based CO_2 mitigation strategy: some results from GORCAM**. *Environmental Science & Policy 2(2): 111-124*

80. Schulze, R.E.1997. **South African Atlas of Agrohydology and Climatology,** *Water Research Commission, Pretoria, Report TT82/96*

81. Senelwa, K., Sims, R.E.H.1998. **Tree biomass equations for short rotation eucalyptus grown in New Zealand.** *Biomass and Bioenergy 13(3):133-140*

82. Serup, H., Falster, H., Gamborg, C., Gundersen, P., Hansen, L., Hedig, N., Jakonsen, H.H., Kofman, P., Nikolaisen, L., Thomsen, I.M. 2002. **Wood for Energy Production Technology- Environment- Economy.** *Centre for Biomass Technology on behalf of Danish Energy Agency: 9-24 (www.ens.dk)*

83. Smith, H, Wingfield, M.J., Pertini, O. 1996. ***Botryosphaeria dithidea* endophtyic in *Eucalyptus grandis* and *E. Nitens* in South Africa**. *Forest Ecology and Management 89: 189-195*

84. Smith, C., Kassier, H, Morley, T.2005.**The effect of stand density and climatic conditions on the growth and yield of *Eucalyptus grandis.*** *ICFR Bulletin 09/2005*, *Pietermaritzberg: Institute for Commercial Forestry Research.*

85. Smith, C. Kassier, H., Morley, T.M. 2006. **The effect of initial stand density on the growth and yield of selected *Eucalyptus grandis* clonal hybrids in the Kwa-Zulu Natal Midlands** *ICFR Bulletin 04/2006*, *Pietermaritzberg: Institute for Commercial Forestry Research.*

86. Snowdon, P., Raison, J., Keith, H., et al., 2002, **Protocol for sampling tree and stand biomass,** *Australian Greenhouse Office, Technical Report No. 13*

87. Sochacki, S., Harper, R., Smettem, K. 2007. **Estimation of woody biomass production from short-rotation bio-energy system in semi-arid Australia.** *Biomass and Bioenergy 31(9): 608-616*

88. Stape, J.L., Binkley, D., Ryan, M.G. 2004. **Eucalyptus production and the supply, use and efficiency of the use of water, light and nitrogen across a geographic gradient in Brazil.** *Forest Ecology and Management 193(1-2):17-31*

89. Strehler, A. 2000. **Technologies of wood combustion.** *Ecological Engineering 16(1):25-40*

90. Sudmeyer, R. A. and Goodreid, A. 2007. **Short-rotation woody crops: a prospective method for phytoremediation of agricultural land at risk of salinisation in southern Australia**, *Ecological Engineering 29(4): 350-361*

91. Swain, T.L., Gardner, R.A.W. 2003. **A summary of cold tolerant eucalypt species (CTE's) grown in South Africa**, *ICFR Bulletin 03/2003, Pietermaritzberg: Institute for Commercial Forestry Research*

92. Thomas, D.S., Montagu, K.D., Conroy, J.P. 2004 **Changes in wood density of *E. camaldulensis* due to temperature- the physiological link between water and viscosity and wood anatomy.** *Forest Ecology and Management 193(1-2): 157-165*

93. Turnbull, J.W., 1986, **Multipurpose Australian trees and shrubs: lesser known for fuelwood and Agroforestry**, ACLAR, Canberry Australia

94. Van den Berg, G. and Little, K.2005. **Interim report on the effect of genetic improvement, fertilisation and weed control on the performance of *Eucalyptus macarthii* and *E.nitens***. *ICFR Bulletin 12/2005*. *Pietermaritzberg: Institute for Commercial Forestry Research.*

95. Van Wyk, G., van Laar, A. and Theron, J.M. 2001**.Yield Potential of selected *Eucalyptus* genetic stock on the sandy soils of the South African Cape West Coast.** *South African Forestry Journal 191: 9-19*

96. Verwijst, T. and Telenius, B. 1999. **Biomass estimation procedures in short rotation forestry.** *Forest Ecology and Management 121(1-2): 137-146*

97. Viero, P.W.M., Little, K.M., Oscroft, D.G. 2000.**Establishment of *Eucalyptus grandis×camaldulensis* clones in Zululand: the effect of soil amended hydrogel.** *ICFR Bulletin 07/2000, Pietermaritzberg: Institute for Commercial Forestry Research.*

98. Von Doderer, C., Kleynhans, T.E., 2009. **Financial viability of Agroforestry for bioelectricity generation on various farm types in the Western Cape, South Africa.** *Unpublished MSc Thesis, University of Stellenbosch.*

99. Von Doderer, C. 2010. *Personal communication*

100. Wilkins, A.P., Horne, R.1991. **Wood density variation of young plantation grown *Eucalyptus grandis* in response to silviculutural treatments.** *Forest Ecology and Management 40(1-2): 39-50*

101. Zöhrer, F. 1980. **Forstinventur: Ein Lietfeaden für Studium und Praxis**.*Verlag Paul Parey*