The potential for *Eucalyptus* hybrids in farm forestry in the semi-arid winter rainfall region of South Africa

by

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Declaration

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Summary

The aim of this study was to investigate *Eucalyptus* hybrids as a source of woody biomass in the semi-arid winter rainfall region of South Africa.

The study focuses on an experimental planting at 10 years of age and the coppice crop from this experiment grown for nine months after clear felling.

The trial investigated the survival, potential production (growth) and coppicability of several *Eucalyptus* hybrids, namely *E. grandis x camaldulensis*, *E. grandis x resinifera*, *E. grandis x tereticornis* and *E. saligna x urophylla*, which were compared to the control of *E. cladocalyx* and commercial controls of *E. dunnii* and *E. grandis x camaldulensis*. The survival and potential production were explored on a taxa and provenance, genotype and stand level, while the coppice results were ranked on a genotype level.

Overall, the survival on the site was above 75 %, excluding the controls of *E. cladocalyx* and *E. dunnii*, which did not perform well. At 10 years of age, the experimental stand achieved a mean annual increment (MAI) of 17.24 $m^3.ha^{-1}.a^{-1}$. Basal area growth was used to rank the growth response of the tested genotypes. The basal area was upscaled from single tree plots which meant that the mean value yielded a useful estimate, however, the upscaled value of individual genotypes from the single tree plots were only reliable to rank genotypes and not to estimate growth potential in field. The upscaled basal area ranged between 12 $m^2.ha^{-1}$ and 55 $m^2.ha^{-1}$. Several of the tested hybrids were well suited to the semi-arid site, namely: *E. gxc* Albacutya CSS01659 (9), *E. gxc* Albacutya CSS01682 (13), *E. gxt* (AUS) seed SR0046xT32 (84) and *E. gxt* (AUS) seed AG049xT08 (83) and *E. gxc* (SA) seed SGR1231xC42 (76).

Slightly less than 50% of the genotypes had good coppicability. The biomass produced in coppice shoots was not significantly different among the taxa at nine months of age.

The potential for deploying the newly tested genotypes in farm forestry projects in semi-arid climates of the Western Cape is discussed.

Opsomming

Die doel van hierdie studie was om *Eucalyptus*-hibriede te ondersoek as ‘n bron van houtagtige biomassa in die halfdorre winterreënvalgebied van Suid-Afrika.

The studie fokus op ʼn 10-jaar-oue eksperimentele aanplanting, asook die stomplootverjonging en daaropvolgende groei tot en met nege maande na kaalkap.

Die proef ondersoek die oorlewing, potensiële produktiwiteit (groei) en vermoë van stomplootverjonging van verskeie *Eucalyptus*-hibriede, naamlik *E. grandis x camaldulensis*, *E. grandis x resinifera*, *E. grandis x tereticornis* en *E. saligna x urophylla*. Dit word vergelyk met die *E. cladocalyx*-kontrole en kommersiële *E. dunnii*- en *E. grandis x camaldulensis*-kontroles. Die oorlewing en potensiële produktiwiteit is ondersoek op ’n takson-, herkoms-, genotipe- en opstandsvlak, terwyl die resultate van die stomplootverjongings gerangskik is van groot na klein op ’n genotipe-vlak.

Oor die algemeen was die oorlewing op die eksperimentele eenheid bo 75 %, behalwe vir die kontroles van *E. cladocalyx* en *E. dunnii*, wat nie goed gevaar het nie. ’n Gemiddelde jaarlikse aanwas van 17.24 $m^3.ha^{-1}.jaar^{-1}$ is behaal op die opstand oor die 10 jaar periode. Basale oppervlakte was gebruik om die rang van die groei respons van die genotipes te toets. Die basale oppervlakte was van enkelboomplotte opgeskaal wat beteken dat die gemiddelde waarde ‘n goeie indikator van groei was. Die opgeskaalde basale oppervlakte van individuele genotipes was egter net betroubaar vir rang en nie vir die skatting groei potensiaal in die veld nie. Die opgeskaalde basale oppervlakte het gewissel van 12 tot 55 $m^3.ha^{-1}$. Verskeie van die getoetste hibriede is skynbaar goed aangepas by die groeiplek, naamlik: *E. gxc* Albacutya CSS01659 (9), *E. gxc* Albacutya CSS01682 (13), *E. gxt* (AUS) seed SR0046xT32 (84) and *E. gxt* (AUS) seed AG049xT08 (83) and *E. gxc* (SA) seed SGR1231xC42 (76).

Amper 50% van die genotipes het ’n goeie stomplootverjongingsvermoë gehad. Die resultate vir die stomplootbiomassa het nie beduidend tussen taksa verskil op nege-maande-oue ouderdom nie.

Die potensiaal vir die ontplooïng van die nuut getoetsde genotipes in plaasbosbouprojekte in die semi-ariede Wes-Kaap word bespreek.

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List of Abbreviations

AI	Aridity index
ACIAR	Australian Centre for International Agricultural Research
ALRTIG	Australian Low Rainfall Tree Improvement Group
ANOVA	Analysis of variance
BI	Biomass Index
DBH	Diameter at breast height
ETP	Potential evapotranspiration
ICFR	Institute for Commercial Forestry Research
MAI	Mean annual increment
MAP	Mean annual precipitation
MAT	Mean annual temperature
MTP	Multiple tree plot
STP	Single tree plot
WC	Western Cape
WD	Water deficit

Chapter 1: Introduction

1.1 Background

South Africa is a semi-arid country with an average rainfall of 450 mm/year/annum (Edwards, 2012). This means that there is little area that is suitable for trees and forest to grow, and the trees that do occur are of great importance.

The limited forests and plantation resources are thus a very important source of sustainable woody biomass and timber. Invasive exotic trees have mainly been used as a source of firewood in the peri-urban areas of the Western Cape (Du Toit *et al*., 2010).

These invasive trees utilised in this way consist mainly of Australian acacias. Black wattle (*Acacia mearnsii*) was introduced into South Africa in 1858 to provide shade, fuelwood and tanbark (Binns *et al*., 2001). Other acacias (notably *A. saligna* and *A. cyclops*) were introduced to stabilise drift sands. Large areas of these invader species are being eradicated by the Working for Water Programme (Binns *et al*., 2001). This means that the woody biomass that was previously utilised is on the decrease and therefore there is a greater need for a sustainable woody biomass source for use in the peri-urban areas of the Western Cape (Du Toit *et al*., 2010).

Within South Africa, high forests (which include natural forests and plantations but exclude woodlands and savannah) cover 1.3% of the total land area, of which 55% (1 266 192 hectares) is planted to exotic trees for mainly commercial forestry purposes (Edwards, 2012). These commercial plantations are mainly limited to the summer rainfall zone of South Africa.

In the Western Cape province, most commercial forestry occurs along the sub-humid and mountainous areas of the southern Cape and some scattered sites in the Overberg and Greater Boland. The Western Cape has an already scarce commercial forestry resource and, of the 12 900 000 hectares the Western Cape comprises, commercial forestry cover 44 030 hectares, which is only 0.3% of the land area (Figure 1) (Godsmark, 2016). According to Van Wyk *et al*. (2001), the Cape Winelands currently has a total of area of 107 662 ha utilised for woodlots and exotic plantations and, according to Von Doderer (2009), a further 106 000 ha are potentially suited for woodlots.

Due to this forest resource being scarce, and with its potential being limited due to moderate to slow growth of even the faster-growing indigenous species (De Cauwer *et al*., 2016; Gush, 2016), South Africa is largely dependent on commercial (exotic) plantations for the supply of woody biomass and timber. It would not be sustainable to harvest the natural forestry resources as a source of woody biomass and timber.

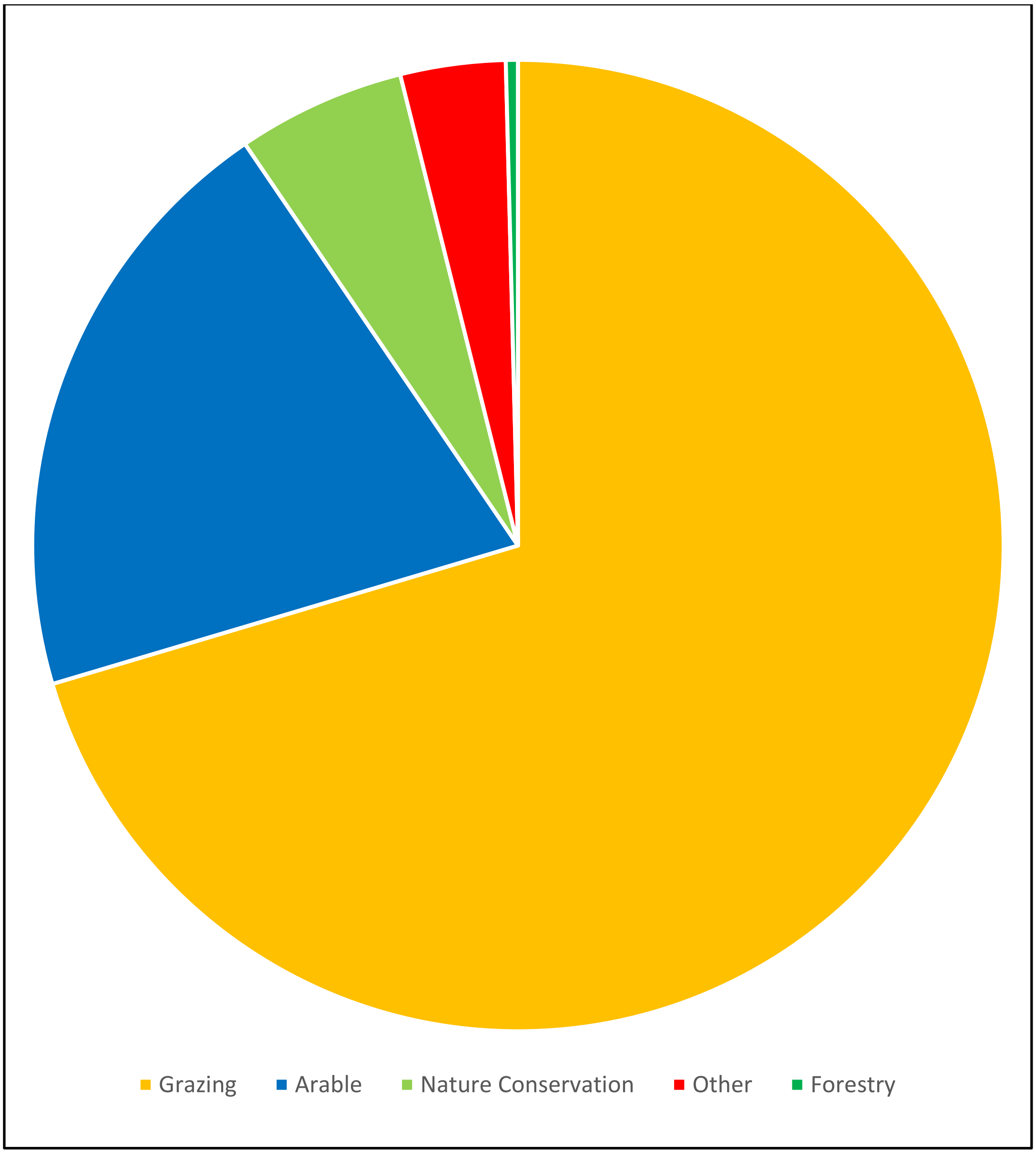


Figure 1: Land use in the Western Cape (Godsmark, 2016)

The limited and slow-growing natural forest resources led the government to start a plantation forestry industry at the end of the nineteenth century. The natural forest is protected from commercial exploitation by various laws, which include the National Forest Act, Act No 84 of 1998, and therefore these resources cannot be utilised, thus increasing the need for the establishment of exotic plantations.

The current reality is that the supply of invader species for woody biomass is decreasing and, together with this, the commercial plantation area is also decreasing due to the exit strategy of the government, in terms of which the commercial forest area of the Western Cape is being replaced by conservation land, which is accordingly rehabilitated to the natural vegetation of the area (VECON, 2006). This is done mainly to conserve and protect the fynbos biome. This programme will be implemented until the end of 2020.

South Africa is a developing country, which means that there is an increase in population and therefore also an increase in the demand for timber in the formal and informal markets. Firewood is a large source of energy for cooking in South Africa. This is also relevant in the Western Cape (WC) province, where there has been an increase in population: The percentage distribution of the projected provincial share of the total population increased from 10.4% in 2002 to 11.5% in 2017, with the current national population at 56 521 948 (Stats SA, 2017). With this increase in population growth, there has also been an increase in migration to the Western Cape. The net migration into the province from 2011 to 2016 was 292 372 people (Stats SA, 2017). The WC is one of the provinces with the highest increase in population due to migration. This trend is set to continue, as it is estimated that the net migration into the WC will increase further to 309 729 for the period from 2016 to 2021 (Stats SA, 2017). This increase in population, together with the decrease in plantation forest area and decrease in invasive trees for fuelwood use, will put more pressure on the already scarce forestry resources of the WC.

Gush (2016) and Seifert *et al*. (2016) already identified the need for the establishment of plantations or woodlots on non-traditional forestry sites in order to meet future woody biomass needs. Therefore, it is important to explore fast-growing trees that can be planted as shelterbelts, plantations or woodlots in the semi-arid Western Cape to meet the future demand for biomass.

One such group of fast-growing trees is the genus of *Eucalyptus.* Eucalypts are mainly planted by farmers as bee forage, windbreaks and some as woodlots for poles, but eucalypts established on farms in the Western Cape (like the species of *E. cladocalyx*) were used as a general-purpose tree (as it was well adapted to the drier conditions). *Eucalyptus cladocalyx* was introduced mainly for bee forage (to stimulate honey production and to provide pollination services).

The commercial plantations of the WC are planted mostly to pine species, and there has been little establishment of *Eucalyptus* species in the province other than on farms. This genus has been under-utilised in the Western Cape as a source of fast-growing biomass. Eucalypts grow faster than Pines over the first eight years (Smith and Scott, 1992) and can thus contribute more biomass over the same period of time. Hybrids have been developed between species that are fast growing and drought tolerant, and thus suited to the study area for biomass production.

An additional advantage of eucalypts is their ability to produce coppice shoots through a bud system that occurs in the cambium of the stem (Little *et al*., 2002). This feature of *Eucalyptus* has been found useful by foresters and farmers, since the coppice can be grown into trees and therefore there is no need to replant after the first and/or second rotation. This means that there is a great saving in the initial re-establishment cost. It is an inexpensive method of growing biomass fast (as the establishment phase is omitted), and therefore it is important to investigate.

1.2 Justification of Study

The findings of the thesis will enable small growers and farmers to choose eucalypt hybrids that are well adapted to the semi-arid sites in the winter rainfall region, thus having the highest rates of survival and potential growth. It will also test the possibility of coppicing these trees after harvesting the first rotation to further aid small growers and farmers in making the decision to establish eucalypts on their unutilised land for windbreaks, shelter belts and woodlots for biomass/firewood or other uses, and to address the predicted shortage in woody biomass in the near future.

1.3 Study Objectives

The study aimed to determine the potential growth and survival of several eucalypt hybrids from parent stock within different provenances, and also to assess the coppicability and the potential growth of the coppice shoots. The hybrids included in this trial are: *E. saligna x urophylla (E. sxu)*, *E. grandis x camaldulensis (E. gxc)*, *E. grandis x resinifera (E. gxr)* and *E. grandis x tereticornis (E. gxt)*.

The growth rate and coppicability of these species in the semi-arid and winter rainfall region are unknown. The research will enable farmers and small growers to plant the hybrids that are most suited to their conditions and therefore produce the highest potential yield.

The goals of the research were to:

1. Investigate the survival of different drought-resistant *Eucalyptus* hybrids in the semi-arid Western Cape
2. Investigate the potential productivity of different drought-resistant *Eucalyptus* hybrids in the semi-arid Western Cape
3. Determine the coppicability and potential coppice growth of different drought-resistant *Eucalyptus* hybrids

1.4 Hypotheses and Research Questions

Only the null hypotheses are given, alongside several key questions that show how the results were quantified. The null hypotheses tested in this experiment were as follows:

1. H_1: The hybrids on the Mariendahl trial site have a greater survival than the commercial *E. dunnii* and the (Kluitjieskraal) *E. cladocalyx* controls.

Research questions:

When comparing mortality at one and at 10 years after establishment, did the survival remain fairly constant?

Do these treatment survival percentages differ significantly in terms of genotype, taxa and E. gxc *provenance at 10 years of age?*

2. H_2: The hybrids on the Mariendahl trial site have higher potential productivity in terms of growth than the *E. dunnii* and the South African Kluitjieskraal *E. cladocalyx* controls

Research question:

Do the potential growth estimates differ significantly at 10 years of age on a taxa, provenance and stand level?

3. H_3: Potential growth differs significantly between the top 20 genotypes in the experiment and *E. dunnii* and the South African Kluitjieskraal *E. cladocalyx* controls.

Research question:

Do the potential growth estimates differ significantly at 10 years of age between the top 20 genotypes and the commercial controls? (this question thus aims to *understand if several genotypes, rather than one or two top performing clones, are suitable for planting in this semi-arid zone).*

4. H_4: The biomass index of coppice in the commercial controls is higher than the tested taxa in the Mariendahl trial. One or more of the treatments' biomass indices for coppice production will be significantly higher than the rest of the treatments tested.

Research questions:

Which Eucalyptus hybrids are suitable for regenerative coppice?

Which genotype has the highest coppice biomass index?

Chapter 2: Literature review

2.1 Investigating the potential growth of alternative *Eucalyptus* species in the semi-arid Greater Boland

2.1.1 Eucalypt species and hybridisation in South Africa

Eucalyptus is a genus of Australian origin. It is one of the most important native Australian forest trees, and has its genealogy under the Eucalypteae tribe. This tribe consists of the genera *Allosyncarpia*, *Angophora*, *Arillastrum*, *Corymbia*, *Eucalyptopsis*, *Eucalyptus* and *Stockwellia*. There are more than 700 different species of *Eucalyptus* (Brooker, 2000) that are spread over different regions of Australia.

The genus of *Eucalyptus* was introduced to South Africa and Africa by settlers, missionaries and government officials in the early nineteenth century (Coppen, 2002). It was recorded as early as in 1828, when the newly appointed Governor of the Cape Colony introduced nine *Eucalyptus globulus* seedlings via Mauritius. Due to its ability to grow rapidly across a wide range of site conditions and climates, other eucalypt species were introduced to South Africa from 1860 onwards (Coppen, 2002).

The rapid expansion of commercial plantation forestry in South Africa from the 1950s to the 1980s prompted research into suitable species for various site types and the genetic improvement of species for improved productivity, wood properties and tree form.

The hybridising of eucalypt species started in South Africa in 1984, and has since become an important part of commercial forestry (Denison & Kietzka, 1993a, 1993b). The hybridisation of species is the mixing of different parent material (species) to optimise the genetic material of the second generation. It is important to mention that most eucalypt hybrids are interspecific.

The main aims of hybridisation in commercial forestry in South Africa are to combine favourable characteristics, exploit hybrid vigour and adapt species to marginal areas. Favourable characteristics of parent species, e.g. drought hardiness, growth, tree form, disease resistance, etc., can be combined into hybrids (Verryn *et al*., 1999). Table 1 is reproduced from Verryn *et al*. (1999) as an example of the properties of different species that are of interest in tree breeding.

The vigour (growth) of *E. grandis* can be combined with resistance to disease of *E. tereticornis* or the drought tolerance of *E. camaldulensis*.

Table 1: Characteristics of different species (Verryn, 2000)

Species	**Vigour**	**Drought tolerance**	**Cold tolerance**	**Resistance to disease**	**Rooting ability**	**Termite resistance**	**Snout beetle resistance**
E. camaldulensis	X	XXX	XX	XX	XXX	X	XX
E. grandis	XXX	X	X	X	XX	X	XXX
E. nitens	XXX	X	XXX	XX	X	X	XXX
E. tereticornis	XX	XX	X	XXX	XX	XXX	XX
E. urophylla	XX	XX	X	XXX	XX	XX	XX

Note: XXX = high ; XX = moderate ; X = low

These species have been bred to enhance growth rate and wood properties, and therefore the response of these species to different sites also needs to be tested.

2.1.2 Site-species matching

The introduction of *Eucalyptus* to South Africa paved the way for site-species matching (determination of climatic/edaphic suitability of species grown on a particular site type). This has been researched by various scholars (Herbert, 1993, 2000; ICFR, 1992; Morris & Pallet, 2000; Schönau & Schulze, 1984; Smith, 2005; Swain & Gardner, 2003; Verryn *et al*., 1996). Site-species matching for commercially grown eucalypts in South Africa is based mainly on locally developed knowledge from experimentation and experience, and does not rely only on matching the site conditions (e.g. climate, geology and soils), with the place of origin of a particular species.

Various site-species matching studies have been conducted over the summer rainfall zone, (for example Gardner *et al.* (2007) and Swain and Gardner (2004)), but these studies have little relevance for the Western Cape, which falls in the winter rainfall zone. There is thus a need to test new hybrids for their suitability to grow in the Mediterranean climate of the Western Cape.

2.1.3 Eucalypts in semi-arid Australia

Eucalypts have their origin in Australia, which is also a water-scarce country. Therefore, the results of studies on the productivity of eucalypts done in Australia in low-rainfall conditions are of relevance to South African conditions.

The Australian Low Rainfall Tree Improvement Group (ALRTIG) focuses on the breeding of eucalypts in the low rainfall zones (400 to 600 mm, with a winter maximum) of southern Australia. The findings of this research group are relevant to the Mediterranean-type climate of the Western Cape, with one major exception, namely that the complement of pest and diseases is very different in the native versus the introduced habitat.

The objective of their breeding is to maximise the net present value of logs produced over a rotation of 20 to 40 years (on a per hectare basis), with the final crop being low-cost, high-value solid wood (for saw logs, veneer and engineered wood products). The main species bred in this programme are: *E. camaldulensis*, *E. cladocalyx*, *E. occidentalis*, *E. sideroxylon* and *E. tricarpa*, and *C. maculata* and *C. citriodora* subsp. *variegata*, which are suited to low rainfall conditions (Harwood *et al*., 2005).

On the drier sites in Western Australia potential of the interspecific hybrids between *E. camaldulensis* and *E. grandis* and *E. camaldulensis* and *E. globulus* have shown some potential where they have outperformed *E. globulus* (Barbour, 2004).

Noble and Arnold (2002) tested three provenances of *E. sideroxylon* and seven provenances of *E. tricarpa* in provenance trials in north-east Victoria. They reported similar species mean growth and survival of 90% at age 1.5 years. At three years of age the mean dbh averaged 6 cm at the Rutherglen site and 5.5 cm at the Indigo Valley site for the *E. sideroxylon,* while *E. tricarpa* showed a mean dbh of 5.1 cm and 5.0 cm for these sites respectively.

ALRTIG also conducted various studies in the low-rainfall summer rainfall regions in the tropical north and subtropical east coast of Australia. These studies are of lesser relevance for the Western Cape, but have been included for comprehensiveness.

A study done by the ALRTIG focused on the developing of genetically adapted species of eucalypt in the marginal areas of northern Australia (Lee *et al*., 2005). The study focused on areas with a rainfall (MAP) of 650 to 900 mm per annum. Two studies focused on tropical (northern Queensland) and sub-tropical (southern

Queensland) Australia. The MAP at the sites ranges from 665 to 1 014 mm, but this rainfall was greatly influenced by lower than usual rainfall.

In the tropical northern Queensland trial, the Sugar Bag Station trial with MAP 793 mm, the best-performing taxa were *E. gxc* (8) clones and *E. urophylla* x *grandis* (*E. uxg*) clones (9), with heights of 3.9 m and 3.3 m in one year respectively. The material for these were selected in Brazil for fast growth and good survival.

The taxa of *E. camaldulensis* (1), *E. tereticornis* (2), *E. tetrodonta* (3), *Corymbia citriodora* spp*. citriodora* (*C. cxc*) (5) and *Corymbia citriodora* subsp*. variegata* (*C. cxv*) (6) showed intermediate growth, with heights ranging between 2.9 and 3.1 m in one year. Poorly performing taxa were *E. cloeziana* (4), mixed eucalypts (7) and *Khaya* spp. (10).

After this study Lee *et al*., 2005 recommended the development of hybrids including *E. grandis* x *E. camaldulensis*, *C. torelliana x C. citriodora* spp. *variegata* and *E. urophylla x E. pellita* for the northern region of Queensland.

In southern Queensland, three sites were used in an experimental series: Wooroolin, Kingaroy and Warwick, with MAPs of 794, 780 and 665 respectively.

At 10 months, *E. tereticornis x grandis* (*E. txg*) (99) had the highest growth, which was significantly higher than that of all the other taxa at Wooroolin, except for *E. UxG* (97) and *E. resinifera x grandis* (*E. rxg*). *Aruacaria cunninghammia* had a significantly lower height compared to all the other taxa. There was no significant difference in the survival between all taxa on the site.

An assessment of the Kingaroy trial site at 15 months showed the following: the tallest taxa were *E. grandis x resinifera* and *E. dunnii* (SAPPI, RSA) (74), which were significantly different to all taxa except for *E. globulus* spp. *maidenii* (50), *E. dunnii* (73) and *E. gxt* (83). All taxa had a survival of more than 90%, although survival was significantly different for all species. The species with the highest survival was *E. tereticornis* (Laura ex Zimbabwe) (80).

The Warwick site (which is closest to the MAP of the Mariendahl trial site in South Africa) was measured at 24 months. The taxa with the greatest height and survival were *E. argophloia* (69) and *E. longirostrata* (77). The three spotted gum taxa had a significantly lower height than all other taxa.

A study by Lee *et al*. (2001) tested a variety of eucalypt material and interspecific hybrids from South Africa in the marginal 600 mm to 1 000 mm rainfall zone in subtropical Queensland in Australia. Trees were measured for productivity and survival at 24 months of age. The species tested in this trial were *E. dunnii*, *E. cloeziana*, *E. gxc*, *E. gxt*, *E. globulus* subsp*. maidenii*, and *Corymbia variegata*.

Although the hybrids of *E. gxc* and *E. gxt* performed the best of the hybrids, it was observed that they were severely affected by pests and disease.

The pure species that were expected to be productive are: *E. cloeziana*, *E. pilularis*, *C. variegata* and *E. argophloia*.

Now that potential species from their native Australia have been investigated, the question that arises is how previous studies in the Western Cape study area compare.

2.1.4 Eucalypts in the winter rainfall region of South Africa

The Western Cape, which is predominantly in a winter rainfall zone, differs greatly in climate from the summer rainfall area, where most commercial forestry occurs, and also differs from the all-year rainfall area of the Southern and Eastern Cape. Thus the site-species and provenance trials done in these areas cannot be used as a comparison to the current study. The semi-arid Western Cape has hot and dry summers and cool and wet winters (Mediterranean climate).

The mean annual precipitation (MAP) on the Mariendahl study trial site is 647 mm, with a mean annual temperature (MAT) of 16.7°C. The mean minimum temperature of the coldest month is 6.8°C, and the mean maximum of the warmest month is 28.9°C.

Some site-interaction and provenance trials were done in the Southern Cape to test *Eucalyptus* (Gardner *et al*., 2003). Gardner *et al*. (2003) tested 12 *Eucalyptus* species and hybrids and eight provenances of *E. globulus* on a wet site and a dry site. The dry site had a MAP of 796 mm and the wet site had a MAP of 990 mm. The species and hybrids tested in this trial were *E. badjensis*, *E. benthamii*, *E. cypellocarpa*, *E. dunnii*, *E. fraxinoides*, *E. globulus* ssp. *bicostata*, *E. globulus* ssp*. globulus*, *E. globulus* ssp. *maidenii*, *E. grandis*, *E grandis x globulus*, *E. grandis x nitens* (three varieties)*, E. grandis x (grandis x camaldulensis)*, *E. grandis x saligna*, *E. macarthurii*, *E. nitens*, *E. saligna x urophylla*, *E. smithii* and *E. viminalis*, with *E. globulus* and *E. diversicolor* as the commercial controls.

The treatments that performed the best after 51 months based on basal area were the two improved *E. grandis* seedlots, *E. saligna x urophylla and E. grandis x nitens*.

The *E. nitens* Badia and Tallaganda provenances performed well and were comparable with the best performers on the relatively drier Jonkersberg site.

The commercial controls had basal areas significantly lower than the trial mean.

Although this study was done in the Western Cape, it cannot be used to directly compare with growth and survival on the Mariendahl trial due to the constant rainfall throughout the year in the Southern Cape region, whereas the rainfall in the semi-arid Western Cape is mainly winter rainfall.

The literature with regard to *Eucalyptus* species in the semi-arid Western Cape is limited. Some site-species interaction trials were done in the sandy soils of the semi-arid West Coast by Van Wyk *et al*. in 2001. This study's focus was mainly on the growth potential and yield of unimproved *Eucalyptus* seedlings of *E. gomphocephala* and *E. cladocalyx*, and hybrids of *E. camaldulensis* and *E. tereticornis* with the parent material of *E. grandis*. Du Toit *et al*. (2017) continued this research by documenting the long-term growth results of eucalypts on four semi-arid sites in the Mediterranean climate zone. The results of this paper included the longer term results of the experiment initially described by Van Wyk *et al*. (2001) plus three other trials. The treatments included in this study were: *E. gomphocephala*, *E. camaldulensis*, *E. tereticornis*, *E. grandis*, *E. cladocalyx*, *E. gxc* and *E. gxt*. *Eucalyptus gomphocephala* (in the drier section of the semi-arid zone) and *E. cladocalyx* (in the wetter section of the semi-arid zone) were found to be the species that performed the best in the study area. The growth performance of *E. cladocalyx* and *E. gomphocephala* was superior to all the other species tested in the Cape West Coast trial by van Wyk *et al*. (2001). MAI estimates ranged between 8.6 $m^3ha^{-1}a^{-1}$ and 9.6 $m^3ha^{-1}a^{-1}$. Van Wyk suggests that, once this is deployed commercially, a yield of 10 $m^3ha^{-1}a^{-1}$ could be achieved.

The biomass study done by Botman (2010) found the actual MAI at six years to be 6.95 $m^3ha^{-1}a^{-1}$ on a semi-arid site (Darling area) and 11.2 $m^3\,ha^{-1}\,a^{-1}$ on the sub-humid site (Stellenbosch area), while the projected potential growth (MAI) at ten years of *E. gxc* and *E. gxu* hybrids on a third, sub-humid site (Paarl area) were approximately 17.89 and 17.84 $m^3\ ha^{-1}\ a^{-1}$ respectively.

2.2 Coppice potential of alternative *Eucalyptus* species for the semi-arid Boland region

2.2.1 What is coppice?

Coppice is defined as "… a forest crop raised from shoots produced from cut stumps (called stools) of the previous crop/rotation. It also describes the operation of felling and regenerating in this way…" (Evans & Turnbull, 2010).

Eucalyptus has the ability to survive and produce new growth following adverse environmental conditions, i.e. drought (Florence, 1996), and after the tree has been cut down. This ability is advantageous in the semi-arid climatic zone, which is more prone to droughts. It is also advantageous due to the shoots that form. The shoots can be managed and utilised as coppice shoots. This is principally a function of the bud system found in eucalypts (Little *et al*., 2002).

Coppice growth after harvesting is as a result of two bud types. These are known as the lignotubers and epicormic buds (Evans & Turnbull, 2010; Little *et al*., 2002; Penfold & Willis, 1961).The abundance of lignotubers and/or epicormic buds will affect the ability of a species to coppice (Little & Gardner, 2003).

The epicormic buds originate from meristemic tissue. They are present in the leaf axils of small seedlings keeping pace with the radial growth of the stem (Florence, 1996). The leaves produce growth hormone which inhibits the sprouting of the buds. When the leaves (and growth hormone) are absent after the removal of the crown during harvesting, the coppice shoots will sprout.

A lignotuber is the additional swelling of meristemic tissue near the base from where coppice shoots sprout. It comprises many vegetative buds and food reserves in vascular tissue from which the shoots form (Evans & Turnbull, 2010). Lignotubers are absent in some species like *E. nitens* (Evans & Turnbull, 2010; Little *et al*., 2002), which partly explains the poor coppicing ability thereof. *E. grandis* is also non-lignotuberous (Penfold & Willis, 1961).

Coppice is useful in forestry, as it can reduce stand regeneration costs due to the fact that no planting operation needs to take place (Crous & Burger, 2015). Opie *et al*. (1984) found that the use of prolifically coppicing species may be an advantage in that it could be cheaper and possibly more productive than in terms of volume to re-establish from coppice. In some situations, the high cost of re-establishment is outweighed by faster growing species with higher yields and quality and may be preferred even if they do not coppice well (Opie et al. 1984). Benefits of shorter rotations are that there is a quicker return on investment and it may also reduce the water use of Eucalyptus when compared to a normal rotation (Mugunga *et al*., 2015). It is in the interest of small growers and farmers to utilise this mechanism where possible, or an alternative, to produce woody biomass more rapidly. It can also be utilised after the first planted rotation to reduce the establishment cost, temporary unplanted area and initial growing period the re-establishment of trees would require. Therefore, the taxon that has the highest rate of growth (volume) and survival of the coppice should be investigated in species-performance trials.

2.3.2 Coppice studies

Many coppice studies have been conducted in South Africa (Little, 2000, 2001; Little & Gardner, 2003; Oscroft & Little, 2008). None of the studies were specific to the semi-arid climatic range.

When deciding to coppice a stand, the most important factors that need to be taken into consideration are whether site-species matching has been done for the species grown on that specific site, whether the stocking and survival are acceptable (> 75% survival), and whether the species has an acceptable coppicing ability on the site in question (Little, 2001). One of the objectives of this thesis was to explore how the chosen species in the trial match to the specific site, and also what the coppicing ability of the species on the site is.

The survival of stumps from the first rotation (original crop) prior to felling is an important factor influencing the ability to coppice. In compartments where the survival of stumps is low, it will not be viable to allow the compartment to coppice, but where the survival of stumps is adequate, it will be a viable decision to allow the compartment to coppice (Little & Gardner, 2003).

In studies done in South Africa, it was found that *E. dunnii*, *E. grandis*, *E. gxc*, *E. grandis x urophylla*, *E. maccarthurii* and *E. oreades* are species with good coppice potential (Little, 2000; Little & Gardner, 2003). In addition to this, Oscroft and Little (2008) tested *E. gxc*, *E. grandis x urophylla* and *E. gxt* for coppicability after a fire. It was found that, of the 89.8% stump survival before the fire, 84.4% of the stumps produced coppice and, of those stumps, 94.4% had coppice present at the first coppice reduction. Therefore, it is expected that *E. dunnii*, *E. gxc* and *E. gxt* will have good coppicability. McMahon *et al*. (2010) reported that *E. cladocalyx* coppices well.

A study of the coppice ability of 20 *Eucalyptus* species at high-altitude sites in South Africa by Little and Gardner (2003) found that the periods of severe drought during 1990 and from early 1992 to late 1995 affected not only the growth, but also the final stocking, of the drought-sensitive species and provenances negatively. *E. smithii* and *E. benthamii* performed well on the site with the harshest growing conditions (Draycott). Other species that were also mentioned to have potential were *E. badjensis* and *E. dunnii*.

However, no literature was found on the coppicability of *E. gxr* and *E. sxu*.

Chapter 3: Materials and Methods

3.1 Site description

The trial site is situated on the Mariendahl experimental farm, about 16 km outside Stellenbosch near Klapmuts (Figure 2). It is situated mid-slope, with a non-perennial river running parallel to the length of the trial at a distance of about 80 m from the trial. This river does not affect the water availability of the experiment, as it is incised in a landscape position approximately 20 to 30 m below the level of the experiment. Site characteristics are summarised in Appendix A.

The trial was laid out and established in 2006. It was initially part of a series of trials conducted in collaboration with the ACIAR and Merensky, which tested different provenances of *E. gxc* and hybrids in semi-arid climates.

Figure 2: Location of trial site in relation to 1) South Africa 2) the Western Cape 3) and Mariendahl Farm (Google, 2018)

3.2 Climate

The Western Cape has a Mediterranean climate with low rainfall in the summer months and the bulk of the rainfall in the winter months. The summers are hot and dry, and the winters are cool and wet. Some frost may occur on cold winter mornings. The mean annual precipitation (MAP) is 647 mm, and potential evapotranspiration (ET_p) is 1 540 mm.

The FAO Aridity Index was used to describe the climatic conditions at the trial site. The Aridity Index is defined as MAP/ET_p, where ET_p is the mean annual potential evapotranspiration as determined by the Penman-Monteith method (Allen *et al.*, 1998). The MAP is low and the ET_p is high for the site, and thus a low Aridity Index was expected. The semi-arid range extends from 0.2 to 0.5 AI units. The range for the semi-arid climate is very broad, and thus Du Toit *et al*. (2017) split the semi-arid climatic range into a relatively wetter "semi-arid +" (AI > 0.35) and relatively drier "Semi-arid –" (AI < 0.35) sub-class for greater precision. The Mariendahl trial site lies within the "Semi-Arid +" classification (Figure 3). The aridity index of 0.42 means that the site is within the upper (more moist) fraction of the semi-arid climatic region (Table 2).

Table 2: Aridity index classes showing a subdivision of the semi-arid class, after Du Toit et al. (2017)

Classification	Aridity Index
Hyper-arid	AI < 0.05
Arid	0.05 < AI < 0.20
Semi-arid -	0.2 < AI < 0.35
Semi-arid +	0.35 < AI < 0.50
Dry sub-humid	0.50 < AI < 0.65
Moist sub-humid	0.65 < AI < 1.00
Humid	1.0 < AI

3.3 Water deficit

The site has a distinct gradient in soil depth, ranging from 1.3 to 2.6 m. It was therefore decided to further subdivide the trial site into relatively drier and relatively wetter subsites, based on soil depth (and hence the ability to store soil water).

This division is supported by tree growth data: Tree height and diameter in the dry subsite were approximately 24 and 13% smaller than the corresponding measures in the wet subsite and were visibly different. Henceforth, the shallow, relatively drier portion of the experimental site will be referred to as the dry subsite, and the relatively wetter portion will be referred to as the wet subsite.

As the depth of the soil and water availability will be key factors limiting tree growth, these factors needed to be considered, and thus the water-holding capacity of the soil and the water deficit of the site were estimated.

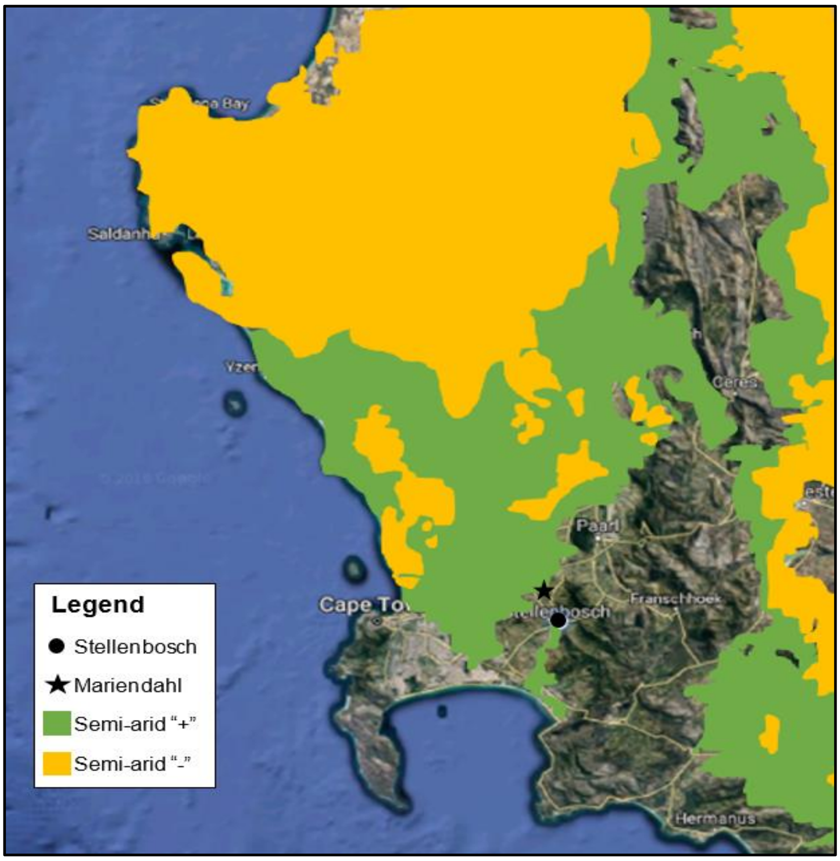


Figure 3: Map of semi-arid areas of the Western Cape Winelands (simplified from Du Toit et al.*, 2017)*

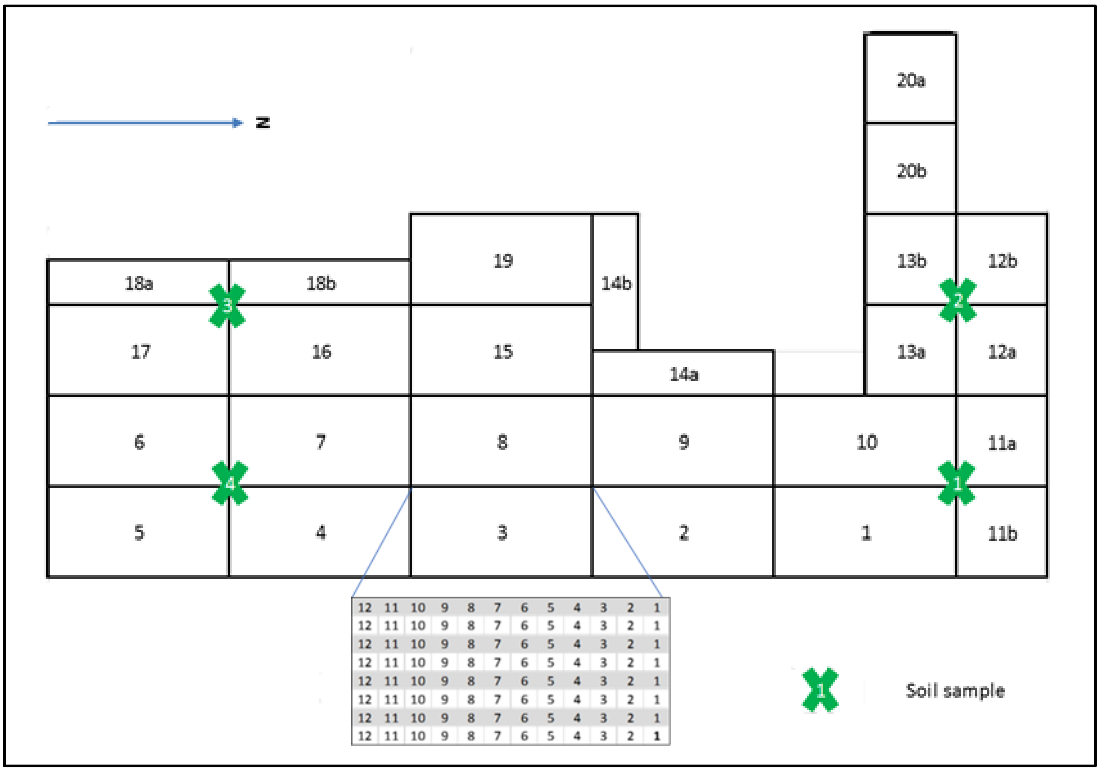
3.3.1 Water-holding capacity

Four sets of soil samples (see Figure 4) were taken within the trial – two from the dry site and two from the wet subsite. Soil analysis for the top 20 cm and water holding capacity were analysed by Bemlab, Somerset West (see Appendix B & C).

Water-holding capacity can be defined as "the depth of water in mm/m^{-1} soil depth between the soil water content at field capacity (S_{fc}, i.e. at -10 kPa) and the soil water content at wilting point (S_{w}, i.e. at -1 500 kPa)".

The water-holding capacity was determined per soil horizon: Soil samples were taken with an extendable Dutch auger at 20 cm intervals until bedrock was reached. These samples were grouped per horizon (i.e. samples with the same characteristics), and the water-holding capacity was determined for the four locations on the site (Figure 3), as follows:

The soil samples were dispersed with a sodium-hexametaphosphate (caglon) solution and sieved to separate the sand fractions. The silt and clay contents were then determined by using the sedimentation rates at 20°C and an ASTM E100 (152H-TP) hydrometer. The soil water-holding capacity was derived from the soil texture model of Saxton *et al*. (1986).



12	11	10	9	8	7	6	5	4	3	2	1
12	11	10	9	8	7	6	5	4	3	2	1
12	11	10	9	8	7	6	5	4	3	2	1
12	11	10	9	8	7	6	5	4	3	2	1
12	11	10	9	8	7	6	5	4	3	2	1
12	11	10	9	8	7	6	5	4	3	2	1
12	11	10	9	8	7	6	5	4	3	2	1
12	11	10	9	8	7	6	5	4	3	2	1

Figure 4: Layout and position of the soil sample sets in the Mariendahl experiment

3.3.2 Water deficit

Thornthwaite's (1948) classification can be used to study the climate of a location or region through the use of the normal climatological water balance. This was further developed by Pereira *et al*. (2007) to work out a water deficit (WD). Water surplus (EXC) and the deficiency of water (DEF) can be calculated from the standard climatological water balance by using thermal availability and potential evapotranspiration (ETP) (Thornthwaite & Maher, 1955). The only climatic data needed for this method are temperature and rainfall, and thus it can easily be used to measure water balance in agricultural, forestry and geographical studies where detailed climatic data is sparse (Scheepers, 2018).

Thornthwaite (1948) developed one of the first methods to measure monthly potential evapotranspiration. The standard potential evapotranspiration (ET_p in mm/month^{-1}), is:

$$ET_p = 16\,(10\frac{T_n}{I})^a \quad 0 \leq T_n \leq 26{,}0\,℃$$

where:

T_n = average temperature of month n in °C

I = index of expressing the level of heat available in the region

a = regional thermal effect

n =s month, where n = 1 is January and n = 2 is February, etc.

The equation of Willmott *et al*. (1985) is used where $T_n > 26.5°C$ and the ET_p will be given by:

$$ET_p = -145{,}85 + 32{,}24\,T_n - 0{,}43\,{T_n}^2 \quad T_n > 26{,}0℃$$

The thermal effect (I) is calculated by the summation of the monthly thermal effect. The value of I depends on the annual temperature rhythm (preferably with normal values) and is an integration of the thermal effect of each month.

Thermal effect is calculated by the following formula:

$$I = \sum_{n=1}^{12} (0.2\,T_n)^{1{,}514}$$

There is also a regional thermal index, in which the exponent a, of equation (x), which is a function of I, is calculated by the polynomial function:

$$a = 6.75\,10^{-7}I^3 - 7.71\,10^{-5}I^2 + 1.7912\,10^{-2}I + 0{,}49239$$

The coefficients *I* and *a* are calculated with the climatological normals that are characteristic of the region and become constant, which means that they are independent of the year of estimation of ET_p.

According to the definition of ET_p by Thornthwaite (1948), a standard month has 30 days, in which each day has a photoperiod of 12 hours under those thermal conditions for the monthly potential evapotranspiration. This means that the ET_p must be adjusted to the number of days per month in which it is measured, and also to the amount of real photoperiod per day of that month.

Therefore, the ETP value must be corrected by the function of the actual number of days and the photoperiod of the month. This formula is given by:

$$ETP = ET_pCor$$

$$Cor = (ND/30)(N/12)$$

where ND is the number of days in the month in question, and N is the average photoperiod of that month.

$$N = \frac{2Hn}{15}$$

in hours photoperiod, where Hn = hour angle of the sun.

The hour angle of the sun is given by the following equation:

$$Hn = \cos^{-1}(-tg\emptyset . tg\delta)$$

where

δ = solar declination in degrees

t_g = the sun hour angle at sunrise (-) and sunset (+)

$\emptyset$ = local latitude in degrees.

The solar declination is given by the equation below:

$$-\delta = 23.45° \sin\left[\frac{N + 284}{365} x360°\right]$$

where N = day of the year

Solar declination is negative due to the site being in the southern hemisphere.

The storage alteration (ALT) was then calculated:

$$\pm ALT = P - ETR - EXC$$

where

P = precipitation

ETR = real evapotranspiration

EXC = the deep drainage or water surplus

The water deficit (WD) is expressed as follows (Pereira *et al*., 2007):

$$DEF = ETP - ET$$

The water average DEF on the site was 332.5 mm.

3.4 Trial layout and design

The trial site was planted at a stocking of 1 667 stems ha^{-1}, with a spacing of 2 x 3 m (as is fairly standard in the industry for pulpwood). The trial site was established in 31/08/2006 and laid out in an alpha lattice design (randomised incomplete block design), consisting of 96 single tree plots (treatments) per replication, 20 replications (Tables 4 and 5) and therefore 1920 trees measured. The provenances are summarised in Table 3, and the location of the Australian provenances is shown in Figure 5. The 20 replications consisting of 8 rows x 12 trees. All trees were measured.

Figure 5: Summary of Australian treatments included in the Mariendahl trial

Table 3: Summary of the number of treatments and provenances in the Mariendahl trial

Treatment no.	Provenance	Taxon	Number of treatments
1 - 20	Albacutya	*E. gxc*	20
21 - 31	De Grey	*E. gxc*	11
32 - 44	Morocco	*E. gxc*	13
45 - 56	Petford	*E. gxc*	12
57 - 70	Silverton	*E. gxc*	14
71 - 73	Wiluna	*E. gxc*	3
74	Yass	*E. gxc*	1
75 - 80	*E. gxc* (SA) seed	*E. gxc*	6
81 - 87	*E. gxt* (Aus) seed	*E. gxt*	7
88 - 89	*E. gxr*	*E. gxr*	2
90	*E. gxc*	*E. gxc*	1
91	*E. dunnii*	*E. dunnii*	1
92	*E. gxc*	*E. gxc*	1
93	*E. gxc* com. control T12	*E. gxc* com. control T12	1
94	*E. gxc* com. control C46	*E. gxc* com. control C46	1
95	*E. cladocalyx*	*E. cladocalyx*	1
96	*E. sxu*	*E. sxu*	1

Two rows of *E. dunnii* were planted around the outer area of the trial to minimise (exclude) the edge effect. The trees were 10 years of age at felling, and the last measurements were taken in the same year.

3.4.1 Survival

Survival was calculated using a scoring of 1 for a live tree and 0 for a dead tree. Survival was then calculated by the summation and averaging of the scores per treatment/provenance/taxon:

$$Survival\ (\%) = \left(\sum Survival\ scores/amount\ of\ scores\right) \times 100$$

3.4.2 Potential productivity

3.4.2.1 Upscaled basal area

The potential productivity was estimated in upscaled basal area (m^2 ha^{-1}) per genotype, *E. gxc* family and treatment. We use the term "upscaled basal area" because it is calculated from single tree plots and thus is not entirely similar to a basal area determined in large plots containing several trees with adequate surround rows to ensure equal, uniform competition by neighbouring trees of the same genotype in the plot. The concept of observations from single trees vs. multiple tree plots is discussed in Section 5.1. The upscaled basal area was calculated on the basis of the tree DBH.

Basal area expresses the area of a cross-section of the stem. The average upscaled basal area per single tree plot was calculated using the following formula (Komakech *et al.*, 2013):

$$G = \left(dbh_i^{\,2} \times \pi/40\,000\right) \times 10\,000/plot\ area$$

where

G = mean plot basal area (m^2 per hectare)

dbh$_i$ = diameter at breast height (1.3 m above ground in cm) of the i^{th} tree

π = 3.142

π/40 000 x 10 000/plot area = conversion factors that take into account the conversion of diameter (measured in cm) to radius and finally expressed as basal area in m^2 ha^{-1})

A Vertex Hypsometer was used to measure the tree height, and a DBH (diameter) tape was used to measure the DBH of each tree.

The trees were all measured at 1.3 m above the ground (DBH). The measurement was taken over the bark. Where forks occurred below 1.3 m, both leaders were measured and the tree was treated as two individual stems; where the fork occurred above 1.3 m, the tree was measured as a single entity (Fuwape *et al.*, 2001; Ravindranath & Ostwald, 2008).

The single-tree basal areas were then averaged to find a mean per treatment (seeing that the information stemmed from single tree plots). The basal area is correlated well with the production of wood (Ræbild *et al.*, 2002).

An average upscaled basal area was then calculated per treatment (taking stocking into account) to give an indication of the potential production. This was done because uniformity, survival and stocking in any given treatment also affect the volume production per hectare (Darrow, 1994, 1997; Dunlop *et al*., 2002).

3.4.2.2 Potential utilisable volume

Tree height and DBH of each tree are needed to determine the volume of each tree. These measurements were entered into a volume equation and used to calculate the total volume of the tree under the bark. The formulas account for the loss of volume in the stump and tip of the tree (up to top-end diameter). Different volume functions and models are used to calculate the volume of trees. The biomass size of a tree can be calculated in cubic metres (m^3), tons (t) or biomass index (BI). The standard in the industry is that tons are used for pulpwood or biomass, and m^3 for saw timber in South Africa. The measurements for this trial were expressed in m^3.

The Schumacher and Hall equation is the most popular formula to calculate individual tree volume (Bredenkamp, 2000).

Due to the taper in different species, form factors or taper functions are used to determine the degree to which the tree decreases in DBH with an increase in height. There are two taper equations, namely the Demaerschalk and Max and Burkhart function.

The Max-Burkhart volume-taper equation (Max & Burkhart, 1976) is also used to calculate total tree volume (V_t). The constant form factor method of Demaerschalk (1973) was used in the volume-taper calculations and the total tree volume was calculated as in an equation by Pienaar and Kotze (2001).

The growth of trees is measured using the mean annual increment (MAI), which is a measure of the growth in m^3 or tons per annum, and this will give an indication of how effectively the site is utilised. It also provides an indication of which trees are best adapted to the site.

The total utilisable volume of each tree (V_t) was used to calculate the total volume of the Mariendahl trial. The Demaerschalk, and Max and Burkhart taper-volume functions, as well as the Schumacher and Hall equations, were used to calculate the volumes, seeing that the best available volume functions had to be chosen from the available literature. The coefficients for this function can be found in Table 7.

Table 4: Summary of treatments and ACIAR codes of the Mariendahl trial site

Treatment no.	Species	ACIAR list (codes and families)	Provenance	Origin
1	*E. grandis x camaldulensis*	G050xSTB-4	Albacutya	CSIR
2	*E. grandis x camaldulensis*	G107xSTB-4	Albacutya	CSIR
3	*E. grandis x camaldulensis*	AG842xAC-1	Albacutya	CSIR
4	*E. grandis x camaldulensis*	CSS01652	Albacutya	CSIR
5	*E. grandis x camaldulensis*	CSS01649	Albacutya	CSIR
6	*E. grandis x camaldulensis*	G017xSTB-4	Albacutya	CSIR
7	*E. grandis x camaldulensis*	CSS01662	Albacutya	CSIR
8	*E. grandis x camaldulensis*	G039xSTB-4	Albacutya	CSIR
9	*E. grandis x camaldulensis*	CSS01659	Albacutya	CSIR
10	*E. grandis x camaldulensis*	CSS01669	Albacutya	CSIR
11	*E. grandis x camaldulensis*	SGR16xSTB-4	Albacutya	CSIR
12	*E. grandis x camaldulensis*	G050xAC-1	Albacutya	CSIR
13	*E. grandis x camaldulensis*	CSS01682	Albacutya	CSIR
14	*E. grandis x camaldulensis*	G017xAC-1	Albacutya	Australia
15	*E. grandis x camaldulensis*	G075xAC-1	Albacutya	Australia
16	*E. grandis x camaldulensis*	CSS01676	Albacutya	Australia
17	*E. grandis x camaldulensis*	G107xAC-1	Albacutya	Australia
18	*E. grandis x camaldulensis*	SGR16xAC-1	Albacutya	Australia
19	*E. grandis x camaldulensis*	G107xCSP/01504	Albacutya	Australia
20	*E. grandis x camaldulensis*	SGR1668xAC-1	Albacutya	Australia
21	*E. grandis x camaldulensis*	G107xSTB-6	De Grey	CSIR
22	*E. grandis x camaldulensis*	G050xSTB-7	De Grey	CSIR
23	*E. grandis x camaldulensis*	G017xSTB-6	De Grey	CSIR
24	*E. grandis x camaldulensis*	SGR71xSTB-7	De Grey	CSIR
25	*E. grandis x camaldulensis*	SGR16xSTB-5	De Grey	CSIR
26	*E. grandis x camaldulensis*	SGR412xSTB-5	De Grey	CSIR
27	*E. grandis x camaldulensis*	SGR481xSTB-5	De Grey	CSIR
28	*E. grandis x camaldulensis*	SGR16xSTB-6	De Grey	CSIR
29	*E. grandis x camaldulensis*	G050xSTB-6	De Grey	CSIR
30	*E. grandis x camaldulensis*	SGR71xSTB-5	De Grey	CSIR
31	*E. grandis x camaldulensis*	SGR71xSTB-6	De Grey	CSIR
32	*E. grandis x camaldulensis*	G050xSTB-1	Morocco	CSIR
33	*E. grandis x camaldulensis*	G015xSTB-2	Morocco	CSIR
34	*E. grandis x camaldulensis*	SGR71xSTB-1	Morocco	CSIR
35	*E. grandis x camaldulensis*	G107xSTB-1	Morocco	CSIR
36	*E. grandis x camaldulensis*	G045xSTB-1	Morocco	CSIR
37	*E. grandis x camaldulensis*	SGR1668xSTB-1	Morocco	CSIR
38	*E. grandis x camaldulensis*	G107xSTB-2	Morocco	CSIR
39	*E. grandis x camaldulensis*	SGR71xSTB-2	Morocco	CSIR
40	*E. grandis x camaldulensis*	FLO578xSTB-1	Morocco	CSIR
41	*E. grandis x camaldulensis*	SGR16xSTB-1	Morocco	CSIR
42	*E. grandis x camaldulensis*	G017xSTB-1	Morocco	CSIR
43	*E. grandis x camaldulensis*	SGR481xSTB-1	Morocco	CSIR
44	*E. grandis x camaldulensis*	G015xSTB-1	Morocco	CSIR
45	*E. grandis x camaldulensis*	G075xAC-2	Petford	CSIR
46	*E. grandis x camaldulensis*	SGR16xAC-2	Petford	CSIR
47	*E. grandis x camaldulensis*	SGR1668xAC-2	Petford	CSIR
48	*E. grandis x camaldulensis*	CSS01653	Petford	CSIR

Table 5: Summary of treatments and ACIAR codes of the Mariendahl trial site (continued)

Treatment No.	Species	ACIAR list (codes and families)	Provenance	Origin
49	*E. grandis x camaldulensis*	CSS01656	Petford	Australia
50	*E. grandis x camaldulensis*	CSS01658	Petford	Australia
51	*E. grandis x camaldulensis*	CSS01661	Petford	Australia
52	*E. grandis x camaldulensis*	G017xAC-2	Petford	Australia
53	*E. grandis x camaldulensis*	CSS01673	Petford	Australia
54	*E. grandis x camaldulensis*	CSS01681	Petford	Australia
55	*E. grandis x camaldulensis*	CSS01685	Petford	Australia
56	*E. grandis x camaldulensis*	CSS01688	Petford	Australia
57	*E. grandis x camaldulensis*	CSS01660	Silverton	CSIR
58	*E. grandis x camaldulensis*	CSS01686	Silverton	CSIR
59	*E. grandis x camaldulensis*	G050xAC-3	Silverton	CSIR
60	*E. grandis x camaldulensis*	CSS01689	Silverton	CSIR
61	*E. grandis x camaldulensis*	G107xCSP/01508	Silverton	CSIR
62	*E. grandis x camaldulensis*	G107xCSP/01509	Silverton	CSIR
63	*E. grandis x camaldulensis*	G017xAC-3	Silverton	Australia
64	*E. grandis x camaldulensis*	SGR16xAC-3	Silverton	Australia
65	*E. grandis x camaldulensis*	CSS01647	Silverton	Australia
66	*E. grandis x camaldulensis*	SGR1668xAC-3	Silverton	Australia
67	*E. grandis x camaldulensis*	CSS01650	Silverton	Australia
68	*E. grandis x camaldulensis*	CSS01663	Silverton	Australia
69	*E. grandis x camaldulensis*	CSS01675	Silverton	Australia
70	*E. grandis x camaldulensis*	CSS01683	Silverton	Australia
71	*E. grandis x camaldulensis*	CSS01691	Wiluna	Australia
72	*E. grandis x camaldulensis*	CSS01654	Wiluna	Australia
73	*E. grandis x camaldulensis*	CSS01655	Wiluna	Australia
74	*E. grandis x camaldulensis*	G015xYASS-CAM	Yass	CSIR
75	*E. grandis x camaldulensis*	G105xC40	GxC(SA) seed	South Africa
76	*E. grandis x camaldulensis*	SGR1231xC42	GxC(SA) seed	South Africa
77	*E. grandis x camaldulensis*	G015xC42	GxC(SA) seed	South Africa
78	*E. grandis x camaldulensis*	G107xC63	GxC(SA) seed	South Africa
79	*E. grandis x camaldulensis*	G015xC49	GxC(SA) seed	South Africa
80	*E. grandis x camaldulensis*	G075xC40	GxC(SA) seed	South Africa
81	*E. grandis x tereticornis*	SRC74	GxT(Aus) seed	Australia
82	*E. grandis x tereticornis*	SRC172	GxT(Aus) seed	Australia
83	*E. grandis x tereticornis*	AG049xT08	GxT(Aus) seed	Australia
84	*E. grandis x tereticornis*	SGR0046xT32	GxT(SA) seed	South Africa
85	*E. grandis x tereticornis*	SRC73	GxT(SA) seed	South Africa
86	*E. grandis x tereticornis*	AG049xT10	GxT(SA) seed	South Africa
87	*E. grandis x tereticornis*	G038xT08	GxT(SA) seed	South Africa
88	*E. grandis x resinifera*	AG840xRES-9	*E. grandis x resinifera*	Australia
89	*E. grandis x resinifera*	AG840xRES-10	*E. grandis x resinifera*	Australia
90	*E. grandis x camaldulensis*	GxC016/008	*E. grandis x camaldulensis*	
91	*E. dunnii*	Mondi - CONTROL	*E. dunnii*	Mondi
92	*E. grandis x camaldulensis*	GxC40/7	*E. grandis x camaldulensis*	
93	*E. grandis x camaldulensis*	T12 - CONTROL	comm control	CSIR
94	*E. grandis x camaldulensis*	C46 - CONTROL	comm control	CSIR
95	*E. cladocalyx*	*E. cladocalyx*	*E. cladocalyx*	Kluitjieskraal
96	*E. sxu*	SxU092	*E. sxu*	

Table 7: Summary of functions and their coefficients used for volume calculations.

Species	**Function**	**B_0**	**B_1**	**B_2**	**B_3**	**B_4**	**B_5**	**Source**
E. grandis x camaldulensis	Max and Burkhart	-1.7658	0.6692	-0.4025	68.5341	0.7251	0.0705	Smith *et al*., 2006
E. grandis x resinifera	Max and Burkhart	-1.7658	0.6692	-0.4025	68.5341	0.7251	0.0705	Smith *et al*., 2006
E. grandis x tereticornis	Max and Burkhart	-1.7658	0.6692	-0.4025	68.5341	0.7251	0.0705	Smith *et al*., 2006
E. cladocalyx	Schumacher and Hall	-10.398	1.977	0.959				Bredenkamp, 1994
E. dunnii	Demaerschalk	0.9312	1.5270					Boreham and Pallet, 2009
E. saligna x urophylla	Max and Burkhart	-1.7658	0.6692	-0.4025	68.5341	0.7251	0.0705	Smith *et al*., 2006

There are no published coefficients for use in volume calculations of the hybrids of *E. grandis x resinifera* and *E. saligna x urophylla*, and the development of such coefficients fell outside the scope of this study. For this reason, the coefficients used by Smith *et al*. (2006) to estimate the volume of *E. grandis x camaldulensis* in that study was used to calculate the volume per tree for the *E. grandis x resinifera* and *E. saligna x urophylla* hybrids also (Table 7).

The Schumacher and Hall model (Bredenkamp, 2000) gives the volume of the tree up to a tip diameter of 75 mm under-bark and is shown by the regression function:

$$lnV = \beta_0 + \beta_1 ln(dbh + f) + \beta_2 lnH$$

where *ln* is the natural logarithm to the base e,

V is the under-bark stem volume in m^3,

DBH is the over-bark diameter at breast height in cm,

f is the correction factor, and *H* is the tree height in metres.

The Max and Burkhart taper-volume function (Max & Burkhart, 1976) gives the total utilisable volume and is shown by the following equation:

$$V_t = \left(\frac{\pi}{40000}\right) * k * DBH^2 * H$$

where $k = \left(\frac{\beta_1}{3}\right) + \left(\frac{\beta_0}{2}\right) - (\beta_0 + \beta_1) + \left(\frac{\beta_2}{3}\right) a_1^3 + \left(\frac{\beta_3}{3}\right) a_2^3$

with joint points: $a_1 = \beta_4; a_2 = \beta_5$

DBH is diameter at breast height at 1.3 m from the ground

H is the total height of the tree from ground to top.

The Demaerschalk taper-volume function (Demaerschalk, 1973) gives the total utilisable volume of the tree up to a diameter of 5 cm under-bark:

$$V_t = \left(\frac{\pi}{40000}\right) * \left(\frac{\beta_0}{\beta_1 + 1}\right) * DBH^2 * H$$

where V_t is the total utilisable volume up to 5 cm

DBH is diameter at breast height at 1.3 m from the ground

H is the total height of the tree from ground to top

β_0 and β_1 are as given in Table 7

These tree volumes were then utilised to work out the average MAI of the stand:

$$MAI = \frac{\sum V_t/ha}{rotation\ age}$$

where V_t is the total utilisable volume of the trees

ha = total trial area in hectares

and rotation age is given in years.

In this trial stand growth was measured by the growth in stem volume and was expressed as utilisable volume produced per hectare. The survival thus also affect the volume production per hectare (Darrow, 1994, 1997; Dunlop *et al*., 2002).

The growth rate of trees can be expressed using the peak mean annual increment (MAI), which is a measure of the growth in m^3 or tons per annum per unit area, and thus provides an indication of which species utilised the site the most effectively. The peak MAI is based on the assumption of optimum rotation age. In this case, the peak

MAI is assumed to be at 10 years of age. This is considered realistic as the site index of the experimental site is 20.8.

The yield of the stand as a whole was measured by the summation of all individual tree volumes. The volume was then converted to a volume per hectare, and finally divided by the age of the rotation to get the MAI in m^3 ha^{-1} a^{-1}.

3.4.3 Coppice potential

The coppice potential of the stumps was tested over six replications on the dry site, with 96 single tree plots per replication.

During harvesting, the stumps were cut at 10 to 15 cm above the ground, as by ICFR recommendations (Little, 2000). If the stump is cut too low, too few shoots will grow, and if cut too high, shoots produced tend to break off.

During the harvesting process, care was taken not the damage the bark and top of the stumps. All logs were removed from the stump so as to not hinder resprouting. Lignotubers and epicormic buds are present around the top of the stump and below the bark. When the stump or bark is damaged, this inhibits the formation of coppice, and therefore caution must be taken during harvesting and extraction of the harvested trees to reduce the damage to the bark (Little, 2000). The harvest residue (bark and branches) was spread evenly over the compartment and kept off the stumps.

The compartment was felled during the rainy season in June 2016. The timing of harvesting is also important, as this affects the ability of the stumps to produce coppice.

The ability of the different hybrids to coppice was assessed by the following factors, in terms of Little and Gardner (2003):

3.4.3.1 Coppice potential

The coppicing potential was calculated as the presence of coppice and expressed as a percentage of living stems per plot prior to harvesting. The number of living trees after felling was assessed when the DBH and height measurements were taken for the resprouting shoots. All stumps that had one or more coppice shoots sprouting from them were measured as a coppiced stump.

3.4.3.2 Coppice distribution

Although the coppicing potential provides an indication of the presence of coppice, it does not provide a measure of the distribution of this coppice around the stump. The extent to which the coppice shoots were distributed around each stump was determined by dividing the circumference of the stump into quarters and recording the presence of coppice shoots in each (after Little, 2013)

A cross was made from wood and placed with the middle of the cross in the centre of the top of the stump. The top end of the cross always faced the tree north of the measured stump, the bottom end faced toward the southern tree next to the measured stump, etc. The quartiles were measured from 1 to 4, going clockwise from where 12 would be on a clock. The northern point of the cross would also correspond to the 12 ‘on the clock’.

The total number of shoots per stump was counted and this gave an indication of the vigour (amount) with which each hybrid produced shoots.

3.4.3.3 Biomass index

The biomass index (BI) was expressed in m^3 and provides a non-destructive measure of tree seedling performance (Eccles *et al*., 1997). This was used to give an indication of the size of the best coppice shoot on each stump for the different species. The dominant shoot was regarded as the coppice shoot with the greatest height. The height was measured from the top of the cut stump plane to the top of the shoot, using a telescopic height-measuring rod. The diameter was measured on the same plane as the stump cut surface using electronic callipers.

The biomass index (*BI*) is given by the following equation:

$$BI = d^2h$$

where h = height of the tallest shoot (measured from cut plane of stump);

d = diameter of tallest (dominant) coppice shoot (measured on the plane of the cut stump).

3.5 Presence of pest and insects

During the rotation of the trial, some insect damage was found on the trees tested. Three different insects were identified: *Eucalyptus* snout beetle (*Gonipterus scutellatus*), *Eucalyptus* gall/Blue Gum Chalcid wasp (*Leptocybe invasa*) and Bronze bug (*Thaumastocoris peregrinus*). Therefore the presence of these pests and insects could have an effect on the results of the trial. This is not the main focus of the trial and thus previous results from Botman (2010) and Noeth (2014) were included. No assessments were done by the researcher. Only results from Botman (2010) and Noeth (2014) were reported and discussed.

These insects/pests (excluding the Eucalyptus gall wasp) were initially identified by Botman (2010) and were further studied by Noeth (2014). Both studies focussed on the presence of these pests at the Coetzenburg and Backsberg trial sites, which are in close proximity to the Mariendahl trial (within 20 km).

Botman (2010) did a visual assessment of infestation levels on the different sites and gave infested trees a numerical rating of 0/1/3/5. Noeth (2014) also did a visual assessment of infestation, but samples were taken mid canopy. The samples taken were branches. Three branches were taken per plot at 4/6 m and then 30 leaves per branch were assessed visually at random for infestation with *Gonipterus scutellatus*, *Leptocybe invasa* and *Thaumastocoris peregrinus* and given a numerical score 0-5.

3.6 Statistical analysis

The data was tested statistically using STATISTICA. First, the data was tested for normality. When the data was normally distributed, the ANOVA (analysis of variance) test was done to test for differences in treatments or groups/populations. The ANOVA is a selection of statistical models in which variances are partitioned into different groups according to different explanatory variables. For an ANOVA to be done, data must be normally distributed and homogenous. Levene’s test was used to test for homogeneity (assessing the equality of variances for a variable calculated for two or more groups).

Least square means (LS means) tests were used to verify significance in the results obtained from the ANOVA. The Bonferroni and Duncan tests were also used to test for this.

If the data was not normally distributed, non-parametric testing was done on the data. The non-parametric test done was the Kruskall-Wallis test, which is the non-parametric alternative to one-way analysis of variance. The test compares population medians.

The non-parametric Games-Howell post hoc test was done to verify significance in the results obtained from the Kruskall-Wallis test.

Chapter 4: Results

The main outcome of this study was to assess the potential productivity of the various Eucalypt hybrids on a trial site at Mariendahl experimental farm, with the aim to extrapolate these result to other sites in the semi-arid Western Cape with a similar climate and water deficit. The results of the Mariendahl trial were based on single-tree plots in an alpha lattice design. The productivity was gauged by assessing the survival and upscaled basal area of the trees at the end of a rotation of 10 years. In addition, the coppice, survival and coppice volume growth after clear felling were assessed at nine months.

As explained in Chapter 3, we focused our analysis on (a) the taxa and provenances within *E. gxc* taxon and (b) all treatments (individual genotypes).

4.1 Survival

Tree survival was calculated from periodic DBH measurement datasets at 10 years of age. The survival was analysed on the level of main taxa, provenances (within the *E. gxc* taxon) and, finally, on a genotype level.

4.1.1 Main taxa

Tree survival was analysed with an ANOVA and it was found that there were significant differences in the survival of the taxa on the Mariendahl trial site ($p < 0.001$) at a 95% confidence interval (Figure 6).

The commercial *E. gxc* control had the highest average survival, at 90%. It had a significantly higher survival than the tested *E. gxc* and the controls of *E. cladocalyx* and *E. dunnii*.

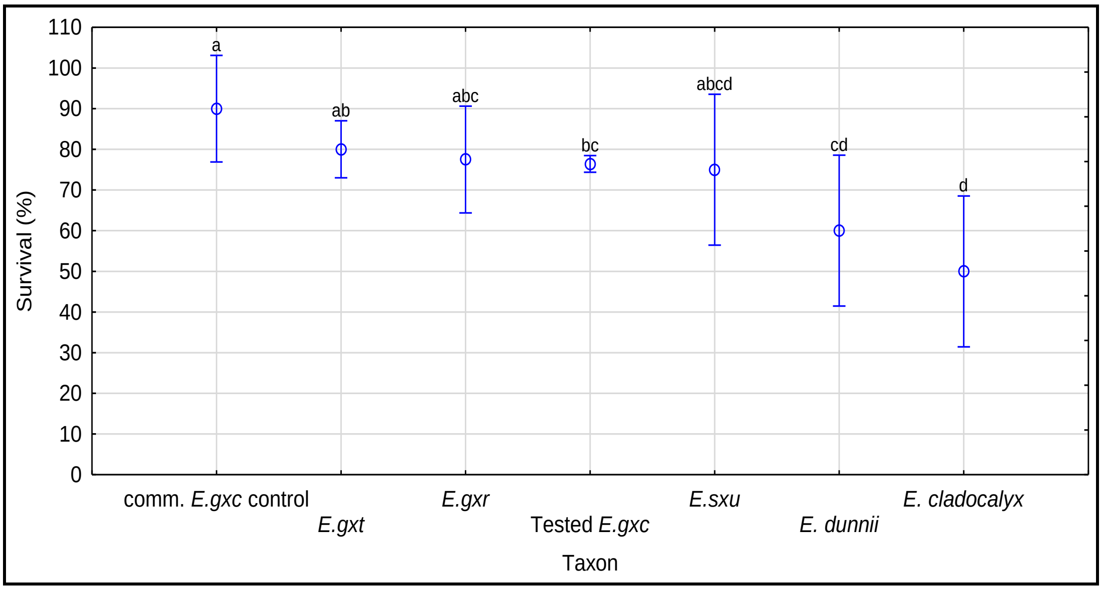


Figure 6: Survival percentages of taxa on the Mariendahl trial site with 95% confidence intervals. Different letters indicate significance (p < 0.05).

The controls of *E. cladocalyx* and *E. dunnii* had the lowest survival on the site, with survivals of 50% and 60% respectively.

E. gxt performed significantly better than the *E. cladocalyx* and *E. dunnii* controls in terms of survival. *Eucalyptus gxr* performed significantly greater in terms of survival than the *E. cladocalyx* control.

The *E. sxu* treatment had a very high variance and was not significantly different to any of the other taxa. The changes in survival of each taxon over the 10-year rotation are summarised in Figure 7. The survival was measured bi-annually.

It was observed that the *E. cladocalyx* had a high mortality at establishment and from year 2008 to 2010, but survival remained constant thereafter. *Eucalyptus dunnii* also had a high mortality after establishment, and declined further at a steady pace thereafter until the end of the rotation.

The commercial control of *E. gxc* had a low mortality after the first four years, and had a steady survival rate from 2010 until the end of the rotation. The other taxa also had a low mortality after establishment and their survival declined consistently until the end of the rotation (Figure 7).

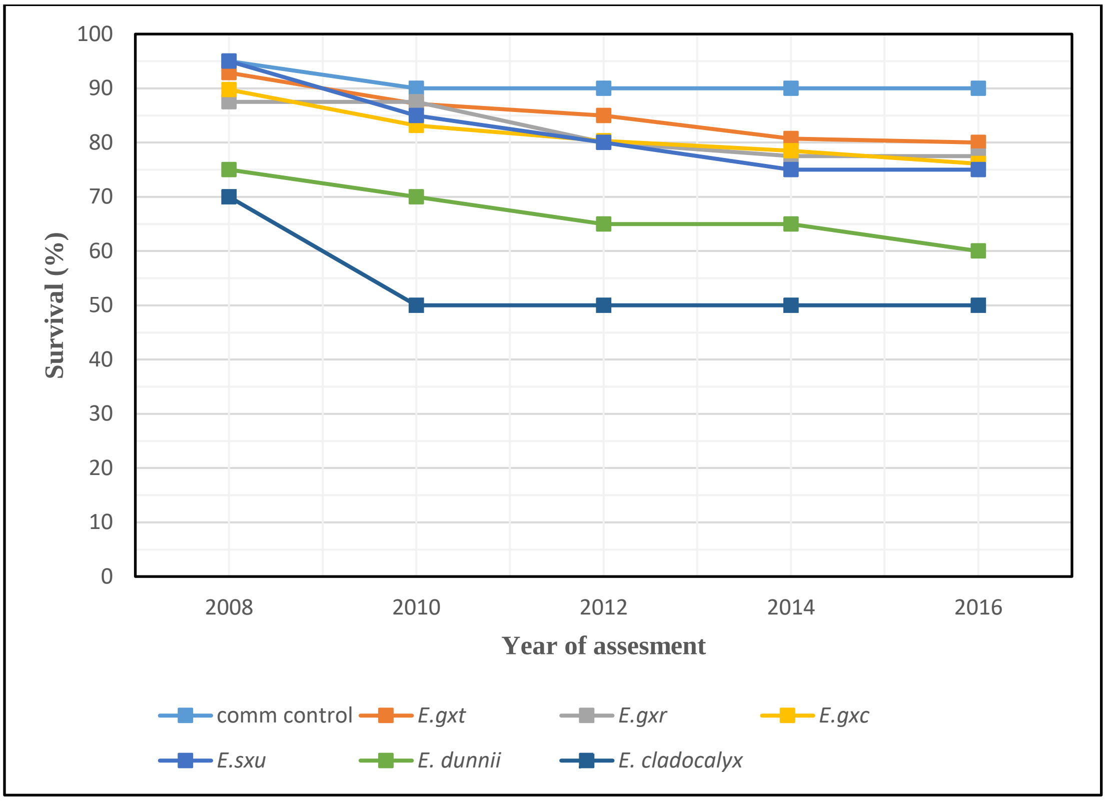


Figure 7: Survival percentage per taxon in the Mariendahl trial, assessed bi-annually.

4.1.2 *E. gxc* provenance

Within the taxon of *E. gxc,* several provenances were compared to the commercial control of *E. gxc*. Survival data was assessed by means of an ANOVA at a 95% confidence interval. There were significant differences among provenances (Figure 8).

The provenance of Yass was the best performer, at a 95% survival. It performed significantly better than the Morocco, Wiluna and De Grey provenances, at 73%, 65% and 62% respectively.

The De Grey provenance was the only provenance that performed significantly poorer than the commercial *E. gxc* control. None of the provenances performed significantly better than the commercial controls or the *E. gxc* (SA) seed.

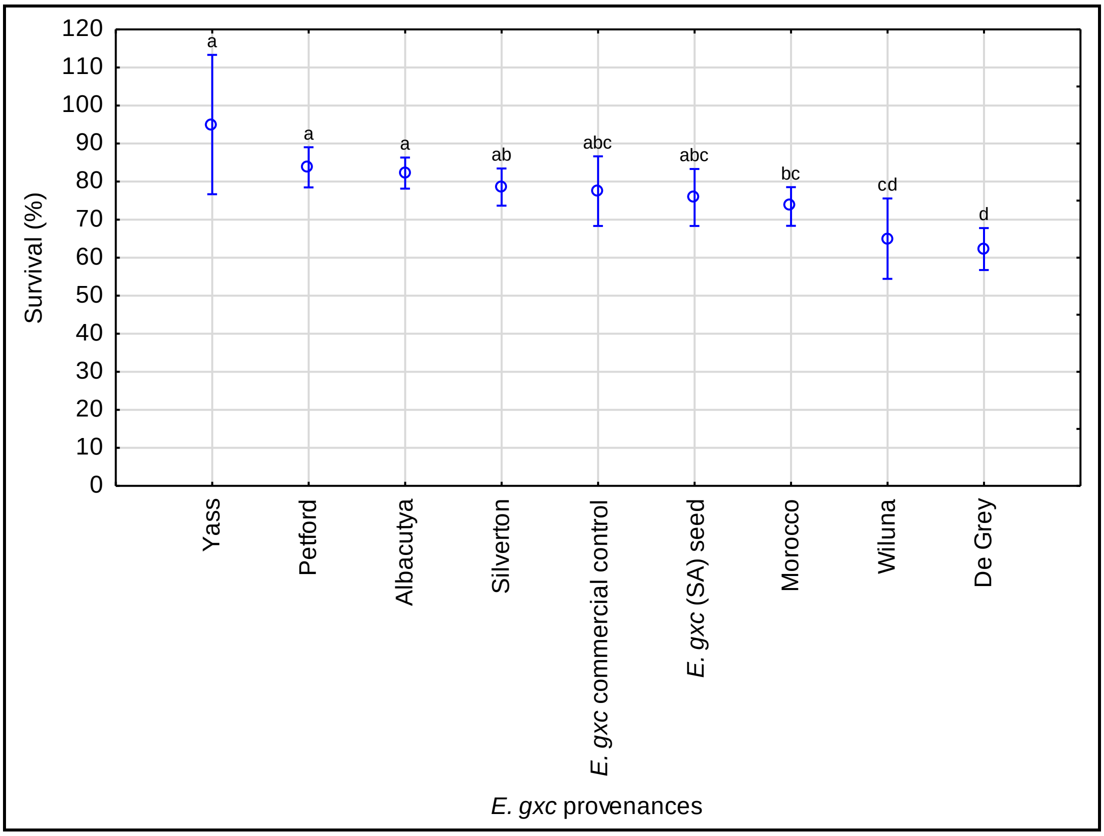


Figure 8: Survival percentages of E. gxc *provenances on the Mariendahl trial site, with 95% confidence intervals. Different letters indicate significance (p < 0.05).*

4.1.3 Genotype

There were significant differences between treatments (genotype) on a 95% confidence interval when an ANOVA was done (Figures 9 and 10).

The three genotypes with the best performance were treatments *E. gxc* (SA) seed G105xC40 (75), *E. gxc* Albacutya SGR16xSTB-4 (11) and *E. gxc* Albacutya G039xSTB-4 (8), with a 100% survival rate. The top three treatments were all from the taxon *E. gxc*, with one being the *E. gxc* (SA) seed and the other two of the Albacutya provenance.

The top 48 treatments (except for Treatment 6) had a survival rate of 80% or more (Figure 9).

The treatment of *E. gxc* De Grey SGR412xSTB-5 (26), *E. gxc* De Grey G050xSTB-7 (22) and G107xSTB-1 (35) were the poorest performing treatments. The poorest performing treatment was *E. gxc* Morocco G107xSTB-1 (35), with a survival of 15%, which was significantly lower than all the treatments barring treatments 22 and 26. The latter two treatments (both *E. gxc* De Grey) had a survival rate of 40%.

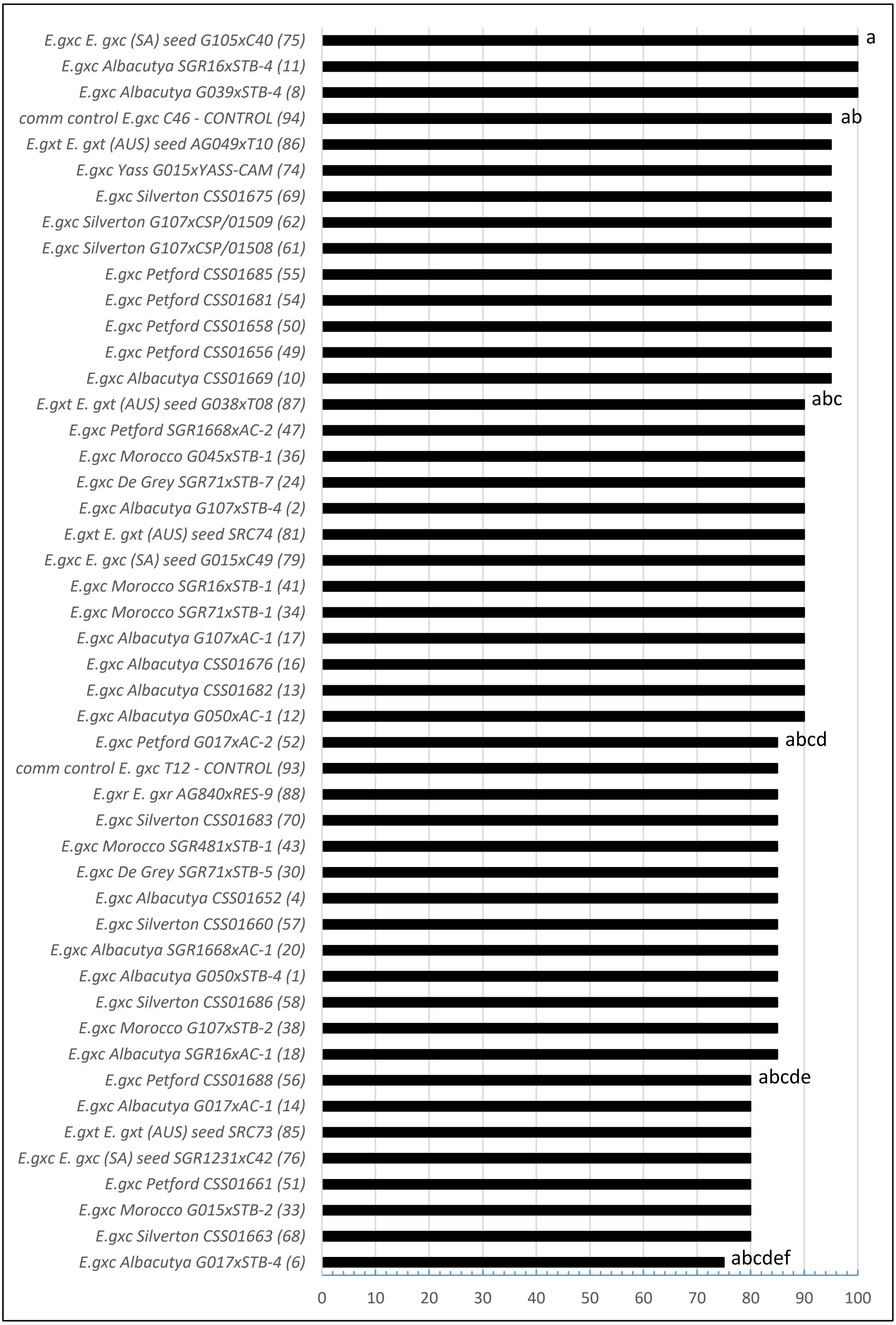


Figure 9: Ranking of survival (%) per genotype on the Mariendahl trial site with significance letter codes.

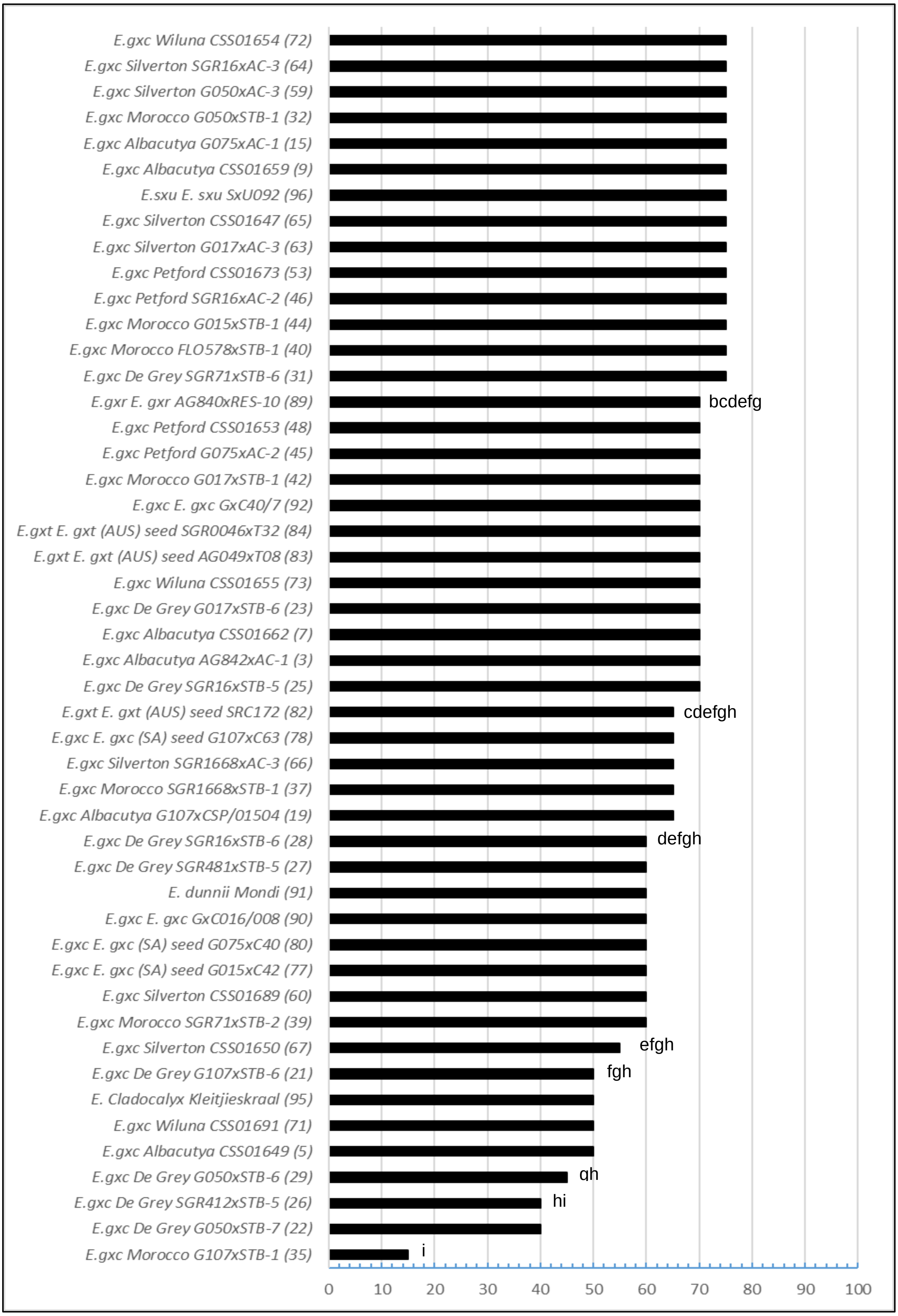


Figure 10: Ranking of survival (%) per genotype on the Mariendahl trial site with significance letter codes (continued).

4.2 Upscaled basal area

The average Upscaled basal area is a measure of the potential growth of trees over time, and thus of their productivity. The upscaled basal area was analysed on a taxon, provenance (within the *E. gxc* taxon) and on a genotype (treatment) level. The reader is again referred to Section 3.3.2.1, where the term upscaled basal area is described.

4.2.1 Taxa

The dataset for potential basal area was not normally distributed, and thus a Kruskall-Wallis test was applied to test for differences between locations on a 95% confidence interval. A significant p-value ($p < 0.01$) indicated that there were differences between average potential basal area of the tested taxa on the Mariendahl trial site (Figure 11).

The taxon of *E. gxr* had the highest average potential basal area, at 38.8 m^2 ha^{-1}. *E. gxr* was followed by *E. gxt* and tested *E. gxc*, at 32.0 m^2 ha^{-1} and 31.3 m^2 ha^{-1} respectively.

The taxa of *E. gxr*, *E. gxt* and tested *E. gxc* had a significantly higher average potential basal area than the controls of *E. gxc*, *E. dunnii* and *E. cladocalyx*, with average potential upscaled basal areas of 14.9 m^2ha^{-1}, 14.0 m^2ha^{-1} and 13.1 m^2ha^{-1} respectively.

The taxon of *E. sxu* was not significantly different to any of the taxa in the trial.

4.2.2 *E. gxc* provenance

There were significant differences between provenances on a 95% confidence interval when a Kruskal-Wallis was done. The Kruskall-Wallis test provided a significant p-value ($p < 0.001$).

There therefore were significant differences between the average upscaled basal areas of the *E. gxc* provenances (Figure 12).

The Albacutya Provenance had the greatest average upscaled basal area, at 37.2 m^2 ha^{-1}; that was significantly greater than all the provenances and controls, excluding Yass and Wiluna, at 36.0 m^2 ha^{-1} and 33.3 m^2 ha^{-1} respectively.

The Yass provenance had a very high variance and was only significantly different from *E. cladocalyx*. Wiluna was significantly larger than the controls of *E. cladocalyx* and *E. dunnii*, which were at 14.0 and 13.1 m^2 ha^{-1} respectively.

The average upscaled basal area of the provenance of Morocco (30.8 m^2 ha^{-1}) was significantly larger than that of Petford (25.6 m^2 ha^{-1}) and all three controls.

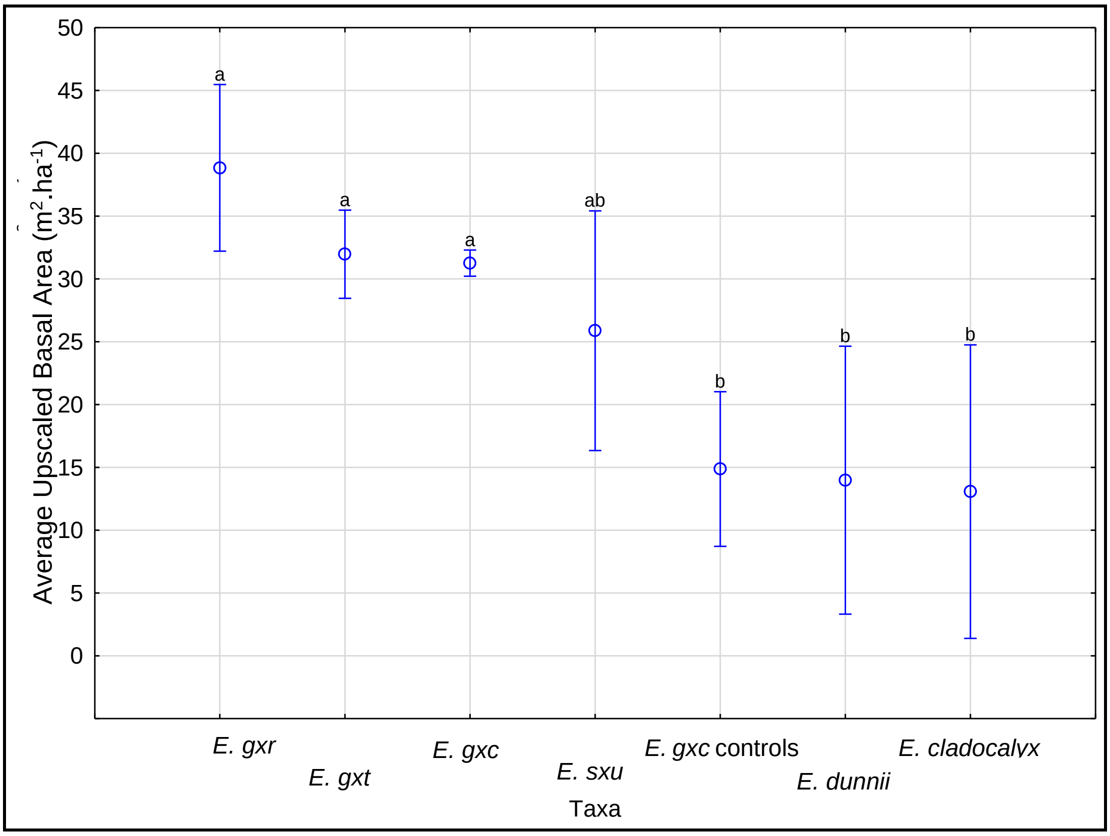


Figure 11: Average upscaled basal area per taxa on the Mariendahl trial site with 95% confidence intervals. Different letters indicate significance (p < 0.05).

The Silverton (29.8 m^2 ha^{-1}) and De Grey (29.4 m^2 ha^{-1}) provenances were significantly larger than the controls.

The upscaled basal area of the *E. gxc* (SA) seed (28.4 m^2 ha^{-1}) was not significantly higher than the *E. gxc* commercial control, at 21.0 m^2 ha^{-1}, but significantly higher than the *E. cladocalyx* and *E. dunnii* controls. The Petford provenance was only significantly higher than the control of *E. dunnii*.

There were no significant differences in the upscaled basal area between the three controls (Figure 11).

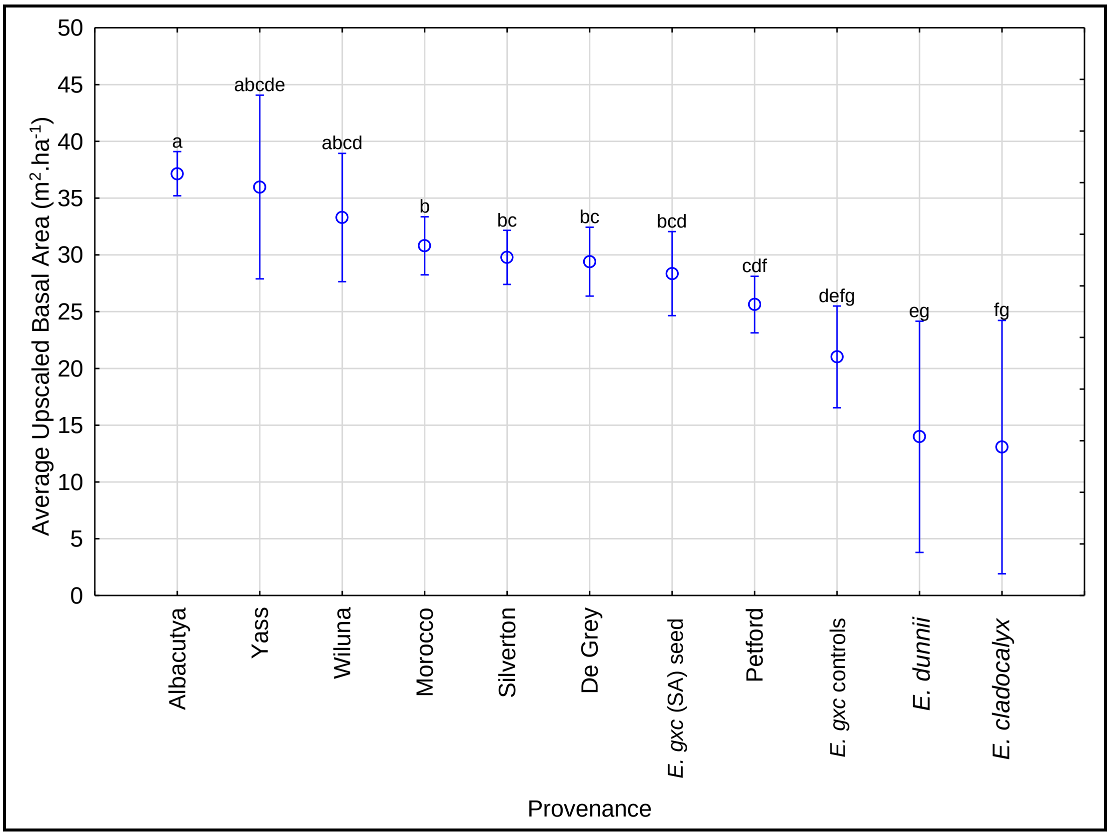


Figure 12: Average upscaled basal area of E. gxc provenances on the Mariendahl trial site with 95% confidence intervals. Different letters indicate significance (p < 0.05)

4.2.3 Genotypes

When the upscaled basal area data per genotype was tested with the Kruskall-Wallis test, a significant result was found ($p < 0.05$). There were thus significant differences among several genotypes in the Mariendahl trial.

The average upscaled basal area estimates per genotype (treatment) are ranked in Figures 13 and 14. The genotypes to take note of would be the top 20 genotypes. The upscaled basal area of the top 20 genotypes was compared with the three control genotypes, and significant differences were found. These are indicated in Figures 13 and 14, with significant lettering only for these genotypes.

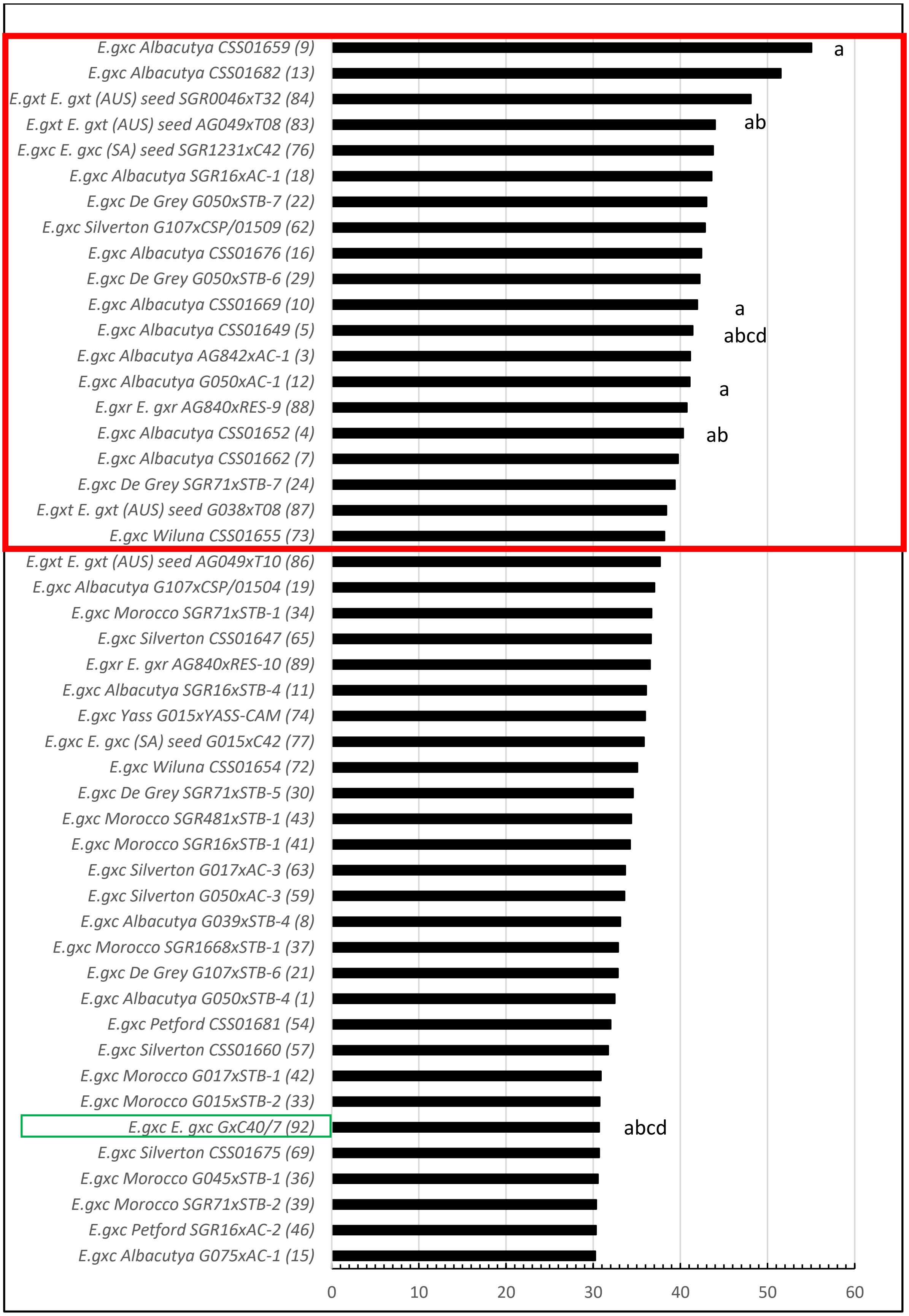


Figure 13: Average upscaled basal area ranking per genotype in the Mariendahl trial, with significant letters for top 20 genotypes with 95% confidence intervals. Different letters indicate significance ($p < 0.05$).

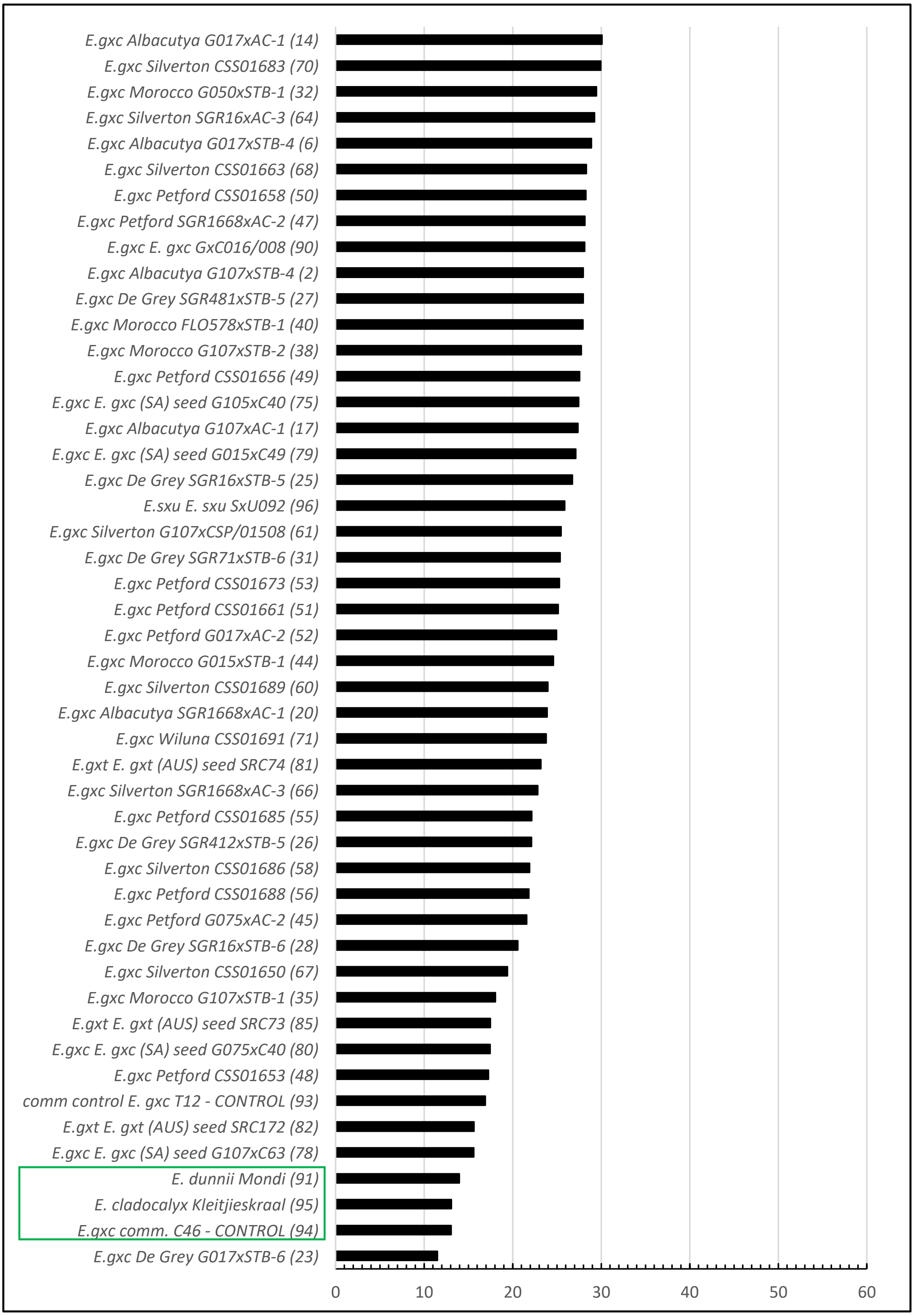


Figure 14: Average upscaled basal area ranking per genotype in the Mariendahl trial, with significant letters for top 20 genotypes with 95% confidence intervals. Different letters indicate significance ($p < 0.05$) (continued).

4.2.4 Total volume on the Mariendahl trial site

It was decided that the total volume growth in terms of total volume per hectare and MAI should be included in the study. The volume growth was included to give an indication of the growth on the trial site, with a specific DEF to give an indication of what growth could be reached on this semi-arid "+" site with a DEF of 322.5 mm.

A total volume per hectare of 170.24 m^2 ha^{-1} was achieved for the Mariendahl trial site, and the average MAI was 17.02 m^2 ha^{-1} a^{-1}.

The mean growth of the trial was used, rather than growth on a taxon, provenance or genotype level, to avoid under- or overinflated volumes arising from the single-tree plot design (see Section 5.1 in Discussion).

4.3 Coppice potential

4.3.1 Coppicability

The coppicability refers to the stumps still alive after harvesting and producing coppice. This is measured as a percentage. The coppicability was measured at a genotype level. There were no significant differences among the treatments. The treatments were therefore ranked according to performance (Figures 15 and 16).

The top 47 genotypes had a coppicability of greater than 75%. The genotypes of *E. gxt* (AUS) seed AG049xT10 (86), *E. gxc* (SA) seed G105xC40 (75), *E. gxc* Petford CSS01681 (54) and *E. gxc* Albacutya SGR16xSTB-4 (11) had the highest coppicability, at 100%. The two best performers (genotypes 86 and 75) were both produced from seed.

The genotypes of *E. cladocalyx* Kluitjieskraal (95), *E. gxc* De Grey SGR412xSTB-5 (26) and *E. gxc* Morocco G107xSTB-1 (35) were the worst performing genotypes, with coppicability scores of 25, 25 and 23 respectively (Figure 16).

The controls of *E. gxc* C46 - CONTROL (94) and *E. gxc* T12 - CONTROL (93) performed well with regard to coppicability, lying in the top five and top 10 at 90% and 88% respectively.

The *E. sxu* SxU092 (96) genotype was within the bottom 50% of treatments, whereas *E. gxr* AG840xRES-10 (89) was within the bottom 50% and *E. gxr* AG840xRES-9 (88) was in the top 50%. Two of the *E. gxt* genotypes made it into the top 50% of treatments (Figure 15).

4.3.2 Distribution of coppice stems

The number of stems per quartile was measured per stump and taxa, and statistically analysed using least square means. There was no significant effect of taxa on stems per quartile at $p = 0.957$ ($p > 0.05$).

There were no species or quartiles that had any significant differences.

4.3.3 Total shoots per stump

The statistical data for the number of shoots per stump was significantly different among treatments ($p < 0.05$) when a Kruskall-Wallis test was done (Figures 17 and 18).

The genotype with the highest number of shoots per stump was *E. gxc* Silverton G107xCSP/01509 (62). This was followed by *E. gxc* Albacutya CSS01676 (16), *E. gxc* Morocco SGR16xSTB-1 (41), *E. gxc* Morocco G017xSTB-1 (42) and *E. gxc* Albacutya G039xSTB-4 (8).

The two genotypes of *E. gxr* were represented in both the top (89) and bottom (88) 50%.

The *E. gxt* genotypes of *E. gxt* (AUS) seed AG049xT08 (83) and *E. gxc* (SA) seed G107xC63 (78) were in the top 50%, while *E. gxt* (AUS) seed SGR0046xT32 (84), *E. gxt* (AUS) seed SRC74 (81), *E. gxt* (AUS) seed SRC73 (85), *E. gxt* (AUS) seed AG049xT10 (86) and *E. gxt* (AUS) seed SRC172 (82) were in the bottom 50%.

The genotype of *E. sxu* SxU092 (96) was in the bottom 50%.

The controls of *E. gxc* GxC40/7 (92), *E. gxc* T12 - CONTROL (93) and 95 (*E. cladocalyx*) were also present in the top 50% of treatments.

4.3.4 Biomass index

An analysis of variance revealed that there were no significant differences ($p > 0.05$) between the treatments with regard to biomass index. Therefore, genotype was ranked from largest to smallest (Figures 19 and 20).

The *E. gxc* Morocco SGR71xSTB-2 (39), *E. gxc* De Grey G017xSTB-6 (23) and *E. gxc* De Grey G050xSTB-6 (29) were the top three genotypes, at 0.0085, 0.006 and 0.0055 m^3 respectively, followed by *E. gxc* Albacutya CSS01669 (10) and *E. gxc* Morocco G050xSTB-1 (32), at 0.0054 and 0.0053 m^3 respectively.

The genotype of *E. gxc* (SA) seed SGR1231xC42 (76) was the poorest performing genotype, followed by *E. gxt* (AUS) seed SRC74 (81) and *E. gxc* Morocco G107xSTB-1 (35), at 0.0008, 0.0009 and 0.001 m^3 respectively.

The genotypes of *E. gxr* performed well, with both treatments in the top 25% of treatments. The genotypes of *E. gxc* (SA) seed G107xC63 (78) and *E. gxt* (AUS) seed AG049xT10 (86) were ranked in the top 50% of treatments, while the treatments of *E. gxc* (SA) seed SGR1231xC42 (76) and *E. gxt* (AUS) seed SRC74 (81) were ranked as the poorest performing treatments. The reader is reminded that the rankings described here were not statistically significant.

The controls of *E. gxc* GxC40/7 (92) and *E. sxu* SxU092 (96) were ranked in the top 20 treatments, while *E. gxc* T12 - CONTROL (93) and *E. cladocalyx* Kluitjieskraal (95) were ranked in the top 50% of genotypes (treatments).

The commercial controls of *E. dunnii* (91) and *E. gxc* C46 - CONTROL (94) were within the bottom 50% of treatments.

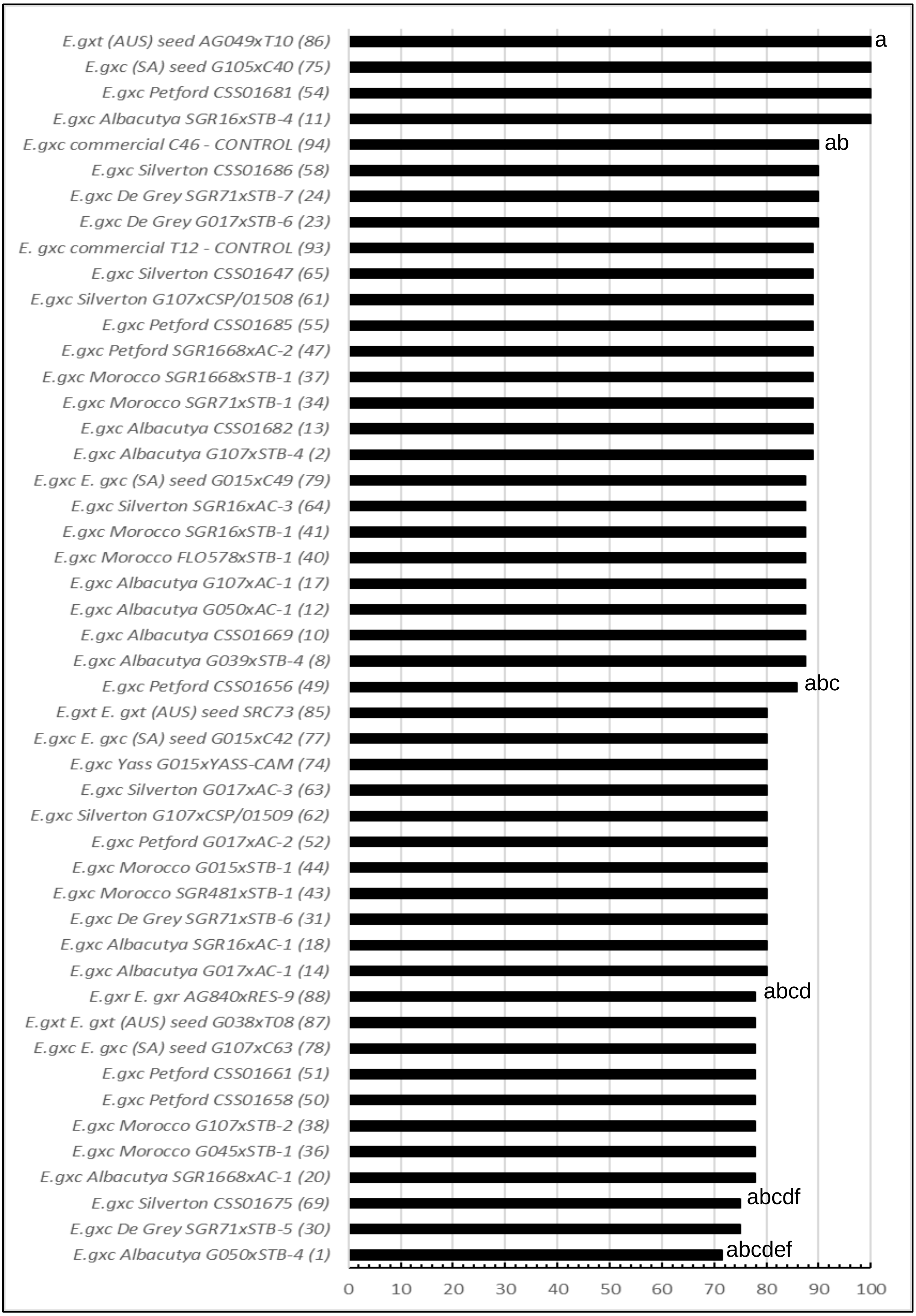


Figure 15: Ranking of coppicability at the Mariendahl trial site with 95% confidence intervals. Different letters indicate significance ($p < 0.05$).

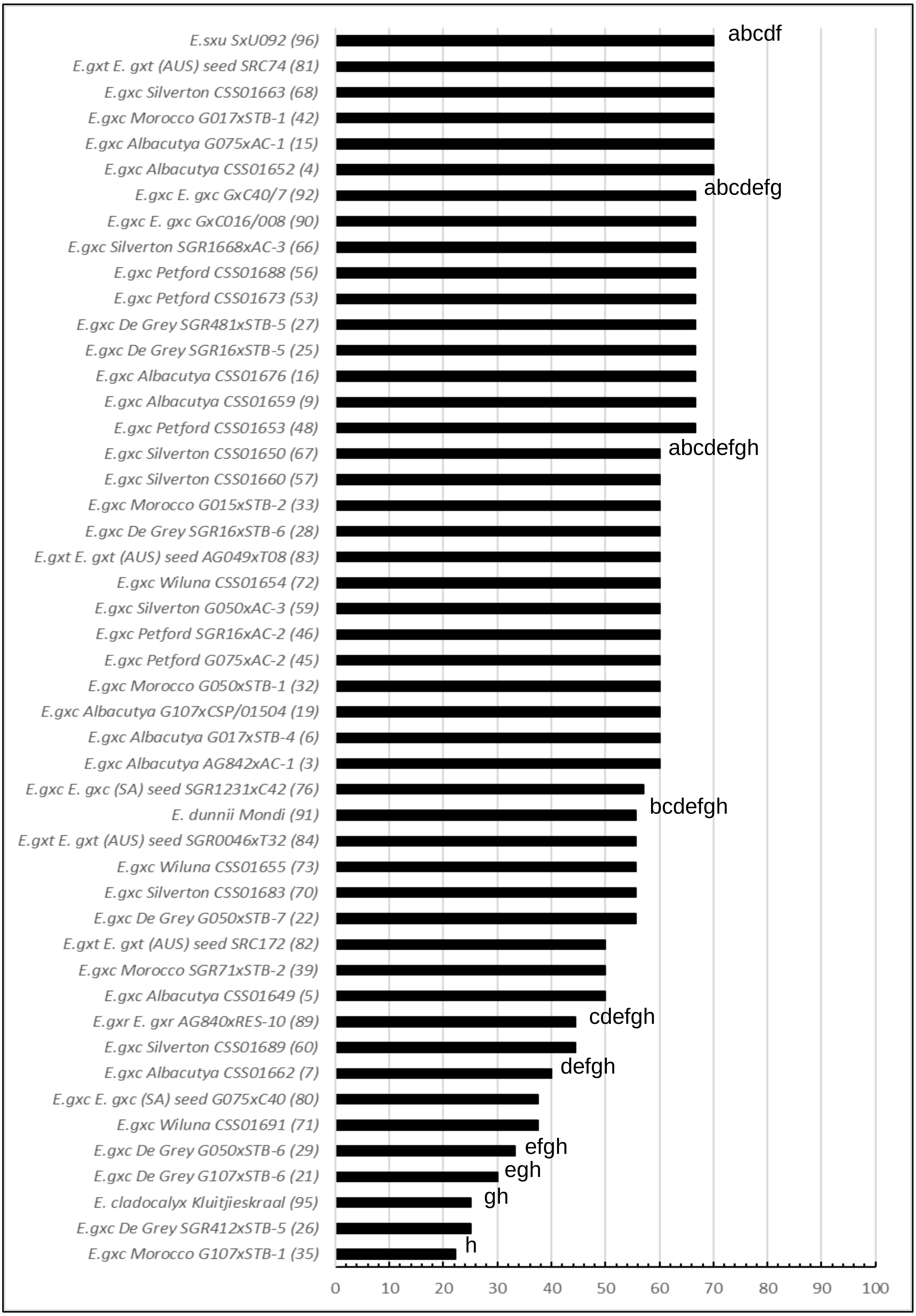


Figure 16: Ranking of coppicability at the Mariendahl trial site with 95% confidence intervals. Different letters indicate significance ($p < 0.05$) (continued).

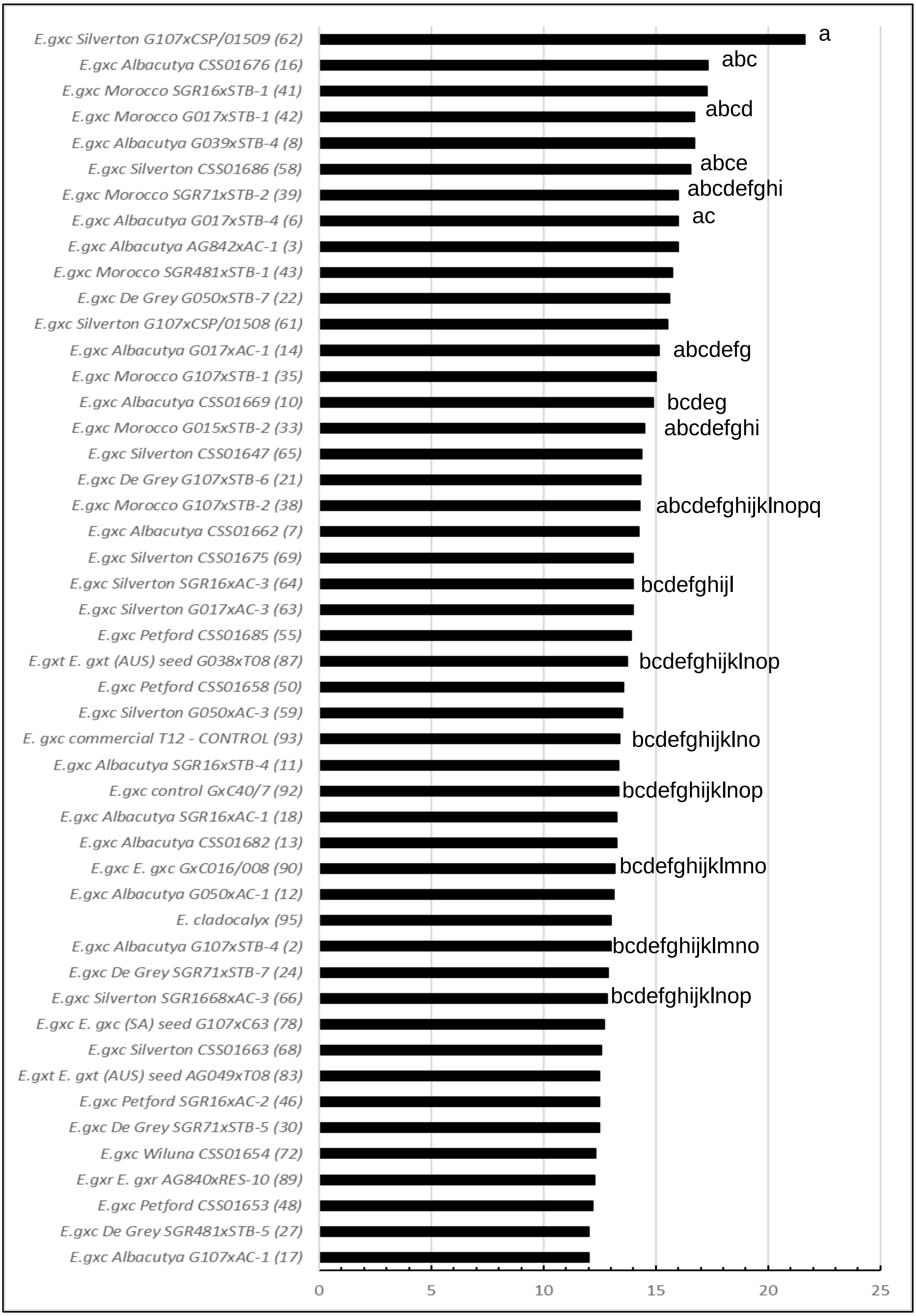


Figure 17: Ranking of the number of coppice shoots per stump with 95% confidence intervals. Different letters indicate significance ($p < 0.05$).

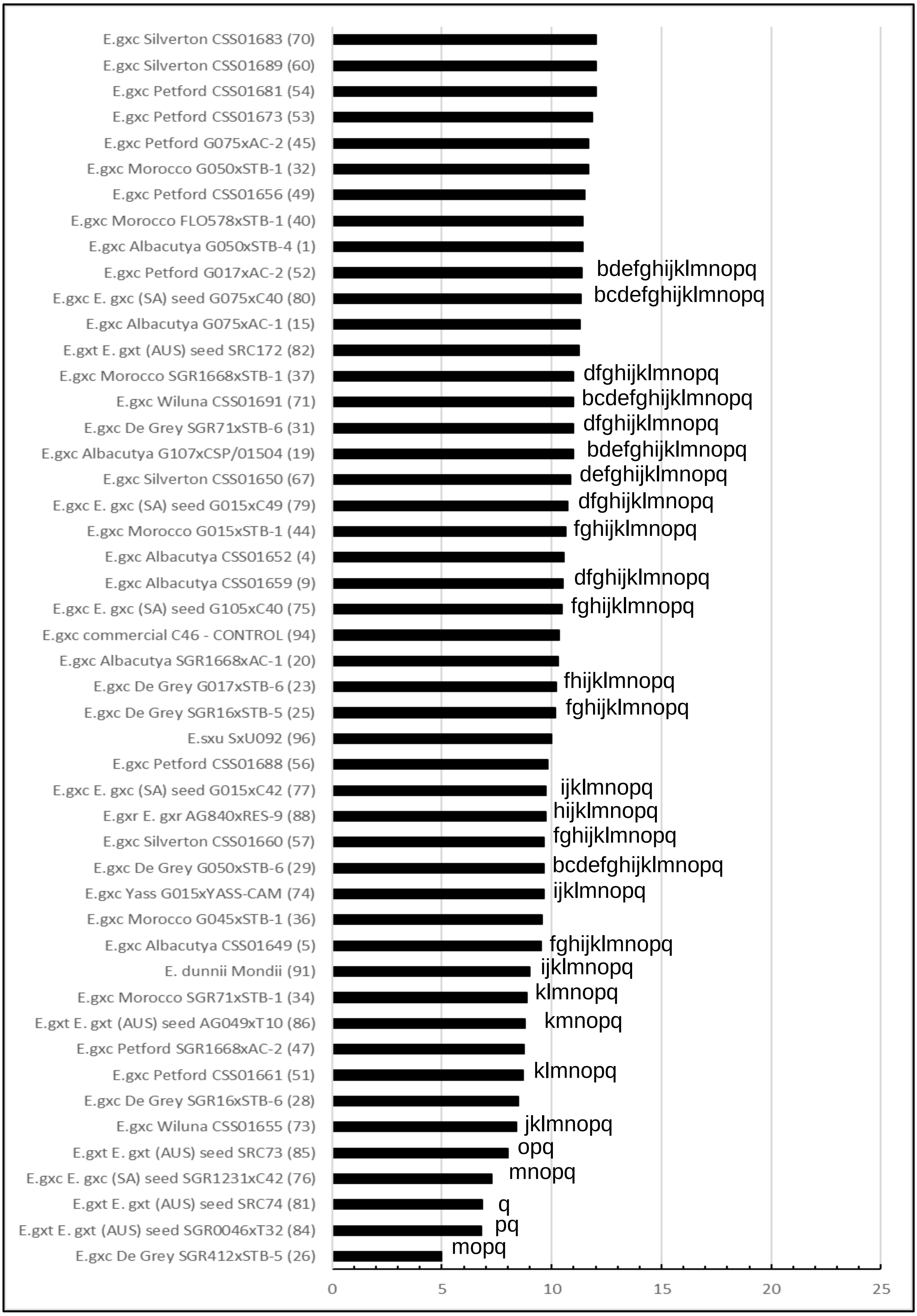


Figure 18: Ranking of the number of coppice shoots per stump with 95% confidence intervals. Different letters indicate significance ($p < 0.05$) (continued).

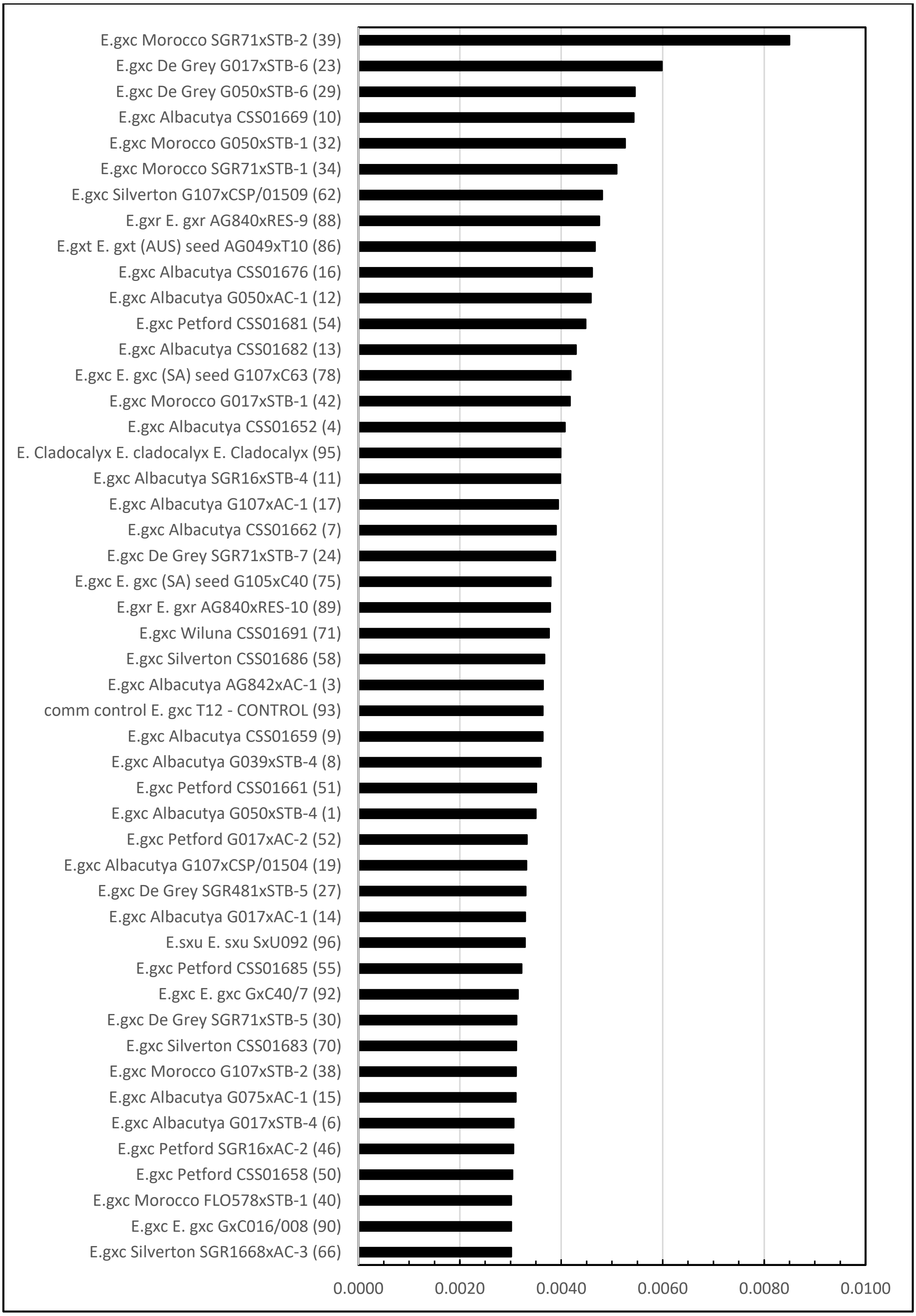


Figure 19: Ranking of biomass index per genotype at the Mariendahl trial site.

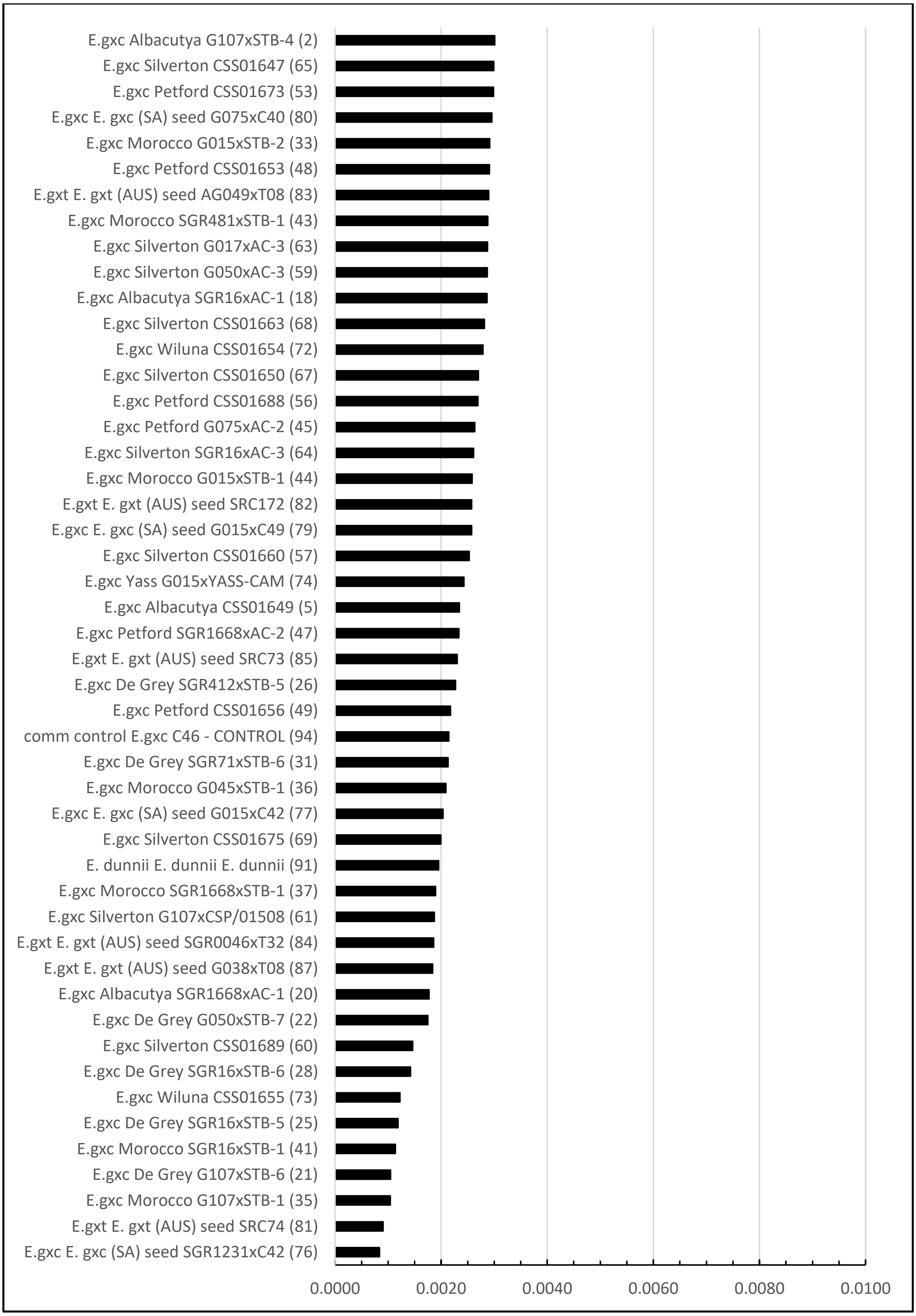


Figure 20: Ranking of biomass index per genotype at the Mariendahl trial site (continued).

4.4 Presence of pests at trial site

It is important to consider the effects of ALL pests and insects on the trial result simultaneously. The Eucalyptus snout beetle would have had an effect on the trees from the establishment of the trial until the end of the trial (Table 6), as it has been present in South Africa since 1916, when it was first identified (Rivera *et al*., 1999). Noeth Botman

Table 6: Summary of the presence of insects/pest at the Mariendahl trial site

Insect/pest common name	**Scientific name**	**Year identified in South Africa**	**Present at stage of trial**			
			2006	**2012**	**2016**	**Coppice**
Eucalyptus snout beetle	*Gonipterus scutellatus*	1916 (Rivera, *et al*., 1999)	Y	Y	Y	Y
Eucalyptus gall wasp	*Leptocybe invasa*	2007 (Slippers, 2010)	N	N	N	Y
Bronze bug	*Thaumastocoris peregrinus*	2003-2005 (Jacobs & Neser, 2005). In Cape by May 2006 (Nadel *et al*., 2010	?	HL	Y	Y

Y = yes N = no HL = highly likely

The Bronze bug was first discovered in South Africa in 2003 (Table 6), and it has been found to have caused significant damage to plantations of *Eucalyptus* spp. in the Gauteng, Mpumalanga and North West provinces since then (Jacobs & Neser, 2005). A quote from Nadel *et al*. (2010) states:

> “Between 2005 and 2006 *T. peregrinus* spread throughout South Africa, infesting 26 *Eucalyptus* species. By mid-2006, it was found as far north as the Soutpansberg, Limpopo province, ±400 km north of Pretoria (since August 2005) and as far south as Cape Town, Western Cape Province, ±1,450 km south of Pretoria (since May 2006).”

The presence of *Leptocybe* was discovered for the first time in South Africa in Pretoria in 2007, and it spread from there. It was identified in northern KwaZulu-Natal at the end of 2009 (Slippers, 2010). It was first identified in the Mariendahl trial during the coppice biomass measurements nine months after harvesting. Therefore it is highly unlikely that it had an effect on the volume production on the site, but it could have in the establishment of future *Eucalyptus* stands.

The incidence of Bronze bug was found to have a great effect on the production volume and also on economic return when compared to stands without the presence of this pest (Holmes *et al*., 2009; Nadel *et al*., 2010).

Chapter 5: Discussion and Conclusion

5.1 Comparison of single-tree (STP) versus multi-tree plots (MTP)

The Mariendahl trial design was laid out in single-tree plots. In a plantation environment with identical genotypes, the resources between the trees are shared equally by all the trees (similar to multi-tree plot-design conditions), and therefore the production of all the trees is evenly constrained. However, in a competition environment with differing genotypes, the sharing of resources is not equal due to plants being of different genetic material (such as single-tree plot-design conditions). As the trees produce more volume in a closed stand, the bigger trees use more of the resources, to the disadvantage of the smaller trees, and differences in the production of the highly competitive trees and small trees become greater (Ford, 1975; Stern, 1969). The faster growers in a competitive environment are the strongest competitors, according to Stanger *et al*. (2011).

There have been few trials to study the difference in results between a single-tree and a multiple-tree trial design. Single-tree plots are often used in genetic testing in tree-breeding programmes, and it is often argued that multiple-tree plots can express actual production traits more accurately (Jansson *et al*., 1998). Few comparisons have been found between MTP and STP based on volume per unit area.

Magnussen (1989) tested the effects of competition bias in progeny trials with single-tree plots and found that they provide reliable rankings of family performance, even in the presence of severe competition. Tuskan and Williams (1989) compared the plot designs for short-term genetic trials and found that plot design had no effect on the family mean ranking. They concluded that competition adversely affected growth, but there were no considerable changes in family rankings across plot designs. It was also reported by Loo-Dinkins and Tauer (1987) that multiple single-tree plots compared to row or block plots had higher statistical value on uniform sites.

Jansson *et al*. (1998) studied the correspondence between single-tree and multiple-tree plot genetic tests for production traits in *Pinus sylvestris* and found a strong genetic correlation between expressions of growth traits from single-tree plots and volume production per unit area. They also found that the efficiency based on the correlated responses was higher for single-tree plots than for multiple-tree plots.

In contrast to this, Stanger *et al*. (2011) tested the effect of plot size on *Eucalyptus* hybrid clonal ranking in coastal Zululand in South Africa. They used single-tree, line and square plots in the study and found that the overall means for the three different plot types were very similar. However, Stanger *et al*. (2011) state:

> "The range of the clonal means for tree volume in the single-tree plots (0.4042 m^3) is more than five times the range for the square plots (0.0709 m^3). Gain predictions using data from the single-tree plots overestimated the realised gains measured in the square plots. The top-performing clone in the single-tree plots had a predicted gain of 74% over the trial mean, but only yielded 7% more in the square plots. Similarly, the worst-ranked clone in the single-tree plots did not perform as poorly as what was predicted (-59%) and produced only 13% less than the trial mean on the square plots."

Stanger et al. (2011) found that, even though the means for tree volume differed slightly between the single and line plot designs, the clonal rankings were very similar, with only one rank change. They also mention that the result might have been hampered by the selected nature and limited number of the clones included in this study. The trial was also restricted to a single site, and therefore the results must be interpreted cautiously.

Therefore, production results may be overestimated, but ranking should give a good indication of which taxa, provenance and genotype are the best suited to be planted on similar sites. Trial means in terms of volume per hectare and MAI could give a better indication of the potential of the trial site.

5.2 Survival

5.2.1 Taxon

The survival from the results on the Mariendahl trial site (see Figure 6, Section 4.1.1) show that the tested taxa outperformed most of the commercial controls of *E. cladocalyx* and *E. dunnii* in the semi-arid (+) climatic zone (AI = 0.42). The commercial controls of *E. gxc* had the highest survival rate on the trial site. This is in stark contrast with the controls of *E. cladocalyx* and *E. dunnii*, which had a high initial mortality during the first two years after establishment, with a survival of 50% and 60% respectively (Figure 7, Section 4.1.1). The survival of *E. cladocalyx* was similar to the survival (58%) obtained at the dry Darling semi-arid site (AI=0.36) by Botman (2010), but this result is even lower on the Mariendahl trial site, whereas on the Coetzenburg site (AI= 0.64), survival ranged between 70 and 97% and on the Backsberg site (AI = 0.68) it was 79%. Botman (2010) found that *E. cladocalyx* performed better on the wetter sites (with higher AI). Therefore, it is unusual that *E. cladocalyx* did not perform well on the Mariendahl trial site. *E. cladocalyx* did not perform well compared to the previous findings in the semi-arid (Du Toit *et al*., 2017) and dry sub-humid (Botman, 2010) regions. Botman (2010) showed that *E. cladocalyx* was able to outperform *E. gomphocephala* in the sub-humid region of the Western Cape (Coetzenburg trial, AI = 0.64), but that it was inferior to *E. gomphocephala* in the semi-arid zone (Darling trial, AI = 0.36). Du Toit *et al*. (2017) suggested that *E. cladocalyx* will only be productive in the wetter section of the semi-arid zone ('Semi-arid +'), especially on low-lying sites where it has access to groundwater. This suggests that *E. cladocalyx* should have performed better on this site.

The poor survival of *E. cladocalyx* and *E. dunnii* may in part be due to the more rapid growth of the hybrids when compared to the pure species (Botman, 2010; Malherbe *et al*., 2015), and therefore there is increased competition from the faster growing hybrids utilising the site resources more effectively and thus suppressing these controls.

E. cladocalyx and *E. dunnii* both experienced high mortality within the first two years of establishment. Thereafter, the survival of *E. cladocalyx* remained constant throughout the trial, and *E. dunnii* decreased consistently (Figure 7 in Section 3.3.1). This high mortality in the first four years was possibly due to an event at establishment. A sulphur deficiency was observed shortly after establishment, but due to the decreased severity of the deficiency observed over the course of the spring months, it was not specifically treated. This may have led to the further suppression of the controls of *E. cladocalyx* and *E. dunnii*.

The consistent survival of *E. cladocalyx* from age four onwards shows that it is suited to the area, whereas the decrease in survival rate of the *E. dunnii* points to the fact that it is not suited to the site, hence the constant mortality.

E. dunnii would be considered an off-site planting due to very low survival and also needing a minimum precipitation of 822 mm (Herbert, 2000). Du Toit *et al*. (2017) observed survival rates of between 55% and 85% on the wetter sites of the semi-arid Mediterranean sites of South Africa for *E. cladocalyx*, which is in line with the results of the current study.

The survival rates on the Mariendahl trial site show that most of the taxa are suited to the semi-arid (+) climatic zone. The commercial *E. gxc* controls outperformed all the tested hybrids and controls, with a survival rate of 90%, although its performance was not significantly higher than the taxa of *E. gxt* (80%) and *E. gxr* (78%) (Figure 6, Section 4.1.1). The commercial control of *E. gxc* significantly outperformed the tested *E. gxc*. This could probably be attributed to the controls coming from previous research studies with improved genetic materials, versus the tested taxon, which is a combination of different *E. gxc* provenances, some of them from non-improved seedlots.

All the hybrids also had survival greater than that of the controls of *E. cladocalyx* and *E. dunnii*. This is in line with observations by Botman (2010) and Malherbe *et al*. (2015), who found that the *Eucalyptus* hybrids performed better than the pure species in the Western Cape.

All the hybrids tested are well suited to the site, with a survival greater than 75%, and are thus well suited to the semi-arid (+) climatic rage in the Western Cape when measured in terms of survival rate. It is of further interest how the different provenances of *E. gxc* performed on the Mariendahl trial site, due to the large number of treatments relating to this taxon (see Section 4.1.2).

5.2.2 *E. gxc* provenance

The survival rates of the *E. gxc* provenances on the Mariendahl trial site (Figure 8, Section 4.1.2) show that most of the provenances are suited to the semi-arid (+) climatic zone. The *E. gxc* provenance of Yass had the highest survival, at 95%, while De Grey had the lowest survival, at 62%. The provenances of Yass, Petford, Albacutya, Silverton, the *E. gxc* commercial controls and *E. gxc* (SA) seed had a survival higher than 75%. All provenances with a survival of 75% or higher were significantly higher than the provenances of Morocco, Wiluna and De Grey.

The eastern Australian provenances of Yass, Petford, Albacutya and Silverton were the top-ranking provenances, while the worst performers were the western Australian provenances of Wiluna and De Grey, which had a survival rate of 65% and 62% respectively. Typically, the eastern provenances are at the higher end of the AI and the western provenances at the lower end, and therefore the wetter provenances performed better in the semi-arid (+) region than the drier provenances.

5.2.3 Individual Genotypes

The survival rates of the *E. gxc* provenances on the Mariendahl trial site show that most of the provenances are suited to the semi-arid (+) climatic zone (Figures 9 and 10, Section 4.1.3). The top three genotypes – two of the *E. gxc* Albacutya provenances and the other *E. gxc* (SA) seed – had a 100% survival rate, while the bottom three were two *E. gxc* De Grey (40%) and an *E. gxc* Morocco (15%). The Albacutya provenance was found to be well suited to the semi-arid climate.

The top 50% of genotypes had a survival rate higher than 80%, and the top 63 genotypes had a survival rate greater than 75%. The survival rates again provide evidence that the eastern Australian provenances generally perform better than the western Australian provenances and the Moroccan provenance.

5.3 Upscaled Basal Area as indicator of growth vigour

5.3.1 Growth vigour between broad taxa

The upscaled basal area was used as the main criterion to rank genotypes and to select top performers. It gives a more accurate representation of the growth potential of the species on the site. The average upscaled basal area ranged from 13 to 39 m^2 ha^{-1} (Figure 11, Section 4.2.2). There were not significant differences in the performance of the tested hybrids (species excluding *E. sxu*), although they performed significantly better than the controls of *E. gxc*, *E. cladocalyx* and *E. dunnii*. The basal area of *E. gxr* was the greatest, followed by *E. gxt*, *E. gxc* and *E. sxu*. The good production potential was not expected for the *E. gxr* hybrid due to the fact that the pure parental species would both be considered as off-site plantings in the semi-arid Mediterranean climate. The species of both *E. grandis* and *E. resinifera* are found mainly in the summer rainfall regions of Australia, with precipitation ranges of 1 000 to 1 750 mm and 1 350 to 1 500 mm respectively (FAO, 1979). *Eucalyptus gxt* apparently performed well due to the high growth potential of the parent material, *E. grandis*, and suitable site conditions for *E. tereticornis. Eucalyptus tereticornis* is well adapted to both summer and winter rainfall regions with precipitation of between 500 and 1 500 mm (FAO, 1979). *E. sxu* had moderate performance in relation to the other tested hybrids, and could be related to both of the parent species in this hybrid, which are more suited to the summer rainfall areas and precipitation higher than 800 mm

(Herbert, 2000). *E. dunnii* was found to maintain a fast growth rate in summer rainfall regions with precipitation higher than 1 000 mm, but it was planted off-site in this trial and did not perform well. *E. cladocalyx* and *E. dunnii* also did not perform well due to intense competition from the fast-growing hybrids brought about by the use of single tree plots (refer to Section 5.2). The hybrids completely outperformed and suppressed the controls, due to the faster growing hybrids utilising the site resources more effectively and outcompeting these controls (Du Toit *et al*., 2017).

5.3.2 Growth performance among *E. gxc* provenances

The average upscaled basal area per *E. gxc* provenance ranged between 13 and 37 m^2 ha^{-1} (Figure 12, Section 4.2.2). The Albacutya provenance performed significantly better than all other provenances and controls excluding Yass and Wiluna, with a very low variance. It is well adapted to the site, with a natural range in the winter rainfall region of Southern Australia and precipitation from 250 to 500 mm. The Albacutya provenance also performed well in Mediterranean Italy and Israel, with precipitation of 684 and 529 mm respectively (FAO, 1979). It also performed well at a site with low rainfall and high temperature in Sidi Slimane, Morocco, with precipitation of 445 mm (FAO, 1979). Yass had the second biggest average basal area, and thus production potential. No literature was available for this provenance. The provenances of Wiluna, Morocco, Silverton and De Grey performed moderately well, which was expected, as these provenances have their origin in the arid regions of Australia. The Petford provenance performed below the trial average for the *E. gxc* provenances. This can most probably be attributed to it being adapted to tropical summer rainfall conditions and slightly higher rainfall, at 650 mm in its natural range.

5.3.3 Genotypes

The average basal area for the top 20 treatments differed significantly (Figures 13 and 14, Section 4.2.3). The top five performing treatments (ranked) were: *E. gxc* Albacutya CSS01659 (9), *E. gxc* Albacutya CSS01682 (83), *E. gxt* (AUS) seed SGR0046xT32 (84), *E. gxt* (AUS) seed AG049xT08 (83) and *E. gxc* (SA) seed SGR1231xC42 (76).

In the top 20 genotypes, 50% of the treatments were from the *E. gxc* Albacutya provenance. The two best-performing treatments were *E. gxc* of the Albacutya provenance. This is a reflection of the suitability of the *E. gxc* Albacutya provenance to the Mediterranean climate. The other three of the top five treatments were of seed origin: two *E. gxt* genotypes from Australia and one *E. gxc* from South Africa. A few *E. gxc* provenances of Silverton, De Grey and Wiluna were also represented in the top 20. The presence in the top 20 of these provenances, which are from the drier Western Australia and semi-arid southern Australia, confirms their suitability for the climatic conditions of the Mariendahl trial site. The genotype of *E. gxr* AG840xRES-9 (88) was also within the top 20 treatments. This is also evidence of the suitability of this genotype for the site and climatic conditions of the Mariendahl trial site. It was able to compete well with the other genotypes in the study.

5.4 Total volume growth on the Mariendahl trial site

The MAI achieved on the Mariendahl site was in line with estimations made by Botman (2010) on the sub-humid Backsberg site in the Cape Winelands. Botman estimated the MAI at 10 years of age from measurements taken at six years of age. Botman estimated that the *E. gxc* and *E. gxu* hybrids would have a peak MAI of 17.89 and 17.84 $m^3ha^{-1}a^{-1}$ respectively on that site (AI = 0.68). This is in line with the performance of the *Eucalyptus* hybrids, with a MAI of 17.02 m^3 ha^{-1} a^{-1}, on the Mariendahl trial site with a AI = 0.42. Therefore, the growth on the Mariendahl trial site was fairly similar to the growth on the Backsberg site, which had a greater AI.

Du Toit *et al*. (2017) reported MAIs of 16.3, 10.8, 19.8 and 7.3 m^3 ha^{-1} a^{-1} for the top five taxa on the Pampoenvlei, Chemfos, Waterboerskraal and Flaminkvlei sites respectively, at 15 years and AI < 0.36. It has to be added that all the trial sites in that study, except for Chemfos, employed line plots. Line plots may exaggerate the upscaled volumes of the top performers to a lesser degree than single-tree plots, but there will be some exaggeration due to the plot design.

The relatively rapid stand growth rates on the Mariendahl trial (semi-arid "+") site may partly be due to the deep soils in the area, which provide moderately large water storage on this site. This is reflected by the average Water deficit estimate of 332.5 mm for the Mariendahl trial site, which indicated moderate rather than severe WD levels when compared to ranges presented by Scheepers (2018).

5.5 Pests and insects at trial site

The presence of pest and disease potentially had a negative effect on growth at the Mariendahl trial site.

A study on 34 sites in Portugal, on the Iberian Peninsula, by Reis *et al*. (2012), found that *G. scutellatus* had a significant economic effect on *Eucalyptus* plantations. She estimated that timber production could decrease by 51% in the affected areas. Therefore, it could be expected that the presence of the *Eucalyptus* snout beetle would have had an effect on the volume production of the Mariendahl trial site, as it was likely to have been present on the site since establishment. However, biological controls are in place that would reduce the effect of snout beetle on the Eucalypts. Therefore, due to the presence of *G. scutellatus* and *T. peregrinus* at the Mariendahl trial site, the results for volume production (in terms of upscaled basal area) would have been affected somewhat negatively.

Botman (2010) found *E. cladocalyx* to be the least susceptible to attack by both *T. peregrinus* and *G. scutellatus* on the Backsberg trial site. *Eucalyptus gxc* was found to be susceptible to *T. peregrinus*, and Noeth (2014) found that *E. cladocalyx* had the lowest damage score for both *G. scutellatus* and *T. peregrinus* on the Backsberg site, while *E. dunnii* had the highest damage score for *G. scutellatus*. Botman (2010) also found *E. cladocalyx* to be the least susceptible to *G. scutellatus* and *T. peregrinus* on the Backsberg site, and *E. gxc* the most susceptible to *T. peregrinus*.

Therefore, Noeth (2014) suggests that *E. cladocalyx* would make a good hybrid partner to increase resistance to *G. scutellatus* and *T. peregrinus*. Noeth (2014) also identified the need for studies to quantify the economic impact of the presence of this pest, and therefore the volume production on the Mariendahl trial site could also have been affected by the Bronze bug. Verleur (2011) found that the impact of *G. scutellatus* could be reduced to insignificant levels if highly susceptible Eucalyptus species were replaced with more tolerant species. Although the Mariendahl trial results were affected by these pests, as aforementioned, there are ways of mitigating the impact of these pests on the Eucalyptus grown in the Cape Winelands of South Africa.

The assessment of the presence of pest and insects on the Mariendahl trial should be investigated and reported in future studies.

5.6 Coppice potential

5.6.1 Coppicability

The coppicability of the genotypes was also tested (Figures 15 and 16, end of Section 4.3.4). The survival of stumps from the first rotation (original crop) prior to felling is an important factor influencing the ability to coppice.

All of the treatments in the top 50% (excluding a single treatment ranked 48) had coppicabilities of greater than 75%, and therefore we can conclude that all of these genotypes are well suited to coppice crop systems. MacLennan and Schönau (1991) found the minimum level of stocking required before coppicing could be considered to be 1 000 stems/ha when planting at 1 333 stems/ha. It follows that a stocking of more than 1 250 stems per hectare, or 75% of stems/ha, should remain of the original levels of stocking at a stocking of 1 666 stems/ha (Little & Gardner, 2003).

In genotypes in which the survival of stumps is low, it will not be viable to allow the compartment to coppice, but where the survival of stumps is adequate (in our estimates set at 75%), it will be feasible to allow the compartment to coppice (Little & Gardner, 2003).

The remainder of tested taxa and controls had coppicabilities of less than 75%. The bottom 48 genotypes (treatments), including the treatment ranked 48th, did not have adequate coppicability. *Eucalyptus gxc* and *E. dunnii* were identified by Little (2001) as species with good coppicability. *Eucalyptus dunnii* should have performed better, and the results of this trial suggest that *E. dunnii* is planted off-site under non-favourable conditions. According to McMahon *et al*. (2010), *E. cladocalyx* coppices well. *Eucalyptus cladocalyx* did not perform well and had a low coppicability in this trial, suggesting that the coppicability could have been influenced by the suppression of the trees due to competition.

Coppicability can generally be attributed to three main factors (Stape, 1997): genetic factors, environmental factors and operational factors. The ability of a stump to coppice is mainly attributed to the species and condition of the stump (Evans & Turnbull, 2010). The different species will have a variance in the amount of lignotuber and epicormic buds present per stump, and therefore there will be a variance in the ability of different species to produce coppice.

An increased mass of debris, when the bark is stripped from the trees and the branches are cut off (hereafter called the harvesting brush), is another factor that can lead to a lower coppicability. The harvesting brush is either spread evenly over the compartment, or moved into brush piles along the interrow. The coppice resulting from stumps with brush on the stumps is often weak and of poor form. This is due to the limited sunlight that is available to the coppice for growth. It has been recommended that post-harvest brush must be left in the interrow and not on the stumps (Little, 2001). This was not a factor in the Mariendahl trial, as the harvest brush was spread and did not inhibit the growth of coppice shoots.

For most hardwood species, recovery from harvesting was strongly related to the season during which the harvesting took place, and the coppicability decreased after a period of rapid growth and increased after a period of rest (Little et al., 2002). Felling in the rainy season produces the most vigorous coppice. This trial was harvested early in winter months with sufficient rain, and thus coppice growth would have been more favourable.

The most probable cause of the poor performance of the taxa in this trial is the drought that was experienced in the whole Western Cape region during the coppice period. The occurrence of drought may also inhibit the production of coppice, and drought at harvesting was found to increase stump mortality (Schönau & Schulze, 1984; Stubbings & Schönau, 1979). A study of the coppice ability of 20 *Eucalyptus* species at high altitude sites in South Africa by Little and Gardner (2003) found that the periods of severe drought in 1990 and from early 1992 to late 1995 had a negative effect on the growth and final stocking of the drought-sensitive species and provenances. The species in the aforementioned study were adapted to high altitude and not to drought (arid) conditions, whereas the species in this study are more drought resistant. We assume that drought-tolerant species would have coppiced more prolifically relative to the less drought-resistant species in times of drought. This can be seen in the difference in coppicability of *E. gxc* and *E. dunnii*. *E. gxc* is better suited to more arid conditions and performed better than *E. dunnii*, which is better suited to conditions with higher rainfall.

5.6.2 Coppice distribution

The distribution of coppice shoots around the stump was fairly even due to no significant differences in the number of shoots per quartile between the different taxa (see Section 3.4.2). The equal distribution of coppice around the stump is favourable for carrying out coppice reduction operations.

5.6.3 Total coppice shoots

There were significant differences in the total number of coppice shoots around the stump between the genotypes tested in this trial (Figures 17 and 18, Section 4.3.4).

Seed origin might also affect the potential of species to coppice (Little & Gardner, 2003). Grunwald and Karschon (1974) found that the variation in tree growth of four different provenances of *E. camaldulensis* determined the amount and rate of coppice regeneration after cutting accordingly. Therefore, there might be significant differences in the coppicing ability of the different provenances of *E. grandis x camaldulensis*. A study by Little *et al*. (2002) found that increases in the amount of bark damage resulted in a decrease in the coppicability of the stumps, and this is due to a decrease in the potential number of buds that can be produced. It was also found that damage to the bark following felling and extraction reduced the coppicing potential of *E. nitens* in that trial. This was not a contributing factor to the trial results.

5.6.4 Biomass index

There was not a significant difference in the average BI of the genotypes tested in this study, and therefore genotypes were only ranked from largest to smallest (Figures 19 and 20, end of Section 4.3.4).

The genotypes representing the *E. gxc* provenances of Albacutya, Morocco and De Grey appear to have performed the best under the top 10 genotypes. These provenances are all native to the more arid regions of Australia. The occurrence of drought may also inhibit the production of coppice, and drought at harvesting was found to increase stump mortality (Schönau, 1984; Stubbings & Schönau, 1980). Due to the current drought in the Western Cape, the genotypes that are the most adapted to drought conditions would have performed the best.

The two genotypes of E. *gxr* performed well, with both genotypes in the top 25% of treatments. The genotypes of *E. gxc* (SA) seed G107xC63 (78) and *E. gxt* (AUS) seed AG049xT10 (86) were ranked in the top 50% of treatments, while the treatments of *E. gxc* (SA) seed SGR1231xC42 (76) and *E. gxt* (AUS) seed SRC74 (81) were ranked among the worst-performing treatments. It was expected that *E. gxc* and *E. gxt* would be good coppicing species (Little, 2000).

The control of *E. gxc* GxC40/7 (92) and *E. sxu* SxU092 (96) were ranked within the top 20 genotypes, but had a coppicability in the lower 50% of all the genotypes. The *E. gxc* T12 - CONTROL (93) and *E. cladocalyx* Kluitjieskraal (95) were ranked among the top 50% of genotypes. *E. cladocalyx* performed well with regard to BI, although it did not perform well when the coppicability (Figures 15 and 16, Section 4.3.4) was measured.

The commercial controls of *E. dunnii* (91) and *E. gxc* C46 - CONTROL (94) did not perform well and were within the bottom 50% of treatments. The *E. dunnii* and *E. gxc* genotypes should have performed better, as the taxa of *E. gxc* and *E. dunnii* were identified by Little (2000) as species with good coppicability.

According to Little and Gardner (2003), site-related performance plays a significant role in deciding which species to plant. Opie *et al*. (1984) suggest the use of species with a high coppicability when deciding to plant with the intention to coppice after the first rotation.

Chapter 6: Conclusion and Recommendations

The hybrids at the Mariendahl trial site had greater survival than the *E. dunnii* and the commercial (Kluitjieskraal) *E. cladocalyx* controls. Although *E. cladocalyx* and *E. dunnii* did have high mortality after establishment, which affected survival and growth negatively, the survival remained fairly constant after the initial mortality until the end of the rotation. The hybrids experienced a constant decline in survival from establishment until the end of rotation. H_1 therefore is not rejected.

> H_1: The hybrids on the Mariendahl trial site have a greater survival than the commercial *E. dunnii* and the (Kluitjieskraal) *E. cladocalyx* controls.

The hybrids at the Mariendahl trial site had higher potential productivity in terms of growth than the *E. dunnii* and South African Kluitjieskraal *E. cladocalyx* controls, and there were significant differences in growth in terms of the genotype, taxon and *E. gxc* provenance at 10 years of age. H_2 therefore is not rejected.

> H_2: The hybrids on the Mariendahl trial site have higher potential productivity in terms of growth than *the E. dunnii* and the South African Kluitjieskraal *E. cladocalyx* controls

The potential growth in terms of upscaled basal area differed significantly among the top 20 treatments and commercial controls in the experiment. H_3 therefore is not rejected.

> H_3: Potential growth differs significantly between the top 20 genotypes in the experiment and *E. dunnii* and the South African Kluitjieskraal *E. cladocalyx* controls.

The biomass index of coppice was not significantly different among the different genotypes in the Mariendahl trial. None of the treatment’s biomass indices for coppice production were significantly higher than the rest of the treatments tested. H_4 hence not accepted.

> H_4: The biomass index of coppice in the commercial controls is higher than the tested taxa in the Mariendahl trial. One or more of the treatments’ biomass indices for coppice production will be significantly higher than the rest of the treatments tested.

The data and arguments presented suggest that the use of the tested hybrids has merit for potential small-scale and farm forestry uses in the semi-arid region of the

Western Cape of South Africa, and could aid in the alleviation of the predicted shortage of woody biomass in the future. The taxa of *E. gxc*, *E. gxr* and *E. gxt* have shown potential to be grown as a source of timber and biomass in terms of survival and potential production (through basal area). Although *E. gxc* has performed well, it is highly susceptible to infestation by insects of *Gonipterus scutellatus* and *Thaumastocoris peregrinus* (refer to Section 4.4). Furthermore, the *E.gxc* was tested in the trial largely in the absence of *Leptocybe invasa*, an insect to which it is more susceptible at a young age (Nyeko, 2005). *Leptocybe* only appeared at the trial site towards the end of the experimental period when trees were already mature. It follows that this taxon should preferably not be planted due to reduced performance as a result of these pests. *E. gxt* is also affected by these pests. The susceptibility of *E. gxr* to *G. scutellatus* and *T. peregrinus* needs to be investigated.

The findings presented in this study were affected by the initial layout of the trial, using single-tree plots, and led to interspecific competition among the different genotypes/treatments in the trial, with certain species being outperformed that might have done well in a complete-block layout. It therefore is suggested that each of the top-performing genotypes be tested in a design with square (multiple tree) plots and compared to the control of *E. cladocalyx*, which performed well in the sub-humid Greater Cape Winelands District (Botman, 2010).

E. resinifera is known in Australia as Red Mahogany and has favourable wood properties for saw timber utilisation. Both the parent species of *E. gxr* have good properties for saw timber utilisation and wood properties and, at the time of felling the trial, the wood of *E. gxr* had a distinct red colour (mahogany). Due to the relatively good performance of the hybrid of *E. gxr* and its possibility as a tree that has faster growing saw timber, it is suggested that the wood properties of this taxon be investigated.

All three hybrids outperformed the control of *E. cladocalyx* in this trial (also due to the reasons explained in Section 4.4), and therefore have potential to be utilised in the semi-arid Western Cape in short-rotation plantations (e.g. as a source of biomass or poles).

The coppice results also show that there is potential to grow coppice after the first rotation as a short-term biomass crop or as a slightly longer term crop for poles and biomass. It is suggested that the economic viability of a short-term biomass coppice crop be investigated further.

From a biological / silvicultural perspective , the hybrids tested have potential to be grown as a source of biomass or poles in short-rotation farm forests in the semi-arid Western Cape region through planting and coppicing, and thereby to aid in the alleviation of the predicted woody biomass shortage in the region.

References

1. Allen RG, Pereira LS, Raes D, Smith M. 1998. Crop evapotranspiration. Guidelines for Computing Crop Water Requirements, FAO Irrigation and Drainage Paper No. 56, FAO, Rome.
2. Barbour EL. 2004. *Eucalypt hybrids in South-West Western Australia*. RIRDC Publication No WO4/021, Canberra.
3. Binns JA, Illgner PM, Nel EA. 2001. Water shortage, deforestation and development: South Africa's Working for Water Programme. *Land Degradation & Development* 12:341-355.
4. Boreham GR, Pallett RN. 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.
5. Botman I. 2010. Production potential of eucalypt woodlots for bioenergy in the Winelands region of the Western Cape. Master's thesis. Stellenbosch: Stellenbosch University.
6. Bredenkamp BV. 1994. The volume of standing trees. *In: Van der Sijde HA* (Ed.). South African forestry handbook. South African Institute of Forestry. Pretoria. South Africa. 846 p.
7. Bredenkamp BV. 2000. Plantation inventory, in DL Owen (ed.). South African forestry handbook 2000, Vol. 1, 2000. South African Institute of Forestry. South Africa. pp 161 - 166. .
8. Brooker MIH. 2000. A new classification of the genus Eucalyptus L'Hér (Myrtaceae). Australian Systematic Botany 13(1):79-148.
9. Coppen JJW (ed) 2002. Eucalyptus: The genus Eucalyptus. Londen: Taylor & Francis.
10. Crous JW, Burger L. 2015. A comparison of planting and coppice regeneration of *Eucalyptus grandis* × *Eucalyptus urophylla* clones in South Africa. *Southern Forests: A Journal of Forest Science* 77(4):277-285. doi:10.2989/20702620.2015.1063031
11. Darrow WK. 1994. Species trials of cold tolerant Eucalyptus in the summer rainfall zone of South Africa. ICFR Bulletin 10/94, Institute for Commercial Forestry Research, Pietermaritzburg.
12. Darrow WK. 1997. Eucalypt site-species trials in Zululand: Results at four years of age. ICFR Bulletin 3/97, Institute for Commercial Forestry Research, Pietermaritzburg.
13. De Cauwer V, Fichtler E, Beeckman H, Graz FP, Mertens J, Van Holsbeeck S, Muys B. 2016. Predicting site productivity of the timber tree *Pterocarpus angolensis. Southern Forests: A Journal of Forest Science* 79(3):259-268. doi:10.2989/20702620.2016.1256042
14. Demaerschalk JP. 1793. Integrated systems for the estimation of tree taper and volume. *Canadian Journal of Forest Research* 3:90-94.
15. Denison NP, Kietzka JA. 1993a. The use and importance of hybrid intensive forestry in South Africa. *South African Forestry Journal* 165:55-60.
16. Denison NP, Kietzka JA. 1993b. The development and utilisation of vegetative propagation in Mondi for commercial afforestation programmes. *South African Forestry Journal* 166:53-60.
17. Dunlop RW, Goodricke TG. De Leur DT. 1997. Five year results from an Australian Acacia species trial at Piet Retief, South Africa. ICFR Bulletin 01/2002. Institute for Commercial Forestry Research, Pietermaritzburg.
18. Du Toit B, Malherbe GF, Kunneke A, Seifert T, Wessels CB. 2017. Survival and long term growth results of eucalypts on semi-arid sites in a Mediterranean climate. Southern Forests. Proceedings of the Dryland Forestry Symposium, March 2015, Stellenbosch.
19. Du Toit B, Swart JPJ, De Waal TJ. 2010. Utilisation du Bois des Arbres Exotiques Invasifs pour la Consommation en Bois-énergie: la Province du Cap, in: J-N Marien (ed.). *Foresterie Urbaine et Périurbaine en Afrique. Quelles Perspectives pour le Bois-énergie? Document de Travail sur la Foresterie Urbaine et Périurbaine n°4, 2010.* Rome: FAO. 53-61.
20. Eccles NS, Kritzinger JL, Little KM. 1997. Appropriateness of non-destructive measures of young pine tree performance in weeding experiments. *Southern African Forestry Journal* 178(1):25-29. doi:10.1080/10295925.1997.9631135

21. Edwards MBP. 2012. Introduction: The South African forest resource, in BV Bredenkamp (ed.) *South African forestry handbook*, 5th edition. Pretoria: South African Institute of Forestry.
22. Evans J, Turnbull J. 2010. *Plantation forestry in the tropics*. 3rd edition. New York: Oxford University Press.
23. FAO. 1979. *Eucalyptus for planting*. Rome: FAO.
24. Florence RG. 1996. *Ecology and silviculture of Eucalypt forests*. Collingwood: CSIRO Publishing.
25. Ford ED. 1975. Competition and stand structure in some even-aged plant monocultures. *Journal of Ecology* 63:311-333.
26. Fuwape JA. 2001. The impacts of forest industries and wood utilization on the environment. *Journal of Tropical Forest Research* 17:78-90.
27. Gardner RAW, Little KM. and Arbuthnot, A. 2007. Wood and Fibre Productivity Potential of Promising New Eucalypt Species for Coastal Zululand, South Africa, Australian Forestry, 70:1, 37-47, DOI: 10.1080/00049158.2007.10676261
28. Gardner R, Swain T, Norris C. 2003. *Eucalypt species and provenance trials in the Southern Cape: Results at four years of age*. Pietermaritzburg: Institute for Commercial Forestry Research.
29. Godsmark R. 2017. South African Forestry and Forest Product Industry 2016. [Online]. 2018. Available at: https://www.forestry.co.za/uploads/File/industry_info/statistical_data/new%20layout/South%20African%20Forestry%20&%20Forest%20Products%20Industry%20-%202016%20(R).pdf. [2018, September 20].
30. Google, 2018. Internet: https://www.google.co.za/maps/place/Australia/@-24.9487376,135.5967573,4z/data=!4m5!3m4!1s0x2b2bfd076787c5df:0x538267a1955b1352!8m2!3d-25.274398!4d133.775136. Accessed: 09:52 07/03/2018
31. Grunwald C, Karschon R. 1974. Effect of seed origin on coppice regeneration in *Eucalyptus camaldulensis* Dehn. *Silvae Genetica* 23:141-144.
32. Gush MB. 2016. The potential of *Vachellia* (*Acacia*) *kosiensis* as a dryland forestry species in terms of its water use, growth rates and resultant water use efficiency. *Southern Forests* 79(3):227-234.
33. Harwood CE, Bird R, Butcher T, Bush DJ, Jackson T, Johnson I, Stackpole D, Underdown M. 2005. *Australia Low Rainfall Tree Improvement Group (ALRTIG): Update of hardwood breeding strategies*. RIRDC Publication NO 05/023.
34. Herbert MA. 1993. Site requirements of exotic hardwood species. ICFR Bulletin Series 02/93. Institute for Commercial Forestry Research, Pietermaritzburg.
35. Herbert MA. 2000. Site requirements and species matching: Eucalypt and wattle species, in Owen, D.L. (ed.). *South African forestry handbook*, Vol 1. 4th edition. Pretoria: South African Institute of Forestry. 85-94.
36. Holmes TP, Aukema JE, Von Holle B, Liebhold A, Sills E. 2009. Economic impacts of invasive species in forests: past, present, and future. The Year in Ecology and Conservation Biology, Volume 1162, pp. 18-38.
37. ICFR. 1992. *Site-species trials summary. ICFR Annual Report 1992*. Pietermaritzburg: Institute for Commercial Forestry Research.
38. Jacobs DH & Neser S. 2005. *Thaumastocoris australicus* Kirkaldy (Heteroptera: Thaumastocoridae): A new insect arrival in South Africa, damaging to Eucalyptus trees. *South African Journal of Science* 101:233-236.
39. Jansson G, Danell Ö, Stener LG. 1998. Correspondence between single-tree and multiple-tree plot genetic test for production trait in Pinus sylvestris. Canadian Journal of Forestry. Res. 28: 450–458.
40. Komakech C, Swain T, Fossey A. 2013. Growth Potential of Eucalyptus cypellocarpa as an Alternative Species for the Mid-altitude Summer Rainfall Region of South Africa, Southern Forests: a Journal of Forest Science, 75:3, 149-154, DOI: 10.2989/20702620.2013.822183
41. Little KM. 2000. Eucalypt coppice management. ICFR Innovations 01/2000, Institute for Commercial Forestry Research, Pietermaritzburg.
42. Little KM. 2001. Investigations into *Eucalyptus grandis* coppice. Regeneration of seedling parent stock in Zululand. ICFR Innovations Bulletin 2000, No.2001/01, Institute for Commercial Forestry Research, Pietermaritzburg.

43. Little KM, Gardner RAW. 2003. Coppicing ability of 20 eucalyptus species grown at two high-altitude sites in South Africa. *Canadian Journal of Forestry Research* 33(2):181-189.
44. Little KM, Van den Berg G, Fuller G. 2002. Coppicing potential of *Eucalyptus nitens*: Results from a field survey. *The Southern African Forestry Journal* 193(1):31-38.
45. Lee DJ, Debuse VJ, Pomroy PC, Robson KJ, Nikles DG. 2005. Developing genetically adapted tree varieties for marginal areas of Northern Australia. RIRDC Publication No 04/186.
46. Lee DJ, Nikles DG, Dickinson GR. 2001. Prospects of eucalypt species, including interspecific hybrids from South Africa, for hardwood plantations in marginal subtropical environments in Queensland, Australia. *The Southern African Forestry Journal*, 190(1):89-94. doi:10.1080/20702620.2001.10434120
47. Loo-Dinkins JA, Tauer CG. 1987. Statistical efficiency of six progeny test field designs on three Loblolly pine (*Pinus taeda L.*) site types. *Canadian Journal of Forestry Research* 17:1066-1070.
48. MacLennan LA, Schönau APG. 1991. Eucalypt coppice re-generation and management. Institute for Commercial Forestry Research, Pietermaritzburg, South Africa. ICFR Pamphlet 1991.
49. Magnussen S. 1989. Effects and adjustments of competition bias in progeny trials with single-tree plots. *Forest Science* 35(2):532-547.
50. Malherbe GF, du Toit B, Kunneke A. 2015. A Comparison of Growth results of Eucalyptus genotypes on dry sites in the Western Cape. IUFRO symposium: Silviculture and management of Dryland Forests. Stellenbosch. 16-19 March 2015.
51. Max TA, Burkhart HE. 1976. Segmented polynomial regression applied to taper equations. *Forest Science* 22(3):283-289.
52. McMahon L, George B, Hean R. 2010. *Eucalyptus cladocalyx*. Prime Fac 1077 brochure, Department of Industry and Investment (Industry & Investment NSW), November.
53. Morris AR, Pallett RN. 2000. Site requirements and species matching: Pines, in Owen DL (ed.). *South African forestry handbook*, Vol 1. 4th edition. Pretoria: South African Institute of Forestry. 80-84.
54. Mugunga CP, Kool D, Van Wijk MT, Mohren GMJ, Giller KE. 2015. Water use by short rotation Eucalyptus woodlots in Southern Rwanda. *Agroforestry Systems* 89(6):1119-1139.
55. Nadel RL, Slippers B, Scholes MC, Lawson SA, Noack AE, Wilcken CF, Bouvet JP, Wingfield MJ. 2010. DNA bar-coding reveals source and patterns of *Thaumastocoris peregrinus* invasions in South Africa and South America. *Biological Invasions* 12:1067-1077.
56. Noble P, Arnold R. 2002. *Ironbark species-provenance trials in North-east Victoria – Growth and form results to age three years*. Proceedings, National Low Rainfall Farm Forestry Conference. 24 – 25 September. Horsham, Victoria, Australia.
57. Noeth KP. 2014. Assessment of damage caused by *Thaumastocoris peregrinus* Carpintero & Dellapé and *Gonipterus "scutellatus"* Gyllenhal on different species and different provenances of *Eucalyptus* in the Cape Winelands. Unpublished postgraduate diploma. Stellenbosch: Stellenbosch University.
58. Nyeko P. 2005. The cause, incidence and severity of a new gall damage on Eucalyptus species at Oruchinga refugee settlement in Mbarara district, Uganda. Uganda Journal of Agricultural Sciences, 11, 47–50.
59. Opie JE, Curtin RA, Incoll WD, 1984. Stand management, in WE Hillis, AG Brown (Eds.). *Eucalypts for wood production*. Sydney: CSIRO Australia/Academic Press. 179-200.
60. Oscroft D, Little KM. 2008. The ability for eucalypts to regenerate via coppice following the September 2005 fires in Zululand, KwaZulu-Natal, South Africa. ICFR Technical Note 2008, Institute for Commercial Forestry Research, Pietermaritzburg.
61. Pereira AR, Angelocci LR, Sentelhas PC. 2007. *Meteorologia Agricola*. Course booklet, ESALQ.
62. Pienaar B, Kotze H. 2001. Growth and yield functions. Mensuration and Modelling Consortium (MMRC) report, MMRC, Pietermaritzburg.
63. Penfold AR, Willis JL. 1961. *The Eucalypts.* New York: Intersc1ence Publishers.

64. Ravindranath NH, Ostwald M. 2008. *Carbon inventory methods: Handbook for greenhouse gas inventory, carbon mitigation and roundwood production projects.* Dordrecht: Springer Science.
65. Ræbild A, Hansen CP, Kjaer ED. 2002. Statistical analysis of data from provenance trials. Guidelines & Technical Notes No. 63, Danida Forest Seed Centre, Humlebaek, Denmark.
66. Reis AR, Ferreira L, Toméa M, Araujo C, Branco M. 2012. Efficiency of biological control of *Gonipterus platensis* (Coleoptera: Curculionidae) by *Anaphes nitens* (Hymenoptera: Mymaridae) in cold areas of the Iberian Peninsula: Implications for defoliation and wood production in *Eucalyptus globulus*. *Forest Ecology and Management* 270:216-222.
67. Rivera AC, Carbone SS & Andres JA. 1999. Life cycle and biological control of the *Eucalyptus* snout beetle (Coleoptera, Curculionidae) by *Anaphes nitens* (Hymenoptera, Mymaridae) in North-west Spain. *Agricultural and Forest Entomology* 1:103-109.
68. Saxton KE, Rawls WJ, Romberger JS, Papendick RI. 1986. Estimating generalized soil water characteristics from texture. Transactions of the ASAE (American Society of Agricultural Engineers) 50:1031-1035.
69. Scheepers GP. 2018. Fertilisation of semi-mature Pinus elliottii and Pinus elliottii x caribaea stands on a climatic gradient in the Tsitsikamma and its effect on system nutrition and stand productivity. PhD thesis. Stellenbosch: Stellenbosch University.
70. Schönau APG, Schulze RE. 1984. Climatic and altitudinal criteria for commercial afforestation with special reference to Natal. *South African Forestry Journal* 130(1):10-18.
71. Seifert T, Ham C, Ham C. 2016. *Sustainable forestry*, in: M Swilling, JK Musango, J Wakeford (eds). *Greening the South African economy*. Claremont: UCT Press. 131-144.
72. Slippers B. 2010. Dealing with new invasive pests of forestry trees: The Leptocybe gall wasp as an example. *Wood SA & Timber Times* November: 15-16.
73. Smith, R. E. and Scott, D. F. The effects of afforestation on low flows in various regions of South Africa. Water SA vol. 18. pp. 185–194.
74. Smith, C.W. 2005. A Site Evaluation for Site: Species Matching in the Summer Rainfall Regions of Southern Africa. ICFR Bulletin Series 03/2005, Institute for Commercial Forestry Research, Pietermaritzburg.
75. Smith CW, Kassier H, Morley T. 2006. The effect of initial stand density on the growth and yield of selected *Eucalyptus grandis* clonal hybrids in Zululand. ICFR Bulletin Series 04/2006. Institute for Commercial Forestry Research, Pietermaritzburg.
76. Stanger TK, Galloway GM, Retief ECL. 2011. Final results from a trial to test the effect of plot size on *Eucalyptus* hybrid clonal ranking in Coastal Zululand, South Africa. *Southern Forests: A Journal of Forest Science* 73:3-4, 131-135, doi:10.2989/20702620.2011.639492
77. Stape JL. 1997. Global planning and standardization of operational procedures of simple coppice in Eucalyptus. Série Técnica Instituto de Pesquisas e Estudos Florestais 11: 51–62. Piracicaba, Brasil.
78. Stats SA. 2017. Mid-year population estimates 2017 report. Pretoria: Statistics South Africa.
79. Stern K. 1969. Einige Beitrage Genetischer Forschung zum Problem der Konkurrenz in Pflanzenbestriden. *Allgemeine Forst und Jagdzeitung* 140:253-262.
80. Stubbings JA, Schonau APG. 1979. Management of short rotation coppice crop of Eucalyptus grandis Hill ex Maiden. *In*: Proc. Tech. Cons. Fast-growing Plantation Broadleaved Trees for Mediterranean and Temperate Zones, October 1979, Lisbon, Vol. 2, pp.237--252.
81. Swain TL, Gardner RAW. 2003. A summary of cold tolerant Eucalypt species (CTEs) grown in South Africa. ICFR Bulletin Series 03/2003. Institute for Commercial Forestry Research, Pietermaritzburg.
82. Swain TL, Gardner RAW. 2004. Cold tolerant Eucalypts in South Africa –Growth information for informed site-species matching in SA. *Southern African Forestry Journal*, 202(1):83-84. doi:10.1080/20702620.2004.10431794
83. Thornthwaite CW. 1948. An approach toward a rational classification of climate. *Geographical Review* 38(1):55-94.

84. Thornthwaite CW, Mather JR. 1955. *The water balance*. Centerton: Publications in Climatology.
85. Tuskan GA, Williams CG. 1989. Comparison of plot designs for short-term genetic trials. Tree Improvement and Genetics, Southern Forest Tree Improvement Conference. June 26-30.Charleston, South Carolina.
86. Van Wyk G, Van Laar A, Theron JM. 2001. Yield potential of selected Eucalyptus genetic stock on the sandy soils of the South African Cape West Coast. *South African Forestry Journal* 191:9-19.
87. VECON. 2006. Review of the original recommendations and decisions taken about phasing out plantations forestry and state forest land in the Southern and Western Cape and recommendations on a decision to reverse the withdrawal strategy. Report to the Department of Agriculture, Forestry and Fisheries, South Africa, by the VECON consortium, Tender 2005-146.
88. Verleur PM. 2011. Monitoring of block plantings in coastal Zululand to establish if *Gonipterus scutellatus* (Eucalyptus snout beetle) has clonal preferences. *In*: Noeth KP. 2014. Assessment of Damage Caused by Thaumastocoris peregrinus Carpintero & Dellapé and Gonipterus "scutellatus" Gyllenhal on Different Species and Different Provenances of Eucalyptus in the Cape Winelands, Postgraduate diploma project (unpublished). Forestry and Wood Science, Stellenbosch University.
89. Verryn SD 2000. Eucalyptus hybrid breeding in South Africa. Environmentek, CSIR, Pretoria.
90. Verryn SD, Fairbanks D, Pierce BT, Dyer C. 1996. Understanding the deployment of various eucalypt species and hybrids on a range of sites in Southern Africa using fuzzy set logic, *In*: Dieters MJ, Matheson AC, Nikles DG, Harwood CE, Walker SM (eds). *Tree improvement for sustainable tropical forestry*. Proceedings of the QFRI-IUFRO Conference, Caloundra, Queensland, Australia. 27 October-1 November. Queensland Forestry Research Institute, Gympie. 347-350.
91. Verryn SD, Snedden, CL, Hettasch M, Pierce BT. 1999. Short course: Specialist Eucalypt Breeding Techniques (Environmentek, CSIR, Pretoria) In: Verryn SD. Eucalyptus hybrid breeding in South Africa. 2000. Environmentek, CSIR, Pretoria. pp 1 - 9.
92. Von Doderer CCC. 2009. Financial viability of Agroforestry for bioelectricity generation on various farm types in the Western Cape, South Africa. Unpublished MSc Thesis, University of Stellenbosch.
93. Willmott CJ, Rowe CM, Mintz Y. 1985. Climatology of the terrestrial seasonal water cycle. *Journal of Climatology* 5:589-606.

Appendix A

Site characteristics for trial site on Mariendahl Experimental Farm, Western Cape, South Africa

Site characteristics	
District, province	Stellenbosch, Western Cape
Weater station	ELSENBURG: CIAT
Latitude	-33.84241
Longitude	18.83937
Altitude (m a. s. l.)	227
Mean annual rainfall (mm)	638.6
Mean annual temperature (˚C)	17.9
Soils	Kroonstad
Taxonomy (FAO)	Lithosol
Parent material	Sandstone
Soil Depth (m)	1.3 - 2.4
Date planted	31/08/2006
Date harvested	18/07/2016
Date coppice assessed	11/04/2017
Total precipitation (mm)*	556.0
*for the period 2 months prior to felling until 10 months after felling	

Appendix B

Table: Water holding capacity analysis of four locations on Mariendahl trial site.

Sample	Depth (cm)	Clay %	Silt %	Sand %	Fine sand %	Medium Sand %	Growwe Sand %	Stone %	Classification	Water Holding Capacity		
										10kPa %	100 kPa %	mm/m
1	0 - 40	11	8	81	44.4	21.2	15.4	7.9	SaLm	22.5	12.13	103.75
1	41 - 100	41	6	53	21	12	20	24.1	SaCl	23.16	16.59	65.63
1	101 - 120	69	8	23	12	4	7	0	Cl	38.55	30.37	81.79
1	121 - 130	63	14	23	14.2	2.4	6.4	0	Cl	40.03	30.9	91.32
2	0 - 40	9	10	81	33.4	19	28.6	7.1	LmSa	22.59	13.15	94.43
2	41 - 120	35	8	57	27.9	14.5	14.6	21.5	SaCl	23.49	15.99	75
2	121 - 200	75	12	13	7.6	2	3.4	0	Cl	41.44	33.36	80.78
3	0 - 40	7	8	85	45.6	24	15.4	14.9	LmSa	19.55	10.01	95.39
3	41 - 60	9	8	83	33.3	21.2	28.5	46.9	LmSa	12.24	7.03	52.09
3	61 - 120	59	24	17	7.2	3.2	6.6	0	Cl	42.01	33.01	90
3	121 - 160	59	34	7	4.4	1.2	1.4	0	Cl	45.98	36.29	96.4
3	161 - 220	53	36	11	6.6	2.2	2.2	0	Cl	45.29	35.25	100.41
3	221 - 260	49	30	21	8.7	4.8	7.5	0	Cl	41.76	32.15	96.16
4	0 - 20	9	8	83	37.3	20	25.7	7.6	LmSa	21.89	12.24	96.47
4	21 - 80	15	6	79	45	18	16	20.1	SaLm	20.33	11.19	91.37
4	81 - 160	35	12	53	29.3	13.3	10.4	25.8	SaCl	23.58	16.03	75.44
4	161 - 200	43	20	37	25.6	4	7.4	8.4	Cl	35.25	25.08	101.77
4	201 - 240	43	20	37	23.4	5.6	8	15.3	Cl	32.08	23.03	90.42

Appendix C

Table: Soil analysis of the top 20 cm on four locations on Mariendahl trial site.

Sample	Soil	pH (KCL)	Resistance (Ohm)	H+ (cmol/kg)	Rock (Vol %)	P (mg/kg) Bray II	K (mg/kg)	Exchangeable cations (cmol(+)/kg)				Effective CEC	Cu (mg/kg)	Zn (mg/kg)	Mn (mg/kg)	B (mg/kg)	Fe (mg/kg)	C%	Soluble S (m/kg)
								Na	K	Ca	Mg								
1	Sand	5.2	6760	0.59	6	59	25	0.03	0.06	1.18	0.47	**1.74**	0.3	0.8	5.8	0.29	125	0.84	9.02
2	Loam	4.2	2910	1.41	7	70	24	0.06	0.06	1	0.58	**1.7**	0.3	1.3	6.8	0.28	225	1.49	12.69
3	Sand	4.5	3900	0.72	11	13	23	0.06	0.06	0.92	0.51	**1.55**	0.2	0.9	4.6	0.28	69	0.66	8.95
4	Loam	3.7	1380	1.08	7	32	18	0.12	0.05	0.21	0.29	**0.67**	0.2	0.5	0.7	0.19	185	0.83	14.05

Appendix D

Table: Precipitation at Elsenberg weather station (January 2005 – July 2017)

Year	Month	Maximum temperature (°C)	Minimum temperature (°C)	Precipitation (mm)
2005	1	28.66	16.25	46.6
2005	2	29.86	16.37	2.5
2005	3	28.36	15.7	13.8
2005	4	24.1	13.65	70.4
2005	5	19.01	12.08	99
2005	6	16.52	9.72	119.6
2005	7	20.09	11.15	67
2005	8	15.63	8.84	119.1
2005	9	20.35	10.22	42.9
2005	10	22.32	11.07	18.7
2005	11	25.34	13.38	28.1
2005	12	27.09	13.33	1.4
2006	1	29.76	16.32	3.1
2006	2	30.34	16.36	15
2006	3	27.24	13.82	9.1
2006	4	24.29	13.23	55.9
2006	5	19.01	11.36	186.3
2006	6	19.62	10.66	84.3
2006	7	16.42	9.53	110.2
2006	8	17.39	9.17	90.5
2006	9	21.73	-7.14	30
2006	10	23.57	12.01	33.9
2006	11	25.93	13.39	61.5
2006	12	26.42	14.52	22.2
2007	1	30.65	16.64	2
2007	2	28.54	15.67	36.7
2007	3	28.55	15.04	33.8
2007	4	24.94	13.42	96.8
2007	5	21.76	12.05	139.7
2007	6	17.67	10.15	153

Year	Month	Maximum temperature (°C)	Minimum temperature (°C)	Precipitation (mm)
2007	7	17.23	8.7	148.7
2007	8	17.18	3.64	127.7
2007	9	19.65	9.95	43.3
2007	10	24.04	11.73	43.7
2007	11	23.96	12.16	53.6
2007	12	28.37	15.71	25.8
2008	1	30.29	16.01	23.3
2008	2	29.71	16.08	41.5
2008	3	29.4	15.25	23
2008	4	25.68	13.39	15
2008	5	21.14	-3.48	70.6
2008	6	17.35	10.69	115.2
2008	7	16.45	8.72	195.4
2008	8	17.74	8.67	109.1
2008	9	17.01	7.93	155.7
2008	10	22.51	11.05	19.2
2008	11	25.07	12.72	56.3
2008	12	28.78	14.8	19
2009	1	28.33	15.59	6.1
2009	2	30.75	16.43	4
2009	3	29.59	15.69	4.6
2009	4	25.92	13.95	52.2
2009	5	20.25	11.71	109.2
2009	6	17.91	11.23	169.1
2009	7	18.88	10.5	139.29
2009	8	18.45	9.51	89.9
2009	9	18.01	9.86	83
2009	10	24.28	11.87	10.5
2009	11	23.94	12.92	118.3
2009	12	26.32	13.66	4.2
2010	1	28.72	14.9	1.1
2010	2	28.88	15.69	16

Year	Month	Maximum temperature (°C)	Minimum temperature (°C)	Precipitation (mm)
2010	3	28.87	15.52	11.2
2010	4	24.31	12.29	22.3
2010	5	20.22	11.36	151.9
2010	6	18.57	10.07	129.9
2010	7	18.92	8.87	60.4
2010	8	19.74	9.67	72.7
2010	9	20.56	10.33	31
2010	10	22.34	11.73	58.6
2010	11	24.51	12.69	37.8
2010	12	28.71	16.56	27.8
2011	1	31.54	16.11	5.1
2011	2	32.28	17.16	9.2
2011	3	29.17	15.51	7
2011	4	23.38	12.41	55.8
2011	5	20.49	11.77	91.4
2011	6	17.48	9.88	108.3
2011	7	19.12	9.86	24.7
2011	8	18.2	8.75	79.7
2011	9	19.69	9.8	38.6
2011	10	22.24	11.28	25
2011	11	23.13	11.25	48.7
2011	12	26.16	13.15	19.3
2012	1	31.15	17.11	2.1
2012	2	28.58	15.67	4.8
2012	3	28.74	16.02	34.3
2012	4	24.34	12.9	68.1
2012	5	19.59	10.69	67
2012	6	17.35	9.86	120.2
2012	7	16.58	8.96	110.4
2012	8	15.91	8.25	147
2012	9	18.46	9.56	123.19
2012	10	21.68	11.6	84.69

Year	Month	Maximum temperature (°C)	Minimum temperature (°C)	Precipitation (mm)
2012	11	25.52	13.04	15.5
2012	12	29.94	16.6	1.9
2013	1	29.23	15.84	15.4
2013	2	28.5	15.9	63
2013	3	27.61	15.61	25.8
2013	4	23.69	12.03	57.2
2013	5	21.86	11.84	61.4
2013	6	17.01	9.53	154.1
2013	7	17.59	9.66	88.8
2013	8	16.53	8.67	265.9
2013	9	17.09	8.52	103.7
2013	10	22.56	11.47	45.2
2013	11	25.12	13.47	110
2013	12	29.72	15.62	2.6
2014	1	28.58	16.2	43.1
2014	2	30.64	16.99	4.8
2014	3	26.08	14.35	52.3
2014	4	27.56	15.02	34
2014	5	20.25	11.35	94.2
2014	6	16.88	9.06	173.5
2014	7	16.9	8.91	109.1
2014	8	18.85	10.18	105.3
2014	9	20.62	10.27	31.8
2014	10	25.88	12.35	10
2014	11	26.16	13.34	46.3
2014	12	28.04	14.65	5.1
2015	1	29.88	16.03	25.3
2015	2	28.38	14.74	15
2015	3	29.05	15.71	2.3
2015	4	25.31	12.86	4.4
2015	5	21.55	11.9	39.5
2015	6	17.59	9.31	116

Year	Month	Maximum temperature (°C)	Minimum temperature (°C)	Precipitation (mm)
2015	7	16.21	8.43	98.4
2015	8	18.79	9.77	52.1
2015	9	20.84	10.61	36
2015	10	25.09	12.33	4.8
2015	11	26.03	12.27	27.7
2015	12	29.18	15.28	20
2016	1	33.63	18.48	18.4
2016	2	30.92	16.64	6.9
2016	3	27.45	14.94	38
2016	4	24.57	13.3	48.1
2016	5	21.7	12.04	20.8
2016	6	17.88	9.63	122.6
2016	7	17.34	9.14	94.8
2016	8	20.6	9.97	58.08
2016	9	20.48	9.32	47.5
2016	10	23.61	10.76	20.57
2016	11	27.7	12.64	2.29
2016	12	29.4	14.3	13.21
2017	1	30.01	15.2	4.57
2017	2	31.15	15.78	0.25
2017	3	29.73	14.6	9.4
2017	4	28.33	15.08	31.75
2017	5	23.75	12.01	11.18
2017	6	17.87	8.97	119.63
2017	7	17.91	8.16	51.82