Economically viable *Eucalyptus* species and hybrid clones for commercial afforestation of mined sand dunes in the Richards Bay area of KwaZulu-Natal

by

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Declaration

I, Christopher Otim Komakech declare that the thesis (or interrelated, publishable manuscripts/published articles or mini-thesis) that I herewith submit for the Doctoral Degree Conservation Biology at the University of the Free State, is my independent work, and that I have not previously submitted it for a qualification at another institution of higher education.

Wherever contributions of others were involved, every effort has been made to indicate this clearly, with due reference to the literature and acknowledgement of collaborative research and discussions. The work was conducted under the guidance of Professor Annabel Fossey [supervisor] and Professor Paul Grobler [co-supervisor].

Christopher Otim Komakech

February 2023

I certify that the above statement is correct.

Study supervisor: Professor Annabel Fossey

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Abbreviations

ANOVA	Analysis of Variance
BD	Basic Density
CA	Cluster Analysis
CSIR	Council for Scientific and Industrial Research
DBH	Diameter at Breast Height
DMRT	Duncan's Multiple Range Test
EPI	Economic Performance Index
GEI	Genotype by Environment Interaction
HT	Height
NRE	Natural Resources and Environment
PCA	Principal Component Analysis
PY	Pulp Yield
RBM	Richards Bay Minerals
RPI	Relative Performance Index
SE	Standard Error
SD	Standard deviation

Abstract

Background: Richards Bay Minerals (RBM) is South Africa's largest mineral sands producer with its principal operations located along the coast just north of Richards Bay in KwaZulu-Natal Province. By dredging the coastal sand dunes, the dune sand becomes nutrient poor and does not support economical land use. *Casuarina equisetifolia* was initially planted for sand dune stabilisation and fuelwood, but its low economic value was of little benefit to the local community. RBM thus undertook a joint venture with the Council for Scientific and Industrial Research (CSIR) to identify genotypes of tree species that were suitable for deployment on the mined sand dunes as alternatives to *C. equisetifolia*.

Methods: In this longitudinal study, a multi-method approach which also included Principal Component Analysis (PCA) was followed to gather and analyse quantitative data over a 6-year period of tree growth. Four trials were established in an alpha lattice design on the mined sand dunes to test 70 genotypes of *Eucalyptus* species and hybrids of related species. Single plot trees were planted in 10 replications per trial, making up 700 trees per trial. The traits of *survival*, *diameter at breast height (DBH)*, and *stem quality* were measured over the 6-year period. At 6 years of tree growth, 26 trees belonging to 13 genotypes were felled to measure their wood and Kraft properties which included, *kappa number*, *pulpability factor*, *screen pulp yield*, *basic density* and *fibre yield*. *Coppicing ability* and *pests and diseases* were recorded on 6-month-old felled tree stumps. Through a stepwise approach, several genotypes with the potential for deployment on the mined sand dunes were identified. Identification of genotypes was achieved by ranking the 70 genotypes according to their relative performance of the traits *survival*, *DBH*, *height* and *stem straightness*, by calculating a Relative Performance Index (RPI). The 13 genotypes of the felled tree population were also ranked according to Relative Performance Index (RPI) values using the traits *kappa number*,

pulpability factor, *screen pulp yield*, *basic density* and *fibre yield*. All 13 genotypes (interspecific *Eucalyptus* hybrid clones) of the felled trees were ranked in the top 15 of the 70 genotype ranking. It thus made sense that these 13 genotypes were appropriate for deployment on the mined sand dunes. They were analysed for their appropriateness for use in the pulp and paper industry, as well as for the woodchips export market, by calculating Economic Performance Indices (EPI) for both market sectors.

Results: The results clearly showed two categories of genotype suitable for deployment on the mined sand dunes. The EPIs revealed a group of genotypes particularly suited to the pulp and paper industry and they consisted of different interspecific hybrid clones of *E. grandis* and *E. urophylla* (G×U). Similarly, the EPIs also revealed a group of genotypes that produced dense wood that would be appropriate for woodchip production for the export market. These genotypes were all different interspecific hybrids of *E. grandis* and *E. camaldulensis* (G×C). The relatively high-ranking pure species of *E. urophylla* (Au7 and Au9) and *C. equisetifolia* (Cas400 and Cas402) also warrant consideration, because they are deployed as seedlings and are substantially cheaper financially to procure than clonal material.

Significance: The knowledge obtained during this study will facilitate the rehabilitation of the mined sand dunes in the Richards Bay area and will also help local communities in gaining access to markets and becoming economically viable.

Keywords: *Eucalyptus* species; clonal hybrids; Richards Bay mined sand dunes; Pulp and paper; Principal Component Analysis; Performance index; Economic index

Chapter 1

Introduction to the Study

1.1 Background to the study

Richards Bay Minerals (RBM) is a South African mining company that operates in the mining and metals industry. RBM is a world leader in heavy mineral sands extraction and refining, and is South Africa's largest mineral sands producer. RBM is a joint venture between Rio Tinto (74%) and Blue Horizon, a consortium of investor along with Host Communities Mbonambi of Sokhulu, Mkhwanazi and Dube, which owns 24%. The remaining shares are held in an employee trust (Silenet & Fikadu, 2018; RBM, n.d.). The company's principal operations are located just north of the coastal town of Richards Bay in the province of KwaZulu-Natal. The company is one of the world's leading mineral producer through extraction of minerals from a 2-kilometer wide and 17-kilometer-long strip of mineral-rich sand dunes (RBM, n.d.). The height of the sand dunes ranges from 60 to 110 metres, with their height increasing northwards.

RBM mines the sand dunes using a dredge mining technique that extracting predominantly ilmenite, rutile and zircon. These materials have widespread use in products ranging from paint to smartphones and sunscreen (RBM, n.d.). The mineral extraction activities of RBM involves several steps. The dune forests and topsoil are first cleared, and thereafter the underlying sand is dredged to remove the minerals from the sand (Camp, 1990). After the removal of minerals from the sand, the "tailings" (the stockpiled sand that has been collected through the dredging process) are shaped to reform dunes. However, vast amounts of mined sand dunes are produced through these mining activities. These sand dunes are relatively nutrient poor and do not support economical land use through forestry or agriculture.

RBM mining activities in the Richards Bay area have had an impact on local communities in diverse ways. Prior to the commencement of the RBM mining activates, local communities were relocated from the lands designated for mining, resulting in limited access to pastoral land for livestock rearing and subsistence farming (Anderson, personal communication). These nutrient poor mined sand dunes are also of little benefit to the local community and do not support traditional crop production. Furthermore, the mined sand dunes have become a major source of pollution in the vicinity of Richards Bay. They pollute the air with widespread atmospheric dust and various chemical emissions (Li et al., 2014; Festin et al., 2019), that have destroyed local floral and faunal biodiversity (Ott, 2017) and contaminated soil and water resources (Pourret et al., 2016; Dlamini & Xulu, 2019).

In South Africa, the Mineral and Petroleum Resources Development Act No. 28 of 2022 (South African Government, 2022a) was passed by the government to make it compulsory for mining companies to rehabilitate the land after mining operations had ceased. The Act requires the integration of economic, environmental, and social aspects into all stages of the mining process to ensure optimised sustainable practices (Casey, 2019). Therefore, in compliance with this law and its own policies, RBM was prompted to develop a programme of sustainable land use options, which they hoped would be of benefit to local communities living in the Richards Bay area. As part of this programme, an initial strategic investigation was undertaken, and it revealed that commercial forestry may be a feasible economic option that could benefit communities living in the area (CES, 2004).

1.2 Problem statement and aim

In the past, RBM had attempted post-mining habitat rehabilitation of the mined sand dunes. This attempt at rehabilitation involved the establishment of plantations of the fuel wood species *Casuarina equisetifolia*. This exotic tree species is fast growing with prolific seeding ability and with the ability to grow in disturbed areas (Warrier et al., 2014). Although *C. equisetifolia* is able to grow on mined sand

dunes, its low economic value does not support much economic development in the local community (Camp, 1990; Fossey & Komakech, 2009). The low productivity of the *C. equisetifolia* plantations led to RBM embarking on a comprehensive investigative study to identify alternative, more economically viable tree plantation genotypes for planting on the mined sand dunes, which would also support the growth and development of the local community. This investigation was undertaken in partnership with the Natural Resources and the Environment (NRE) division of the Council for Scientific and Industrial Research (CSIR). Because *Eucalyptus* tree species and several clonal hybrids have been commercially deployed in the KwaZulu-Natal Province and the inland region near Richards Bay, a wealth of knowledge already exits about a wide range of potential *Eucalyptus* genotypes planted in the broader commercial forestry areas in the Zululand area. Knowledge of survival, growth uniformity, growth rates, yield, wood quality, coppicing ability, as well as susceptibility to pests and diseases is thus available for genotypes that can be tested for deployment on the mined sand dunes. Therefore, the aim of this project was to identify *Eucalyptus* genotypes that could be deployed on the sand dunes in the Richards Bay area as alternative genotypes to *C. equisetifolia*. The main research question of this study was thus:

Which Eucalyptus genotypes can be planted on the mined sand dunes in the Richard Bay area as alternative genotypes to C. equisetifolia?

To meet the aim of the study, the following objectives were devised:

1. To undertake a site inspection and perform site delineation for the establishment of the trials on the mined sand dunes of Richards Bay;
2. To select appropriate genotypes, mostly *Eucalyptus* species and hybrids, for testing on the mined sand dunes;
3. To establish four trials on the mined sand dunes;
4. To assess survival, growth and stem quality traits throughout the 6-year growth period;

5. To assess wood and Kraft pulp properties on 6-year-old felled trees;
6. To assess coppicing ability, as well as pest and disease susceptibility on 6-year-old felled tree stumps; and
7. To identify economically viable germplasm for deployment on the mined sand dunes of Richards Bay.

1.3 Summary of the study methodology

In the quest to identify *Eucalyptus* genotypes and other potential genotypes suitable for deployment on mined sand dunes in the Richards Bay area, a positivistic philosophical viewpoint guided the study. Existing knowledge and understanding of *Eucalyptus* genotype qualities formed the foundation of the investigation. Thus, deductive reasoning was applied in which a multi-methods approach was followed to gather and analyse quantitative data. This was a longitudinal study in which data were gathered at several times during the tree growth period. The study was executed in four phases. In Phase 1, the four trials were prepared and established on the mined sand dunes of Richards Bay. In Phase 2, trial measurements were gathered. Survival measurements were gathered at 2 and 4 weeks after planting, then again at 1, 3 and 6 years of tree growth. Growth and stem quality measurements were gathered at 1, 3 and 6 years of tree growth. Wood and Kraft pulp measurements were gathered at 6 years of tree growth on a subset of trees that were felled. Coppicing ability, as well as pest and disease susceptibility were also assessed on the felled tree stumps at 6 months after felling. The data gathered in Phase 2 were analysed as part of Phase 3 by calculating summary statistics and performing several inferential statistical analyses. In Phase 4, economically viable genotypes were identified by applying a stepwise analytical approach, which included Principal Component Analyses and specifically devised formulas that were used to identify genotypes suited for the paper and pulp industry and for the woodchip export market. Finally, the genotypes were ranked and identified for their appropriateness for use in the two main industries in the Richards Bay area.

1.4 Significance of the study

In this study 70 different tree genotypes, of which the majority were *Eucalyptus* species and clonal hybrid genotypes, were tested for their potential deployment on the nutrient poor mined sand dunes in the Richards Bay area. After an in-depth assessment of genotype productivity, several genotypes were found to be suitable for deployment on the mined sand dunes. During this study, knowledge of how well the different genotypes performed on the mined sand dunes was gained, particularly on survival, growth, coppicing ability, wood, and pulping properties. Another significant outcome of the study was an understanding of how to prepare the mined sand dunes for commercial forestry plantations. This knowledge will go a long way towards facilitating the rehabilitation of mined sand dunes in the Richards Bay area and will also assist local communities in gaining access pulp and paper production markets and becoming economically viable.

1.5 Limitations of the study

Several limitations were identified during this study. Firstly, the research study was conducted on a 30-hectare piece of land for security and other management reasons. This might not be a true reflection of the growth conditions of the approximately 8,000 hectares of mined sand dunes. Secondly, the genotypes used in the study depended on their availability from both the CSIR seed stock, and commercial clones from partner organisations, and therefore only readily available genotypes at the time for planting were selected for assessment. A further limitation to the study was the trial design, which had to be within a limited space demarcated for this study. In addition, old stumps of the previous crop had to be taken into account during planting. Furthermore, a single plot trial design was adopted to accommodate a large collection of genotypes to be tested on the small space. The planting density of 3 × 3 metres was determined by the previous crop planted on the area.

Finally, because of financial constraints, the wood and Kraft pulp property analyses were conducted on a small sub-sample of genotypes.

1.6 Role of the researcher in the study

The researcher's responsibilities in this study were naturally comprehensive. Besides being involved with the planning, which included site inspection, site delineation and selection of genotypes, the researcher was also responsible for many other activities. The activities included, raising of the plants in the nurseries and field establishment of the four trials, training of the field workforce teams recruited from local communities for execution of tasks, the collection of all measurement data throughout the six years of tree growth, the capture and analysis of all measurement data, and general project management activities, which included budgeting and monthly reporting to the CSIR and RBM.

1.7 Ethical considerations

Permission to use the data for this PhD study was granted by Professor Moses Cho from the CSIR. The permission letter is presented in Appendix A.

Permission for this project was granted by the Research Committee of the Department of Genetics, University of the Free State (UFS). Approved Date: 01/06/2021 Project Number: Res 09/2021. The approval letter is presented in Appendix B.

1.8 Layout of the thesis

This thesis is arranged into nine chapters. Briefly, each chapter comprises the following content:

Chapter 1: Introduction to the study

In this chapter, the field of study is introduced. The research problem, the aim, significance, and limitations of the study are also presented, together with a brief summary of the methodology.

Chapter 2: Literature Review

In this chapter, currently available literature is discussed, covering topics such as forestry in South Africa, forestry legislation, *Eucalyptus* taxonomy, *Eucalyptus* breeding, economically important *Eucalyptus* traits and forestry industries.

Chapter 3: Materials and Methods

In this chapter, the philosophical underpinnings, conceptualisation, conceptual framework, and research design are presented. The four phases that were followed to complete the study are described: Phase 1: Trial preparation and establishment; Phase 2: Trial measurement; Phase 3: Trial data analysis; and Phase 4: Genotype selection. The materials, methods and data analysis that accompanied the phases are detailed in full.

Chapter 4: Germplasm survival

In this chapter, the results of the survival measurements gathered in the four trials at 2 and 4 weeks of tree age, as well as at 1, 3 and 6 years of tree growth, are presented.

Chapter 5: Germplasm growth volume

In this chapter, the results of growth volume are presented. Although tree diameter at breast height and tree height were measured in the four trials at 1, 3 and 6 years of tree growth, growth volume, calculated from diameter at breast height and height, is presented separately here.

Chapter 6: Germplasm stem quality

In this chapter, the results of stem quality measurements gathered in the four trials at 1, 3 and 6 years of tree growth, are presented. The stem quality traits included stem straightness, heavy branching, forked stem and butt sweep.

Chapter 7: Wood and Kraft pulp properties, coppicing, pests and disease

In this chapter, the results of measurements performed on 6-year-old felled trees and tree stumps, are presented. The felled trees were processed to measure wood and Kraft pulp properties in the laboratory. Field measurements of coppicing ability and susceptibility to pests and diseases were gathered from the tree stumps at 6 months after feeling.

Chapter 8: Economically viable germplasm for the Richards Bay area

In this chapter, the stepwise approach followed to identify economically viable genotypes for deployment on the mined sand dunes of Richards Bay, is presented. The genotypes identified through this approach are also discussed in terms of their suitability for use in different forestry industries.

Chapter 9: Discussion and concluding remarks

In this final chapter, the key findings of this research project are discussed and compared to related and current understandings. This chapter also contains concluding remarks to the study, as well as recommendations and proposals for future research.

References

Appendices

Appendix A: Permission letter to use the data for this study.

Appendix B: Approval letter from the department of Genetics, UFS, to undertake the study.

Appendix C: Layout of the Steep, Flat and Inland-facing trials.

Appendix D: Extract of DBH and height measurements.

Chapter 2

Literature Review

2.1 Introduction

Thriving forests are an essential part of the health of the planet. Besides providing humans with clean air, forests provide a wide range of products that sustain the livelihoods of many people. The ever-increasing world population has brought about concerns for the world's forests and natural resources (Grebner et al., 2013). Globally, forests cover nearly one third of the land area. These forests are not equally distributed around the world (FAO, 2020). More than half of the world's forests are found mainly in five countries; Brazil, Canada, China, the Russian Federation, and the United States of America. Almost half of these forested areas are relatively intact, while a small percentage (less than 10%) of forest is found in fragments with little or no connectivity. Approximately 34% of the forests are primary forests, defined as naturally regenerated forests of native tree species with no clear indications of human intervention (FAO, 2020).

The biodiversity of forests varies considerably. Forests differ in their type, geography, climate, soils, and human use (FAO, 2020). Most forests are found in the temperate regions and tend to have large geographical distributions. In areas where human populations are relatively dense and agriculture intense, forest biodiversity is less intact, particularly in Europe, parts of China, and in North America. Northern Africa, southern Australia, coastal Brazil, Madagascar and South Africa, have been identified as areas with prominent losses in biodiversity (FAO, 2020).

People depend on forests because of their biodiversity. Forests support the livelihoods of many people worldwide. Forests supply water, mitigate climate change and provide habitats for many pollinators,

which are essential for sustainable food production. It is estimated that forests provide more than 86 million jobs and support many more people (FAO, 2020). Increasingly, forests have been recognised for their role as a nature-based solution to many sustainable development challenges.

2.2 South Africa's forestry resources

The Department of Forestry, Fisheries and Environment (DFFE) is the custodian of South Africa's forestry resources. Forestry resources cover 40 million ha (about 36.7%) of South Africa's land surface area, which includes indigenous forests of all forms and plantations with exotic species (South African Government, 2019). The forestry sector provides jobs to more than 150,000 people and supports the livelihoods of 688,000 rural people. The pulp and paper industry provides about 13,200 direct and 10,800 indirect jobs; sawmilling provides 20,000 direct and 8,000 indirect jobs; timber-board 6,000 jobs; and the mining timber industries 2,200 jobs, while a further 10,000 workers are employed in miscellaneous forestry jobs (South African Government, 2019). The afforested area of South Africa is about 1.22 million ha or about 1.0% of the total South African land area of 122.3 million ha. Forestry contributes 0.6% to South Africa's GDP and supports several manufacturing subsectors. These subsectors include pulp, paper and cellulose manufacturing; sawmilling; pole treating; panel and fibre board manufacturing; mining timber manufacturing, tannin extraction and charcoal manufacturing (South African Government, 2019). In terms of regional GDP, forestry in the KwaZulu-Natal Province of South Africa contributes 3.3%; Mpumalanga 3.2%; Eastern Cape 0.8%; Limpopo 0.7% and Western Cape about 0.2%.

A relatively small land area in South Africa is used for commercial forestry. Only 1% of the afforested area is used for commercial forestry of which 82% is privately owned (South African Government, 2019). Commercial plantations that have achieved Forest Stewardship Council (FSC) certification for compliance with sustainable management practices stand at 82% (DAFF, 2015).

The Mpumalanga Province has the highest investment shares in plantations at R19.6 billion (41.9%), followed by KwaZulu-Natal with R16.6 billion (35.6%), the Eastern Cape at R6.4 billion (13.7%), Limpopo R2.1 billion (4.75%) and the Western Cape at R2.0 billion (4.4%) (South African Government, 2019).The share of planted area by species type is 51% hardwood species and 49% softwoods.

In South African commercial forestry, mainly three types of trees are planted. *Pinus* and *Eucalyptus* are the two genera that are predominantly planted, whereas additionally *Acacia* plantations make a small contribution. The plantations of these three genera include over 40 species and many more clones (FSA, 2021). *Pinus* makes up 51.1% of the plantations, with *Eucalyptus* making up 48.6% and *Acacia* 7.9% (South African Government, 2019). These commercial forestry tree species are grown mainly to produce pulpwood (57%), saw logs (38%), and for mining timber (2%). The remaining 3% is used for miscellaneous purposes, with for example *Acacia* bark being used in the tanning and adhesives industry.

2.3 Eucalypt taxonomy and distribution

The taxonomical group of eucalypts includes species in three main genera that include *Eucalyptus*, *Corymbia* and *Angophora* (Slee et al., 2006; Myburg et al., 2014). Eucalypts are mostly identified by either the fusion of the sepals or petals which form an operculum structure from which their naming is derived. The Greek word *eu* means “well” whereas calyptos means “covered” (Eldridge et al., 1993). The operculum has probably undergone evolution independently in different eucalypt ancestries, which was not true in *Angophora* (Ladiges, 1997; Myburg et al., 2014). Still today there is debate as to whether the genera *Corymbia* and *Angophora* (blood wood taxa) warrant separation from the genus *Eucalyptus* (non-blood wood taxa). Evidence of the separation is supported by several molecular studies done independently (Steane et al., 2002; Ladiges et al., 2003; Myburg et al., 2014). Brooker (2000), in the more recent taxonomic revision of the eucalypts, recognises more than 700 species that

belong to 13 main evolutionary ancestry, with the blood wood eucalypts as subgenera of Symphyomyrtus which contains some of the economically productive species including *Eucalyptus grandis*, *Eucalyptus urophylla* and *Eucalyptus globulus* (Doughty, 2000; Grattapaglia et al., 2012). However, that number has been revised upward recently to nearly 900 species (Boland et al., 2015). Most of these species dominate the tree flora of Australia (Government of Australia Bureau of Rural Sciences, 2008).

The genus *Eucalyptus* is mainly planted in the southern hemisphere in areas experiencing both tropical and sub-tropical climate. *Eucalyptus* is a diverse genus of trees comprising many species of different forms that include which include some of the tallest flowering plants on the planet (Boland et al., 1985; Potts et al., 2003). The genus *Eucalyptus* belongs to the division Angiospermae, class dicotyledon, order Myrtales, and family Myrtaceae. However, two species of *Eucalyptus* are of non-Australian origin occur in Papua New Guinea and Timor (Pryor, 1981). The distribution of the genus covers a wide latitudinal range from 7ºN to 43ºS. This distribution is partly enhanced by its wide usage by diverse groups of communities in the world who depend on *Eucalyptus* for meeting their basic domestic needs such as fuelwood for cooking and poles for building purposes (Oballa et al., 2010; Mengistu et al., 2020).

The genus *Eucalyptus* has the ability to adapt to a range of different environmental conditions. This unique capability to adapt bear its roots from rainforest origin, and evolution over millions of years under changing extreme global conditions (Eldridge et al., 1993). The genetic variation that exist within the genus is influenced in parts by wide geographical distribution, since both gene flow and genetic drift are triggered differently in non-uniform environments (Eckert et al., 2008). Natural hybridisation is a normal occurrence amongst *Eucalyptus* species and is considered to have played a role in the evolution and diversity of the species within the genus (Potts & Reid, 1990; Barbour et al., 2007). Hybridisation as it is known facilitates gene flow resulting in more homogeneous populations. This

process can also generate unique adaptive phenotypes that can lead to heterogeneous populations (Rieseberg et al., 2003). Within particular species, differentiated genetic groups at population level are a common occurrence (Pryor & Johnson, 1971; Pryor, 1981; Dutkowski & Potts, 1999). Genetic variation between populations in quantitative traits is often continuous, and is affected mainly by environmental gradients and are associated mainly with changes in latitude, continent, or altitude (Pryor, 1976; Potts & Wiltshire, 1997). Many recognised species hybridise along such gradients, resulting in complexes of closely related species with no clear morphological discontinuity (Jordan et al., 1993; Holman et al., 2003). *Eucalyptus* species and their hybrids are now amongst the most widely planted commercial trees globally. This has been possible because the genus has the ability to flourish under diverse growing conditions typical in both tropical and sub-tropical zones (Pryor & Johnson, 1971).

2.4 History of *Eucalyptus* in South Africa

Eucalyptus was introduced into South Africa as an exotic tree early in the 19th century. These eucalypts plants were introduced in 1823 when nine seedlings of *Eucalyptus globulus* were brought to the Cape Colony from Mauritius by Sir Lowry Cole, the then governor (Poynton, 1979). Initially experiments were performed in arboreta together with *Pinus* and *Acacia* species (Foelkel, 2008). Around 1930, commercial *Eucalyptus* forestry started to intensify to meet demands for wood destined for underground mining. *Eucalyptus grandis*, known as saligna gum, was imported and established locally for this purpose. By 1950, the *Eucalyptus* forest base in South Africa was 170,000 ha, which has since grown to its current base of more than 500,000 ha (DAFF, 2019). By 1979, Poynton could list 134 *Eucalyptus* species that had been tested in experimental plantings of a reasonable scale, and 62 species that had been tested in very limited trials. From 1970 to 1990, research started to play a pivotal role in forest improvement in South Africa. Besides classical *Eucalyptus* breeding, a fundamental component of *Eucalyptus* improvement today emphasizes molecular breeding and forest

biotechnology (Foelkel, 2008). In South Africa, *E. grandis* and its hybrids continue to be the most important genetic material and are the most cultivated hardwoods in the country (Hajari, 2004; Komakech, 2008).

2.5 *Eucalyptus* plantations in South Africa

The South African forestry industry is heavily dependent on exotic forestry species of *Eucalyptus.* The total area under *Eucalyptus* plantation is approximately 520,000 ha as pure species, or interspecific hybrid clones (DAFF, 2019). The origins of *Eucalyptus* have allowed it to adapt and grow in both favourable and unfavourable conditions, which are commonly found in South Africa (Morris, 2008). The species *E. grandis* has traditionally been the preferred hardwood species for the forestry industry, mostly because of its rapid growth and acceptable wood properties (Poynton, 1979; Denison & Kietzka, 1993). However, an increase in demand for hardwoods, particularly for the pulp and paper industry in the late 1980s, resulted in the expansion of hardwoods into low productivity sites where *E. grandis* performs poorly (Swain & Gardner, 2003). These low productivity sites are generally drier and warmer, or drier and colder and therefore not suited to the plantation of *E. grandis.*

In warm and humid regions, *E. grandis* demonstrates increased susceptibility to pests and diseases (Darrow, 1994). The fungal pathogens that are responsible for causing diseases include *Crysoporthe austroafricana* and *Coniothyrium* sp. (Van Zyl & Wingfield, 1999; Van Heerden & Wingfield, 2002), especially in regions experiencing sub-tropical climates as is found in the Zululand area of South Africa (E. C. L. Retief & Stanger, 2009). Lately, *E. grandis* has become susceptible to the gall wasp *Leptocybe invasa*, whereas *Eucalyptus urophylla* appears to be more tolerant of insect pests diseases in the Zululand area and is therefore often used as a hybrid partner with *E. grandis* (E. C. L. Retief & Stanger, 2009; Mphahlele et al., 2021).

In colder and higher altitude areas, *Eucalyptus nitens* is the preferred species. This species is well adapted to the range of environmental conditions encountered at cold, high altitude sites in the summer rainfall regions of South Africa, particularly in areas as high as 1,350 m and with Mean Annual Temperatures (MAT) greater than 13ºC, but less than 16ºC (Swain & Gardner, 2003; Gardner & Bertling, 2005). Therefore, *E. nitens* has become the most favoured eucalypt for commercial pulpwood production in these areas (Clarke, 2000; Little et al., 2002). The previously planted species in the colder areas suitable to *E. nitens* that include; *Eucalyptus fraxinoides*, *Eucalyptus regnans*, *Eucalyptus fastigata*, *Eucalyptus oreades*, and *Eucalyptus elata* from the subgenus *Monocalyptus* have largely been replaced with *E. nitens*, primarily because of the former species' susceptibility to pests and diseases, poor growth performance, poor wood properties and market shift (Clarke & Jones, 1998; Clarke, 2000).

Interspecific clonal hybrids have been developed for both warm subtropical and colder more temperate sites that are not suited to growing of *E. grandis.* As early as the 1980s, the forestry industry in South Africa embarked on the development, testing and commercial deployment of alternative *Eucalyptus* species and interspecific hybrid clones at low productivity sites (Gardner, 2001). In the warmer Zululand regions of KwaZulu-Natal, *E. grandis* is being replaced with the clonal hybrids of *E. grandis* × *E. urophylla* and *E. grandis* × *E. camaldulensis* (Morris, 2008; Jacob et al., 2015). These clonal hybrids are better alternatives for subtropical areas and have the benefits of faster growth and improved disease tolerance (Denison & Kietzka, 1993). By contrast, in the cooler regions of the KwaZulu-Natal midlands, *E. grandis* is being replaced with interspecific hybrids of *E. grandis* × *E. nitens*, which have superior tolerance to frost (Clarke et al., 1997).

New species are introduced and investigated for their potential to be commercially deployed in South Africa. Most of these species originate from areas in Australia experiencing similar growth conditions to South Africa (Gardner, 2000). In the summer rainfall timber growing areas, cold-tolerant *Eucalyptus*

badjensis and *Eucalyptus benthamii* have been introduced for their potential deployment on sites too cold and dry for *E. grandis* (Swain & Jones, 2004; Gardner et al., 2007). Komakech (2008) showed that *Eucalyptus nobilis* could be developed for deployment on cold and frosty low productivity sites.

Several eucalypts are currently under investigation for deployment in the subtropical low productivity coastal areas in Zululand and KwaZulu-Natal. *Eucalyptus longirostrata* has demonstrated that it may be an alternative source of pulp, because of its high disease resistance, vigorous growth, acceptable pulp quality, and high fibre productivity (Gardner, 2001; Gardner et al., 2007). Subsequently, the hybrids of *E. grandis* × *E. longirostrata* and *E. urophylla* × *E. longirostrata* were developed by the CSIR's Tree Improvement Group in collaboration with the NCT Forestry Co-operative Ltd for testing as pulp sources. Other tree species have also shown productivity potential for the coastal region. The species *Corymbia henryi*, *C. citriodora* ssp. *citriodora*, *E. pilularis* and *E. tereticornis*, have all demonstrated good overall growth and the potential for wood and fibre productivity (Gardner, 2001).

2.6 *Eucalyptus* breeding

Tree breeding is an integral part of operational silviculture for most plantation forestry programmes. Tree breeding programmes aim to develop genetically improved germplasm for afforestation. Most tree breeding programmes have breeding strategies in place, which involves selective breeding for general combining ability (Van den Berg, 2017). The goal of breeding is to improve performance of the population while maintaining genetic diversity, rather than to develop outstanding genotypes for immediate use. Through repeated cycles of selection, breeding, and genetic testing, the frequency of favourable alleles of a few important traits are progressively increased. Thus, through genetic tests during each cycle of breeding, parents in the breeding population are ranked so that gains can be increased through selection. Each breeding cycle thus produces quantifiable gains and results in the selection of the most productive individuals (parents) needed to produce improved seed and clonal

hybrids. Important aspects of a tree breeding programme include the design, implementation, and analysis of genetic tests so that genetic gains can be maximised at minimum cost per unit time. Therefore, when formulating the breeding objectives of a breeding programme, they must be aligned with the long-term business strategy. The most relevant breeding objectives and related traits should be considered (Rezende et al., 2014). An understanding of the genetic control and correlations between the important traits is very important, as this will impact different choices and activities related to the breeding programme.

For effective implementation of tree breeding strategy, there is a need to have in place three sets of populations; a base population, a breeding population and a production population. The aim for having effective breeding programme is to have a well-adapted and broad genetic base with sufficient genetic diversity that can be sustained over time (Eldridge et al., 1993). The breeding population is derived from the base population and comprises progeny trials and clonal archives in which the breeding cycle of selection and mating is repeated over many generations. Tree breeders constantly on the look out to improve breeding populations, while ensuring that inbreeding is minimised (Eldridge et al., 1993). A production population of a given generation is constitutes individuals from the breeding population. The selections are used to produce genetically improved offspring for operational afforestation. Genetic gains in tree breeding programme rely heavily on effective selection (Cotterill & Dean, 1990). Forward selection involves selection of the best individuals within the best families, based on data assembled from an individual and its family (siblings). On the other hand, backward selection involves the selection of parents based on the performance of their offspring (Shelbourne et al., 1999). Decisions about which traits to base the selection on, the optimum age to select and the method of selection are thus important aspects to consider in the breeding programme (Rezende et al., 2014). If vegetative propagation is possible in a species, superior selections can be cloned into clonal archives or clonal seed orchards for production of open-pollinated or control-pollinated elite seed. The most relevant breeding objectives to consider in *Eucalyptus* breeding, according to Rezende et al. (2014),

include: (1) increased productivity, (2) increased tolerance to pests and diseases; (3) increased rooting ability, and (4) attention should be given to wood basic density which is relevant to almost all end uses.

Mating with common parentage (full-sib) through controlled pollination and only one shared parentage (half-sib) through open pollination are options available in breeding programmes. Through full-sib mating, inbreeding is partially avoided, good specific combiners can be identified, and good estimates of full-sib performances can be obtained (Hamilton et al., 2008). Controlled pollination is usually performed in specific controlled crosses across trials, breeding lines or generations, while most selections are performed in families. Mating mating designs are necessary for the creation of structured, pedigreed families for testing, allows for the accurate assessment of genetic parameters and selection of superior genotypes to be used in breeding and seed orchard establishment (Lambeth & Dill, 2001). The difficulty in performing full-sib mating programme is the abnormally high number of crosses required to meet breeding objectives, which can logistically be difficult and costly in terms of both financial and human resources. Furthermore, the resultant offspring of full-sib crosses in some cases may not be the offspring of the intended parents (El-Kassaby & Lstibürek, 2009). In contrast to full-sib crosses, in half-sib crosses only one maternal parent is known and inbreeding is rarely controlled. These half-sib crosses may result in decreased genetic variation over time because of lack of diversity. Half-sib crosses are suitable for both between family and within-family selection, and therefore, can be used to determine general combining ability status of parents (Otegbeye, 1998).

2.6.1 *Eucalyptus* hybrid breeding

Interspecific hybrids of *Eucalyptus* have been part of the forestry industry for a long time. *Eucalyptus* and its hybrids have become some of the world's leading sources of woody biomass and the largest plantation hardwoods used for pulpwood and timber production (Madhibha et al., 2013). The use of hybrids became known since the widespread use of *E. urophylla* × *E. grandis* hybrid clones in Brazil (R. Griffin et al., 2008) and the Congo (Vigneron et al., 2000). Initially, plantations were established

from hybrids that arose naturally (Potts & Dungey, 2004). Thereafter, the introduction of intentional hybridisation into breeding programmes commenced rapidly. *E. grandis* and several of its hybrids are currently being grown extensively in South Africa (Verryn et al., 1996). The use of hybridisation comes at a relatively low cost in a breeding programme, but with great impact (de Assis et al., 2004). Hybridisation allows for the combination of superior wood characteristics with tolerance to biotic and abiotic stress, and thus providing a source of superior individuals, capable of yielding genetic gains in forest productivity and wood properties. Crossing *Eucalyptus* species of different characteristics allows production of complementary wood properties in trees to meet industry requirements. Reasons proposed for the superiority of hybrids over pure species include: (1) heterosis (de Assis et al., 2004), (2) complementarity, where, for example, the intermediate expression of traits in the hybrid is superior, when compared to the extreme expression of these traits in the ancestral species (de Assis et al., 2004), and (3) exploitation of greater allelic diversity through recombination and selection within backcrossed or advanced generation hybrids (Potts & Dungey, 2004).

The gains from clonal selection are a dead-end for a population. Thus, breeding programmes based on recurrent selection (recombination, evaluation and selection in successive generations), are required to allow for the generation and deployment of new commercial clones (Rezende et al., 2014). Extra effort is needed in clonal breeding, because evaluation of individual performance in progeny trials is not robust enough to predict performance of the same individual as a clone over a range of different environmental and silvicultural conditions (Reis et al., 2011). This necessitates two evaluations and selection phases, which greatly impact on the time required for clonal deployment. Two alternative approaches are under investigation, but still need to be proven operationally (Rezende et al., 2014): (1) simultaneous testing of families and clones, and (2) molecular techniques based on the direct identification of useful variation at the DNA level following marker-assisted selection (MAS) approaches. Genomic-wide selection (GWS) is a form of MAS in which genetic markers covering the whole genome are used so that all quantitative trait loci (QTL) are in linkage disequilibrium with at

least one marker (Rezende et al., 2014). This approach became feasible, with the discovery of a large number of single nucleotide polymorphisms (SNP). In this approach, genomic breeding values (GBV) of individuals can be predicted in an experimental or "training" population, based on prediction models constructed from regressing phenotypes on whole-genome marker genotypes for several hundred to a few thousand individuals. These prediction models can then be used to estimate the GBVs of yet to be phenotyped individuals at early ages based on marker data only (Grattapaglia et al., 2009).

2.6.2 Data analysis in tree breeding

Data analysis in tree breeding programmes are executed through statistical modelling frameworks. Scientific research usually involves the construction of an appropriate statistical model that adequately characterises relationships or phenomena (Smith and Edwards, 2017). Relationship is based on the specification of expected values and variance-covariance structures of observed data (Stroup, 1989). The traditional fixed linear model is considered restrictive in nature, the normality assumption usually succumbs to a lack of robustness against departures from the normal distribution. Confirming the normality assumption is not an easy task for random effects; hence its suitability becomes questionable (Ghidey et al., 2004). In contrast, the general linear mixed model can accommodate covariances among observations. The mixed model handles correlated data by incorporating random effects and estimating their associated variance components to model variability over and above the residual error (Wolfinger and Tobias, 1998). Because of the estimation procedures usually involved, mixed model approaches can circumvent the troublesome for handling unbalanced and incomplete data.

Advances in statistical procedures in recent years has enabled development of a general algorithm using mixed model approaches. Linear mixed models are perhaps the most popular class of models for statistical analysis, which includes analysis of variance (ANOVA) models of a broad spectrum of areas, such as multilevel, clustered data, repeated measures, and longitudinal data (Agostinelli and

Yohai, 2016; Kuran and Özkale, 2021). These models are applicable to data that satisfy the normality assumption, making it possible to use of maximum likelihood (ML) principle in parameter estimation (Agostinelli and Yohai, 2016). In contrast, Restricted Maximum Likelihood (REML) has been developed for estimating variance parameters in linear mixed models (LMM) using algorithm which is not dependent on balance (Gad and EL-Zayat, 2018). Restricted Maximum Likelihood (REML) allows for spatial and/or temporal correlations, so can be used for repeated measures or field-correlated data. Restricted Maximum Likelihood (REML) procedure allows for changing variances, so can be used in experiments where some treatments (for example different spacing, trees growing duration, plot sizes induced competition) have a changing variance structure.

Unbalanced and incomplete data set can be as a consequence of many reasons which demand for compromises. These brings complications for meeting objectives of research trials to identify the best genotypes for a site should be designed as a sequence of trials (Eldridge et al. 1993). According to Rosemary and Trevor (2009), trial designs are often compromises between available resources and the statistical robustness of trials. Reasons for the compromises may include; limited availability of land, lack of land units of suitable size with appropriately homogeneous climate and soil types, occurrence of environmental gradients across the site, cost of establishment and maintenance of a research trial and limited availability of appropriate genetic material. Therefore, it is always important to understand the variance-covariance structure of the dataset first before blindly assuming the classical structure. Ideally, an adequate variance-covariance structure is the one with the least number of parameters, which eventually provides a larger number of degrees of freedom for the tests and estimates.

2.7 Economic importance of *Eucalyptus*

Eucalyptus plantation forestry is of economic importance because of the increasing demand for a diverse range of wood products in the market. *Eucalyptus* is a highly rated genus because of its high biomass production at short rotation, ease of cultivation and wide adaptability to varying climates and soil conditions (Silenet & Fikadu, 2018). Economic profitability and productivity of plantation trees for different end products depend on repeated cycles of selection and breeding for multiple traits, of which the traits survival rate, growth volume, wood and pulp properties, the stem quality, and resistance to pests and diseases are important.

2.7.1 Survival

Plantation forestry takes place across a wide variety of edaphic and climatic conditions. Soil moisture conditions at planting have a strong effect on initial plant growth and survival (Breugel et al., 2011). While the number of trees planted can be an important factor in gauging the potential impact of these efforts, tree establishment and longevity must ultimately be considered when assessing long-term afforestation success (Eshetie et al., 2020). Plantation establishment is a costly activity and thus if seedling or clone plantlet mortality is high an additional cost of replanting will be incurred (Thomas, 2009). Besides planting high quality genotypes, plantation management is of the utmost importance in reducing the risk of mortality of the planted material.

To maximise the survival of the planted material, several aspects should be considered. Initially, the choice of species should be based on recommendations derived from trials matching species with particular sites (Malan, 1993; Darrow, 1995; Komakech et al., 2013) For example, the survival of *Eucalyptus* species and hybrids were tested in trials on the semi-arid west coast plain of South Africa (with mean annual potential evapotranspiration ranging from 0.21 to 0.36 mm and mean annual precipitation from 228 to 423mm (du Toit et al., 2017). Mortality was high on the driest site, however,

Eucalyptus gomphocephala, *E. camaldulensis* and *E. tereticornis*, as well as *E. grandis* hybrids with *E. camaldulensis* and *E. tereticornis* survived and grew well on the less dry sites. *Eucalyptus cladocalyx* survived well and attained competitive growth rates only on the wettest site. The quality of plant material, as well as age are a major consideration and could influence the potential for survival during the establishment phase of a plantation (Zwolinski et al., 1995; Morris, 2008). Naidu and Jones (2007) showed that seed size effects of *E. grandis* and *Eucalyptus smithii* seed germination were transitory, and only apparent in the nursery, which indicated that smaller seeds can be used in a commercial nursery if they are sown with similar sized seeds to allow for management of poor germination and crop uniformity. Plantation planting espacement is another important consideration. For example, the survival rates of *E. grandis* trees planted in Zululand were much lower in high plant density plots than in plots with lower density (Dickel et al., 2010). After planting, post-planting care is important (Abraham, 2014). The application of appropriate silvicultural practice standards is essential for the specific conditions of a site (Turvey, 1996). Soil moisture is of utmost importance during the initial stages of plantation establishment and should be carefully managed (Eshetie et al., 2020).

2.7.2 Growth properties

Productivity in plantation forestry is one of the most important factors to consider in the industry. Forest site productivity is defined as the amount of stem dry matter produced per unit of area and time (Whitehead & Beadle, 2004). The productivity of a plantation is the result of the interaction among edaphic, climatic, physiographic and biotic factors, and is also influenced by adopted forest management and silvicultural practices (Resende et al., 2018; de Freitas et al., 2020). By understanding the factors that influence the productivity and resource use efficiency of a site, a manager is able to implement correct selection and treatment decisions so that industry demands can be met (Resende et al., 2018; de Freitas et al., 2020). Land use conflicts, high land purchase prices, and owners' objectives, have all compelled forest managers to apply more intensive silvicultural treatments to increase site productivity at existing sites. The growth rates of trees are determined by

the quantity of photosynthetically active radiation (APAR) and how efficient this radiation is used to convert atmospheric CO_2 into carbohydrates, expressed in the amount of stem wood per amount of absorbed light (le Maire et al., 2019). The highest *Eucalyptus* productivity in the world was reported for *E. grandis* and hybrids between *E. grandis* and *E. urophylla* in Brazil, reaching yields of mean annual increments (MAI) of around 80 m^3 ha^{-1} y^{-1} in the most productive areas (Stape et al., 2010; Pulito et al., 2015). This high productivity was as a result of genetic characteristics, breeding, silvicultural techniques and favourable edaphoclimatic conditions (Pallett & Sale, 2004).

The role of edaphic properties in forest productivity should be an important consideration in ensuring significant gains. Organic matter and clay content in soil determines soil water availability and explains greater yields in some plantation sites (Gonçalves et al., 2012). *Eucalyptus* plantations in Brazil planted on soils with greater water availability were characterised by higher productivity, whereas plantations planted on soil with low water availability showed lower productivity even with fertiliser (Stape et al., 2010; da Silva et al., 2013). Tree water-use efficiency (WUE) is also a critical factor considered for the evaluation of tree performance (Lévesque et al., 2014). Four different *E. grandis* clones growing on the same site in South Africa showed large differences in WUE, as a result of differences in growth rates rather than transpiration rates (Lévesque et al., 2014; Battie-Laclau et al., 2016). Stocking or stand densities also determines the resultant size of a tree. Although higher stockings or stand densities often reduce diameter growth, mean height or mean dominant height (often defined as the tallest 100 trees ha^{-1}) is generally less affected by stocking in eucalypts (Forrester et al., 2010). Stand volume often increases significantly up to about 1,200 trees ha^{-1} with smaller increases thereafter.

Silvicultural practices play a major role in plantation productivity. Typically, silvicultural practices that increase tree growth increase WUE (Battie-Laclau et al., 2016). Fertiliser for example, increases light interception, photosynthesis, and the partitioning of photosynthates to stem wood growth, with tree

growth increases typically exceeding any increase in water use (Whitehead & Beadle, 2004). In a trial of a *E. grandis* × *E. camaldulensis* hybrid planted at a subtropical site in KwaZulu-Natal, South Africa, a manual weeding treatment produced 62% more merchantable timber, with an increased sale profit margin of 30%, when compared to the non-weeded control (Little & Van Staden, 2005). This result demonstrated the potential gains that can be obtained through vegetation control.

Standing trees are commonly measured for diameter and height. Diameter and height measurements are used to estimate the volume and thus the value of individual trees (Burkhart, 2007). Traditionally, diameter is measured as diameter at breast height (DBH), which is measured at a height of 1.3 – 1.4 m above the average ground line with dendrometers, such as tapes or callipers. In South Africa, tree height is measured using hypsometers. Measurements are taken at a fixed horizontal distance from a tree and the height calculated by applying trigonometry principles.

2.7.3 Wood qualities

Wood is an important material because it is a sustainable and renewable resource. Forest plantations provide raw material for different end-use products at the marketplace, including pulp and paper, energy products, wood panels and sawn wood (Rocha et al., 2019). The term “wood quality” describes the attributes that make wood valuable for a particular use. For example, attributes of interest to paper production are low density wood combined with long fibres, which provide collapsible, easy bonding fibres that exhibit low porosity and high strength. By contrast, structural wood requires high density wood, with small knots, and straight grain characteristics to ensure high quality products (Joza & Middleton, 1994).

Currently, the pulp and paper industry is the major market for *Eucalyptus* wood, with several major product classes. *Eucalyptus* species and its hybrids are among the most important short-rotation hardwoods, planted worldwide for the pulp and paper industry (Rocha et al., 2019). Even though the

genus *Eucalyptus* comprises more than 700 species, only about a dozen species are used for pulping purposes (Neiva et al., 2015). Tree breeders are continually searching for new additions to this collection. In the last two decades, interest in using *Eucalyptus* plantations for saw timber, veneers and reconstituted wood products has grown substantially (Raymond & Apiolaza, 2004). By recognising the need to breed for wood properties, forestry companies have in recent times placed more emphasis on aligning breeding programmes with economic objectives to address the suitability and economic viability of various range of products (Table 2.1)

Table 2.1 Markets, products and economic drivers.
(Taken from Raymond and Apiolaza, 2004)

Market	Product type	Product	Economic driver
Pulp and paper	Kraft pulp	Photocopy paper Fine writing paper	Chemical consumption
	Mechanical pulp	Newsprint	Energy consumption, Paper quality
Solid timber	Sawn timber	Furniture Flooring Structure	Recovery (green and dry), grade, drying cost, drying degrade, sawing productivity
Composites	Veneers	Furniture Laminated veneer lumber	Recovery, grade, degrade during drying, glue usage
	Composites	Medium density fibre board Orientated strand board	Resin/glue usage, energy consumption

Knowledge of economic drivers determines their relationships with a desirable tree. Therefore, wood properties play an important role in the quality of wood products (Little & du Toit, 2003; So et al., 2004). Several key properties have been linked to particular wood end products as shown in Table 2.2

Table 2.2 Key wood properties linked to a range of end products.
(Taken from Raymond and Apiolaza, 2004)

Paper and pulp	Sawn timber	Composites
Wood property		
Basic density Pulp yield Cellulose content Fibre length	Basic density and gradient Microfibril angle	Basic density Lignin content Extractives content Cellulose content
	Shrinkage and collapse Tension wood Knot size Incidence and decay, spiral grain and end splits	
Product property		
	Strength stiffness Dimensional stability Lack of internal checking, cook and bow	Strength stiffness Durability Gluability Hardness

Wood has a heterogeneous nature and a complex composition. Wood comprises non-structural and structural components (Kilulya et al., 2014; Penín et al., 2020). The non-structural components are mainly extractives, which include resins, oils, alcohols and fatty acids. The structural component, on the other hand, makes up about 90% of the dry weight and includes cellulose, hemicellulose and lignin. Amongst the wood extractives, the lipophilic extractives are resistant to the pulping chemicals, which negatively impacts the pulping process and the quality of the pulp (Kilulya et al., 2014).

Because of the complex nature of wood, wood properties vary greatly amongst trees of the same species. Wood properties can be categorised into physical and chemical properties (Malan & Hoon, 1992). The main physical properties of wood are basic wood density and the angle of microfibrils situated in the cell wall. The angle of microfibrils is a major determinant of the strength of solid wood products (Sandercock et al., 1995). Chemically, wood properties relate to the chemical constituent of cellulose, hemicellulose, lignin, and extractives (Clarke, 2000). These properties are important determinants to consider for the different end use wood products. For example, they play an important

role in determining pulp yield and rate of delignification in *Eucalyptus* pulpwood paper production (Sandercock et al., 1995; Clarke, 2000; So et al., 2004).

The properties of wood are governed by tree genotype and environment. One of the important factors that influences wood property variation is the tree growth of the trees (Zobel & Buijtenen, 1989). Environmental influences include the climate, site properties and silvicultural practices (Rocha et al., 2019). Silvicultural practices include irrigation, thinning, plant spacing, pruning and fertiliser application. The effect of silvicultural practices on *Eucalyptus* planting can influence tree growth, as revealed in many studies, of which some examples are shown in Table 2.3.

Table 2.3 Examples of studies showing the effect of different silvicultural treatments on wood properties.

Species	Silvicultural treatment	Major finding	Reference
E. grandis × *E. urophylla*	Plant spacing Irrigated and non-irrigated	Larger spacing levels: higher lignin and hemicellulose levels Irrigated area: higher levels of extractives	Moulin et al. (2015)
E. grandis × *E. urophylla*	Soil slope Wind regime	Land without inclination: Higher wood density Area with higher wind regime: higher MFA and MOE variation	Hein et al. (2016)
E. grandis × *E. camaldulensis*	Plant spacing	Larger spacing: tend to produce trees with denser woods	Rocha et al. (2019)

Most of the world's short fibre pulp is produced from *Eucalyptus* species. Growth, basic wood density, and pulp yield are imperative traits for breeding programmes focused on pulp and paper production (Hamilton et al., 2017). Pulp and paper industries are interested in tons of pulp produced per hectare per year, which is calculated from the product of the mean annual volume increment, basic wood density, and pulp yield (Gallo et al., 2018). Thus, wood quality traits (basic wood density, pulp yield,

lignin content, and extractive content) should be determined before pulping studies commence (Gallo et al., 2018).

Wood properties vary between *Eucalyptus* species. This variability is heritable and can be integrated into breeding programmes to obtain varieties with improved wood properties, thus enhancing the quality of the end product (Bailleres et al., 2002). It is generally accepted that wood density is a key trait in determining whole wood quality and is usually the first trait to be assessed in a tree breeding programme (Rocha et al., 2019). Basic wood density is the mass of oven-dry wood per volume unit of wood in green condition (Zobel & Buijtenen, 1989). Basic wood density variation is caused by variation in wood anatomical structure and the amount of extractive substances per volume unit. This directly influences many wood attributes, such as strength, shrinkage and pulp yields (Joza & Middleton, 1994). Increased cell wall thickness of fibres or an increase in the proportion of fibres to the proportion of vessels may result in an increase in density. Conversely, an increase in the proportion of vessels with or without a decrease in cell wall thickness leads to a reduction in density (Oliveira & Silva, 2003). The density of wood directly influences wood attributes, including attributes such as shrinkage and pulp yields (Joza & Middleton, 1994). Table 2.4 provides a number of examples of *Eucalyptus* studies for wood and pulp production.

Table 2.4 Examples of eucalypt studies for wood pulp production.

Species	Aim	Major finding	Reference
E. grandis × *E. urophylla*, *E. grandis and E. dunnii*	To identify suitable wood materials for pulping with respect to their lipophilic extractives contents. The effect of site, species and tree sizes on the amount of lipophilic extractives was evaluated in trees planted in South Africa.	High amounts of lipophilic extractives were found in trees grown at sites of high clay soil and organic matter. *E. dunnii* was found to contain a higher amount of lipophilic extractives than *E. grandis* in all the sampled sites, implying an increased risk of pitch formation during the pulping process.	Kilulya et al. (2014)
E. dunnii	The phenotype index mean annual pulp increment was calculated using the values of mean annual increment, basic wood density,	*E. dunnii* clone was better than the commercial control clone for annual pulp mean increment. Therefore, the selection based on growth and wood quality traits is essential for pulp and paper sector.	Gallo et al. (2018)

Species	Aim	Major finding	Reference
	and pulp yield for trees planted on different sites.		
E. camaldulensis	Suitability of wood as raw material for pulp and paper products using principal component analysis (PCA) and clustering was determined.	Significant differences in fibre diameter, fibre lumen diameter, and Runkel ratio were found among families.	Nezu et al. (2021)
E. globulus and *E. nitens*	Wood properties and fibre quality of 6-year-old trees were determined using PCA.	*Eucalyptus nitens* trees had a higher density and amplitude average and smaller Pilodyn values than *E. globulus* trees, while the latter had higher coarseness, fibre length and diameter at breast height than *E. nitens* trees. However, *E. nitens* showed larger differences between features of early wood and latewood in a growth ring than *E. globulus* trees.	Carrillo et al. (2017)
E. nitens	Wood properties affecting the quality of pulpwood and peeled veneer products were studied	Results indicate that it should be possible for breeders to simultaneously improve properties in pulpwood and peeled veneer products and that Acoustic wave velocity measured in the standing tree shows promise as a breeding selection criterion for both pulpwood and peeled veneer products.	Hamilton et al. (2017)
E. camaldulensis	To promote solid wood production, the diameter at breast height, height, stress-wave velocity, surface-released strain, basic density and compressive strength parallel to the grain were measured for 10 half-sib families of 12-year-old trees.	No significant correlations were found between growth characteristics and wood properties. Significant variances in the height, stress wave velocity, and basic density were found among families. To obtain trees for solid wood production, family selection should be conducted using the outer wood of aged trees.	Nezu et al. (2020)
Thirteen angiosperms and 12 gymnosperms including *Casuarina* and *Eucalyptus*	The hypothesis was tested that wood density variation in provenance trials would be shaped by the provenance climatic variables using thirty publications published between 1966 and 2015, which included 25 species.	Eight species showed significant positive correlations between wood density and drought conditions of the provenance, two species showed the opposite trend and the remaining 15 species showed no correlation with the climatic conditions of the provenances.	Nabais et al. (2018)
Corymbia henryi, *C. citriodora* ssp. *citriodora*, *E. longirostrata*, *E. pilularis,* and *E. tereticornis*	To identify species that would enable profitable forestry on low productivity coastal plain of Zululand in South African, by measuring wood and fibre productivity.	For wood production, *E. longirostrata* showed potential for high productivity (wet) sites on the Zululand coastal plain, and *C. citriodora* ssp. *citriodora* and *C. henryi* for marginal (moderately dry) sites. On the basis of fibre production, *E. longirostrata* and *C. henryi* showed potential for high productivity sites, and *C. citriodora* ssp. *citriodora* and *C. henryi* for marginal sites.	Gardner et al. (2007)

2.7.4 Stem quality

Stem quality of a standing tree is important when determining the value of a tree or timber. The concept of stem quality includes both the external and internal features of a stem (Ehrenberg, 1970). The morphology, anatomy, chemical composition, and physiology, all contribute to the quality of a stem. Stem quality is mainly characterised by the form of a stem, as well as the growth and development of branches. Stem forking is undesirable especially if it occurs near the tree base (Krause & Plourde, 2008). Such stem defects reduce the volume and value of timber produced for both pulp and solid wood applications. In particular, stem straightness determines the value of a tree and resulting timber (Cameron et al., 2012). The ability to make an effective assessment of tree stems before harvesting is useful for forest managers and practitioners to improve forecasting, planning, marketing and resource use (Price et al., 2017). The profitability of solid wood depends mainly on stem size and straightness, which in turn influences the yield of sawn products (Callister et al., 2011). The key feature in an ideal plantation forest is a straight stems showing relatively low taper and small 'flat' horizontal branches (Cameron et al., 2012). Forking is a significant defect, because it can reduce saw log length. Stem straightness of *E. globulus* in four Argentinean trials showed significant variation between native sources (Australia) stands and landraces (Cameron et al., 2012).

2.7.5 Coppicing ability

Eucalyptus is a seed propagating genus. It is also able to regrow from harvested tree stumps. The shoots produced from the cambium layer beneath the bark are known as "coppice" (Zbonak & Bush, 2008). The ability of *Eucalyptus* to coppice allows forestry managers to use the coppice regrowth to establish 2nd and later rotations. The regrowth is often faster than seedling growth, partly attributed to the translocation of below-ground reserves to support the development of new shoots (Drake et al., 2013). This can be partly attributed to high root to shoot ratio of coppice allows access to large quantities of soil resources. Coppice management in *Eucalyptus* plantations has been practised

successfully for a number of species with success in many parts of the world including South Africa (Little & du Toit, 2003; Crous & Burger, 2015), Brazil (Rocha et al., 2019; da Silva et al., 2020), Australia (Strandgard & Mitchell, 2018), and China (Zhou et al., 2017).The cost of producing a coppice rotation is approximately half of the prior planted rotation, with less machine traffic, lower labour inputs, and environmental gain in terms of carbon emission (Hakamada et al., 2015). Furthermore, productivity of a coppice rotation can be influenced by genotypes and harvesting techniques on the stumps (Hakamada et al., 2022). Other important factors to consider in harvesting operations are soil damage (Kozlowski, 1999), stump damage (Spinelli et al., 2017) and the amount of carbohydrates available to initiate the coppice rotation (Luostarinen & Kauppi, 2005).

In remote rural areas, especially in communities where access to plantation areas is difficult during the establishment phase, coppicing as a management practice is the best option with less activities. Firstly, in sensitive areas, that require less soil disturbance, coppicing regeneration can help to maintain the productivity of a site in the long term, by reducing the need for intensive site preparation practices experienced during replanting (Mendham & White, 2019). Secondly, coppicing may also be a better option on low productivity sites for communities where the low cost of establishment and higher productivity will help the grower to obtain better financial returns (Hardiyanto et al., 2021). Unreliable rainfall pattern in an area can also be mitigated through coppice regeneration where the need for replanting will not be necessary (Hardiyanto et al., 2022).

2.7.6 Pests and diseases

Insect pests and diseases threaten growth and productivity of exotic plantations worldwide. Exotic plantations are generally more susceptible to pests and diseases than existing forests in their natural environment (Heather & Griffin, 1984). The introduction and establishment of non-native invasive organisms is increasing globally (Graziosi et al., 2020). Numerous native and non-native species of herbivorous insects and pathogenic microorganisms are reported to be harming exotic plantations

across Africa. The Food and Agriculture Organization reported that approximately 100 species of insects and pathogens are affecting planted and natural forests trees across northern, western, eastern, central, and southern African countries (Ghana, Kenya, Malawi, Mauritius, Morocco, South Africa, and Sudan) (FAO, 2009a; FAO, 2009b). Half of these asserted pathogenic species, more than a third are non-native invaders of which 15% are of unknown origin. Non-native pathogenic species species represent over one third of insects known to cause damage to trees, while almost two thirds of the species are non-native or of unknown origin.

Fungal diseases have had a negative impact on the cultivation of *Eucalyptus* species worldwide and in South Africa. *Mycosphaerella* leaf blotch was one of the first diseases to seriously damage plantations of *Eucalyptus* outside their native range (P. W. Crous et al., 2006; Komakech et al., 2009). A number of fungal diseases cause severe damage to *Eucalyptus* trees in South Africa. The most notable of these are *Cryphonectria* canker (P. W. Crous & Wingfield, 1996), *Teratosphaeria zuluensis* formerly *Coniothyrium* canker (Wingfield et al., 1996), *Botryosphaeria* canker (H. Smith et al., 1996), and *Mycosphaerella* leaf blight (Hunter et al., 2004; P. W. Crous et al., 2006; Komakech et al., 2009). Only two bacterial diseases have been reported; bacterial wilt caused by *Pseudomonas solanacearum* (Dianese et al., 1990) and bacterial dieback caused by *Xanthomonas eucalypti* (Truman, 1974). In 1998, a severe disease appeared in a single nursery in KwaZulu-Natal, on ramets of an *E. grandis* × *E. nitens* hybrid clone. Subsequently, the disease spread to other nurseries and plantations affecting different *Eucalyptus* species, hybrids, and clones (Coutinho et al., 2002). The symptoms were typically of bacterial blight showing tip dieback and spots on young leaves. A bacterium was consistently isolated from symptomatic tissue and tentatively identified as an *Erwinia* sp. *Phytophthora* collar and root rot is also a widespread disease in South Africa affecting several cold-tolerant *Eucalyptus* spp. (Maseko et al., 2007). The most typical disease symptom is progressive wilting of the leaves due to the girdling of the root collars.

Numerous native and non-native species of herbivorous insect harm indigenous and exotic plantations. These pests attack *Eucalyptus* trees and bushes, particularly if they are diseased. Of particular interest is the gall wasp, *Leptocybe invasa*, which is native to Australia. Today, it is a worldwide pest in *Eucalyptus* plantations (Eskiviski et al., 2018). The female wasp lays eggs in plant tissues causing the formation of galls on the leaf midribs and petioles, as well as on the stem of new shoots. In time, leaf-curling and premature aging of the leaves occur. Egg overloading could cause death in young shoots, while severe attacks lead to leaf fall, stunted growth and weakening of the tree (Mendel et al., 2004). *Eucalyptus* species show different susceptibilities to wasp attacks (Mendel et al., 2004) with *E. grandis*, *E. camaldulensis* and *E. tereticornis* being the most susceptible (Thu et al., 2009). The hybrids *E. nitens* × *E. grandis* and *E. grandis* × *E. camaldulensis* also (Festin et al., 2019) show susceptibility to *L. invasa* (Dittrich-Schröder et al., 2012). On the other hand, *E. dunnii*, *E. nitens*, *E. smithii*, *E. urophylla* and *E. saligna* × *E. urophylla* exhibited little or no infestation (Dittrich-Schröder et al., 2012).

The bronze bug *Thaumastocoris peregrinus* is probably a recent arrival in South Africa. It was first reported in South Africa in 2003 (Nadel et al., 2010). Today this insect has achieved wide distribution over several regions in South Africa on 26 *Eucalyptus* species. Since December 2003, *T. peregrinus* has become one of South Africa's most significant *Eucalyptus* pests. It is currently distributed throughout southern Africa and has moved northwards to the rest of Africa, having reached Zimbabwe in August 2007 and Malawi in June 2008 (Nadel et al., 2010). Typical symptoms of infestation are initial reddening of the canopy leaves, and subsequently, yellowing of the foliage. In severe infestations, loss of leaves leads to severe canopy thinning and this may lead to branch dieback.

2.8 Forestry legislation in South Africa

Natural indigenous forests occupy a very small component of South Africa's land surface. Less than 1% of the land surface is known for its high biodiversity (FSA, 2021). Environmental conservation and protection is enshrined in the South African Bill of Rights contained within the Constitution of the Republic of South Africa (South African Government, 1996). Section 24 states: with reference to the environment everyone has the right to an environment that is not harmful to their health or well-being; and to a protected environment for the benefit of present and future generations. This right is achieved through reasonable legislative and other measures that prevent pollution and ecological degradation; promote conservation; and secure ecologically sustainable development and the use of natural resources, while promoting justifiable economic and social development (FSA, 2021). There are four main acts that govern the forest industry in South Africa:

- National Forests Act 84 of 1998 (NFA);
- National Environmental Management Act 107 of 1998, (including the EIA Regulations) (NEMA);
- National Water Act 36 of 1998 (NWA); and
- National Environmental Management: Biodiversity Act 10 of 2004 (NEMBA).

The NFA promotes the sustainable management and development of forests for the benefit of all. This act provides special measures for the protection of certain forests and trees; and promotes sustainable use of forests for environmental, economic, educational, recreational, cultural, health and spiritual purposes (South African Government, 2022b). The NEMA plays an important role in forestry operations and emphasises that: "*Every person who causes, has caused or may cause significant pollution or degradation of the environment must take reasonable measures to prevent such pollution or degradation from occurring, continuing or recurring, or, in so far as such harm to the environment*

is authorised by law or cannot reasonably be avoided or stopped, to minimise and rectify such pollution or degradation of the environment." The NWA is the primary legislation regulating water use in South Africa. The limited water supplies of South Africa should be used efficiently and effectively. This act thus suggests that commercial forestry operations put in place appropriate best management practices to limit the further impact of commercial forestry operations on both the quantity and quality of water. Domestic and urban use accounts for approximately 10% of water use in South Africa, while mining, power generation and industries account for 11%, and commercial forestry only 3% (FSA, 2021). Commercial forestry is mainly regulated by Steam Flow Reduction Activity (SFRA) under the NWA. This has resulted in preferential allocation of suitable land to conservation and agriculture (Dyer, 2007; Jacobson et al., 2008). Therefore, under these regulations, all activities classified as SFRA require licences before they can be undertaken and the requirement seeks to ensure that water resources are conserved. Under Section 22(1) of NWA, water use without a licence is permitted only under specific conditions. For the forestry industry, any plantation established up to 18 October 2020 do not require a permit. Any extension to a plantation or establishment of a new plantation requires a permit. Genus exchange has been practised in the commercial forestry industry for over 100 years. However, in terms of sustainable water use, this has become an issue in South Africa. Thus, today under the NEMBA, the forestry industry requires a permit when changing genera or species of trees used for commercial afforestation.

Plantation forestry regulations recognise two categories of tree species. The first category of species are exempt from the requirement of a permit for restricted activities that relate to an existing plantation. The second category of species requires a permit for restricted activities that apply to existing plantations (FSA, 2021). Therefore, permits are not required for restricted activities in existing plantations with the following *Pinus* species (*P. elliotti*, *P. patula*, *P. roxburghii* and *P. taeda* and hybrids), *Eucalyptus* species (*E. grandis*, *E. tereticornis, E. urophylla* and hybrids) and *Acacia* species

(*A. decurrens*, *A. mearnsii* and *A. melanoxylon* and hybrids). By contrast, as of 1st October 2016 permits are required for restricted activities for the species *P. pinaster,* and *P. radiata* and hybrids, varieties and selections in Western Cape.

2.9 Mines sand rehabilitation

Mined sand site rehabilitation is a process of restoring land to its natural state after mining operations had ceased. Restoration is a lengthy process which includes making a mined site safe and stable, and restoring is for use in the future. In some instances, this restoration may be complex, because of extensive environment damage caused by mining (Bolong et al. 2016; Duri, 2016). In South Africa, the economic and environment impact of mining, which may be detrimental to the local communities, have received attention in recent times (Sincovich et al. 2018). The impact of mining sand dunes includes the destruction of floral and faunal biodiversity (Zhang and Moffat, 2015), contamination of soil and water resources (Pourret et al. 2016), and the pollution of the atmosphere by dust and chemical emissions (Li et al. 2018). The monitoring of mined sand dunes is crucial for the sustainable development of local communities (Sonter et al. 2014). Therefore, mining companies should seek sustainable options to improve the economic impact on communities, as well as undertaking the rehabilitation of the mine damaged environments and ecosystems.

2.10 Conclusion

Commercial forestry is an important economic resource worldwide. It supports a wide range of industries, including the pulp and paper industry, as well as the solid wood industries. Through intensive tree breeding and the development of new highly productive genotypes, commercial *Eucalyptus* plantations have become highly profitable, providing jobs for many hundreds of people and families. In South Africa, tree breeding initially centred on improving pure species. Breeding

progressed to hybridisation of species producing a wide range of interspecific hybrids. Today, clonal forests are a major feature in South African *Eucalyptus* commercial forestry. Currently, there is limitation to expansion of commercial forestry into highly productive areas, and therefore, research into developing and testing genotypes that are better suited to low productivity areas has become a major focus. Research into testing genotypes that will flourish in cold and high-altitude regions, as well as nutrient-poor soils such as the sandy coastal regions of Zululand, is an ongoing endeavour.

Chapter 3

Materials and Methods

3.1 Introduction

Prior to this study, Richards Bay Minerals (RBM) had attempted post-mining habitat rehabilitation of the mined sand dunes in the Richards Bay area. In this initial attempt to rehabilitate mined sand dunes, *Casuarina equisetifolia* plantations were established to meet the local community's fuelwood needs. Although *C. equisetifolia* is able to grow on mined sand dunes, economically it is a low value crop with less potential to support significant economic development in the local community. This low economic value of *C. equisetifolia* plantations thus prompted RBM to undertake a comprehensive investigation to identify alternative, more economically viable tree plantation genotypes for planting on the mined sand dunes. These genotypes that would also support the economic growth and development of the local community. This investigation was undertaken in partnership with the Natural Resources and the Environment (NRE) division of the CSIR. Because *Eucalyptus* tree species and several clonal hybrids have been commercially deployed in the KwaZulu-Natal Province and specifically in the inland region near Richards Bay, a wealth of knowledge already exists on a wide range of potential *Eucalyptus* genotypes. Information on survival, growth uniformity, growth rates, yield, wood quality, coppice ability, and pests and diseases susceptibility was known for a wide ranges of genotypes planted in the broader Zululand area. Based on this prior knowledge, genotypes were selected for testing on the mined sand dunes of Richards Bay. Thus, the main aim of this study was to identify *Eucalyptus* genotypes that could be deployed on the mined sand dunes in the Richards Bay area as alternative germplasm source to *C. equisetifolia.*

The main research question of this study was therefore:

Which Eucalyptus genotypes can be planted on the mined sand dunes in the Richard Bay area as alternative genotypes to Casuarina equisetifolia?

3.2 Conceptualisation of the study

Conceptualising this study required an understanding of the overall operational chain of plantation establishment and measurement. The main components of this chain include the initial planning, establishment of trials, measurement of plant traits in trials, analysis of trial data, and finally the selection of economically suitable genotypes for the mined sand dunes in the Richards Bay area. Therefore, prior to the commencement of the study, an area was delineated based on site variables, which included aspects of proximity to the sea, flatness and steepness of the terrain, and inland-facing sites. Consequently, the study area was partitioned into four aspects by incorporating these physical variables into the design decision. These aspects sites were named, Sea-facing, Steep, Flat and Inland-facing aspect sites. One trial was established on each of these aspect sites. A large group of genotypes were selected for testing in the Richards Bay area, including species and interspecific hybrids, using prior knowledge of genotypes planted in the broader sub-tropical region of KwaZulu-Natal. Previously factors considered for the selection of genotypes included survival against sandblast during the first year after planting, wind-throw, drought hardiness and resistance to stem diseases during subsequent years (Gardner, 2001). Growth and stem quality of the trees were also considered, because both together they reflect the quality of individual trees, and provide a reliable basis for selection (Gardner, 2001). In addition, growth and stem quality of the trees were also considered, because together they reflect the quality of individual trees, and provide a reliable basis for selection (Luechanimitchit et al., 2017). Other considerations included coppicing ability and susceptibility to pest and disease (R. J. Retief et al., 1997; Stanger, 2004). The coppicing ability of genotypes, particularly

interspecific hybrid clones, is important for their propagation and maintenance of the hybrid genotype (Little & Gardner, 2021). Susceptibility to pest and disease lowers site productivity through either a reduction in growth or increased mortality (Denison & Kietzka, 1993).

3.3 Research philosophies

In the quest to identify *Eucalyptus* genotypes that are suitable for deployment on mined sand dunes in the Richards Bay area, the positivistic philosophical viewpoint guided the study. Existing knowledge and understandings of *Eucalyptus* genotype qualities formed the foundation of the investigation into which genotypes were suitable for deployment. Thus, deductive reasoning was applied through which a multi-methods approach was followed to gather and analyse quantitative data. The study commenced with assertions about the potential of a collection of *Eucalyptus* genotypes for deployment, followed by analysing data gathered at different times (ages). This longitudinal study revealed specific genotypes suited for planting on the mined sand dunes in the Richards Bay area. In summary, this research project can be described in terms of peeling the layers of the research onion devised by (Saunders et al., 2009; Saunders et al., 2019).

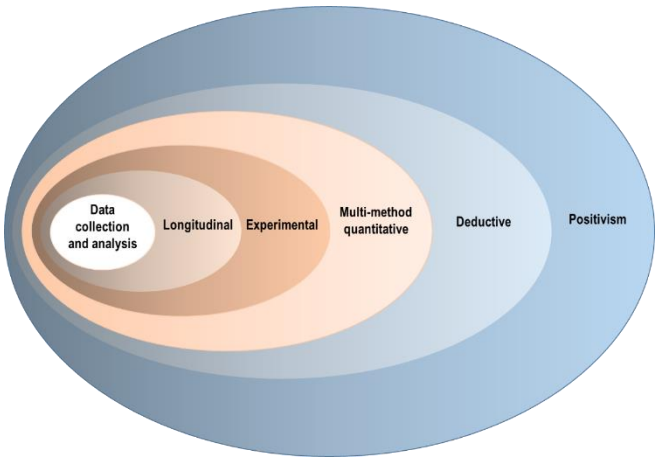


Figure 3.1. Diagram of the research onion depicting the research philosophies and methodological approaches followed in this study.

3.4 Research design

The *Eucalyptus* genotypes, suited for deployment on the Richards Bay mined sand dunes, were identified by following specific tasks at different times of the growth phase of trees. The study was thus divided into four phases (Figure 3.2). These phases addressed the preparation of the project, the measurement of traits, the analysis of measurement data, and finally the selection of genotypes suitable for deployment on the mined sand dunes.

Phase 1: Trial preparation and establishment

In the trial preparation and establishment phase, stakeholder engagement, as well as land preparation and planting activities took place. In this phase the germplasm that was going to be tested for possible deployment on mined sand dunes was identified. The aspect sites were delineated and then prepared for planting of trials. Land preparation and planting activities included trial design, manual pitting of planting holes, and actual planting of aspect site trials.

Phase 2: Trial measurement

In the trial measurement phase, tasks including the measurement of survival, growth, stem quality, wood and Kraft pulping properties, coppicing ability, as well as pest and diseases, were undertaken. The main activities under these tasks can be grouped into two categories. The first category comprised measurement activities performed throughout the growth of the trees, from two weeks after planting to six years of tree growth. Measurements during this time included those of survival, growth, and stem quality. In the second category, measurements were performed after the final growth measurements of the 6-year-old trees. These measurements included wood and Kraft pulp properties, coppicing ability, and susceptibility to pests and disease.

Phase 3: Trial data analysis

In this phase, measurements generated in Phase 2 were analysed. The activities included the analysis of measurement data for survival, growth, stem quality, wood and Kraft pulping properties, coppicing ability, as well as pest and disease susceptibility. Several statistical analyses were performed on the data, which included the calculation of summary statistics and inferential statistics.

Phase 4: Genotype selection

Genotype selection for the Richards Bay area took place in Phase 4. The selection was based on results generated in Phase 3. For the identification of suitable genotypes for deployment on the mined sand dunes of Richards Bay, Principal Component Analyses were performed to rank the genotypes. The rankings were then used to select genotypes of economic importance for deployment on the sand dunes. The diagram shown in Figure 3.2 summarises the four phases of this study showing the main components of each phase.

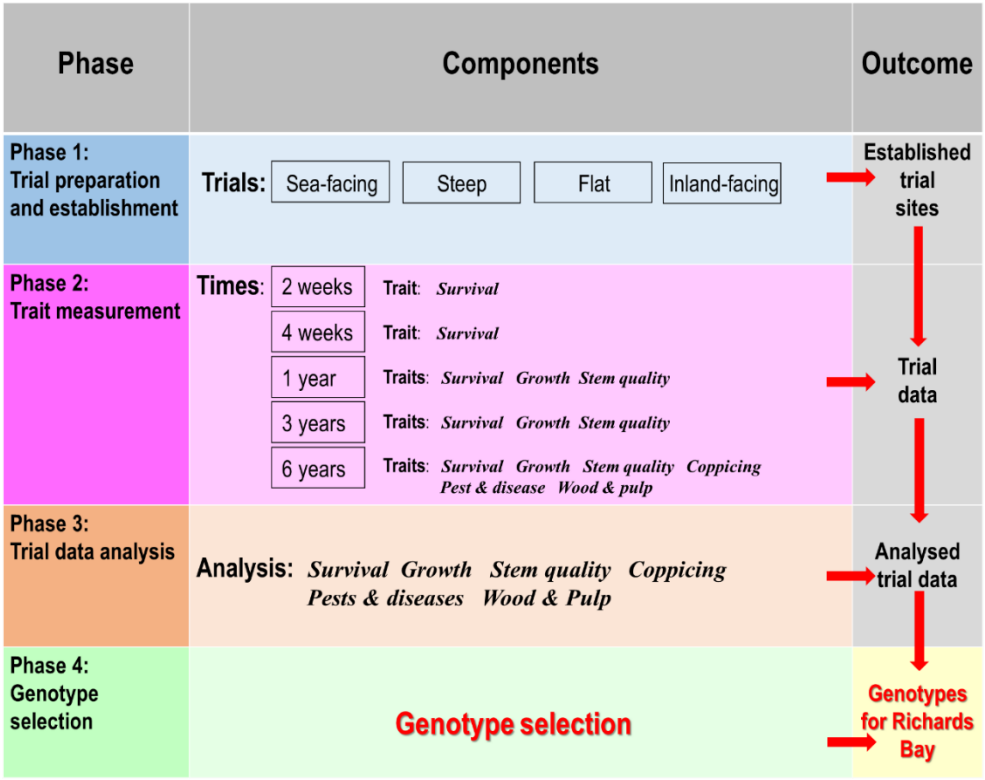


Figure 3.2 Diagram showing the four phases of the research project.

The current research process was guided by several tasks performed to address the main aim of the study and was accompanied by a number of objectives. For each of the four phases, several tasks were performed. The objectives associated with each project phase indicated what actions were required to accomplish the aim of the study. Table 3.1 summarises the tasks for each phase and their associated objectives (actions) that were executed to determine economically viable germplasm for the mined sand dunes of the Richards Bay area. The table also indicates in which chapters of the thesis the results of the tasks were reported.

Table 3.1 Research tasks and objectives.

Phase	Task name	Objective	Chapter reported in
1	Stakeholder engagement and site delineation	1. Choose germplasm 2. Delineate aspect sites 3. Assemble germplasm	3
	Land preparation and planting of trials	4. Design trial layout 5. Pitting planting holes in trials 6. Plant germplasm	
2	Survival measurement	1. Measure at 2 weeks 2. Measure at 4 weeks 3. Measure at 12 months	3
	Growth measurement	1. Measure at 1 year 2. Measure at 3 years 3. Measure at 6 years	
	Stem quality measurement	1. Assess at 1 year 2. Assess at 3 years 3. Assess at 6 years	
	Wood and Kraft pulping property measurement	1. Fell selected trees 2. Prepare wood samples for analysis 3. Analyse wood samples	
	Pests and disease measurement	4. Assess at 6 years	
3	Analysis of traits	1. Analyse survival data 2. Analyse growth data 3. Analyse stem quality data 4. Analyse wood and Kraft pulp property data 5. Analyse pests and disease data	4 5 6 7

Phase	Task name	Objective	Chapter reported in
4	Selection of genotypes Selections of economically viable genotypes	1. Perform principal component analysis 2. Formulate and index to rank genotypes 3. Rank genotypes 4. Select genotypes for Richards Bay area	8

3.5 Study location

The location of this study was along the KwaZulu-Natal coast near Richards Bay in South Africa. The study area extends along a 40 km strip of the coast between Richards Bay (28° 25' 00" S; 32° 12' 00" E) and the dunes at the Mapelane Nature Reserve (32° 25' 00" S; 28° 27' 00" E). This stretch of land is part of the Mozambique coastal plain, situated south of Maputaland and north-east of Richards Bay. The dunes on this stretch of land are generally less than 50 m high and consist of recent sands in the Port Durnford bed, which has been overlain by wave and tidal current deposited sand (Hicks & Green, 2017).

The climate of this area is subtropical, hot and humid, with rain falling throughout the year. The mean annual rainfall for this area is approximately 1,220mm with most of the rain falling in the months of September to April (Dlamini & Xulu, 2019). The mean monthly maximum temperature ranges from 29.0°C in summer to 23.0°C in winter. The area also experiences strong windy weather conditions in summer (DWAF, 2004).

The four trials of this study were laid out on mined sand dunes located 17 km north-east of Richards Bay. This 30-hectare area of the project had a mix of steep and flat dune profiles. The area had been lying fallow for several years and was populated with a regrowth of harvested *C. equisetifolia* trees, weeds and grass. Figure 3.3 shows the location of the trials of the project near Richards Bay.

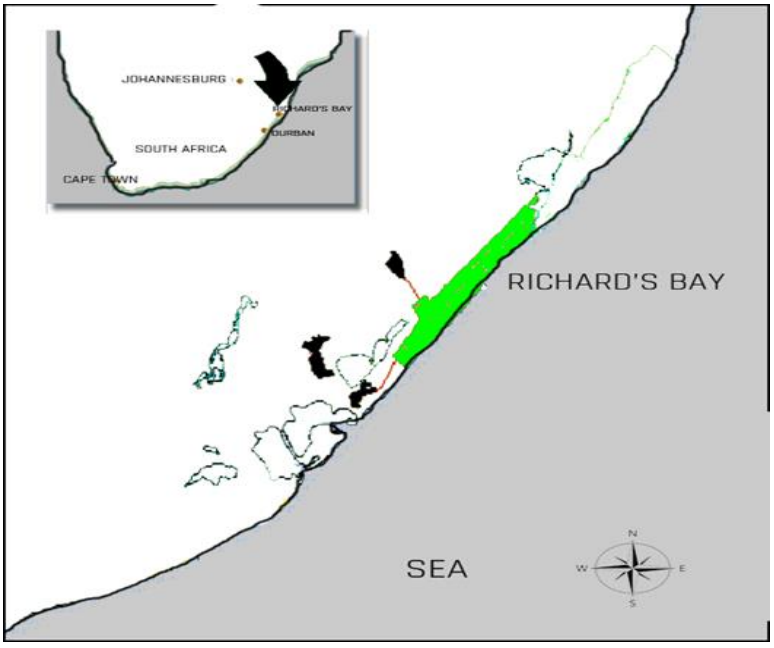


Figure 3.3 **Location of research study site (green) near Richards Bay, along the north-east coast of KwaZulu-Natal, South Africa.**

3.6 Study material

3.6.1 Species and hybrids

Eucalyptus species and clonal hybrids were the main planting materials targeted for inclusion in this study. The species and interspecific hybrid genotypes were chosen through consultation with NRE scientists of the CSIR, RBM and local communities. During the consultation process, it was decided that species and interspecific hybrid genotypes for short rotation forestry would be tested. Within the eucalypts, there are a variety of fast growing and high yielding commercially important forestry species, as well as interspecific hybrids available to choose from (Potts & Dungey, 2004). Thus, several eucalypts species and their hybrids, as well as other related genera were selected for testing in this project, because of their diversity and ability to grow in a range of environmental conditions on short rotation. The species and hybrids included in this study were selected for their survival potential, economic value, vigour, and potential for deployment on the mined sand dunes in the Richards Bay

area. Economic considerations were for use as sawn timber, pulp and paper industry, poles and firewood. Seven pure species and seven interspecific hybrids were selected as test material. The species *C. equisetifolia* was specifically included in the study, because it had been previously grown in the test area and can be considered as the control genotype (Table 3.2). Where possible, genotypes planted in this study originated from genetically improved stocks.

Table 3.2 Species and interspecific hybrids tested in this study.

Type	Description	Reference
E. camaldulensis	Diverse species planted for drought, frost, heat and salt-laden sea air tolerance, and suited to shallow soils and low rainfall.	Nieto & Rodriguez (2003) Veenin et al. (2005)
E. grandis	Highly adapted commercial species planted widely in South Africa for its good growth, stem straightness and wood properties (pulp and sawn timber).	Wright (1997)
E. resinifera	Sub-tropical species, known as red mahogany, a desirable sawn timber with dark brown colour.	Boland et al. (2006)
E. tereticornis	Hardy species tolerant of shallow soils and drought. It is best suited to a sub-tropical climate and flourishes in the drier parts.	Boer (1997)
E. urophylla	Species with highly desirable wood properties for the paper and pulp industry, and disease *tolerance*.	Gwaze et al. (2000)
E. grandis × *E. camaldulensis* (G×C) clone	Hybrid with proven drought hardiness and good vigour.	Gwaze et al. (2000)
E. grandis × *E. longirostrata* (G×L) seedlings	Promising new hybrid being tested for the pulp market. It may produce above standard pulp wood and may be hardier than *E. grandis.* This hybrid was specifically included in the study, because of its high survival rate, good growth and acceptable wood properties for marginal sites, specifically in Zululand.	Henson et al. (2008)
E. grandis × *E. saligna* (G×S) clone	Hybrid being developed for saw timber market.	Gwaze et al. (2000)
E. grandis × *E. tereticornis* (G×T) seedlings	Hybrid with proven drought hardiness and good vigour.	Bisht et al. (1999) Daehler (2005)
E. grandis × *E. urophylla* (G×U) clone	Disease tolerant, vigorous hybrid with good pulp and sawn timber properties.	Wright (1997) Rojas et al. (1999)

Type	Description	Reference
E. grandis × *E. urophylla* (G×U) seedlings	Disease tolerant, vigorous hybrid with good pulp and sawn timber properties.	Wright (1997) Rojas et al. (1999)
E. saligna × *E. urophylla* (S×U) clone	Disease tolerant, vigorous hybrid with good timber properties.	Rojas et al. (1999)
C. citriodora ssp *citriodora*	Hardy species tolerant to pests, grown for sawn timber and essential oil production.	Gardner (2001) Balkrishna (2018)
C. henryi	New species under development for deployment in the Zululand area for pulp market. This species was specifically included in the study, because of high its disease resistance, high survival rate, good growth and acceptable wood properties for drier and hotter marginal sites, such as in Zululand.	Gardner (2001) Gardner et al. (2007)
C. maculata	Hardy species tolerant to pests grown for sawn timber markets.	Gardner et al. (2007)
C. torelliana	Sub-tropical species good hybrid partner for pulp and paper production.	Segura & Da Silva (2016)
C. equisetifolia	The nitrogen fixing properties of this species are useful in soil rehabilitation. It is a hard wood, useful for charcoal and energy uses.	El-Lakany (1991) Djogo (1996)

3.6.1 Genotype groups

Fourteen genotype groups (taxa) comprising of pure species and interspecific hybrids were assembled for planting in the study area. Seven pure species groups were included in this study, of which five were pure *Eucalyptus* species and one group each for both *Corymbia* and *Casuarina*. The remaining seven groups were all interspecific hybrids of *Eucalyptus* species (Table 3.3). Three of the interspecific hybrids were hybrid families with *E. grandis* as maternal parent crossed with *E. longirostrata*, *E. tereticornis* and *E. urophylla*. The other four groups were production clones of interspecific hybrids between *E. grandis* with *E. camaldulensis*, *E. saligna* and *E. urophylla*, as well as one clonal hybrid of *E. saligna* crossed with *E. urophylla.*

Table 3.3 Genotype group name, type of material and origin of the 14 groups included in this study.

Genotype group	Seedlot/family/clone	Origin
E. grandis	5 Seedlots	CSIR
E. resinifera	5 Seedlots	CSIRO, ZFC
E. tereticornis	5 Seedlots	CSIR
E. urophylla	5 Seedlots	CSIR
E. camaldulensis	5 Seedlots	CSIR
C. equisetifolia	5 Seedlots	Zululand
Corymbia	5 Species	CSIR, CSIRO, ZFC
E. grandis × *E. longirostrata*	5 Hybrid families	CSIR
E. grandis × *E. tereticornis*	5 Hybrid families	CSIR
E. grandis × *E. urophylla*	5 Hybrid families	CSIR
E. grandis × *E. camaldulensis*	5 Hybrid clones	CSIR
E. saligna × *E. urophylla*	5 Hybrid clones	CSIR
E. grandis × *E. urophylla*	5 Hybrid clones	CSIR
E. grandis × *E. saligna*	5 Hybrid clones	NT

CSIR = Council for Scientific and Industrial Research; CSIRO = Council for Scientific and Industrial Research Organisation; ZFC = Zimbabwe Forestry Commission; NT = Northern Timbers.

3.6.2 Genotypes

Overall, a total of 70 different genotypes were chosen from the 14 genotype groups. Each of the groups contributed five representative seedlots, families or clones to ensure diversity in the test material. Genetic diversity was also considered to ensure sufficient genetic depth amongst the genotypes. This was achieved by including genotypes from seed sources (seedlots), as well as from interspecific hybrid clones (Table 3.4).

Table 3.4 Genotype and species name of the 70 genotypes included in this study.

Genotype number	Genotype (Seedlot/Clone)	Genotype group number	Species	Type C or S	Code	Source Institution	Region/ country / province
1	B9-075	1	*E. grandis*	S	G	CSIR	Dukuduku KZN
2	B9-008	1	*E. grandis*	S	G	CSIR	Dukuduku KZN
3	B9-689	1	*E. grandis*	S	G	CSIR	Dukuduku KZN
4	B9-346	1	*E. grandis*	S	G	CSIR	Dukuduku KZN
5	B10-513	1	*E. grandis*	S	G	CSIR	Dukuduku KZN
6	AT4	2	*E. tereticornis*	S	T	CSIR	Frankfort MPU
7	AT6	2	*E. tereticornis*	S	T	CSIR	Frankfort MPU
8	AT9	2	*E. tereticornis*	S	T	CSIR	Frankfort MPU
9	T22	2	*E. tereticornis*	S	T	CSIR	Salique MPU
10	T37	2	*E. tereticornis*	S	T	CSIR	Salique MPU
11	C37	3	*E. camaldulensis*	S	C	CSIR	Salique MPU
12	C40	3	*E. camaldulensis*	S	C	CSIR	Salique MPU
13	C63	3	*E. camaldulensis*	S	C	CSIR	Salique MPU
14	C69	3	*E. camaldulensis*	S	C	CSIR	Salique MPU
15	C58	3	*E. camaldulensis*	S	C	CSIR	Salique MPU
16	Au03	4	*E. urophylla*	S	U	CSIR	Tzaneen LPO
17	Au07	4	*E. urophylla*	S	U	CSIR	Tzaneen LPO
18	Au09	4	*E. urophylla*	S	U	CSIR	Tzaneen LPO
19	Au21	4	*E. urophylla*	S	U	CSIR	Tzaneen LPO
20	Au33	4	*E. urophylla*	S	U	CSIR	Tzaneen LPO
21	SN34021	5	*E. resinifera*	S	R	CSIRO	Australia
22	SN34023	5	*E. resinifera*	S	R	CSIRO	Australia
23	R19032	5	*E. resinifera*	S	R	ZFC	Zimbabwe
24	SN34032	5	*E. resinifera*	S	R	CSIRO	Australia
25	SN33994	5	*E. resinifera*	S	R	CSIRO	Australia
26	Maculata1	6	*C. maculata*	S	Cor	CSIR	Witrivier MPU
27	Maculata2	6	*C. maculata*	S	Cor	CSIR	Witrivier MPU
28	Tor	6	*C. torelliana*	S	Cor	CSIR	Nelspruit MPU
29	Henryi	6	*C. henryi*	S	Cor	ICFR	Bushlands KZN
30	SN18062	6	*C. citriodora* ssp. *citriodora*	S	Cor	CSIRO	Australia
31	G91× T10	7	*E. grandis* × *E. tereticornis*	S	G×T	CSIR	Nelspruit MPU
32	SGR1220×T10	7	*E. grandis* × *E. tereticornis*	S	G×T	CSIR	Nelspruit MPU
33	SGR1231×T10	7	*E. grandis* × *E. tereticornis*	S	G×T	CSIR	Nelspruit MPU
34	SGR1220×T32	7	*E. grandis* × *E. tereticornis*	S	G×T	CSIR	Nelspruit MPU
35	G×T Mix	7	*E. grandis* × *E. tereticornis*	S	G×T	CSIR	Nelspruit MPU
36	G17×U Mix	8	*E. grandis* × *E. urophylla*	S	G×U	CSIR	Nelspruit MPU
37	SGR1683×U Mix	8	*E. grandis* × *E. urophylla*	S	G×U	CSIR	Nelspruit MPU
38	SGR1198×U Mix	8	*E. grandis* × *E. urophylla*	S	G×U	CSIR	Nelspruit MPU
39	G15×U Mix	8	*E. grandis* × *E. urophylla*	S	G×U	CSIR	Nelspruit MPU

Genotype number	Genotype (Seedlot/Clone)	Genotype group number	Species	Type C or S	Code	Source Institution	Region/ country / province
40	SGR1668×U Mix	8	*E. grandis* × *E. urophylla*	S	G×U	CSIR	Nelspruit MPU
41	G×U56	9	*E. grandis* × *E. urophylla*	C	G×U	CSIR	Tzaneen LPO
42	G×U111	9	*E. grandis* × *E. urophylla*	C	G×U	CSIR	Tzaneen LPO
43	G×U82	9	*E. grandis* × *E. urophylla*	C	G×U	CSIR	Tzaneen LPO
44	G×U608	9	*E. grandis* × *E. urophylla*	C	G×U	CSIR	Zululand KZN
45	G×U21	9	*E. grandis* × *E. urophylla*	C	G×U	CSIR	Zululand KZN
46	G15×LPM-01	10	*E. grandis* × *E. longirostrata*	S	G×L	CSIR	Nelspruit MPU
47	G50×LMix	10	*E. grandis* × *E. longirostrata*	S	G×L	CSIR	Nelspruit MPU
48	SGR1198×LPM02	10	*E. grandis* × *E. longirostrata*	S	G×L	CSIR	Nelspruit MPU
49	SGR1272×LPM02	10	*E. grandis* × *E. longirostrata*	S	G×L	CSIR	Nelspruit MPU
50	SGR1668×LPM04	10	*E. grandis* × *E. longirostrata*	S	G×L	CSIR	Nelspruit MPU
51	S×U7	11	*E. saligna* × *E. urophylla*	C	S×U	CSIR	Zululand KZN
52	G×U5	11	*E. grandis* × *E. urophylla*	C	G×U	CSIR	Zululand KZN
53	S×U92	11	*E. saligna* × *E. urophylla*	C	S×U	CSIR	Tzaneen LPO
54	S×U84	11	*E. saligna* × *E. urophylla*	C	S×U	CSIR	Tzaneen LPO
55	S×U107	11	*E. saligna* × *E. urophylla*	C	S×U	CSIR	Tzaneen LPO
56	G×C215	12	*E. grandis* × *E. camaldulensis*	C	G×C	CSIR	Tzaneen LPO
57	G×C 231	12	*E. grandis* × *E. camaldulensis*	C	G×C	CSIR	Tzaneen LPO
58	G×C225	12	*E. grandis* × *E. camaldulensis*	C	G×C	CSIR	Tzaneen LPO
59	G×C962	12	*E. grandis* × *E. camaldulensis*	C	G×C	CSIR	Zululand KZN
60	G×C121	12	*E. grandis* × *E. camaldulensis*	C	G×C	CSIR	Zululand KZN
61	G×S147	13	*E. grandis* × *E. saligna*	C	G×S	Northern Timbers	Tzaneen LPO
62	G×S136	13	*E. grandis* × *E. saligna*	C	G×S	Northern Timbers	Tzaneen LPO
63	G×S143	13	*E. grandis* × *E. saligna*	C	G×S	Northern Timbers	Tzaneen LPO
64	G×S146	13	*E. grandis* × *E. saligna*	C	G×S	Northern Timbers	Tzaneen LPO
65	G×S137	13	*E. grandis* × *E. saligna*	C	G×S	Northern Timbers	Tzaneen LPO
66	Cas400	14	*C. equisetifolia*	S	Cas1	Zululand	St. Lucia KZN
67	Cas401	14	*C. equisetifolia*	S	Cas2	Zululand	St. Lucia KZN
68	Cas402	14	*C. equisetifolia*	S	Cas3	Zululand	St. Lucia KZN
69	Cas403	14	*C. equisetifolia*	S	Cas4	Zululand	St. Lucia KZN
70	Cas404	14	*C. equisetifolia*	S	Cas5	Zululand	St. Lucia KZN

MPU = Mpumalanga Province; LPO = Limpopo Province; KZN = KwaZulu-Natal Province; C = Clone and S = Seedling.

3.7 Phase 1: Trial preparation and establishment

3.7.1 Layout of the trials

After scouting the mined sand dune area where the trials were going to be established, four aspect sites were identified for laying out trials. The aspect sites were identified based on environmental

condition of the aspect, topography and previous plantings, which created root channels (Table 3.5). One of the aspect sites faced the sea (Sea-facing aspect site), one faced inland (Inland-facing aspect site), one had a steep topography (Steep aspect site), and one had a flat topography (Flat aspect site).

Table 3.5 Environmental conditions associated with each aspect site established on the mined sand dunes in the study area.

Aspect site	Description
Sea-facing	This site faces the south with less light exposure compared to the other sites. It is shielded from strong winds and therefore less tree breakages are expected. It is, however, affected by heavily salt-laden sea breezes.
Steep	This site is an exposed site and liable to tree stem and top breakages. Nutrient accumulation is limited by the steep slope.
Flat	This site is far less affect by salt-laden sea breezes. It is not shielded by windbreaks and is thus affected by strong prevailing winds (August/September months), which could result in tree stem breakages, top breakages and abnormalities.
Inland-facing	This site is shielded from strong winds. Daylight exposure is longer and warmer than the other sites. Because of its location, it is also more inclined to nutrient accumulation.

The four aspect sites of this study were chosen to represent the spectrum of environmental conditions and profiles of the mined sand dunes. Each of the aspects sites was approximately 0.6 ha in size making up a total of 2.4 ha. Figure 3.4 shows an aerial view of the positioning and layout of the four aspect sites planted in this study.

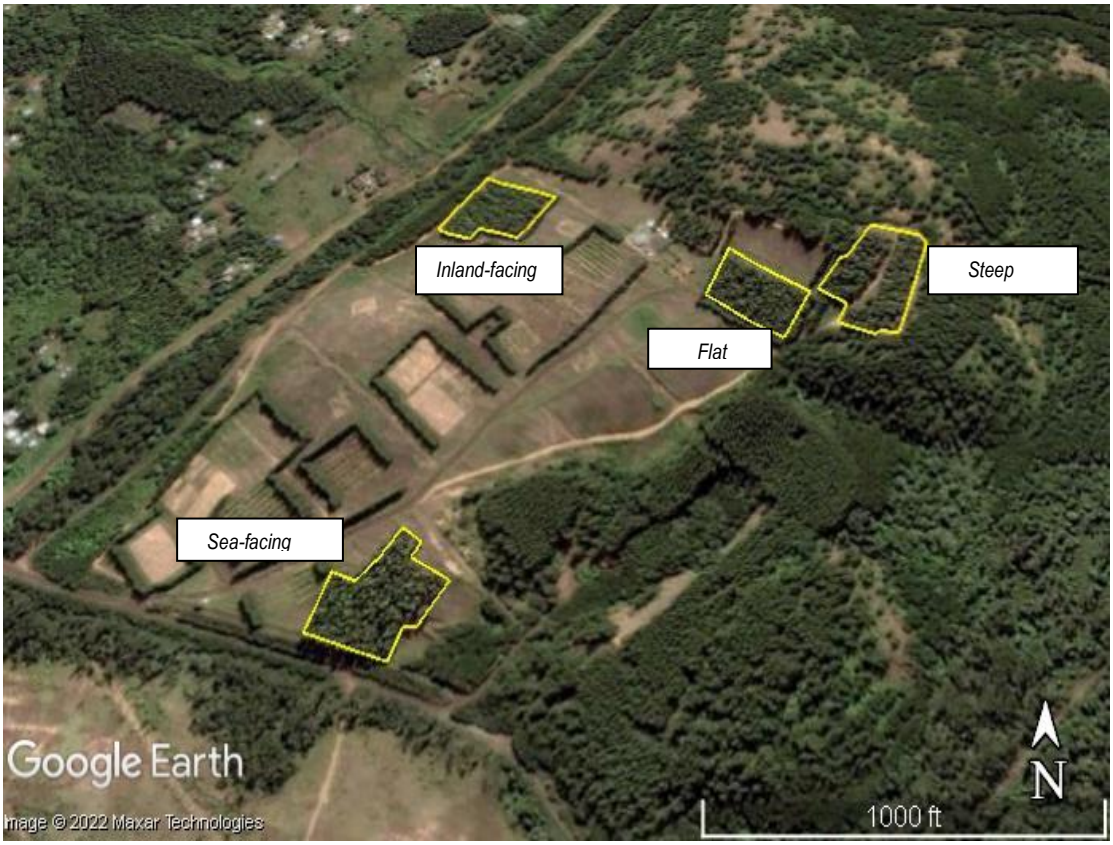


Figure 3.4 Arial view of the layout of the four trials on the mined sand dunes.

Each of the aspect sites were unique in terms of their position on the mined sand dunes. Table 3.6 provides location details of the four aspect sites.

Table 3.6 Location details of the four aspect sites established on the mined dune sands in Richards Bay area.

Trial number	Aspect site name	Latitude S	Longitude E	Altitude m.a.s.l.
1010202EA0002.01	Sea-facing	28º42'31.8"	32º11'16.8"	75
1010202EA0002.02	Steep	28º42'22.9"	32º11'35.4"	95
1010202EA0002.03	Flat	28º42'22.0"	32º11'29.8"	86
1010202EA0002.04	Inland-facing	28º42'18.6"	32º11'21.4"	65

m.a.s.l. = metres above sea level.

3.7.2 Design of the trials

The trials for this study were designed so that the performance of the genotypes could be assessed in terms of several economically important traits for potential deployment on the Richard Bay mined sand dunes. The design priority was to control, as far as possible, and minimize experimental error so that the best possible genotype selections could be made for deployment on the mined sand dunes. Therefore, an alpha lattice design was implemented in the study, since it was important to control random variation, particularly for evaluation of trials of many genotypes (Patterson & Williams, 1976). An alpha lattice design is typically an incomplete block experimental design that overcomes the limitations imposed by the large square and rectangular lattice designs developed by Cochran and Cox (1957). In the alpha lattice design, blocks do not have to be orthogonal and can be applied to a wide range of treatments (genotypes), blocks and block sizes, and replications. The design also offer some flexibility, especially in situations where neither replications nor blocks capture any variation, which then leads to data being analysed as normal random complete block design (Williams & Matheson, 1994).

The trial design comprised several specific components. These components included the number of repeats per trial, number of blocks per replication and number of genotypes (treatments) (Table 3.7). A total of 70 genotypes (treatments) were blocked by species or hybrid type (taxa) per trial site, making up a total of 700 single tree plots per trial. Single tree plots were preferred to square or row plots, because square or row plots may introduce considerable within plot environmental variation, which cannot be corrected for by the trial design. Single tree plots also improved the accuracy of performance testing of the large collection of genotypes by better controlling for error variance. In this study, the planting spacing was limited to 3 m $\times$ 3 m, which is the spacing used during planting of the previous crop on the aspect sites.

Table 3.7 Summary of trial design for the four trails planted on Richards Bay mined sand dunes.

Design component	Specification
Trial design	Alpha lattice
Number of replications	10
Number of blocks per replication	2 (20 blocks per trial)
Genotypes	70 genotypes in 14 groups (blocked by species or hybrid type)
Plot size	Single tree
Spacing	3 m × 3 m
Measured traits	*Survival, stem straightness, diameter at breast height (DBH), height, pest and disease*
Control species	*C. equiesitifolia*

Within each of these four trials, 10 replications were established. Around each trial, two rows of seedlings and clones of known origin were planted as buffers. Figure 3.5 presents the layout of the different repetitions within each of the trials.

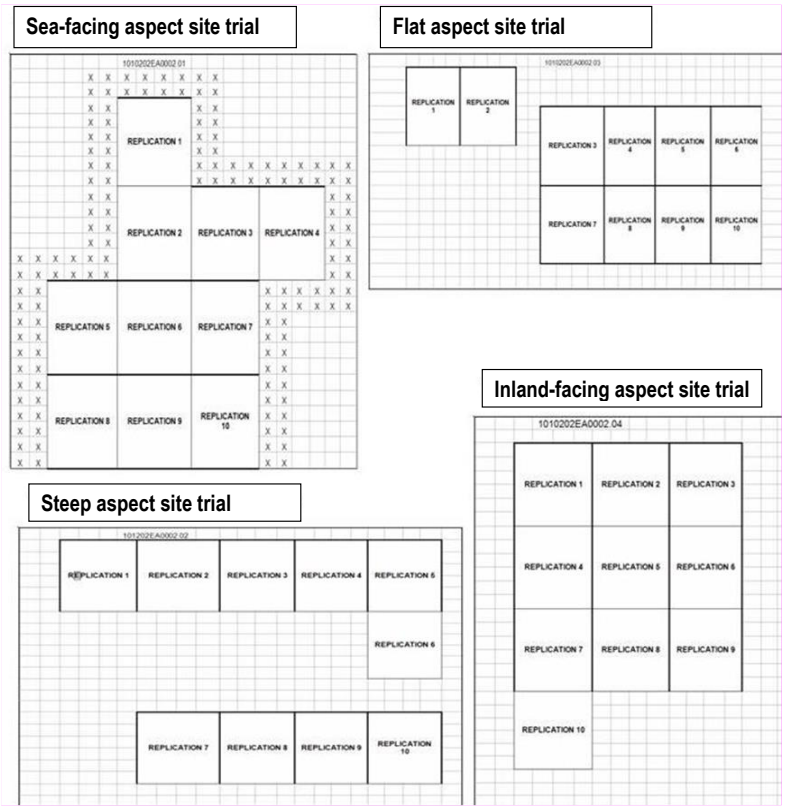


Figure 3.5 Layout design of the replications in the four trials.

Before the genotypes were planted in the trials, specific genotypes were allocated to specific single tree plots in the block of the different replications. Each of the 10 replications in a trial comprised two incomplete blocks, making up 20 incomplete blocks per trial. The 70 different genotypes were randomly allocated to single tree plots of the two replication blocks, with 35 genotypes in each block. Thus, each replication contained the complete set of 70 genotypes tested for their suitability for deployment on the mines sand dunes of Richard Bay. In total 700 trees were assessed in each trial. Table 3.8 shows the plots and genotype allocation for the ten replications of the Sea-facing aspect site trial. The plot and genotype allocation to the 10 replications of the other three trials are presented in Appendix C.

Table 3.8 Sea-facing aspect site trial replications, blocks and genotype allocation to plots.

Field plot/genotype layout

Rep. 1

	PLT	TMT	PLT	TMT	PLT	TMT	PLT	TMT	PLT	TMT	PLT	TMT	PLT	TMT
BLK 1	1	21	10	6	11	16	20	54	21	1	30	36	31	27
	2	25	9	10	12	20	19	55	22	4	29	39	32	28
	3	22	8	8	13	18	18	52	23	3	28	38	33	29
	4	24	7	9	14	19	17	53	24	5	27	40	34	30
	5	23	6	7	15	17	16	51	25	2	26	37	35	26
BLK2	66	56	65	48	56	32	55	66	46	62	45	44	36	11
	67	57	64	49	57	33	54	67	47	63	44	42	37	13
	68	60	63	47	58	34	53	68	48	65	43	41	38	12
	69	59	62	50	59	31	52	69	49	61	42	45	39	14
	70	58	61	46	60	35	51	70	50	64	41	43	40	15

Rep. 2

BLK 1	71	54	80	37	81	26	90	1	91	12	100	22	101	58
	72	53	79	38	82	28	89	2	92	13	99	23	102	59
	73	55	78	36	83	27	88	3	93	14	98	24	103	60
	74	52	77	39	84	30	87	5	94	11	97	25	104	57
	75	51	76	40	85	29	86	4	95	15	96	21	105	56
BLK 2	136	42	135	6	126	66	125	47	116	32	115	61	106	20
	137	43	134	10	127	67	124	50	117	33	114	63	107	19
	138	44	133	9	128	68	123	49	118	34	113	62	108	16
	139	41	132	8	129	70	122	46	119	35	112	64	109	17
	140	45	131	7	130	69	121	48	120	31	111	65	110	18

Rep. 3

BLK 1	141	11	150	31	151	61	160	42	161	46	170	1	171	8
	142	12	149	34	152	65	159	43	162	47	169	2	172	9
	143	15	148	32	153	64	158	41	163	50	168	4	173	10
	144	14	147	35	154	63	157	44	164	48	167	3	174	7
	145	13	146	33	155	62	156	45	165	49	166	5	175	6
BLK 2	206	58	205	66	196	17	195	27	186	21	185	37	176	53
	207	59	204	67	197	19	194	29	187	23	184	39	177	55
	208	60	203	70	198	16	193	28	188	24	183	38	178	54
	209	56	202	69	199	20	192	30	189	22	182	40	179	52
	210	57	201	68	200	18	191	26	190	25	181	36	180	51

Rep. 4

BLK 1	211	32	220	56	221	12	230	46	231	36	240	1	241	9
	212	33	219	57	222	14	229	48	232	39	239	2	242	10
	213	35	218	59	223	15	228	49	233	37	238	4	243	8
	214	31	217	60	224	11	227	47	234	38	237	3	244	7
	215	34	216	58	225	13	226	50	235	40	236	5	245	6
BLK 2	276	41	275	66	266	62	265	17	256	22	255	51	246	27
	277	42	274	67	267	63	264	18	257	23	254	54	247	29
	278	44	273	68	268	61	263	19	258	24	253	52	248	26
	279	43	272	70	269	64	262	16	259	21	252	55	249	30
	280	45	271	69	270	65	261	20	260	25	251	53	250	28

Rep. 5

BLK 1	281	3	290	21	291	7	300	17	301	62	310	43	311	11
	282	2	289	22	292	8	299	18	302	63	309	44	312	12
	283	5	288	24	293	9	298	16	303	64	308	45	313	15
	284	1	287	23	294	6	297	19	304	65	307	42	314	14
	285	4	286	25	295	10	296	20	305	61	306	41	315	13
BLK 2	346	26	345	52	336	32	335	37	326	69	325	59	316	48
	347	29	344	53	337	33	334	38	327	66	324	58	317	50
	348	27	343	54	338	34	333	40	328	68	323	57	318	49
	349	30	342	51	339	31	332	39	329	67	322	56	319	46
	350	28	341	55	340	35	331	36	330	70	321	60	320	47

Rep. 6

BLK 1	351	69	360	42	361	37	370	51	371	63	380	29	381	16
	352	66	359	41	362	38	369	54	372	64	379	30	382	17
	353	67	358	44	363	40	368	53	373	62	378	28	383	19
	354	70	357	43	364	39	367	55	374	65	377	27	384	18
	355	68	356	45	365	36	366	52	375	61	376	26	385	20
BLK 2	416	57	415	31	406	22	405	4	396	14	395	6	386	47
	417	56	414	32	407	24	404	3	397	15	394	7	387	49
	418	58	413	34	408	21	403	2	398	13	393	8	388	50
	419	60	412	33	409	25	402	1	399	12	392	10	389	46
	420	59	411	35	410	23	401	5	400	11	391	9	390	48

Rep. 7

BLK 1	421	21	430	10	431	66	440	1	441	59	450	12	451	53
	422	22	429	9	432	69	439	2	442	60	449	13	452	52
	423	23	428	8	433	67	438	3	443	58	448	15	453	55
	424	25	427	7	434	70	437	5	444	57	447	14	454	51
	425	24	426	6	435	68	436	4	445	56	446	11	455	54
BLK 2	486	62	485	37	476	27	475	49	466	16	465	32	456	43
	487	64	484	40	477	30	474	46	467	19	464	33	457	42
	488	61	483	38	478	29	473	48	468	17	463	31	458	41
	489	65	482	39	479	28	472	47	469	20	462	34	459	44
	490	63	481	36	480	26	471	50	470	18	461	35	460	45

Rep. 8

BLK 1	491	32	500	57	501	26	510	68	511	47	520	17	521	22
	492	31	499	58	502	28	509	70	512	48	519	16	522	23
	493	34	498	56	503	27	508	67	513	46	518	18	523	24
	494	33	497	59	504	30	507	69	514	50	517	20	524	21
	495	35	496	60	505	29	506	66	515	49	516	19	525	25
BLK 2	556	6	555	43	546	4	545	62	536	12	535	37	526	54
	557	7	554	41	547	5	544	63	537	13	534	38	527	51
	558	10	553	42	548	3	543	65	538	14	533	40	528	52
	559	9	552	44	549	2	542	61	539	11	532	36	529	55
	560	8	551	45	550	1	541	64	540	15	531	39	530	53

Rep. 9

BLK 1	561	22	570	57	571	44	580	9	581	39	590	27	591	14
	562	24	569	58	572	43	579	7	582	40	589	28	592	15
	563	21	568	56	573	42	578	8	583	38	588	30	593	13
	564	25	567	59	574	41	577	6	584	37	587	26	594	12
	565	23	566	60	575	45	576	10	585	36	586	29	595	11
BLK 2	626	32	625	1	616	48	615	63	606	67	605	17	596	53
	627	33	624	2	617	49	614	61	607	68	604	20	597	51
	628	34	623	3	618	47	613	64	608	66	603	18	598	55
	629	35	622	4	619	50	612	62	609	69	602	19	599	54
	630	31	621	5	620	46	611	65	610	70	601	16	600	52

Rep. 10

BLK 1	631	62	640	33	641	9	650	53	651	26	660	67	661	14
	632	64	639	32	642	8	649	54	652	27	659	69	662	15
	633	65	638	31	643	6	648	55	653	29	658	68	663	13
	634	61	637	34	644	7	647	51	654	30	657	70	664	12
	635	63	636	35	645	10	646	52	655	28	656	66	665	11
BLK 2	696	41	695	4	686	58	685	17	676	25	675	48	666	36
	697	44	694	2	687	56	684	18	677	23	674	47	667	37
	698	43	693	1	688	60	683	16	678	22	673	46	668	38
	699	45	692	3	689	59	682	20	679	24	672	49	669	39
	700	42	691	5	690	57	681	19	680	21	671	50	670	40

PLT = plot; TMT = treatment (genotype); Rep = replication.

3.7.3 Preparation of the material for planting

Most of the test material was obtained from the CSIR's nursery in Mbombela (formerly Nelspruit), Mpumalanga. Where genotypes could not be supplied by the CSIR, they were sourced from commercial forestry nurseries. Standard unigro (128) insert trays were used filled with soilless growth mediums from all sources. Although 40 seedlings or plantlets were required per genotype for planting in the four trials (10 per trial), approximately 50% more were raised to ensure that there was enough material to replace dead plants at 2 and 4 weeks after planting. The seedlings and clone plantlets were grown to a minimum height of 15 cm before they were planted in the trials.

3.7.4 Planting of the trials

The planting of the four trials took place over a two day period in November 2007. Standard silvicultural operations were applied according to the practices used to establish the previous *C. equesitifolia* plantations on the mined dune sands in the Richard Bay area (Table 3.9). For each trial site, 700 plants of test material were established together with approximately 200 buffer plants planted in two rows around each trial. The buffer plants ensured that the environmental conditions of the test trees in a trial were relatively similar. The total surface area of a trial was approximately 0.6 ha, making up 2.4 hectares total planted area. A total of 2,800 seedlings and interspecific hybrid clone plantlets were planted on the four aspect sites together with a total of 800 buffer seedlings and clone plantlets.

Table 3.9 Silvicultural operations carried out during the planting operation.

Operation	Activity
Field preparation	All *Casuarina* regrowth from the previous planting and broad leaved weeds were manually slashed and later removed. No chemical pre-planting spray was used on the trial sites. Residues were also not burnt to avoid both soil disturbance and ash bed effect. Planting lines were laid out within the old *Casuarina* stump lines without de-

Operation	Activity
	stumping. The test material was planted at a spacing of 3 m × 3 m after making pits with a hand hoe, measuring 50 cm wide and 25 cm deep.
Planting	The four trials were planted on the four aspect sites by the CSIR research team and a local contractor's team using the puddle planting method. After planting, each planted seedling and interspecific clone plantlet was given 500 ml of water mixed with planting polymer (hydrogel solution mix of 2.5 grams per litres of water).
Fertiliser application	Within the first two weeks after planting, one hundred and fifty grams of 2.3.2 (22) NPK fertiliser was applied in radius of 25 cm around each plant.
Blanking	Survival assessments were conducted at 2 and 4 weeks after planting. During this assessment, all the dead plants were replaced by the same genotype and fertilised.
Post-planting care	Throughout the first twelve months, and where practical, the sites were kept weed free. Manual line hoeing (strip weeding) to 1.5 m width was applied by onsite contractors. In line with strict environmental and safety regulations, no herbicides were applied.

3.8 Phase 2: Trial measurement

Several traits were measured during the 6-year growth period of the four trials. During the first four weeks, *survival* was measured at two and at four weeks. All dead trees at 2 weeks and 4 weeks were replaced (blanked) with the same genotypes. At tree ages of 1 year, 3 and 6 years, all trees of the trials were measured for *survival*, for growth traits, *diameter at breast height* (*DBH*) and *height*, as well as for stem qualities. After the final survival, growth and stem quality measurements of the 6-year-old trees, a subset of outstanding trees (based on preliminary analyses) were selected and felled for the measurement of wood and Kraft pulp properties. Tree felling provided the opportunity to measure coppicing ability from the stumps of the felled trees, as well as the presence of pests and diseases. Table 3.10 provides a summary of the traits that were measured in this project, the tree age when measurements were made and the locations where the measurements were made.

Table 3.10 Traits measured during the 6-year growth period.

Variable	Age of measurement	Measurement	Field or Laboratory measurement
Survival	2 and 4 weeks 1, 3 and 6 years	Counts	Field
Growth variables (*DBH, height*)	1, 3 and 6 years	DBH tape (cm) height rods (m)	Field
Stem qualities	1, 3 and 6 years	*Stem straightness* (1 – 8 Scale) stem abnormalities (counts)	Field
Wood and Kraft pulp properties	6 years	Laboratory measurements	Laboratory
Coppicing	6 years	Coppice sprout counts, Stump coppicing quadrant counts	Field
Pests and diseases	1, 3 and 6 years	Field measurements on coppiced stumps	Field

3.8.1 Measurement of survival

One of the major costs in plantation forestry are costs incurred during plantation establishment. A key component of the cost is the procurement of plant material. Furthermore, if seedling or clone plantlet mortality is high then an additional cost of replanting will be incurred (Thomas, 2009). To reduce the risk of plant mortality, plantation management is of the utmost importance to maximise plant *survival* of the plants. Therefore, *survival* is one of the most important traits to consider in plantation establishment. In this study, *survival* measurements were performed throughout the growth period of the study. *Survival* measurements were performed at 2 weeks, 4 weeks, 1 year, 3 years and at 6 years of tree growth. *Survival* of trees were scored by awarding a "1" for a live tree and "0" for a dead tree and recording these values on prepared scoring sheets. The number of dead trees were also recorded at 1, 3 and 6 years of tree growth, while measuring the growth properties. After each round of *survival* measurements, score sheets were transferred to Excel spread sheets.

3.8.2 Measurement of tree growth

Growth properties of a genotype are of particular importance for various forest industrial applications. Growth traits give an indication of species productivity and for its different genotypes. Forest productivity is thus the ultimate expression of adaptation to a particular environment. Besides *survival*, measuring growth provides an understanding of a genotype's productivity potential in a particular environment. Growth is determined by a tree species' ability to obtain sunlight, water, nutrients, and air in a specific climate. The mined sand dunes of Richards Bay are deemed areas with poor productivity, mainly because of the nutrient poor soil. Besides *survival*, the measurement of growth is an important indicator of a species' ability to grow in this low productivity area. Important growth traits are *DBH* and *height*.

The growth measurements *DBH* and tree *height* were measured at 1 year, 3 years and at 6 years of tree growth. *DBH* was measured over bark in millimetres at a height of 1.3 m above the ground using a diameter tape. *Height* was measured in metres at 1 year tree growth from the base of the tree to the tip of a tree using height rods. At 3 and 6 years of tree growth, *height* was measured with a vertex hypsometer. Figure 3.6 shows the instruments used to measure *DBH* and *height* after 12 months.

A.

B.

Figure 3.6 **Instruments used to measure DBH and height. A. Diameter tape used for DBH measurements. B. Vertex hypsometer used for height measurements.**

Growth volume was calculated based on both *DBH* measurements and *height* using species-specific volume equations. The *growth volume* calculations for the following species (*E. grandis*, *E. urophylla*, *E. resinifera*, *C. equiesitifolia* and species within the *Corymbia* group) were based on the *growth volume* function formulated by Schumacher and Hall in 1933:

$$Log\ V = b_0 + b_1 \log (DBH + d) + b_2 \log H \quad (1)$$

where:
log is the common logarithm to the base 10;
V is the *growth volume* (m^3) to 75 mm tip diameter;
b_0, b_1 and b_2 are coefficient fits for various *Eucalyptus* species
DBH is the *diameter at breast height* (mm);
d is the correction factor (mm); and
H is the tree height (m).

Where possible, species-specific equations were used to calculate *growth volume*, otherwise equations of closely related species were used (Table 3.11).

Table 3.11 Equations used to calculate growth volume.

Species	Volume equation	Reference
E. grandis	*log10 vol = -11.1622 + 3.6517 log 10 (DBH) + 1.1476 log 10ht*	Bredenkamp & Loveday (1984)
E. urophylla, E. resinifera	*log10 vol = - 4.5686 + 1.9831 log 10 (DBH) + 0.987 1log 10ht*	Bredenkamp & Loveday (1984)
C. maculata, C. henryi, C. torelliana, C. citriodora ssp. *citriodora*	*Log 10 vol = - 5.1411 + 2.3484 log 10 (DBH) + 1.0109 log 10ht*	Bredenkamp & Loveday (1984)
C. equisetifolia	*log10 vol = - 4.4013 + 1.7137 log 10 (DBH) + 1.1656 log 10ht*	Bredenkamp & Loveday (1984)

Species	Volume equation	Reference
E. grandis × *E. urophylla*	*log10 vol = -12.5483 + 1.7139 log 10 (DBH) + 1.9994 log 10ht*	Morley & Little (2012)
E. grandis × *E. camaldulensis*	*log10 vol = -10.6435 + 1.9185 log 10 (DBH) + 1.1494 log 10ht*	C. W. Smith et al. (2006)
E. longirostrata	Vol = 0.35 πht (DBH/200)^2 note: DBH in m	Henson et al. (2008)
E. camaldulensis, E. tereticornis	Vol = 0.454 (0.00007854) (DBH) 2ht	Alder (2006)
Interspecific hybrids (G×L)	Vol = [(vol of parent 1) + (vol of parent 2)] / 2	Bredenkamp & Loveday (1984) Henson et al. (2008)

ht = *height* measurement; DBH = *Diameter at breast height*

3.8.3 Measurement of stem quality

The shape of trees is very important in determining timber volume recovery and hence value. Straight stems provide the best processing options and highest volume recovery (Price et al., 2017). The ability to make an effective assessment before harvesting is useful for forest managers to improve forecasting, planning and marketing the resource. For example, only trees with acceptable stem quality are selected for saw logs (Wessels et al., 2016). The shape of trees is also an important component of tree stability in wind. In this study, stem quality was measured at 1 year and at 3 and 6 years of tree growth. Several stem quality characteristics were measured. The characteristic *stem straightness* was measured visually by applying an industry standard 8-point scoring scale, where a score of "1" indicated a very crooked stem and a score of "8" a straight stem (Table 3.12). In this scoring scale, the extent to which a stem deviated from the vertical axis was the major consideration. Three members of the measurement team scored each stem at a distance of approximately two tree lengths from the tree being measured. After reaching a consensus measurement, it was recorded on a prepared scoring sheet. These scores were later transferred to an Excel spread sheet for analysis.

Table 3.12 Industry standard eight-point scoring scale used to measure stem straightness.

Score	Measurement option description	Characteristic description
8	Straight stem (pole quality)	Straight no defects
7	Slight sweep and/or 1 minor bend	Nearly straight 1 - 2 minor defects
6	One slight sweep with more than 1 minor bends OR More than 1 slight sweep with 1 minor bend OR More than 2 minor bends	Very slightly crooked 3 - 4 minor defects
5	Moderate sweep with 1 moderate bend OR Two moderate sweeps with minor defect OR Two moderate bends with minor defect	Slightly crooked 3 - 4 moderate defects
4	Moderate sweep with major bend OR More than two moderate sweeps OR More than two moderate bends OR Two major bends with minor defects	Moderately crooked 2 major and minor defects
3	Obvious sinuosity or major crooks	Crooked few major and moderate defects
2	Presence of multiple severe straightness defects	Very crooked several major and moderate defects
1	Not merchantable as a short log (cork screw)	Malformed major defects

The other stem quality characteristics that were also noted were referred to as stem abnormalities, also referred to as off-type trees. These stem qualities included forked stem, broken top, runts kinked at the base, and heavy branching. These off-type trees were treated as a single group in further analyses and their occurrence expressed as percentages of the total number of trees planted in the trial.

The number of trees with abnormalities were put into six different categories and the total number with abnormal characteristics were counted and expressed as a percentage of total trees in a trial at group levels. Runt trees were not assessed, and neither were the tree heights with pronounced broken tops.

Table 3.13 Stem qualities of off-type trees and codes used for recording the abnormalities.

Stem quality trait	Code
Forked middle	FM
Broken top	BT
Forked base	FB
Kinked base	KB
Heavy branching	HB
Runts	R

3.8.4 Measurement of wood and Kraft pulp properties

For the deployment of suitable genotypes on the mined sand dunes of Richards Bay, several wood and Kraft pulp properties were assessed. Knowledge of these properties determine the type of forestry industry the genotypes could serve. For example, pulps are used in printing and writing papers, whereas wood density contributes to specific paper characteristics (Fiserova & Gigac, 2011). In addition to tree growth, *basic density* and *pulp yield* are considered as key parameters for pulping (Santos et al., 2012). Wood and Kraft pulp properties are complex and related to both the anatomical structure and chemical composition of wood, as well as the response to genetic expression, environmental and physiological influences. The measurements of wood and Kraft pulp properties are costly, time-consuming, scarce, and use destructive methods (Gallo et al., 2018). Therefore, a sample of trees was felled for these analyses. For this study, 26 trees were felled for processing in a laboratory to measure wood and Kraft pulp properties. These trees belonged to 13 genotypes, two trees per

genotype. Because genetic by environment interaction (GEI) calculations for *growth volume* revealed an absence of interaction between genotype and aspect sites. Therefore, accordingly it was considered to be enough justification to sample trees from one aspect site trial. Trees in the Inland-facing trial with no defects and free of pests and diseases, were selected for felling. In addition, access to the Inland-facing trial was an important logistical consideration that informed the decision. Before felling, *DBH* and *height* were measured, after which the trees were felled 10 to 15 cm above the ground (Little, 2000). On the stump of the selected tree, trial replication, plot and genotype numbers were labelled for further studies. After the trees were felled, they were cut into one-metre-long billets. Because a tree contains differently aged tissues, a 15-mm-thick-disc was cut from the top of the first billets, at *DBH*. After cutting and debarking the discs and billets, they were labelled, and packed in hessian bags for transportation to the laboratory where the wood and Kraft pulp properties (*basic density*, *kappa number*, *pulpability factor*, *screened pulp yield* and *pulp yield*) were measured. The stumps of felled trees were also labelled with aluminium plates bearing the tree's replication, plot and genotype numbers. The laboratory that performed the measurements was the Forestry and Forest Products (FFP) Research Centre in Durban, KwaZulu-Natal (CSIR's ISO accredited pulp and paper laboratory).

Measurement of the Kraft pulp properties

For the measurement of Kraft pulp properties, billets of the same genotypes were bulked to reduce costs. Two batches were prepared for each genotype and processed separately. The discs were used to measure *basic density*. The following steps were performed to determine the Kraft pulp properties and wood *basic density*:

1. Preparation of the woodchips

   In the first step of the process woodchips were prepared for cooking and then cooked in a specifically prepared. The billets were chipped in a pilot scale chipper "(Precision husky type" at the CSIR, Forestry and Forest Products Research Centre Laboratory). Thereafter, the woodchips were screened using a vibrating screen to remove both undersized and oversized chips (rejects). Woodchips with an average chip thickness of 3 to 8 mm were collected for the measurement of Kraft pulp properties. The woodchips were allowed to air-dry for two weeks to reach moisture content equilibrium. Woodchips moisture content was determined according to the TAPPI test method T258om-94 (Berzins, 1965).

2. Preparation and standardisation of Kraft cooking liquor

   Cooking liquor was prepared and standardised according to TAPPI test method T624 cm-85. The cooking liquor specifications were total alkalinity (155.3 g l-1 as Na_2O), effective alkali (153.5 g l-1 as Na_2O) and a sulphidity of 26-27%. The quality of the liquor in terms of effective alkali (E. A.) and sulphidity were measured regularly during the cooking process.

3. Pulping of woodchips

   The pulping measurements were conducted using a 7-litre rotating digester to produce several pulp samples. The pulping temperature profile was controlled by a computer. The ramping time was 90 minutes at a ramp rate of 1.2 °C/minute. The pulping of woodchips was conducted using a standard Kraft pulping method. The pulping conditions were: liquor dosage 18% (oven dried woodchips mass), liquor to wood ratio 4.5:1, ramping time to pulping temperature was 90 minutes, and pulping temperature of 170°C. The pulp samples were subsequently spin dried for 10 minutes, and weighed. After weighing, a portion of the pulp was then taken from each sample for determining pulp moisture. Moisture data were used in the measurement of total *pulp yield*. The rest of the pulp samples were packed in plastic bags and stored in the refrigerator at 4°C. At the end of each cook, the black liquor sample was collected and used for residual alkali analysis. The *screen pulp yield* was calculated as the percentage of total pulp yield, where *pulp yield* derived from rejects was subtracted from pulp yield derived from acceptable sized woodchips. *Pulpability factor* was calculated by dividing *screen pulp yield* by *kappa number* giving a good indication of pulp quality.

4. Measurement of *kappa number*

   After the pulping process, pulp samples were screened in a Sommerville screen with 0.15 mm slots. After screening, the samples were spin dried for 10 minutes and then weighed. After weighing, a portion of the pulp was taken to determine the pulp moisture and *kappa number*. The other portion was packed into plastic bags and stored in the refrigerator at 4°C. *Kappa number* was determined using TAPPI test method T236om-99 (Berzins, 1965). This measurement determines how much lignin is present in pulp. Higher *kappa number* samples requires more bleach, while samples with lower numbers have less lignin and needs less bleach as explained in the equation: % of lignin in pulp = *kappa number* × 0.13 (Berzins, 1965).

5. Measurement of *basic density*

   To measure *basic density*, a pith to bark wedge was excised from the disks. Strips of uniform thickness were cut along the radius using a twin-blade saw. Radial wood strips were scanned at consecutive 0.5 mm intervals, from bark to pith, using a gamma-ray densitometer. Weighted mean *basic density* was then calculated for each tree.

3.8.5 Measurement of coppicing

The ability of a genotypes to coppice is measured in terms of the number for shoots produced from stumps (or stools) of felled trees of the previous tree crop/rotation. In this study, *coppicing* was measured using the methods of Little and du Toit (2003), as well as Little and Gardner (2003). *Coppicing* was thus measured in the following manner:

1. After felling a tree, the area surrounding a stump was first cleared of debris and branches to enhance sprouting. Care was taken not to damage the bark and the top of stumps.
2. After six months, *coppicing* was measured by dividing a stump into four quadrants and then counting the number of quadrants that had coppiced by counting in a clockwise rotation.
3. Thereafter, the number of total healthy shoots on a stump was counted.
4. All measurements were recorded on a score sheet and later transferred to an Excel spread sheet.

3.8.6 Measurement of pests and diseases

The presence of pest damage and diseased trees in the test trials were monitored throughout the six years of tree growth. Pests were monitored in the four trials from trial establishment until the trees were 6 years old. Of importance were the pests *Eucalyptus* gall/blue gum chalcid wasp (*Leptocybe invasa*) and bronze bug (*Thaumastocoris peregrinus*) (Slippers, 2010). A simple scoring system was used to record the presence or absence of insect infestation on the entire bole from base to live crown, where the presence was scored with a "1" and absence with a "0". Furthermore, because these pests are known to affect young trees with juvenile foliage, it was decided to also monitor their presence on the coppiced material of the 26 tree stumps produced after tree felling for the assessment of the wood and Kraft pulp properties. At coppice age of six months, evidence of the presence of the two pests was recorded by applying the industry standard scale score based on the infestation index devised by Thu et al. (2009) (Table 3.14).

Table 3.14 Industry standard subjective scale score for assessing the presence of pests.

Score	Health status	% Coverage of coppice foliage
0	No visual sign of gall infestation	NIL
1	Some visual gall infestation	Up to 25
2	Mild visual gall infestation	>25 to 50
3	Moderate visual gall infestation	>50 to 75
4	Severe visual gall infestation	>75

The presence of three highly prevalent stem cankers affecting eucalypts and interspecific hybrids in the sub-tropical region of South Africa were monitored. These cankers are caused by the fungal pathogens *Teratosphaeria zuluense* (previously known as *Coniothyrium*), *Botryosphaeria dothidea* and *Endothia gyrosa*. A simple presence or absence scoring system was applied to score

stem cankers, where the presence on the entire bole from base to live crown was scored with a "1" and absence with a "0".

3.9 Phase 3: Trial data analysis

3.9.1 Data verification

Prior to data analysis, the measurements were transferred to Excel spreadsheets and then checked for accuracy and inconsistencies. The field measurements were transferred from prepared coding sheets used in the field, while the wood and Kraft pulp property measurements were transferred from laboratory reports. Another check was performed to ensure that the data had been accurately transferred. In instances where SAS/STAT software, Version 9.2 of the SAS System for Windows was used in the analysis of the data (SAS Institute, 2008), the Excel spreadsheets were transferred to SAS spreadsheet format.

3.9.2 Statistical analysis

Before the data were analysed, the data were first subjected to tests for normality. Tests for normality were done through the calculation of skewness and kurtosis (Gibson, 1982). All tests for normality were undertaken using the options available in the SAS/STAT software, Version 9.2 of the SAS package (SAS Institute, 2008). For *DBH*, tree *height* and *growth volume* distributions showed normality, with no skewness or excess kurtosis. The data for trees sampled for wood property studies showed positive skewness for all growth traits. This was, expected as most of the trees sampled for wood property tests were from improved sources and ranked the top half of the rankings for *growth volume* and therefore, inclined to have better quality for all the growth traits.

Several statistical procedures were followed to analyse the trait measurements in this study. This included the following:

1. Summary statistics were calculated for all the measured traits using Microsoft Excel.
2. Analysis of variance (ANOVA) tests for an unbalanced design were performed to compare the four trials in terms of genotype groups and genotypes using SAS software. These statistical tests were performed at a 95% confidence level ($\alpha = 0.05$).
3. For the analysis of data for each aspect site trial, replicate and block within replicate effects were considered fixed, and genotype group and genotypes within-group effects random. Each of the trials were analysed as a random complete block (block effects were all non-significant and therefore, there was no need for correction). The model used for the analysis of variance of the data for each aspect site trial was:

$$y_{ijkl} = \mu + R_i + G_j + g_{k(j)} + e_{ijkl} \quad (2)$$

where,

y_{ijkl} is the lth tree of the kth genotype in the jth group in the ith replicate;

μ is the overall mean;

R_i is the effect of the ith replicate where i = 1, 2, .., 10;

G_j is the effect of the jth group where j=1,2,.., 14;

$g_{k(j)}$ is the effect of the kth genotype nested in the j$^{th\ group}$ where k = 1, 2,…, 5 (mean number = 5); and

e_{ijkl} is the random error.

4. In instances where an ANOVA test was significant, a Duncan's Multiple Range post hoc Test (DMRT) using Residual Maximum Likelihood (REML) means was performed with Genstat software, Release 21.1 (VSN, 2022), to rank genotype groups at a 95% confidence level ($\alpha = 0.05$).
5. Pearson's correlation coefficients were calculated using SAS software to ascertain what type of relationship existed between different pairs of the wood and Kraft pulp properties. The strength of these relationships was interpreted using the rule of thumb presented in Table 3.15.

Table 3.15 Classification of strength relationships used for the interpretation of Pearson's correlations.

Pearson correlation coefficient (*r*) value	Strength	Direction
> 0.5	Strong	Positive
> 0.3 to 0.5	Moderate	Positive
> 0 to 0.3	Weak	Positive
0	None	None
< 0 to –0.3	Weak	Negative
< –0.3 to –0.5	Moderate	Negative
< –0.5	Strong	Negative

6. Genotype-by-environment interactions (GEI) occur when the relative performance of genotypes differs when grown in different environments. A GEI analysis was performed on *growth volume* to establish if aspect site differences existed. When two traits are measured on different individuals within genetic groups and for example show a correlation between trees of the same genotypes grown in different environments, the correlation is designated a Type B correlation (Burdon, 1977). Type B correlations at the genotype level (r_{Bg}) were estimated for all possible site pairs of species and interspecific hybrid genotypes using the following formula:

$$r_{Bg} = \frac{\sigma^2_{genotype}}{\sigma^2_{genotype} + \sigma^2_{site*genotype}} \quad (3)$$

The ratio of genotype variance to the sum of genotype and environment × genotype variance is equivalent to a Type B correlation calculated from paired genotypes across sites. High Type B correlations indicate very little, or absent GEI. A type B correlation (r_{Bg}) of 0.67 is the level at which the GEI variance represents 50% of the total variance, and is the point where it is postulated that the GEI exists amongst the aspect sites (sites played a role in ranking of genotypes for growth volume) (Shelbourne, 1972). Variances were obtained using the model:

$$y = XA + ZB + Hf + Wp + TS + Qsf + e \quad (4)$$

where:

y is trait or data vector;

XA is replication effects (fixed);

ZB is block effects (fixed);

Hf is genotype/group (random);

Wp is plot effects (random);

Ts is site effect (fixed);

Qsf is site/genotype interaction coefficient; and

e is random error effect.

7. As part of selecting genotypes suitable for deployment on the mined sand dunes, several Principal Component Analyses (PCAs) were performed using the options available in the Genstat software, Release 21.1 (VSN, 2022). For the PCA, an orthogonal transformation of the original traits to a new set of uncorrelated traits was applied by decreasing the order of importance (Chatfield & Collins, 1980). The formula that was used in all the PCAs was:

   If Y_{ijk} is the measured trait, the equation for the PCA was (Nachit et al., 1992):

$$Y_{ijk} = \mu + \sum_{K=1}^{M} \lambda_k * \propto_{ik} * \gamma_{jk} + \rho_{ij} \quad (5)$$

   where:

   Y_{ijk} is the contribution of the i^{th} trait in the j^{th} PC;

   μ is the effect of the i^{th} trait;

   M is the number of PCA axes retained within the model;

   λ_k is the square root of the eigenvalue of the k^{th} Interaction Principal Component (IPCA) axis; α_{ik} and γ_{jk} is the principal component scores for IPCA axis k of the i^{th} trait and the j^{th} PC, respectively; and

   ρ_{ij} is the deviation of trait i^{th} PC j^{th} from the model.

8. A Cluster Analysis (CA) was performed on the genotypes to group genotypes of similar values for the measured traits: The Mahalanobis distance (D^2) was used as a measure of the distances between pairs of traits in each of any two groups. The Mahalanobis distance is an alternative to multicollinearity and is performed to normalise the data and to compensate for correlations among traits (Hair Jr et al., 2009).

3.10 Phase 4: Genotype selection

The selection of genotypes for deployment on mined sand dunes in the Richards Bay area was based on two sets of measurements of the 6-year-old trees. Before the genotypes could be selected, GEI was estimated for *growth volume* to ascertain if aspect site effects played a role. In this study, Type B correlations revealed that no GEI existed amongst the aspect sites. Therefore, two datasets were used for the selection of genotypes. One dataset comprised all the measurements gathered from the four trials (2,800 measurements per trait), while the other dataset comprised the measurements gathered from the 26 felled trees (26 measurements per trait).

In the first step towards identifying genotypes suitable for the mined sand dunes, Relative Performance Indices (RPIs) were calculated for each dataset. These indices were multivariate weighted indices, where the value of each trait (variable) was multiplied with a weighting. The weightings of the traits were obtained from one or two Principal Components (PCs) determined through a PCA performed on the data. The weightings were percentages of the explained variance of a trait in a PC. The general formula used to calculate an RPI for an individual genotype was:

$$RPI = \sum_{j=1}^{m}[P_m(\sum_{i=1}^{n} a_i \, v_i)] \quad (4)$$

where:

m = number of PCs;

P = percentage of total variance attributed to m^{th} PC;

n = number of traits

a_i = weighting of i^{th} trait obtained from the m^{th} PC percentage variance explained; and

$\underline{v_i}$ = mean measurement of the i^{th} trait.

The RPIs were used to rank the genotypes of each dataset. Thereafter, rankings were compared to identify potential genotypes for deployment on the mined sand dunes. Once genotypes were identified, Economic Performance Indices (EPIs) were calculated to establish the market which they suited. The EPIs were calculated for fibre production related to the pulp and paper industry, as well as for the

woodchip export market. To calculate the EPIs, the RPI formula was modified by changing specific weightings. For the pulp and paper industry the weighting of the trait *screen pulp yield* was doubled, and for the woodchip industry the weighting for the trait *basic density* was doubled.

Chapter 4

Germplasm Survival

4.1 Introduction

One of the major concerns when establishing a forest plantation is the survival rate of young seedlings or cloned plantlets. Environmental factors play a vital role in successful plantation establishment and cultivation. However, it can be difficult to establish forest plantations on dry sandy soils as found in the mined sand dunes of Richards Bay. Seedling and cloned plantlet survival are thus important factors to consider when selecting suitable genotypes for these mined sand dunes. Genotypes that demonstrate relatively poor survival rates could impact plantation establishment costs severely, not only because of replanting (blanking), but also because of downstream loss of germplasm. Thus, after measuring the *survival* of the genotypes planted in the four trials at 2 and 4 weeks, as well as at 1, 3 and 6 years of tree growth in Phase 2, the measurements were analysed in Phase 3 (Figure 4.1).

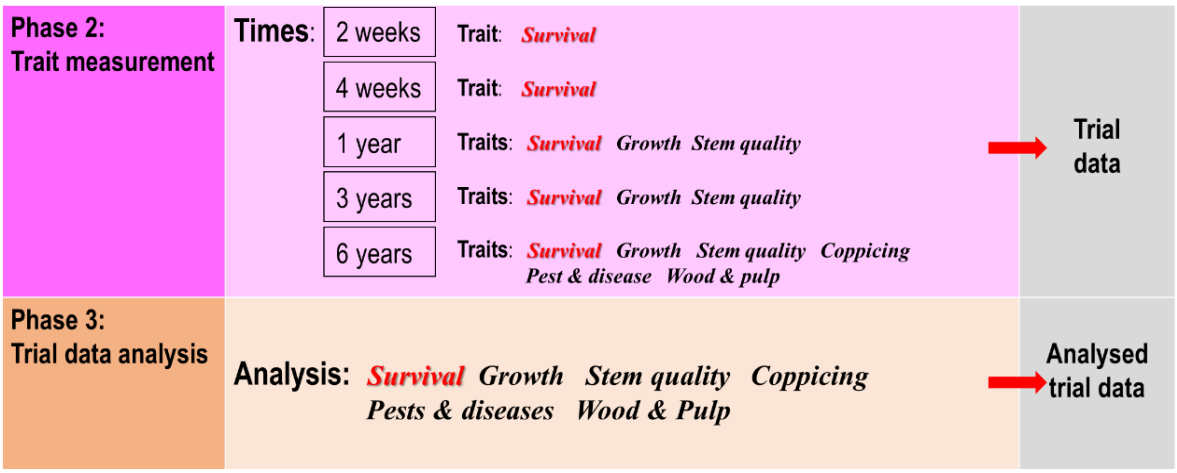


Figure 4.1 **Extract of the study design highlighting the survival aspect for measurement and analysis.**

The objectives to measure and analyse survival were:

1. To measure *survival* at 2 weeks;
2. To measure *survival* at 4 weeks;
3. To measure *survival* at 1 year;
4. To measure *survival* at 3 years;
5. To measure *survival* at 6 years; and
6. Analyse the measurements.

When assessing *survival* in a trial, the number of dead or missing trees were noted and used to calculate the percentage *survival*. Figure 4.2 shows examples of *survival* presentations in a trial.

A. **B.** **C.**

Figure 4.2 **Photographs of germplasm survival. A. Arrow indicates missing plant at 2 weeks after planting. B. Arrow indicates missing young tree at 4 weeks after planting. C. Arrow indicates missing tree at 1 year after planting.**

4.2 Survival of germplasm

Survival percentages were calculated for the trials planted at the four aspect sites considered in this study. These percentages were calculated over five measurement times (germplasm ages), stretching from germplasm age of two weeks to six years. The *survival* percentages of the four trials were relatively high, mostly greater than 80% at all measurement ages (Table 4.1). Although all dead plants were blanked at 2 and 4 weeks after planting, *survival* percentages of the 4-week-old germplasm were lower than at 2-week-old germplasm for all four trials. The higher *survival* percentages of the

2-week-old germplasm could be attributed to the regular watering and fertilising of the germplasm during the first two weeks of growth of the trials. When the *survival* percentages of 1-year-old germplasm were compared to the 4-week-old germplasm, their percentages were higher, which could be attributed to the final round of blanking that took place at 4 weeks after planting. From the first year after planting until 6 years of tree growth, *survival* percentages of the germplasm showed a steady decline. An ANOVA test at year six revealed significant differences in *survival* percentages between trials at a 95% confidence level (α = 0.05; F (13, 2388) = 102.30; P < 0.001). A Duncan Multiple Range Test (DMRT) revealed two significantly different aspect site groupings at all germplasm ages.

Table 4.1 Trial survival percentage per aspect site and germplasm age.

Germplasm age	Survival % per aspect site (n = 700)			
	Sea- facing	Steep	Flat	Inland-facing
2 weeks	89 B	93 A	97 A	96 A
4 weeks	86 A	81 A	76 A	93 B
1 year	91 B	95 A	96 A	93 B
3 years	89 B	86 B	91 A	90 A
6 years	84 B	83 B	87 A	87 A

Different letters in the same row indicates significant differences in survival between aspect sites.

4.3 Survival per genotype group

4.3.1 Sea-facing aspect site

Survival percentages of the 14 genotype groups planted at the Sea-facing aspect site were compared. From the youngest germplasm age to age 6 years, all the genotype groups demonstrated a small decrease in *survival*. The top three *survival* percentages of 6-year-old trees were displayed by interspecific hybrids, of which *E. grandis* (G×C and G×U) and *E. urophylla* (G×U and S×U) were parents in two of the three clones (Table 4.2). These three genotype groups presented *survival*

percentages of 98 and 100%, of which G×C demonstrated 100% *survival*. Although *E. urophylla* was one of the parents of the top three genotypes at germplasm age of 6 years, the pure species of *E. urophylla* demonstrated the lowest *survival* percentages at all germplasm ages. Of the 14 6-year-old genotype groups, the *survival* percentages of two of the groups were below the 70% of the industry standard. An ANOVA revealed significant differences in *survival* percentages between genotype groups at 95% confidence level (α = 0.05; F (13, 585) = 12.94; P < 0.001). A DMRT revealed that the mean *survival* percentages of the top three ranking genotype groups belonged to the same DMRT ranking group, while the remainder of the genotype groups were distributed amongst five DMRT ranking groups.

Table 4.2 Survival percentages of genotype groups at different ages planted on the Sea-facing aspect site and ranked based on 6-year-old age.

Germplasm group	Species or group name	Germplasm type Clone (C) or Seedling (S)	Survival % at 2 weeks	Survival % at 4 weeks	Survival % at 1 year	Survival % at 3 years	Survival % at 6 years	DMRT grouping
G×C	*E. grandis* × *E. camaldulensis*	C	100	100	100	100	100	A
G×U	*E. grandis* × *E. urophylla*	C	97	97	96	94	98	AB
S×U	*E. saligna* × *E. urophylla*	C	100	100	100	98	98	AB
G×U	*E. grandis* × *E. urophylla*	S	98	98	98	94	92	BC
C	*E. camaldulensis*	S	100	100	100	98	92	BC
T	*E. tereticornis*	S	96	96	96	90	86	CD
G×S	*E. grandis* × *E. saligna*	C	84	84	84	84	82	DE
G	*E. grandis*	S	98	98	98	96	80	DE
Cor	*Corymbia*	S	84	84	84	81	80	DE
Cas	*C. equisetifolia*	S	86	86	86	78	78	E
R	*E. resinifera*	S	92	92	92	84	78	E
G×T	*E. grandis* × *E. tereticornis*	S	78	78	78	75	74	F
G×L	*E. grandis* ×	S	90	90	90	78	68	F

Germplasm group	Species or group name	Germplasm type Clone (C) or Seedling (S)	Survival % at 2 weeks	Survival % at 4 weeks	Survival % at 1 year	Survival % at 3 years	Survival % at 6 years	DMRT grouping
	E. longirostrata							
U	*E. urophylla*	S	74	74	74	70	66	F
Mean			89	86	91	89	85.5	
SE			4.2	4.0	4.4	4.3	4.0	

4.3.2 Steep aspect site

Survival percentages were also calculated for the genotype groups planted on the Steep aspect site. In this trial, a small decrease in *survival* percentages across all the genotype groups was also noted from the youngest germplasm age to age 6. Similar to the Sea-facing trial, 6-year-old G×C trees also demonstrated 100% *survival* on the Steep aspect site. Three genotype groups demonstrated *survival* percentages in the 90% ranges. Two were interspecific hybrid clones (G×U and S×U) and one a pure species (*E. camaldulensis*), ranked in the second position (Table 4.3). Two of the top ranking three genotype groups were constituted with *E. grandis* as a parent. Similar to the Sea-facing trial, the *survival* percentages of two 6-year-old genotype groups were below the industry standard of 70%. These groups were the pure species *E. tereticornis* and the interspecific hybrid seedling genotype group of *E. grandis* × *E. longirostrata* (G×L). An ANOVA test also revealed significant differences in mean *survival* percentages amongst the genotype groups at a 95% confidence level (α = 0.05; F (13, 577) = 13.13; P < 0.001). In this trial the top ranking clone ranked in a separate DMRT grouping, while the remainder of the genotypes groups ranked into seven different DMRT groupings.

Table 4.3 Survival percentages of genotype groups at different ages planted on the Steep aspect site and ranked based on 6-year-old age.

Germplasm group	Species or group name	Germplasm type Clone (C) or Seedling (S)	Survival % at 2 weeks	Survival % at 4 weeks	Survival % at 1 year	Survival % at 3 years	Survival % at 6 years	DMRT grouping
G×C	*E. grandis* × *E. camaldulensis*	C	100	100	100	100	100	A
C	*E. camaldulensis*	S	100	100	100	94	94	B
G×U	*E. grandis* × *E. urophylla*	C	97	98	98	92	90	C
S×U	*E. saligna* × *E. urophylla*	C	96	96	96	94	90	C
G×T	*E. grandis* × *E. tereticornis*	S	98	98	98	88	88	CD
G×U	*E. grandis* × *E. urophylla*	S	96	96	96	92	88	CD
G×S	*E. grandis* × *E. saligna*	C	100	100	100	94	88	CD
U	*E. urophylla*	S	88	88	88	88	86	CDE
Cor	*Corymbia*	S	96	96	96	88	82	FG
Cas	*C. equisetifolia*	S	88	88	88	82	82	FG
G	*E. grandis*	S	96	96	96	87	80	FG
R	*E. resinifera*	S	94	94	94	79	74	GH
T	*E. tereticornis*	S	90	90	90	71	68	GH
G×L	*E. grandis* × *E. longirostrata*	S	90	90	90	72	60	H
Mean			93	81	95	89	84.5	
SE			3.0	3.2	3.5	3.4	3.2	

In DMRT grouping column, different letters indicate significantly different mean survival percentages between genotype groups.

4.3.3 Flat aspect site

The *survival* percentages for the genotype germplasm group planted in the Flat aspect site trial also showed a decrease in *survival* percentages from the youngest to the oldest germplasm measurements (Table 4.4). An ANOVA test revealed significant differences in *survival* percentages amongst the genotype groups at a 95% confidence level (α = 0.05; F (13, 608) = 14.76; P < 0.001). The *survival* percentages of the top eight genotype groups were in the 90% ranges, ranging from 90-94%, making up two DMRT groupings. These eight genotype groups comprised of five hybrid clones and three pure species. The DMRT grouping A consisted of three hybrid clones and the pure species *Corymbia. E. grandis* and *E. urophylla* were one of the parents in two of the hybrid clones. Similarly to both the Sea-facing and Steep trials, the *survival* percentage of hybrid of *E. grandis* × *E. longirostrata* (G×L) genotype group was also below the industry standard of 70%.

Table 4.4 Survival percentages of genotype groups at different ages planted on the Flat aspect site and ranked based on 6-year-old age.

Germplasm group	Species or group name	Germplasm type Clone (C) or Seedling (S)	Survival % at 2 weeks	Survival % at 4 weeks	Survival % at 1 year	Survival % at 3 years	Survival % at 6 years	DMRT grouping
G×C	*E. grandis* × *E. camaldulensis*	C	96	96	96	96	94	A
S×U	*E. saligna* × *E. urophylla*	C	96	96	96	94	94	A
Cor	*Corymbia*	S	98	98	98	98	94	A
G×U	*E. grandis* × *E. urophylla*	C	98	100	100	100	93	A
G×T	*E. grandis* × *E. tereticornis*	S	94	94	94	94	92	A B
C	*E. camaldulensis*	S	96	96	96	94	90	BC
G×U	*E. grandis* × *E. urophylla*	S	98	98	98	92	90	BC
Cas	*C. equisetifolia*	S	96	96	96	96	90	BC
G×S	*E. grandis* × *E. saligna*	C	98	98	98	90	88	BCD
R	*E. resinifera*	S	92	92	92	92	82	CD
G	*E. grandis*	S	98	98	98	87	80	E

Germplasm group	Species or group name	Germplasm type Clone (C) or Seedling (S)	Survival % at 2 weeks	Survival % at 4 weeks	Survival % at 1 year	Survival % at 3 years	Survival % at 6 years	DMRT grouping
U	*E. urophylla*	S	90	90	90	89	76	F
T	*E. tereticornis*	S	98	98	98	88	72	F
G×L	*E. grandis* × *E. longirostrata*	S	98	98	98	72	60	G
Mean			97	76	96	91	87	
SE			4.5	3.2	4.3	4.0	3.8	

In DMRT grouping column, different letters indicate significantly different mean survival percentages between genotype groups.

4.3.4 Inland-facing aspect site

The *survival* percentages for the 14 genotype groups for the aspect facing inland site was also calculated. As was demonstrated there was slight decrease in *survival* percentages from the youngest to the oldest germplasm. In contrast, the Sea-facing and Steep sites, 6-year-old trees of the pure species *C. equisetifolia* (control species) ranked number one with 100% *survival* (Table 4.5). An ANOVA test also revealed significant differences in *survival* percentages amongst the genotype groups at a 95% confidence level (α = 0.05; F (13, 610) = 17.18; P < 0.001). *C. equisetifolia* ranked into a separate DMRT grouping (A), while six other genotype groups displayed *survival* percentages in the 90s, making up two more DMRT groupings. The two pure species *E. tereticornis* and *E. camaldulensis* grouped with hybrid clones in this group of six genotype groups. In contrast to the other three trials, none of the genotype groups displayed *survival* percentage below the industry standard of 70% in the Inland-facing trial.

Table 4.5 Survival percentages of genotype groups at different ages planted on the Inland-facing aspect site and ranked based on 6-year-old age.

Germplasm group	Species or group name	Germplasm type Clone (C) or Seedling (S)	Survival % at 2 weeks	Survival % at 4 weeks	Survival % at 1 year	Survival % at 3 years	Survival % at 6 years	DMRT grouping
Cas	*C. equisetifolia*	S	100	100	100	100	100	A
G×C	*E. grandis* × *E. camaldulensis*	C	96	96	96	96	96	AB
G×U	*E. grandis* × *E. urophylla*	C	96	96	96	96	96	AB
S×U	*E. saligna* × *E. urophylla*	C	96	96	96	96	96	AB
T	*E. tereticornis*	S	95	94	94	94	94	BC
C	*E. camaldulensis*	S	98	96	96	95	92	CD
G×S	*E. grandis* × *E. saligna*	C	96	95	95	91	90	DE
G×U	*E. grandis* × *E. urophylla*	S	92	92	92	92	88	DE
G	*E. grandis*	S	92	88	88	88	86	DE
U	*E. urophylla*	S	92	90	90	86	84	DEF
Cor	*Corymbia*	S	86	81	81	80	78	CFG
R	*E. resinifera*	S	82	78	78	78	76	FG
G×T	*E. grandis* × *E. tereticornis*	S	92	86	86	81	76	FG
G×L	*E. grandis* × *E. longirostrata*	S	84	80	80	72	72	G
Mean			96	93	93	90	87	
SE			4.4	4.2	4.3	4.0	4.0	

In DMRT grouping column, different letters indicate significantly different mean survival percentages between genotype groups.

4.4 Survival per genotype

4.4.1 Sea-facing aspect site

Survival percentages were calculated for the different 6-year-old genotypes planted on the Sea-facing aspect site. Of the 70 genotypes, 21 (30%) demonstrated 100% *survival*, of which 14 of the genotypes were interspecific hybrid clones and seven interspecific hybrid seedlings (Table 4.6). Of

the 14 interspecific hybrid clones, 11 were hybrids of *E. grandis* in combination with either *E. camaldulensis* (G×C) or *E. urophylla* (G×U). The other three interspecific hybrid clones were *E. saligna* in combination with *E. urophylla* (S×U). The seven interspecific hybrid seedling genotypes constituted three *E. grandis* genotypes, hybridised with either *E. urophylla* (G×U) or *E. longirostrata* (G×L). Lastly, only the two pure species *E. camaldulensis* and *E. tereticornis* demonstrated 100% *survival*. Of the 70 genotypes, seven (10%) showed *survival* percentages below the industry standard of 70%.

Table 4.6 Ranking of 6-year-old genotypes planted on the Sea-facing aspect site based on survival percentages.

Genotype	Clone (C) or Seedling (S)	Rank	Survival % at 6 years	Genotype	Clone (C) or Seedling (S)	Rank	Survival % at 6 years
G×U608	C	1	100 A	Maculata1	S	36	90 B
G×C225	C	2	100 A	Au9	S	37	80 C
G×C215	C	3	100 A	B10-513	S	38	80 C
G×C231	C	4	100 A	SGR1668×U mix	S	39	80 C
G×C121	C	5	100 A	Cit	S	40	80 C
G×U56	C	6	100 A	B09-075	S	41	80 C
G×U5	C	7	100 A	Cas404	S	42	80 C
G×U82	C	8	100 A	B09-689	S	43	80 C
SGR1198×Umix	S	9	100 A	T37	S	44	80 C
G×U21	C	10	100 A	Cas401	S	45	80 C
S×U92	C	11	100 A	Another	S	46	80 C
S×U107	C	12	100 A	G×S146	C	47	80 C
G×C962	C	13	100 A	SGR1668×LMP04	S	48	80 C
C40	S	14	100 A	SN34023	S	49	80 C
C58	S	15	100 A	SN34032	S	50	80 C
AT9	S	16	100 A	Maulata2	S	51	80 C
C69	S	17	100 A	SGR1272×LPM02	S	52	70 D
G15×Umix	S	18	100 A	Au3	S	53	70 D
G×U7	C	19	100 A	Au7	S	54	70 D
G50×Lmix	S	20	100 A	Cas402	S	55	70 D

Genotype	Clone (C) or Seedling (S)	Rank	Survival % at 6 years	Genotype	Clone (C) or Seedling (S)	Rank	Survival % at 6 years
S×U84	C	21	100 A	B9-008	S	56	70 D
G×S147	C	22	90 B	Cas403	S	57	70 D
SGR1220×T32	S	23	90 B	C63	S	58	70 D
SGR1683×U mix	S	24	90 B	SGR1220×T10	S	59	70 D
T22	S	25	90 B	AT4	S	60	70 D
Cas400	S	26	90 B	G91×AT10	S	61	70 D
G×S146	C	27	90 B	SN34021	S	62	70 D
B09-346	S	28	90 B	SN33994	S	63	70 D
G×U111	C	29	90 B	Au33	S	64	60 E
G17×Umix	S	30	90 B	SGR1231×T10	S	65	60 E
G×S143	C	31	90 B	G×S143	C	66	60 E
C37	S	32	90 B	Henryi	S	67	60 E
AT6	S	33	90 B	Au21	S	68	50 F
R19032	S	34	90 B	G15×LPM01	S	69	50 F
Tor	S	35	90 B	SGR1198×LPM02	S	70	40 G
Mean	84						
SE	3.4						

In DMRT grouping column, different letters indicate significantly different mean survival percentages between genotypes.

4.4.2 Steep aspect site

The genotypes planted on the Steep aspect site were also ranked based on *survival* of the germplasm. Of the 70 genotypes, approximately 16 (22.8%) genotypes demonstrated 100% *survival*, which 10 were interspecific hybrid clones and six seedlings (Table 4.7). Nine of these interspecific hybrid clones were hybrids of *E. grandis* in combination with *E. camadulensis* (G×C) and *E. urophylla* (G×U). Similar to the Sea-facing trial, one of the interspecific hybrid clones was *E. saligna* in combination with *E. urophylla* (S×U). The six seedling genotypes that demonstrated 100% *survival* were three interspecific hybrids of *E. grandis* with *E. urophylla* (G×U) or *E. tereticornis* (G×T), and three pure species of *E. camaldulensis* and *E. grandis*. Of the 70 genotypes, nine (12.8%) showed *survival* percentages below the industry standard of 70%.

Table 4.7 Ranking of 6-year-old genotypes planted on the Steep aspect site based on survival percentages.

Genotype	Clone (C) or Seedling (S)	Rank	Survival % at 6 years	Genotype	Clone (C) or Seedling (S)	Rank	Survival % at 6 years
G×C215	C	1	100 A	G×U111	C	36	80 D
G×C121	C	2	100 A	B09-075	S	37	80 D
G×C225	C	3	100 A	Au9	S	38	80 D
G×U82	C	4	100 A	Au7	S	39	80 D
G×C962	C	5	100 A	Cas402	S	40	80 D
G×U7	C	6	100 A	G45×T32	S	41	80 D
SGR1220×T32	S	7	100 A	C37	S	42	80 D
G×U56	C	8	100 A	Cas401	S	43	80 D
G×U21	C	9	100 A	SGR1198×Umix	S	44	80 D
S×U92	C	10	100 A	B10-513	S	45	80 D
G×C231	C	11	100 A	SGR1220×T10	S	46	80 D
SGR1683×Umix	S	12	100 A	G15×Umix	S	47	80 D
G17×Umix	S	13	100 A	Cit	S	48	80 D
B09-689	S	14	100 A	AT9	S	49	80 D
C69	S	15	100 A	SN34023	S	50	80 D
C58	S	16	100 A	R19032	S	51	80 D
G×U608	C	17	98 B	Henryi	S	52	80 D
G×S147	C	18	90 C	Tor	S	53	80 D
G50×Lmix	S	19	90 C	SN34032	S	54	80 D
G×U5	C	20	90 C	Cas403	S	55	70 E
SGR1668×LMP02	S	21	90 C	B09-008	S	56	70 E
Cas400	S	22	90 C	SGR1668×Umix	S	57	70 E
SGR1231×T10	S	23	90 C	Au21	S	58	70 E
S×U107	C	24	90 C	T37	S	59	70 E
Au33	S	25	90 C	S×U84	C	60	70 E
Cas404	S	26	90 C	G×S146	C	61	70 E
Au03	S	27	90 C	SN34021	S	62	60 F
C40	S	28	90 C	SN33994	S	63	60 F

Genotype	Clone (C) or Seedling (S)	Rank	Survival % at 6 years	Genotype	Clone (C) or Seedling (S)	Rank	Survival % at 6 years
Maculata2	S	29	90 C	AT6	S	64	60 F
G×S143	C	30	90 C	T22	S	65	60 F
G×S136	C	31	90 C	AT4	S	66	60 F
G91×AT10	S	32	90 C	SGR1198×LPM02	S	67	50 G
G×S137	C	33	90 C	B09-346	S	68	50 G
C63	S	34	90 C	G15×LPM01	S	69	50 G
Maculata1	S	35	90 C	SGR1272×LPM02	S	70	20 H
Mean	83						
SE	3.8						

In DMRT grouping column, different letters indicate significantly different mean survival percentages between genotypes.

4.4.3 Flat aspect site

The genotypes planted on the Flat aspect site were also ranked for *survival* percentages. Of these genotypes, 23 (32.8%) demonstrated 100% *survival*, of which 11 were interspecific hybrids and 12 seedling genotypes (Table 4.8). Of the 11 interspecific hybrids, nine genotypes were hybrids of *E. grandis* in combination with *E. camaldulensis* (G×C) or *E. urophylla* (G×U). The other two genotypes were interspecific hybrids of *E. saligna* in combination with *E. urophylla* (S×U). Of the 12 seedling genotypes that also showed 100% *survival*, eight were pure species and four interspecific hybrid seedlings of *E. grandis* with either *E. urophylla* (G×U) or *E. tereticornis* (G×T). Similar to the Sea-facing trial, seven (10%) of the 70 genotypes showed *survival* percentages below the industry standard of 70%.

Table 4.8 Ranking of 6-year-old genotypes planted on the Flat aspect site based on survival percentages.

Genotype	Clone (C) or Seedling (S)	Rank	Survival % at 6 years	Genotype	Clone (C) or Seedling (S)	Rank	Survival % at 6 years
G×C121	C	1	100 A	G17×Umix	S	36	90 C
G×C231	C	2	100 A	G×S137	C	37	90 C
G×C225	C	3	100 A	C37	S	38	90 C
G×U608	C	4	100 A	C63	S	39	90 C
G×U82	C	5	100 A	G×S143	C	40	90 C
G×U111	C	6	100 A	Maulata2	S	41	90 C
SGR1220×T32	S	7	100 A	S×U84	C	42	90 C
G×U5	C	8	100 A	SN34023	S	43	90 C
G×U56	C	9	100 A	G×S136	C	44	90 C
Au9	S	10	100 A	AT9	S	45	90 C
Cas402	S	11	100 A	Cit	S	46	90 C
S×U107	C	12	100 A	Henryi	S	47	90 C
B9-075	S	13	100 A	G×S143	C	48	80 D
G×U7	C	14	100 A	G×C962	C	49	80 D
SGR1198×Umi	S	15	100 A	Au33	S	50	80 D
C58	S	16	100 A	Au21	S	51	80 D
SGR1220×T10	S	17	100 A	B9-346	S	52	80 D
SGR1683xUmix	S	18	100 A	G50×Lmix	S	53	80 D
G×S147	C	19	100 A	Cas403	S	54	80 D
AT6	S	20	100 A	B9-689	S	55	80 D
Tor	S	21	100 A	G91× AT10	S	56	80 D
Maculata1	S	22	100 A	AT4	S	57	80 D
SN33994	S	23	100 A	C69	S	58	80 D
G×C215	C	24	93 B	T22	S	59	80 D
Cas400	S	25	90 C	SN34021	S	60	80 D
S×U92	C	26	90 C	SN34032	S	61	80 D
Cas404	S	27	90 C	SGR1668×LMP02	S	62	70 E
T10×SGR1231	S	28	90 C	SGR1272×LPM02	S	63	70 E

Genotype	Clone (C) or Seedling (S)	Rank	Survival % at 6 years	Genotype	Clone (C) or Seedling (S)	Rank	Survival % at 6 years
G×U21	C	29	90 C	Au7	S	64	60 F
B9-008	S	30	90 C	SGR1668×LMP04	S	65	60 F
C40	S	31	90 C	Au3	S	66	60 F
G×S136	S	32	90 C	R19032	S	67	60 F
Cas401	S	33	90 C	B10-513	S	68	50 G
G15×Umix	S	34	90 C	G15×LPM01	S	69	50 G
T37	S	35	90 C	SGR1198×LPM02	S	70	40 H
Mean	87						
SE	2.5						

In DMRT grouping column, different letters indicate significantly different mean survival percentages between genotypes.

4.4.4 Inland-facing aspect site

The *survival* percentages for the 70 different genotypes planted on the Inland-facing aspect site were also ranked. Of these genotypes, 26 (37.1%) demonstrated 100% *survival*, of which 12 were interspecific hybrid clones and 14 seedlings (Table 4.9). Nine of the interspecific hybrid clones constituted *E. grandis* in combination with *E. camaldulensis* (G×C) and *E. urophylla* (G×U), while the other three were hybrids of *E. saligna* with *E. urophylla* (S×U). Of the 14 seedling genotypes, 11 were pure species and three interspecific hybrid seedlings of *E. grandis* crossed with *E. urophylla* (G×U). In contrast to the other three trials, only five (7.1%) genotypes showed *survival* percentages below the industry standard in the Inland-facing trial.

Table 4.9 Ranking of 6-year-old genotypes planted on the Inland-facing aspect site based on survival percentages.

Genotype	Clone (C) or Seedling (S)	Rank	Survival % at 6 years	Genotype	Clone (C) or Seedling (S)	Rank	Survival % at 6 years
G×S147	C	1	100 A	AT9	S	36	90 C
G×U608	C	2	100 A	T37	S	37	90 C
G×C215	C	3	100 A	Cit	S	38	90 C
G×C962	C	4	100 A	SGR 1220×T10	S	39	90 C
G×C121	C	5	100 A	G×S143	C	40	90 C
G×U21	C	6	100 A	AT6	S	41	90 C
Cas400	S	7	100 A	G×S136	C	42	90 C
G×U7	C	8	100 A	SN34023	S	43	90 C
Cas404	S	9	100 A	SN34032	S	44	90 C
Cas402	S	10	100 A	Tor	S	45	90 C
G×U56	C	11	100 A	Au7	S	46	82 CD
Cas403	S	12	100 A	G×U82	C	47	81 D
Cas401	S	13	100 A	B10-513	S	48	80 D
G×U5	C	14	100 A	S×U92	C	49	80 D
G×U111	C	15	100 A	G5×0Lmix	S	50	80 D
S×U107	C	16	100 A	G×S137	C	51	80 D
SGR1198×Umix	S	17	100 A	G×U21	C	52	80 D
SGR1683×Umix	S	18	100 A	R19032	S	53	80 D
C69	S	19	100 A	B9-075	S	54	80 D
C58	S	20	100 A	SGR 1231×T10	S	55	80 D
SxU84	C	21	100 A	G×S147	S	56	80 D
G17×Umix	S	22	100 A	Au3	S	57	80 D
C40	S	23	100 A	SGR1198×LPM02	S	58	70 E
C63	S	24	100 A	SGR1220×T32	S	59	70 E
T22	S	25	100 A	SGR1272×LPM02	S	60	70 E
AT4	S	26	100 A	SGR1668×LMP04	S	61	70 E
G×C231	C	27	92 B	G15×LPM01	S	62	70 E
G×C225	C	28	90 C	Henryi	S	63	70 E
Au9	S	29	90 C	Maulata2	S	64	70 E

Genotype	Clone (C) or Seedling (S)	Rank	Survival % at 6 years	Genotype	Clone (C) or Seedling (S)	Rank	Survival % at 6 years
SGR1683×Umix	S	30	90 C	Maculata1	S	65	70 E
B9-689	S	31	90 C	C37	S	66	60 F
B9-346	S	32	90 C	SN34021	S	67	60 F
G×S136	C	33	90 C	G91×T10	S	68	60 F
Au33	S	34	90 C	SN33994	S	69	60 G
B9-008	S	35	90 C	G15×Umix	S	70	50 G
Mean	87						
SE	1.9						

In DMRT grouping column, different letters indicate significantly different mean survival percentages between genotypes.

4.4.5 Comparison of trials

To obtain a better understanding of which genotypes demonstrated 100% *survival* across the four aspect sites, 6-year-old germplasm that showed 100% *survival* in three or four trials were listed. Eleven interspecific hybrid clones of the 70 genotypes that were investigated in this study showed 100% *survival* in three or four of the trials (Table 4.10). All these genotypes were interspecific hybrid clones of which 10 hybrids constituted *E. grandis* as maternal parent and one with *E. saligna* (G×S) as maternal parent. The other parents of the hybrids were either *E. camaldulensis* or *E. urophylla* (G×C).

Table 4.10 Top ranking genotypes in four or three trials for survival.

Genotype name	Top ranking genotypes per aspect site				Occurrence in trials
	Sea-facing	Steep	Flat	Inland-facing	
E. grandis × *E. camaldulensis*	G×C121	G×C121	G×C121	G×C121	4
E. grandis × *E. urophylla*	G×U56	G×U56	G×U56	G×U56	4
E. grandis × *E. urophylla*	G×U7	G×U7	G×U7	G×U7	4
E. grandis × *E. camaldulensis*	G×C225	G×C225	G×C225		3
E. grandis × *E. camaldulensis*	G×C215	G×C215		G ×C215	3
E. grandis × *E. camaldulensis*	G×C231	G×C231	G×C231		3
E. grandis × *E. camaldulensis*	G×C962	G×C962		G×C962	3
E. grandis × *E. urophylla*	G×U608		G×U608	G×U608	3
E. grandis × *E. urophylla*	G×U21	G×U21		G×U21	3
E. grandis × *E. urophylla*	G×U5		G×U5	G×U5	3
E. saligna × *E. urophylla*	S×U107		S×U107	S×U107	3
Total	11	8	8	9	

4.5 Discussion

Survival percentages in this study were relatively high. One of the major contributors to the high *survival* percentages was the adherence to strict silvicultural practices (Turvey, 1996; Abraham, 2014). When the *survival* percentages of the 70 genotypes were considered, several genotypes demonstrated high *survival* percentages on all four aspect sites and have the potential for deployment on the mined sand dunes of Richards Bay. The most important of these genotypes were interspecific hybrids derived from *E. grandis* as maternal parent with *E. urophylla* and *E. camaldulensis.* In particular, the good survival performance of hybrids between *E. grandis* and *E. camaldulensis* can be traced to the original *E. camaldulensis* selections used in the creation of the

hybrids. Because these selections were made in the North-West Province in close proximity to salt-laden mine dumps, their salt tolerance made them suitable for sand dunes in Richards Bay, which are exposed to salt-laden sea breezes. These results also support survival data obtained from site species matching trials performed in Zululand by Darrow (1995). Furthermore, these hybrid were constituted from highly improved genetic material with survival was part of the selection criteria (Morris, 2008). However, other properties still need to be considered before genotype choices can be made for mined sand dune deployment in the Richards Bay area. For example, some genotypes may be susceptible to fungal diseases (Darrow, 1994) or may not have the desired wood properties for the pulp and paper industry (E. C. L. Retief & Stanger, 2007). Furthermore, properties such as growth habit, coppicing ability, and pest and disease susceptibility are all of importance when choosing genotypes for deployment on mined sand dunes in the Richards Bay area (Komakech & Eatwell, 2013).

Chapter 5

Germplasm Growth Volume

5.1 Introduction

The overall productivity of trees in a plantation ultimately reflects the population's expression of adaptation to a particular environment. Tree growth is thus a tree's response to its ability to obtain sunlight, water, nutrients, and soil aeration in a specific climate. In this study, growth traits *diameter at breast height* (*DBH*) and *height* were measured to ascertain how well the tested genotypes responded to the particular environmental conditions of the four aspect sites on the mined sand dunes of Richards Bay. Thus, after measuring the growth traits in Phase 2, the measurements were analysed in Phase 3. The growth traits *DBH* and *height* of the genotypes planted in the four trials were measured at 2 and 4 weeks, as well as at 1, 3 and 6 years of tree growth (Figure 5.1). The growth trait *growth volume*, which was calculated using both measurements *DBH* and *height* by applying formulas that were specifically developed for each species, are reported on here (this chapter). The analysed measurements of *DBH* and *height* are presented in Appendix D. Thus, in this section of Phase 2, *growth volume* traits were measured and analysed (Phase 3) (Figure 6.1).

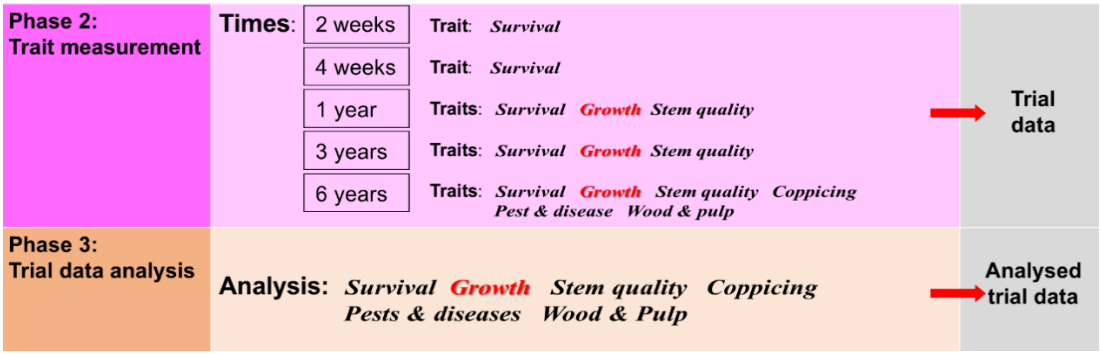
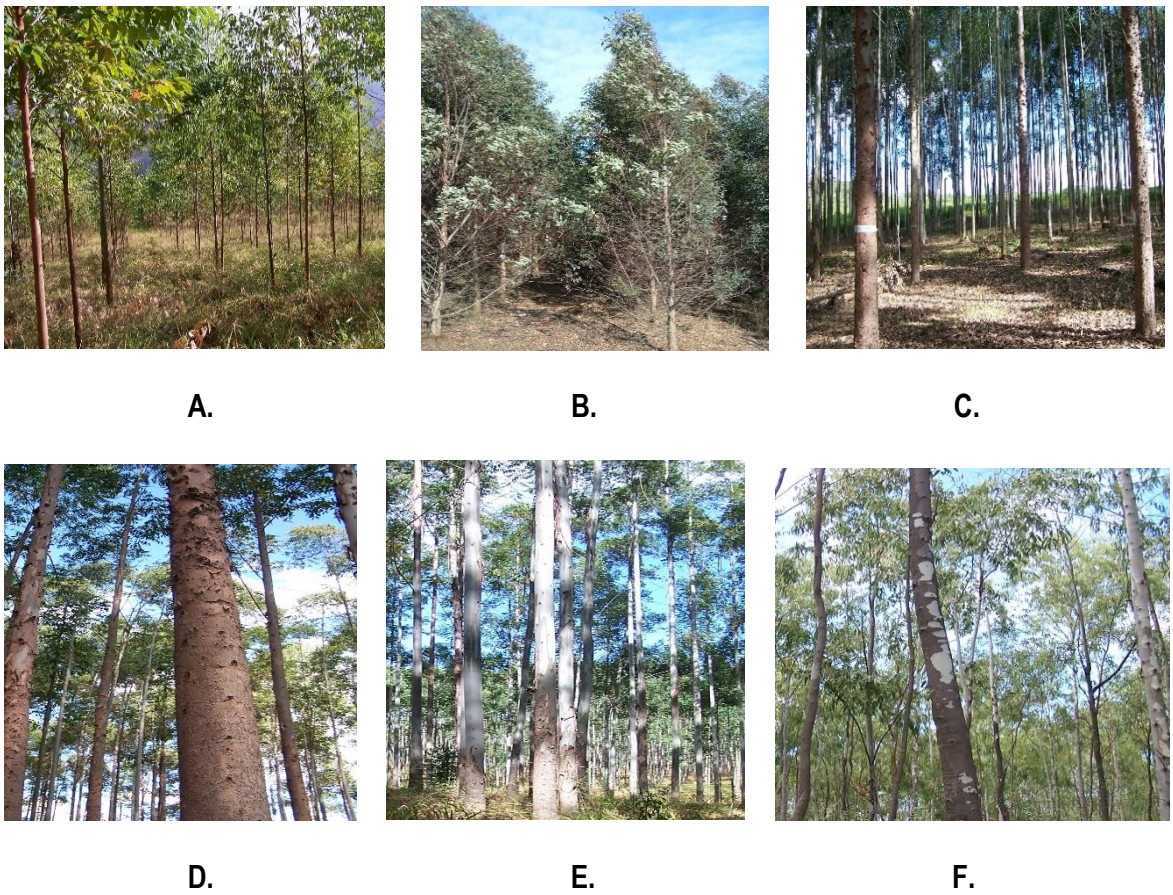


Figure 5.1 **Extract of the study design highlighting the growth aspect for measurement and analysis.**

The objectives to measure and analyse *growth volume* trait were:

1. To measure and analyse *growth volume* trait at 1 year of tree growth;
2. To measure and analyse *growth volume* trait at 3 years of tree growth;
3. To measure and analyse *growth volume* trait at 6 years of tree growth; and
4. Analyse the measurements.

The growth of the trees in a plantation is generally discerned by the sizes of trees. Trees with substantial diameters and heights demonstrate high productivity, whereas thin stick-like trees demonstrate low productivity. Figure 5.2 shows examples of tree growth volumes different ages in a trial.



A. **B.** **C.**

D. **E.** **F.**

Figure 5.2 **Examples of germplasm growth volume. A. Growth volume at 1 year after planting B. Growth volume at 3 years after planting. C. Growth volume at 6 years after planting. D. Large growth volume trees of *E. grandis* × *E. urophylla* (G×U) hybrid. E. Growth volume of *E. grandis*. F. Growth volume of *E. camaldulensis*.**

5.2 Growth volume of germplasm

The *growth volume* calculations were used to compare the overall productivity of the four trials planted on the four aspect sites in the Richards Bay area, irrespective of the genotypes. Trees of the Inland-facing trial demonstrated the highest mean *growth volumes* for all tree ages (Table 5.1). Mean *growth volumes* of the other three trials were substantially less for all ages when compared to the Inland-facing trial. The Inland-facing trial also showed the greatest increase in mean *growth volume* between year 1 and year 3, as well as between years 3 and 6. ANOVA tests revealed significant differences in mean *growth volume* at a 95% confidence level (α = 0.05) for *growth volumes* between trials at germplasm ages of 1 year $F(3, 2623) = 45.41$; $P < 0.001$), 3 years ($F(3, 2490) = 19.81$; $P < 0.001$) and 6 years ($F(3, 2386) = 93.48$; $P < 0.001$). Duncan Multiple Range tests (DMRT) showed, in particular, that the mean *growth volume* of the trees planted in the Inland-facing trial was significantly greater than the mean *growth volumes* of the other trials. Furthermore, the DMRT also revealed that the mean *growth volume* of the 3 and 6-year-old trees planted in the Sea-facing trial were significantly greater than the mean *growth volumes* of trees planted in the Steep and Flat trials.

Table 5.1 Trial growth volume per aspect site and germplasm age.

Germplasm age	Mean growth volume per aspect site in m³ (n = 700 per trial)							
	Sea- facing		Steep		Flat		Inland- facing	
	Mean growth volume	Difference between years	Mean growth volume	Difference between years	Mean growth volume	Difference between years	Mean growth volume	Difference between years
1 Year	0.0085^{B}		0.0075^{B}		0.0069^{B}		0.0103^{A}	
Difference (Yr 3 – 1)		0.0083		0.0065		0.0068		0.0101
3 Years	0.0170^{B}		0.0140^{C}		0.0137^{C}		0.0204^{A}	
Difference (Yr 6 – 3)		0.0183		0.0146		0.0138		0.0201
6 Years	0.0353^{B}		0.0286^{C}		0.0275^{C}		0.0405^{A}	

Within rows, letters indicate significantly different mean *growth volumes* between trial mean *growth volumes*; Yr = year.

5.3 Growth volume per genotype group

5.3.1 Sea-facing aspect site

The calculated mean *growth volumes* of the 14 genotype groups planted at the Sea-facing aspect site were compared. ANOVA tests revealed significant differences in mean *growth volumes* amongst the genotype groups planted per site at each of the three germplasm ages at a 95% confidence level (α = 0.05; 1-year-old P < 0.001, 3-year-old P < 0.001; 6-year-old P < 0.001). A DMRT revealed that two of the top three ranking 6-year-old genotype groups were interspecific hybrids of *E. grandis* with *E. camaldulensis* (G×C) and *E. urophylla* (G×U), whereas the third top ranking genotype was the pure species *E. urophylla* (Table 5.2). The mean *growth volumes* of *Corymbia* and *E. resinifera* were the lowest ranking genotype groups and were grouped into one DMRT grouping.

Table 5.2 Mean growth volumes calculated for different ages of genotype groups planted on the Sea-facing aspect site and ranked based on 6-year-old growth volumes.

Germplasm group	Species or group name	Germplasm type Clone (C) or Seedling (S)	Mean growth volume at 1 year (m^3)	Mean growth volume at 3 years (m^3)	Mean growth volume at 6 years (m^3)	DMRT grouping
G×C	*E. grandis* × *E. camaldulensis*	C	0.0119	0.0372	0.1139	A
U	*E. urophylla*	S	0.0100	0.0300	0.1034	A
G×U	*E. grandis* × *E. urophylla*	C	0.0091	0.0283	0.0918	AB
S×U	*E. saligna* × *E. urophylla*	C	0.0085	0.0185	0.0842	AB
G×U	*E. grandis* × *E. urophylla*	S	0.0060	0.0183	0.0809	AB
G	*E. grandis*	S	0.0060	0.0180	0.0798	AB
G×S	*E. grandis* × *E. saligna*	C	0.0057	0.0167	0.0519	BC
Cas	*C. equisetifolia*	S	0.0049	0.0144	0.0497	BC

Germplasm group	Species or group name	Germplasm type Clone (C) or Seedling (S)	Mean growth volume at 1 year (m^3)	Mean growth volume at 3 years (m^3)	Mean growth volume at 6 years (m^3)	DMRT grouping
G×L	*E. grandis* × *E. longirostrata*	S	0.0046	0.0138	0.0451	BC
C	*E. camaldulensis*	S	0.0045	0.0135	0.0204	C
G×T	*E. grandis* × *E. tereticornis*	S	0.0042	0.0135	0.0189	C
T	*E. tereticornis*	S	0.0039	0.0116	0.0168	C
Cor	*Corymbia*	S	0.0014	0.0043	0.0075	C
R	*E. resinifera*	S	0.0011	0.0021	0.0057	C
Mean			0.0085	0.0170	0.0353	
SE			0.0005	0.0008	0.0017	

In DMRT grouping column, letters indicate significantly different mean growth volumes between genotype groups.

5.3.2 Steep aspect site

For growth *volumes* of genotype groups planted on the Steep aspect site, ANOVA tests revealed significant differences in the *growth volumes* amongst the genotype groups of all ages at a 95% confidence level (α = 0.05; 1-year-old $P < 0.001$, 3-year-old $P < 0.001$; 6-year-old $P < 0.001$). A DMRT performed on 6-year-old tree *growth volumes* revealed that the top two genotype groups were interspecific hybrid clones grouped into a single DMRT grouping (Table 5.3). These interspecific hybrid clones were hybrids of *E. grandis* with *E. camaldulensis* (G×C) and *E. urophylla* (G×U). The seedling hybrid of *E. grandis* with *E. longirostrata* (G×L) was grouped into the third position. In contrast to the Sea-facing trial, the pure species *E. urophylla* was ranked fourth compared to second position in the Sea-facing trial. Similarly to the Sea-facing trial, the mean *growth volumes* of the *Corymbia* and *E. resinifera* genotype groups were ranked the lowest in the range and were also grouped together in the same DMRT grouping.

Table 5.3 Mean growth volumes calculated for different ages of genotype groups planted on the Steep aspect site and ranked based on 6-year-old growth volumes.

Germplasm group	Species or group name	Germplasm type Clone (C) or Seedling (S)	Mean growth volume at 1 year (m^3)	Mean growth volume at 3 years (m^3)	Mean growth volume at 6 years (m^3)	DMRT grouping
G×C	*E. grandis* × *E. camaldulensis*	C	0.0101	0.0312	0.0931	A
G×U	*E. grandis* × *E. urophylla*	C	0.0091	0.0273	0.0781	AB
G×L	*E. grandis* × *E. longirostrata*	S	0.0076	0.0229	0.0706	ABC
U	*E. urophylla*	S	0.0059	0.0168	0.0690	ABC
S×U	*E. saligna* × *E. urophylla*	C	0.0051	0.0156	0.0629	ABC
Cas	*C. equisetifolia*	S	0.0047	0.0141	0.0506	BCD
G×T	*E. grandis* × *E. tereticornis*	S	0.0046	0.0135	0.0493	BCDE
G	*E. grandis*	S	0.0045	0.0135	0.0484	BCDE
G×S	*E. grandis* × *E. saligna*	C	0.0045	0.0118	0.0396	CDE
G×U	*E. grandis* × *E. urophylla*	S	0.0036	0.0109	0.0348	DEF
C	*E. camaldulensis*	S	0.0029	0.0087	0.0189	DEF
T	*E. tereticornis*	S	0.0018	0.0055	0.0139	DEF
Cor	*Corymbia*	S	0.0014	0.0036	0.0128	EF
R	*E. resinifera*	S	0.0012	0.0038	0.0049	F
Mean			0.0075	0.0140	0.0286	
SE			0.0003	0.0005	0.0012	

In DMRT grouping column, letters indicate significantly different mean growth volumes between genotype groups.

5.3.3 Flat aspect site

For the Flat aspect trial, ANOVA tests for mean *growth volumes* revealed significant differences in the *growth volumes* amongst genotype groups at all ages at 95% confidence level (α = 0.05; 1-year-old P < 0.001, 3-year-old P < 0.001; 3-year-old P < 0.001). Interestingly, the top three genotype groups were the same as those in the Sea-facing trial, though in a different order. In the Flat aspect trial, the pure species of *E. urophylla* was ranked third in comparison to second in the Sea-facing trail (Table 5.4). The first two positions were occupied by the two interspecific hybrid clones of hybrids of *E. grandis* with *E. camaldulensis* (G×C) and with *E. urophylla* (G×U). The DMRT on *growth volumes* of the 6-year-old trees grouped the top ranking interspecific clone (G×C) into a separate DMRT grouping. Similarly to both the Sea-facing and Steep aspect sites, the mean *growth volumes* of groups *Corymbia* and *E. resinifera* were also ranked in the lowest DMRT grouping.

Table 5.4 Mean growth volumes calculated for different ages of genotype groups planted on the Flat aspect site and ranked based on 6-year-old growth volumes.

Germplasm group	Species or group name	Germplasm type Clone (C) or Seedling (S)	Mean growth volume at 1 year (m^3)	Mean growth volume at 3 years (m^3)	Mean growth volume at 6 years (m^3)	DMRT grouping
G×C	*E. grandis* × *E. camaldulensis*	C	0.0115	0.0346	0.0889	A
G×U	*E. grandis* × *E. urophylla*	C	0.0076	0.0227	0.0847	AB
U	*E. urophylla*	S	0.0061	0.0183	0.0752	ABC
Cas	*C. equisetifolia*	S	0.0057	0.0170	0.0650	ABC
S×U	*E. saligna* × *E. urophylla*	C	0.0054	0.0162	0.0606	ABC
G×T	*E. grandis* × *E. tereticornis*	S	0.0045	0.0134	0.0505	BCD
G	*E. grandis*	S	0.0044	0.0131	0.0482	CD
G×S	*E. grandis* ×	C	0.0040	0.0120	0.0468	CDE

Germplasm group	Species or group name	Germplasm type Clone (C) or Seedling (S)	Mean growth volume at 1 year (m^3)	Mean growth volume at 3 years (m^3)	Mean growth volume at 6 years (m^3)	DMRT grouping
	E. saligna					
G×U	*E. grandis* × *E. urophylla*	S	0.0034	0.0102	0.0190	DEF
C	*E. camaldulensis*	S	0.0032	0.0097	0.0103	EF
G×L	*E. grandis* × *E. longirostrata*	S	0.0028	0.0085	0.0086	EF
T	*E. tereticornis*	S	0.0023	0.0065	0.0072	F
Cor	*Corymbia*	S	0.0012	0.0036	0.0071	F
R	*E. resinifera*	S	0.0011	0.0032	0.0064	G
Mean			0.0069	0.0137	0.0275	
SE			0.0003	0.0007	0.0012	

In DMRT grouping column, letters indicate significantly different mean growth volumes between genotype groups.

5.3.4 Inland-facing aspect site

The mean *growth volumes* were also calculated for the germplasm genotype groups planted on the Inland-facing aspect site. Similarly to the Sea-facing and Flat aspect sites, two interspecific hybrid clones and one pure species were ranked in the top three positions for mean *growth volume* (Table 5.5). The two interspecific hybrid clones were also hybrids of *E. grandis* with *E. camaldulensis* (G×C) and *E. urophylla* (G×U). However, in contrast to the Sea-facing and Flat trials, the pure species was *C. equisetifolia* was ranked third. The ANOVA tests performed on the *growth volumes* of the Inland-facing trial also revealed significant differences amongst the genotype groups at all three ages (α = 0.05; 1-year-old $P < 0.001$, 3-year-old $P < 0.001$; 3-year-old $P < 0.001$). A DMRT performed on the 6-year-old trees' *growth volumes* grouped the top ranking interspecific hybrid (G×C) into a single DMRT grouping. Once again, *E. resinifera* and *Corymbia* were also the lowest ranking of the 14 genotype groups and grouped into a single DMRT grouping, together with the pure species *E. tereticornis*.

Table 5.5 Mean growth volumes calculated for different ages of genotype groups planted on the Inland-facing aspect site and ranked based on 6-year-old growth volumes

Germplasm group	Species or group name	Germplasm type Clone (C) or Seedling (S)	Mean growth volume at 1 year (m^3)	Mean growth volume at 3 years (m^3)	Mean growth volume at 6 years (m^3)	DMRT grouping
G×C	*E. grandis* × *E. camaldulensis*	C	0.0134	0.0404	0.0784	A
G×U	*E. grandis* × *E. urophylla*	C	0.0097	0.0290	0.0763	A
Cas	*C. equisetifolia*	S	0.0083	0.0250	0.0628	AB
S×U	*E. saligna* × *E. urophylla*	C	0.0079	0.0238	0.0612	AB
G×S	*E. grandis* × *E. saligna*	C	0.0075	0.0225	0.0533	AB
G×U	*E. grandis* × *E. urophylla*	S	0.0072	0.0216	0.0497	ABC
G×L	*E. grandis* × *E. longirostrata*	S	0.0070	0.0209	0.0465	BCD
G	*E. grandis*	S	0.0068	0.0205	0.0436	BCD
U	*E. urophylla*	S	0.0068	0.0204	0.0226	CDE
C	*E. camaldulensis*	S	0.0055	0.0164	0.0179	DEF
G×T	*E. grandis* × *E. tereticornis*	S	0.0040	0.0119	0.0168	DEF
T	*E. tereticornis*	S	0.0034	0.0102	0.0165	DEF
R	*E. resinifera*	S	0.0027	0.0082	0.0113	EF
Cor	*Corymbia*	S	0.0020	0.0060	0.0068	F
Mean			0.0103	0.0204	0.0405	
SE			0.0004	0.0008	0.0014	

In DMRT grouping column, letters indicate significantly different mean growth volumes between genotype groups.

5.4 Growth volume per genotype

5.4.1 Sea-facing aspect site

The mean *growth volume* of 6-year-old genotypes planted on the Sea-facing aspect site were ranked to determine the best performing genotypes. Four of the five top ranking genotypes were interspecific hybrid clones of *E. grandis* as a maternal species hybridised with *E. urophylla* (G×U), *E. camaldulensis* (G×C) and *E. saligna* (G×S). One of the pure species, *E. urophylla* (Au), ranked fourth (Table 5.6). When considering the lowest ranking genotypes for mean *growth volume*, the bottom 10 genotypes were all from seedling sources.

Table 5.6 Ranking based on growth volume of 6-year-old genotypes planted on the Sea-facing aspect site.

Genotype	Clone (C) or Seedling (S)	Rank	Growth volume at 6 years (m^3)	Genotype	Clone (C) or Seedling (S)	Rank	Growth volume at 6 years (m^3)
G×U608	C	1	0.2164	B09-346	S	36	0.0384
G×C225	C	2	0.2140	B9-008	S	37	0.0373
G×S147	C	3	0.1608	G15×Umix	S	38	0.0368
Au33	S	4	0.1439	B09-689	S	39	0.0361
G×C215	C	5	0.1401	CAS404	S	40	0.0360
Au9	S	6	0.1383	G×U111	C	41	0.0354
Au21	S	7	0.1204	G×U7	C	42	0.0328
G×C231	C	8	0.1170	CAS403	S	43	0.0321
G×C121	C	9	0.1163	B09-075	S	44	0.0285
B10-513	S	10	0.1108	G17×Umix	S	45	0.0281
SGR1272×LPM02	S	11	0.1084	T37	S	46	0.0260
G×U56	C	12	0.1066	C63	S	47	0.0249
G×U5	C	13	0.1054	Cas400	S	48	0.0236
Au3	S	14	0.1024	G50×Lmix	S	49	0.0231
SGR1220×T32	S	15	0.0944	G×S146	C	50	0.0215
G×U82	C	16	0.0859	S×U84	C	51	0.0199

Genotype	Clone (C) or Seedling (S)	Rank	Growth volume at 6 years (m^3)	Genotype	Clone (C) or Seedling (S)	Rank	Growth volume at 6 years (m^3)
SGR1198×LPM02	S	17	0.0858	G×S147	C	52	0.0180
SGR1198×Umix	S	18	0.0802	G×S137	C	53	0.0168
G×U21	C	19	0.0800	G×S136	C	54	0.0149
Au7	S	20	0.0759	SGR1220×T10	S	55	0.0122
SGR1683×Umix	S	21	0.0719	C37	S	56	0.0095
SGR1668×Umix	S	22	0.0715	AT4	S	57	0.0088
SGR1231×T10	S	23	0.0687	SGR1668×LMP04	S	58	0.0087
T22	S	24	0.0615	AT6	S	59	0.0077
S×U92	C	25	0.0611	G91×AT10	S	60	0.0073
Cas401	S	26	0.0608	SN34023	S	61	0.0071
S×U107	C	27	0.0521	G15×LPM01	S	62	0.0067
G×C962	C	28	0.0512	SN34032	S	63	0.0066
Cit	S	29	0.0454	R19032	S	64	0.0064
C40	S	30	0.0446	Maulata2	S	65	0.0056
Cas402	S	31	0.0419	SN34021	S	66	0.0050
C58	S	32	0.0418	Tor	S	67	0.0048
AT9	S	33	0.0403	Henryi	S	68	0.0035
C69	S	34	0.0401	Maculata1	S	69	0.0020
G×S137	C	35	0.0388	SN33994	S	70	0.0008
Mean	0.0353						
SE	0.0017						

5.4.2 Steep aspect site

In contrast to the Sea-facing trial, the top ten genotypes were all interspecific hybrid genotypes when the mean growth volumes of the genotypes planted on the Steep aspect site were ranked. These interspecific hybrids were hybrids with *E. grandis* as the maternal parental species (Table 5.7). The other parental species of the top ten ranked hybrid genotypes were *E. camaldulensis* (G×C), *E.*

urophylla (G×U) and *E. longirostrata* (G×L). Similarly to the Sea-facing aspect site, the bottom 10 ranking genotypes all originated from seedling sources.

Table 5.7 Ranking based on growth volume of 6-year-old genotypes planted on the Steep aspect site.

Genotype	Clone (C) or Seedling (S)	Rank	Growth volume at 6 years (m^3)	Genotype	Clone (C) or Seedling (S)	Rank	Growth volume at 6 years (m^3)
G×C215	C	1	0.1478	SGR1198×Umix	S	36	0.0354
SGR1198×LPM-02	S	2	0.1393	Cas404	S	37	0.0353
G×U608	C	3	0.1051	Au3	S	38	0.0333
G×C121	C	4	0.1047	C40	S	39	0.0330
G×C225	C	5	0.1011	G17×Umix	S	40	0.0326
G×U82	C	6	0.0953	T37	S	41	0.0315
G×S147	C	7	0.0933	B09-346	S	42	0.0307
G50×Lmix	S	8	0.0910	B10-513	S	43	0.0274
G×U111	C	9	0.0858	B09-689	S	44	0.0252
G×C962	C	10	0.0828	Maulata2	S	45	0.0251
B09-075	S	11	0.0810	G×S143	C	46	0.0242
Au7	S	12	0.0773	G×S146	C	47	0.0240
Au9	S	13	0.0769	G15×LPM01	S	48	0.0238
SGR1220×T32	S	14	0.0762	C69	S	49	0.0230
G×U56	C	15	0.0735	C58	S	50	0.0228
G×U21	C	16	0.0707	G91×AT10	S	51	0.0215
G×U7	C	17	0.0688	S×U84	C	52	0.0203
S×U92	C	18	0.0679	SGR1220×T10	S	53	0.0196
SGR1272×LPM02	S	19	0.0662	G×S136	C	54	0.0174
G×C231	C	20	0.0656	G×S136	C	55	0.0161
Cas402	S	21	0.0655	G15×Umix	S	56	0.0160
Cas403	S	22	0.0635	Cit	S	57	0.0151
G×S137	C	23	0.0594	SN34021	S	58	0.0142
B9-008	S	24	0.0587	SN33994	S	59	0.0130
G×U5	C	25	0.0581	AT9	S	60	0.0130
SGR1668×Umix	S	26	0.0546	AT6	S	61	0.0115
C37	S	27	0.0543	SN34023	S	62	0.0102

Genotype	Clone (C) or Seedling (S)	Rank	Growth volume at 6 years (m^3)	Genotype	Clone (C) or Seedling (S)	Rank	Growth volume at 6 years (m^3)
SGR1668×LMP-04	S	28	0.0526	C63	S	63	0.0099
Cas400	S	29	0.0499	T22	S	64	0.0083
SGR1231×T10	S	30	0.0457	R19032	S	65	0.0071
SGR1683×Umix	S	31	0.0455	AT4	S	66	0.0053
S×U107	C	32	0.0427	Henryi	S	67	0.0047
Au33	S	33	0.0389	Maculata1	S	68	0.0014
Cas401	S	34	0.0369	Tor	S	69	0.0006
Au21	S	35	0.0362	SN34032	S	70	0.0006
Mean	0.0286						
SE	0.0012						

5.4.3 Flat aspect site

For the mean *growth volumes* of 6-year-old germplasm for the Flat aspect trial, genotypes in the top ten 10 were all hybrid clones, except for one pure species ranked sixth (*E. urophylla*, Au), (Table 5.8). Similar to the Sea-facing and Steep trials, these interspecific hybrids were also hybrids with *E. grandis* as a maternal parental species. The other parents of these interspecific hybrids were *E. camaldulensis* (G×C), *E. urophylla* (G×U) and *E. saligna* (G×S). As was the case for the Sea-facing and Flat trials, the genotypes with the lowest ranking mean *growth volumes* all originated from seedlings.

Table 5.8 Ranking based on growth volume of 6-year-old genotypes planted on the Flat aspect site.

Genotype	Clone (C) or Seedling (S)	Rank	Growth volume at 6 years (m^3)	Genotype	Clone (C) or Seedling (S)	Rank	Growth volume at 6 years (m^3)
G×C215	C	1	0.1798	G15×Umix	S	36	0.0389
G×C121	C	2	0.1168	C58	S	37	0.0379
G×C231	C	3	0.1166	T37	S	38	0.0340
G×C225	C	4	0.1093	G17×Umix	S	39	0.0337
G×S147	C	5	0.1024	G×S137	C	40	0.0317

Genotype	Clone (C) or Seedling (S)	Rank	Growth volume at 6 years (m^3)	Genotype	Clone (C) or Seedling (S)	Rank	Growth volume at 6 years (m^3)
Au7	S	6	0.0979	G91×AT10	S	41	0.0306
G×U608	C	7	0.0962	SGR1668×Umix	S	42	0.0301
G×U82	C	8	0.0947	AT4	S	43	0.0292
G×U111	C	9	0.0938	C37	S	44	0.0224
G×C962	C	10	0.0933	C63	S	45	0.0219
SGR1220×T32	S	11	0.0904	SGR1220×T10	S	46	0.0213
G×U5	C	12	0.0824	SGR1683×Umix	S	47	0.0197
Cas400	S	13	0.0814	C69	S	48	0.0187
S×U92	C	14	0.0762	G×S147	C	49	0.0187
G×U56	C	15	0.0743	G×S143	C	50	0.0179
Au9	S	16	0.0736	Maulata2	S	51	0.0166
Cas402	S	17	0.0722	S×U84	C	52	0.0149
Au33	S	18	0.0714	SN34023	S	53	0.0145
Cas404	S	19	0.0697	G×S136	C	54	0.0140
Au21	S	20	0.0674	B10-513	S	55	0.0140
S×U107	C	21	0.0605	SGR1668×LMP-04	S	56	0.0140
B09-346	S	22	0.0601	Au3	S	57	0.0110
G50×Lmix	S	23	0.0583	AT9	S	58	0.0098
SGR1198×LPM-02	S	24	0.0575	R19032	S	59	0.0088
SGR1231×T10	S	25	0.0572	AT6	S	60	0.0088
G×U21	C	26	0.0542	Cit	S	61	0.0064
Cas403	S	27	0.0537	T22	S	62	0.0039
B9-008	S	28	0.0498	Tor	S	63	0.0030
B09-075	S	29	0.0491	SGR1272×LPM02	S	64	0.0028
C40	S	30	0.0480	Henryi	S	65	0.0028
G×U7	C	31	0.0475	SN34021	S	66	0.0023
G×S136	C	32	0.0475	Maculata1	S	67	0.0019
SGR1198×Umix	S	33	0.0475	SN34032	S	68	0.0004
B09-689	S	34	0.0471	SN33994	S	69	0.0003
Cas401	S	35	0.0470	G15×LPM-01	S	70	0.0002
Mean	0.0275						
SE	0.0012						

5.4.4 Inland-facing aspect site

Of the 70 genotypes planted on the Inland-facing aspect site, nine of the top ten genotypes were interspecific hybrid clones with *E. grandis* as the maternal parental species (Table 5.9). The other parents of these hybrids were different hybrids with *E. camaldulensis* (G×C), *E. urophylla* (G×U) and *E. saligna* (G×S). The pure species *E. urophylla* (Au) was ranked tenth in this ranking of genotypes. Similarly to the other trial the lowest ranking genotypes all originated from seedling sources.

Table 5.9 Ranking based on growth volume of 6-year-old genotypes planted on the Inland-facing aspect site.

Genotype	Clone (C) or Seedling (S)	Rank	Growth volume at 6 years (m^3)	Genotype	Clone (C) or Seedling (S)	Rank	Growth volume at 6 years (m^3)
G×S147	C	1	0.1798	G×S143	C	36	0.0352
G×U608	C	2	0.1205	Au33	S	37	0.0350
G×C215	C	3	0.0984	B9-008	S	38	0.0346
G×C231	C	4	0.0830	C58	S	39	0.0341
G×C962	C	5	0.0793	G×S137	C	40	0.0340
G×C121	C	6	0.0785	Au21	S	41	0.0297
SGR1198×LPM-02	S	7	0.0780	SN34021	S	42	0.0284
G×U21	C	8	0.0745	AT9	S	43	0.0271
G×C225	C	9	0.0729	R19032	S	44	0.0254
Au7	S	10	0.0721	SGR1668×LMP-04	S	45	0.0213
Au9	S	11	0.0718	B09-075	S	46	0.0210
Cas400	S	12	0.0707	T37	S	47	0.0207
G×U82	C	13	0.0691	S×U84	C	48	0.0206
SGR1668×Umix	S	14	0.0637	G17×Umix	S	49	0.0200
G×U7	C	15	0.0636	C40	S	50	0.0178
B10-513	S	16	0.0609	SGR1231×T10	S	51	0.0147
C37	S	17	0.0600	Cit	S	52	0.0146
Cas404	S	18	0.0598	G×S137	C	53	0.0145
Cas402	S	19	0.0594	G15×LPM-01	S	54	0.0140

Genotype	Clone (C) or Seedling (S)	Rank	Growth volume at 6 years (m^3)	Genotype	Clone (C) or Seedling (S)	Rank	Growth volume at 6 years (m^3)
G×U56	C	20	0.0541	SGR1220×T10	S	55	0.0134
Cas403	S	21	0.0519	G×S146	C	56	0.0125
Cas401	S	22	0.0515	C63	S	57	0.0122
B09-689	S	23	0.0507	Au3	S	58	0.0089
G×U5	C	24	0.0504	AT6	S	59	0.0080
G×U111	C	25	0.0453	G×S136	C	60	0.0075
S×U107	C	26	0.0452	T22	S	61	0.0074
SGR1198×Umix	S	27	0.0434	Henryi	S	62	0.0061
SGR1683×Umix	S	28	0.0417	Maulata2	S	63	0.0056
G15×Umix	S	29	0.0410	SN34023	S	64	0.0055
S×U92	C	30	0.0404	G91×AT10	S	65	0.0053
B09-346	S	31	0.0377	AT4	S	66	0.0051
SGR1220×T32	S	32	0.0365	SN34032	S	67	0.0049
C69	S	33	0.0363	Maculata1	S	68	0.0045
G50×Lmix	S	34	0.0360	Tor	S	69	0.0035
SGR1272×LPM02	S	35	0.0359	SN33994	S	70	0.0009
Mean	0.0405						
SE	0.0014						

5.5 Comparison of trials at genotype level

The four trials were compared in terms of genotypic *growth volumes* to establish if trial site differences existed for *growth volumes*. An ANOVA test revealed that the mean genotypic *growth volumes* of the genotypes (Site × Genotype) did not differ in the trails at a 95% confidence level (α = 0.05). Table 5.10 shows the results of the ANOVA test performed on the *growth volumes*, indicating specifically that a Site × Genotype interaction could not be established.

Table 5.10 ANOVA test results comparing 6-year-old genotypes growth volume across trial sites.

Source	DF	SS	MS	*F* value	*P* value
Sites	3	92.539	30.846	18.35	< 0.001
Rep	9	36.805	4.089	2.43	0.009
Genotype	69	1709.400	24.774	14.74	< 0.001
Site × Genotype	207	409.029	1.976	1.84	0.051
Residual	2131	3582.367			
Total	2501	5830.139			

After establishing an absence of Site × Genotype interaction, Type B correlations (r_{Bg}) were estimated for 6-year-old germplasm trial pairs to ascertain if genotype by environment interactions (GEI) existed between trials. All correlations between the trial pairs were greater than 72%, confirming that GEI was absent, as all the correlations were greater than 0.67 (Burdon, 1977). Table 5.11 shows Type B correlation estimates for the different trial pairs.

Table 5.11 Type B correlation estimates (r_{Bg}) comparing 6-year-old genotype growth volume across trial sites.

Aspect site	Sea-facing	Steep	Flat	Inland-facing
Sea-facing	*			
Steep	0.725331	*		
Flat	0.725381	0.857566	*	
Inland-facing	0.78994	0.826061	0.818875	*

Having established that GEI was absent between trails, the mean genotypic *growth volumes* of 6-year-old germplasm were pooled to rank the genotypes in terms of overall mean *growth volumes*

across trials. An ANOVA test revealed that the genotypes were significantly different at a 95% confidence level (α = 0.05; $F(69, 2388) = 8463.16$; $P < 0.001$). A DMRT performed on the overall *growth volumes* of 6-year-old tree germplasm revealed five DMRT groupings for the top 20 genotypes (Table 5.12). The top eight of the were all interspecific hybrids with *E. grandis* as the maternal parent.

Table 5.12 Ranking based on mean growth volume of 6-year-old top 20 genotypes planted on the total planted area.

Abbreviated germplasm name	Germplasm name	Germplasm type clone (C) or seedling (S)	Overall mean growth volume at 6 years (m^3)	DMRT grouping
G×U608	*E. grandis* × *E. urophylla*	C	0.1813	A
G×C215	*E. grandis* × *E. camaldulensis*	C	0.1422	AB
G×S147	*E. grandis* × *E. saligna*	C	0.1009	BC
G×C225	*E. grandis* × *E. camaldulensis*	C	0.0990	BCD
G×C121	*E. grandis* × *E. camaldulensis*	C	0.0960	CDE
G×C231	*E. grandis* × *E. camaldulensis*	C	0.0901	CDEF
SGR1198×LPM-02	*E. grandis* × *E. longirostrata*	S	0.0882	CDEFG
G×U82	*E. grandis* × *E. urophylla*	C	0.0878	CDEFGH
Au9	*E. urophylla*	S	0.0851	CDEFGHI
G×C962	*E. grandis* × *E. camaldulensis*	C	0.0832	CDEFGHI
Au7	*E. urophylla*	S	0.0815	CDEFGHIJ
G×U21	*E. grandis* × *E. urophylla*	C	0.0791	CDEFGHIJ
G×U56	*E. grandis* × *E. urophylla*	C	0.0756	CDEFGHIJK
SGR1220×T32	*E. grandis* × *E. tereticornis*	S	0.0754	CDEFGHIJK
G×U111	*E. grandis* × *E. urophylla*	C	0.0724	CDEFGHIJK
G×U5	*E. grandis* × *E. urophylla*	C	0.0707	CDEFGHIJK
Au33	*E. urophylla*	S	0.0687	CDEFGHIJK
Cas404	*C. equisetifolia*	S	0.0684	CDEFGHIJK
S×U92	*E. saligna* × *E. urophylla*	C	0.0648	CDEFGHIJK

Abbreviated germplasm name	Germplasm name	Germplasm type clone (C) or seedling (S)	Overall mean growth volume at 6 years (m^3)	DMRT grouping
Au21	*E. urophylla*	S	0.0637	CDEFGHIJK
Mean 0.0330				
SE 0.0023				

In DMRT grouping column, letters indicate significantly different mean growth volumes between genotype.

5.6 Discussion

Growth properties are important when considering productivity in plantation forestry. Productivity is influenced by many factors that interact with one another. These factors include edaphic, climatic, physiographic and biotic factors, as well as forest management and silvicultural practices (Resende et al., 2018; de Freitas et al., 2020). Growth properties of a genotype are thus of particular importance when selecting genotypes for deployment on the mined sand dunes in the Richards Bay area. The mean *growth volume* of the top 20 highest performing genotypes was relatively high and ranged from 43.107 m^3 ha^{-1} to 94.543 m^3 ha^{-1}. These relatively high volumes could be explained, in part, by the strict silvicultural techniques performed in this study (Pallett & Sale, 2004). For example, the application of the correct type of fertiliser, which was performed in this study, increases light interception, photosynthesis, and the partitioning of photosynthates to stem wood growth (Whitehead & Beadle, 2004). In a trial of a *E. grandis* × *E. camaldulensis* hybrid planted at a subtropical site in KwaZulu-Natal, the silvicultural practice of manual weeding produced 62% more timber (Little & Van Staden, 2005). Several genotypes (17) outperformed the control species, *C. equisetifolia*, which delivered a mean *growth volume* of 44.218 m^3 ha^{-1}, and thus have the potential for deployment on the mined sand dunes. Most of these genotypes were mainly interspecific hybrid clones of *E. grandis* as the maternal parental species with *E. camaldulensis* (G×C), *E. urophylla* (G×U) or *E. saligna* (G×S), which also were the hybrids that demonstrated high *survival* percentages. Four of top six genotypes

were G×C hybrids (215, 225, 121, and 231), who demonstrated superior *growth volume*, probably as a result of the presence of *E. camaldulensis* in the hybrid, which was selected based on adaption to salt-laden mine dumps (Darrow, 1995). Furthermore, in this study GEI for *growth volume* could not be demonstrated amongst the different aspect sites, probably because of the small sizes of the trials, which were spread over a relatively small area in close proximity to one another, as well as similar soil moisture contents, soil depth and average temperature gradients (Shelbourne, 1972). Furthermore, the high average rainfall was relatively equally distributed amongst the trails contributing to the realisation of an absence of GEI (Breugel et al. 2011). Therefore, the selection of suitable genotypes for the Richards Bay mined sand dunes based on *growth volume* could be undertaken using the data generated from a single trial. However, the final choice of genotypes for deployment on the mined sand dunes requires knowledge about stem quality, wood and Kraft properties, coppicing ability, as well as pest and disease susceptibility (Thomas, 2009).

Chapter 6

Germplasm Stem Quality

6.1 Introduction

Besides developing an understanding of the *survival* rates and growth properties of genotypes tested in this study, knowledge of stem quality was also important consideration, because stem quality has a major influence on downstream activities in the forestry industry. The shape of a tree determines timber volume recovery and thus its value. It also determines processing options of the trees (Price et al., 2017). Analysis of the measurements of stem quality will provide important knowledge about the forestry industries the genotypes will be able to serve. In this study, besides measuring *stem straightness*, other stem qualities were also noted. These included heavy branching, forked stem and butt sweep, which were collectively referred to as off-types. Thus, in this section of Phase 2, stem quality traits were measured and analysed (Phase 3) (Figure 6.1).

Figure 6.1 **Extract of the study design highlighting the stem quality aspect for measurement.**

The objectives that were targeted to measure and analyse stem quality traits were:

5. To measure and analyse stem quality traits at 1 year of tree growth;
6. To measure and analyse stem quality traits at 3 years of tree growth;
7. To measure and analyse stem quality traits at 6 years of tree growth; and
8. Analyse the measurements.

Trees can display a variety of shapes. From displaying a straight stem, trees can be forked or heavily branched. These characteristics determine the type of forestry industry a tree is destined for (Figure 6.2).

A.

B.

C.

D. E. F.

Figure 6.2 Photographs of stem quality. A. Trees with excellent stem straightness. B. Tree with moderate stem straightness. C. Trees with poor stem. straightness. D. Tree forked at base. E. Trees showing kink base. F. Trees showing heavy branching.

6.2 Stem straightness of germplasm

Stem straightness was determined for all trees planted in the trails at the four aspect sites, irrespective of genotype. A subjective score ranging from 1 to 8 was used to score *stem straightness* of 3-year-old and 6-year-old germplasm, where a score of 8 indicated the straightest stem. *Stem straightness* among the older trees scored substantially higher than the younger trees (Table 6.1). ANOVA tests revealed significant differences in mean *stem straightness* at a 95% confidence level (α = 0.05) for 3-year-old germplasm (F (3, 2468) = 45.41; P < 0.001) and 6 years (F (3, 2416) = 1.17; P < 0.001). Furthermore, Duncan Multiple Range Tests (DMRT) showed, in particular, that the mean *stem straightness* of 3-year-old trees planted in the Inland-facing trial was significantly straighter than the tree stems from the other trials. In contrast, the stems of 6-year-old trees planted on Sea-facing aspect trial were significantly straighter than the tree stems of the other trials.

Table 6.1 Trial stem straightness per aspect site and germplasm age.

Germplasm age (years)	Mean stem straightness per aspect site n = 700				Mean stem straightness per total planted area
	Sea-facing	Steep	Flat	Inland-facing	
3	3.68 B	3.61 B	3.13 C	4.59 A	3.76
6	5.27 A	4.44 C	4.65 B	4.61 B C	4.70

Within the rows, letters indicate significantly different mean *stem straightness* values between trials.

6.3 Stem straightness per genotype group

6.3.1 Sea-facing aspect site

The mean *stem straightness* of the 14 genotype groups planted on the Sea-facing aspect site were compared with one another. The mean *stem straightness* of the 6-year-old genotype group of trees was substantially straighter than the younger 3-year-old trees, probably attributable to the trees still undergoing differentiation (Table 6.2). ANOVA tests revealed significant differences in mean *stem straightness* amongst the genotype groups planted on the Sea-facing site for both germplasm ages at a 95% confidence level (α = 0.05; 3-year-old P < 0.001; 6-year-old P < 0.001). A DMRT revealed that one of the top five ranking 6-year-old genotype groups was the pure species *E. urophylla*, the other four groups were interspecific hybrid clones. The interspecific hybrids were hybrids of *E. grandis* with *E. camaldulensis* (G×C) and *E. urophylla* (G×U), as well as *E. saligna* with *E. urophylla* (S×U). The two pure species groups, *Corymbia* and *E. resinifera*, showed the lowest mean values for *stem straightness* in the Sea-facing trial.

Table 6.2 Mean stem straightness of different ages for genotype groups planted on the Sea-facing aspect site and ranked based on 6-year-old age stem straightness values.

Germplasm group	Species or group name	Germplasm type clone (C) or seedling (S)	Mean stem straightness at 3 years	Mean stem straightness at 6 years	DMRT grouping
G×C	*E. grandis* × *E. camaldulensis*	C	4.72	5.82	A
S×U	*E. saligna* × *E. urophylla*	C	4.42	5.67	AB
U	*E. urophylla*	S	4.40	5.34	AB
G×U	*E. grandis* × *E. urophylla*	C	4.25	5.27	AB
G×U	*E. grandis* × *E. urophylla*	S	3.83	5.21	AB
G	*E. grandis*	S	3.32	5.02	ABC
Cas	*C. equisetifolia*	S	4.62	4.86	ABCD
G×S	*E. grandis* × *E. saligna*	C	3.91	4.67	ABCDE
G×T	*E. grandis* × *E. tereticornis*	S	3.82	4.62	BCDE
C	*E. camaldulensis*	S	3.32	4.00	CDEF
T	*E. tereticornis*	S	3.04	3.75	DEF
G×L	*E. grandis* × *E. longirostrata*	S	2.69	3.44	EF
Cor	*Corymbia*	S	2.48	3.24	F
R	*E. resinifera*	S	2.58	3.21	F
Mean			3.68	4.70	
SE			0.27	0.24	

In DMRT grouping column, letters indicate significantly different mean stem straightness between genotype groups.

The number of off-type trees for stem characteristics was counted for the different genotype groups, in the trial. The occurrence of forked, butt sweep and heavy branching were relatively rare, overall less than 10% in the Sea-facing trial. In this trial, forked trees were very rare, less than 1% (Table 6.3). Four interspecific hybrids and two seedling genotype groups showed the lowest percentages of off-type trees for the different stem characteristics, ranging from 2 to 10%. Eight of the nine seedling genotype groups demonstrated the highest numbers of butt sweep and heavy branching stem characteristics in this trial.

Table 6.3 Stem straightness characteristics of 6-year-old genotype groups planted on the Sea-facing aspect site.

Abbreviated germplasm name	Species or group name	Germplasm type Clone (C) or Seedling (S)	Number of forked trees	Number of trees with butt sweep	Number of trees with heavy branching	Total number of off-type trees	% of off-type trees (n = 50)
Cas	*C. equisetifolia*	S	-	1	-	1	2
G×C	*E. grandis* × *E. camaldulensis*	C	-	1	1	1	2
S×U	*E. saligna* × *E. urophylla*	C	-	2	1	2	4
U	*E. urophylla*	S	1	2	-	3	6
G×S	*E. grandis* × *E. saligna*	C	-	3	1	4	8
G×U	*E. grandis* × *E. urophylla*	C	-	4	1	5	10
Cor	*Corymbia*	S	1	-	5	6	12
C	*E. camaldulensis*	S	1	-	2	6	12
G	*E. grandis*	S	1	-	2	6	12
R	*E. resinifera*	S	-	-	6	6	12
T	*E. tereticornis*	S	-	2	4	6	12
G×L	*E. grandis* × *E. longirostrata*	S	-	2	4	6	12
G×T	*E. grandis* × *E. tereticornis*	S	-	3	3	6	12
G×U	*E. grandis* × *E. urophylla*	S	-	3	3	6	12

Abbreviated germplasm name	Species or group name	Germplasm type Clone (C) or Seedling (S)	Number of forked trees	Number of trees with butt sweep	Number of trees with heavy branching	Total number of off-type trees	% of off-type trees (n = 50)
Total number off-types in the trial (n = 700)			4	23	33	64	
% off-types			0.57	3.29	4.71	9.14	

6.3.2 Steep aspect site

When the *stem straightness* of the 3-year old and 6-year old genotype groups on the Steep aspect site were compared, the mean values of the 3-year old germplasm were distinctly lower than the mean values of the 6-year old germplasm. These differences in *stem straightness* means can also be attributed to the younger germplasm still undergoing differentiation (Table 6.4). Five interspecific hybrid clones of the 14 groups showed the highest mean *stem straightness* values at both germplasm ages. Four of the top five interspecific hybrid clones were hybrids of *E. grandis* with *E. camaldulensis* (G×C), *E. urophylla* (G×U), *E. saligna* (G×S) and *E. tereticornis* (G×T). An ANOVA test revealed significant differences in mean *stem straightness* between genotype groups in the Steep trial at 95% confidence level (α = 0.05; P < 0.001). A DMRT test revealed that the interspecific hybrid clone *E. grandis* × *E. camaldulensis* (G×C) demonstrated *stem straightness* values were significantly different from all the other groups. Furthermore, the second most significant mean *stem straightness* values were recorded for the two interspecific hybrid clones *E. grandis* × *E. urophylla* (G×U) and *E. grandis* × *saligna* (G×S). The two pure species groups, *Corymbia* and *E. camaldulensis*, showed the lowest mean values for mean *stem straightness* in the Steep trial.

Table 6.4 Mean stem straightness of different ages for genotype groups planted on the Steep aspect site and ranked based on 6-year-old age stem straightness values.

Germplasm group	Species or group name	Germplasm type clone (C) or seedling (S)	Mean stem straightness at 3 years	Mean stem straightness at 6 years	DMRT grouping
G×C	*E. grandis* × *E. camaldulensis*	C	5.05	5.58	A
G×U	*E. grandis* × *E. urophylla*	C	4.28	5.42	AB
G×S	*E. grandis* × *E. saligna*	C	3.16	5.17	ABC
G×T	*E. grandis* × *E. tereticornis*	C	4.12	4.89	ABC
S×U	*E. saligna* × *E. urophylla*	C	3.61	4.75	ABCD
Cas	*C. equisetifolia*	S	4.15	4.59	BCD
G	*E. grandis*	S	3.31	4.46	BCDE
G×U	*E. grandis* × *E. urophylla*	S	3.79	4.39	CDEF
U	*E. urophylla*	S	3.73	4.35	CDEF
T	*E. tereticornis*	S	2.82	4.17	CDEFG
G×L	*E. grandis* × *E. longirostrata*	S	4.45	3.84	DEFG
R	*E. resinifera*	S	2.98	3.51	EFG
C	*E. camaldulensis*	S	3.07	3.38	FG
Cor	*Corymbia*	S	2.21	3.13	G
Mean			3.61	5.05	
SE			0.35	0.20	

In DMRT grouping column, letters indicate significantly different mean stem straightness between genotype groups.

When the of off-type trees of the different genotype groups in the Steep trial were counted, the occurrence of forked, butt sweep and heavy branching were relatively rare, overall less than 12%

(Table 6.5). Four interspecific hybrids and two seedling genotype groups showed the lowest number of off-type trees for the different stem characteristics. The forked stem characteristic was the dominant off-type in this trial, occurring mostly in the trees that originated from the seedling genotype groups of both the interspecific hybrids and pure species.

Table 6.5 Stem straightness characteristics of 6-year-old genotype groups planted on the Steep aspect site.

Abbreviated germplasm name	Species or group name	Germplasm type Clone (C) or Seedling (S)	Number of forked trees	Number of trees with butt sweep	Number of trees with heavy branching	Total number of off-type trees	% Off-type trees (n = 50)
G	*E. grandis*	S	2	1	1	4	8
T	*E. tereticornis*	S	1	3	2	6	8
G×C	*E. grandis* × *E. camaldulensis*	C	4	-	-	4	8
G×S	*E. grandis* × *E. saligna*	C	2	1	1	4	8
Cas	*C. equisetifolia*	S	4	1	-	5	10
C	*E. camaldulensis*	S	1	2	5	8	10
G×L	*E. grandis* × *E. longirostrata*	S	1	2	2	5	10
S×U	*E. saligna* × *E. urophylla*	C	1	3	1	5	10
Cor	*Corymbia*	S	r	3	3	8	12
G×T	*E. grandis* × *E. tereticornis*	S	3	2	1	6	12
G×U	*E. grandis* × *E. urophylla*	C	4	2	-	6	12
R	*E. resinifera*	S	1	3	3	7	14
U	*E. urophylla*	S	4	1	1	6	14
G×U	*E. grandis* × *E. urophylla*	S	3	5	1	9	18
Total number off-types in the trial (n = 700)			33	29	21	83	
% off types			4.71	4.14	3.00	11.86	

6.3.3 Flat aspect site

Similar to the Sea-facing and Steep trials, the *stem straightness* means of the 3-year-old germplasm in the Flat trial was also distinctly lower than the mean values of the 6-year-old germplasm (Table 6.6). An ANOVA test also revealed significant differences in mean *stem straightness* values between genotype groups at a 95% confidence level (α = 0.05; P < 0.001). A DMRT revealed that the interspecific hybrids, *E. grandis* × *E. camaldulensis* (G×C), *E. grandis* × *E. urophylla* (G×U), and the control species *C. equisetifolia* ranked in the first three positions for mean *stem straightness* values. The lowest ranking genotype groups for stem straightness in the Flat aspect trial were *E. resinifera* and the hybrid *E. grandis* × *E. longirostrata* (G×L).

Table 6.6 Mean stem straightness of different ages for genotype groups planted on the Flat aspect site and ranked based on 6-year-old age stem straightness values.

Germplasm group	Species or group name	Germplasm type clone (C) or seedling (S)	Mean stem straightness at 3 years	Mean stem straightness at 6 years	DMRT grouping
G×C	*E. grandis* × *E. camaldulensis*	C	4.24	5.09	A
G×U	*E. grandis* × *E. urophylla*	C	3.52	4.90	AB
Cas	*C. equisetifolia*	S	4.50	4.79	AB
S×U	*E. saligna* × *E. urophylla*	C	3.65	4.79	AB
G×U	*E. grandis* × *E. urophylla*	S	3.11	4.53	AB
G×T	*E. grandis* × *E. tereticornis*	S	3.90	4.36	ABC
U	*E. urophylla*	S	3.38	4.29	ABC
G×S	*E. grandis* × *E. saligna*	C	2.72	4.05	BCD
G	*E. grandis*	S	2.53	4.02	BCD
C	*E. camaldulensis*	S	2.92	3.52	CDE
T	*E. tereticornis*	S	2.50	3.21	DE

Germplasm group	Species or group name	Germplasm type clone (C) or seedling (S)	Mean stem straightness at 3 years	Mean stem straightness at 6 years	DMRT grouping
Cor	*Corymbia*	S	2.23	3.14	DE
R	*E. resinifera*	S	2.59	2.83	E
G×L	*E. grandis* × *E. longirostrata*	S	1.87	2.77	E
Mean			3.13	4.65	
SE			0.22	0.19	

In DMRT grouping column, letters indicate significantly different mean stem straightness between genotype groups.

Similarly to the Sea-facing and Steep trials, the number of trees with off-type stem characteristics were also relatively rare, overall less than 15%. Trees with forked branches were the rarest of the stem off-types in the Flat trial (Table 6.7). Three interspecific hybrids and two seedling genotype groups showed the lowest percentages of off-type trees for the different stem characteristics, ranging from 6 to 10%. Of the three off-type stem characteristics, trees with heavy branching were the dominant stem off-type amongst the trees and occurred mostly in the trees that originated from seedling genotype groups of both interspecific hybrids and pure species.

Table 6.7 Stem straightness characteristics of 6-year-old genotype groups on the Flat aspect site.

Abbreviated germplasm name	Species or group name	Germplasm type Clone (C) or Seedling (S)	Number of forked trees	Number of trees with butt sweep	Number of trees with heavy branching	Total number of off-type trees	% Off-type trees (n = 50)
Cas	*C. equisetifolia*	S	2	1	-	3	6
G	*E. grandis*	S	1	1	2	4	6
G×C	*E. grandis* × *E. camaldulensis*	C	3	1	-	4	6
S×U	*E. saligna* × *E. urophylla*	C	2	4	-	6	8
G×S	*E. grandis* × *E. saligna*	C	1	4	1	6	10
C	*E. camaldulensis*	S	2	2	4	8	12

Abbreviated germplasm name	Species or group name	Germplasm type Clone (C) or Seedling (S)	Number of forked trees	Number of trees with butt sweep	Number of trees with heavy branching	Total number of off-type trees	% Off-type trees (n = 50)
T	*E. tereticornis*	S		1	5	6	12
U	*E. urophylla*	S	1	3	3	7	12
G×U	*E. grandis* × *E. urophylla*	C	2	6	-	8	12
R	*E. resinifera*	S	-	-	7	7	14
G×T	*E. grandis* × *E. tereticornis*	S	2	3	2	7	14
G×L	*E. grandis* × *E. longirostrata*	S	-	1	7	8	16
G×U	*E. grandis* × *E. urophylla*	S	2	4	2	8	16
Cor	*Corymbia*	S	2	1	6	9	18
Total number off-types in the trial (n = 700)			20	32	39	91	
% off types			2.86	4.57	5.57	13.00	

6.3.4 Inland-facing aspect site

In the Inland-facing trial, the *stem straightness* means of the 3-year-old germplasm were also distinctly lower than the mean values of the 6-year-old germplasm (Table 6.8). An ANOVA test also revealed significant differences in mean *stem straightness* between genotype groups in this trial at a 95% confidence (α = 0.05; P < 0.001). The DMRT showed that three interspecific hybrid clones and two pure species were the top ranking genotype groups for *stem straightness*. Of these interspecific hybrid clones, *E. grandis* (G×C and G×U) and *E. urophylla* (S×U and G×U), were each parents in two of the genotype groups. In this trial, the control pure species *C. equisetifolia*, *also* ranked high for *stem straightness*, as was the case for the previous two sites.

Table 6.8 Mean stem straightness of different ages for genotype groups planted on the Inland-facing aspect site and ranked based on 6-year-old age stem straightness values.

Germplasm group	Species or group name	Germplasm type clone (C) or seedling (S)	Mean stem straightness at 3 years	Mean stem straightness at 6 years	DMRT grouping
G×C	*E. grandis* × *E. camaldulensis*	C	5.90	5.91	A
Cas	*C. equisetifolia*	S	5.38	5.38	AB
S×U	*E. saligna* × *E. urophylla*	C	4.90	5.50	ABC
G×U	*E. grandis* × *E. urophylla*	C	5.15	5.31	ABCD
G	*E. grandis*	S	5.07	5.08	ABCDE
G×U	*E. grandis* × *E. urophylla*	S	4.80	4.88	ABCDEF
U	*E. urophylla*	S	4.53	4.76	BCDEF
G×S	*E. grandis* × *E. saligna*	C	4.30	4.71	BCDEF
G×T	*E. grandis* × *E. tereticornis*	S	4.00	4.49	CDEF
C	*E. camaldulensis*	S	4.04	4.43	DEFG
R	*E. resinifera*	S	4.00	3.92	EFG
Cor	*Corymbia*	S	3.85	3.87	EFG
T	*E. tereticornis*	S	3.74	3.73	FG
G×L	*E. grandis* × *E. longirostrata*	S	3.58	3.64	G
Mean			4.59	3.84	
SE			0.20	0.22	

In DMRT grouping column, letters indicate significantly different mean stem straightness between genotype groups.

In the Inland-facing trail, similar patterns of stem characteristics were encountered. Trees with forked branches were also rare (Table 6.9). Three interspecific hybrids and two seedling genotype groups showed the lowest percentages of off-type trees for the different stem characteristics, ranging from 6 to 10%. Similar to the other trials, heavy branching was also the dominant stem characteristic.

Table 6.9 Stem straightness characteristics of 6-year-old genotype groups on the Inland-facing aspect site.

Abbreviated germplasm name	Species or group name	Germplasm type Clone (C) or Seedling (S)	Number of forked trees	Number of trees with butt sweep	Number of trees with heavy branching	Total number of off-type trees	% Off-type trees (n = 50)
G×C	*E. grandis* × *E. camaldulensis*	C	-	-	-	-	0
Cas	*C. equisetifolia*	S	1	-	-	1	2
C	*E. camaldulensis*	S	-	-	1	1	2
S×U	*E. saligna* × *E. urophylla*	C	1	1	-	2	4
U	*E. urophylla*	S	1	1	1	3	6
G×S	*E. grandis* × *E. saligna*	C	-	-	1	1	2
G×U	*E. grandis* × *E. urophylla*	C	-	-	1	1	2
Cor	*Corymbia*	S	1	1	2	4	8
G	*E. grandis*	S	2	2	1	5	10
R	*E. resinifera*	S	-	-	3	3	6
G×T	*E. grandis* × *E. tereticornis*	S	-	-	3	3	6
T	*E. tereticornis*	S	2	2	3	7	10
G×L	*E. grandis* × *E. longirostrata*	S	1	1	6	8	14
G×U	*E. grandis* × *E. urophylla*	S	4	4	-	8	14
Total number off-types in the trial (n = 700)			13	12	22	47	
% off types			1.86	1.71	3.42	6.71	6.71

6.4 Stem straightness per genotype

6.4.1 Sea-facing aspect site

The mean *stem straightness* values of the individual genotypes planted on the Sea-facing aspect site were compared with one another. The mean *stem straightness* values of 6-year-old trees ranged from 2 to more than 7 (Table 6.10). Four interspecific hybrid clones and two *Eucalyptus* pure species had mean *stem straightness* values of 7 or greater. Three of the four hybrids were different hybrid between *E. grandis* and *E. camaldulensis* (G×C). The pure species were two different *E. urophylla* genotypes. The lowest ranking genotypes all originated from seedlings sources and were mostly pure species.

Table 6.10 Ranking based on stem straightness of 6-year-old genotypes planted on the Sea-facing aspect site.

Genotype	Clone (C) or Seedling (S)	Rank	Mean stem straightness at 6 years	Genotype	Clone (C) or Seedling (S)	Rank	Mean stem straightness at 6 years
G×C215	C	1	6.73	Cas400	S	36	4.60
Au33	S	2	6.64	Cas401	S	37	4.53
G×U608	C	3	6.55	C58	S	38	4.53
G×C225	C	4	6.34	B09-689	S	39	4.53
G×C231	C	5	6.04	G×U82	C	40	4.49
Au21	S	6	5.97	SGR1272×LPM02	S	41	4.48
G×U5	C	7	5.88	G15×Umix	S	42	4.45
G×U21	C	8	5.84	G×S147	C	43	4.33
S×U107	C	9	5.72	B09-346	S	44	4.32
G×S 146	S	10	5.67	G45×T32	S	45	4.32
SGR1198×Umix	S	11	5.67	G×S143	C	46	4.30
B9-008	S	12	5.64	C69	S	47	4.24
S×U92	C	13	5.64	T37	S	48	4.21
SGR1683×Umix	S	14	5.64	C40	S	49	4.03
G×C121	C	15	5.62	C37	S	50	3.99
G17×Umix	S	16	5.58	G91×T10	S	51	3.85

Genotype	Clone (C) or Seedling (S)	Rank	Mean stem straightness at 6 years	Genotype	Clone (C) or Seedling (S)	Rank	Mean stem straightness at 6 years
Au3	S	17	5.47	SN34032	S	52	3.84
Au9	S	18	5.38	T22	S	53	3.51
B10-513	S	19	5.28	AT6	S	54	3.40
SGR1231×T10	S	20	5.27	SN34023	S	55	3.22
G×C962	C	21	5.27	SGR1220×T10	S	56	3.13
G×S137	C	22	5.24	G×S136	C	57	3.13
G×U111	C	23	5.23	Maulata2	S	58	3.09
G×U7	C	24	5.17	Tor	S	59	3.06
Cas403	C	25	5.12	C63	S	60	2.94
SGR1668×Umix	S	26	5.03	Cit	S	61	2.90
Cas404	S	27	4.94	G50×Lmix	S	62	2.87
SGR1198×LPM02	S	28	4.92	SGR1668×LMP04	S	63	2.82
B09-075	S	29	4.81	SN34021	S	64	2.72
Cas402	S	30	4.77	Maculata1	S	65	2.71
G×U56	C	31	4.73	Henryi	S	66	2.70
AT9	S	32	4.71	AT4	S	67	2.70
S×U84	C	33	4.69	R19032	S	68	2.68
Au7	S	34	4.67	G15×LPM01	S	69	2.65
SGR1220×T32	S	35	4.62	SN33994	S	70	2.59
Mean	5.27						
SE	0.09						

6.4.2 Steep aspect site

The range of *stem straightness* values of this trail was smaller when compared to the Sea-facing trial and ranged 2 from to just greater than 6 (Table 6.11). The four genotypes with mean *stem straightness* values greater than 6 were all interspecific hybrid clones, of which three were *E. grandis* and *E. camadulensis* (G×C) hybrids. Similarly to the Sea-facing trial, the lowest ranking genotypes were mostly pure species that originated from seedling sources.

Table 6.11 Ranking based on stem straightness of 6-year-old genotypes planted on the Steep aspect site.

Genotype	Clone (C) or Seedling (S)	Rank	Mean stem straightness at 6 years	Genotype	Clone (C) or Seedling (S)	Rank	Mean stem straightness at 6 years
G×C121	C	1	6.17	Cas403	S	36	4.73
G×C962	C	2	6.06	B10-513	S	37	4.36
G×C231	C	3	5.69	SGR1198×LPM02	S	38	4.26
G×U608	C	4	5.67	G×S147	C	39	4.12
G×U7	C	5	5.62	Au33	S	40	4.11
G×C215	C	6	5.60	SGR1668×Umix	S	41	4.09
G×U21	C	7	5.47	Au7	S	42	4.08
G×S137	C	8	5.46	SGR1220×T10	S	43	4.07
G×U5	C	9	5.41	G15×Umix	S	44	4.07
SGR1220×T32	S	10	5.40	B09-689	S	45	3.93
G91×T10	S	11	5.37	SN33994	S	46	3.91
Au9	S	12	5.32	Maulata2	S	47	3.90
SGR1231×T10	S	13	5.27	B09-346	S	48	3.82
B09-075	S	14	5.26	G50×Lmix	S	49	3.76
G×U608	C	15	5.24	C40	S	50	3.71
AT4	S	16	5.16	T22	S	51	3.70
G×U82	C	17	5.14	C37	S	52	3.70
G17×Umix	S	18	5.11	S×U84	C	53	3.69
S×U107	C	19	5.09	T37	S	54	3.69
G×C225	C	20	5.07	SGR1198×Umix	S	55	3.69
SN34021	S	21	5.05	SGR1668×LMP04	S	56	3.62
B9-008	S	22	5.02	C69	S	57	3.60
G45×T32	S	23	5.01	Au3	S	58	3.45
S×U92	C	24	4.90	R19032	S	59	3.43
SGR1683×Umix	S	25	4.90	AT9	S	60	3.43
G×U56	C	26	4.87	C58	S	61	3.33
G×U111	C	27	4.87	G15×LPM01	S	62	3.17
G×S136	C	28	4.80	SN34023	S	63	3.16
G×S143	C	29	4.80	Henryi	S	64	3.07
Cas402	S	30	4.69	SGR1272×LPM02	S	65	3.03

Genotype	Clone (C) or Seedling (S)	Rank	Mean stem straightness at 6 years	Genotype	Clone (C) or Seedling (S)	Rank	Mean stem straightness at 6 years
Cas401	S	31	4.68	Maculata1	S	66	3.02
Cas404	S	32	4.68	C63	S	67	2.99
Cas400	S	33	4.50	Cit	S	68	2.79
Au21	S	34	4.47	SN34032	S	69	2.67
AT6	S	35	4.45	Tor	S	70	2.67
Mean	4.44						
SE	0.07						

6.4.3 Flat aspect site

Similar to the Steep trial, the *stem straightness* values of the 70 genotypes planted on the Flat aspect site also ranked from 2 to less than 7 (Table 6.12). The six genotypes with mean *stem straightness* values greater than 6 were all interspecific hybrids of which four were hybrids between *E. grandis* and *E. camaldulensis* (G×C). The lowest ranking genotypes for *stem straightness* were interspecific hybrids and pure species, all originating from seedling sources.

Table 6.12 Ranking based on stem straightness of 6-year-old genotypes planted on the Flat aspect site.

Genotype	Clone (C) or Seedling (S)	Rank	Mean stem straightness at 6 years	Genotype	Clone (C) or Seedling (S)	Rank	Mean stem straightness at 6 years
G×C215	C	1	6.59	B09-075	S	36	3.98
G×C121	C	2	5.68	SN34023	S	37	3.89
G×C962	C	3	5.31	G17×Umix	S	38	3.87
G×U608	C	4	5.25	SGR1220×T10	S	39	3.85
S×U92	C	5	5.24	B9-008	S	40	3.82
G×C225	C	6	5.21	S×U84	C	41	3.80
G×U5	C	7	5.10	B09-689	S	42	3.78
SGR1668×Umix	S	8	5.09	C40	S	43	3.75
G×U111	C	9	5.08	C58	S	44	3.69

Genotype	Clone (C) or Seedling (S)	Rank	Mean stem straightness at 6 years	Genotype	Clone (C) or Seedling (S)	Rank	Mean stem straightness at 6 years
G×S147	C	10	5.05	Cit	S	45	3.69
G×U82	C	11	5.01	G50×Lmix	S	46	3.67
Cas401	S	12	5.00	Au3	S	47	3.62
G×C231	C	13	4.93	G×S143	S	48	3.52
G×U7	C	14	4.90	B09-346	S	49	3.52
Cas403	S	15	4.90	R19032	S	50	3.48
Cas400	S	16	4.87	Maculata2	S	51	3.46
Cas404	S	17	4.86	C37	S	52	3.38
G×U56	C	18	4.82	AT9	S	53	3.32
Au9	S	19	4.80	C69	S	54	3.30
SGR1220×T32	S	20	4.71	AT6	S	55	3.30
G45×T32	S	21	4.68	SGR1198×LPM02	S	56	3.24
G×U21	C	22	4.65	G×S136	S	57	3.18
G15×Umix	S	23	4.55	SN34021	S	58	3.18
Cas402	S	24	4.43	Tor	S	59	3.02
S×U107	C	25	4.41	B10-513	S	60	3.01
G91×T10	S	26	4.34	AT4	S	61	2.92
Au21	S	27	4.34	Henryi	S	62	2.88
SGR1198×Umix	S	28	4.31	Maculata1	S	63	2.87
SGR1231×T10	S	29	4.27	SN34032	S	64	2.87
Au7	S	30	4.27	SGR1668×LMP04	S	65	2.72
Au33	S	31	4.19	C63	S	66	2.64
G×S136	C	32	4.11	SGR1272×LPM02	S	67	2.60
T37	S	33	4.11	T22	S	68	2.56
SGR1683×Umix	S	34	4.07	SN33994	S	69	1.92
G×S137	C	35	4.00	G15×LPM01	S	70	1.90
Mean	4.65						
SE	0.08						

6.4.4 Inland-facing aspect site

The range of the mean *stem straightness* values for this trial was narrower than the ranges of the Steep and Flat trials, ranging from 2.5 to less than 7 (Table 6.13). In this trial the top ranking genotype was an *E. grandis* genotype. The other genotypes with mean *stem straightness* values greater than 6 were all interspecific hybrids of which two were hybrids between *E. grandis* and *E. camadulensis* (G×C) and one a hybrid between *E. grandis* and *E. urophylla* (G×U). As was the case with the other three trials, the lowest ranking genotypes were hybrids and pure species, all originating from seedling sources.

Table 6.13 Ranking based on stem straightness of 6-year-old genotypes planted on the In-facing aspect site.

Genotype	Clone (C) or Seedling (S)	Rank	Mean stem straightness at 6 years	Genotype	Clone (C) or Seedling (S)	Rank	Mean stem straightness at 6 years
B10-513	S	1	7.32	R19032	S	36	4.25
G×C121	C	2	6.22	G×S137	C	37	4.24
G×C962	C	3	5.91	Au21	S	38	4.20
G×U608	C	4	5.70	C58	S	39	4.18
G×C215	C	5	5.62	G45×T32	S	40	4.13
G×U5	C	6	5.56	S×U84	C	41	4.11
G×C231	C	7	5.50	B09-689	S	42	4.10
G×U21	C	8	5.24	C40	S	43	4.00
Cas400	S	9	5.23	C58	S	44	4.00
G×S146	C	10	5.21	Cit	S	45	3.97
Cas404	S	11	5.18	G50×Lmix	S	46	3.96
Cas401	S	12	5.14	Au3	S	47	3.90
G×U7	C	13	5.09	G×S143	C	48	3.87
Cas402	S	14	5.03	B09-346	S	49	3.86
G×U82	C	15	5.03	R19032	S	50	3.76
G×C225	C	16	5.03	Maculata2	S	51	3.68
G×S147	C	17	5.02	C37	S	52	3.59
S×U107	C	18	5.02	AT9	S	53	3.56
SGR1220×T32	S	19	4.93	C69	S	54	3.56

Genotype	Clone (C) or Seedling (S)	Rank	Mean stem straightness at 6 years	Genotype	Clone (C) or Seedling (S)	Rank	Mean stem straightness at 6 years
B09-346	S	20	4.92	AT6	S	55	3.55
SN34021	S	21	4.91	SGR1198×LPM02	S	56	3.52
S×U92	C	22	4.83	G×S136	S	57	3.50
Au9	S	23	4.82	SN34021	S	58	3.46
G15×Umix	S	24	4.78	Tor	S	59	3.39
B9-008	S	25	4.78	B10-513	S	60	3.37
Henryi	S	26	4.77	AT4	S	61	3.33
G17×Umix	S	27	4.73	Henryi	S	62	3.31
Au33	S	28	4.62	Maculata1	S	63	3.30
G×U56	C	29	4.57	SN34032	S	64	3.28
SGR1683×Umix	S	30	4.46	SGR1668×LMP04	S	65	3.23
B09-689	S	31	4.45	C63	S	66	3.23
Cas404	S	32	4.41	SGR1272×LPM02	S	67	3.21
SGR1198×Umix	S	33	4.38	Cit	S	68	3.09
SGR1668×Umix	S	34	4.30	SN33994	S	69	3.08
Au7	S	35	4.28	G15×LPM01	S	70	2.65
Mean	4.61						
SE	0.07						

6.5 Comparison of trials at genotypic level

To obtain a better understanding of which genotypes demonstrated good *stem straightness* across the four aspect sites, 6-year-old genotypes that occurred in the top 15 positions and occurred in three or four trials, were listed. Nine interspecific hybrid clones of the 70 genotypes occurred in the top 15 lists of three or four of the trials (Table 6.14). All nine genotypes appeared in the list of In-facing aspect site, whereas the other three lists comprised of less than nine genotypes. All nine genotypes had *E. grandis* as the maternal parent. In eight of genotypes the other parent was either *E. camaldulensis* or *E. urophylla.* One of the genotypes was a hybrid between *E. grandis* and *E. saligna.* Only two of the interspecific hybrids were listed in all four top 15 lists. It should be noted that the hybrids of *E. grandis* × *E. camaldulensis* (*G*×C215) and *E. grandis* × *E. urophylla* (G×U5) were top-ranked in all four trials.

Table 6.14 Top ranking genotypes in four or three trials for stem straightness.

Genotype name	Top ranking genotypes per aspect site				Occurrence in trials
	Sea-facing	Steep	Flat	Inland-facing	
E. grandis × *E. camaldulensis*	G×C215	G×C215	G×C215	G×C215	4
E. grandis × *E. urophylla*	G×U5	G×U5	G×U5	G×U5	4
E. grandis × *E. camaldulensis*		G×C121	G×C121	G×C121	3
E. grandis × *E. urophylla*	G×U608		G×U608	G×U608	3
E. grandis × *E. camaldulensis*	G×C231	G×C231		G×C231	3
E. grandis × *E. urophylla*	G×U21	G×U21		G×U21	3
E. grandis × *E. saligna*	G×S 146		G×S146	G×S146	3
E. grandis × *E. camaldulensis*		G×C962	G×C962	G×C962	3
E. grandis × *E. urophylla*		G×U7	G×U7	G×U7	3
Total	6	7	7	9	

6.6 Discussion

Stem quality refers to the shape of a tree, which determines timber volume recovery and plays a major role in determining downstream processing options of the trees. The quality of a stem includes both external and internal features, which result from morphology, anatomy, chemical composition and physiology (Ehrenberg, 1970). This quality characteristic comprises of the form of a stem, as well as the growth and development of the branches. Features such as stem forking near the tree base and heavy branching are undesirable stem defects (Krause & Plourde, 2008), referred to as off-types in this study. Therefore, poor stem quality reduces the value of a tree, which affects profitability of pulp and paper production (Cameron et al., 2012). The profitability of solid wood depends mainly on stem size and *stem straightness*, which in turn influences the yield of sawn products (Callister et al., 2011). This study revealed several genotypes with *stem straightness* values that were better than the control

species *C. equisetifolia*, which could be considered for deployment on the mined sand dunes of Richards Bay. Most of these genotypes were interspecific hybrids of *E. grandis* as maternal parental species with *E. camadulensis* and *E. urophylla.* In particular, the hybrids G×C215 and G×U5 had top ranked values for mean *stem straightness* on all four aspect sites. The *stem straightness* of these different genotypes of the hybrids *E. grandis* × *E. camaldulensis* and *E. grandis* × *E. urophylla* could be of interest for pulp and paper production by reducing operational costs (Price et al., 2017). If pure species are to be reconsidered, *E. urophylla* necessitates consideration. In this study, off-type trees were relatively rare in the four trials with the Inland-facing and Sea-facing trials showing the least number of off-types, which could be explained by these sites been shielded from strong winds when compared to the other two sites. Although stem quality appears to be promising, the decision about which genotypes should be deployed on the mined sand dunes is determined by further trait considerations, which include survival percentage, wood and Kraft pulp properties, coppicing ability, and susceptibility to pests and diseases.

Chapter 7

Wood and Kraft Pulp Properties, Coppicing, Pests and Diseases

7.1 Introduction

In the pursuit of suitable genotypes for deployment on the mined sand dunes of Richards Bay, several other tree properties were assessed. These properties were wood and Kraft pulp properties, *coppicing* ability and the susceptibility to *pests and diseases*. The wood and Kraft pulp properties in the form of *kappa number*, *pulpability factor*, *screen pulp yield*, *basic density* and *fibre yield*, were measured at the accredited Forestry and Forest Products (FFP) laboratory of the CSIR in Durban. Because of financial constraints, 26 trees, belonging to 13 genotypes, were felled on the Inland-facing aspect site. At felling, the growth properties of *diameter at breast height* (*DBH*), *height* and *stem straightness* were measured. *Growth volume* was calculated using *DBH* and the *height* measurements by applying the appropriate formulas. The tree stumps of felled tree provided a unique opportunity to also measure the *coppicing* ability of the 13 genotypes (at 6 months) and check for *pests and diseases*. The measurements of wood and Kraft pulp properties, *coppicing* ability, as well as susceptibility to *pests and diseases* will together with the *survival* and growth trait measurements facilitate the selection of genotypes for deployment on the mined sand dunes of Richards Bay. Thus, in this section of Phase 2, the wood and Kraft properties, *coppicing* ability, as well as susceptibility to *pests and diseases* were measured at 6 years of tree growth and analysed (Phase 3). Figure 7.1 shows how the overall study these results fit in. The aspects are highlighted in the diagram.

Figure 7.1 **Extract of the study design highlighting the coppicing, wood and Kraft properties, and pest and disease aspects for measurement and analysis.**

7.2 Growth properties of trees selected for felling

For the analysis of wood properties, 26 six-year-old interspecific hybrid genotypes of four hybrid groups, growing on the Inland-facing aspect site were felled and cross-cut for laboratory processing. At felling, the growth properties *diameter at breast height* (*DBH*) and *height*, as well as *stem straightness* were measured. Of the four interspecific hybrid genotype groups, the hybrids between *E. grandis* and *E. urophylla* (G×U) exhibited the highest mean measurements for *DBH* and *height*, and thus for *growth volume* too (Table 7.1). Two hybrids, G×U and G×S, had the straightest mean stem scores of the four interspecific hybrids.

Table 7.1 **Growth traits and stem straightness measurements of selected trees at felling.**

Abbreviated germplasm name	Replication number	Plot number	DBH (cm)	Height (m)	Growth volume (m^3)	Stem straightness (1-8)
G×U608	6	414	18.50	17.10	0.1658	7.0
	8	531	18.00	17.00	0.1554	7.0
G×U111	7	468	17.50	17.20	0.1463	6.0
	10	640	18.00	17.30	0.1593	7.0

Abbreviated germplasm name	Replication number	Plot number	DBH (cm)	Height (m)	Growth volume (m^3)	Stem straightness (1-8)
G×U82	6	412	17.30	16.20	0.1336	6.0
	7	467	16.50	16.40	0.1299	6.0
G×U56	4	276	16.00	15.00	0.1018	6.0
	8	534	15.40	14.70	0.0913	6.0
G×U21	4	217	18.10	17.60	0.1651	7.0
	8	547	18.10	17.70	0.1665	7.0
G×U5	7	430	18.80	17.10	0.1715	7.0
	6	373	18.20	17.30	0.1630	7.0
Mean			15.92	16.28	0.1375	6.5
SE			0.50	0.61	0.0012	0.00
G×C962	6	366	17.60	16.70	0.1446	6.0
	7	441	16.90	14.30	0.1065	6.0
G×C231	2	80	17.60	16.30	0.1396	6.0
	7	443	16.80	15.20	0.1147	6.0
G×C225	5	334	16.20	15.90	0.1135	6.0
	3	205	13.60	14.40	0.0911	6.0
G×C215	2	79	15.70	14.20	0.0905	6.0
	4	249	16.20	15.50	0.1094	6.0
G×C121	7	445	19.80	18.30	0.1103	8.0
	5	331	18.20	17.00	0.1296	7.0
Mean			15.45	15.68	0.1250	6.2
SE			0.04	0.04	0.0012	0.0
G×S147	2	100	17.30	16.20	0.1336	7.0
	9	624	16.30	15.20	0.0858	6.0
Mean			12.20	15.20	0.1097	6.5
SE			0.06	0.04	0.0011	0.02
S×U92	1	38	14.30	13.60	0.0771	6.0
	9	629	14.90	13.70	0.0701	6.0
Mean			10.73	13.65	0.0736	6.0
SE			0.01	0.00	0.0000	0.00

ANOVA tests were performed on the growth traits and *stem straightness* measurements of the different interspecific hybrid genotypes selected for felling. These tests revealed significant differences

for *DBH* and *growth volume* at a 95% confidence level (α = 0.05). Table 7.2 presents the ANOVA tables for the growth traits and *stem straightness* of the trees at felling.

Table 7.2 ANOVA tests results comparing interspecific hybrid genotype growth traits and stem straightness of selected trees at felling.

Source	Trait	DF	SS	MS	*F value*	*P value*
Between genotypes	*DBH*	12	43.48	3.62	3.51	0.016
Within genotypes		13	13.42	1.03		
Total		25	56.90			
Between genotypes	*Height*	12	32.65	2.72	2. 05	0.107
Within genotypes		13	17.25	1.33		
Total		25	82.25			
Between genotypes	*Stem straightness*	12	6.38	0.53	1.98	0.120
Within genotypes		13	3.50	0.27		
Total		25	9.88			
Between genotypes	*Growth volume*	12	0.024	0.002	2.64	0.047
Within genotypes		13	0.009	0.001		
Total		25	0.033			

After performing ANOVA tests on the genotype growth traits and *stem straightness* measurements, Duncan's Multiple Range Tests (DMRTs) were performed on the measurements of *DBH* and *growth volume* to establish interspecific hybrid genotypes that differed significantly from one another. The tests produced five significant DMRT groupings for *DBH* and four for *growth volume*. For both *DBH* and *growth volume* the top two DMRT groupings comprised of the hybrid genotypes of *E. grandis* with *E. urophylla* (G×U) and *E. grandis* with *E. camaldulensis* (G×C) (Table 7.3). Interestingly, the interspecific hybrid between *E. saligna* and *E. urophylla* (S×U) appeared in the lowest ranking category for both traits.

Table 7.3 Ranking of interspecific hybrid genotypes based on *DBH* and *growth volume* of selected trees at felling.

Genotype name	Abbreviated germplasm name	Mean measurement	SE	DMRT grouping
DBH (cm)				
E. grandis × *E. urophylla*	G×U5	18.50	0.180	A
E. grandis × *E. camaldulensis*	G×C121	18.50	3.380	A
E. grandis × *E. urophylla*	G×U608	18.25	0.130	A
E. grandis × *E. urophylla*	G×U21	18.10	0.001	A B
E. grandis × *E. camaldulensis*	G×C962	17.25	0.250	B
E. grandis × *E. camaldulensis*	G×C231	17.20	0.320	B
E. grandis × *E. urophylla*	G×U111	16.75	3.130	C
E. grandis × *E. camaldulensis*	G×C225	16.30	2.000	C
E. grandis × *E. camaldulensis*	G×C215	15.95	0.130	C D
E. grandis × *E. urophylla*	G×U56	15.70	0.180	D
E. grandis × *E. urophylla*	G×U82	15.70	0.180	D
E. saligna × *E. urophylla*	S×U92	14.90	3.380	E
E. grandis × *E. saligna*	G×S147	14.60	0.180	E
Growth volume (m^3)				
E. grandis × *E. camaldulensis*	G×C121	0.1700	0.003	A
E. grandis × *E. urophylla*	G×U5	0.1673	0.000	A
E. grandis × *E. urophylla*	G×U21	0.1658	0.000	A
E. grandis × *E. urophylla*	G×U608	0.1606	0.000	A
E. grandis × *E. camaldulensis*	G×C231	0.1272	0.003	B
E. grandis × *E. camaldulensis*	G×C962	0.1256	0.001	B
E. grandis × *E. urophylla*	G×U111	0.1228	0.003	B
E. grandis × *E. urophylla*	G×U82	0.1118	0.001	B C
E. grandis × *E. saligna*	G×S147	0.1097	0.001	C
E. grandis × *E. camaldulensis*	G×C225	0.1023	0.000	C
E. grandis × *E. camaldulensis*	G×C215	0.1000	0.001	C

Genotype name	Abbreviated germplasm name	Mean measurement	SE	DMRT grouping
E. grandis × *E. urophylla*	G×U56	0.0966	0.000	C D
E. saligna × *E. urophylla*	S×U92	0.0736	0.002	D

In DMRT grouping column, different letters indicate significantly different *DBH* and mean *growth volume* between genotypes.

7.3 Coppicing ability from stumps of felled trees

In this study, the ability of a genotype to coppice was measured in terms of two different measures. These measures were the number of stump quadrants that had coppiced and the number of shoots on a stump of a felled tree. Figure 7.2 shows different numbers of stump quadrants that had coppiced.

A. **B.** **C.**

Figure 7.2 **Coppicing of stumps at six months after felling. A. Four quadrants showing coppicing. B. Two quadrants showing coppicing. C. One quadrant showing coppicing.**

7.3.1 Coppiced stump quadrants

Coppicing of the 13 interspecific hybrids was measured in terms of the number of stump quadrants that coppiced. For the most, the hybrids of *E. grandis* with *E. urophylla* (G×U) and *E. grandis* with *E. camaldulensis* (G×C) displayed a high rate of *coppicing* in all four stump quadrants, with mean scores

greater than 3.5 (Table 7.4). On the other hand, the hybrids of *E. grandis* with *E. saligna* (G×S) and *E. saligna* with *E. urophylla* (S×U) displayed mostly 50% or less quadrants that coppiced.

Table 7.4 Number of coppiced stumps quadrants of felled trees stumps.

Interspecific hybrid	Abbreviated germplasm name	Replication number	Plot number	Number of coppiced quadrants
E. grandis × *E. urophylla*	G×U608	6	414	3
		8	531	4
	G×U111	7	468	4
		10	640	4
	G×U82	6	412	3
		7	467	4
	G×U56	4	276	3
		8	534	4
	G×U21	4	217	4
		8	547	4
	G×U5	7	430	4
		6	373	3
Mean				3.7
E. grandis × *E. camaldulensis*	G×C962	6	366	4
		7	441	4
	G×C231	2	80	3
		7	443	4
	G×C225	5	334	4
		3	205	4
	G×C215	2	79	4
		4	249	4
	G×C121	7	445	4
		5	331	4
Mean				3.9
E. grandis × *E. saligna*	G×S147	2	100	3
		9	624	2
Mean				2.5
E. saligna × *E. urophylla*	S×U92	1	38	2
		9	629	2
Mean				2
Overall Mean				3.5
SD				0.7

Stump quadrant *coppicing* of the 13 different interspecific hybrids were compared by performing an ANOVA test on the mean number of stump quadrants that coppiced. The test revealed significant differences amongst the interspecific hybrid mean number of coppiced stump quadrants at a 95% confidence level (α = 0.05; F(12, 13) = 3.47; P = 0.018). A DMRT revealed that the interspecific hybrids of *E. grandis* hybrids with *E. urophylla* (G×U) and *E. grandis* with *E. camaldulensis* (G×C) were mostly grouped into the two highest ranking DMRT groupings (Table 7.5). In contrast, the two hybrids with *E. saligna* as one of the parents, were placed in the two lowest DMRT groupings.

Table 7.5 Ranking of interspecific hybrid genotypes based on the number of coppiced stump quadrants of felled trees.

Interspecific hybrid	Abbreviated germplasm name	Mean number coppiced quadrants	Duncan grouping
E. grandis × *E. urophylla*	G×U21	4.0	A
	G×U111	4.0	A
E. grandis × *E. camaldulensis*	G×C962	4.0	A
	G×C121	4.0	A
	G×C215	4.0	A
	G×C225	4.0	A
E. grandis × *E. urophylla*	G×U608	3.5	B
	G×U56	3.5	B
	G×U82	3.5	B
	G×U5	3.5	B
E. grandis × *E. camaldulensis*	G×C231	3.5	B
E. grandis × *E. saligna*	G×S147	2.5	C
E. saligna × *E. urophylla*	S×U92	2.0	D

7.3.2 Coppice shoots on stumps

Coppicing of the 13 interspecific hybrids was also measured in terms of the number of shoots on a stump of a felled tree. The genotypes of the two interspecific hybrids of *E. grandis* × *E. urophylla*

(G×U) and *E. grandis* × *E. camaldulensis* (G×C) produced more than 30 coppiced shoots on a stump of a felled tree (Table 7.6). On the other hand, the two hybrids with *E. saligna* as a parent produced less than 30 shoots on a stump of a felled tree.

Table 7.6 Number of coppiced shoots on stumps of felled trees.

Genotype group name	Abbreviated germplasm name	Replication number	Plot number	Number of shoots
E. grandis × *E. urophylla*	G×U608	6	414	35
		8	531	38
	G×U111	7	468	41
		10	640	32
	G×U82	6	412	33
		7	467	40
	G×U56	4	276	27
		8	534	32
	G×U21	4	217	36
		8	547	38
	G×U5	7	430	27
		6	373	22
Mean				33.4
E. grandis × *E. camaldulensis*	G×C962	6	366	37
		7	441	44
	G×C231	2	80	35
		7	443	44
	G×C225	5	334	38
		3	205	39
	G×C215	2	79	41
		4	249	40
	G×C121	7	445	39
		5	331	42
Mean				30.9
E. grandis × *E. saligna*	G×S147	2	100	25
		9	624	15
Mean				20.00
E. saligna × *E. urophylla*	S×U92	1	38	10
		9	629	12
Overall mean				33.15
SD				9.55

Coppicing of the 13 different interspecific hybrids were also compared by performing an ANOVA test on the mean number of coppiced shoots on a stump. The test revealed significant differences amongst the interspecific hybrid mean number of coppiced shoots at a 95% confidence level (α = 0.05; F(12, 13) = 10.20 ; P < 0.001). A DMRT further revealed that, similarly to the test on the mean number of coppiced stump quadrants, that the interspecific hybrids of *E. grandis* with *E. urophylla* (G×U) and *E. grandis* with *E. camaldulensis* (G×C) were mostly grouped into the two highest ranking DMRT groupings with mostly more than 30 shoots per stump (Table 7.7). The two hybrids with *E. saligna* as one of the parents, also ranked the lowest in this measurement of *coppicing*, with 20 or less shoots per stump.

Table 7.7 Ranking of interspecific hybrids based on mean number of coppiced shoots on stumps of felled trees

Genotype group name	Abbreviated germplasm name	Mean number of shoots	SE	DMRT grouping
E. grandis × *E. camaldulensis*	G×C962	40.5	0.71	A
	G×C121	40.5	2.12	A
	G×C215	40.5	6.36	A
	G×C231	39.5	0.71	A
	G×C225	38.5	6.36	A B
E. grandis × *E. urophylla*	G×U21	37.0	3.54	B
	G×U608	36.5	2.12	B
	G×U82	36.5	1.41	B
	G×U111	36.5	5.00	B
	G×U56	29.5	5.00	C
	G×U5	24.5	3.54	C
E. grandis × *E. saligna*	G×S147	20.0	7.07	D
E. saligna × *E. urophylla*	S×U92	11.0	1.41	E

7.4 Wood and Kraft pulp properties

The 26 six-year-old interspecific hybrid clones that were felled were cut into 1 m long billets, from which 15 mm thick discs were cut. After debarking the discs, they were appropriately labelled, packed and sent for analysis to the FFP laboratory of the CSIR in Durban. Figure 7.3 shows photos of a felled tree cut into billets and discs.

A. **B.** **C.**

Figure 7.3 **Billets and discs prepared for transport to wood testing laboratory. A. One metre length billets cut from a felled tree. B. Discs cut from billet ends and labelled according to genotype. C. Discs packed in breathable bags for transport to wood testing laboratory.**

In the FFP laboratory, the discs were processed for the measurement of five wood and Kraft pulp properties, *kappa number*, *pulpability factor*, *screen pulp yield*, *basic density* and *fibre yield*. These measurements revealed that the interspecific hybrids of *E. grandis* and *E. urophylla* (G×U) exhibited the highest mean measurements for *pulpability factor* and for *screen pulp yield*, but the lowest mean measurements for *basic density* and *pulp yield* (Table 7.8). On the other hand, the hybrids between *E. grandis* and *E. camaldulensis* (G×C) exhibited the highest mean measurements for *kappa number* and *basic density*, but lowest mean values for *pulpability factor* and *screen pulp yield*. The two interspecific hybrid clones *E. grandis* and *E. camaldulensis* (G×C) and *E. grandis* × *E. camaldulensis* (G×S) exhibited the highest *fibre yield* values.

Table 7.8 Wood and Kraft pulp property measurements of felled trees.

Genotype group name	Abbreviated germplasm name	Plot number	Kappa number	Pulpability factor	Screen pulp yield (%)	Basic density (Kg/m^3)	Fibre yield per hectare (Ton/ha)
E. grandis × *E. urophylla*	G×U608	414	21.3	2.49	53.0	511.0	21.78
		531	21.6	2.37	52.2	510.7	21.77
	G×U111	468	21.8	2.36	51.4	502.3	20.68
		640	21.7	2.38	51.6	503.4	20.82
	G×U82	412	20.1	2.51	50.1	492.0	20.30
		467	20.6	2.49	51.2	491.5	22.09
	G×U56	276	20.1	2.51	50.1	492.0	20.30
		534	20.1	2.51	50.1	492.0	20.30
	G×U21	217	21.4	2.45	50.1	496.0	19.19
		547	21.4	2.45	50.2	496.0	19.19
	G×U5	430	21.3	2.34	49.9	502.3	20.68
		373	21.9	2.33	51.1	502.3	20.68
Mean			21.09	2.49	51.0	414.74	21.13
SD			0.40	0.01	0.80	15.99	3.77
E. grandis × *E. camaldulensis*	G×C962	366	26.8	1.81	45.8	600.0	22.90
		441	26.8	1.81	45.8	616.0	27.60
	G×C231	80	29.2	1.78	46.2	700.0	30.83
		443	29.1	1.83	46.5	664.7	30.91
	G×C225	334	26.7	1.83	45.3	625.0	28.82
		205	26.8	1.84	44.2	639.0	28.82
	G×C215	79	24.2	1.79	44.2	639.0	28.24
		249	24.5	1.75	44.3	640.0	28.30
	G×C121	445	25.5	1.92	44.0	746.0	32.82
		331	25.6	1.90	43.70	700.0	31.89
Mean			26.38	1.81	44.7	640.17	29.04
SD			1.69	0.01	0.80	57.02	9.69
E. saligna × *E. urophylla*	S×U92	38	22.8	2.03	46.6	634.0	29.17
		629	21.9	2.04	46.8	635.0	29.72
Mean			22.50	2.03	46.7	634.0	29.30
SD			0.18	0.00	0.02	50.00	0.16
E. grandis × *E. saligna*	G×S147	100	19.8	2.35	46.6	522.0	23.91
		624	19.6	2.44	46.8	523.0	24.48
Mean			19.65	2.40	46.6	522.50	24.45
SD			1.81	0.02	0.13	12.50	0.15

ANOVA tests were performed on the wood and Kraft pulp property measurements of the different interspecific hybrid genotypes to establish if significant differences existed amongst the genotypes for the different wood and Kraft pulp properties. These tests revealed significant differences for all five wood and Kraft pulp properties at a 95% confidence level (α = 0.05). Table 7.9 presents the ANOVA tables for the wood and Kraft pulp properties of the felled trees.

Table 7.9 ANOVA test results comparing interspecific hybrid genotypes for wood and Kraft pulp properties of felled trees.

Source	Trait	DF	SS	MS	*F value*	*p value*
Between genotypes	*Kappa*	12	198.03	16.50	25.21	< 0.001
Within genotypes	*number*	13	8.51	0.65		
Total		25	206.54			
Between genotypes	*Pulping factor*	12	2.24	0.187	42.52	< 0.001
Within genotypes		13	0.06	0.004		
Total		25	2.30			
Between genotypes	*Screen*	12	230.90	19.24	39.15	< 0.001
Within genotypes	*pulp yield*	13	6.39	0.49		
Total		25	237.29			
Between genotypes	*Basic density*	12	368806.03	30733.84	17.45	< 0.001
Within genotypes		13	22898.45	1761.42		
Total		25	391704.48			
Between genotypes	*Fibre yield*	12	472.82	39.40	12.71	< 0.001
Within genotypes		13	40.30	3.10		
Total		25				

After performing ANOVA tests on the measurements of the wood and Kraft pulp properties, DMRTs were performed on all five properties to establish interspecific hybrid genotypes that differed significantly from one another. These tests identified three significant DMRT groupings of genotypes for *pulpability factor* and six groupings for *basic density* (Table 7.10). The DMRT revealed three

significant groupings for the other three properties. The top two DMRT groupings of the three properties *kappa number*, *basic density* and *fibre yield* all contained genotypes of interspecific hybrids between *E. grandis* and *E. camaldulensis* (G×C). However, the groupings of *basic density* and *fibre yield* also contained a hybrid between *E. grandis* with *E. saligna* (G×S). In contrast, for properties *pulpability factor* and *screen pulp yield*, the genotypes in the top two DMRT groupings were mostly hybrids of *E. grandis* with *E. urophylla* (G×U). However, three of the nine genotypes in the top two groupings of *pulpability factor* were not G×U hybrids.

Table 7.10 Ranking of interspecific hybrid genotypes based on wood and Kraft pulp properties of felled trees.

Genotype group name	Abbreviated germplasm name	Wood and Kraft pulp properties measurements	SE	DMRT grouping
		Kappa number		
E. grandis × *E. camaldulensis*	G×C121	28.1	2.42	A
	G×C231	26.6	0.08	A
	G×C962	26.3	0.50	A B
	G×C215	25.6	0.01	B
	G×C225	25.4	2.65	B
E. grandis × *E. saligna*	G×S147	21.9	1.81	C
E. grandis × *E. urophylla*	G×U56	21.8	0.01	C
	G×U5	21.6	0.18	C
	G×U608	21.5	0.05	C D
	G×U111	20.9	0.50	D
	G×U82	20.5	0.02	D
	G×U21	20.4	0.13	D E
E. saligna × *E. urophylla*	S×U92	19.5	0.18	E
		Pulpability factor		
E. grandis × *E. urophylla*	G×U82	2.5	0.000	A
	G×U21	2.5	0.001	A
	G×U608	2.4	0.007	A B
	G×U111	2.4	0.005	A B
E. saligna × *E. urophylla*	S×U92	2.4	0.004	A B
E. grandis × *E. urophylla*	G×U56	2.4	0.000	A B
	G×U5	2.3	0.000	B
E. grandis × *E. saligna*	G×S147	2.1	0.022	B
E. grandis × *E. camaldulensis*	G×C215	1.9	0.000	B C
	G×C231	1.8	0.000	C

Genotype group name	Abbreviated germplasm name	Wood and Kraft pulp properties measurements	SE	DMRT grouping
	G×C225	1.8	0.001	C
	G×C962	1.8	0.005	C
	G×C121	1.8	0.011	C
		***Screen pulp yield* (%)**		
E. grandis × *E. urophylla*	G×U608	52.10	1.62	A
	G×U56	51.50	0.02	A
	G×U82	51.30	0.02	A B
	G×U5	50.50	0.72	B
	G×U21	50.25	0.04	B
	G×U111	50.10	0.02	B
E. saligna × *E. urophylla*	S×U92	46.70	0.02	C
E. grandis × *E. saligna*	G×S147	46.55	0.13	C
E. grandis × *E. camaldulensis*	G×C121	45.35	2.64	C D
	G×C962	45.30	0.50	D
	G×C231	44.75	0.60	D
	G×C225	44.25	0.00	D
	G×C215	43.85	0.04	D E
		***Basic density* (Kg/m^3)**		
E. grandis × *E. camaldulensis*	G×C121	715.35	1.67	A
	G×C215	715.00	0.21	A
	G×C225	642.00	0.07	B
	G×S147	632.50	0.35	B
	G×C231	615.50	0.78	B
	G×C962	558.00	0.71	C
E. saligna × *E. urophylla*	S×U92	518.00	0.14	C
E. grandis × *E. urophylla*	G×U5	464.65	0.85	D
	G×U21	437.15	0.21	D
	G×U608	408.35	1.27	D E
	G×U56	402.85	0.14	E
	G×U82	397.60	0.14	E
	G×U111	377.85	0.14	E F
		***Fibre yield* (Tons/ha)**		
E. grandis × *E. camaldulensis*	G×C121	32.38	4.32	A
	G×C215	31.36	4.29	A
E. grandis × *E. saligna*	G×S147	29.45	0.15	A B
E. grandis × *E. camaldulensis*	G×C225	28.41	0.05	B
	G×C231	27.82	2.00	B
	G×C962	25.25	11.05	B C
E. saligna × *E. urophylla*	S×U92	24.20	0.16	C
E. grandis × *E. urophylla*	G×U5	23.45	5.15	C
	G×U21	21.97	5.71	C D
	G×U608	21.28	0.51	D
	G×U56	20.75	0.01	D

Genotype group name	Abbreviated germplasm name	Wood and Kraft pulp properties measurements	SE	DMRT grouping
	G×U82	20.39	5.78	D
	G×U111	18.94	1.11	D E

Pearson's correlation coefficients were calculated to ascertain the type of relationship that existed between different pairs of wood and Kraft pulp properties. The correlation coefficients revealed that all relationships between the property pairs were either strong positive ($r > 0.5$) or strong negative ($r < -0.5$) (Table 7.11). More specifically, the relationship between *fibre yield* and *basic density* was nearly a perfect positive relationship of close to 100%, while the relationship between *basic density* and *screen pulp yield* was also nearly perfect, but negative.

Table 7.11 Pearson's correlation coefficients for wood and Kraft pulp property pairs

Wood and Kraft pulp property	*Kappa number*	*Pulpability factor*	*Screen pulp yield*	*Basic density*	*Fibre yield*
Kappa number					
Pulpability factor	–0.7344				
Screen pulp yield	–0.7344	+0.8731			
Basic density	+0.7471	–0.8254	–0.9045		
Fibre yield	+0.7127	–0.7748	–0.8403	+0.9901	

7.5 Diseases

Throughout the study, the germplasm was measured for disease, particularly for the fungal disease of stem canker, which is caused by *Crysoporthe austroafricana*. This stem canker has been labelled as one of the world's most serious diseases of eucalypts (Wingfield & Kemp, 1993). Other fungal stem cankers, caused by *Botryosphearia dothidea*, *Endothia gyrosa* and *Teratosphaeria zuluensis*

(various forms), were also monitored. During the six years, only a few *Corymbia* trees showed kino exudation.

7.6 Pests

The wasp blue gum chalcid (*Leptocyte invasa*) and bronze bug (*Thaumastocoris peregrinus*) are known for attacking eucalypts. The blue gum chalcid wasp is an invasive insect species known for its preference for young foliage. These insects are responsible for gall formation on leaves that result in foliage dying (Figure 7.4).

A. **B.**

Figure 7.4 **Coppice *Leptocybe invasa* infestation at six months after felling. A. Healthy coppice shoots and twigs. B. Severely infested coppice showing dying off shoots and twigs.**

The presence of blue gum chalcid wasps (*Leptocybe invasa*) and Bronze bugs (*Thaumastocoris peregrinus*) were measured in the four trials from trial establishment until the trees were 6 years old. The presence of these two pests during this period was negligible. Because it is known that these pests prefer young foliage, they were counted when present on coppiced shoots of the stumps of the felled trees six months after felling. No evidence of bronze bug could be found on the 26 stumps of the felled trees. However, few (one or sometimes two) blue gum chalcid wasps were found on the

coppiced shoots of 12 of the 26 the stumps (Table 7.12). The limited data perhaps also indicated that the hybrid *E. grandis* × *E. urophylla* may be less susceptible to blue chalcid wasp infestation than the other three interspecific hybrids, though this should be confirmed with a larger sample size.

Table 7.12 Counts of blue chalcid wasps on coppiced shoot stumps of felled trees.

Genotype group name	Abbreviated germplasm name	Replication number	Plot number	Pest score
E. grandis × *E. urophylla*	G×U608	6	414	1
		8	531	0
	G×U111	7	468	0
		10	640	0
	G×U82	6	412	0
		7	467	0
	G×U56	4	276	0
		8	534	0
	G×U21	4	217	1
		8	547	0
	G×U5	7	430	0
		6	373	0
E. grandis × *E. camaldulensis*	G×C962	6	366	1
		7	441	1
	G×C231	2	80	0
		7	443	0
	G×C225	5	334	1
		3	205	1
	G×C215	2	79	1
		4	249	1
	G×C121	7	445	0
		5	331	0
E. saligna × *E. urophylla*	S×U92	1	38	2
		9	629	1
E. grandis × *E. saligna*	G×S147	2	100	2
		9	624	1
Total number of stumps showing infestation				14

7.7 Discussion

A sample of trees comprising of 13 genotypes from four interspecific hybrid groups were selected from the Inland-facing trial at Richards Bay to obtain an understanding of the wood and Kraft pulp properties of these trees. Because these trees were felled, knowledge of the *coppicing*, as well as *pests and disease* could also be gathered. For the wood and Kraft pulp properties, the hybrid of *E. grandis* with *E. urophylla* (G×U) exhibited the highest mean measurements for *screen pulp yield*, but the lowest mean measurements for *basic density* and *pulp yield*. The six genotypes of the *E. grandis* × *E. urophylla* hybrid exhibited the highest *screen pulp yield* values of all the genotypes, with percentages of over 50%, while the percentages of the other groups were just under 50%. These high *screen pulp yield* values of the *E. grandis* × *E. urophylla* genotypes are of particular importance to paper production, because these yields translate into substantially higher productive operations and profitability of large local pulp and paper mills (Downes et al., 1997; Clarke et al., 2008). The *E. grandis* × *E. urophylla* hybrids were the only genotypes in this collection that displayed measurements for *pulpability factor* acceptable to the South African commercial industry standard of ≥ 2.34 (Gardner et al., 2007). These results strongly suggest that genotypes that have been derived from pure species genetic crosses and have undergone several cycles of improvement, are well suited for the local pulp and paper industry in the Richards Bay area (Snedden et al., 2007).

Some of the *E. grandis* × *E. camaldulensis* genotypes exhibited highest mean measurements for *kappa number* and *basic density*. Because of these high measurements, high chemical inputs will be required in the pulping process making these genotypes uneconomical for local paper production (Gardner et al., 2007). However, they are suitable for the woodchip export markets, because their relatively high weights are important considerations in the transportation of the woodchip tonnage versus volume (Kibblewhite, 1999; Gardner et al., 2007; Norris, 2012).

When the *coppicing* ability of the different genotypes was considered, the genotypes of the interspecific hybrids of *E. grandis* × *E. camaldulensis* and *E. grandis* × *E. urophylla* produced large numbers of healthy coppiced sprouts, which are advantageous for plantation regeneration without the need for replanting (Little, 2000; J. W. Crous & Burger, 2015). Negligible occurrences of pests and diseases were recorded in this study. However, these results should be viewed with caution, because the data were gathered from older trees, which are known to be less susceptible (Nyeko, 2005). It could therefore be concluded that the pests and diseases were relatively unimportant when considering genotypes for deployment on mined sand dunes in the Richards Bay area, but may require further studies.

Chapter 8

Economically Viable Genotypes for the mined sand dunes of Richards Bay Area

8.1 Introduction

In Phase 4 of this study (final phase), a stepwise procedure was followed to identify genotypes with the potential for deployment on the mined sand dunes of Richards Bay. The relative importance of the traits (*survival*, *DBH*, *height* and *stem straightness*), measured in the four trials, were determined using a Principal Component Analysis (PCA). Thereafter, the relative importance of the properties measured on the felled trees and stumps (*kappa number*, *pulpability factor*, *screen pulp yield*, *basic density* and *fibre yield*) was also established with a PCA. In the pursuit to identify genotypes suited for deployment on the mined sand dunes, the relative contribution of the traits to the variance in a few Principal Components (PCs) was used to devise index formulas to rank the genotypes in terms of the relative importance of the measured traits (Figure 8.1). Thereafter, the formulas were applied to determine genotypes that will be suitable to forestry industries of importance in the Richards Bay area. The two industries addressed in this analysis was the pulp and paper industry, as well as woodchip industry for export markets.

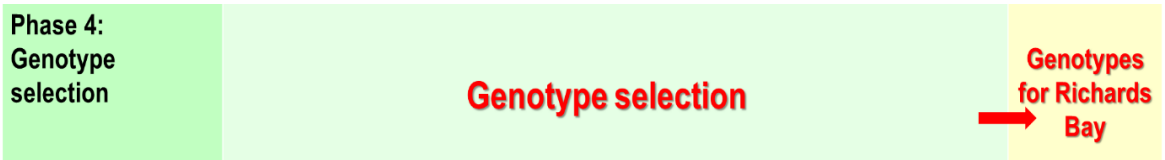


Figure 8.1 **Extract of the study design highlighting the final phase in which genotypes were selected for deployment on the Richards Bay mined sand dunes.**

The following objectives were targeted to identify genotypes were suitable for deployment on the mined sand dunes in the Richards Bay area:

1. To determine the relative importance of the trial and felled tree traits using PCA;
2. To rank the genotypes for each trial and felled tree traits using the Relative Performance Index (RPI);
3. To select potential genotypes based on relative performance;
4. To determine the relative importance of combined trial and felled tree traits using PCA;
5. To rank the genotypes for combined trial and felled tree traits using the RPI;
6. To select genotypes using the Economic Performance Index (EPI) for fibre production industry; and
7. To select genotypes using the EPI for woodchip export market.

8.2 Relative importance of the traits measured in the trials

8.2.1 Strength of relationships

PCA was performed using measurements of the four traits, *survival*, *DBH*, *height*, and *stem straightness*, to establish the strength of relationships amongst the traits. By reducing the dimensionality of the measurement dataset and retaining most of the variation in a few PCs, it was possible to identify how strongly the traits related to one another. According to the general rule of thumb, the calculated Pearson's correlations (r) revealed two categories of relationship strengths amongst the pairs of traits. A strong positive relationship ($r > 0.5$) was identified between three pairs of traits, *DBH* and *height*, *DBH* and *stem straightness*, and *height* and *stem straightness* ($r > 0.5$), while a weak positive relationship ($r > 0$ to 0.5) was established between the paired traits *survival* and *DBH*, *survival* and *height*, and *survival* and *stem straightness* (Table 8.1). The relationship between *DBH* and *height* was a nearly perfect positive relationship (r close to 1).

Table 8.1 Pearson's correlations showing strength relationships between trait pairs.

Trait	Survival	DBH	Height	Stem straightness
Survival	SURV	0.07	0.07	0.09
DBH		DBH	0.98	0.85
Height			HT	0.85
Stem straightness				STEM

8.2.2 Variation retained in Principal Components

PCA was performed using measurements of the trial traits to bring out relationship patterns from the multivariate dataset. Eigenvalues revealed the amount of variation retained by each of the PCs. PCA showed that two of the four the PCs, PC1 and PC2, retained nearly 100% of the variance with PC1 retaining the majority of the variance. Table 8.2 shows eigenvalues of the four PCs, their portion attributed of variance, and cumulative variance. This table shows that the cumulative information retained by PC1 and PC2 was close to 95%.

Table 8.2 Principal component eigenvalues and associated variance proportions explained by the PCs.

Principal component	Eigenvalue	Standard deviation	Proportion of variance	Cumulative variation
1	2.81	2.051	0.701	0.701
2	0.99	0.829	0.248	0.949
3	0.19	0.281	0.047	0.996
4	0.02	0.041	0.004	1.0000

By determining the variation retained by the respective PCs, it was possible to visualise the explained variance in the dataset by constructing a scree plot. The plot shows that most of the trait variance was explained by PC1 and the second most by PC2, which is substantially less. The small remainder of the variance is distributed over PCs 3 and 4. Figure 8.2 shows the scree plot of the variance distribution amongst the PCs.

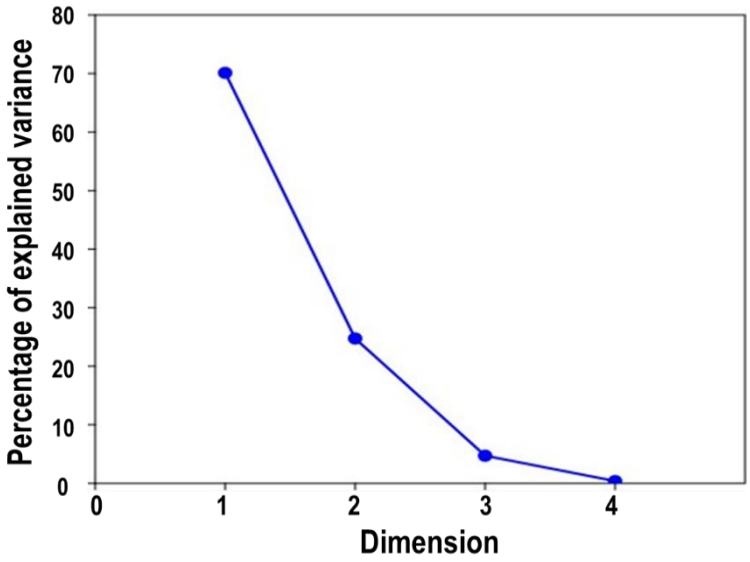


Figure 8.2 Scree plot showing how much of the trait information was explained by the four PCA dimensions.

The loadings determined through the PCA provided an indication of the relative importance of the four traits to each of the PCs. The four traits associated mostly with PC1 and PC2 (Table 8.3) PC1 was positively correlated with the traits *DBH*, *height* and *stem straightness* in more or less equal amounts. Therefore, by increasing the values of *DBH*, *height* and *stem straightness* will result in an increase in the value of PC1. In contrast, PC2 was nearly 100% positively correlated with *survival*, which meant that *survival* had a large and positive influence on the value of PC2. The loadings of *DBH*, *height* and *stem straightness* revealed that these traits were only slightly associated with

PC2, which was also the case for *survival* and PC1. The influences of the four traits on the remainder of the PCs were small, as indicated by their small loading values and percentage contributions.

Table 8.3 Loadings of trial survival, growth traits and stem straightness to show association with PCs.

Trait	Principal component 1		Principal component 2		Principal component 3		Principal component 4	
	Loading	%	Loading	%	Loading	%	Loading	%
Survival	0.09	3.4	0.99	28.49	-0.03	0.5	0.00	0.0
DBH	0.59	23.0	-0.05	-1.43	-0.40	11.2	-0.71	15.4
Height	0.59	23.0	-0.06	-1.72	-0.40	4.8	0.71	19.4
Stem straightness	0.56	21.0	-0.02	-0.59	0.83	10.2	0.00	65.1
% of total variance		70.13		24.75		4.73		0.40

8.2.3 Relative ranking of genotypes

To obtain an understanding of a genotype's overall performance in terms of the relative importance of the trial traits, *survival*, *DBH*, *height* and *stem straightness*, mean RPI values were calculated for the 70 genotypes across the four trails. The RPI is a multivariate weighted index, where the weightings were extracted from the variance percentages of the traits explained by PC1 and PC2. Table 8.4 shows the ranking of the top 20 genotypes based on the RPIs. The top 11 genotypes were all interspecific hybrid clones, where eight of these hybrid genotypes were hybrids of *E. grandis* with *E. camaldulensis* or *E. urophylla* (G×C) and (G×U). Interestingly, the highest ranking hybrid was a hybrid between *E. grandis* and *E. saligna* (G×S). Four pure species made the top 20 ranking, of which two genotypes were *E. urophylla* (Au) and two were *C. equisetifolia* (Cas).

Table 8.4 Ranking of the top 20 genotypes based on the Relative Performance Index.

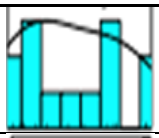
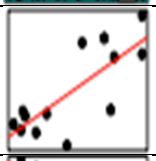
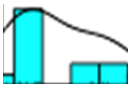
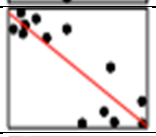
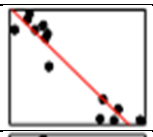
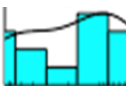
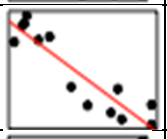
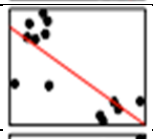
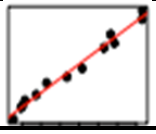
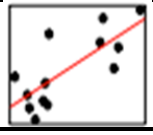
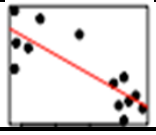
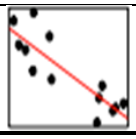
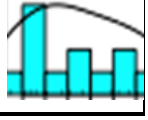
Genotype	Survival (%)	DBH (cm)	Height (m)	Stem straightness (Score 1 – 8)	RPI value	Ranking
G×S147	90	17.54	16.34	5.50	31.96	1
G×U608	97	17.07	15.81	6.22	31.56	2
G×C215	97	15.41	14.44	6.40	29.65	3
G×C225	98	14.88	13.90	6.20	28.84	4
G×C121	90	14.58	13.71	6.41	28.83	5
G×U21	97	14.74	13.80	5.94	28.72	6
G×U56	100	14.36	13.27	5.28	28.17	7
G×U5	97	14.19	13.21	6.00	27.83	8
G×C231	97	13.95	12.97	6.20	27.66	9
S×U92	92	14.19	13.14	5.72	27.42	10
S×U107	100	13.27	12.38	5.96	26.91	11
Au9	88	14.11	12.99	5.00	26.83	12
G×U82	95	13.57	12.71	5.45	26.83	13
G×U111	92	13.29	12.43	5.23	26.32	14
G×C962	95	13.03	12.08	6.24	26.25	15
SGR1198×Umix	98	12.78	12.02	5.00	59.89	16
Cas400	90	13.27	12.27	5.00	26.07	17
Cas402	88	13.45	12.43	5.00	26.01	18
SGR1120×T32	90	12.89	12.08	5.00	25.69	19
Au7	80	13.69	12.83	5.00	25.63	20
Mean top 20	89	14.21	12.67	5.17	26.47	
SD top 20	2.43	1.95	1.85	0.57	1.79	
Mean of 70 genotypes across trials	86	10.41	9.79	4.33	53.25	
SD 70 genotypes	9.77	2.84	2.84	0.84	6.43	

8.3 Relative importance of traits measured on felled trees

8.3.1 Strength of relationships

To establish the strength of relationships amongst the wood and Kraft properties, *kappa number*, *pulpability factor*, *screen pulp yield*, *basic density* and *fibre yield*, Pearson's correlation coefficients were calculated using the measurements gathered from the felled trees. According to the general rule of thumb, the calculated correlations (r) revealed two categories of relationship strengths between the 10 pairs of traits (Table 8.5). Strong positive relationships were identified for four of the pairs ($r > 0.5$), while strong negative relationships were established for the other six trait pairs ($r > 0.3$ to 0.5).

Table 8.5 **Pearson's correlations showing strength relationships between traits measured on felled trees.**

Trait	Basic density	Kappa number	Pulping factor	Screen Pulp yield	Pulp yield
Basic density		0.76	-0.79	-0.82	0.96
Kappa number			-0.95	-0.73	0.71
Pulping factor				0.87	-0.77
Screen pulp yield					-0.84
Pulp yield					

8.3.2 Variation retained in Principal Components

The PCA that was performed on the measurements of traits gathered from the felled trees also brought about relationship patterns from the multivariate dataset. The eigenvalues revealed that three of the five PCs, PC1, PC2 and PC3, retained nearly 100% of the variance, where PC1 retained the majority of the variance. Table 8.6 shows the eigenvalues of the five PCs, their portion attributed of variance, and cumulative variance. This table shows that the cumulative information explained by PC 1 and PC 2 was approximately 95%.

Table 8.6 Principal component eigenvalues and associated variance proportions explained by the PCs.

Principal component	Eigenvalue	Proportion of variance	Cumulative variance
1	4.29	0.857	0.857
2	0.44	0.087	0.944
3	0.22	0.044	0.988
4	0.04	0.008	0.996
5	0.02	0.004	1.000

By determining how much variation was explained by the respective PCs, it was possible to visualise the trait information in the dataset of the felled trees by constructing a scree plot. The plot shows that most of the variance in the multivariate dataset is explained by PC1. The small remainder of the variance was distributed over PCs 2, 3, 4 and 5. Figure 8.3 shows the scree plot of the variance distribution amongst the PCs.

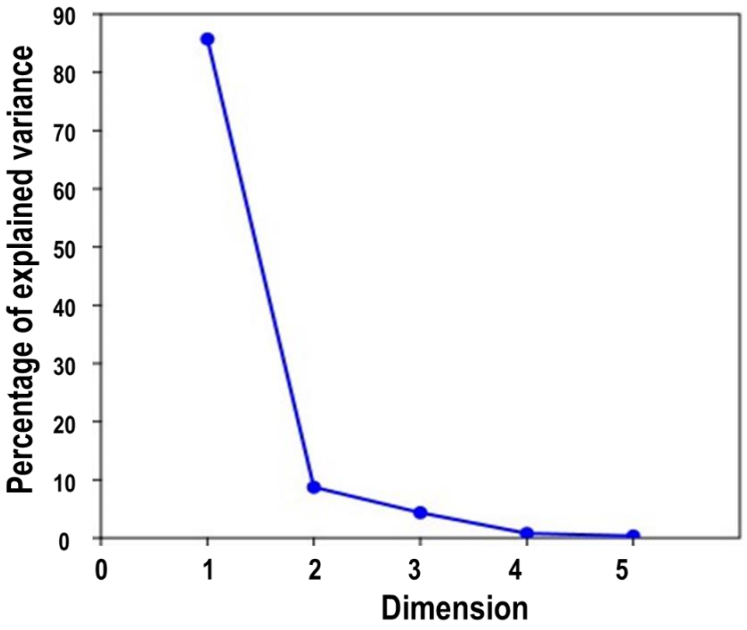


Figure 8.3 Scree plot showing how much of the felled tree trait variation was explained by the five PCA dimensions.

The loadings determined through the PCA provided an indication of the relative importance of the felled tree traits to each of the PCs. The five traits were correlated with PC1, more or less in equal proportions (Table 8.7). However, three of the traits were positively correlated (*kappa number*, *basic density* and *fibre yield*) and two negatively correlated (*pulpability factor* and *screen pulp yield.* For PC2, the loading for *screen pulp yield* was much less than the loadings of the other four traits. Also for PC2, the three traits (*pulpability factor, basic density* and *fibre yield*) were positively correlated and two traits (*kappa number* and *screen pulp yield*) negatively correlated. The influences of the wood and pulp property traits on the remainder of the PCs were small as indicated by their small loading values and percentage contribution.

Table 8.7 Loadings of wood and pulp property traits to show association with PCs.

Trait	Principal component 1		Principal component 2		Principal component 3		Principal component 4		Principal component 5	
	Loading	%	Loading	%	Loading	%	Loading	%	Loading	%
Kappa number	0.43	19	-0.60	28	0.39	20	0.05	3	0.55	28
Pulpability factor	-0.46	21	0.45	22	0.15	8	0.22	12	0.72	36
Screen pulp yield	-0.45	20	-0.11	5	0.80	42	-0.21	12	-0.32	16
Basic density	0.45	20	0.41	20	0.38	20	0.65	35	-0.25	13
Pulp yield	0.45	20	0.51	25	0.19	10	-0.69	38	0.14	7
% of total variance	85.74		8.74		4.37		0.80		0.35	

8.3.3 Relative ranking of genotypes

To obtain an understanding of a genotype's overall performance in terms of the felled tree traits, *kappa number*, *pulpability factor, screen pulp yield, basic density* and *pulp yield*, mean RPI values were calculated for the 13 genotypes of the felled tree population. The weightings of the multivariate weighted RPI index, were extracted from the variance percentages of the traits explained by PC1 and PC2. The RPI index shows that the top five genotypes were all different genotypes of interspecific hybrids of *E. grandis* with *E. camaldulensis* (G×C), while the bottom six were different genotypes of *E. grandis* with *E. urophylla* (G×U). The remaining two interspecific hybrids were ranked in the middle of the ranking, both were hybrids with *E. saligna* as a parent (G×S and S×U).

Table 8.9 Ranking of the 13 genotypes based on the Relative Performance Index.

Genotype name	Sample tree	Kappa number	Pulpability factor	Screen pulp yield	Basic density	Pulp yield	RPI value	Rank
G×C215	1	25.5	1.92	44.0	746.0	32.82	4621	1
	2	25.6	1.90	43.7	700.0	31.89	4360	2
G×C231	1	29.2	1.78	46.2	700.0	30.85	4333	3
	2	29.1	1.83	46.5	664.7	30.91	4137	4
G×C225	1	26.7	1.83	45.3	625.0	28.82	3999	5
	2	26.8	1.84	44.2	639.0	28.82	3998	6
G×C121	1	24.2	1.79	44.2	639.0	28.24	3997	7
	2	24.5	1.75	44.3	640.0	28.30	3973	8
G×C962	1	26.8	1.81	45.8	600.0	26.90	3827	9
	2	26.8	1.81	45.8	616.0	27.60	3736	10
G×S147	1	19.8	2.35	46.6	522.0	23.91	3289	11
	2	19.6	2.44	46.8	523.0	24.48	283	12
S×U92	1	22.8	2.03	46.6	634.0	29.17	3224	13
	2	21.9	2.04	46.8	635.0	29.72	3224	14
G×U608	1	21.3	2.49	53.0	511.0	21.78	3182	15
	2	21.6	2.37	52.2	510.7	21.77	3178	16
G×U5	1	21.3	2.34	49.9	502.0	22.01	3135	17
	2	21.9	2.33	51.1	499.0	21.84	3108	18
G×U111	1	21.8	2.36	51.4	502.3	20.68	3105	19
	2	21.7	2.38	51.6	503.4	20.82	3100	20
G×U21	1	21.4	2.45	50.1	495.7	19.19	3090	21
	2	21.4	2.45	50.2	496.0	19.68	3081	22
G×U56	1	20.1	2.51	50.1	492.0	20.30	3072	23
	2	20.1	2.51	50.1	492.0	20.30	3066	24
G×U82	1	20.6	2.49	51.2	491.5	22.09	3064	25
	2	20.4	2.52	51.4	493.7	21.69	3056	26
Mean		23.061	2.159	47.884	566.11	25.04		
SD		2.818	0.297	3.021	89.49	4.44		

8.4 Relative importance of combined trial and felled tree traits

After creating the relative genotype rankings based on the RPIs for the trial traits and felled tree traits, genotypes were selected for their potential suitability for deployment on the mined sand dunes by comparing these two rankings. After comparing the two rankings, it was established that all genotypes used to gather the felled tree data appeared in the top 15 of the top 20 of the ranking of the trial trait measurements. Based on this outcome, it was decided to continue with the 13 genotypes of the felled trees, because data of all the trial traits and felled tree traits were available for these genotypes. This outcome also shows that the preliminary data used to select the 26 trees for felling were based on sound preliminary calculations. Data for the 13 genotypes (26 trees) were then analysed further to select genotypes that were appropriate for the fibre production and woodchip export market. Towards the selection of genotypes for the two market sectors, the combined data of four trail traits (*survival*, *DBH*, *height* and *stem straightness*) and five felled tree traits (*kappa number*, *pulpability factor*, *screen pulp yield*, *basic density* and *pulp yield*) were subjected to PCA.

8.4.1 Variation retained in Principal Components

The loadings determined through the PCA performed on the combined dataset provided an indication of the relative importance of the nine traits to each of the PCs. Approximately 80% of the variance in the dataset was retained by PC1 and PC2 (Table 8.8). PC1 was positively correlated with the traits *survival, stem straightness*, *kappa number*, *basic density* and *pulp yield.* The remainder of the traits were negatively correlated with PC1. Approximately 50% less of the variance in explained by PC2 when compared to PC1. In terms of PC2, the traits, *DBH*, *height*, *stem straightness*, *pulpability factor*, *basic density*, and *pulp yield*, were all positively correlated with PC2.

Table 8.8 Loadings of the combined trial and felled tree traits to show association with PCs.

Trait	PC 1		PC 2		PC 3		PC 4	PC 5	PC 6	PC 7	PC 8	PC 9
	Loading	%	Loading	%	Loading	%	Loading	Loading	Loading	Loading	Loading	Loading
Survival	0.059	2	-0.383	17	0.891	45	-0.147	0.034	0.087	-0.121	-0.100	0.034
DBH	-0.065	2	0.619	28	0.267	13	-0.008	0.144	-0.145	-0.104	-0.197	-0.670
Height	-0.059	2	0.623	28	0.261	13	-0.011	0.066	-0.143	0.020	0.036	0.717
Stem straightness	0.345	13	0.153	7	0.152	7	0.725	-0.168	0.490	0.059	0.186	-0.046
Kappa number	0.416	16	-0.130	6	0.081	4	0.209	0.347	-0.651	0.249	0.386	-0.067
Pulpability factor	-0.434	17	0.039	2	0.098	5	-0.163	0.361	0.366	0.496	0.503	-0.107
Screen pulp yield	-0.379	15	-0.174	8	-0.066	3	0.493	0.635	-0.012	-0.264	-0.304	0.114
Basic density	0.438	17	0.030	1	-0.076	4	-0.173	0.330	0.237	0.521	-0.575	0.065
Pulp yield	0.416	16	0.092	3	-0.133	6	-0.330	0.427	0.312	-0.567	0.301	0.020
Eigenvalue	4.881		2.388		0.779		0.584	0.194	0.137	0.024	0.012	0.001
% variance	54.20		26.53		8.66		6.49	2.16	1.52	0.26	0.133	0.006

8.4.2 Grouping of genotypes

Cluster analysis of the combined dataset including the trial and felled tree traits revealed four distinct groups. The grouping B comprised mostly of interspecific hybrids of *E. grandis* and *E. urophylla*, which were strongly associated with *pulpability factor* and *screen pulp yield* (Figure 8.4). This association strongly indicated that these genotypes are suited to fibre production. Then group D comprised mainly hybrids of *E. grandis* and *E. camaldulensis,* which were strongly associated with *stem straightness*, *kappa number*, *basic density*, and *pulp yield*. This association strongly suggests that these genotypes were suited to the woodchip market. The remaining two groupings, A and C, are probably more intermediate type of genotypes.

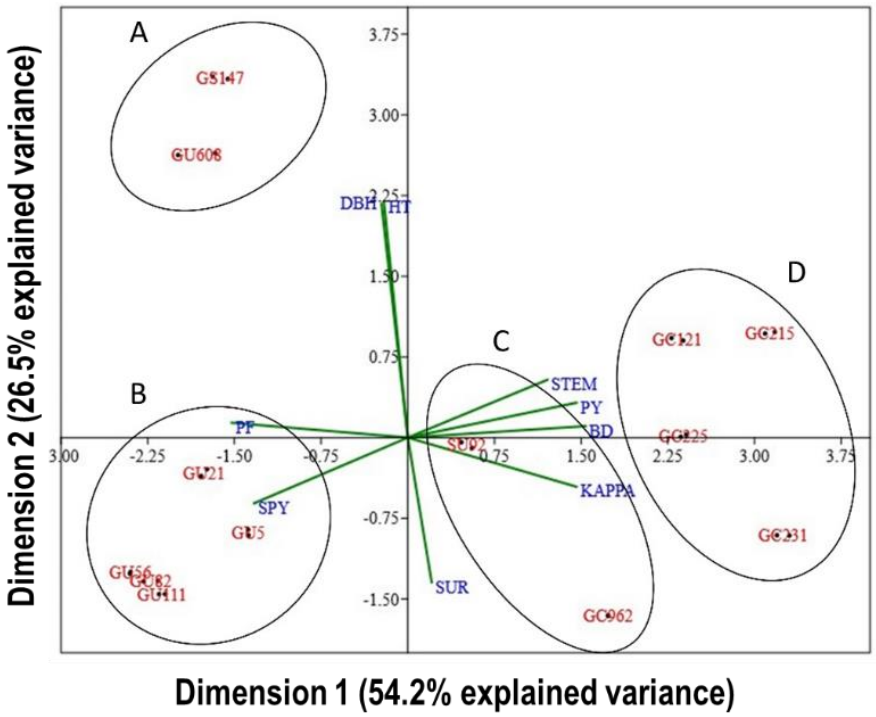


Figure 8.4 Cluster analysis of combined dataset of 13 genotypes of felled trees.

A dendrogram was also constructed using the combined dataset of the trial and the felled tree traits to reveal distance relationships amongst the 13 genotypes using the Euclidean distance calculation. The dendrogram also highlighted two major groups (Figure 8.5). Group A comprised mostly of different interspecific hybrids of *E. grandis* and *E. urophylla*, while Group B comprised mostly of different interspecific hybrids of *E. grandis* and *E. camaldulensis.*

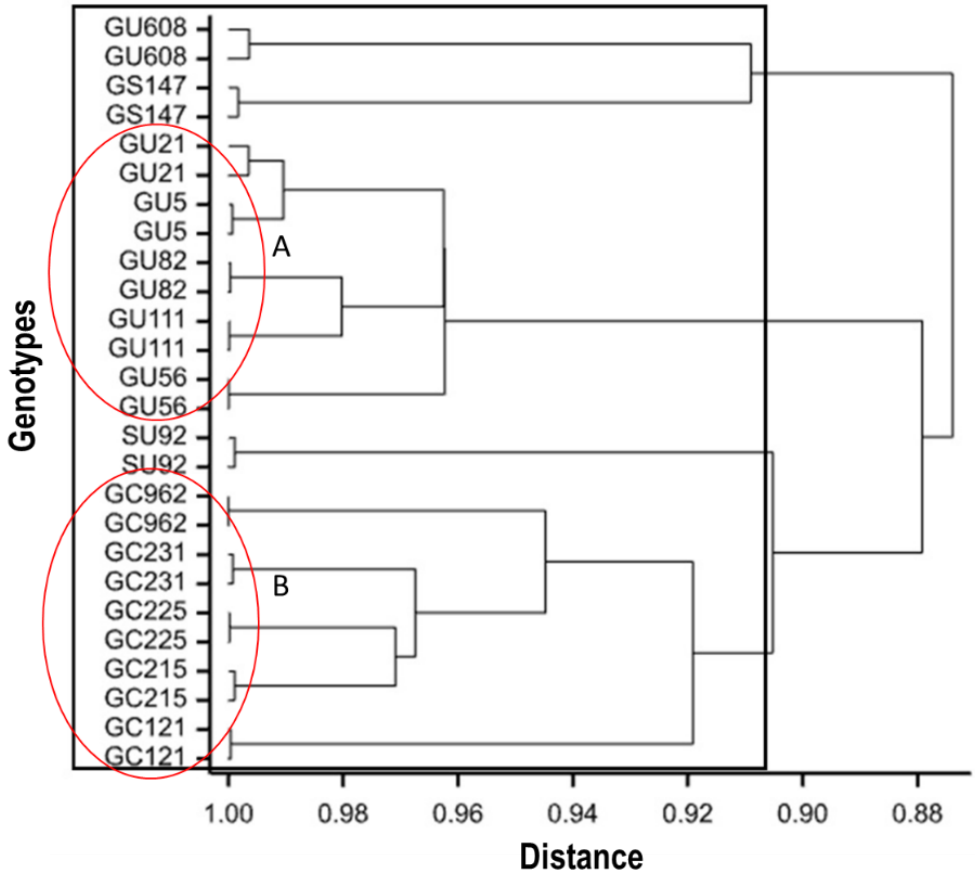


Figure 8.5 Dendrogram showing distance relationships between genotypes.

8.4.3 Relative ranking of genotypes

To gain some understanding of how the 13 genotypes (26 trees) performed relative to one another, the mean RPI was also calculated using the combined trial and felled tree trait dataset. In this incidence the weightings of the RPI were extracted from PC1 and PC2 of the PCA conducted on the combined dataset (Table 8.9). The RPIs showed that the interspecific hybrids of *E. grandis* with *E. camaldulensis* (G×C) ranked the highest, while the genotypes of the interspecific hybrids of *E. grandis* with *E. urophylla* (G×U) ranked towards the bottom of the ranking list.

Table 8.9 Ranking of the 13 genotypes of the felled tree population based on the Relative Performance Index.

Genotype name	Sample tree	RPI value	Rank
G×C121	1	219	1
	2	218	2
G×C215	1	210	3
	2	210	4
G×C225	1	205	5
	2	204	6
G×C231	1	203	7
	2	203	8
G×C962	1	201	9
	2	200	10
S×U92	1	199	11
	2	198	12
G×U56	1	197	13
	2	195	14
G×U111	1	194	15
	2	194	16
G×U82	1	192	17
	2	190	18
G×U5	1	189	19
	2	189	20
G×U21	1	185	21
	2	182	22
G×S147	1	180	23
	2	180	24
G×U608	1	175	25
	2	174	26

8.4.4 Genotypes selection process for the mined sand dunes of Richards Bay

In the last step of this study, the genotypes were assessed in terms of their appropriateness for fibre production for the pulp and paper industry, and the woodchip export market. Two EPIs were calculated for the genotypes. The one EPI was formulated to bring to the forefront genotypes that were suited to the fibre production market for the pulp and paper industry. To calculate this EPI, the RPI formula was adjusted by doubling the weight of the trait *screen pulp yield*. On the other hand, the EPI for the wood chip market was formulated to bring to the forefront genotypes that were suited to the woodchip export market by doubling the weight of the trait *basic density* in the RPI formula. Table 8.10 shows that the genotypes best suited to fibre production were different interspecific hybrids of *E. grandis* with *E. urophylla* (G×U), while genotypes best suited to the woodchip export market were different interspecific hybrids of *E. grandis* with *E. camaldulensis* (G×C).

Table 8.10 Ranking of the 13 genotypes for the pulp and paper industry and the woodchip export market.

Genotype for pulp and paper industry	Genotype for wood chip industry	EPI ranking
G×U82	G×C215	1
G×U56	G×C231	2
G×U21	G×C225	3
G×U5	G×C121	4
G×U111	G×C962	5
G×U608	G×S147	6
S×U92	S×U92	7
G×S147	G×U608	8
G×C962	G×U5	9
G×C225	G×U111	10
G×C121	G×U21	11
G×C231	G×U56	12

Genotype for pulp and paper industry	Genotype for wood chip industry	EPI ranking
G×C215	G×U82	13

8.5 Discussion

Through a stepwise approach, genotypes could be identified that have the potential for deployment on the mined sand dunes of Richards Bay. By applying the multivariate technique of PCA, the amount of variance retained in PCs could be determined and used to calculate RPIs of the different genotypes. These performance indexes were then used to rank and select genotypes suitable for the mined sand dunes of the Richards Bay area. This multivariate approach has been applied in a few instances in forestry in recent times. Couto et al. (2013) applied PCA and cluster analysis to select suitable *Eucalyptus* clones for bioenergy production. To increase the pulpwood production efficiency, wood anatomical characteristics of *E. camaldulensis*, planted in Thailand, were classified using PCA and cluster analysis (Nezu et al., 2021). The genetic variability and growth performance of eight *E. tereticornis* clones were studied using PCA (Sahoo & Kumar, 2022). Owino et al. (2020) measured seed quality variability among *Pinus patula* clonal seed orchards using cluster analysis and PCA. (Nezu et al., 2021).

By ranking the 70 genotypes based on the RPIs, calculated from trail measurements of *survival*, *DBH*, *height* and *stem straightness*, it was possible to show that the top performing genotypes were interspecific hybrids of *E. grandis* with *E. camaldulensis* (G×C), and *E. grandis* with *E. urophylla* (G×U). The 13 genotypes of the felled tree population were also ranked based on the RPIs using the measurements of *kappa number*, *pulpability factor*, *screen pulp yield*, *basic density* and *fibre yield*. RPI analysis revealed that the 13 genotypes of the felled tree population were the same genotypes that ranked at the top of the ranking of the 70 genotypes tested in this study. It thus made

sense that the 13 genotypes of the felled tree population were an appropriate collection of genotypes for deployment on the mined sand dunes.

When economic factors were integrated into the calculation of EPIs, the results clearly revealed a group of genotypes that was specific for the production of fibre for the pulp and paper industry. This group consisted of different interspecific hybrid clones of *E. grandis* and *E. urophylla* (G×U). Similarly, the EPIs also revealed a clear group of genotypes that produced dense wood that would be appropriate for woodchip production for the export market. These genotypes were different interspecific hybrid clones of *E. grandis* and *E. camaldulensis* (G×C). The two pure species *C. citriodora* ssp. *citriodora* and *C. henryi,* recommended by Gardner et al. (2007) for the Zululand coastal plains did not feature in the top rankings. Similarly, the interspecific hybrid of *E. grandis* × *E. longirostrata* recommended by Henson et al. (2008) for the Zululand coastal plains, also did not feature in the top rankings. It should, however, be noted that the relatively high ranking pure species *E. urophylla* (Au7 and Au9) and *C. equisetifolia* (Cas400 and Cas402) also warrant consideration, because they are deployed as seedlings and are substantially cheaper than clonal material (A. R. Griffin, 2014). Though systematic analyses of the performances of 70 genotypes, several *Eucalyptus* hybrids and a few pure species were identified with the potential for deployment on the mined sand dunes of Richards Bay.

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Chapter 9

Overall Discussion and Concluding Remarks

Richards Bay Minerals (RBM) is South Africa's largest mineral sands producer. Its principal operations are located just north of Richards Bay in KwaZulu-Natal. By dredging the coastal sand dunes to extract minerals, the "tailings" are shaped to reform dunes (Camp, 1990). These disturbed coastal sand dunes are relatively nutrient poor and do not support economical land use through forestry and agriculture, and are also of little benefit to the local community. Furthermore, they are a major source of pollution, polluting the air with widespread chemical laden dust (Li et al., 2014). The dust emissions have destroyed local floral and faunal biodiversity (Zhang & Moffat, 2015) and contaminated soil and water resources (Pourret et al., 2016). Because of the Mineral and Petroleum Resources Development Act No. 28 of 2022 (South African Government, 2022a), which compels mining companies to rehabilitate the land after mining operations had ceased, RMB embarked on a rehabilitation programme and decided to plant trees on the disturbed sand dunes. Planting tree species could help restore ecosystem functions of the mined sand dunes and also be a sustainable resource of wood to the local community (de Farias et al., 2016). Initially, the tree species *C. equisetifolia* was tested on the mined sand dunes. However, this wood species' low economic value was of little economic benefit to the local community (Letsoalo et al., 2005). Thus, RBM together with the NRE of the CSIR, undertook this project to identify tree genotypes that would be suitable for deployment on the mined sand dunes in the Richards Bay area.

9.1 Genotypes for mined sand dunes

Several genotypes of *Eucalyptus* were successfully identified after testing 70 genotypes in four trials. These were mostly *Eucalyptus* pure species, as well as interspecific hybrid clones of seed and clonal

origins. Although Gardner (2001) stated that *E. grandis* or its hybrids with *E. urophylla*, *E. camaldulensis* or *E. tereticornis* were not adequately adapted to the low productivity environments of the Zululand area, several genotypes of these species and hybrids were included in the study, because they are currently under investigation in other areas on the Zululand (Snedden et al., 2007). The pure species *C. citriodora* ssp. *citriodora* and *C. henryi* were also included in the collection of the 70 genotypes, because Gardner et al. (2007) showed that these species had the potential for high productivity of fibre and merchantable wood on the low productivity sites of the Zululand coastal plains. Hybrid genotypes of *E. grandis* × *E. longirostrata* were also included, because they showed promise for the coastal plains of Zululand (Henson et al., 2008).

In this longitudinal study, several traits (*survival*, *DBH*, *height*, *growth volume*, *stem quality*) were measured throughout the six years of tree growth since trial establishment. At the end of the study, additional properties that relate to wood and pulping properties were also measured (*kappa number*, *pulpability factor*, *screen pulp yield*, *basic density*, *fibre yield*, *coppicing ability*, and *pests and disease*), making up a total of 12 traits that were measured to facilitate the identification of suitable genotypes for deployment on the mined sand dunes. The absence of genetic by environmental interactions (GEI) made it possible to select genotypes that could be deployed on the entire study area, as the ranking of the performance of the genotypes did not differ significantly across aspect sites.

Results of growth traits showed highly positive correlations with *DBH*, as well as *height*, which was also demonstrated for the species of *Eucalyptus globulus* subsp. *bicostata, Eucalyptus cypellocarpa* and *Eucalyptus nobilis* (Komakech et al., 2007). However, there was a weak but positive correlation between growth and wood property traits, which was in line with studies performed on the interspecific hybrids between *E. urophylla* as maternal parent and *E. grandis* (Bouvet et al., 2020).

Through the application of a unique stepwise approach using Principal Component Analyses (PCAs) and the amount of variance retained in Principal Components (PCs), Relative Performance Indexes (RPIs) were formulated. These formulas were used to calculate each genotype's relative performance, which was then used to rank the genotypes in terms of the relative importance of the measured traits. The rankings revealed that all genotypes suitable for deployment on the mined sand dunes were interspecific hybrid genotypes. After identifying the top ranking genotypes, Economic Performance Indexes were formulated to identify genotypes for fibre production for the pulp and paper industry, as well as for the merchantable wood industry, in particular the wood chip export market. PCA and cluster analysis have also been successfully applied in forestry research to select suitable *Eucalyptus* clones for bioenergy production (Couto et al., 2013), to classify *E. camaldulensis* genotypes according to wood anatomical characteristics (Nezu et al., 2021), to determine the genetic variability and growth performance of *E. tereticornis* clones (Sahoo & Kumar, 2022), and to measure seed quality variability among *Pinus patula* clonal seed orchards (Owino et al., 2020).

Through these calculations it was possible to identify two main categories of interspecific hybrids. The one category mostly comprised different hybrid genotypes of *E. grandis* as the maternal parent with *E. urophylla* (G×U), while the other category consisted of different hybrid genotypes of *E. grandis* as maternal parent with *E. camaldulensis* (G×C). The *E. grandis* × *E. urophylla* hybrids are particularly suited for fibre production, while the *E. grandis* × *E. camaldulensis* hybrids are particularly suited for the woodchip export market, as mentioned by Gardner et al. (2006).

The results of this study to some extent contradict the suggestions made from other studies. The *E. grandis* hybrids in this study, particularly hybrids with *E. urophylla* and *E. camaldulensis,* have shown good potential for deployment on the mined sand dunes. This result contradicts the statement of Gardner (2001), who stated that these hybrids were not adequately adapted to these low productivity sites. However, it should be noted that the remark by Gardner (2001) was based on sites delineated

by rainfall and soil depth differences, whereas in this study the uniqueness of the site was based on terrain aspects and the proximity to the sea, which could explain the differences in performance of the hybrids. In addition, the expected association of *E. grandis* with disease did not emerge as problem in this study, as was found in an earlier study by Gardner (2001). This could possibly be explained by the good growth of the genotypes in this high rainfall study area. Furthermore, it was interesting to find that the recommended species *C. citriodora* ssp. *citriodora* and *C. henryi* (Gardner et al., 2007), as well as the *E. grandis* × *E. longirostrata* hybrid genotypes (Henson et al., 2008) did not appear in the top 20 genotype performance ranking. These species and hybrid probably were more sensitive to the salt-laden sea breezes and deficient nutrients in the soil, compared to the sites where they were originally studied.

9.2 Recommended approach to plantation establishment on mined sand dunes

With the identification of several genotypes that have the potential to thrive on the mined sand dunes of Richards Bay and support economic development of the local community, other considerations have to be taken into account before deployment. Plantation establishment is a costly endeavour (Thomas, 2009). Therefore, all aspects of plantation establishment should be considered by plantation managers. One of the important aspects that plantation managers take into account is the cost of material to be planted. It is advised that improved seed of well performing species should be procured, as seed is substantially cheaper than clonal material (A. R. Griffin, 2014). In the case where cost plays a major role, genotypes that are alternatives to the identified interspecific hybrid clones can be considered. Although genotypes that were identified as appropriate for deployment on the mined sand dunes were all interspecific hybrid clones, several seedling genotypes ranked in the top 20 of the trail rankings and could also be considered. These genotypes include the pure species *E. urophylla* (for example genotypes Au7 and Au9) and *C. equisetifolia* (for example genotypes Cas400 and Cas402).

Both *E. urophylla* and *C. equisetifolia* demonstrated excellent growth and therefore, have a role to play in commercial forestry in the Richards Bay area. Although the *Casuarina* ranked relatively low in the top 20 genotypes based on the RPI, this species could be an important inclusion to the recommended list, because of its nitrogen fixing ability which could rejuvenate the nutrient poor soils of the mined sand dunes (El-Lakany, 1991; Djogo, 1996). Furthermore, its high basic density makes it an excellent fuel wood source for the local community.

9.3 Considerations for the future

After measuring several traits over a 6-year period and through a process of systematic analysis of measurement data, several high productivity genotypes with the potential to be deployed on the mined sand dunes of Richards Bay, were successfully identified. These genotypes included several interspecific hybrid clones and pure species. In terms of further research, consideration should be given to improve the unimproved interspecific hybrid *E. grandis* × *E. tereticornis* (seedling source) and unimproved pure species *C. equisetifolia* and *E. urophylla.* These genotypes have demonstrated their potential for planting on the mined sand dunes. Finally, by planting suitable genotypes on the mined sand dunes in the Richards Bay area could provide support the economic development of the local community living in the surrounding areas.

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Appendixes

Appendix A: Permission letter to use the data for this project.

CSIR | touching lives through innovation

CSIR, Advanced Agriculture and Food
PO Box 395 Pretoria 0001 South Africa
Tel: +27 12 841 3669
Email: Mcho@csir.co.za

15 MARCH 2021

University of Free State (UFS)
Research Ethics Committee

Dear Madam/Sir,

REF: USE OF DATA COLLECTED FROM RICHARDSBAY CROP TRIALS FOR STUDY PURPOSES

I hereby give consent to Mr. Christopher Otim Komakech to use data collected in the Richards bay Crop Trial research conducted by CSIR for a period of six years beginning in 2006 for study purposes only. Mr Komatech participated in the data collection exercise. Data for tree species and clonal hybrid trials from our unit will be provided on condition that any publications from the study will not only acknowledge CSIR's contribution but will include CSIR's co-authorship. We would also like to receive correspondence regarding study progress/development.

Any assistance that will be accorded to Christopher Otim will be highly appreciated.

Yours faithfully

Prof. Moses A. Cho
Research Group Leader, Precision Agriculture (CSIR) and
Acting Impact Area Manager, Advanced Agriculture and Food Cluster.

www.csir.co.za

Appendix B: Department of Genetics, UFS, approval to undertaken the study

UNIVERSITY OF THE FREE STATE
UNIVERSITEIT VAN DIE VRYSTAAT
YUNIVESITHI YA FREISTATA

UFS·UV
NATURAL AND AGRICULTURAL SCIENCES
NATUUR- EN LANDBOUWETENSKAPPE

DECISION LETTER: DEPARTMENT OF GENETICS RESEARCH COMMITTEE

To: C. Komakech
Department of Genetics, University of the Free State.

From: The Chairperson: Department of Genetics Research Committee.
Date: 01/06/2021

Project Number: Res 09/2021
Project Title: Economically viable *Eucalyptus* species and hybrid clones for commercial afforestation of mined dune sands in the Richards Bay area of KwaZulu-Natal

This is to confirm that your project has been considered by the Departmental Research Committee. The decision is as follows:

a	The full proposal has been approved without modification.	
b	A resubmission of the full application is required for approval, with changes made at the discretion of the supervisor.	√
c	The application is rejected, based on the reasons outlined in the attached list.	

Note: It is the responsibility of the Principle Investigator to notify the Department of Genetics Research Committee if the project or title changes along with the date of the Faculty meeting where the title change has been approved. Documentation relevant to the study such as permits and ethics approvals should be submitted to the Department of Genetics Research Committee, within a month after it has been obtained.

Yours Sincerely,

R Rebello

R Rebello: The Chairperson: Department of Genetics Research Committee

JP Grobler: HOD Department of Genetics

205 Nelson Mandela Drive/Rylaan, Park West/Parkwes, Bloemfontein 9301, South Africa/Suid-Afrika
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Appendix C: Layout of the Steep, Flat and Inland-facing trials

Steep trail

RBM TRIAL 2: FIELD PLOT/TMT LAYOUT

REP 1

	PLT	TMT	PLT	TMT	PLT	TMT	PLT	TMT	PLT	TMT	PLT	TMT	PLT	TMT
BLK 1	1	33	10	61	11	3	20	56	21	41	30	67	31	23
	2	31	9	62	12	4	19	58	22	44	29	66	32	25
	3	32	8	64	13	2	18	57	23	45	28	68	33	22
	4	34	7	63	14	5	17	60	24	43	27	70	34	24
	5	35	6	65	15	1	16	59	25	42	26	69	35	21
BLK2	66	51	65	29	56	48	55	6	46	18	45	37	36	12
	67	52	64	30	57	50	54	9	47	19	44	38	37	11
	68	53	63	28	58	47	53	8	48	20	43	36	38	13
	69	55	62	27	59	46	52	7	49	17	42	40	39	15
	70	54	61	26	60	49	51	10	50	16	41	39	40	14

REP 2

BLK 1	71	61	80	28	81	36	90	57	91	10	100	34	101	13
	72	62	79	27	82	40	89	58	92	9	99	33	102	14
	73	65	78	29	83	37	88	56	93	8	98	35	103	15
	74	63	77	26	84	39	87	59	94	7	97	32	104	12
	75	64	76	30	85	38	86	60	95	6	96	31	105	11
BLK 2	136	22	135	51	126	1	125	47	116	42	115	68	106	19
	137	23	134	55	127	2	124	48	117	43	114	67	107	20
	138	21	133	52	128	3	123	46	118	41	113	66	108	16
	139	24	132	54	129	4	122	49	119	44	112	69	109	17
	140	25	131	53	130	5	121	50	120	45	111	70	110	18

REP 3

BLK 1	141	8	150	11	151	66	160	38	161	63	170	52	171	47
	142	9	149	12	152	69	159	39	162	64	169	51	172	46
	143	7	148	15	153	68	158	40	163	65	168	53	173	48
	144	10	147	14	154	70	157	37	164	62	167	54	174	49
	145	6	146	13	155	67	156	36	165	61	166	55	175	50
BLK 2	206	42	205	17	196	34	195	1	186	21	185	28	176	57
	207	41	204	16	197	33	194	5	187	22	184	26	177	58
	208	43	203	18	198	35	193	2	188	23	183	27	178	59
	209	45	202	20	199	32	192	3	189	25	182	29	179	56
	210	44	201	19	200	31	191	4	190	24	181	30	180	60

REP 4

BLK 1	211	52	220	21	221	29	230	57	231	44	240	12	241	6
	212	51	219	22	222	30	229	60	232	42	239	13	242	7
	213	55	218	24	223	28	228	56	233	43	238	11	243	8
	214	54	217	23	224	27	227	58	234	45	237	14	244	10
	215	53	216	25	225	26	226	59	235	41	236	15	245	9
BLK 2	276	20	275	68	266	1	265	32	256	38	255	47	246	62

277	17	274	67	267	2	264	33	257	37	254	46	247	64
278	16	273	66	268	3	263	34	258	36	253	48	248	61
279	19	272	69	269	5	262	35	259	39	252	49	249	63
280	18	271	70	270	4	261	31	260	40	251	50	250	65

REP 5

BLK 1	281	63	290	31	291	16	300	44	301	21	310	29	311	11
	282	64	289	34	292	18	299	43	302	22	309	28	312	12
	283	65	288	33	293	17	298	42	303	25	308	27	313	15
	284	62	287	32	294	19	297	41	304	23	307	26	314	14
	285	61	286	35	295	20	296	45	305	24	306	30	315	13
BLK 2	346	6	345	57	336	52	335	39	326	68	325	1	316	49
	347	9	344	56	337	53	334	38	327	67	324	2	317	48
	348	10	343	58	338	55	333	37	328	66	323	5	318	46
	349	7	342	59	339	54	332	36	329	69	322	4	319	50
	350	8	341	60	340	51	331	40	330	70	321	3	320	47

REP 6

BLK 1	351	33	360	37	361	23	370	49	371	7	380	29	381	16
	352	32	359	38	362	24	369	50	372	6	379	28	382	20
	353	31	358	39	363	25	368	48	373	8	378	26	383	19
	354	34	357	40	364	22	367	47	374	9	377	27	384	17
	355	35	356	36	365	21	366	46	375	10	376	30	385	18
BLK 2	416	2	415	57	406	51	405	44	396	11	395	67	386	63
	417	4	414	56	407	54	404	41	397	12	394	68	387	64
	418	1	413	58	408	53	403	42	398	13	393	69	388	65
	419	3	412	59	409	52	402	45	399	15	392	70	389	62
	420	5	411	60	410	55	401	43	400	14	391	66	390	61

REP 7

BLK 1	421	31	430	27	431	23	440	40	441	51	450	10	451	4
	422	33	429	28	432	22	439	37	442	52	449	9	452	5
	423	32	428	26	433	21	438	36	443	53	448	8	453	3
	424	35	427	29	434	25	437	39	444	54	447	6	454	2
	425	34	426	30	435	24	436	38	445	55	446	7	455	1
BLK 2	486	13	485	42	476	59	475	63	466	46	465	67	456	17
	487	12	484	43	477	58	474	62	467	50	464	66	457	16
	488	11	483	45	478	57	473	61	468	47	463	68	458	18
	489	14	482	44	479	56	472	64	469	48	462	70	459	19
	490	15	481	41	480	60	471	65	470	49	461	69	460	20

REP 8

BLK 1	491	69	500	12	501	63	510	52	511	1	520	29	521	32
	492	68	499	11	502	62	509	51	512	3	519	28	522	31
	493	66	498	13	503	61	508	53	513	2	518	27	523	35
	494	67	497	14	504	64	507	54	514	5	517	26	524	33
	495	70	496	15	505	65	506	55	515	4	516	30	525	34
BLK 2	556	16	555	39	546	49	545	7	536	24	535	58	526	44
	557	20	554	38	547	47	544	6	537	23	534	57	527	43
	558	17	553	37	548	46	543	10	538	22	533	56	528	42

559	19	552	40	549	50	542	8	539	21	532	59	529	41
560	18	551	36	550	48	541	9	540	25	531	60	530	45

REP 9

BLK 1	561	68	570	27	571	7	580	43	581	17	590	63	591	39
	562	67	569	26	572	6	579	41	582	19	589	64	592	38
	563	69	568	28	573	8	578	42	583	20	588	62	593	37
	564	66	567	29	574	9	577	44	584	16	587	61	594	36
	565	70	566	30	575	10	576	45	585	18	586	65	595	40
BLK 2	626	47	625	12	616	3	615	24	606	57	605	33	596	51
	627	46	624	11	617	5	614	23	607	56	604	32	597	55
	628	49	623	13	618	2	613	22	608	58	603	31	598	52
	629	48	622	14	619	1	612	21	609	59	602	34	599	53
	630	50	621	15	620	4	611	25	610	60	601	35	600	54

REP 10

BLK 1	631	28	640	23	641	49	650	58	651	31	660	68	661	17
	632	27	639	24	642	48	649	57	652	32	659	67	662	16
	633	26	638	25	643	47	648	60	653	35	658	66	663	18
	634	29	637	21	644	46	647	59	654	33	657	70	664	19
	635	30	636	22	645	50	646	56	655	34	656	69	665	20
BLK 2	696	62	695	12	686	4	685	9	676	52	675	38	666	44
	697	61	694	11	687	5	684	10	677	54	674	36	667	45
	698	63	693	13	688	3	683	7	678	51	673	39	668	41
	699	64	692	14	689	1	682	8	679	55	672	37	669	43
	700	65	691	15	690	2	681	6	680	53	671	40	670	42

Flat trial

RBM TRIAL 3: FIELD PLOT/TMT LAYOUT

REP 1

	PLT	**TMT**	**PLT**	**TMT**	**PLT**	**TMT**	**PLT**	**TMT**	**PLT**	**TMT**	**PLT**	**TMT**	**PLT**	**TMT**
BLK 1	1	13	10	37	11	68	20	48	21	2	30	10	31	63
	2	12	9	38	12	69	19	50	22	1	29	8	32	64
	3	11	8	40	13	70	18	47	23	4	28	7	33	65
	4	14	7	39	14	67	17	46	24	5	27	6	34	62
	5	15	6	36	15	66	16	49	25	3	26	9	35	61
BLK2	66	52	65	42	56	27	55	60	46	17	45	25	36	32
	67	51	64	41	57	26	54	56	47	16	44	23	37	35
	68	55	63	45	58	30	53	57	48	18	43	22	38	31
	69	53	62	43	59	28	52	58	49	20	42	21	39	34
	70	54	61	44	60	29	51	59	50	19	41	24	40	33

REP 2

BLK 1	71	63	80	31	81	37	90	18	91	60	100	27	101	3
	72	64	79	33	82	36	89	17	92	58	99	30	102	5
	73	62	78	32	83	38	88	20	93	59	98	26	103	2
	74	61	77	34	84	40	87	16	94	57	97	28	104	4
	75	65	76	35	85	39	86	19	95	56	96	29	105	1
BLK 2	136	46	135	44	126	67	125	53	116	12	115	8	106	23

137	50	134	43	127	68	124	52	117	13	114	7	107	22
138	47	133	42	128	70	123	51	118	11	113	6	108	21
139	48	132	41	129	66	122	55	119	14	112	10	109	25
140	49	131	45	130	69	121	54	120	15	111	9	110	24

REP 3

BLK 1	141	17	150	31	151	15	160	65	161	44	170	54	171	70
	142	18	149	32	152	11	159	62	162	41	169	53	172	69
	143	19	148	33	153	14	158	61	163	42	168	55	173	66
	144	20	147	35	154	13	157	64	164	43	167	52	174	68
	145	16	146	34	155	12	156	63	165	45	166	51	175	67
BLK 2	206	8	205	57	196	5	195	37	186	29	185	48	176	22
	207	10	204	56	197	2	194	36	187	30	184	50	177	21
	208	7	203	58	198	1	193	40	188	26	183	46	178	23
	209	9	202	60	199	4	192	38	189	27	182	47	179	24
	210	6	201	59	200	3	191	39	190	28	181	49	180	25

REP 4

BLK 1	211	41	220	6	221	24	230	67	231	4	240	58	241	64
	212	42	219	7	222	25	229	66	232	3	239	57	242	63
	213	43	218	8	223	23	228	68	233	2	238	56	243	65
	214	45	217	9	224	22	227	69	234	1	237	60	244	62
	215	44	216	10	225	21	226	70	235	5	236	59	245	61
BLK 2	276	46	275	38	266	53	265	31	256	27	255	16	246	12
	277	49	274	39	267	52	264	32	257	29	254	17	247	11
	278	47	273	37	268	51	263	34	258	30	253	20	248	14
	279	48	272	40	269	54	262	33	259	26	252	19	249	15
	280	50	271	36	270	55	261	35	260	28	251	18	250	13

REP 5

BLK 1	281	53	290	28	291	1	300	24	301	34	310	7	311	63
	282	51	289	27	292	4	299	22	302	33	309	8	312	62
	283	52	288	26	293	2	298	25	303	32	308	6	313	61
	284	54	287	29	294	5	297	23	304	31	307	9	314	65
	285	55	286	30	295	3	296	21	305	35	306	10	315	64
BLK 2	346	46	345	43	336	12	335	70	326	58	325	17	316	37
	347	49	344	42	337	14	334	67	327	60	324	18	317	38
	348	47	343	41	338	15	333	68	328	57	323	16	318	39
	349	50	342	44	339	11	332	66	329	56	322	19	319	36
	350	48	341	45	340	13	331	69	330	59	321	20	320	40

REP 6

BLK 1	351	10	360	32	361	48	370	52	371	69	380	56	381	4
	352	7	359	34	362	49	369	51	372	66	379	57	382	3
	353	6	358	35	363	47	368	55	373	68	378	58	383	2
	354	9	357	31	364	50	367	53	374	67	377	60	384	1
	355	8	356	33	365	46	366	54	375	70	376	59	385	5
BLK 2	416	26	415	44	406	63	405	17	396	38	395	12	386	23
	417	29	414	42	407	62	404	16	397	37	394	11	387	21
	418	27	413	41	408	61	403	18	398	39	393	15	388	22

419	28	412	45	409	64	402	20	399	36	392	13	389	25
420	30	411	43	410	65	401	19	400	40	391	14	390	24

REP 7

BLK 1	421	42	430	32	431	49	440	27	441	39	450	20	451	58
	422	43	429	34	432	50	439	30	442	36	449	19	452	59
	423	44	428	35	433	48	438	26	443	37	448	16	453	60
	424	45	427	31	434	46	437	29	444	38	447	18	454	56
	425	41	426	33	435	47	436	28	445	40	446	17	455	57
BLK 2	486	12	485	9	476	68	475	54	466	1	465	62	456	24
	487	11	484	8	477	67	474	55	467	2	464	63	457	21
	488	13	483	7	478	66	473	53	468	3	463	61	458	22
	489	14	482	6	479	69	472	52	469	5	462	64	459	25
	490	15	481	10	480	70	471	51	470	4	461	65	460	23

REP 8

BLK 1	491	52	500	31	501	48	510	12	511	39	520	2	521	18
	492	53	499	35	502	47	509	11	512	38	519	5	522	19
	493	51	498	32	503	46	508	13	513	37	518	4	523	17
	494	54	497	34	504	49	507	14	514	36	517	1	524	16
	495	55	496	33	505	50	506	15	515	40	516	3	525	20
BLK 2	556	21	555	68	546	44	545	64	536	8	535	27	526	56
	557	25	554	69	547	43	544	65	537	7	534	28	527	57
	558	24	553	66	548	42	543	63	538	6	533	29	528	58
	559	23	552	67	549	41	542	62	539	10	532	26	529	59
	560	22	551	70	550	45	541	61	540	9	531	30	530	60

REP 9

BLK 1	561	31	570	62	571	1	580	21	581	70	590	57	591	11
	562	35	569	61	572	4	579	22	582	66	589	59	592	14
	563	32	568	64	573	2	578	24	583	67	588	56	593	12
	564	33	567	63	574	5	577	23	584	69	587	60	594	15
	565	34	566	65	575	3	576	25	585	68	586	58	595	13
BLK 2	626	54	625	27	616	47	615	42	606	17	605	40	596	7
	627	52	624	30	617	49	614	43	607	19	604	39	597	8
	628	51	623	29	618	50	613	44	608	20	603	38	598	9
	629	55	622	26	619	48	612	45	609	18	602	37	599	6
	630	53	621	28	620	46	611	41	610	16	601	36	600	10

REP 10

BLK 1	631	42	640	65	641	3	650	51	651	60	660	68	661	7
	632	43	639	62	642	4	649	54	652	59	659	67	662	8
	633	44	638	61	643	5	648	52	653	58	658	70	663	9
	634	45	637	64	644	2	647	53	654	57	657	69	664	6
	635	41	636	63	645	1	646	55	655	56	656	66	665	10
BLK 2	696	17	695	24	686	31	685	36	676	27	675	12	666	46
	697	18	694	23	687	35	684	40	677	30	674	15	667	50
	698	19	693	22	688	32	683	37	678	28	673	13	668	49

699	16	692	21	689	33	682	38	679	29	672	11	669	48
700	20	691	25	690	34	681	39	680	26	671	14	670	47

Inland-facing trial

RBM TRIAL 4: FIELD PLOT/TMT LAYOUT

REP 1

	PLT	TMT	PLT	TMT	PLT	TMT	PLT	TMT	PLT	TMT	PLT	TMT	PLT	TMT
BLK 1	1	6	10	27	11	16	20	41	21	48	30	3	31	67
	2	10	9	28	12	20	19	43	22	50	29	4	32	66
	3	8	8	26	13	17	18	42	23	47	28	5	33	69
	4	7	7	29	14	18	17	45	24	49	27	2	34	68
	5	9	6	30	15	19	16	44	25	46	26	1	35	70
BLK2	66	12	65	36	56	57	55	24	46	35	45	63	36	52
	67	13	64	39	57	60	54	21	47	32	44	62	37	51
	68	11	63	37	58	58	53	22	48	31	43	64	38	53
	69	14	62	38	59	56	52	23	49	33	42	61	39	54
	70	15	61	40	60	59	51	25	50	34	41	65	40	55

REP 2

BLK 1	71	13	80	57	81	7	90	22	91	46	100	61	101	42
	72	12	79	56	82	10	89	23	92	48	99	64	102	45
	73	11	78	60	83	6	88	24	93	47	98	62	103	41
	74	14	77	59	84	8	87	25	94	49	97	63	104	43
	75	15	76	58	85	9	86	21	95	50	96	65	105	44
BLK 2	136	37	135	69	126	1	125	29	116	16	115	32	106	54
	137	36	134	70	127	4	124	27	117	17	114	31	107	53
	138	38	133	68	128	2	123	28	118	18	113	33	108	52
	139	40	132	66	129	5	122	26	119	19	112	35	109	51
	140	39	131	67	130	3	121	30	120	20	111	34	110	55

REP 3

BLK 1	141	33	150	2	151	8	160	37	161	46	170	21	171	29
	142	32	149	3	152	9	159	38	162	47	169	25	172	28
	143	31	148	1	153	10	158	36	163	49	168	23	173	26
	144	34	147	4	154	7	157	39	164	50	167	22	174	27
	145	35	146	5	155	6	156	40	165	48	166	24	175	30
BLK 2	206	53	205	58	196	42	195	68	186	11	185	20	176	63
	207	51	204	57	197	43	194	67	187	15	184	17	177	62
	208	52	203	56	198	45	193	66	188	12	183	16	178	61
	209	54	202	59	199	44	192	69	189	13	182	18	179	64
	210	55	201	60	200	41	191	70	190	14	181	19	180	65

REP 4

BLK 1	211	21	220	54	221	33	230	37	231	11	240	2	241	17
	212	23	219	55	222	32	229	38	232	13	239	5	242	20
	213	22	218	53	223	31	228	36	233	12	238	4	243	16
	214	24	217	52	224	34	227	39	234	15	237	1	244	18
	215	25	216	51	225	35	226	40	235	14	236	3	245	19
BLK 2	276	41	275	67	266	48	265	30	256	9	255	63	246	59

277	44	274	68	267	46	264	26	257	8	254	62	247	60
278	42	273	69	268	47	263	27	258	7	253	61	248	58
279	43	272	66	269	49	262	28	259	10	252	64	249	56
280	45	271	70	270	50	261	29	260	6	251	65	250	57

REP 5

BLK 1	281	29	290	35	291	40	300	13	301	45	310	4	311	10
	282	28	289	34	292	39	299	14	302	42	309	5	312	8
	283	27	288	33	293	38	298	11	303	41	308	1	313	7
	284	26	287	32	294	37	297	12	304	43	307	3	314	6
	285	30	286	31	295	36	296	15	305	44	306	2	315	9
BLK 2	346	46	345	23	336	18	335	59	326	64	325	51	316	70
	347	47	344	22	337	17	334	58	327	63	324	52	317	67
	348	48	343	21	338	16	333	57	328	62	323	53	318	66
	349	49	342	24	339	19	332	56	329	61	322	54	319	68
	350	50	341	25	340	20	331	60	330	65	321	55	320	69

REP 6

BLK 1	351	32	360	62	361	67	370	56	371	53	380	17	381	27
	352	31	359	61	362	66	369	57	372	52	379	16	382	28
	353	33	358	63	363	68	368	58	373	51	378	18	383	26
	354	34	357	64	364	69	367	60	374	54	377	20	384	29
	355	35	356	65	365	70	366	59	375	55	376	19	385	30
BLK 2	416	22	415	41	406	7	405	13	396	5	395	37	386	50
	417	21	414	44	407	6	404	14	397	4	394	40	387	48
	418	23	413	42	408	9	403	15	398	1	393	38	388	47
	419	25	412	43	409	8	402	11	399	3	392	36	389	46
	420	24	411	45	410	10	401	12	400	2	391	39	390	49

REP 7

BLK 1	421	13	430	51	431	17	440	8	441	59	450	39	451	48
	422	12	429	52	432	18	439	7	442	58	449	38	452	47
	423	11	428	53	433	19	438	6	443	57	448	37	453	46
	424	14	427	55	434	20	437	9	444	56	447	36	454	49
	425	15	426	54	435	16	436	10	445	60	446	40	455	50
BLK 2	486	22	485	27	476	64	475	33	466	45	465	3	456	69
	487	24	484	30	477	63	474	32	467	43	464	4	457	67
	488	23	483	26	478	62	473	31	468	42	463	5	458	66
	489	25	482	28	479	65	472	34	469	41	462	2	459	70
	490	21	481	29	480	61	471	35	470	44	461	1	460	68

REP 8

BLK 1	491	26	500	47	501	33	510	23	511	37	520	7	521	3
	492	28	499	48	502	32	509	22	512	36	519	6	522	2
	493	27	498	46	503	31	508	21	513	38	518	8	523	5
	494	29	497	49	504	34	507	24	514	40	517	9	524	1
	495	30	496	50	505	35	506	25	515	39	516	10	525	4
BLK 2	556	63	555	13	546	53	545	17	536	68	535	42	526	58
	557	61	554	11	547	52	544	16	537	67	534	41	527	57
	558	62	553	12	548	51	543	18	538	66	533	45	528	56

559	64	552	14	549	54	542	19	539	69	532	43	529	60
560	65	551	15	550	55	541	20	540	70	531	44	530	59

REP 9

BLK 1	561	11	570	66	571	43	580	3	581	17	590	37	591	27
	562	13	569	69	572	42	579	5	582	19	589	38	592	28
	563	12	568	67	573	41	578	2	583	16	588	36	593	29
	564	15	567	70	574	44	577	1	584	18	587	39	594	26
	565	14	566	68	575	45	576	4	585	20	586	40	595	30
BLK 2	626	51	625	62	616	46	615	23	606	7	605	34	596	58
	627	54	624	61	617	47	614	24	607	6	604	33	597	57
	628	52	623	63	618	49	613	22	608	9	603	31	598	56
	629	53	622	65	619	48	612	21	609	8	602	32	599	60
	630	55	621	64	620	50	611	25	610	10	601	35	600	59

REP 10

BLK 1	631	57	640	42	641	52	650	2	651	8	660	21	661	63
	632	59	639	41	642	51	649	5	652	6	659	23	662	62
	633	60	638	43	643	55	648	4	653	9	658	22	663	61
	634	56	637	44	644	54	647	3	654	10	657	24	664	64
	635	58	636	45	645	53	646	1	655	7	656	25	665	65
BLK 2	696	33	695	37	686	17	685	49	676	28	675	67	666	13
	697	32	694	39	687	16	684	47	677	29	674	68	667	12
	698	31	693	36	688	19	683	46	678	27	673	70	668	11
	699	34	692	38	689	18	682	50	679	26	672	66	669	14
	700	35	691	40	690	20	681	48	680	30	671	69	670	15

Appendix D: Extract of DBH and height measurements of Sea-facing trial replication 1

	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
1	REP	BLOCK	GROUP	PLOT	GENOTYPE	2 Wks	4 Wks	12 M	Dbh 12 M	Ht 12 M	Vol 12 M	12 M Stem	12 M Com	36 M	36 M Dbh	36 M Ht	Vol 36 M	36 M Stem	36 M Com	72 M	72 M Dbh	72 M Ht	Vol 72 M	72 M Stem	72 M Com
38	9	2	1	625	1	1	1	1	2,75	2,6	**0,000210**	3		1	5,50	5,1	**0,002378**	3		1	11,50	10,7	**0,031655**	5	
39	10	2	1	691	5	1	1	1	6,00	4,0	**0,002013**	5		1	12,00	11,2	**0,036908**	6		1	21,30	19,7	**0,271922**	7	
40	10	2	1	692	3	1	1	1	2,15	3,0	**0,000159**	5		1	4,30	6,0	**0,001799**	5		1	5,70	4,5	**0,002142**	5	
41	10	2	1	693	1	1	1	1	2,20	3,1	**0,000174**	5		1	4,40	6,2	**0,001978**	6		1	9,30	8,7	**0,015162**	6	
42	10	2	1	694	2	1	1	1	3,85	4,1	**0,000831**	5		1	7,70	8,2	**0,009417**	6		1	16,00	15,3	**0,104673**	7	
43	10	2	1	695	4	1	*	1	1,70	2,9	**0,000091**	3		1	3,40	5,7	**0,001027**	3		1	4,00	7,2	**0,002009**	3	
44	1	1	2	6	7	1	1	1	1,55	1,8	**0,000037**	2		1	3,10	3,5	**0,000423**	2		1	10,10	8,1	**0,016249**	2	
45	1	1	2	7	9	1	1	1	2,15	2,0	**0,000089**	2		1	4,30	4,0	**0,001009**	2		1	10,50	8,8	**0,019826**	4	
46	1	1	2	8	8	1	1	1	3,45	2,7	**0,000355**	3		1	6,90	5,3	**0,004022**	3		1	8,40	7,8	**0,010503**	3	
47	1	1	2	9	10	*	*	1	0,80	0,6	**0,000002**	1		1	1,00	1,0	**0,000007**	1		1	2,00	2,5	**0,000105**	2	
48	1	1	2	10	6	*	*	1	0,50	0,5	**0,000001**	1		1	1,00	1,0	**0,000007**	1		1	2,00	2,5	**0,000105**	1	
49	2	2	2	131	7	1	1	1	2,35	2,6	**0,000156**	4		1	4,70	5,2	**0,001764**	4		1	7,30	6,1	**0,005525**	4	
50	2	2	2	132	8	1	1	1	1,85	1,7	**0,000049**	4		1	3,70	3,3	**0,000561**	4		1	6,80	5,9	**0,004547**	5	
51	2	2	2	133	9	1	1	1	1,45	2,0	**0,000039**	2		1	2,90	4,0	**0,000445**	2		1	6,50	6,5	**0,004755**	2	
52	2	2	2	134	10	1	1	1	1,50	1,5	**0,000028**	2		1	3,00	3,0	**0,000317**	2		1	5,60	4,9	**0,002331**	3	
53	2	2	2	135	6	1	1	1	1,00	1,0	**0,000007**	2		1	2,00	2,0	**0,000077**	2		1	2,00	3,5	**0,000170**	3	
54	3	1	2	171	8	1	1	1	4,20	3,7	**0,000843**	4		1	8,40	7,3	**0,009555**	4		1	12,90	11,9	**0,046762**	5	
55	3	1	2	172	9	1	1	1	3,85	3,5	**0,000649**	3		1	7,70	6,9	**0,007360**	3		1	11,00	10,4	**0,027717**	5	
56	3	1	2	173	10	1	1	1	3,90	3,6	**0,000709**	4		1	7,80	7,2	**0,008033**	5		1	13,50	12,0	**0,052007**	5	
57	3	1	2	174	7	1	1	1	2,95	2,8	**0,000277**	3		1	5,90	5,6	**0,003144**	3		1	9,10	8,1	**0,013088**	4	
58	4	1	2	241	9	1	1	1	4,25	3,6	**0,000830**	4		1	8,50	7,1	**0,009412**	6		1	15,10	14,4	**0,085126**	6	
59	4	1	2	242	10	1	1	1	1,10	2,0	**0,000022**	1		1	2,20	4,0	**0,000251**	1		1	2,00	3,5	**0,000170**	3	
60	4	1	2	243	8	1	1	1	1,95	2,3	**0,000089**	2		1	3,90	4,6	**0,001005**	2		1	7,20	6,1	**0,005370**	2	
61	4	1	2	244	7	1	*	1	1,00	1,5	**0,000012**	1		1	2,00	3,0	**0,000137**	1		1	6,80	5,5	**0,004114**	2	
62	4	1	2	245	6	1	*	1	1,00	1,0	**0,000007**	1		1	2,00	2,0	**0,000077**	1		1	2,00	3,5	**0,000170**	2	
63	5	1	2	291	7	1	1	1	1,00	1,0	**0,000007**	1		1	2,00	2,0	**0,000077**	1		1	5,00	3,5	**0,001140**	3	
64	5	1	2	292	8	1	1	1	2,55	2,2	**0,000145**	4		1	5,10	4,4	**0,001647**	6		1	9,60	8,9	**0,016729**	6	
65	5	1	2	293	9	1	1	1	4,70	4,1	**0,001257**	4		1	9,40	8,2	**0,014246**	4		1	13,30	12,6	**0,054058**	6	
66	5	1	2	295	10	1	1	1	2,90	1,9	**0,000148**	4		1	5,80	3,7	**0,001679**	4		1	6,80	5,2	**0,003797**	4	
67	6	2	2	391	9	*	*	1	0,80	2,4	**0,000014**	1		1	1,60	4,7	**0,000163**	1		1	2,00	3,5	**0,000170**	3	

... Genotype means 36mth | Trial and group means 72mth | Genotype means 72mth