# Environmental Factors affecting Wood Properties of *Eucalyptus* spp. grown on the Zululand Coastal Plain and along the Mpumalanga Escarpment of South Africa.

By

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# Abstract

The environmental factors affecting wood property formation of *Eucalyptus* spp. trees in two distinct geographic areas within South Africa were studied.

Wood property data for trees from 43 sites (26 in Zululand and 17 in Mpumalanga) were collected from work conducted at the Forest and Forest Products Research Centre (FFPRC) at the CSIR (Council for Scientific and Industrial Research) in Durban. The wood properties considered included screened pulp yield, fibre length, wood density and active alkali chemical consumption during pulping. The effect of environmental factors on growth rate (expressed as Site Index at a base age of 5 years) was also measured.

A detailed site description for each forest compartment was carried out. Detailed annual and monthly rainfall and minimum and maximum temperature estimates were calculated for each site by interpolating long term means of these variables by splining using the software package Anusplin. These estimates of climatic factors were validated by comparison to the data published in the South African Atlas of Agrohydrology and -Climatology. The outputs of the Anusplin model were used to derive surrogate bioclimatic parameters for each site using the computer program Bioclim. These parameters are considered as better descriptors of the energy-water balance experienced by the plant than normal measures of climate such as mean monthly or annual precipitation. Soil characteristics were measured on samples taken from the individual sites.

The effects of these environmental and bioclimatic variables on wood properties were analysed using appropriate statistical techniques. Multiple regression models were used to predict wood properties and it is suggested that this approach could form part of a fibre management system.

Wood property prediction models incorporating climate (and bioclimate) alone were preferred to those including soil data as no further site data are required. The effect of edaphic factors was considered to describe any further variation not accounted for by bioclimate alone. Particle size distribution of the soil, as an indication of the water holding capacity of that soil, was not found to effect wood properties or growth significantly. A weak influence of organic matter content in the topsoil on wood density was noted in Mpumalanga. In Zululand, a multiple linear regression using both rainfall of the wettest quarter and mean diurnal temperature range as inputs yielded the best predictive model for growth rate. In this region a combination of precipitation seasonality and mean diurnal temperature range gave the best linear regression model describing variation in screened pulp yield and fibre length. In Mpumalanga effective rooting depth was found to have a pervasive effect on plant development. Solar radiation (as a measure of energy supply), calculated from a function of latitude, aspect, slope and time of year, was also found to significantly affect the growth rate and SPY of plant material in Mpumalanga. Measures of temperature in both geographic regions were found to significantly affect wood density.

*Key Words: Eucalyptus spp., wood properties, site classification, climate, bioclimate, soil, Anusplin, multiple linear regression.*

# Preface

I, the undersigned author, state that experimental work described in this dissertation represents original work that has not otherwise been submitted in any form for any degree or diploma to any tertiary institution. Where use has been made of the work of others it is duly acknowledged in the text.

Frank Leo Venter

Signed this 17th day of December 2003 at Durban.

# Acknowledgements

My ultimate gratitude in everything goes to Jesus Christ, my Saviour, Friend and Shepherd of my soul.

"He is the image of the invisible God, the firstborn over all creation. For by Him all things were created: things in heaven and on earth, visible and invisible, whether thrones or powers or rulers or authorities; all things were created by him and for him. He is before all things and in him all things all together."

*Colossians 1:15-17* (NIV)

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# Table of Contents

# List of Figures

# List of Tables

# List of Symbols used for Variables

| | |
|---|---|
| AA | Active Alkali Absorption (%) |
| ADT/ha | Air Dry Tons (kg) per Hectare |
| AGE | Age of trees at which they were felled (years) |
| CLAY_B | Clay content in the sub-soil (%) |
| DEPTH_CLAS | Soil depth class (1 – deep; 0 – shallow) |
| DBH | Diameter (cm) of tree stem at Breast Height (~1.3m) over bark |
| DIUR_RANG | Mean Diurnal Temperature Range (°C) |
| ERD | Effective Rooting Depth of soil (cm) |
| FL_WM | Weighted Mean Fibre Length (mm) |
| MAP | Mean Annual Precipitation (mm) |
| MAT | Mean Annual Temperature (°C) |
| OM_A | Organic Matter content of the topsoil (%) |
| PREC_DQ | Precipitation of the Driest Quarter (mm) |
| PREC_SEAS | Precipitation Seasonality (Coefficient of Variation %) |
| PREC_WQ | Precipitation of the Wettest Quarter (mm) |
| SI | Site Index (m), dominant height of trees at reference age |
| SOL_RAD | Average Solar Radiation ($MJ/m^2/day$) |
| SPY | Screened Pulp Yield (%) |
| TEMP_ANN_R | Annual Temperature Range (°C) |
| TEMP_SEAS | Temperature Seasonality (Coefficient of Variation %) |
| TEMP_WQ | Average Temperature of Wettest Quarter (°C) |
| WMD | Weighted Mean Density ($kg/m^3$) |

# Chapter One

# General Introduction

Traditionally, the production of eucalyptus timber for pulping and papermaking in South Africa has focused on producing greater volumes of wood. This has resulted in a number of site-growth studies that have focused on developing models for predicting volume yields for different species or hybrid clones growing under different conditions. This involves site-growth studies where tree growth is related to site factors influencing tree response.

More recently, the focus of research in the timber industry has changed direction. Trees and stands of trees are established with the goal of optimizing the fibre yield. Du Plessis (2002) states that "the knowledge of site quality and its influence on tree growth, wood and fibre properties is of strategic importance to the forestry industry in South Africa." The processing of wood involving the extraction of lignin and other impurities and the production of paper with good fibre characteristics is an expensive process. Matching processing conditions to raw material properties can reduce production costs through improved pulp yield and lower energy and chemical requirements (Clarke, 1999). Alternatively, pulpwood of varying properties can be blended to produce more consistent products. Pulp mills often receive a wide range of fibre types in terms of basic densities, wood age and geographic origin. Since raw material variability directly effects pulping plant productivity and efficiency, an effective fibre management system is essential to ensure that a consistent mix of correctly identified fibre types, matched to target products and product quality, enters the mill. It is thus obvious that the factors controlling the quality of fibre supply be further understood.

The main factors identified as affecting wood properties of trees are age, genetics and site (Creber and Chaloner, 1984; Carlquist, 1988). Tree breeding has sought to increase good quality fibre yield where hybridization has sought to improve wood quality through the use of site suitable clones (Malan, 1993).

The term 'site' has been used by various authors in different contexts. The understanding of site is intrinsic in the application of this understanding. For practical reasons, site can be described as the collective interactions between climate, topography, geology and soil characteristics (Du Plessis, 2002). Site essentially describes areas of environmental homogeneity: attempting to categorise areas of land where the environmental variables within that site are of such a nature as to result in the plant growth response being the same throughout that area.

A number of studies conducted in the past have investigated the influences of site on the wood properties of *Eucalyptus* spp. in various parts of the world. It has been found that the wood properties of eucalypts are affected by the interacting effects of environment factors both directly and indirectly. Wood properties may be directly affected by a particular site variable, or indirectly by the physiological response (i.e. growth response) of the tree to that factor. The site variables affecting wood quality have been categorized as being climatic, edaphic, or biological in nature. In the past, discrete variables such as site index (SI) have served to explain the influence of the entire environment on the tree with some success. Site index is measured as the height of dominant trees in a plantation or forest at a certain reference age. Site index, as a substitute for site variables, has been shown to correlate well with certain wood properties of *Eucalyptus* spp. grown in South Africa (Megown *et al.*, 1998; Turner and Retief, 1998; Turner *et al.*, 2001). There is a need to break down or characterize those factors of the environment affecting site index that have a resultant effect on the wood properties of those trees. Lee and Sypolt (1974) stated that analysis of the environment offers a logical alternative to estimating site quality. In this way, a system for assessing existing sites as well as evaluating future sites for planting may be considered not only in terms of potential volume yield, but also in terms of potential wood quality yielded for pulping and paper making. Through knowledge of how site factors affect wood properties, fibre management systems may be more efficiently devised to supply pulp mills with raw material that meets desired criteria. This will not only affect the harvesting regime currently at work, but will also affect planning for future planting.

Not much work exists in South Africa relating wood properties of trees for pulp and paper making to the effects of the individual environmental factors that affect site index. While the influence of SI on wood properties is known, it is useful to include information gathered from site-growth studies in a study of this kind. In this way knowledge of site factors as determinants of tree growth may be useful in understanding the role of the environment in influencing wood properties of eucalypts grown in South Africa. Furthermore, such information may prove useful in the creation of a site wood property model that predicts the wood properties of trees on areas of land that have not been afforested before.

Numerous site-growth studies have indicated the dominance of climate as the major driving factor determining tree growth in plantation forestry. The effects of other site variables such as soil factors are usually experienced by trees through the overriding climatic conditions of that site. For example, Louw (1997) found that mean precipitation in August combined with total soil depth and organic matter content explained 80% of the growth of *Eucalyptus grandis* on the Mpumalanga escarpment. Louw (1997) noted that most of this variation was due to the effect of rainfall. This result is supported by Pierce (2000) who, working in KwaZulu-Natal, Mpumalanga and the Limpopo Province (formerly Northern Province), explained 77% of the variation in volume production of *Eucalyptus grandis* purely as a function of mean annual precipitation (MAP). Furthermore, no major correlations were found between growth and soil factors, although it was noted that this was probably due to the fact that all sites under consideration were ideal *E. grandis* growing sites in terms of soil depth, rainfall and temperature. Raymond and Muneri (2000), working in the south eastern regions of Australia, again showed that the climate has a large influence on other site factors, where the effect of fertilizer application on wood properties of *Eucalyptus globulus* was influenced by rainfall and temperature. However, work conducted by Noble *et al.* (1991) on the Zululand coastal plain showed the relevance of certain soil factors in particular geographical regions. They found a strong relationship ($R^2$=0.76) between organic carbon content of the A horizon and tree growth. Schafer (1988b) described 85% of the growth variation in *Pinus pinaster*, grown in the Southern Cape, as a function of seven different soil variables including textural classes, exchangeable cations and organic matter content. It is obvious that the relative contribution of site factors to tree growth varies with geographic location, making the creation of broad relationships between tree response and the environment difficult. While reviewing site-growth studies at large in South Africa, Louw (1999) found that with increasingly larger geographical areas, there is a decrease in correspondence between SI and site factors. Furthermore, Louw (1999) concludes that the evaluation of the complex relationship between soil moisture availability, nutrient status and tree growth on different sites is crucial to both the interpretation of results from silvicultural experiments and to the development of sound management practices. Du Plessis (2002) has concluded that "further research of physical soil properties and climate should improve the understanding of site growth relationships in Zululand." Louw (1997) mentions the lack of high resolution climatic data as a drawback for these types of studies.

As mentioned above, climate is an important determinant of the distribution of most plants and animals, although every organism responds differently to climate. On world maps, the boundaries of natural vegetation zones, soil types and climatic regions coincide roughly (Eyre, 1968, 1971). It is clear though, that climate is not the only determinant of the actual or potential distribution of an organism. Various other factors such as edaphic factors (including texture, nutrient status and drainage) and biotic factors (including disease, predation and competition) are also important. Due to the variability of these factors, modeling their role as biotic determinants is extremely complex. Because climate does have such pervasive biological significance, bioclimatic modeling has great potential in biogeographic studies (Richardson, 1991).

Richardson and Bond (1991) state that bioclimatic modeling has essentially evolved from 'homocline analysis by common sense'. Humans have always been aware that species introduced from regions with similar climate to that of the target area are more likely to succeed than species from dissimilar climatic regions. Therefore, bioclimatic modeling is generally understood to be any method of predicting under what climatic conditions an organism will live, grow and reproduce. In the context of this study, the effect of bioclimate on the type of growth of *Eucalyptus* spp. (expressed through wood properties) will be considered. Advances in mathematical techniques of interpolation and climate analysis and the emergence of geographical information systems have facilitated rapid progress in bioclimatic modeling. There are a number of different approaches to the concept of 'bioclimatic modeling' although commonly all attempt to better relate climate to the performance of the biota experiencing that climate.

With this in mind, the main objectives of this study may be summarized as follows,

a. Study and identify the variation in wood properties of *Eucalyptus* spp. due to the combined effects of climate and edaphic factors on tree growth and wood development.

b. Create a site-wood-property model for *Eucalyptus* spp. using easily measurable and/or already available site variable data.

There are many practical considerations in creating any model to predict a tree response from environmental factors. The time and economic resources spent in acquiring input data for any site-growth response model is of utmost importance. Realistically, any model that requires input data that is time and cost effective to gather will be favoured as a practical tool in industry and research alike.

# Chapter Two
# Review of wood properties and the factors affecting wood properties

## *2.1 Wood Properties and Quality*

### 2.1.1 Basic Wood Anatomy

The stem of the plant supports the branches, which in turn supports the foliage: in this way the plant maximizes its interception of radiation from the sun resulting in increased photosynthesis (Kramer and Kozlowski, 1979). The products of this photosynthesis, carbohydrates, are in turn used to make new leaves, shoots, wood and roots (Haygreen and Bowyer, 1982). Within this woody tissue, secondary functions of vital importance take place. Wood not only serves as a conduit for water, but may also function to store these elements along with waste products or hazardous materials (Kramer and Kozlowski, 1979).

The bulk of what is often referred to as the stem of a tree consists of woody tissue. The tree stem is essentially a bark-enclosed column of wood, composed of a series of layers or annual increments added one around the other (Kramer and Kozlowski, 1979; Haygreen and Bowyer, 1982). Wood within the stem may be broadly subdivided into two separate types, sapwood and heartwood.

The heartwood of the xylem is dead, consisting of vessel, tracheid and fibre cells that are often filled with tyloses that have grown through the lumens to block of the vessels (Kramer and Kozlowski, 1979). Tylose filled cells prevent the formation of embolisms, or air pockets, in the vessel elements of the stem during periods of low plant water availability (Carlquist, 1988). The heartwood also provides mechanical support to the tree and stores metabolically active and undesirable products such as fungicidal compounds (Kramer and Kozlowski, 1979).

The cells of the sapwood are living, and in the case of hardwood (angiosperm) trees such as *Eucalyptus* spp., consists of both vessel and tracheid elements. Softwood trees (gymnosperm), such as *Pinus* spp. contain only tracheid elements (Kramer and Kozlowski, 1979). The sapwood of the xylem is responsible for the transport of water, nutrients and growth factors (Kramer and Kozlowski, 1979; Haygreen and Bowyer, 1982). Vessel elements do not have end walls, fitting one on top of the other to form xylem vessels. Tracheids are often a hundred times longer than they are wide, have tapered ends, consist of thickened cell walls and are smaller in diameter than vessels (Carlquist, 1988). In *Eucalyptus* spp., the function of vessels and tracheids is separate. The vessels function as water conduits while the tracheids, also in this case referred to as fibres, function to provide mechanical support to the tree (Carlquist, 1988).

The cambium, situated between the xylem and the bark, functions as a site for secondary growth of the tree. The cambial cells are meristematically active, and forms a zone of division for the tree vascular system (Kramer and Kozlowski, 1979; Haygreen and Bowyer, 1982).

Surrounding the cambium is the outer ring of the tree stem, which has been loosely called the bark of the tree. The phloem, situated externally to the cambium, is responsible for the vertical transport of photosynthate from the leaves to the other parts of the plant (Haygreen and Bowyer, 1982; Carlquist, 1988).

### 2.1.2 Variation in wood anatomy and wood properties

The heartwood of the tree stem contains chemicals that are hot water and alcohol-benzene extractable. These extractives are removed as waste products during the pulping process. The sapwood contains less of these extractives and thus trees that display higher sapwood to heartwood ratios will consume fewer chemicals during processing. In addition, many other wood properties function at a cellular level to affect wood quality. Of significant importance to *Eucalyptus* spp. grown in South Africa are those wood properties related to water availability. The specific wood properties that have been identified with regard to this include the length of vessels and tracheids, the size of lumen, the individual cell diameter and the vessel frequency (Haygreen and Bowyer, 1982).

The composition of cell walls, or more specifically the ratio of lignin to cellulose within the cell walls, is another important wood property affecting the cooking time of pulp in the mill. Pulp is manufactured by releasing cellulose-rich fibres from the lignin that bonds them together (Clarke, 1999). This is usually done by cooking the raw material in alkaline or acid liquor at high temperature and pressure. Some lignin is left behind in the resulting pulp and this improves the strength properties of the paper produced. Before pulp enters the paper machines, the lignin content is finely controlled using oxidizing agents in the bleach plant (Clarke, 1999).

### 2.1.3 Wood Quality

The term wood quality refers to the combination of individual wood properties within harvested material that act together to determine how suitable a particular wood is for various end uses. These wood properties are often inter-related, for example: an increase in wood density is often accompanied by an increase in wood extractives content. Whereas an increase in the former is desirable, an increase in the latter is not. For this reason it is easier to refer to values of individual wood properties rather than attempting to assign an overall numerical value for wood quality.

An understanding of wood properties has become increasingly important in the timber industry both for the saw-timber market and for the pulp and paper making process (Clarke *et al.*, 1999). This study is concerned with those wood properties of eucalyptus trees that are most important to the pulp and paper making process. Knowledge of the wood properties of the raw material entering a mill will aid in process optimisation and control of end-product quality. When the properties of pulpwood are known, the wood may be graded and separated into different categories to be processed according to their grading. This pre-process grading of wood chips is known as a 'fibre management system'. The importance and relevance of this system lies in reduction of factory running costs. Matching processing conditions to raw material properties can reduce production costs through improved pulp yield and lower energy and chemical requirements (Clarke, 1999).

Currently, research into wood properties involves:

- The study of how certain wood properties affect the pulp and paper making process as well as the quality of the end-product.

- Breeding trees for better fibre characteristics

- Screening techniques for rapidly assessing certain wood properties either in field or post harvest. Eg. Near Infra-Red Absorption Spectrometry (NIRA) scanning for cellulose and lignin content

- Understanding the influence of age and genotype-environment interactions on wood properties.

The two primary goals of the above research initiatives are firstly to improve the wood properties of harvested material, and secondly to reduce the variability of this material. Secondary to this is the increased ability to predict the quality of material before entering the mill.

Cloning is one of the most effective ways to reduce wood property variability and is an important strategy in the breeding of Eucalypts. Trees that have been bred and found to exhibit superior survival and growth rates are cloned vegetatively. Cloned trees will exhibit greatly reduced within-site variation of wood properties and growth. Only a small proportion of plantation eucalyptus forests in Zululand and Mpumalanga are cloned as yet, although forestry companies are making concerted efforts to establish cloned material more widely. When the genotype-environment interaction and its influence on wood properties are better understood, the result will be a timber resource that is far more predictable in terms of these wood properties. An understanding of environment-genotype interactions may lead to the opportunity to model fibre characteristics and lead to the development of a more effective harvest scheduling and management system. This system may be practically implemented in the controlling of the quality of raw material entering the mill.

### 2.1.4 Wood properties considered in this study

Weighted Mean Density (WMD), Screened Pulp Yield (SPY), Weighted Mean Fibre Length (FL_WM) and Active Alkali Absorption (AA) are considered in this study. WMD and SPY are important wood properties, and combined with knowledge of tree volume are a measure of the potential fibre production per hectare (Clarke, 1999). Fibre length is an important anatomical property that affects the strength of the paper produced. Longer fibres are most often preferred as they result in stronger paper with higher tear and tensile qualities. Active alkali absorption is a measure of the consumption of chemicals during the bleaching of wood pulp. The consumption of alkali chemicals alludes to the presence of lignin and hemicelluloses. This measure, should however be viewed with caution, and is reliably useful only as a measure of potential chemical usage by industry. Higher measures of AA indicate less chemical usage and therefore more favourable wood properties for industrial processes.

The wood property data used for analysis in this study was taken from the results of work conducted by the Forest and Forest Products Research Centre (FFPRC) at the CSIR (Council for Scientific and Industrial Research), Durban. The FFPRC is involved in a co-operative with the University of Natal, Mondi Forests and SAPPI (South African Pulp and Paper Industry) to research different aspects of wood quality assessment and improvement. The data used were collected from numerous studies carried out by the FFPRC from 1996 to present. It was decided to make use of this dataset for the following reasons:

- The acquisition of wood property data is very expensive. In general, the collection and choice of desired wood property data forms part of an integrated research approach with many proposed outcomes.

- This dataset is already quite large, allowing for a wide selection of sites to choose from.

- Time was saved gathering the data. Due to constraints on time and the nature of the study, it was logical to make use of a data set that has taken 6 years to gather.

## *2.2 Environmental factors affecting wood properties*

A review of available literature has indicated that the factors affecting the wood properties of trees are: genetics, age and environment (Clarke, 2000). Much work has been conducted to breed hybrids of trees that produce greater volumes of better quality raw material. Hybrids are bred not only to produce better wood characteristics in themselves, but also to thrive on otherwise marginal growing areas in South Africa (Malan, 1993). This approach has seen much improvement in fibre yield per hectare which is of primary concern to industry (Clarke, 1999). Fibre yield is expressed as air-dry tonnes of wood per hectare (ADT/ha). Wood properties change as the tree ages and much research at the FFPRC has involved the effects of site and age on wood properties where site quality is expressed as site index (a measure of growth rate).

Various workers have categorized the effects of environment: the general distinction in environmental factors is that which separates climatic, edaphic and biological effects. This approach is widely used by most researchers in site-growth studies (Grey, 1987; Schonau, 1988; Louw, 1991; Noble *et al.*, 1991; Strydom, 1991a; Schafer, 1994; Louw, 1997; Pierce, 2000; Du Plessis, 2002).

Site Index (SI) is currently the most widely used benchmark of forest site quality. SI is a measure of the growth rate of a stand of trees, expressed as the dominant height of trees in a stand at a reference age. SI is regarded as a composite expression of the effect of interacting factors of site variables on tree growth. SI has been shown to be well correlated with certain wood properties and is currently considered the best method of predicting wood quality of *Eucalyptus* spp. in South Africa. Megown *et al.* (1998), working on the Zululand coastal plain, and Turner *et al.* (2001), working along the Mpumalanga escarpment, correlated SI with pulp yield and fibre length of eucalyptus hybrid clones and seedling-derived material. Site-growth studies may be viewed as attempts to break down SI, by identifying those environmental variables that significantly contribute to the growth of trees.

Some workers have quantified individual site factors and developed regression equations that predicted the SI of various species. Schafer (1988a, 1988b) and Louw (1991) both presented regression equations using independent site variables to predict site index of *Pinus* spp. Site variables included effective soil depth, terrain features, rainfall, slope and certain soil physical and chemical parameters. Schonau (1988) developed an equation that accurately accounts for 85% of the site index variability of *Eucalyptus grandis* using seven different soil variables, including textural classes, exchangeable cations and soil organic carbon.

Although site factors may be considered as individual components, it must be noted that these factors interact with each other to create a single specific plant growth environment (Louw, 1997).

The relationships between the environment, physiological responses and wood properties are intrinsically linked and difficult to understand on their own. Downes *et al.* (1999) state that in order to fully understand the complex relationships between plant and environment, the whole tree physiological responses to climatic variable interactions needs to be understood in terms of the effects on cambial activity, stem increment and wood properties.

### 2.2.1 The effect of Climatic Factors on Wood Properties

The effect of the climate experienced by a stand of trees, both on a macro- and a micro-climate level, is complex and influenced by other environmental factors. For example, the amount of moisture ultimately made available to a growing tree is affected not only by the amount of rainfall, but also by the soil and terrain characteristics of the site (Pritchett and Fisher, 1987).

Climate as a site variable has been shown to be a major influencing factor on other determinants of wood quality such as soil properties. Soil type has been shown to affect many factors contributing to site quality, including water retention and availability, effective rooting depth and the nutrient availability of that soil (Pritchett and Fisher, 1987). These factors in turn affect the cambial activity of the tree, resulting in changes to not only the rate, but also the type of xylem cell development (Denne and Dodd, 1981). Factors of the environment most often referred to in literature include rainfall, temperature (including frosts), humidity and total radiation.

Water availability is commonly regarded as the single most limiting factor to forest growth in South Africa (Boden, 1991; Dye, 1996; Louw, 1997; Clarke *et al.*, 1999) Therefore, rainfall is almost always considered first when viewing the effects of climate on a site. The mean annual precipitation (MAP) of a site does not always give an accurate indication of the amount of plant available water; the influence the amount of annual rainfall exerts on the growth and properties of a tree depends on the fate of the precipitated water. The rainfall received by an area does not result in all trees in that area experiencing the same amount of plant available water. Soil depth, texture, steepness of slope, amount of canopy cover, undergrowth and leaf litter can all affect the final amount water available to a forest tree (Pritchett and Fisher, 1987). It must be noted, however, that sites that receive a higher MAP usually experience better growth and different wood properties to those drier sites (Megown *et al.*, 1998; Turner *et al.*, 2001).

Raymond and Muneri (2000) showed how the effects of rainfall and temperature interact with soil nutrient status to affect wood properties of *Eucalyptus globulus*. Clarke *et al.* (1999) studied the effects of differences in climate on growth and wood and pulp properties of *Eucalyptus* spp. grown on a cold (low rainfall) and a warm site. Although wood properties differed among eucalyptus species, site characteristics were found to significantly affect growth, wood, and pulp properties except for cellulose content and fibre mass. Trees grown on the colder site were found to have higher wood densities. Mean pulp yield and pulp brightness was found to be higher in trees grown on the warm site.

Photosynthesis may be affected by the temperature experienced by the site. Battaglia *et al.* (1996a) showed that photosynthesis in *Eucalyptus nitens* is either increased or reduced with increasing or decreasing temperature respectively. This may in turn affect the rate of production of carbohydrates, which has an effect on the type and number of xylem cells developed (Denne and Dodd, 1981). Davidson *et al.* (1995) working with *Eucalyptus nitens* in northern Tasmania, found that the occurrence of mild frost reduced the rate of photosynthesis and they attributed this to the slightly decreased carbon gain in the stems of these trees. They found that photosynthesis was reduced by 10-15% in 9 month old trees experiencing mild frosts, where night time temperatures ranged from –4.6 to 7.4°C. In addition, Davidson *et al.* (1995) found that this effect was reversed by the end of the day following the frost, and that these reductions in photosynthesis were less in trees that had been hardened in the nursery before being planted into the field. They concluded that trees, which experienced days where temperatures were sufficiently elevated consequent to frost nights, recovered their photosynthetic rate sufficiently to negate significant losses in overall biomass production of those trees.

Clarke (2000) compared growth and wood properties of *Eucalyptus nitens* and *Eucalyptus grandis* grown on a cold and a warm site in South Africa. Temperature significantly affected pulp properties: wood harvested from the colder site yielded more extractives during processing, adversely affecting the alkali consumption and pulp brightness.

Drew *et al.* (2001) analysed wood property data from a *Eucalyptus grandis* (Tag5) clone grown in Kwa-Zulu Natal, South Africa, to establish correlations with climatic and other site data. Fibre length was correlated with median annual rainfall ($R^2$ = 0.68) and SPY was also found to correlate well with SI ($R^2$ = 0.77). It was supposed that this change in wood properties was attributed to a change in growth rate and tree vigour as a response to the improvement in the environment.

### 2.2.2 Soil-plant-water relations and the effects on Wood Quality

Both the quantity and quality of wood produced by a tree are affected directly and indirectly by water supply (Kramer, 1964). Readily available plant water is accepted to be that water held by the soil between matric potentials of –10 and –100 kPa (Hillel, 1980). There are a number of site factors, both climatic and edaphic, that interact to affect plant-water availability. Primary to this uptake and translocation is the difference in water potential between the soil and the atmosphere, such that the force imposed by gravity and the resistance within the vessel elements, roots and leaves is overcome (Salisbury and Ross, 1985). The water availability within a particular soil is inherently dependent on the amount of water held in that soil (Pritchett and Fisher, 1987). The rate and amount of water infiltrating the soil profile is affected by the slope of the ground, the presence of surface crusts and the hydraulic conductivity of that soil. The amount of water retained in the soil profile depends on the soil texture, the amount of organic matter therein, the depth and the slope of the soil profile (Hillel, 1980; Duchafour, 1982).

Carlquist (1988) reports that the onset of drought along with decreasing temperatures may bring about cessation of cambial activity and radial growth. Water stress has also been shown to reduce cell enlargement permanently, resulting in differing widths of tracheids and proportions of latewood (Kozlowski *et al.*, 1991). February (1993) and February *et al.* (1995), attempting to predict water use efficiency in *Eucalyptus* spp., found vessel element diameter and length to decrease while vessel frequency increased with decreasing water availability. February *et al.* (1995) also showed vessel diameter, elasticity and length to be relative to the amount of available water as well as the genotype of the tree.

The leaf-area/sapwood area ratio of *Eucalyptus globulus* and *Eucalyptus nitens* is affected by water availability. White *et al.* (1998) showed that this ratio decreased with a reduction in water supply to the plant. Maherali and deLucia (2000) showed how the amount of water available and taken up by *Pinus ponderosa* influenced the sapwood to heartwood ratio of harvested material.

### 2.2.3 Soil nutrient availability and the effects on wood properties

There is a considerable of variability in the results of research conducted to study the effects of nutrient availability on wood properties. This may be attributed to the variability between those studies: different species of trees were grown on different sites (or on the same site), resulting in differences in wood properties. The lack of continuity between results of previous studies has resulted in there being no accepted rule describing the response of wood properties to plant nutrient supply. Nevertheless, a review of literature may provide the framework within which to interpret experimental data (Denne and Dodd, 1981), and shows that the development of site-species specific nutrient availability-wood property relationships may be useful in prediction and management of that wood quality.

Various nutrients exert a direct influence on wood properties. Salisbury and Ross (1985) state that calcium is an essential part of cell walls and that a deficiency

# Chapter Three
# Site Classification

Site classification may be seen as a model of the ecological features and relationships that characterise a specific ecosystem and its distribution within a region (Louw and Scholes, 2002). Forest site quality estimation generally tends to quantify the potential productivity of that forest (Carmean, 1975).

As stated before, the term 'site' has come to mean different things to different workers. Du Plessis (2002) stated that for practical reasons, site may be described as the collective interactions between climate, topography, geology and soil characteristics. Earlier workers viewed "site" as a primary ecological unit (Grey, 1980). Grey (1980; cited in Louw and Scholes, 2002) described site as a natural unit, a spatial entity, which can be described, classified, recorded and mapped, but which cannot be further subdivided without the loss of some intrinsic factors. This resulted in the general understanding of site to be an integrated complex of all environmental factors within a prescribed area (Louw and Scholes, 2002). Earlier, Louw (1997) defined a site as follows:
"A forest site is an area that requires homogenous silviculture practice, regarding species choice, management and amelioration techniques and expected yields. Sites will be relatively homogenous regarding soils, climate and parent material and topography. Furthermore, sites will inevitably have similar silvicultural implications such as sensitivity to compaction and erosion, as well as the risk to damage from insects, diseases and windthrow."

In the context of this study, the term site is used interchangeably with compartment and refers to the actual forest compartment where trees were harvested for wood property analysis. It is assumed that each compartment represents a site, ie. that within each compartment climatic and edaphic features remain the same. This assumption is bound to introduce error due to the large size of some of the compartments. Some compartments in the Mpumalanga region were in excess of 60 Hectares (ha) in size, and within site variation of environmental factors, however small, may be expected.

### *3.1 Site index*

Forest site quality estimation generally intends to quantify potential productivity (volume yield) of that forest (Carmean, 1975). Site index is presently the most widely used indicator of site quality.

Site index is defined as the mean height of dominant trees in an even-aged stand, at a specific base age (McLeod and Running, 1987; von Gadow and Bredenkamp, 1992). The determination of site index is usually accomplished by measuring the height and age of a number of trees in a forest stand, accessing a set of guide curves with these data pairs, and inferring site index by interpolating the mean dominant height to a defined base age (Jones, 1969). This method is true for stands of trees of differing ages. In South Africa, *Eucalyptus* spp. plantations consist of trees of the same species and age, resulting in trees of one stand being measured in height over their entire life span for derivation of the site index curve.

Site index curves are developed by measuring height and age of many stands at single points in time, fitting an average curve of height-on-age to these data and constructing a series of higher or lower curves with the same shape as the guide (Pritchett and Fisher, 1987). More reliable and accurate methods of developing site index curves for certain species such as *Pinus* spp. involve stem analysis or internode measurements (Carmean, 1975).

The capacity of trees to thrive and successfully compete on a particular site is influenced by both internal (physiological) and external (environmental) factors. This may be explained as an expression of the genetic makeup of the tree (that is fixed) through physiological responses that are affected by the environment. The integration of these combined properties determines forest productivity. The external or environmental factors, therefore, entirely determine site quality, or inherent plant growth potential for a particular species. Site quality is therefore a function of the physiography, climate, soil and other features of the environment not easily altered (Pritchett and Fisher, 1987). Often, measuring forest productivity in terms of site index is not wholly representative of site potential, and alternatives to tree dependent indices of site quality are therefore needed (McLeod and Running, 1987).

Lee and Sypolt (1974) state that analysis of the environment offers a logical alternative for estimating site quality (as site index). Because site index is highly empirical and provides limited information except that concerning the current tree stand (Pritchett and Fisher, 1987), it cannot be used for sites with no trees, for those lacking suitable trees, or for the conversion of species. Furthermore, it provides little understanding of the biological limitations of a site (McLeod and Running, 1987; Pritchett and Fisher, 1987). Site index is, however, according to Carmean (1975) a useful guide to potential tree growth for a particular species under a given set of conditions.

It may be said that site quality, being subject to internal (plant) and external (environmental) factors, is a function of temperature, radiation, moisture and nutrients as well as the species ie. genetic variance (McLeod and Running, 1987).

### *3.2 Geology and Soils*

There are a number of biological factors that contribute to the overall productivity of a forest site, which may be included in a site classification. These variables are considered more transitory, but failure to recognise them can lead to errors in the measurement of site productivity. Some biotic components of particular importance are stand density, genetic variability, competing vegetation, mychorrizal fungi and disease and insect activity (Pritchett and Fisher, 1987). Competition for light, nutrients and water by weeds and other trees also constitutes a major biotic factor affecting plant growth. Turner *et al.* (2001) documented significant effects of different weeding regimes on *Eucalyptus* spp. growth and wood properties. Although the effect of biotic site variables on tree growth is a real one, these factors fell beyond the scope of this study.

Abiotic factors of the environment that affect tree growth can be broadly grouped into climatic, physiographic and edaphic variables.

Pritchett and Fisher (1987) state that the influence of physiographic variables on forest productivity have been recognised longer than most other site components. Topography exerts an effect on growth through the local modification of climate and edaphic variables, particularly light, moisture and temperature regimes (Louw, 1997). Topographic factors are important features of many land classification systems, where measures of aspect, slope, elevation and shape of slope may be included to group homogenous growing areas. For these reasons, the aspect and steepness of the dominant slope of forest compartments was measured and recorded. Louw (1999) suggests that where measures of macro-climate may not effectively describe tree growth, this variation may be explained in changes in micro- and meso-climate as a function of topographical features.

Edaphic factors comprise a large group of abiotic factors that significantly affect tree growth. An edaphic factor is defined as "a condition or characteristic of the soil (chemical, physical or biological) which influences organisms", in this case tree growth and wood properties (Harmse *et al.,* 1984). The soil effectively makes up the growing medium, or substrate of the growing plant. The substrate and orientation of that substrate have been shown to greatly affect plant growth as a result of changes in effective rooting depth, nutrient status as well as water retention and impedance to root growth (Pritchett and Fisher, 1987).

Because of the deep rooting habit of most trees, soil parent material and the condition of the geological substrata are important factors that affect forest productivity. The underlying geology of a site may affect tree growth through changes in effective rooting depth and mineral composition of the soil that results from the degradation of that material (Louw, 1997). The parent material of a soil will affect the dominant physical and chemical composition of that soil: clay amount and type are influenced by the type and degree of weathering of this parent material (Duchafour, 1982). Soil depth is an indication of the volume of soil available to plant root growth. Greater depth of soil results in increased levels of water and nutrient supply. An increase in soil depth is usually accompanied by an increase in effective rooting depth (ERD). The ERD is described as the depth to which trees can maintain metabolically active roots during the major portion of the growing season (Pritchett and Fisher, 1987).

Features such as stone-lines, high water tables or toxic substances may restrict root penetration into a soil that may otherwise permit deep rooting. Stone-lines may impede root development by providing a physical barrier to growth, while soils with perched water tables become anaerobic in those zones, inhibiting respiration and consequent growth of root material (Duchafour, 1982). Abrupt changes in soil texture also contribute to root obstruction mechanically and via oxygen deficiencies brought about by water saturation and a lack of air movement in the soil profile. This feature is most often recognised by the presence of mottling, streaking or concretions in the soil horizon (Soil Classification Working Group, 1991).

Soil organic matter (SOM) content of the topsoil is regarded as an important determinant of soil fertility (Duchafour, 1982). Furthermore, increased levels of soil organic matter results in a greater water retention capacity of the soil. Noble and Herbert (1991) and Louw (1997) have shown positive growth responses in *Eucalyptus* spp. due to increased levels of SOM in Zululand and Mpumalanga respectively. In Zululand, elevated levels of SOM increased tree responsiveness to applied nitrogen fertiliser. The relationship between measurable SOM and tree growth response may not be directly related to the SOM itself. Increased levels of SOM may be indicative of cooler and wetter sites yielding site-growth relationships that may contradict conventional understanding of the role of SOM (Duchafour, 1982; Pritchett and Fisher, 1987).

### 3.2.1 Soil-water retentivity

The study of soil-water dynamics, starting at rainfall interception and progressing through slope runoff, infiltration, retention, movement in the soil profile and uptake by plants is a large area of study that this project could not address in detail. However, a basic understanding of the soil-water retention characteristics as affected by soil texture has been included in this study to provide a better understanding of the fate of precipitated water. Retentivity curves represent the relationship between soil water content (on a volume or mass basis) and matric potential. Matric potential is a measure of how firmly water is held by or bound to the surfaces of soil particles (Harmse *et al.*, 1984), and may be quantified as the force required (kPa) by plant roots to absorb water held by the soil. Large differences in the retentivity characteristics of a soil might account for differences in tree growth on sites that receive similar rainfall and temperature regimes. Most retentivity curves are calculated from saturated undisturbed soil cores that are placed on a tension table and subjected to varying degrees of suction over time. Water content in the soil cores is recorded at different pressure potentials and a retentivity curve is generated. Much work has involved the derivation of soil-water retention characteristics using 'pedo-transfer functions' (PTF's) from measures of soil texture and bulk density (Zhuang *et al.*, 2001; Medina *et al.*, 2002; Romano and Palladino, 2002). In South Africa work conducted by Smith *et al.* (2001) described the water retention in soils that fall into specific textural classes. These data were used to describe the soil-water retentivity characteristics of the study sites in an attempt to quantify the possible effect of increased soil-water retention on tree growth.

### *3.3 Climate and Bioclimate*

Climate has a pervasive role on the distribution of vegetation. One of the oldest and greatest generalisations of plant ecology is that, on a continental or global scale, the distribution of vegetation types is strongly influenced by climate (Richardson and Bond, 1991). Despite the strength of this generalisation, our understanding of precisely which aspects of climate most influence vegetation distribution, and by which mechanisms, is rather vague (Stephenson, 1990). Most studies regarding the association between climate and vegetation physiology have considered measures related to annual energy (eg, mean annual temperature) and annual water supply (eg. mean annual precipitation), or their ratios.

Mean annual and monthly climatic variables in conjunction with edaphic factors have been used with marked success to explain forest tree growth in South Africa (Grey, 1987; Schafer, 1988a; Schafer, 1994; Strydom, 1991a; Louw, 1997; Pierce, 2000; Du Plessis, 2002). The main measures of climate commonly used are rainfall (which comprises by far the major component of total precipitation) and temperature, A-pan evaporation and solar radiation at a mean and median annual and monthy level.

### 3.3.1 Rainfall

Mean annual precipitation (MAP) is the most commonly referred to climatic variable at a regional scale. Du Plessis (2002) refers to MAP as a defining factor of forest growth, while assuming other factors such as nutrients, light and suitable substrate are not in limited supply to the trees. Water and water availability is understood to be the most limiting factor to plantation forest growth in Southern Africa (Dye, 1996). Schulze (1997) states that, while well known and easy to use, the concept of MAP has certain problems in the South African context:

- The distribution of MAP is typically not normal. MAP in South Africa shows a positive skew, i.e. there are more lower than average rainfall years than higher than average ones
- Values for MAP are frequently inflated by a few very high annual totals. This effect is decidedly marked in more arid areas of the country.

Nevertheless, MAP is still useful in providing a quick overview of the ability of a region to support plant growth. It is limited in that it 'smoothes' the effects of intra-year variability at a monthly time interval. Rainfall seasonality is not captured in MAP and therefore necessitates the need for monthly rainfall values to describe better the intra-year variation in rainfall (Schulze, 1997). Monthly rainfall values impart some idea of rainfall seasonality, and are necessary to derive better measures of the plant-growth environment and its changes throughout the year expressed as bioclimate (Nix, 1986). Ultimately, the amount, frequency and intensity of rainfall received will affect the amount of water entering the soil system, and along with soil factors, will affect how much moisture is available to sustain plant growth.

### 3.3.2 Temperature

Mean monthly maximum and minimum temperatures are basic measures of the energy supply and balance to an environment. The temperature experienced by any single forest compartment is affected by a host of factors. On a macroclimate scale, factors such as latitude, altitude and distance from the sea affect ambient air temperature. At a microclimate level, factors such as topography and slope may

Commonly, measures of this kind have been referred to as being measures of the 'bioclimate' of an environment (Busby, 1986a; Nix, 1986; Booth *et al.*, 1987; Richardson and Bond, 1991). Despite this distinction in climate measures in most research, certain forest site-growth studies in South Africa have included some measure of bioclimate in their site classification and evaluation (Grey, 1987; Strydom, 1991a; Louw, 1997).

The advantage to using measures of climate (and consequently bioclimate) in any biogeographic study is that they are generally widely available, and have been measured using standard techniques. Edaphic and biological features of the environment are highly varied, often difficult to measure and complex to model (Richardson, 1991). As stated above, bioclimate in essence attempts to better describe the conditions experienced by living organisms in any one place by considering not only the relative amounts but also the temporal variation in supply of water and energy to the growing environment.

Many workers have developed different approaches to modelling this relationship. Richardson (1991) states that these have developed from "homocline analysis by common sense": species introduced into new areas either accidentally or intentionally are usually grown in areas of similar climate to their natural habitat. Most approaches to bioclimatic modelling are done so with the aim of predicting potential distributions of plants and animals both now and in a future where climate change is already affecting plant growth. Potential new ranges for species distribution have been a concern for years and the South African forestry industry is no exception. Schulze (1989) presented findings proposing the impact of climate change on the location of optimum growing areas of commercial timber species in Natal. Schulze later developed his own bioclimatic approach in the form of an agrohydrological modelling system called ACRU (Agricultural Catchments Research Unit) (Smithers and Caldecott, 1994). Nix (1986) initially co-developed (with Busby, 1986a) the Bioclim prediction system used in this project to analyse the distribution of Australian Elapid snakes. Sutherst and Maywald (1985) developed the well known Climex system. The main use of Climex is to predict an animal or plant's relative abundance and geographical distribution as determined by climate. Even earlier than that, Emberger (1954), cited by Richardson (1991), derived a parameter he called the

### 3.4.2 Anusplin

A new method of obtaining unknown point values for climatic variables was explored and used in this project. This method involved the interpolation of long term means for climatic variables between data points using the Anusplin suite of programs as described by Hutchinson (1995).

Anusplin is a suite of Fortran programs developed at the Australian National University that calculates and optimises thin-plate smoothing splines fitted to data sets distributed across a large number of climatic locations (Hutchinson, 1991, 1999). Splining is a method of fitting a 'smooth curve' or surface to a set of data points. Partial thin-plate splines have been developed for various applications in geosciences, but have been noted as being particularly suitable for interpolating rainfall mean (Hutchinson, 1995). This technique has been developed and used for climate prediction since the turn of the century when Thiessen (1911, cited in Hutchinson, 1998) calculated 'Thiessen polygons' for use in rainfall data interpolation.

Thin-plate smoothing splines may be regarded as a generalisation of the standard multivariate linear regression, in which the parametric model is replaced by a suitably smooth non-parametric function. Splines are calibrated by optimising a single smoothing parameter to determine the degree of smoothing. This is achieved by minimising the generalised cross validation (GCV). The GCV is a direct measure of the predictive error of the fitted surface. The GCV is calculated by removing each data point in turn and forming a weighted sum of the square of discrepancy of each omitted data point from the surface fitted to all the other data points (Hutchinson, 1998).

One advantage to using splines to interpolate rainfall is that they can be applied to data systems where record lengths are short and the data are noisy (plenty of inter-annual and monthly variation) – typically the case with a network of rain gauges (Hutchinson, 1995; Fairbanks and Chapman, 1997).

Although Anusplin is versatile and can accept numerous independent variables (up to 10) and co-variates (up to 7) as inputs to interpolate data, these features were deemed beyond the extent of this project. This method was rather developed as a potential tool for the rapid production of bioclimatic data that may assist in the modelling and prediction of wood properties. For this reason, rainfall and temperature surface coefficients were calculated using latitude, longitude and altitude as the three independent input variables. The monthly coefficient of variation (CV) values as made available from the CCWR server were further required for interpolation by Anusplin.

Mean annual and mean monthly rainfall and temperature values were obtained using Anusplin for all study sites concerned. This exercise was not intended to replace or improve on data presented in the SAAAC. This additional climate modelling was performed with the primary aim of deriving bioclimate from those values. Bioclim only accepts the surface coefficient files created by Anusplin as inputs. Although it was not expected that Anusplin would perform better than the region specific regression models developed by Dent *et al.* (1989), it was hoped that Anusplin would generate rainfall and temperature values that compared favourably enough to be used to derive reliable estimates of the bioclimate.

Hutchinson (1995) states that rainfall is typically the most variable climatic parameter over short distances. The climate values published in the SAAAC are at a 1 min x 1 min of a degree resolution. This inherently assumes that the rainfall estimates are constant over areas within 1 min x 1 min of a degree (≈ 1667 x 1667 m) cells, or that those estimates are averages of varying actual rainfall values within that cell. Louw (1997) mentions that the lack of high-resolution climatic data poses a drawback to site-growth studies in South Africa. Anusplin can calculate an estimated value of climate for any given X-Y coordinate pair using coefficients derived from initial input data. This is explained further in the materials and methods section. A 400 m grid size digital elevation model (DEM) was used to create spatial outputs of rainfall, temperature and bioclimatic estimates for visual presentation and comparison purposes. Rainfall values for study sites estimated by Anusplin using a 400 m DEM were well correlated ($R^2 = 0.86$) with figures published in the SAAAC. These results are presented in the results section.

Anusplin has been shown by other workers globally to provide robust, reliable estimates of rainfall. Price *et al.* (2000) working in Canada, compared rainfall estimates from Anusplin with those generated by a Gradient plus Inverse Distance Weighting (GIDS) model. In almost all cases, Anusplin was found to produce more reliable estimates of rainfall.

Hartkamp *et al.* (1999) performed a similar exercise in Mexico where they compared Inverse Distance Weighting Average (IDWA), thin-plate smoothing splines (using Anusplin) and co-Kriging. Their study area covered 20 000 km$^2$ and their results concluded that "taking into account valued error prediction, data assumptions and computational simplicity," they recommend the "use of thin-plate smoothing splines for interpolating climatic variables."

Fairbanks and Chapman (1997) attempted to compare the results of Anusplin for mean and median annual and monthly rainfall values with those published in the SAAAC. Using Anusplin, they remodelled rainfall surfaces for the Letaba River Catchment valley in South Africa, citing studies, where edge matching problems and interpolation errors in the data were reported, as their motivation. Furthermore, they identified a need for work of this kind within their own research interests within the CSIR. Their results showed that Anusplin is robust in its rainfall prediction capabilities. Direct comparison with the work conducted by Dent *et al.* (1989) was not possible due to those surfaces being manually fitted through the existing weather station data. However, they did evaluate Anusplin by randomly removing 10% of the input data points before remodelling the surface. The predicted versus the actual rainfall values yielded significant $R^2$ values of between 0.92-0.93 for annual rainfall. Hutchinson (1995), Hartkamp *et al.* (1999) and Price *et al.* (2000) both used this method of withholding 10% of the data points to validate the interpolation.

### 3.4.3 Bioclim

Bioclim forms part of the suite of programs called Anuclim developed at the Australian National University (ANU). Nix (1986) describes Bioclim as "a bioclimatic prediction system which uses surrogate terms (also known as bioclimatic parameters) derived from mean monthly estimates, to approximate energy and water balances at a given location." Summarised bioclimatic parameters were derived for the list of study sites and statistical methods employed to analyse their influence on wood properties.

The list of inputs required by Bioclim includes (Houlder *et al.,* 2001):

- Surface coefficient files generated by Anusplin for mean monthly rainfall, minimum and maximum temperature, solar radiation and potential evaporation (A-pan) containing 12 monthly values. It is not necessary to have surface coefficient files for all 5 meteorological variables as the program will create the parameters it can from available information.

- A list of sites of interest containing latitude, longitude and elevation.

- A digital elevation model (DEM) if spatial output data is required or if the Biomap feature is required to predict species distribution.

Although the climate surfaces describe the climate variables spatially at a monthly time interval, these values are normally interpolated into weekly values by Bioclim in order to get a finer start-time and end-time granularity for the period (1 week) and quarter based parameters. The procedure for converting from a monthly to a weekly time step is based on cubic Bessel interpolation of the cumulative monthly totals during the year (De Boor and Golub, 1978). For example, the wettest quarter of the year may begin in the 3$^{rd}$ week of January and continue to the 4$^{th}$ week of March. Monthly time steps may smooth out this kind of fluctuation and result in inaccurate results (Houlder *et al.*, 2001).

Bioclim can potentially generate 36 different climatic and bioclimatic parameters of the environment. Due to the input data surfaces being restricted to those describing rainfall and temperature, only 19 of these parameters were calculated. Of these 19 bioclimatic parameters, nine were chosen for analyses. Measures of rainfall were favoured for analyses while those that described temperature alone were mostly excluded. The reason for this was that temperature does not appear to show much variation within each geographic area whereas rainfall does. This conclusion was drawn from the temperature and rainfall maps published in the SAAAC. Furthermore, because both geographic regions are summer rainfall areas, inspection of the parameters revealed that some were co-variates of one another: rainfall in the wettest quarter is equivalent to the rainfall in the warmest quarter. Co-varying parameters were reduced by deleting one of them.

The nine parameters used are described by Houdler *et al.,* (2001) (for a derivation assuming a weekly time step):

1. **Mean Annual Temperature (MAT)**

   The mean of all weekly mean temperatures. Each weekly mean temperature is the mean of that week's maximum and minimum temperatures.

2. **Mean Diurnal Range (Mean(period Max-Min)) (DIUR_RANG)**

   The mean of all the weekly diurnal temperature ranges. Each weekly diurnal range is the difference between that week's maximum and minimum temperature.

3. **Temperature Seasonality (Coefficient of Variation) (TEMP_SEAS)**

   The standard deviation of the weekly mean temperatures expressed as a percentage of the mean of those temperatures.

4. **Temperature Annual Range (TEMP_ANN_R)**

   The difference between the maximum temperature of the warmest period and the minimum temperature of the coldest period.

5. **Mean Temperature of the Wettest Quarter (TEMP_WQ)**

   The mean temperature of the 13 consecutive weeks receiving the most rain throughout the year.

6. **Mean Annual Precipitation (MAP)**

   The sum of all the monthly precipitation estimates (mm).

7. **Precipitation Seasonality (CV) (PREC_SEAS)**

   The Coefficient of Variation is the standard deviation of the weekly precipitation estimates expressed as a percentage of the mean of those estimates.

8. **Precipitation of the Wettest Quarter (PREC_WQ)**

   The total rainfall (mm) of the wettest quarter of the year

9. **Precipitation of the Driest Quarter (PREC_DQ)**

   The total rainfall (mm) of the driest quarter of the year.

# Chapter Four
# Materials and Methods

### *4.1 Site Choice*

The choice of study sites was limited to those sites for which wood property data exist as a result of research conducted by the CSIR. These results are unpublished and available at the FFP. Sites where trees were sampled between the ages of 3 and 12 were considered. Forest sites were initially chosen for wood property evaluation based on: age, species, and site index as a substitute for site quality. This has resulted in a set of sites that range from poor to very good quality in terms of site index across different age classes. The total number of sites chosen to conduct this study was 43. Of these, 26 were situated in the Zululand coastal plain, while the remaining 17 were to be found in the Mpumalanga escarpment region. Sites were selected with the following criteria in mind:

a. Sites were chosen which were separated by the greatest geographical variation possible for the given data set.

b. Sites which had the most complete wood property data set were favoured for those which only had limited data.

c. Sites whose trees had been felled at an age of younger than 3 or older than 12 were excluded. While the largest possible dataset for a study of this type is favoured, any unwanted variation due to age of the trees was not.

On the Zululand coastal plain, 13 sites were situated in the Kwambonambi region, while 8 and 5 sites were located in the Mtunzini and False Bay areas respectively. On the Mpumalanga escarpment, 13 sites were situated near Barbeton in the Glenthorpe plantations, with the remaining 3 sites placed at Venus (2) and Waterhoutboom (1) near the town of Graskop. Table 1 is a complete list of all the sites considered in this study. Figure 1 is a map indicating the location of each of the sites.

*Table 1. Details of study site names, owners and locations.*

| Site Number | Geographic Region | Estate | Compartment Code | Owner | Latitude (°S) | Longitude (°E) | Altitude (m) |
|---|---|---|---|---|---|---|---|
| 1 | Zululand | Rattrays | RC42 | Mondi | 28 37 00 | 32 07 03 | 53 |
| 2 | Zululand | Rattrays | RC09 | Mondi | 28 36 17 | 32 06 25 | 68 |
| 3 | Zululand | Rattrays | RD26 | Mondi | 28 34 39 | 32 06 31 | 76 |
| 4 | Zululand | False Bay | J20 | Chennels | 28 00 50 | 32 19 56 | 12 |
| 5 | Zululand | Rattrays | RE41 | Mondi | 28 35 16 | 32 10 24 | 49 |
| 6 | Zululand | Teza | TH20 | Mondi | 28 31 12 | 32 08 25 | 61 |
| 7 | Zululand | Mtunzini | Q05 | Mondi | 29 01 06 | 31 40 40 | 64 |
| 8 | Zululand | Salpine1 | D3b | Sappi | 28 34 26 | 32 13 58 | 52 |
| 9 | Zululand | Salpine2 | H17 | Sappi | 28 34 10 | 32 14 48 | 45 |
| 10 | Zululand | The Gage | Gage | Mondi | 28 39 08 | 32 03 16 | 45 |
| 11 | Zululand | Kwambo Timbers | H9 | Sappi | 28 36 18 | 32 09 31 | 61 |
| 12 | Zululand | Hluhluwe | LO3A | Chennels | 27 57 00 | 32 21 00 | 76 |
| 13 | Zululand | Mtunzini | K13F | Mondi | 29 02 44 | 31 40 03 | 23 |
| 14 | Zululand | Mtunzini | K16A | Mondi | 29 02 31 | 31 39 31 | 76 |
| 15 | Zululand | False Bay | JO6 | Chennels | 28 01 00 | 32 20 00 | 79 |
| 16 | Zululand | Mfezi | ICO72MFZ | Mondi | 28 25 00 | 32 12 00 | 65 |
| 17 | Zululand | Mtunzini | KO8a | Mondi | 29 03 11 | 31 39 49 | 13 |
| 18 | Zululand | Mtunzini | KO3e | Mondi | 29 02 43 | 31 39 00 | 96 |
| 19 | Zululand | Mtunzini | G07 | Mondi | 28 54 10 | 31 47 18 | 57 |
| 20 | Zululand | False Bay | J07 | Chennels | 28 00 56 | 32 20 25 | 14 |
| 21 | Zululand | False Bay | J11 | Chennels | 28 00 50 | 32 19 56 | 12 |
| 22 | Zululand | Mavuya | C8 | Sappi | 28 31 00 | 32 12 00 | 42 |
| 23 | Zululand | Mtunzini | F17 | Mondi | 29 00 00 | 31 41 55 | 60 |

*Table 1. Continued.*

| Site Number | Geographic Region | Estate | Compartment Code | Owner | Latitude (°S) | Longitude (°E) | Altitude (m) |
|---|---|---|---|---|---|---|---|
| **24** | Zululand | Rattrays | RE10 | Mondi | 28 35 12 | 32 11 40 | 57 |
| **25** | Zululand | Mtunzini | H09a | Mondi | 28 54 47 | 31 47 26 | 55 |
| **26** | Zululand | Teza | TH22B | Mondi | 28 30 57 | 32 08 45 | 59 |
| **27** | Mpumalanga | Glenthorpe | F124 | Sappi | 25 48 53 | 30 53 53 | 841 |
| **28** | Mpumalanga | Glenthorpe | F105 | Sappi | 25 48 00 | 30 53 56 | 889 |
| **29** | Mpumalanga | Glenthorpe | F122 | Sappi | 25 49 11 | 30 53 27 | 917 |
| **30** | Mpumalanga | Glenthorpe | F77 | Sappi | 25 47 45 | 30 53 17 | 932 |
| **31** | Mpumalanga | Glenthorpe | F146 | Sappi | 25 49 07 | 30 54 24 | 1027 |
| **32** | Mpumalanga | Glenthorpe | B19 | Sappi | 25 40 30 | 30 48 00 | 973 |
| **33** | Mpumalanga | Glenthorpe | B88 | Sappi | 25 41 01 | 30 49 08 | 1002 |
| **34** | Mpumalanga | Glenthorpe | B17 | Sappi | 25 40 17 | 30 48 19 | 842 |
| **35** | Mpumalanga | Glenthorpe | B115 | Sappi | 25 41 48 | 30 50 43 | 916 |
| **36** | Mpumalanga | Glenthorpe | G10 | Sappi | 25 43 16 | 30 50 13 | 875 |
| **37** | Mpumalanga | Glenthorpe | M35 | Sappi | 25 37 39 | 30 50 36 | 879 |
| **38** | Mpumalanga | Glenthorpe | D2B | Sappi | 25 38 22 | 30 46 14 | 1032 |
| **39** | Mpumalanga | Glenthorpe | E5 | Sappi | 25 30 26 | 30 51 36 | 945 |
| **40** | Mpumalanga | Sabey | D54 | Sappi | 25 39 15 | 30 47 27 | 803 |
| **41** | Mpumalanga | Venus | A14 | Sappi | 25 00 09 | 30 54 56 | 751 |
| **42** | Mpumalanga | Venus | A33 | Sappi | 25 00 19 | 30 56 36 | 1048 |
| **43** | Mpumalanga | Waterhoutbome | H09 | Mondi | 24 56 56 | 30 52 50 | 1027 |

**Note: "Sabey" and the well known "Sabie" areas are geographically distinct.**

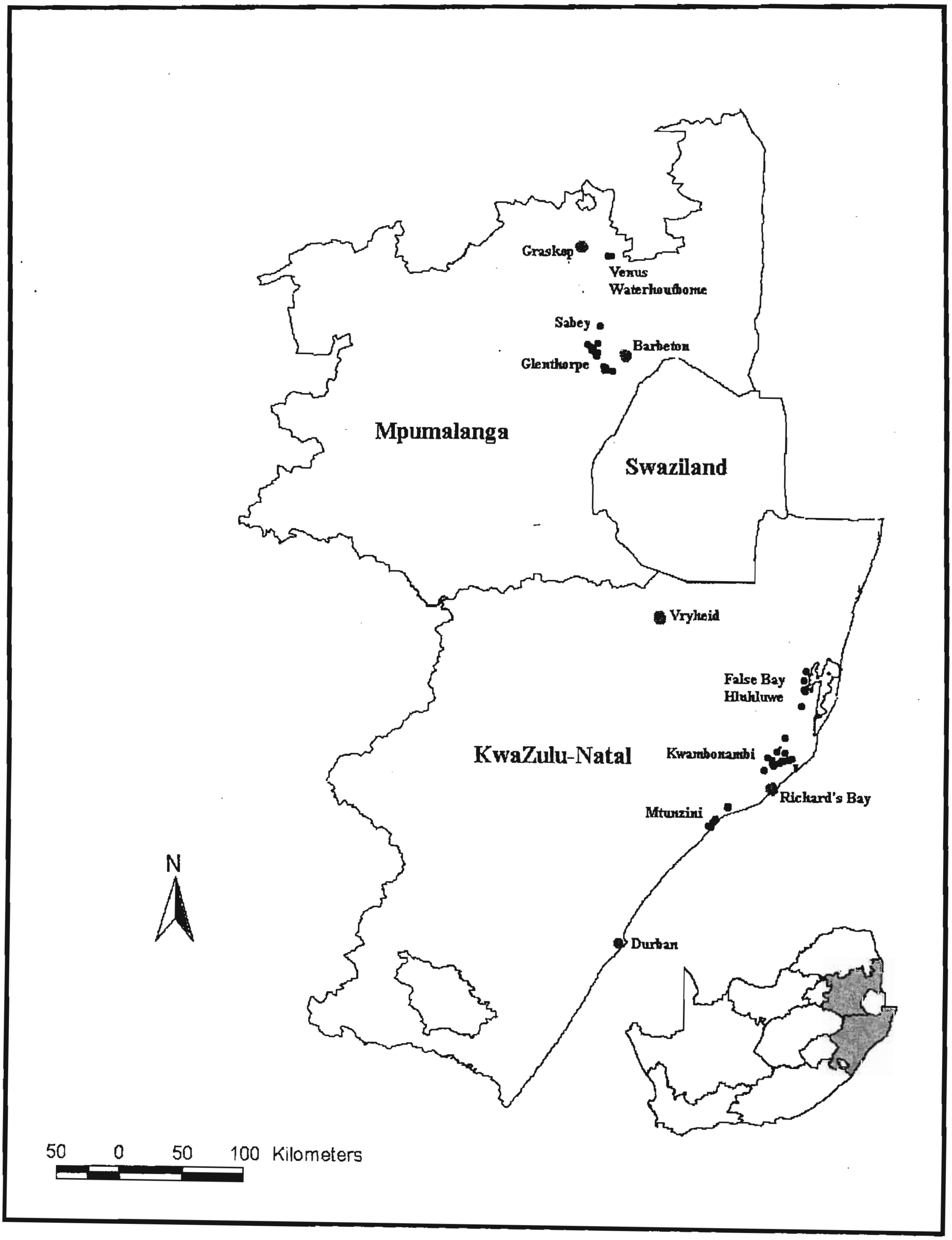


*Figure 1. Map showing study site locations in the Mpumalanga and KwaZulu-Natal provinces of South Africa.*

## *4.2 Wood Property Determination*

The measurement of any wood property of a particular stand of trees is a complex process that requires careful planning and consideration of all the factors that will affect the final value assigned to those trees. The process must take into account all sources of variability and potential error and these should be considered when viewing the final results.

### 4.2.1 Tree felling

Wood property measurement starts in the field before trees are sampled. Although there are destructive and non-destructive methods for sampling trees for wood property measurement, all wood quality data used in this study was collected from destructively sampled trees. Destructive sampling involved felling selected trees and taking disks and billets (set lengths of the tree stem) at specific heights for analyses. Non-destructive methods involve taking wood cores from specific heights on the trees and subjecting these samples to tests in the laboratory.

Trees for analyses were sampled from areas within the plantation compartment called sample plots. All trees were sampled from the control plots of the various studies. Numerous sample plots within each compartment were sampled to more accurately determine a representative value for wood properties. The work was undertaken using a compartment factorial design where age and SI were factors. The number of sample plots as well as the number of trees felled within each sample plot varied for each of the individual studies. Table 2 is a summary of the different studies from which data was taken for this project. Table 2 highlights the number of geographically separated sites in each study, the number of trees sampled at each site, as well as the number of randomly placed sample plots from within each site. Enumeration of the sample plots was carried out by measuring diameter at breast height (DBH), and after felling, total height and height to where the stem diameter was 0.07m for every tree within the plot. Trees were randomly chosen from within those felled per site for actual wood property analysis as shown in Table 2.

*Table 2. Differences in sampling procedure and number of trees felled for wood property determination between study sites.*

| Study Name | Species or Clone | Number of sites | Trees Sampled/site | Sample Plots | Trees for analysis | Trees used for analysis |
|---|---|---|---|---|---|---|
| Tag5 - 1996/1998 | Tag5 | 16 | 20 | 5 plots/site | 10 trees/site ; 2/plot | 10 |
| GC550 -site | GC550 | 3 | 10 | 5 plots/site | 5 trees/site ; 1/plot | 5 |
| Genotype | Various | 1 | 180 | 3 plots/genotype | 5 trees/plot | 90 |
| Weeding | GC341 | 1 | 60 | 4 plots/treatment | 20 trees/treatment | 60 |
| Fertiliser + Other | GUA380 | 5 | 6 | 3 plots/site | 6 trees/site | 24 |
| Geographic | E.g. seedling | 17 | 20 | 20 trees/site | 20 trees/site | 20 |

The study name refers to the name of the CSIR project and consequently the source of the wood property data. Most studies were conducted using cloned tree material: Tag5 refers to a popular *E. grandis* clone, GC550 and GC341 are clones of *E. grandis* cross *camaldulensis*, while GUA380 is a highly successful E. *grandis* cross *urophylla* clone owned by Sappi. The Genotype trial included tree material from all of the above sources to compare the effect of species/clone grown in the same environment on wood properties. Silvicultural practices cound have a considerable effect on growth rate and wood properties. However, unfortunately much of the initial site data had been mislaid and this factor could not be included in the analysis. It is possible that some of the variation in the data set could have been due to silvicultural practice.

### 4.2.2 Pulping and laboratory methods

A common pulping environment was used for all cooks. A source of error was, however, introduced into the study through variation in the choice of disks from various locations on the tree stem to pulp, as well as through the distinction between an average value for a bulked pulp sample as opposed to the average of many individual tree pulps. Table 3 summarises the different methods of sampling for wood property determination. Pulping was carried out on 800g oven-dry wood samples. These samples were pulped in an electrically heated rotating laboratory digester using the kraft process. Pulping conditions were selected to achieve a kappa number of between 20 and 22.

Pulping conditions were as follows:

| | |
|---|---|
| - AA charge (%$Na_2O$) on oven-dry wood | 16% |
| - Sulphidity | 25% |
| - Liquor to wood ratio | 4.5:1 |
| - Pulping cycle: Ambient to 170°C | 90 minutes |
| Time at 170°C | 50 minutes |

- Degassing was carried out at 115°C and 135°C remove gases not condensable in water
- Blow-down atmospheric pressure at end of cook 20 minutes

A spent liquor sample was taken at the end of the cook and analyzed for AA content according to TAPPI method T625 om-85.

Pulp yield, and subsequently, screened pulp yield (SPY) was calculated. The SPY may be described as the pulp yield after uncooked fibres, dirt and bark (rejects) have been removed through a plate with narrow (0.2 mm) slots. It is usually expressed as a percentage in terms of oven dry mass of pulp per unit oven dry mass of the original wood. No error is expected due to the differences in measuring SPY by averaging single trees or pulping a bulked sample (P.Turner, Pers.Comm., 2003). Some unforced variation in results may exist as a result of different parts of the tree being used for pulping as indicated in Table 3. Density was measured on strips of wood cut from discs as shown by Table 3. The cut strips of wood were allowed to dry until equilibrium moisture content was reached. Strips 2.5 mm in thickness were cut from the original strips. A densitometric scan was carried out at 0.5 mm intervals from pith to bark to determine the density profile using a Gamma-Ray Densitometer. Weighted mean density is calculated by multiplying each density value by the area at which it was measured; these values are then added together, and this is divided by the sum of the squares of all the distances from the pith. There is no introduced error in the density measurements due to varying methods of determination between studies. Fibre length was measured on a sub-sample of pulp from the original cook. For all studies, fibre length was measured using a Kajaani fibre length analyzer located either at Mondi's Richard's Bay Laboratory, or at Sappi's laboratory in Springs.

*Table 3. Comparison of wood property determination techniques between studies.*

| Study Name | Tag5 – 1996 | Tag5 - 1998 | GC550 -site |
|---|---|---|---|
| Species | E. grandis (Tag5) | E. grandis (Tag5) | GxC550 |
| Pulping (1) | 20 mm discs from 5,10,15...100% top height | 20 mm discs at 1 m intervals (ind tree) | 20 mm discs at 1 m intervals (ind tree) |
| Wood Properties (2) | 60mm disc at 5,15,35,65% of tree Ht | 60mm disc at 5,15,35,65% of tree Ht | 60mm disc at 5,15,35,65% of tree Ht |
| Density | discs from (2) - γ-Ray Densitometer | discs from (2) - γ-Ray Densitometer | discs from (2) - γ-Ray Densitometer |
| Pulping (3) | ave. of single tree values from (1) | ave. of single tree values from (1) | ave. of single tree values from (1) |
| Fibre length | sample from (3) Kajaani | sample from (3) Kajaani | sample from (3) Kajaani |
| Active alkali | TAPPI method T625 om-85 | TAPPI method T625 om-85 | TAPPI method T625 om-85 |
| **Study Name** | **Genotype** | **Weeding** | **Fertiliser** |
| Species | Various | GxC341 | GxUA380 |
| Pulping (1) | 20 mm discs at 1 m intervals (ind tree) | 20 mm discs at 1 m intervals (ind tree) | 1.5m billets at tree base |
| Wood Properties (2) | 60 mm disc at 5,15,35,65% of tree Ht | 60 mm disc at 5,15,35,65% of tree Ht | 60 mm disc at 5,15,35,65% of tree Ht |
| Density | discs from (2) - γ-Ray Densitometer | discs from (2) - γ-Ray Densitometer | discs from (2) - γ-Ray Densitometer |
| Pulping (3) | ave. of single tree values from (1) | ave. of single tree values from (1) | ave. of single tree values from (1) |
| Fibre length | sample from (3) Kajaani | sample from (3) Kajaani | sample from (3) Kajaani |
| Active alkali | TAPPI method T625 om-85 | TAPPI method T625 om-85 | TAPPI method T625 om-85 |
| **Study Name** | **Geographic** | | |
| Species | E. grandis seedling | | |
| Pulping (1) | 20 mm discs at 1 m intervals (bulked) | | |
| Wood Properties (2) | 60 mm disc at 5,15,35,65% of tree Ht | | |
| Density | discs from (2) - γ-Ray Densitometer | | |
| Pulping (3) | Bulked sample from 20 trees | | |
| Fibre length | n/a | | |
| Active alkali | TAPPI method T625 om-85 | | |

### *4.3 Geology and Soils*

#### 4.3.1 Geology and Soil sampling and analyses

1:250 000 scale geological maps were consulted to determine the underlying parent material of the sites.

Representative soil samples of each site were taken by collecting samples along random transects throughout the site. Both topsoil and subsoil samples were sampled by auger and described to a depth of 1500 mm. Soils were identified and classified to the family level according the Soil Classification Working Group (1991). The topsoil was regarded as that soil contained in the top 300 mm of the soil (0-300 mm) while subsoil samples were taken at a common depth of 500 mm where possible. Note was made of instances where parent material or stone lines impeded auger penetration to this depth and this was regarded as the Effective Rooting Depth (ERD). The aspect and topography of each individual site was also recorded. The steepness of the dominant slope was measured using a Vertex III Hypsometer and recorded as a percentage. The cardinal direction in which the dominant slope faced (aspect) was recorded using a common surveyor's compass. Any other outstanding features of the site were recorded, including evidence of wetness and the prevalence of surface boulders.

Soil samples were subjected to particle size distribution (PSD) analysis according to the method outlined by Gee and Bauder (1986) for both the topsoil and subsoil samples. Organic carbon content was determined for all the topsoil samples by means of the Walkley-Black method (Walkley, 1947). These results were multiplied by a constant factor to estimate organic matter content (OM). Soil samples were prepared and soil analyses were carried out by laboratory staff at the Soil Science Divison of the School of Applied and Environmental Sciences, University of Natal, Pietermaritzburg.

### 4.3.2 Soil water retentivity determination

Soil water retentivity characteristics were determined for all the study sites based on measures of the relative proportions of sand, silt and clay (PSD) in each soil profile. This was performed based on work conducted by Smith *et al.* (2001) where standard retentivity curves were derived for South African soils that fell into particular soil textural classes. Each site was classed into a textural class based on its PSD, before standard water retention characteristics for these classes were recorded.

## *4.4 Site Index determination*

Site index at a base age 5 was determined for all sites using an unpublished site index derivation curve and coefficients supplied by Mondi Forests and represented by the equation,

$$\mathrm{SI}_5 = exp(b_1 + b_4 * exp(-b_1/\mathrm{age}_1)) * (ln(\mathrm{Ht}) + (b_3 - b_2/\mathrm{age}_1)) \qquad ...1$$

Region and species specific coefficients were used for Zululand and Mpumalanga as supplied by Mondi. Region specific methods of determining site index may have resulted in some discrepancy when including these figures in the same analyses across geographic regions. This source of error was duly noted and considered when reviewing the results of statistical analyses.

## *4.5 Rainfall and Temperature*

### 4.5.1 South African Atlas of Agrohydrology and –Climatology (SAAAC)

The methodology followed by Dent *et al.* (1989) to derive MAP estimates is summarised by Schulze (1997) as follows: "South Africa (including Lesotho and Swaziland) was divided into 34 regions each considered homogenous in relation to "controls" of rainfall distributions. The "controls" for rainfall in each region included altitude, distance from sea, aspect, terrain roughness and direction of prevailing rain bearing winds. Point data from more than 6000 rainfall stations were used to develop equations for MAP for each region. From this, a 1 min x 1 min of a degree gridded values of MAP were generated."

This data was interrogated using the GIS (Geographical Information System) software package Arc/Info 8.0.2 to obtain MAP values for all the study sites to be used in surface comparison against those estimates produced by Anusplin.

### 4.5.2 Anusplin

Figure 2 is a flow chart showing the basic methodology followed in this project to estimate rainfall and temperature values.

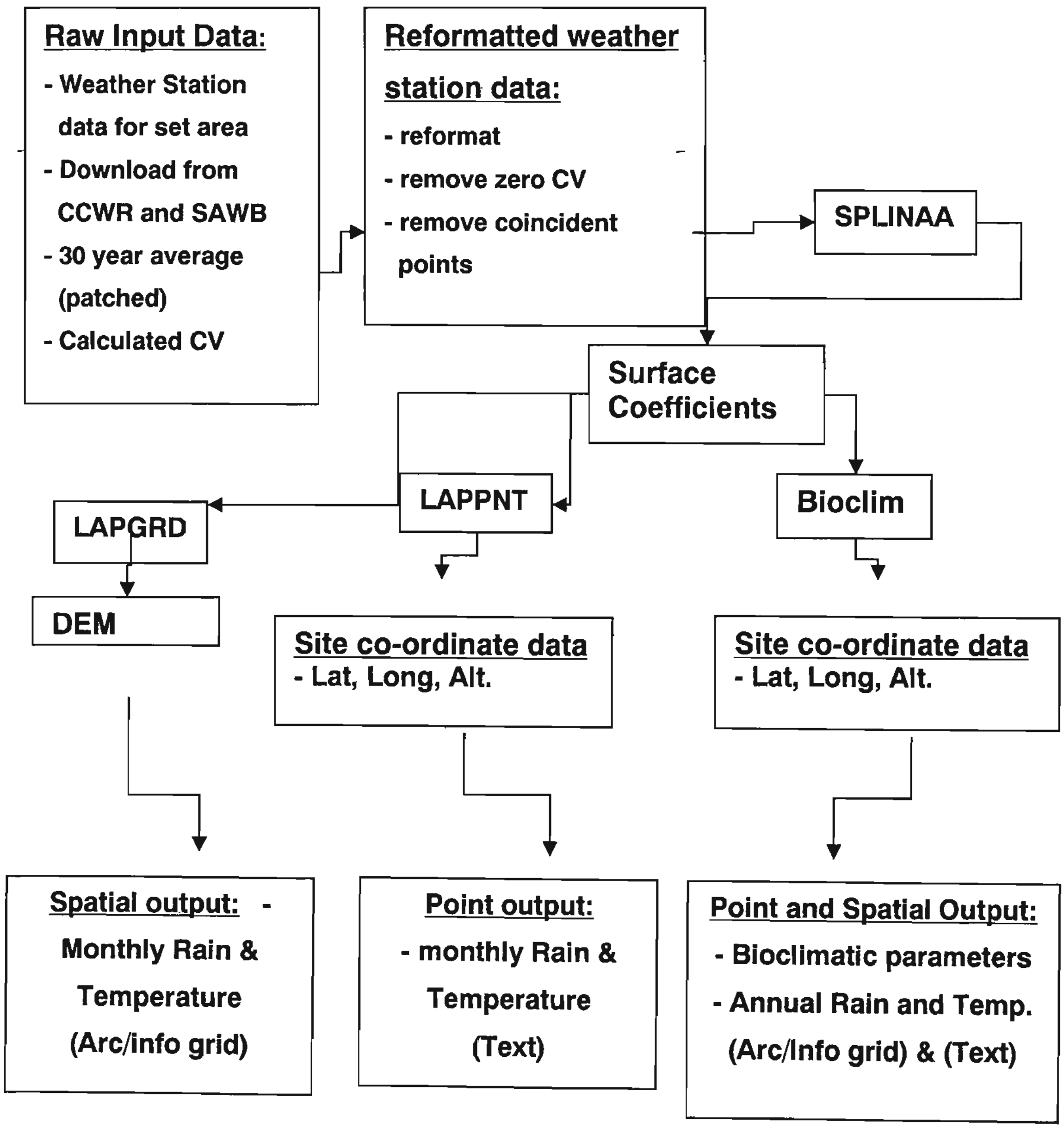


*Figure 2. Flow chart describing the use of Anusplin and the prediction of climatic variables*

Annual and mean monthly rainfall and temperature coefficients were calculated using the SPLINAA program within Anusplin. SPLINAA is described as a program that fits partial thin-plate spline functions of one or more independent variables, with different relative variances for each surface (Anusplin User Documentation, 3.1). SPLINAA outputs surface coefficient files that describe the climatic variable surface as a function of the independent variables. Monthly mean predicted values for rainfall and temperature were calculated for each site using the LAPPNT program. LAPPNT calculates values of the spline surfaces at specific points supplied by a text file containing the latitude, longitude and altitude (in the case of rainfall and temperature) of each study site. Bioclim also calculates values of spline surfaces given this input, but uses this input to generate bioclimatic surrogate parameters of the environment. In both instances, this was performed without the use of a digital elevation model (DEM), indicating the independence of these values from any effects of grid size or other problems associated with a DEM. A DEM of 400 m grid size was used to create Arc/Info grids for all climatic and bioclimate measures. This spatial data was also used at a later stage to create spatial outputs of wood property estimation.

Raw climatic input data (as individual weather station records) were downloaded from the CCWR server located at the University of Natal, Pietermaritzburg. Only weather stations with records exceeding 30 years in duration were chosen for interpolation. Dunne and Leopold (1978) state that this is typically required when interpolating rainfall statistics because inter-annual and monthly variance is required. This input dataset was extracted from the CCWR 'patched' dataset. The patched dataset included those weather stations with missing or incomplete data. Statistical methods at the CCWR have filled in missing years' data to create more reliable long-term means. These data were included to increase the number of input data points to the Anusplin model and improve interpolation reliability. This dataset was reviewed and stations with zero CV values for rainfall records and co-incident data points were removed as Anusplin does not accept these. The dataset was also rearranged to a format suitable for input into the Anusplin model.

Surface coefficient files were calculated (SPLINAA) for two main areas (MPM and KZN) within which the study sites fell. The areas demarcated for climate surface determinations were made larger than was needed to contain the study sites. The goal of this was to include more input data points into the Aunsplin model from each geographic area to ensure the best possible coefficient calculation for that region. The two main areas for which coefficients of each climatic variable were calculated by SPLINAA are depicted in Figure 3.

The co-ordinate limits for these areas are (decimal degrees):

[ $X_{min}X_{max}Y_{min}Y_{max}$ ; Area ($km^2$) ]

| | | | | | |
|---|---|---|---|---|---|
| Zululand: | 31.000 | 32.500 | -29.500 | -27.000 | 39 500 $km^2$ |
| Mpumalanga: | 30.000 | 32.000 | -26.000 | -24.000 | 40 000 $km^2$ |

Within these demarcated areas, 95 weather stations in KZN and 180 in MPM were found to fit the selection criteria stated above. This resulted in an approximate data point density of 1/395 $km^2$ and 1/222 $km^2$ for KZN and MPM respectively.

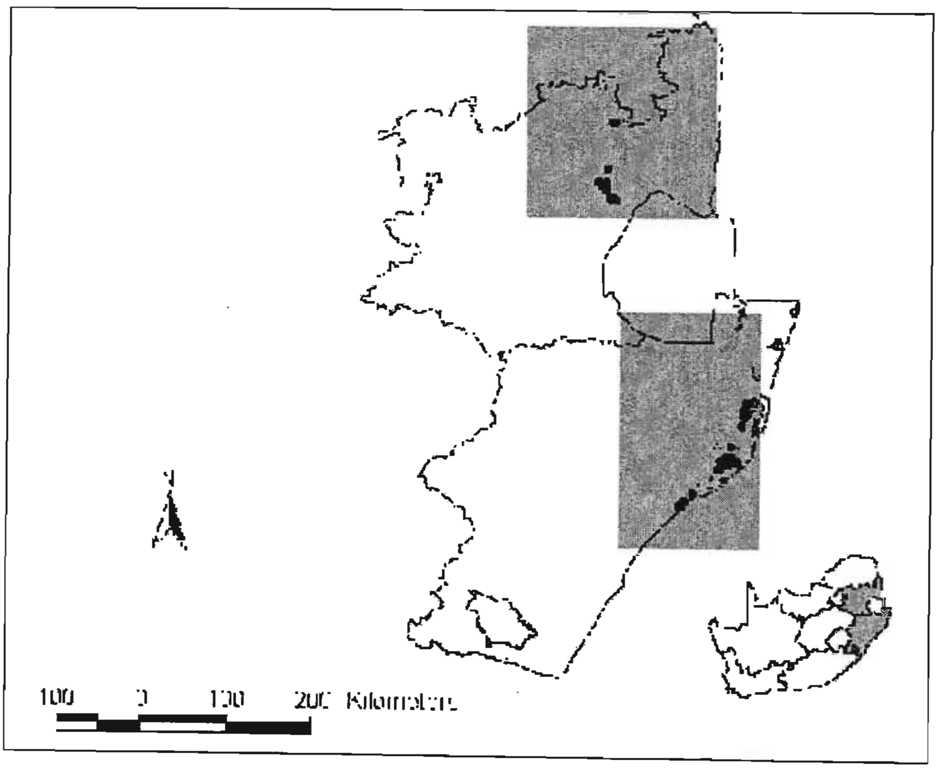

*Figure 3. Map showing the location and extent of the areas for which rainfall and temperature were modelled using Anusplin. Study sites within these areas are also shown.*

Two methods were employed to test the validity of the ability of Anusplin to predict rainfall. These analyses were conducted on predicted MAP values only. The sum of the individual monthly mean rainfall values predicted by Anusplin were almost identical to the MAP predicted from annual rainfall input data.

Firstly, 10% of the input data points from each dataset were randomly chosen and withheld and new rainfall values were predicted using these reduced datasets (Hutchinson, 1995, 1998; Price *et al.,* 2000; Hartkamp *et al.,* 1999). Predicted rainfall of these withheld stations was compared with actual rainfall using linear regression. Figure 4 plots predicted MAP against actual MAP recorded for the withheld data points.

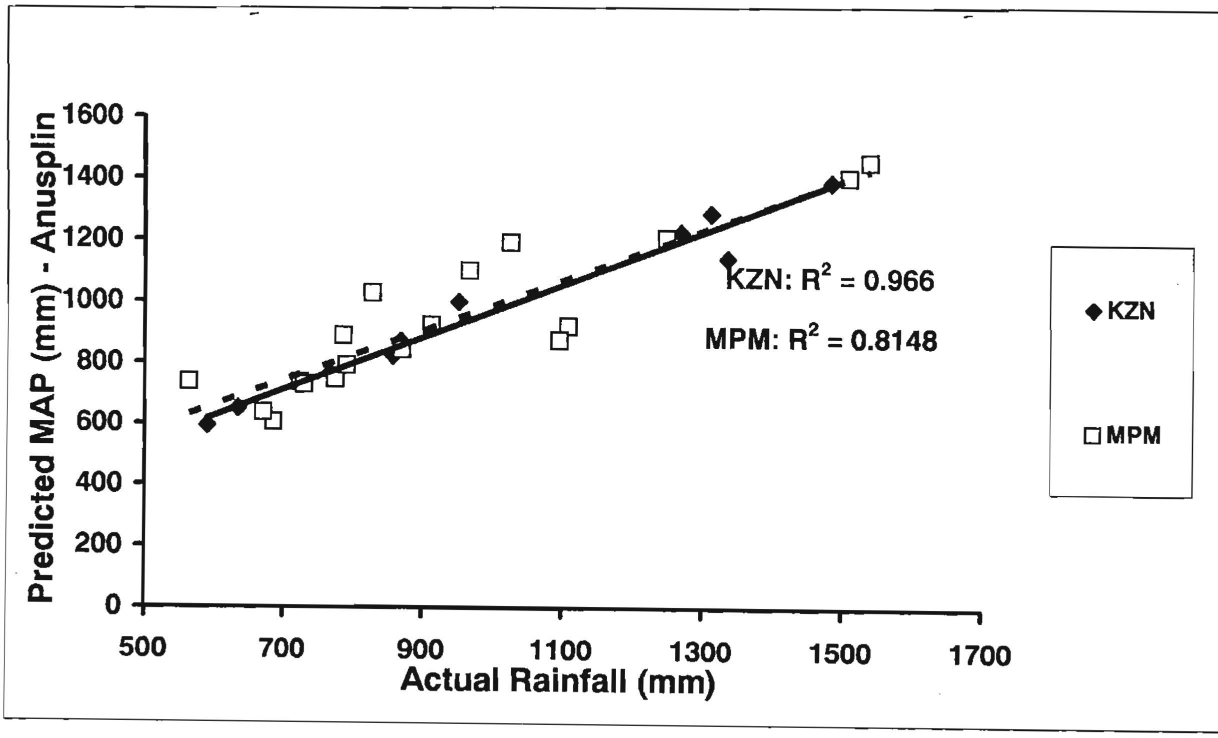


*Figure 4. Graph plotting Anusplin predicted MAP against actual rainfall values of withheld data point*

Results show that Anusplin predicts rainfall more accurately in Zululand than in Mpumalanga. This is expected as the factors driving rainfall on the Mpumalanga escarpment are likely to be more complex than those of the Zululand coastal plain due to a greater distance from the ocean and a more varied topography (Du Plessis, 2002).

The second method of validating Anusplin involved comparing predicted values with those of the SAAAC. Since Dent *et al.* (1989) manually fitted their modelled MAP surface to pass through actual data points, it was not possible to gauge the performance of this surface as compared to actual rainfall values. Therefore, values predicted by the two modelling approaches were compared. Such comparison, using all the study sites reveals a high correlation ($R^2$=0.86 $p<0.01$) between Anusplin and SAAAC predicted values of MAP. Figure 5 is a plot of the predicted values for MAP by Anusplin and SAAAC. Two outliers were removed from the dataset, where Anusplin predicted values for MAP of more than 300mm lower than those in the SAAAC.

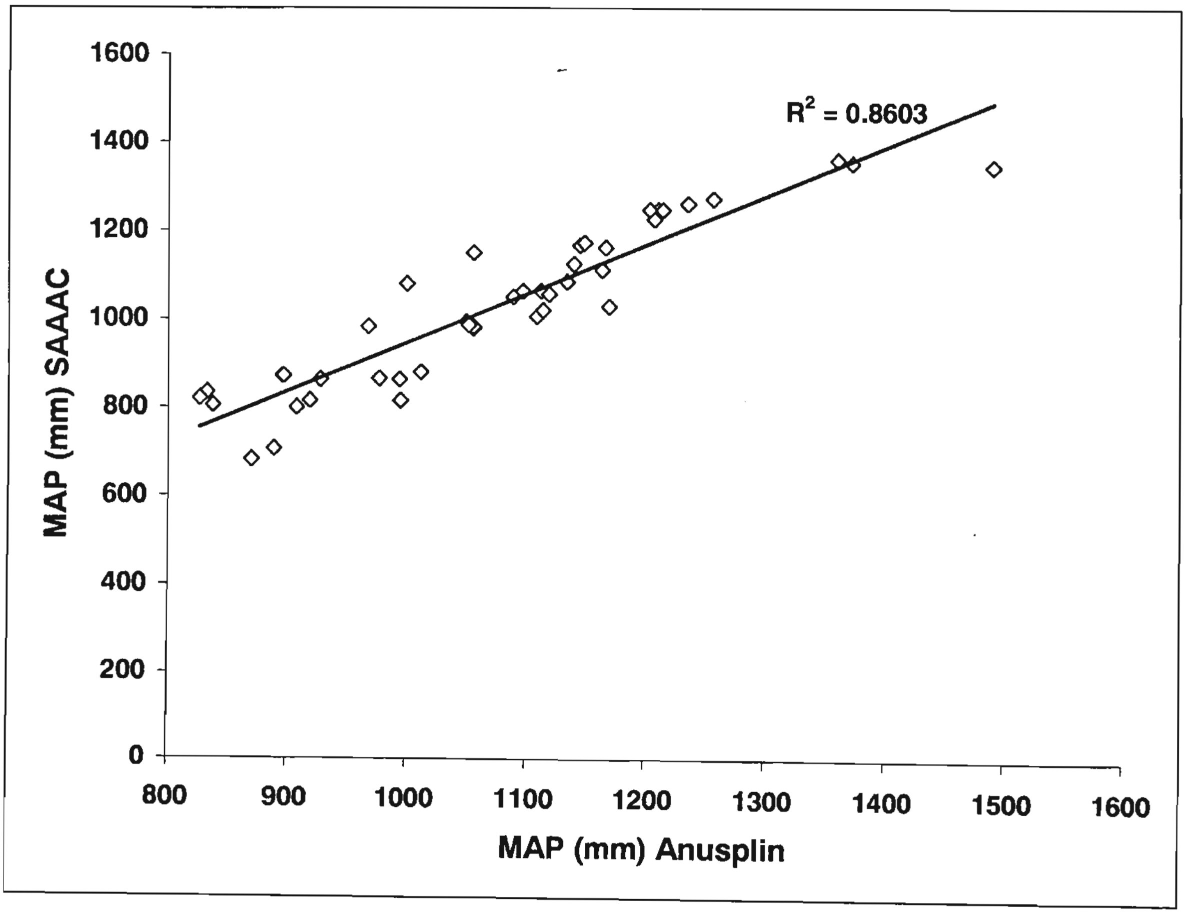


*Figure 5. Graph plotting predicted MAP (mm) of Anusplin against predicted MAP (mm) of SAAAC.*

Likewise, a regression performed between MAT values predicted by Anusplin and those published in the SAAAC showed a significant and strong relationship between the two: $R^2=0.84$ [$p<0.01$].

Figures 6 and 7 show comparative histograms for Anusplin and SAAAC MAP grids in Zululand and Mpumalanga respectively. The histograms represent the incidence (count) of particular rainfall classes within the modelled area. The classes represented in Figures 6 and 7 encompass the same range of rainfall values ie. they are of even sizes between classes and between Anusplin and SAAAC. The histograms created for the SAAAC values were done so from clipped areas of the national coverage grid that corresponded to those used for Anusplin. Anusplin MAP grids were created using a digital elevation model (DEM) with a 1 min x 1 min of a degree grid size.

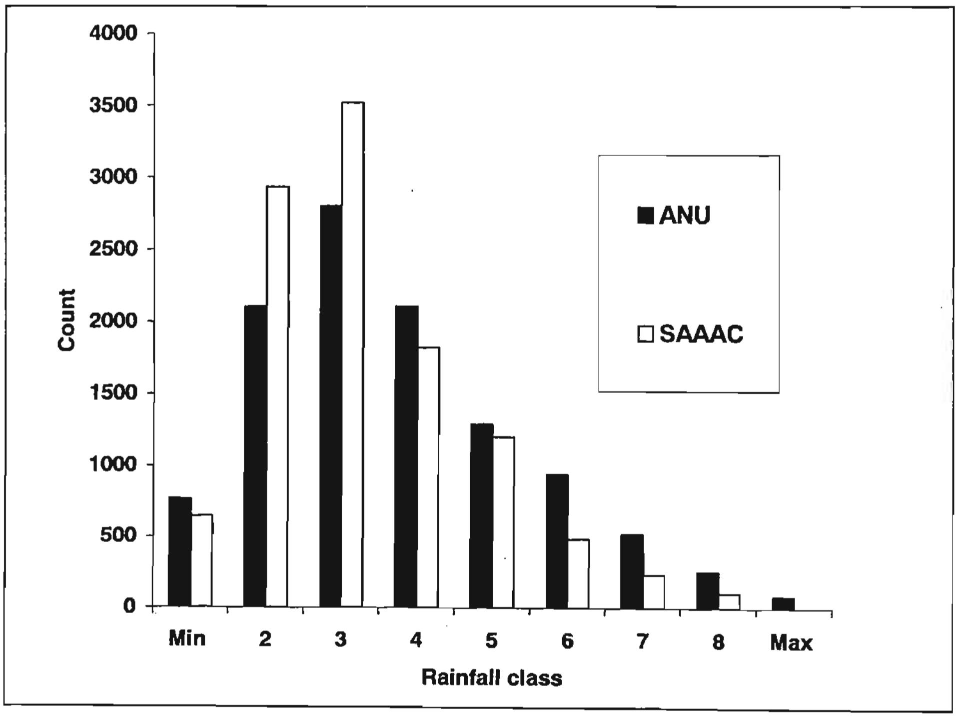


*Figure 6. Histograms of rainfall distribution of Anusplin and SAAAC grids of MAP (mm) in Zululand.*

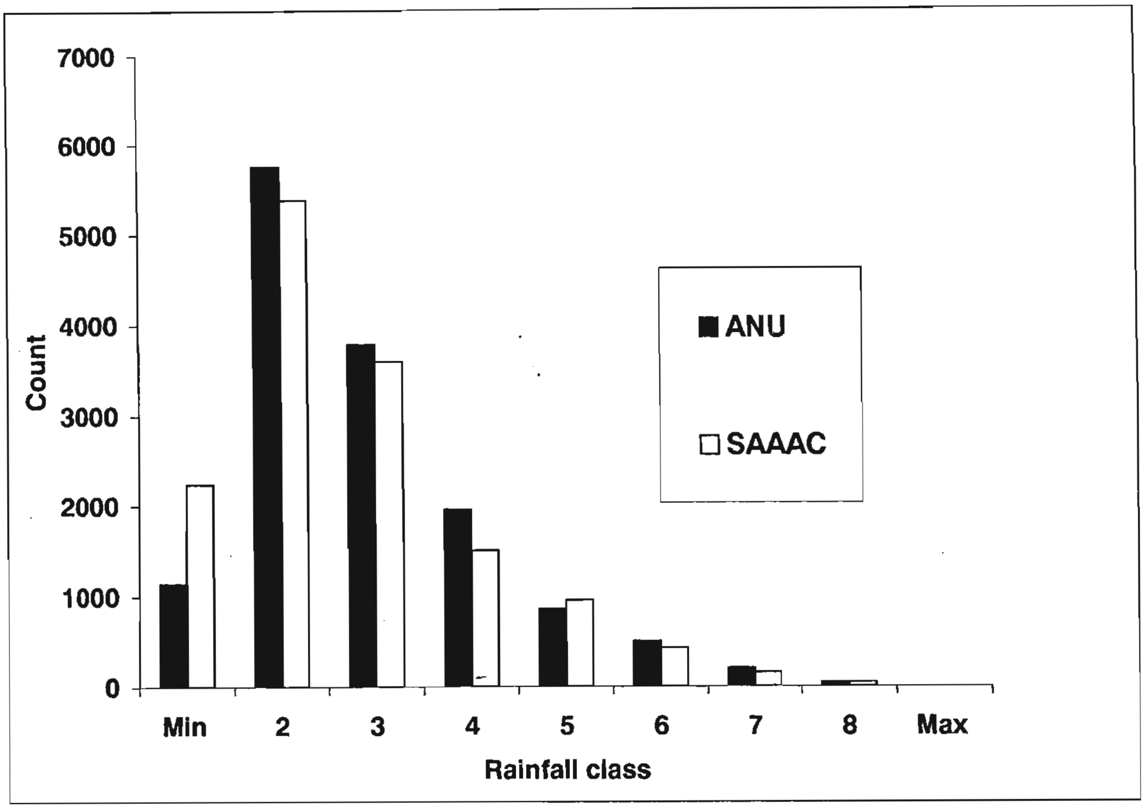


*Figure 7. Histograms of rainfall distribution of Anusplin and SAAAC grids of MAP (mm) in Mpumalanga.*

Both rainfall distributions for MAP show a positive skew which is indicative of rainfall patterns in South Africa according to Schulze (1997). The rainfall distributions also showed similar trends between Anusplin and SAAAC grids although the ranges of predicted values differed between the two. As a rule, the values predicted by the work of Dent *et al.* (1989) were higher than those of Anusplin.

Based on the above information, the ability of Anusplin to predict rainfall and temperature for the purposes of this project was considered reliable and robust.

### *4.6 Solar Radiation*

Solar radiation (MJ/m$^2$/day) was calculated for 3 specific seasonal times throughout the growing year (summer and winter solstices and the equinox) for each site in

Mpumalanga based on the function presented by Schulze (1997) in the SAAAC. This function takes latitude, time of year, aspect and slope into account.

# Chapter Five

# Results – Wood Properties and Site Characteristics

### *5.1 Wood Properties*

Complete results for SPY and FL_WM are included in Table A3 of Appendix 3. Summary statistics for all measured wood properties are shown in Table 4. Reduced values of n indicate missing data for those wood properties.

*Table 4. Summary statistics for all wood properties of concern as well as age and diameter at breast height (1.3m) (DBH).*

| Wood property / variable | Geographic Area | n | Mean | Min | Max | Standard Deviation |
|---|---|---|---|---|---|---|
| SPY (%) | All | 42 | 49.76 | 45.80 | 53.70 | 1.9 |
| | Zululand | 25 | 49.30 | 45.80 | 51.90 | 1.7 |
| | Mpumalanga | 17 | 50.47 | 46.65 | 53.70 | 1.9 |
| WMD ($kg/m^3$) | All | 35 | 456 | 369 | 590 | 50.2 |
| | Zululand | 25 | 471 | 388 | 590 | 46.7 |
| | Mpumalanga | 10 | 416 | 369 | 475 | 35.8 |
| FL_WM (mm) | All | n/a | n/a | n/a | n/a | n/a |
| | Zululand | 25 | 0.78 | 0.63 | 0.98 | 0.101 |
| | Mpumalanga | n/a | n/a | n/a | n/a | n/a |
| AA (%) | All | 41 | 82.73 | 70.90 | 91.70 | 4.84 |
| | Zululand | 24 | 82.30 | 70.93 | 91.26 | 4.43 |
| | Mpumalanga | 17 | 83.35 | 70.90 | 91.70 | 5.44 |
| DBH (cm) | All | 39 | 16.04 | 10.30 | 26.00 | 3.50 |
| | Zululand | 26 | 16.40 | 11.50 | 23.30 | 3.20 |
| | Mpumalanga | 13 | 15.34 | 10.30 | 26.00 | 4.10 |
| Age (years) | All | 43 | 7.20 | 2.8 | 12.0 | 2.0 |
| | Zululand | 26 | 6.90 | 5.0 | 9.0 | 1.2 |
| | Mpumalanga | 17 | 7.64 | 2.8 | 12.0 | 2.8 |

(SI – Site Index, WMD - Weighted Mean density, FL_WM – Weighted mean Fibre Length, AA – Active Alkali absorption, DBH – Diameter Breast Height)

### *5.2 Geology*

Site specific geological data is recorded in Appendix 1.

The underlying geology of the Zululand coastal plain consists of recent sands. Most sites were underlain by either yellow redistributed sands or red cordon sands that resulted in an overlying soil mantle of mostly sandy texture. Most study sites in Mpumalanga were found to lie on granitic parent material. Due to the lack of variation in underlying geology between study sites within geographical areas, the influence of this factor was not included in analyses.

### *5.3 Soils*

Complete soils data for each site is presented in Appendix 2. Data presented include soil classification (form and family), organic matter content and effective rooting depth (Table A2), particle size distribution, textural class categorization (Table A3).

Table 5 presents a summary of the soil effective rooting depth (cm) and organic matter content (%) of sites in each geographical region.

*Table 5. Summary of soil depth (cm) and organic matter content (%) data used in this study*

| Soil Variable | Geographical area | n | Mean | Min | Max | Standard Deviation |
|---|---|---|---|---|---|---|
| Effective Rooting Depth (ERD) (cm) | All | 43 | 135 | 25 | >150 | 37 |
| | Zululand | 26 | 146 | 35 | >150 | 22 |
| | Mpumalanga | 17 | 118 | 25 | >150 | 48.44 |
| Soil Organic Matter (%) | All | 43 | 2.48 | 0.33 | 9.31 | 2.23 |
| | Zululand | 26 | 1.15 | 0.33 | 4.36 | 0.93 |
| | Mpumalanga | 17 | 4.66 | 1.13 | 9.31 | 1.94 |

Most of the soils of the Zululand coastal plain were classified into the Clovelly, Constantia, Fernwood or Hutton soil forms (Soil Survey Working Group, 1991). Soils displayed luvic conditions as a rule, with clay content increasing slightly down the soil profile (Appendix 2). Most soils in this area were deep (>150 cm) and did not appear to inhibit root development. Soils in Zululand generally exhibited very low amounts of soil organic matter (Table 5). Subtropical climates with warm wet summers and mild winters lead to the rapid cycling of biomass and consequent small reservoir of soil organic matter (Duchafour, 1982). Soils in Mpumalanga contained appreciably higher amounts of organic matter in the topsoil than those in Zululand indicative of colder (and sometimes wetter) climatic conditions. Soils identified and classified at the Mpumalanga sites included Nomanci, Lusiki, Mispah, Valsrivier, Shortlands and Magwa soil forms (Appendix 2).

There was very little variation in soil texture between sites (Appendix 2) within geographical region, resulting in almost all the soils in Zululand falling into the same textural class (Sand). This resulted in identical values for soil-water retention for these soils according to the methods of Smith *et al.* (2001). The same was true for the textural classes of sites in Mpumalanga, with most sites being classed as clays, clay-loams or sandy-clay-loams (Appendix 2). Figure 8 represents comparative average sand, silt and clay fraction values for all the study sites in Zululand and Mpumalanga. Individual site values were calculated by averaging the values of the top- and subsoils. Soils on the Zululand coastal plain are mostly recent sands that contain nominal amounts of clay. Sites in Mpumalanga contained much higher levels of clay in both the topsoil and subsoil, and consequently had much better soil-water retention characteristics.

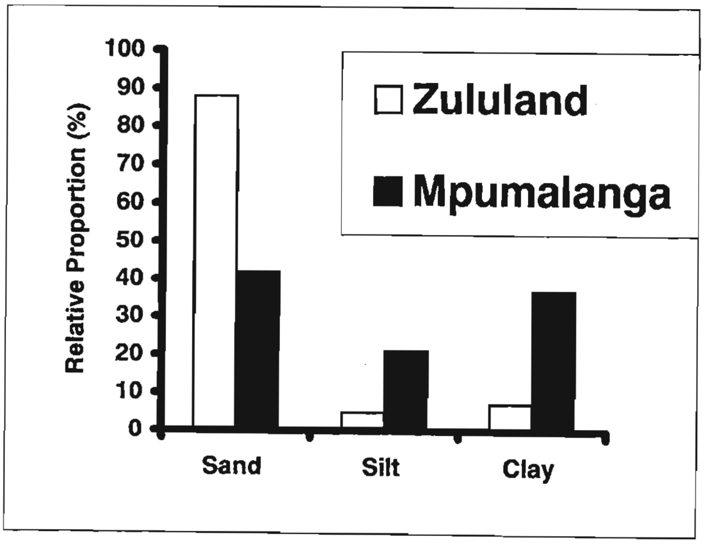


*Figure 8. Comparative average sand, silt and clay fractions for study sites in Zululand and Mpumalanga*

Figure 9 shows retentivity curves calculated from the average values of sand, silt and clay for each geographic region.

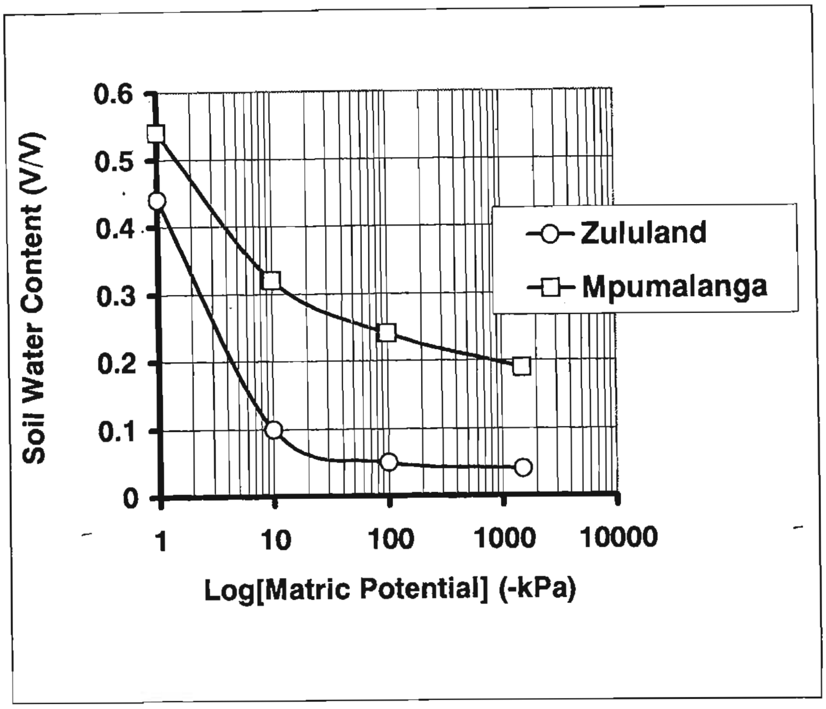


*Figure 9. Retentivity curves derived from average textural values for study sites in Zululand and Mpumalanga respectively.*

The results of Figure 9 indicate a large difference in retentivity characteristics between the sites in Zululand and Mpumalanga. Smith *et al.* (2001) state that the available water content (AWC) is that water held by the soil between the matric potentials of –10 kPa and –1500 kPa (field capacity and wilting point). The AWC is also referred to as plant available water (PAW). Similarly, that water held between –10 kPa and –100 kPa is understood to be amount of 'readily' available water (RAW) (Smith *et al.*, 2001). The ratio between RAW and PAW is an indication of the percentage of plant available water that is 'readily' available for plant uptake and use. The average RAW/PAW for the Zululand sites was 79%, whereas that for Mpumalanga was 63%. Although water is potentially more available to plants in times of drought in Mpumalanga, the opposite is true during the rainfall season. These results indicate that during times of abundant water supply, this water is more easily accessible by trees in Zululand.

Extremely high clay contents in soils such as some of those found in Mpumalanga may form zones that hinder root growth. Furthermore, the shrink-swell nature of these soils may damage tree roots. These factors, however minor, may impede tree growth and subsequently wood properties of those trees. Conversely, soils with high sand fractions, such as those in Zululand, lack structure (aggregation of soil particles) and are more susceptible to compaction and hard setting (Hillel, 1980) and this may cause tree growth stress by affecting water drainage and root growth.. This was particularly noted for sites that had high medium and fine sand fractions (Appendix 2)

The above results support the general acceptance of the Zululand coastal plain as a superior growing region in South Africa. Despite the obvious infertility of soils in Zululand, their sandy nature enhances the RAW during times of abundant water supply. The Zululand Coastal Plain is far more homogenous in terms of soils and topography than the Mpumalanga landscape which is affected by variation in soil depth, aspect and topography that contribute to the fate of precipitated water. It was expected that the Mpumalanga landscape would prove far more complex in terms of a site-growth study and that a distinction in site-growth responses may have to be made between Zululand and Mpumalanga.

## *5.4 Climate*

### 5.4.1 Rainfall and Temperature

Full results for mean annual and monthly rainfall and minimum and maximum temperature for individual study sites are presented in Appendix 3.

Table 6 presents summary statistics for monthly rainfall values (mm) for each site calculated by LAPPNT from surface coefficient files generated by SPLINAA. These statistics are calculated from the individual sites values and not from the climate surfaces as a whole. Maximum and minimum values are predicted values for the site with the lowest and the site with the highest average value respectively.

*Table 6. Summary statistics of monthly and annual rainfall data (mm) for study sites as predicted by Anusplin. Maximum and minimum represent values for the site with the highest and the site with the lowest predicted values respectively.*

| | Geographic Area | n | Mean | Minimum | Maximum | Standard Deviation |
|---|---|---|---|---|---|---|
| **Jan** | **All** | **43** | 147 | 111 | 252 | 26.96 |
| | **Zululand** | **26** | 131 | 111 | 145 | 11.19 |
| | **Mpumalanga** | **17** | 170 | 133 | 252 | 26.86 |
| **Feb** | **All** | **43** | 148 | 116 | 238 | 20.94 |
| | **Zululand** | **26** | 140 | 116 | 165 | 13.91 |
| | **Mpumalanga** | **17** | 159 | 131 | 238 | 24.76 |
| **Mar** | **All** | **43** | 128 | 100 | 183 | 16.75 |
| | **Zululand** | **26** | 132 | 104 | 155 | 15.02 |
| | **Mpumalanga** | **17** | 123 | 100 | 183 | 18.19 |
| **Apr** | **All** | **43** | 73 | 47 | 103 | 14.25 |
| | **Zululand** | **26** | 80 | 59 | 103 | 11.99 |
| | **Mpumalanga** | **17** | 62 | 47 | 93 | 10.67 |
| **May** | **All** | **43** | 49 | 19 | 88 | 23.66 |
| | **Zululand** | **26** | 67 | 47 | 88 | 12.69 |
| | **Mpumalanga** | **17** | 24 | 19 | 32 | 3.27 |
| **Jun** | **All** | **43** | 36 | 8 | 66 | 21.68 |
| | **Zululand** | **26** | 52 | 38 | 66 | 8.13 |
| | **Mpumalanga** | **17** | 11 | 8 | 17 | 2.35 |

*Table 6. Continued.*

| | Geographic Area | n | Mean | Minimum | Maximum | Standard Deviation |
|---|---|---|---|---|---|---|
| **Jul** | **All** | **43** | 33 | 10 | 63 | 18.47 |
| | **Zululand** | **26** | 47 | 30 | 63 | 10.14 |
| | **Mpumalanga** | **17** | 13 | 10 | 25 | 3.18 |
| **Aug** | **All** | **43** | 38 | 8 | 66 | 21.68 |
| | **Zululand** | **26** | 55 | 43 | 66 | 6.48 |
| | **Mpumalanga** | **17** | 13 | 8 | 25 | 4.43 |
| **Sep** | **All** | **43** | 59 | 27 | 95 | 21.29 |
| | **Zululand** | **26** | 74 | 53 | 95 | 12.66 |
| | **Mpumalanga** | **17** | 37 | 27 | 55 | 7.13 |
| **Oct** | **All** | **43** | 99 | 71 | 121 | 14.23 |
| | **Zululand** | **26** | 107 | 91 | 121 | 8.57 |
| | **Mpumalanga** | **17** | 85 | 71 | 101 | 10.16 |
| **Nov** | **All** | **43** | 124 | 93 | 179 | 23.16 |
| | **Zululand** | **26** | 110 | 93 | 134 | 12.82 |
| | **Mpumalanga** | **17** | 146 | 119 | 179 | 18.25 |
| **Dec** | **All** | **43** | 139 | 98 | 244 | 32.11 |
| | **Zululand** | **26** | 118 | 98 | 139 | 13.20 |
| | **Mpumalanga** | **17** | 171 | 133 | 244 | 25.29 |
| **MAP** | **All** | **43** | 1074 | 821 | 1442 | 145.72 |
| | **Zululand** | **26** | 1114 | 886 | 1333 | 133.37 |
| | **Mpumalanga** | **17** | 1013 | 821 | 1442 | 146.19 |

Table 7 shows solar radiation values for each site in Mpumalanga based on the latitude, slope and aspect dependant function presented by Schulze (1997). Slope and aspect are included with these results. These values do not take cloud cover into consideration. Average values were calculated from the summer, winter and two equinox values to represent an annual cycle.

*Table 7. Average seasonal solar radiation (MJ/m$^2$/day) values for Mpumalanga sites.*

| Estate | Compartment code | Slope (degrees) | Aspect (cardinal) | Radiation flux (MJ/m$^2$/day) Summer | Equinox | Winter | Average |
|---|---|---|---|---|---|---|---|
| Glenthorpe | **F124** | **13.7** | **N** | 30 | 26.5 | 21.5 | 26.13 |
| Glenthorpe | **F105** | **7.7** | **W-NW** | 31 | 26 | 18 | 25.25 |
| Glenthorpe | **F122** | **3.2** | **NNW** | 32.5 | 25.5 | 17.5 | 25.25 |
| Glenthorpe | **F77** | **12.6** | **SSW** | 32.5 | 22 | 17.5 | 23.50 |
| Glenthorpe | **F146** | **16.2** | **N-NNW** | 30.5 | 27 | 22 | 26.63 |
| Glenthorpe | **B19** | **37.8** | **NE** | 25 | 24.5 | 21.5 | 23.88 |
| Glenthorpe | **B88** | **12.6** | **S** | 32.5 | 22 | 16 | 23.13 |
| Glenthorpe | **B17** | **7.7** | **E** | 31 | 25 | 16.5 | 24.38 |
| Glenthorpe | **B115** | **6.3** | **E** | 31 | 25 | 16.5 | 24.38 |
| Glenthorpe | **G10** | **4.5** | **SW** | 31.5 | 24.5 | 15 | 23.88 |
| Glenthorpe | **M35** | **0.1** | **none** | 32 | 25 | 21 | 25.75 |
| Glenthorpe | **D2B** | **19.8** | **SE** | 31 | 22 | 12 | 21.75 |
| Glenthorpe | **E5** | **11.7** | **N** | 31 | 26 | 18 | 25.25 |
| Sabey | **D54** | **13.5** | **N** | 30 | 26.5 | 21.5 | 26.13 |
| Venus | **A14** | **29.7** | **E-NE** | 22 | 22.5 | 15 | 20.50 |
| Venus | **A33** | **40.5** | **W** | 26 | 20 | 13.5 | 19.88 |
| Waterhoutboom | **H09** | **0.1** | **none** | 32.5 | 25 | 21.5 | 26.00 |

Slopes facing north received higher amounts of solar energy as an annual average, while those facing south, west and east received less. Warmer slopes are both advantageous during the wet growing season, and a disadvantage during the dry season when water demands might be higher than on cooler, more southern facing slopes.

### *5.5 Bioclimate*

Full Results for all bioclimatic parameters predicted by Bioclim are included in Appendix 3. Summary statistics for all bioclimatic parameters are presented in Table 9.

The results of the bioclimatic parameters clearly indicate differences in the climate between Zululand and Mpumalanga. It may be concluded from these results that in terms of climate, Zululand presents the better growing environment to trees. On an annual and seasonal scale, Zululand appears to be warmer than Mpumalanga. Furthermore, the climate of the coastal plain is more temperate with smaller fluctuations in annual temperature than that of the Escarpment. Although the precipitation of the wettest quarter (PWQ) is higher in Mpumalanga, growth may be limited by less energy (lower temperature) during this time. Furthermore, there is an obvious winter period in Mpumalanga, which is characterized by low rainfall. This period might result in long periods where trees are put under water stress, and productivity of these trees is reduced.

These differences in bioclimate are sufficiently described when the geographical areas are classified according to the Worldwide Bioclimatic Classification System presented by Rivas-Martinez *et al.* (1999). These classifications are summarized in Table 8 below. The full summarised results for bioclimatic parameter values is presented in Table 9.

*Table 8. Climatic classification of the Zululand and Mpumalanga growing areas according to the Worldwide Bioclimatic Classification System of Rivas-Martinez et al. (1999).*

| Geographical Region | Macrobioclimate | Bioclimate | Thermotype | Ombrotype |
|---|---|---|---|---|
| Zululand | Subtropical | Pluvial Tropical | Thermotropical | Ultrahyperhumid |
| Mpumalanga | Subtropical | Pluviseasonal Tropical | Mesotropical | Ultrahyperhumid |

*Table 9. Summary statistics of 9 bioclimatic parameters for all sites as well as those in each geographic region. Maximum and minimum are values for the site with the highest and the site with the lowest predicted values respectively.*

| BioClimatic Parameter | Geographic Area | n | Mean | Minimum | Maximum | Standard Deviation |
|---|---|---|---|---|---|---|
| Mean Annual Temperature | All | 43 | 20.77 | 17.2 | 22.3 | 1.62 |
| | Zululand | 26 | 22.03 | 21.8 | 22.3 | 0.16 |
| | Mpumalanga | 17 | 18.83 | 17.2 | 19.6 | 0.55 |
| Mean Diurnal Range | All | 43 | 10.80 | 8.5 | 13.4 | 1.86 |
| | Zululand | 26 | 9.36 | 8.5 | 9.9 | 0.45 |
| | Mpumalanga | 17 | 13.00 | 11.4 | 13.4 | 0.50 |
| Temperature Wettest Quarter | All | 43 | 24.20 | 20.3 | 25.8 | 1.52 |
| | Zululand | 26 | 25.3 | 24.9 | 25.8 | 0.26 |
| | Mpumalanga | 17 | 22.4 | 20.3 | 23.4 | 0.75 |
| Temperature Seasonaltity (CV) | All | 43 | 1.01 | 0.89 | 1.18 | 0.11 |
| | Zululand | 26 | 0.93 | 0.89 | 0.98 | 0.03 |
| | Mpumalanga | 17 | 1.13 | 1 | 1.18 | 0.05 |
| Temperature Annual Range | All | 43 | 20.23 | 17 | 24 | 2.49 |
| | Zululand | 26 | 18.38 | 17 | 19.8 | 0.86 |
| | Mpumalanga | 17 | 23.07 | 20.2 | 24 | 0.99 |
| Mean Annual Precipitation | All | 43 | 1077 | 821 | 1442 | 149 |
| | Zululand | 26 | 1121 | 886 | 1333 | 133 |
| | Mpumalanga | 17 | 1008 | 821 | 1442 | 149 |
| Precipitation Seasonaltity (CV) | All | 43 | 53.00 | 33 | 79 | 19.88 |
| | Zululand | 26 | 37.23 | 33 | 43 | 3.01 |
| | Mpumalanga | 17 | 77.12 | 75 | 79 | 0.99 |
| Precipitation Wettest Quarter | All | 43 | 448 | 337 | 740 | 74 |
| | Zululand | 26 | 412 | 337 | 466 | 40 |
| | Mpumalanga | 17 | 505 | 411 | 740 | 79 |
| Precipitation Driest Quarter | All | 43 | 108 | 26 | 195 | 63 |
| | Zululand | 26 | 155 | 110 | 195 | 25 |
| | Mpumalanga | 17 | 35 | 26 | 63 | 9 |

### *5.6 Site Index*

Site index for each study site is presented in Table A3 of Appendix 3. Summary statistics for the calculated Site Index data are presented in Table 10. SI was not calculated for two sites in Zululand due to incomplete enumeration data.

*Table 10. Site Index$_5$ summary statistics.*

| | Geographical area | N | Mean | Minimum | Maximum | Standard Deviation |
|---|---|---|---|---|---|---|
| Site | All | 41 | 18.78 | 9.6 | 24.9 | 4.42 |
| Index | Zululand | 24 | 19.86 | 13.3 | 24.9 | 3.85 |
| ($SI_5$) | Mpumalanga | 17 | 17.27 | 9.6 | 24.8 | 4.83 |

# Chapter Six
# Modelling Wood Properties

### 6.1 Introduction

Statistical methods provide tools whereby meaningful interpretations of collected data may be obtained. Different types of analyses are designed and used to answer various questions based on the type of data, as well as the quantity and quality of that data. Most statistical methods are designed to give the results and conclusions obtained a measure of significance or relevance.

The statistical methods employed in this project were correlation analysis, comparison of two population means (t-test), cluster analysis and multiple regression. The creation of a robust predictive model required firstly that the dataset be reduced by removing variables that did not have a significant impact on wood properties. Correlation analysis preceded further analyses to aid in the refinement of selection of relevant independent variables for input in multiple regression models.

Where poor correlations were encountered, t-tests were used to identify significant differences in the population means of independent variables as grouped by k-means cluster analysis. Cluster analysis served as a method of grouping dependent variables so as to maximise between-group variation while minimising within-group variation.

### *6.2 Data*

All dependent and independent variables considered are presented below in Table 11.

*Table 11. Dependent and independent variables used for statistical analyses*

| Independent | Abbreviation |
|---|---|
| Mean Annual Temperature (°C) | **MAT** |
| Mean Diurnal Range (°C) | **DIUR_RANG** |
| Mean Temperature of Wettest Quarter (°C) | **TEMP_WQ** |
| Temperature Seasonality (CV) | **TEMP_SEAS** |
| Temperature Annual Range (°C) | **TEMP_ANN_R** |
| Mean Annual Precipitation (mm) | **MAP** |
| Precipitation Seasonality (CV) | **PREC_SEAS** |
| Precipitation of Wettest Quarter (mm) | **PREC_WQ** |
| Precipitation of Driest Quarter (mm) | **PREC_DQ** |
| Subsoil Clay Content (%) | **CLAY_B** |
| Topsoil Organic Matter Content (%) | **OM_A** |
| Soil Depth Class | **DEPTH_CLAS** |
| Solar Radiation (MJ/m$^2$/day) | **SOL_RAD** |
| Age at felling (years) | **AGE** |
| **Dependent** | |
| Site Index (Base age 5) | **SI** |
| Weighted Mean Density (kg/m$^3$) | **WMD** |
| Active Alkali Absorption (%) | **AA** |
| Screened Pulp Yield (%) | **SPY** |
| Weighted Mean Fibre Length (mm) | **FL_WM** |

Although site index is included as a dependent variable, it was also used in multiple regression as an independent variable. The relationship between SI and wood properties for this dataset was needed to establish if climatic or other influences could describe any variation in wood properties that growth rate could not. Subsoil clay content (CLAY_B) was preferred as a basic measure of the variability in water holding capacity of the soils to actual retentivity data, since most soils within each geographic area fell into the same texture class. This resulted in most sites being allocated identical water holding capacity values resulting in a dataset that did not have much variation in the data with respect to this variable. Age was included as another independent variable that has a known impact on wood density (Turner *et* *al.*, 2001). Since site selection was carried out with the goal of including as many geographically separated sites as possible, a large range in tree ages (2-12) existed in the dataset. Soil depth was included as an ordinal variable (either shallow: <150 cm or deep: >150 cm) since soil depth could not be measured past 150 cm. Basic measures of climate (MAP and MAT) were considered to compare their efficacy in describing plant growth against bioclimatic parameters.

Wood property variation due to genetic variability was excluded from the analyses. Although the effect of genetic variability on wood properties is known and a specific species clone versus site interaction is expected, this effect was not considered due to:

- The small size of the dataset – in some instances a particular species was not repeated more than once in the dataset.
- It was hoped that a universal wood property response model incorporating various clones of the same species as well as *E. grandis* seedling material would create a robust model that
  - Was applicable across a range of *E. grandis* clones and seedling material,
  - Would highlight the strong relationships between bioclimate and wood properties despite whatever genetic variation may have been introduced into the dataset.

### *6.3 Data Verification – Kolmorogov-Smirnov test for normality*

The statistical computer package SPSS® 11.51 for Windows® was used for all statistical analyses.

Before the data was used for further analyses, descriptive statistics as well as tests for normality were calculated for all variables. Descriptive statistics for all variables have been included in previous chapters where appropriate. Tests for normality are important because most common statistical methods assume that the data are at least approximately normally distributed. The Kolmogorov-Smirnov test was used to test the distribution of the data around normality. A Kolmorogov-Smirnov test for normality showed that MAT, DIUR_RANG, TEMP_SEAS, PREC_DQ, CLAY_B and OM_A were not normally distributed thereby excluding these variables from the initial Pearson's correlation calculations.

### *6.4 Correlation Analysis*

Correlation is a measure of the linear relation between two or more variables (Ennos, 2000). An example of a simple linear correlation is the Pearson's correlation. A Pearson correlation assumes that the two variables are measured on at least interval scales and it determines the extent to which values of the two variables are proportional to each other. 'Proportional' means linearly related; that is, the correlation is high if it can be summarized by a straight line (sloped upwards or downwards). The value of correlation expressed as the correlation coefficient (r), does not depend on the specific measurement units used (Statistica, 1997). The correlation coefficient measures the degree of correlation (Clarke and Cooke, 1978). Pearson's correlations assume that the data are normally distributed. Other correlation methods designed for non-parametric data include Kendell's and Tau's correlations (SPPS, 2002). Non-normally distributed data were removed from the dataset before separate correlation matrices were generated for the individual geographic regions using the Pearson Correlation Coefficient (r) (SPPS, 2002).

If the correlation coefficient is squared, then the resulting value ($r^2$, the coefficient of determination) will represent the proportion of common variation in the two variables (i.e., the "strength" or "magnitude" of the relationship). In order to evaluate the correlation between variables, it is important to know this "magnitude" or "strength" as well as the *significance* (p) of the correlation.

Values of r near to -1 or 1 indicate the strong possibility of a correlation between two independent variables. Intermediate values of r require an objective way of assessing and testing the results of the calculations (Clarke and Cooke, 1978). This is achieved by calculating a value of significance for the linear relationship, called p. The value of p is calculated where observed variables are modelled by random variables: both variables are assumed jointly normally distributed with a correlation coefficient p. This test essentially compares the symmetry between independent variables and a theoretical normal distribution, and ascribes a value for the confidence at which one can assume that the results of the correlation will be true for those of the entire population (Clarke and Cooke, 1978, Statsoft, 2001). The p value is reported as a significance level for all correlations in the correlation matrices. Correlations are marked as being either significant at the 99% ($p<0.01$) or 95% ($p<0.05$) levels of confidence based on the calculated p value.

### 6.4.1 Correlations within dataset across geographical areas

A correlation matrix of normally distributed datasets geographical regions is presented in Table 12. The Pearson's Correlation Coefficient (r) as well as the significance level of those correlations is presented. The choice of variables for this analysis is based on conclusions drawn from pre-emptive analysis with earlier datasets.

*Table 12. Matrix showing correlation coefficients (r) where significant correlations at the 99% and 95% level have been marked.*

| | TEMP_ANN_R | MAP | PREC_WQ | AGE | SI | WMD | AA | SPY |
|---|---|---|---|---|---|---|---|---|
| **TEMP_ANN_R** | 1.000 | -0.481(**) | 0.454(**) | 0.081 | -0.361(*) | -0.373(*) | 0.303(*) | 0.175 |
| **MAP** | -0.481 | 1.000 | 0.450(**) | 0.164 | 0.519(**) | 0.233 | -0,346(*) | 0.309(*) |
| **PREC_WQ** | 0.454 | 0.450(**) | 1.000 | 0.321(*) | 0.172 | -0.303 | -0.241 | 0.561(**) |
| **AGE** | 0.081 | 0.164 | 0.321(*) | 1.000 | -0.129 | 0.301 | -0.345(*) | 0.142 |
| **SI** | -0.361 | 0.519(**) | 0.172 | -0.129 | 1.000 | -0.011 | -0.375(*) | 0.696(**) |
| **WMD** | -0.373 | 0.233 | -0.303 | 0.301 | -0.011 | 1.000 | 0.049 | -0.324 |
| **AA** | 0.303 | -0.346(*) | -0.241 | -0.345(*) | -0.375(**) | 0.049 | 1.000 | -0.435(**) |
| **SPY** | 0.175 | 0.309(*) | 0.561(**) | 0.142 | 0.696(**) | -0.324 | -0.435(**) | 1.000 |

** Correlation is significant at the 0.01 level (2-tailed). * Correlation is significant at the 0.05 level (2-tailed).

SI was variable most strongly correlated with MAP ($r=0.519$, $p<0.01$), TEMP_ANN_R ($r=-0.361$, $p<0.05$) and SPY ($r=0.696$, $p<0.01$). Despite the use of region specific functions to calculate SI, the relationship between SI and SPY is strong and indicates the pervasive effect that rate of tree growth has in SPY in *Eucalyptus spp.* Trees.

TEMP_ANN_R was also correlated with WMD ($r=-0.373$, $p<0.05$) and AA ($r=0.303$, $p<0.05$). MAP was also negatively correlated with AA ($r=-0.346$, $p<0.05$). AA increased with decreasing SPY ($r=-0.435$, $p<0.01$) and decreasing AGE ($r=-0.345$, $p<0.01$). The only bioclimatic measure of rainfall to show an improved correlation with wood properties was PREC_WQ. SPY correlated with PREC_WQ ($r=0.561$, $p<0.01$) more strongly than with MAP ($r=0.309$, $p<0.05$).

These results suggest that at a macro-scale (across geographical regions) increasing total water supply along with a decreasing seasonality in temperature results in greater tree growth rates and better wood properties for pulping. A decrease in annual temperature range would appear to result in an increase in wood density, while resulting in a corresponding decrease in active alkali consumption. It may be tentatively suggested from these results that the best growth sites for eucalyptus trees are those with the most summer rainfall and least summer to winter seasonal change in temperature (and water) regime.

Non-parametric correlations, such as Kendell's or Tau's correlation coefficients, were not calculated for the non-normally distributed data as the calculation could not include the normally distributed data. The non-normally distributed data comprised a small part of the entire data-set, and was therefore disregarded.

### 6.4.2 Correlations within datasets of individual geographical areas

It was decided to block out the effect of geographical region by splitting the study between Zululand and Mpumalanga. The reasons for this split may be summarized as follows:

- The world bioclimatic classification system of Rivas-Martinez *et al.* (1999) classified the bioclimates of Zululand and Mpumalanga as different. Although this was initially regarded as a possible reason for variation in growth and wood properties, it was decided to check the variation in these caused by changes in climate within homogenous bioclimatic zones.
- The topography and soils of Zululand are relatively homogenous. It was hoped that this would result in better correlations of tree growth with climate and bioclimate.
- Similarly, the topographical variability in Mpumalanga was hoped to account for some variation in tree growth that climate and bioclimate could not.

Separate datasets for sites in Zululand and Mpumalanga were tested for data normality using the Kolmorogov-Smirnov test. The results of these tests for normality indicate that most data are normally distributed. In Zululand, the only variable that did not display a normal distribution was clay content of the subsoil (CLAY_B), probably due to the small variation of data within the dataset. All data within the Mpumalanga dataset was normally distributed except soil depth class. Individual correlation matrices for both geographical areas are presented in Tables 13 and 14.

*Table 13. Matrix showing correlation coefficients (r) for variables in Zululand where significant correlations at the 99% and 95% level have been marked.*

| | MAT | DIUR_ RANG | TEMP_ WQ | TEMP_ SEAS | TEMP_ ANN_R | MAP | PREC_ SEAS | PREC_ WQ | PREC_DQ | OM_A | AGE | SI | WMD | AA | SPY | FL_WM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MAT | 1 | .669(**) | 0.970(**) | 0.690(**) | 0.771(**) | -0.31 | 0.147 | -.408(*) | -0.275 | -0.068 | -0.095 | -.623(**) | 0.38 | 0.391 | -0.464(*) | -0.256 |
| DIUR_RANG | .669(**) | 1 | 0.633(**) | 0.873(**) | 0.945(**) | -0.161 | -0.001 | -0.344 | -0.151 | -0.175 | 0.079 | -0.66(**) | 0,395 | 0.479(*) | -0.63(**) | -0.397(*) |
| TEMP_WQ | .970(**) | 0.633(**) | 1 | 0.711(**) | 0.764(**) | -0.373 | 0.211 | -.469(*) | -0.331 | -0.054 | -0.131 | -0.63(**) | 0.289 | 0.364 | -0.456(*) | -0.244 |
| TEMP_SEAS | .690(**) | 0.873(**) | 0.711(**) | 1 | 0.914(**) | 0.029 | -0.215 | -0.162 | 0.07 | -0.07 | 0.061 | -0.446(*) | 0.425(*) | 0.420(*) | -0.366 | -0.121 |
| TEMP_ANN_R | .771(**) | 0.95(**) | 0.764(**) | 0.914(**) | 1 | -0.243 | 0.047 | -.428(*) | -0.213 | -0.12 | -0.003 | -0.67(**) | 0.358 | 0.514(*) | -0.60(**) | -0.36 |
| MAP | -0.31 | -0.161 | -0.373 | 0.029 | -0.243 | 1 | -.963(**) | 0.977(**) | 0.997(**) | 0.25 | 0.253 | 0.733(**) | 0.204 | -0.175 | 0.65(**) | 0.594(**) |
| PREC_SEAS | 0.147 | -0.001 | 0.211 | -0.215 | 0.047 | -0.96(**) | 1 | -0.89(**) | -0.972(**) | -0.259 | -0.248 | -0.63(**) | -0.319 | 0.079 | -0.55(**) | -0.56(**) |
| PREC_WQ | -.408(*) | -0.344 | -0.469(*) | -0.162 | -.428(*) | 0.977(**) | -0.89(**) | 1 | 0.968(**) | 0.264 | 0.21 | 0.809(**) | 0.117 | -0.269 | 0.730(**) | 0.634(**) |
| PREC_DQ | -0.275 | -0.151 | -0.331 | 0.07 | -0.213 | 0.997(**) | -0.97(**) | 0.968(**) | 1 | 0.253 | 0.251 | 0.730(**) | 0.223 | -0.162 | 0.649(**) | 0.613(**) |
| OM_A | -0.068 | -0.175 | -0.054 | -0.07 | -0.12 | 0.25 | -0.259 | 0.264 | 0.253 | 1 | -0.227 | 0.182 | -0.26 | -0.109 | 0.265 | -0.027 |
| AGE | -0.095 | 0.079 | -0.131 | 0.061 | -0.003 | 0.253 | -0.248 | 0.21 | 0.251 | -0.227 | 1 | 0.103 | 0.434(*) | -0.16 | -0.021 | 0.215 |
| SI | -0.62(**) | -0.66(**) | -0.63(**) | -0.446(*) | -.671(**) | 0.733(**) | -0.63(**) | 0.809(**) | 0.730(**) | 0.182 | 0.103 | 1 | 0.034 | -0.47(*) | 0.874(**) | 0.767(**) |
| WMD | 0.38 | 0.395 | 0.289 | 0.425(*) | 0.358 | 0.204 | -0.319 | 0.117 | 0.223 | -0.26 | .434(*) | 0.034 | 1 | 0.081 | -0.136 | 0.354 |
| AA | 0.391 | 0.479(*) | 0.364 | 0.420(*) | 0.514(*) | -0.175 | 0.079 | -0.269 | -0.162 | -0.109 | -0.16 | -.473(*) | 0.081 | 1 | -0.402 | -0.467(*) |
| SPY | -0.46(*) | -0.63(**) | -0.456(*) | -0.366 | -.601(**) | 0.648(**) | -0.55(**) | 0.730(**) | 0.649(**) | 0.265 | -0.021 | .874(**) | -0.136 | -0.402 | 1 | 0.755(**) |
| FL_WM | -0.256 | -0.39(*) | -0.244 | -0.121 | -0.36 | 0.594(**) | -0.56(**) | 0.634(**) | 0.613(**) | -0.027 | 0.215 | .767(**) | 0.354 | -0.47(*) | 0.755(**) | 1 |

** Correlation is significant at the 0.01 level (2-tailed). * Correlation is significant at the 0.05 level (2-tailed).

*Table 14. Matrix showing correlation coefficients (r) for variables in Mpumalanga where significant correlations at the 99% and 95% level have been marked.*

| | MAT | DIUR_ RANG | TEMP_ WQ | TEMP_ SEAS | TEMP_ ANN_R | MAP | PREC_ SEAS | PREC_ WQ | PREC_DQ | CLAY_B | OM_A | SOL_ RAD | AGE | SI | WMD | AA | SPY |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **MAT** | 1 | 0.952(**) | 0.992(**) | 0.908(**) | 0.930(**) | -0.504(*) | 0.626(**) | -0.425 | -0.406 | 0.416 | -0.297 | -0.066 | -0.315 | 0.27 | 0.342 | 0.463 | 0.108 |
| **DIUR_RANG** | 0.952(**) | 1 | 0.963(**) | 0.924(**) | 0.975(**) | -0.424 | 0.584(*) | -0.353 | -0.382 | 0.308 | -0.372 | 0.062 | -0.38 | 0.129 | 0.257 | 0.492(*) | 0.011 |
| **TEMP_WQ** | 0.992(**) | 0.963(**) | 1 | 0.941(**) | 0.955(**) | -0.54(*) | 0.627(**) | -0.461 | -0.456 | 0.42 | -0.26 | -0.061 | -0.328 | 0.216 | 0.387 | 0.493(*) | 0.072 |
| **TEMP_SEAS** | 0.908(**) | 0.924(**) | 0.941(**) | 1 | 0.975(**) | -.631(**) | 0.563(*) | -0.575(*) | -0.615(**) | 0.42 | -0.203 | -0.084 | -0.407 | 0.01 | 0.35 | 0.620(**) | -0.129 |
| **TEMP_ANN_R** | 0.930(**) | 0.975(**) | 0.955(**) | 0.975(**) | 1 | -.564(*) | 0.614(**) | -0.50(*) | -0.551(*) | 0.352 | -0.331 | 0.037 | -0.417 | 0.037 | 0.264 | 0.600(*) | -0.087 |
| **MAP** | -0.504(*) | -0.424 | -0.537(*) | -0.63(**) | -0.564(*) | 1 | -0.527(*) | 0.995(**) | 0.958(**) | -0.736(**) | -0.036 | -0.122 | 0.284 | 0.209 | -0.251 | -0.496(*) | 0.291 |
| **PREC_SEAS** | 0.626(**) | 0.584(*) | 0.627(**) | 0.563(*) | 0.614(**) | -0.53(*) | 1 | -0.473 | -0.524(*) | 0.312 | -0.429 | 0.093 | -0.165 | 0.286 | 0.227 | 0.385 | 0.125 |
| **PREC_WQ** | -0.425 | -0.353 | -0.461 | -0.575(*) | -0.503(*) | 0.995(**) | -0.473 | 1 | 0.968(**) | -0.71(**) | -0.052 | -0.154 | 0.29 | ·0.268 | -0.231 | -0.500(*) | 0.352 |
| **PREC_DQ** | -0.406 | -0.382 | -0.456 | -0.62(**) | -0.551(*) | 0.958(**) | -0.524(*) | 0.968(**) | 1 | -0.61(**) | 0.045 | -0.176 | 0.355 | 0.315 | -0.224 | -0.63(**) | 0.425 |
| **CLAY_B** | 0.416 | 0.308 | 0.42 | 0.42 | 0.352 | -0.74(**) | 0.312 | -0.71(**) | -0.607(**) | 1 | 0.349 | 0.06 | -0.074 | -0.063 | 0.299 | 0.101 | -0.054 |
| **OM_A** | -0.297 | -0.372 | -0.26 | -0.203 | -0.331 | -0.036 | -0.429 | -0.052 | 0.045 | 0.349 | 1 | -0.243 | 0.407 | -0.189 | 0.651(*) | -0.35 | 0.023 |
| **SOL_RAD** | -0.066 | 0.062 | -0.061 | -0.084 | 0.037 | -0.122 | 0.093 | -0.154 | -0.176 | 0.06 | -0.243 | 1 | 0.055 | -.564(*) | 0.112 | 0.181 | -0.523(*) |
| **AGE** | -0.315 | -0.38 | -0.328 | -0.407 | -0.417 | 0.284 | -0.165 | 0.29 | 0.355 | -0.074 | 0.407 | 0.055 | 1 | -0.181 | 0.629(*) | -0.508(*) | 0.162 |
| **SI** | 0.27 | 0.129 | 0.216 | 0.01 | 0.037 | 0.209 | 0.286 | 0.268 | 0.315 | -0.063 | -0.189 | -0.56(*) | -0.181 | 1 | -0.503 | -0.252 | 0.807(**) |
| **WMD** | 0.342 | 0.257 | 0.387 | 0.35 | 0.264 | -0.251 | 0.227 | -0.231 | -0.224 | 0.299 | .651(*) | 0.112 | 0.629(*) | -0.503 | 1 | 0.346 | -0.487 |
| **AA** | 0.463 | 0.492(*) | 0.493(*) | .620(**) | 0.600(*) | -.496(*) | 0.385 | -.500(*) | -0.628(**) | 0.101 | -0.35 | 0.181 | -0.51(*) | -0.252 | 0.346 | 1 | -0.61(*) |
| **SPY** | 0.108 | 0.011 | 0.072 | -0.129 | -0.087 | 0.291 | 0.125 | 0.352 | 0.425 | -0.054 | 0.023 | -0.52(*) | 0.162 | .807(**) | -0.487 | -0.605(*) | 1 |

** Correlation is significant at the 0.01 level (2-tailed). ; * Correlation is significant at the 0.05 level (2-tailed).

## Zululand (Table 13)

Stronger correlations were noted between variables within Zululand and Mpumalanga separately as opposed to when analyses were performed on the dataset from both geographical areas together.

Site index (SI) displayed the most number of strong relationships with other variables either as an independent or dependent variable. Measures of rainfall and temperature were significantly related to SI either as basic climatic measures or as bioclimatic parameters. The coefficients of determination ($R^2$) improved by 16% when SI was correlated with TEMP_ANN_R ($r=-0.671$, $p<0.01$), and by 21% when correlated with PREC_WQ ($r=0.809$, $p<0.01$) as opposed to MAT ($r=-0.623$, $p<0.01$) and MAP ($r=0.733$, $p<0.01$) respectively. SI was also correlated with PREC_SEAS ($r=-0.625$, $p<0.01$). SPY and FL_WM were strongly correlated with SI ($r=0.874$, $p<0.01$) and ($r=0.767$, $p<0.01$) and to a lesser extent with AA ($r=-0.473$, $p<0.05$). This supports previous findings that growth rate affects wood properties (Megown *et al.*, 1998, Turner and Retief, 1998, Turner *et al.*, 2001).

WMD was weakly correlated with both TEMP_SEAS ($r=0.425$, $p<0.05$) and AGE ($r=0.434$, $p<0.05$). AA was weakly correlated with TEMP_ANN_R ($r=0.514$, $p<0.05$).

Bioclimatic parameters yielded higher correlations with SPY than did basic climatic measures. The $R^2$ improved by 68% when SPY was correlated with TEMP_ANN_R ($r=-0.601$, $p<0.01$) as opposed to MAT ($r=-0.464$, $p<0.05$). This relationship again improved by 27% when SPY was correlated with PREC_WQ ($r=0.730$, $p<0.01$) rather than MAP ($r=0.648$, $p<0.01$). SPY was also strongly correlated with FL_WM ($r=0.755$, $p<0.01$).

FL_WM was correlated to DIUR_RANG ($r=-0.397$, $p<0.05$). PREC_WQ ($r=0.634$, $p<0.01$) accounted for a 14% increase in $R^2$ over MAP ($r=0.594$, $p<0.01$) when correlated with FL_WM.

Similarly to the results of the entire dataset, the correlations found within the Zululand data indicate that water supply during summer periods and measures of climate seasonal change are the main determinants of tree growth rate and wood properties. These results are discussed in more detail in section 6.6.3.

**Mpumalanga (Table 14)**

Fewer significant correlations existed between climate and bioclimate and tree growth rate and wood properties in Mpumalanga than in Zululand. The lack of significant strong correlations in the Mpumalanga dataset was attributed to two main factors:

1- The dataset size was very small (n=17) (Due to data unavailability, n was frequently less for certain wood properties)
2- Other factors that were not measured in this study could be affecting wood properties such as soil nutrient status. Soil depth, known to affect tree growth significantly (Louw, 1997), could not be included in the correlation matrix due to lack of variation in the dataset.

Nevertheless, some correlations within the Mpumalanga dataset did exist:

SI was negatively correlated with SOL_RAD ($r=-0.564$, $p<0.05$). SI was well correlated with SPY ($R^2=0.65$, $p<0.01$). This result shows that although the same environmental factors might not affect growth in similar ways in Zululand and Mpumalanga, an increase in growth rate will result in an increase in SPY regardless of geographical position.

WMD was correlated with OM_A ($r=0.651$, $p<0.05$) as well as AGE ($r=0.629$, $p<0.1$). The latter result, although only significant at the 10% confidence level, has been confirmed by other workers (Turner *et al.,* 2001). The correlation between WMD and OM_A was checked by drawing a scatter plot of the data points. The scatter plot showed that this result could not be wholly accepted due to very few data points (n=10) and slight data clumping at high values of WMD.

AA was correlated with TEMP_SEAS ($r=0.620$, $p<0.01$) and PREC_DQ ($r=-0.62$, $p<0.01$) as well as AGE ($r=-0.508$, $p<0.05$). These results suggests that more pronounced winter period of low temperatures and less rainfall will result in trees that consume more chemicals during the pulping process.

### *6.5 Analysis of variance within Mpumalanga data*

#### 6.5.1 The effect of soil depth

Due to the lack of strong correlations and the small size of the dataset in the Mpumalanga data, other approaches to answering the questions posed in this study were pursued. Sites in Mpumalanga were grouped according to DEPTH_CLAS and a t-test was performed for the means of wood property variables between classes. Appendix 5 contains full results of this t-test. The results of this t-test indicated a significant difference in SPY and SI between depth classes. DEPTH_CLAS was found to significantly affect SI and SPY regardless of the bioclimate experienced by the site. This effect may have been captured to some extent by the SOL_RAD variable. The SOL_RAD values, calculated using slope and aspect as variables, could contain some measure of DEPTH_CLAS due to the fact that steeper slopes usually have shallower soils.

#### 6.5.2 Cluster Analysis

The clustering technique known as k-means clustering was used to group sites in Mpumalanga for further analysis. This type of clustering is used to group data based on dependent variables. Computationally, the technique clusters data into a specified number of groups so as to minimise the within group variance while maximising the between group variance of those clusters. The process is iterative and starts by allocating data to random groups before moving them between groups to meet the above mentioned criteria (Statsoft, 2001).

K-means clustering was used to group sites in the Mpumalanga dataset according to SI, SPY, WMD, and AA. Due to the small size of the data set, the maximum number of clusters was limited to two to increase the number of data points in each cluster. Appendix 4 contains the results of the k-means cluster analysis performed by SPSS 11.51 that include cluster allocation numbers for each site. Clustered sites were assigned a categorical value (high or low) and a simple t-test was performed for selected variables to establish if there was a significant change in environmental variables between clusters.

T-test result tables for environmental variables between sites grouped by k-means clustering for the dependent variables SI, SPY, WMD and AA respectively are included in Appendix 5.

The results of these analyses show that PREC_SEAS and SPY both significantly differ between SI classes: growth rate increased with a decrease in precipitation seasonality, while an increase in growth rate accompanied an increase in screened pulp yield. Elevated levels of incoming solar radiation appear to decrease the screened pulp yield, while wood density also increased significantly with an increase in tree age.

### *6.6 Modelling growth and wood property response to the environment*

One of the primary aims of this project was to construct a suitable model that could be used for the prediction of wood properties from easily measured environmental variables. The practicality of this model would be greatly increased if this model were constructed from variables that are readily available and cost effective to acquire. Spatial climatic data fits these criteria in that it already exists, and is available at little or no cost in South Africa. Soils data is costly and time consuming to collect, and although site-growth studies have shown that tree growth may be affected considerably by certain soil factors, these variables were only considered to explain variation that climate could not. The derivation of bioclimatic parameters added value to basic climatic data and have been shown to account for more variation in growth in Zululand than the original simple measures of climatic. Three main criteria were held constant during the entire modelling process and are as follows:

- To create a model that described the most possible variation in the dependent variable while using the least possible number of independent variables,
- that contained the least possible error and,
- that was true for the entire population within moderate confidence levels.

### 6.6.1 Multiple regression

The general purpose of multiple regression (linear and non-linear) is to learn more about the relationship between several independent or predictor variables and a dependent variable (Ennos, 2001). One or more independent variables may be entered into the model to best predict a single dependent variable. The regression line expresses the best prediction of the dependent variable given the independent variables. One of the main limitations to multiple regression is the fact that it does not offer any explanation to the underlying causal factors determining the observed relationship. Relationships may be established and quantified, but care should be taken when explaining the cause of these relationships (Clarke and Cooke, 1978).

A multiple regression model may be shown by the equation,

$$y = B_o + B_1x_1 + B_2x_2 + \ldots B_kx_k + e \qquad \ldots 2$$

where $B_1$, $B_2 \ldots B_k$ refer to the partial slopes in the equation and $x_1, x_2 \ldots x_k$ refer to values of the independent variables, and $e$ refers to the error of the model. (Ott, 1993).

Ott (1993) highlights three main steps when creating a multiple regression model. Firstly, variables must be selected, followed by model formation, followed by the residual analysis. Following these steps once for a given problem will not ensure the creation of an appropriate model, and it is rather a repeated application of these steps that results in the evolution of an appropriate model.

The selection of potential variables for model creation was carried out using the results of the correlation matrices and factor analyses (Sections 6.4 and 6.6). When selecting appropriate independent variables to input into the model, two extremes of data choice must be considered. Too few independent variables entered into the model may result in a model which is underspecified, and the additional variability in the dependent variable that would be accounted for with these variables becomes part of the estimated error variance (Ott, 1993). Too many independent variables in a regression model results in a strong possibility of multicollinearity where one or more of the independents factors are correlated with one another, resulting in model instability and often an over estimation of the predicted variable (Clarke and Cooke, 1978; Ennos, 2001).

### 6.6.2 Non-linear regression methodology and results

The relationships between dependent and independent variables were tested by fitting theoretical distribution curves to the data. The distribution curves fitted to the data included linear, logarithmic, inverse, compound, power, S-type, growth and exponential curves. The $R^2$ values for the fitted curves were inspected to identify the strongest relationships.

No significant increases in $R^2$ values over linear regression were observed for the non-linear fitted curves. This may be due to the relatively small size of both datasets: a non-linear relationship would not be evident in a dataset covering a small range in variation of the dependent variable. For this reason, multiple linear regression modelling techniques were used to model wood properties.

In general, linear regression techniques are favoured over non-linear ones due to the problems associated with non-linear regression. Non-linear regression may be biased towards the given dataset, and is affected by the method of estimation as well as the starting conditions specified by the user (Van Laar, 1991).

Simple linear regression may be shown by the equation,

$$y = B_0 + B_1 x + e \qquad \ldots 3$$

where $y$ denotes the predicted values, $B_1$ the slope of the line, $B_o$ the intercept, and $x$ is independent variable. The $e$ stands for the expected value of error for the model, and under the assumption that $e=0$, the model is depicted by a straight line (Ott, 1993).

When using multiple linear regression to predict a dependent variable, certain assumptions are made:

- All the relationships between the independents and dependent variables are linear in nature.
- The residual values are normally distributed.

Most (if not all) biological systems are statistically imperfect, resulting in a substantial variation of the observed points around the fitted regression line. The deviation of a particular point from the regression line, or its predicted value, is called the residual value (Statsoft, 2001). One of the aims when using multiple regression techniques is to obtain the smallest possible residual values and variation relative to the regression line. Smaller residual values indicate a model that is capable of better prediction of the dependent than one with larger residual values. The distribution of the residual values should be approximately normal to further validate the model (Clarke and Cooke, 1978; Ott, 1993).

### 6.6.3 Linear regression methodology and results

#### Variable selection

The results of the correlation matrix for Zululand and Mpumalanga were used to choose variables for regression analysis. Environmental variables which were strongly correlated with dependent variables were chosen for model inclusion. Correlations that were more significant were favoured over less significant correlations.

The environmental variables chosen as input data for regression analysis in Zululand included: MAP, MAT, TEMP_ANN_R, DIUR_RANG, TEMP_SEAS, PREC_SEAS, PREC_WQ and AGE.

The environmental variables chosen for model inclusion for Mpumalanga included: SOL_RAD, TEMP_SEAS, PREC_DQ and AGE.

#### Model Creation

Independent variables were entered into a multiple linear regression model using the 'stepwise' option within SPSS 11.51. This method sets limits for the significance of the F-value at which independent variables may be entered into the regression model. Variables that do not fall within the specified significance of limits for the F-value are excluded from the regression model. The critical limit for variable inclusion was set to an F-value significance of <0.05 and the F-value limits for the exclusion of variables was set to <0.1. TEMP_SEAS and PREC_DQ were not entered into any regression models in the Mpumalanga data as they did not meet the critical limit criteria for variable inclusion. Entering these variables into regression models by removing these critical limits produced models of little strength or significance once the $R^2$ values were adjusted for dataset size and standard error.

A summary of simple and multiple linear regression models for the prediction of SI, SPY, WMD and AA is summarised in Table 15. The distribution of the residual values for each model were tested for normality using the Kolmorogov-Smirnov test, where values >0.05 indicate a significant conformity of the data to a theoretical normal distribution (SPSS, 2001). Residual plots were also inspected for any abnormalities such as outliers which were removed before remodelling the relationship. The model significance is included by categorising models into classes where $p<0.05$ or $0.1>p>0.05$. Coefficient of determination values ($R^2_{adj}$) that have been corrected for sample size and standard error as calculated by SPSS have been reported to give a less biased value for the strength of the relationships. Potential multi-colinearity of independent variables within these models was ruled out by checking the correlations between the independent variables. Independent variables that were significantly and strongly correlated were not included together in the same multiple linear regressions, eg. PREC_WQ and PREC_SEAS ($R^2_{adj}$=0.79, $p<0.01$). Variables that were correlated with an $R^2_{adj}$ value of over 0.1 were not included together as predictors in the same multiple linear regression model.

In Zululand, PREC_WQ was the single best predictor of SI ($R^2_{adj}$=0.634, $p<0.05$). Consideration of the climate of Zululand shows that the wettest and warmest quarters of the year are the same 13 consecutive weeks. The best multiple regression model predicting SI was described by a combination of the factors PREC_WQ and DIUR_RANG ($R^2_{adj}$=0.773, $p<0.05$) although the model incorporating PREC_SEAS and DIUR_RANG was not much weaker ($R^2_{adj}$=0.765 $p<0.05$). SI was the best predictor of SPY ($R^2_{adj}$=0.752, $p<0.05$) and FL_WM ($R^2_{adj}$=0.569, $p<0.05$). The combination of the variables PREC_SEAS and DIUR_RANG combined to yield the best predictive model for SPY ($R^2_{adj}$=0.678, $p<0.05$) and FL_WM ($R^2_{adj}$=0.428, $p<0.05$).

The results suggest that eucalyptus tree growth rate on the Zululand plain is affected not only by the absolute amounts of rainfall, but also by the seasonal availability and variability of both water and energy (temperature). Increased amounts of water during the warmer summer months create conditions favourable to tree growth; this should be balanced by the suggestion that trees prefer reduced seasonal fluctuations in both water and temperature supply. The latter statement should be viewed with caution, as it refers to climates whose average amounts of rainfall and temperature rarely (if ever) fall below critical limits for eucalyptus growth.

That is to say that a temperate climate that has an average temperature of below zero would not be beneficial to eucalyptus tree growth.

In Mpumalanga, SOL_RAD was the only variable that was entered in a multiple linear regression that described SI ($R^2_{adj}$=0.273, P<0.1). The integrated nature of the SOL_RAD variable which includes measures of slope, aspect, latitude and time of year, makes the possible implications of this model difficult to describe. These factors may affect the fate of precipitated water through runoff, infiltration and evaporation. Higher SOL_RAD values could result in periods of increased water shortage during drier winter months and hotter summer months resulting in growth stress to the trees. SI accounted for the most variation in SPY ($R^2_{adj}$=0.628, p<0.05), while SOL_RAD on its own only accounted for 22% of the variation in SPY ($R^2_{adj}$=0.225, p<0.1). WMD was correlated with AGE ($R^2_{adj}$=0.32, p<0.05).

*Table 15. Summary table for linear regression models predicting SI, SPY, FL_WM and WMD in Zululand and Mpumalanga. Results of the test for normality of residual values are included.*

| Zululand | | | Residual Normality | Model Significance | |
|---|---|---|---|---|---|
| SI | R2(adj) | SE | Asymp. Sig. (2-tailed) | ** (p<0.05) | * (p<0.10) |
| [MAP] | 0.516 | 2.7 | 0.685 | ** | |
| [MAT] | 0.36 | 3.1 | 0.842 | ** | |
| [MAP][MAT] | 0.664 | 2.25 | 0.867 | ** | |
| [PWQ] | 0.634 | 2.34 | 0.846 | ** | |
| [PREC_SEAS] | 0.363 | 3.09 | 0.536 | ** | |
| [TEMP_ANN_R] | 0.426 | 2.94 | 0.997 | ** | |
| [TEMP_SEAS] | 0.163 | 3.55 | 0.777 | * | |
| [DIUR_RANG] | 0.409 | 2.98 | 0.73 | ** | |
| [PWQ][TEMP_ANN_R] | 0.737 | 1.99 | 0.739 | ** | |
| [PWQ][TEMP_SEAS] | 0.7 | 2.12 | 0.717 | ** | |
| [PWQ][DIUR_RANG] | 0.773 | 1.85 | 0.928 | ** | |
| [PREC_SEAS][DIUR_RANG] | 0.765 | 1.88 | 0.403 | ** | |
| SPY | | | | | |
| [SI] | 0.752 | 0.872 | 0.995 | | |
| [MAP] | 0.394 | 1.31 | 0.947 | ** | |
| [PWQ] | 0.513 | 1.18 | 0.98 | ** | |
| [PREC_SEAS] | 0.274 | 1.44 | 0.455 | ** | |
| [TEMP_ANN_R] | 0.334 | 1.4 | 0.857 | ** | |
| [DIUR_RANG] | 0.37 | 1.34 | 0.842 | ** | |
| [PWQ][TEMP_ANN_R] | 0.606 | 1.06 | 0.97 | ** | |
| [PWQ][DIUR_RANG] | 0.675 | 0.96 | 0.998 | ** | |
| [PREC_SEAS][DIUR_RANG] | 0.678 | 0.97 | 0.913 | ** | |
| FL_WM | | | | | |
| [SI] | 0.569 | 0.07 | 0.967 | | |
| [MAP] | 0.325 | 0.08 | 0.899 | ** | |
| [PWQ] | 0.377 | 0.08 | 0.818 | ** | |
| [PREC_SEAS] | 0.285 | 0.085 | 0.813 | ** | |
| [PREC_SEAS][DIUR_RANG] | 0.428 | 0.076 | 0.957 | ** | |
| WMD | | | | | |
| [TEMP_SEAS] | 0.145 | 43.19 | 0.927 | * | |
| [AGE] | 0.153 | 43 | 0.758 | * | |
| | | | | | |
| Mpumalanga | | | | | |
| SI | | | | | |
| [SOL_RAD] | 0.273 | 4.28 | 0.939 | * | |
| WMD | | | | | |
| [AGE] | 0.32 | 30.27 | 0.923 | ** | |
| SPY | | | | | |
| [SI] | 0.628 | 1.167 | 0.958 | ** | |
| [SOL_RAD] | 0.225 | 1.68 | 0.98 | * | |
| | | | | | |

# Chapter Seven
# Conclusions and Recommendations

At the outset of the project, the main objectives were:

- To study and identify the variation in wood properties of *Eucalyptus* spp. as a result of the combined effects of climate and edaphic factors on tree growth and wood development.
- Use this data to create a model for the prediction of those wood properties.

Individual site climatic factors were effectively determined by interpolating long term climatic means by thin plate smooth splining using geographical location and altitude as independent input variables. These results were verified by comparison to other modelled data as well as actual data through random exclusion of data points. This climatic data was used to derive bioclimatic parameters for each of the study sites using the Bioclim software package. Soils for individual sites were classified and organic matter content and water retentivity values were obtained. Topographical data including slope and aspect were also recorded at each site location.

A comparison of the bioclimate and terrain features between Zululand and Mpumalanga revealed that it was not possible to create a universal model to describe tree growth: due to different bioclimatic classifications, as well as wholly different topography and soil characteristics between the two regions, the geographical areas were considered separately.

The complexity of the Mpumalanga environment in terms of soils, topography and greater seasonality of both rainfall and temperature resulted in few significant site-growth relationships being identified. Site index, as a composite measure of site quality was found to account for most of the variation in screened pulp yield. Soil depth measured as an ordinal variable (either deep or shallow) was found to significantly affect site index and screened pulp yield. A measure of average solar radiation accounted for some variation in site index and screened pulp yield. This measure of solar radiation took into account time of year, latitude, aspect and steepness of slope indicating the convolution of this parameter and consequent difficulty in explaining these results. The negative correlations infer that trees growing on sites that receive more solar radiation on average will be detrimentally affected - possibly by reduced plant available water during the dry winter months. Furthermore, this parameter may be capturing the effect of soil depth expressed as slope as generally that steeper slopes have shallower soils.

Conversely, the lack of terrain and soil variability in Zululand resulted in strong relationships being found between bioclimate and tree growth of trees from numerous *Eucalyptus grandis* hybrids together. This is in contrast to other site-growth studies conducted in Zululand where edaphic factors contributed significantly to variation in tree growth (Noble *et al.*, 1991, Noble and Herbert, 1991). A lack in variation of organic matter content and water retentivity of the Zululand soils in this dataset resulted in most of the variation being captured by measures of bioclimate. Rainfall of the wettest quarter and mean diurnal temperature range were found to best predict site index, while precipitation seasonality and mean diurnal temperature range were found to explain most of the variation in screened pulp yield and fibre length when combined in multiple linear regression models. In all cases, growth rate and wood properties were more strongly correlated with bioclimatic parameters than with basic measures of climate.

Current research at the FFPRC indicates the important effect tree age has on screened pulp yield, sometimes accounting for up to 30% of total variation for clones grown in Zululand (P.Turner, Pers.Comm., 2003). This variation was not wholly captured due to the skew nature of the age distribution of the dataset. Age did, however, account for some variation in wood density in both Zululand and Mpumalanga. It is suggested that a more complete prediction model for screened pulp yield may be achieved by incorporating age into the multiple regression model. This should be noted in the event of further such research.

## Potential Applications

Regression equations were used in conjunction with spatial bioclimatic data to output spatial predictions for site index, screened pulp yield and fibre length in Zululand. SI was included due to the strong relationship between SI and wood properties.

As an example of the value of this work to industry, a spatial prediction of Air Dry Tonnes per hectare (ADT/ha) may be developed. A value for standing volume yield ($m^3$/ha) is needed along with a value for WMD and SPY. An equation for calculating ADT/ha is shown as:

$$\text{ADT/ha} = \text{Volume } (m^3/\text{ha}) \times \text{Density } (\text{kg}/m^3) \times \text{Screened Pulp Yield } (\%).$$

Incomplete volume data was available in the dataset (although not included in the main analyses) and the best fitting multiple linear regression model to predict volume in Zululand is shown by the equation:

$$\text{Volume } (m^3/\text{ha}) = 48.11 * ln(\text{PREC\_WQ}) + 172.38$$

Since the WMD data in Zululand did not correlate well with any climatic influence, the average value (430 kg/$m^{3)}$ for this variable for seven year old trees at various study sites was used. The spatial predictions for SPY were used as further inputs to calculate values for ADT/ha shown in Figure 13.

Figures 10 - 13 are spatial outputs of predicted values of site index (SI), screened pulp yield (SPY), fibre length (FL_WM) and fibre yield (ADT/ha) along the Zululand coastal plain. These prediction values were calculated using the multiple linear regression models referred to in Table 15. The maps are represented at a 400 m grid size resolution.

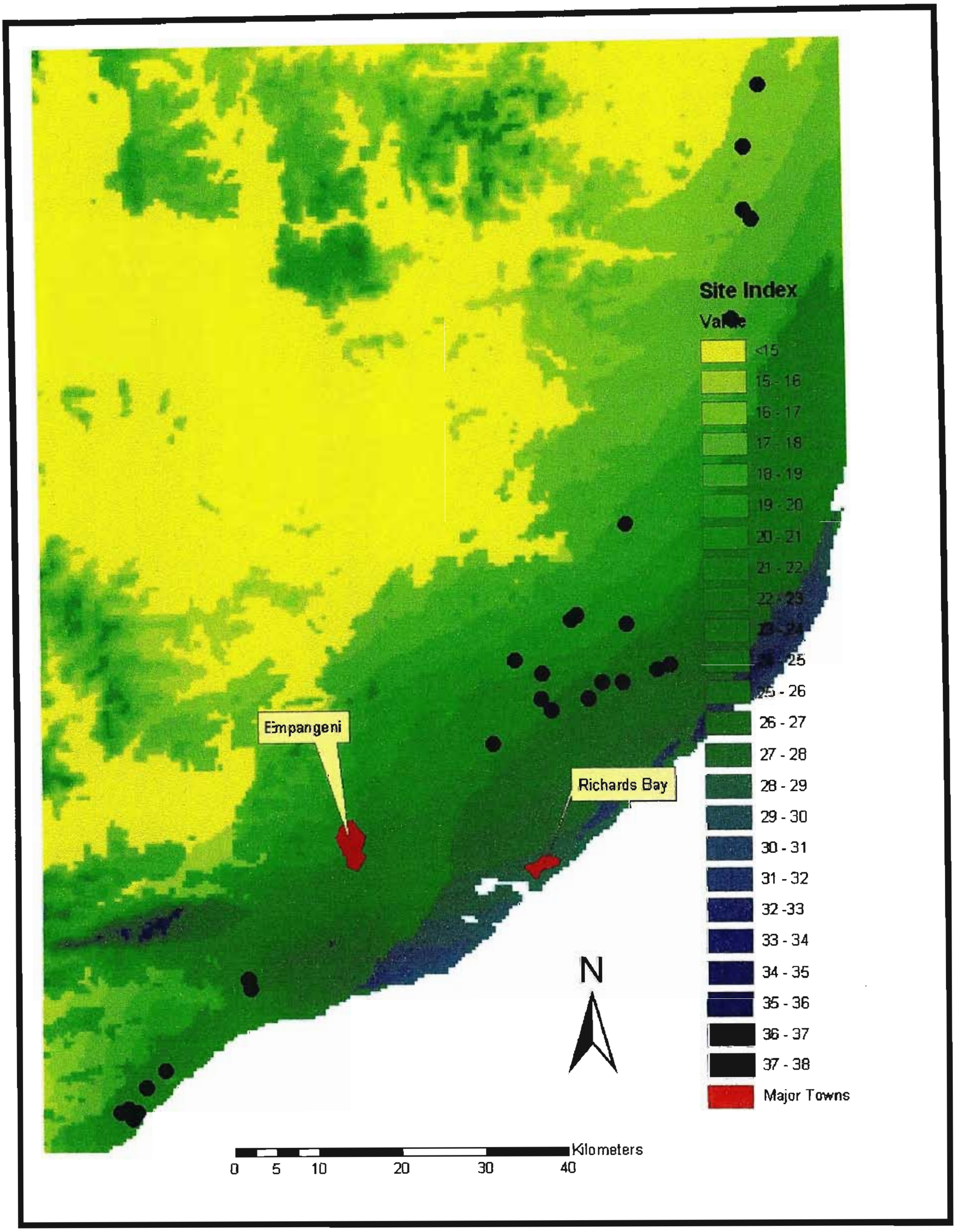


*Figure 10. Spatial prediction of Site Index for Eucalyptus grandis hybrids grown on the Zululand coastal plain. SI = 26.121 + 0.06218(PREC_WQ) – 3.39(DIUR_RANG), ($R^2$=0.773, $p$<0.01). Study sites indicated by black dots.*

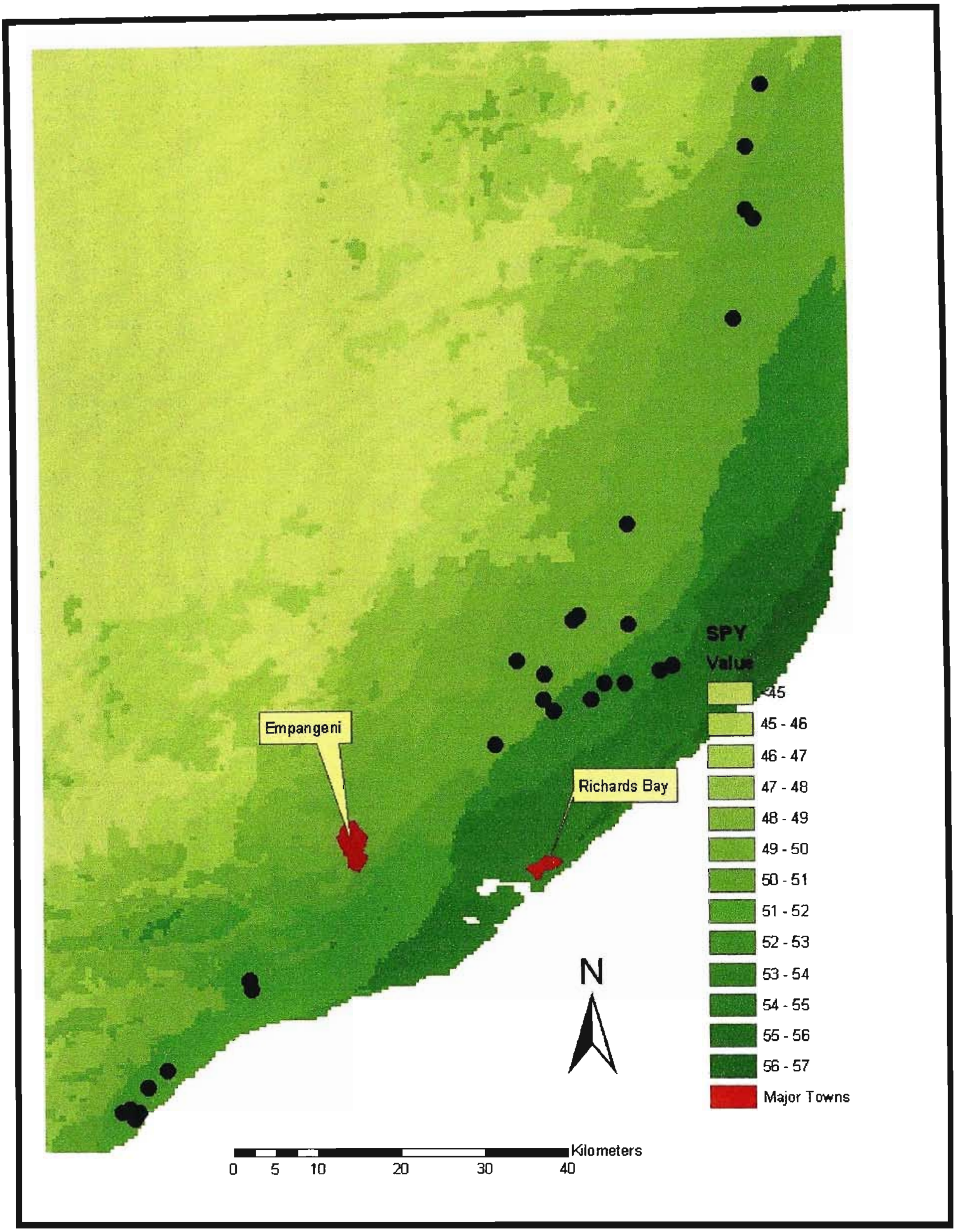


*Figure 11. Spatial prediction of screened pulp yield for Eucalyptus grandis hybrids grown on the Zululand coastal plain. SPY = 83.485 – 2.43(DIUR_RANG) – 0.306(PREC_SEAS), (R2=0.68 p<0.01). Study sites indicated by black dots.*

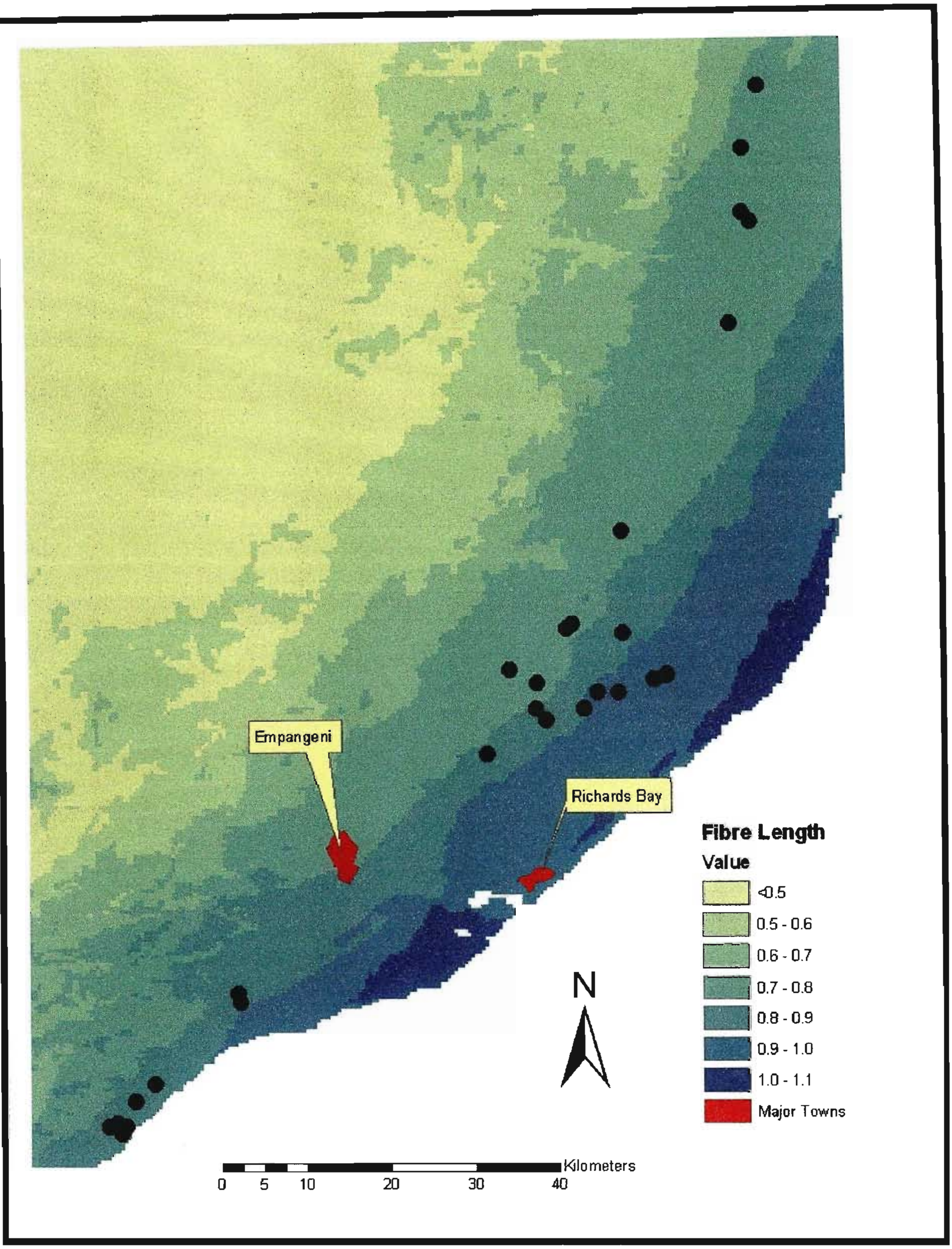


*Figure 12. Spatial Prediction of fibre length for Eucalyptus grandis hybrids grown on the Zululand coastal plain. FL_WM = 2.335 – 0.09193(DIUR_RANG) – 0.01858(PREC_SEAS), ($R^2$=0.43, $p$<0.01). Study sites shown by black dots.*

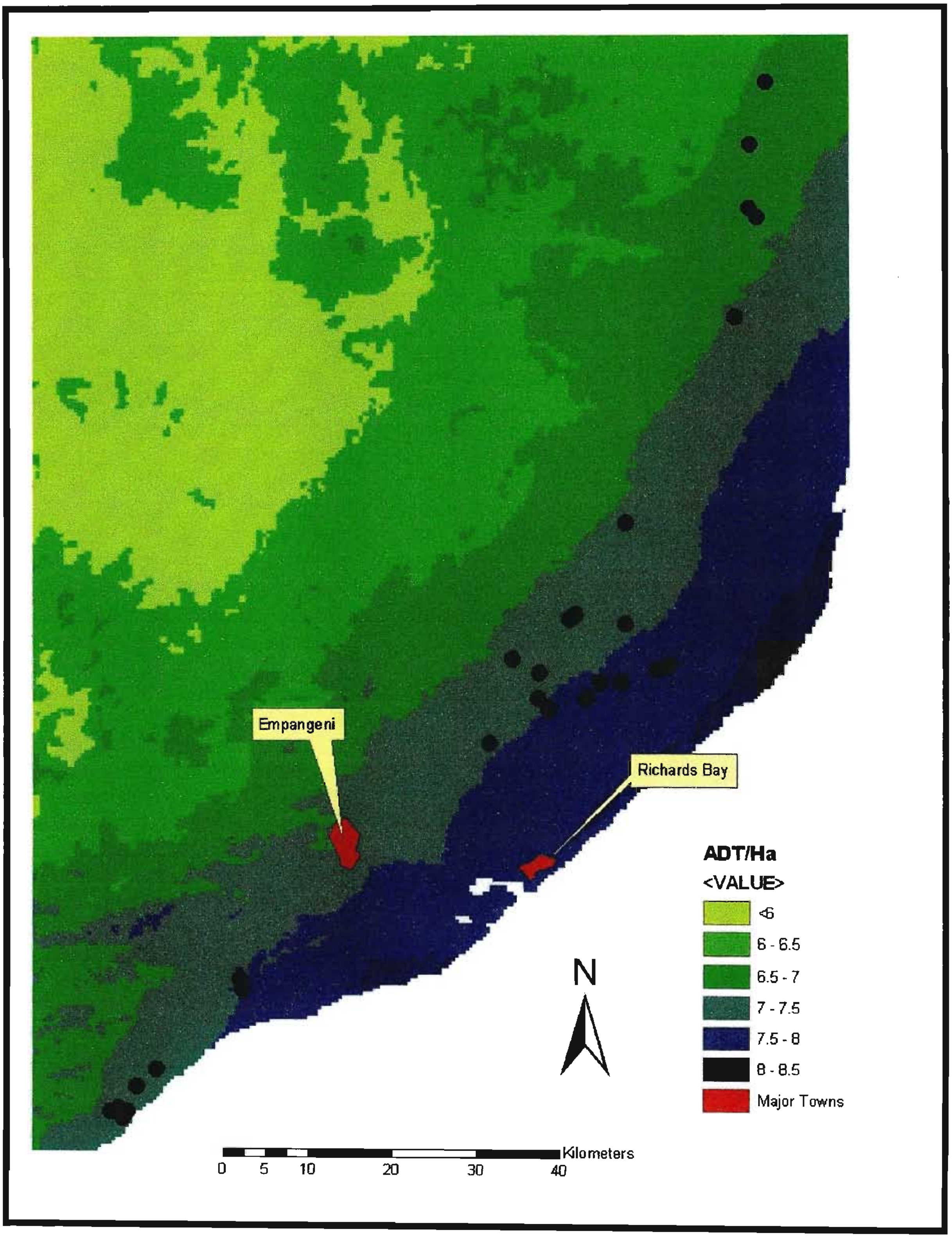


*Figure 13. Spatial Prediction of fibre yield (ADT/ha) for Eucalyptus grandis hybrids grown for Zululand coastal plain. Study sites shown by black dots.*

There a number of considerations regarding the above predictions:

- The models do not describe all the variation seen in a particular variable. The regression equations used to derive figures 10 - 13 captured only a certain percentage of the total variation in the predicted variable ranging from 43-77%. In the case of predicted values of ADT/ha (Figure 13), a function for calculating standing volume ($m^3$/ha) as well as SPY were used, introducing further error to the predicted values.
- The models are believable only in a narrow band along the Zululand coastal plain where the study sites were located. Any prediction inland of the coastal plain is not regarded as authentic due to the introduction of other site factors (especially topography as in the case of Mpumalanga) that may affect tree growth.
- The area of higher tree growth estimates closer to the ocean are also viewed with scepticism as no study sites were placed in these areas. Rainfall estimates indicate higher rainfall areas in these areas, but a more robust model may be derived by including sites that experience more extreme values for rainfall.

Further work and the improvement and verification of these prediction models may be useful in all aspects of forestry: site choice may be improved to increase fibre yield, while harvesting and management regimes optimised to improve fibre management of raw material entering the mill.

The results of this work have indicated opportunities for more intensive studies aimed at creating prediction models of wood properties. A number of recommendations can be made for future studies in both Zululand and Mpumalanga:

- The ongoing improvement in the generation of spatial climatic data will produce more reliable estimates of climate and bioclimate that may be more strongly correlated to dependent variables.
- The choice of study sites should use existing spatial climatic data to choose sites that have a large range in rainfall and temperature values. This site

choice should be careful to include extremes of these measures of climate to create a more robust model. The choice of sites in this study was limited to those for which wood property data was available.

- Future studies should aim to exclude genetic variability from tree growth. The disadvantage of this is that the model created will only be true for that species or clone.
- The effect of age should be specifically included in the study by harvesting material with a wide range of ages. Conversely, the effect of age can be blocked by sampling material of identical ages.
- Sites in areas of topographical variability, such as Mpumalanga and the KwaZulu-Natal Midlands, should be chosen to display the widest possible range in rainfall and temperature seasonality. Careful note should also be made of the other factors affecting the micro-climate of those sites including slope, aspect and soil depth. If possible, sites should be chosen to replicate these factors.

Much work has involved the development of process based models such as 3PGS to predict the volume yield of trees. The relationship between site index and wood properties has clearly shown that increased tree growth rate produces wood that is more desirable for pulp and paper making. The ongoing improvement and verification of process based models such as 3PGS may be useful in drawing inferences about wood properties based on modelled tree growth rate.

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# APPENDIX 1. Geology Data

***Table A1. Underlying geology for each study site (1:250000 Geological Maps)***

| Site Number | Estate | Compartment Code | Description | Formation | Group |
|---|---|---|---|---|---|
| 1 | Rattrays | RC42 | Yellowish redistributed sand | | |
| 2 | Rattrays | RC09 | Yellowish redistributed sand | | |
| 3 | Rattrays | RD26 | Yellowish redistributed sand | | |
| 4 | False Bay | J20 | Red dune cordon sand | Berea | |
| 5 | Rattrays | RE41 | Yellowish redistributed sand | | |
| 6 | Teza (IC118TEZ) | TH20 | Yellowish redistributed sand | | |
| 7 | Mtunzini | Q05 | Calcareous sandstone | Bluff | |
| 8 | Salpine1 | D3b | Yellowish redistributed sand | | |
| 9 | Salpine2 | H17 | Yellowish redistributed sand | | |
| 10 | The Gage | Gage | Yellowish redistributed sand | | |
| 11 | Kwambo Timbers | H9 | Yellowish redistributed sand | | |
| 12 | Hluhluwe | LO3A | Marine glauconitic siltstone | Mzinene | Zululand |
| 13 | Mtunzini | K13F | Calcareous sandstone | Bluff | |
| 14 | Mtunzini | K16A | Calcareous sandstone | Bluff | |
| 15 | False Bay | JO6 | Red dune cordon sand | Berea | |
| 16 | Mfezi | ICO72MFZ | Yellowish redistributed sand | | |
| 17 | Mtunzini | KO8a | Calcareous sandstone | Bluff | |
| 18 | Mtunzini | KO3e | Sandstone - subordinate grey shale | Vryheid | Ecca |
| 19 | Mtunzini | G07 | Biotite rich gneiss | Intumze | Matigulu |
| 20 | False Bay | J07 | Red dune cordon sand | Berea | |
| 21 | False Bay | J11 | Red dune cordon sand | Berea | |
| 22 | Trial CSI 02 - Mavuya | C8 | Yellowish redistributed sand | | |
| 23 | Mtunzini | F17 | Calcareous sandstone | Bluff | |
| 24 | Rattrays | RE10 | Yellowish redistributed sand | | |
| 25 | Mtunzini | H09a | Biotite rich gneiss | Intumze | Matigulu |
| 26 | Teza | TH22B | Yellowish redistributed sand | | |

***Table A1. Continued.***

| Site Number | Estate | Compartment Code | Description | Formation | Group |
|---|---|---|---|---|---|
| 27 | Glenthorpe | F124 | Serpentinised dunite, harzburgite | | |
| 28 | Glenthorpe | F105 | Kaap Valley granite; Hornblende biotite granite | | |
| 29 | Glenthorpe | F122 | Basalt | | |
| 30 | Glenthorpe | F77 | Kaap Valley granite; Hornblende biotite granite | | |
| 31 | Glenthorpe | F146 | Serpentinised dunite, harzburgite | | |
| 32 | Glenthorpe | B19 | Kaap Valley granite; Hornblende biotite granite | | |
| 33 | Glenthorpe | B88 | Kaap Valley granite; Hornblende biotite granite | | |
| 34 | Glenthorpe | B17 | Kaap Valley granite; Hornblende biotite granite | | |
| 35 | Glenthorpe | B115 | Kaap Valley granite; Hornblende biotite granite | | |
| 36 | Glenthorpe | G10 | Kaap Valley granite; Hornblende biotite granite | | |
| 37 | Glenthorpe | M35 | Kaap Valley granite; Hornblende biotite granite | | |
| 38 | Glenthorpe | D2B | Kaap Valley granite; Hornblende biotite granite | | |
| 39 | Glenthorpe | E5 | Biotite - trondhjmite gneiss | | |
| 40 | Sabey | D54 | Kaap Valley granite; Hornblende biotite granite | | |
| 41 | Venus | A14 | Diabase | | |
| 42 | Venus | A33 | Diabase | | |
| 43 | Waterhoutboom | H09 | Biotite bearing porphyritic granite | | |

# APPENDIX 2. Soils Data

***Table A2. General soils data for each study site***

| Site Number | Estate | Compartment Code | Soil Form | Soil Family | Abbreviation | OM_A (%) | Depth (cm) |
|---|---|---|---|---|---|---|---|
| **1** | Rattrays | **RC42** | Fernwood | 1210 | **Fw** | 0.47 | 150+ |
| **2** | Rattrays | **RC09** | Fernwood | 1210 | **Fw** | 0.97 | 150+ |
| **3** | Rattrays | **RD26** | Fernwood | 1210 | **Fw** | 0.77 | 150+ |
| **4** | False Bay | **J20** | Hutton | 1100 | **Hu** | 1.27 | 150+ |
| **5** | Rattrays | **RE41** | Fernwood | 1210 | **Fw** | 4.36 | 150+ |
| **6** | Teza (IC118TEZ) | **TH20** | Fernwood | 1210 | **Fw** | 1.24 | 150+ |
| **7** | Mtunzini | **Q05** | Constantia | 1100 | **Ct** | 0.7 | 150+ |
| **8** | Salpine1 | **D3b** | Fernwood | 1210 | **Fw** | 0.57 | 150+ |
| **9** | Salpine2 | **H17** | Fernwood | 1210 | **Fw** | 1.38 | 150+ |
| **10** | The Gage | **Gage** | Fernwood | 1210 | **Fw** | 0.47 | 150+ |
| **11** | Kwambo Timbers | **H9** | Clovelly | 1100 | **Cv** | 2.55 | 150+ |
| **12** | Hluhluwe | **LO3A** | Hutton | 1100 | **Hu** | 0.4 | 150+ |
| **13** | Mtunzini | **K13F** | Constantia | 1100 | **Ct** | 0.74 | 150+ |
| **14** | Mtunzini | **K16A** | Constantia | 1100 | **Ct** | 0.47 | 150+ |
| **15** | False Bay | **JO6** | Hutton | 1100 | **Hu** | 0.37 | 150+ |
| **16** | Mfezi | **ICO72MFZ** | Fernwood | 1210 | **Fw** | 0.8 | 150+ |
| **17** | Mtunzini | **KO8a** | Constantia | 1100 | **Ct** | 2.41 | 150+ |
| **18** | Mtunzini | **KO3e** | Constantia | 1100 | **Ct** | 1.61 | 150+ |
| **19** | Mtunzini | **G07** | Glenrosa | 1221 | **Gs** | 2.82 | 30-40 |
| **20** | False Bay | **J07** | Hutton | 1100 | **Hu** | 0.8 | 150+ |
| **21** | False Bay | **J11** | Hutton | 1100 | **Hu** | 0.8 | 150+ |
| **22** | Trial CSI 02 - Mavuya | **C8** | Fernwood | 1210 | **Fw** | 0.33 | 150+ |
| **23** | Mtunzini | **F17** | Fernwood | 1210 | **Fw** | 0.67 | 150+ |
| **24** | Rattrays | **RE10** | Fernwood | 1210 | **Fw** | 0.84 | 150+ |
| **25** | Mtunzini | **H09a** | Constantia | 1100 | **Ct** | 0.87 | 150+ |
| **26** | Teza | **TH22B** | Fernwood | 1210 | **Fw** | 1.24 | 150+ |
| **27** | Glenthorpe | **F124** | Nomanci | 2200 | **No** | 5.68 | 25 |
| **28** | Glenthorpe | **F105** | Lusiki | 1220 | **Lu** | 4.29 | 150+ |
| **29** | Glenthorpe | **F122** | Nomanci | 2200 | **No** | 5.72 | 50 |
| **30** | Glenthorpe | **F77** | Lusiki | 1220 | **Lu** | 6.48 | 150+ |
| **31** | Glenthorpe | **F146** | Nomanci | 2200 | **No** | 5.52 | 30 |
| **32** | Glenthorpe | **B19** | Mispah | 1100 | **Ms** | 1.13 | 50 |
| **33** | Glenthorpe | **B88** | Lusiki | 1210 | **Lu** | 3.12 | 150+ |
| **34** | Glenthorpe | **B17** | Nomanci | 2200 | **No** | 5.62 | 100 |
| **35** | Glenthorpe | **B115** | Lusiki | 1220 | **Lu** | 3.02 | 150+ |
| **36** | Glenthorpe | **G10** | Valsrivier | 1121 | **Vs** | 1.96 | 150+ |
| **37** | Glenthorpe | **M35** | Lusiki | 1210 | **Lu** | 5.18 | 150+ |
| **38** | Glenthorpe | **D2B** | Nomanci | 2100 | **No** | 9.31 | 100 |
| **39** | Glenthorpe | **E5** | Shortlands | 1220 | **Sd** | 3.62 | 150+ |
| **40** | Sabey | **D54** | Lusiki | 1220 | **Lu** | 3.12 | 150+ |
| **41** | Venus | **A14** | Lusiki | 1220 | **Lu** | 5.05 | 150+ |
| **42** | Venus | **A33** | Lusiki | 1220 | **Lu** | 6.25 | 150+ |
| **43** | Waterhoutboom | **H09** | Magwa | 1100 | **Ma** | 4.2 | 150+ |

***Table B2. Particle size analysis results and texture classes for all sites***

| Site Number | Soil Horizon | Clay % | Fine Silt % | Coarse Silt % | Fine Sand % | Medium Sand % | Coarse Sand % | Texture Class |
|---|---|---|---|---|---|---|---|---|
| 1 | A | 1.88 | 1.41 | 1.88 | 63.98 | 26.55 | 4.3 | Sand |
| 1 | B | 3.99 | 2.82 | 2.35 | 65.19 | 21.95 | 3.7 | Sand |
| 2 | A | 9.15 | 3.99 | 3.05 | 54.51 | 24.9 | 4.4 | Loamy Sand |
| 2 | B | 13.85 | 3.05 | 3.05 | 50.4 | 26.55 | 3.1 | Sandy Loam |
| 3 | A | 3.76 | 2.82 | 1.41 | 69.76 | 21 | 1.25 | Sand |
| 3 | B | 4.93 | 2.58 | 2.58 | 74.61 | 14.8 | 0.5 | Sand |
| 4 | A | 4.69 | 2.58 | 0.47 | 33.7 | 47.91 | 10.65 | Sand |
| 4 | B | 4.46 | 2.11 | 1.41 | 33.87 | 48.65 | 9.5 | Sand |
| 5 | A | 12.76 | 11.32 | 5.06 | 50.59 | 17.96 | 2.31 | Sandy Loam |
| 5 | B | 9.39 | 2.82 | 2.35 | 46.09 | 32.35 | 7 | Loamy Sand |
| 6 | A | 3.52 | 2.11 | 1.17 | 41.05 | 43.35 | 8.8 | Sand |
| 6 | B | 3.05 | 1.64 | 0.94 | 37 | 50.82 | 6.55 | Sand |
| 7 | A | 4.93 | 2.35 | 2.35 | 60.82 | 28.45 | 1.1 | Sand |
| 7 | B | 6.34 | 2.58 | 2.82 | 60.31 | 26.8 | 1.15 | Loamy Sand |
| 8 | A | 3.29 | 2.11 | 1.17 | 44.28 | 42.2 | 6.95 | Sand |
| 8 | B | 4.46 | 1.41 | 0.94 | 50.29 | 37.4 | 5.5 | Sand |
| 9 | A | 2.58 | 2.82 | 1.64 | 52.51 | 35.35 | 5.1 | Sand |
| 9 | B | 2.82 | 2.82 | 2.35 | 58.61 | 29.85 | 3.55 | Sand |
| 10 | A | 2.11 | 1.88 | 1.17 | 68.44 | 24.65 | 1.75 | Sand |
| 10 | B | 3.99 | 1.88 | 1.41 | 71.27 | 20.3 | 1.15 | Sand |
| 11 | A | 5.87 | 4.22 | 2.82 | 44.99 | 35.3 | 6.8 | Loamy Sand |
| 11 | B | 8.45 | 3.05 | 2.58 | 52.37 | 29.6 | 3.95 | Loamy Sand |
| 12 | A | 4.72 | 2.6 | 0.4 | 31.5 | 48.9 | 11.32 | Sand |
| 12 | B | 4.53 | 2.12 | 1.48 | 34.56 | 50.01 | 9.21 | Sand |
| 13 | A | 2.35 | 1.64 | 1.88 | 44.13 | 41.6 | 8.4 | Sand |
| 13 | B | 2.35 | 3.52 | 2.11 | 45.77 | 40.6 | 5.65 | Sand |
| 14 | A | 3.29 | 2.11 | 1.64 | 44.21 | 44.65 | 4.1 | Sand |
| 14 | B | 3.76 | 3.29 | 1.41 | 44.15 | 43.34 | 4.05 | Sand |

***Table B2. Continued***

| Site Number | Soil Horizon | Clay % | Fine Silt % | Coarse Silt % | Fine Sand % | Medium Sand % | Coarse Sand % | Texture Class |
|---|---|---|---|---|---|---|---|---|
| 15 | A | 7.51 | 2.11 | 1.88 | 52.75 | 30.7 | 5.05 | Sand |
| 15 | B | 7.64 | 2.08 | 1.5 | 50.68 | 32.7 | 4.9 | Sand |
| 16 | A | 3.52 | 2.11 | 1.17 | 41.05 | 43.35 | 8.8 | Sand |
| 16 | B | 3.05 | 1.64 | 0.94 | 37 | 50.82 | 6.55 | Sand |
| 17 | A | 12.77 | 6.26 | 3.62 | 41.68 | 29.35 | 6.32 | Sandy Loam |
| 17 | B | 23.4 | 4.14 | 3.42 | 36.84 | 26.69 | 5.51 | Sandy Clay Loam |
| 18 | A | 5.63 | 3.52 | 2.35 | 64.4 | 22.7 | 1.4 | Sand |
| 18 | B | 43.43 | 4.37 | 2.31 | 37.39 | 12.17 | 0.33 | Sandy Clay |
| 19 | A | 29.77 | 9.1 | 4.42 | 24.84 | 15.15 | 16.72 | Sandy Clay Loam |
| 19 | B | 39.92 | 8.31 | 5.13 | 18.32 | 12.91 | 15.41 | Sandy Clay |
| 20 | A | 4.72 | 2.6 | 0.4 | 31.5 | 48.9 | 11.32 | Sand |
| 20 | B | 4.53 | 2.12 | 1.48 | 34.56 | 50.01 | 9.21 | Sand |
| 21 | A | 4.69 | 2.58 | 0.47 | 33.7 | 47.91 | 10.65 | Sand |
| 21 | B | 4.46 | 2.11 | 1.41 | 33.87 | 48.65 | 9.5 | Sand |
| 22 | A | 2.82 | 3.99 | 3.05 | 67.24 | 18.95 | 3.95 | Sand |
| 22 | B | 3.05 | 4.22 | 3.52 | 71.36 | 15.5 | 2.35 | Sand |
| 23 | A | 3.76 | 1.41 | 0 | 55.93 | 37.65 | 1.25 | Sand |
| 23 | B | 4.93 | 1.41 | 0.7 | 54.06 | 38 | 0.9 | Sand |
| 24 | A | 2.82 | 2.11 | 0.94 | 40.33 | 42.2 | 11.6 | Sand |
| 24 | B | 5.16 | 1.41 | 1.88 | 46.25 | 36.35 | 8.95 | Sand |
| 25 | A | 3.05 | 2.11 | 0.7 | 36.35 | 50.55 | 7.24 | Sand |
| 25 | B | 3.05 | 1.64 | 0.94 | 37 | 50.82 | 6.55 | Sand |
| 26 | A | 3.52 | 2.11 | 1.17 | 41.05 | 43.35 | 8.8 | Sand |
| 26 | B | 3.05 | 1.64 | 0.94 | 37 | 50.82 | 6.55 | Sand |
| 27 | A | 38.88 | 15.49 | 5.63 | 26.00 | 6.45 | 7.55 | Clay Loam |
| 27 | B | 58.40 | 14.08 | 11.27 | 6.10 | 2.90 | 7.25 | Clay |
| 28 | A | 42.63 | 12.44 | 5.63 | 17.90 | 11.10 | 10.30 | Clay |
| 28 | B | 64.67 | 11.03 | 6.10 | 8.80 | 4.90 | 4.50 | Clay |
| 29 | A | 44.71 | 28.16 | 12.67 | 8.50 | 2.05 | 3.90 | Silty Clay |
| 29 | B | 58.40 | 14.08 | 11.27 | 6.10 | 2.90 | 7.25 | Clay |

***Table B2. Continued***

| Site Number | Soil Horizon | Clay % | Fine Silt % | Coarse Silt % | Fine Sand % | Medium Sand % | Coarse Sand % | Texture Class |
|---|---|---|---|---|---|---|---|---|
| 30 | A | 33.38 | 18.31 | 7.51 | 28.80 | 9.00 | 3.00 | Clay Loam |
| 30 | B | 39.06 | 14.55 | 7.04 | 27.80 | 8.90 | 2.65 | Clay Loam |
| 31 | A | 29.72 | 19.95 | 14.08 | 23.70 | 4.45 | 8.10 | Clay Loam |
| 31 | B | 33.20 | 38.73 | 15.72 | 10.55 | 1.05 | 0.75 | Silty Clay Loam |
| 32 | A | 24.10 | 14.79 | 4.46 | 19.05 | 15.75 | 21.85 | Sandy Clay Loam |
| 32 | B | 6.34 | 21.48 | 6.34 | 19.55 | 16.25 | 30.05 | Sandy Loam |
| 33 | A | 28.92 | 11.50 | 2.58 | 13.20 | 17.65 | 26.15 | Sandy Clay Loam |
| 33 | B | 38.45 | 13.61 | 3.29 | 9.80 | 11.05 | 23.80 | Clay Loam |
| 34 | A | 33.89 | 17.84 | 3.52 | 18.50 | 15.10 | 11.15 | Clay Loam |
| 34 | B | 47.19 | 25.58 | 4.22 | 8.95 | 7.10 | 6.95 | Clay |
| 35 | A | 35.67 | 8.21 | 3.52 | 16.80 | 17.25 | 18.55 | Sandy Clay |
| 35 | B | 50.96 | 7.98 | 3.76 | 12.70 | 9.80 | 14.80 | Clay |
| 36 | A | 13.04 | 11.50 | 4.46 | 23.00 | 21.35 | 26.65 | Sandy Loam |
| 36 | B | 33.54 | 12.44 | 2.82 | 16.30 | 14.80 | 20.10 | Sandy Clay Loam |
| 37 | A | 38.12 | 19.25 | 5.63 | 8.25 | 8.10 | 20.65 | Clay Loam |
| 37 | B | 56.00 | 16.43 | 5.87 | 6.00 | 4.45 | 11.25 | Clay |
| 38 | A | 37.74 | 16.43 | 1.88 | 10.95 | 9.85 | 23.15 | Clay Loam |
| 38 | B | 39.64 | 16.19 | 2.82 | 8.40 | 8.25 | 24.70 | Clay Loam |
| 39 | A | 40.44 | 11.27 | 5.40 | 24.05 | 13.20 | 5.65 | Clay |
| 39 | B | 52.89 | 8.21 | 4.69 | 19.60 | 9.75 | 4.85 | Clay |
| 40 | A | 27.02 | 19.71 | 2.11 | 18.60 | 16.35 | 16.20 | Sandy Clay Loam |
| 40 | B | 29.87 | 8.68 | 1.64 | 18.80 | 22.20 | 18.80 | Sandy Clay Loam |
| 41 | A | 35.87 | 11.50 | 1.88 | 7.80 | 10.25 | 32.70 | Sandy Clay |
| 41 | B | 46.73 | 11.03 | 3.29 | 8.75 | 9.75 | 20.45 | Clay |
| 42 | A | 24.92 | 25.82 | 4.46 | 9.00 | 8.85 | 26.95 | Loam |
| 42 | B | 37.26 | 16.90 | 3.99 | 8.30 | 10.55 | 23.00 | Clay Loam |
| 43 | A | 16.73 | 13.85 | 1.88 | 12.25 | 12.65 | 42.65 | Sandy Loam |
| 43 | B | 15.40 | 10.56 | 1.64 | 10.00 | 12.90 | 49.50 | Sandy Loam |

***Table C2. Soil Water Retentivity data for topsoil and subsoil samples from all sites***

| Site Number | Horizon | Saturated Porosity ($m^3/m^3$) | Water content ($m^3/m^3$) (-10kPa) | (-100kPa) | (-1500kPa) | RAW (mm/m) | RAW/horizon | RAW (in 1.5m) | PAWC (mm/m) | AWC/horizon | AWC (in 1.5m) | RAW/PAW * 100 (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | A | 0.44 | 0.1 | 0.05 | 0.04 | 50 | 15 | | 60 | 18 | | |
| 1 | B | 0.44 | 0.1 | 0.05 | 0.04 | 50 | 60 | 75 | 60 | 72 | 90 | **83** |
| 2 | A | 0.46 | 0.14 | 0.08 | 0.06 | 60 | 18 | | 80 | 24 | | |
| 2 | B | 0.48 | 0.19 | 0.11 | 0.08 | 80 | 96 | 114 | 110 | 132 | 156 | **73** |
| 3 | A | 0.44 | 0.1 | 0.05 | 0.04 | 50 | 15 | | 60 | 18 | | |
| 3 | B | 0.44 | 0.1 | 0.05 | 0.04 | 50 | 60 | 75 | 60 | 72 | 90 | **83** |
| 4 | A | 0.44 | 0.1 | 0.05 | 0.04 | 50 | 15 | | 60 | 18 | | |
| 4 | B | 0.44 | 0.1 | 0.05 | 0.04 | 50 | 60 | 75 | 60 | 72 | 90 | **83** |
| 5 | A | 0.48 | 0.19 | 0.11 | 0.08 | 80 | 24 | | 110 | 33 | | |
| 5 | B | 0.46 | 0.14 | 0.08 | 0.06 | 60 | 72 | 96 | 80 | 96 | 129 | **74** |
| 6 | A | 0.44 | 0.1 | 0.05 | 0.04 | 50 | 15 | | 60 | 18 | | |
| 6 | B | 0.44 | 0.1 | 0.05 | 0.04 | 50 | 60 | 75 | 60 | 72 | 90 | **83** |
| 7 | A | 0.44 | 0.1 | 0.05 | 0.04 | 50 | 15 | | 60 | 18 | | |
| 7 | B | 0.46 | 0.14 | 0.08 | 0.06 | 60 | 72 | 87 | 80 | 96 | 114 | **76** |
| 8 | A | 0.44 | 0.1 | 0.05 | 0.04 | 50 | 15 | | 60 | 18 | | |
| 8 | B | 0.44 | 0.1 | 0.05 | 0.04 | 50 | 60 | 75 | 60 | 72 | 90 | **83** |
| 9 | A | 0.44 | 0.1 | 0.05 | 0.04 | 50 | 15 | | 60 | 18 | | |
| 9 | B | 0.44 | 0.1 | 0.05 | 0.04 | 50 | 60 | 75 | 60 | 72 | 90 | **83** |
| 10 | A | 0.44 | 0.1 | 0.05 | 0.04 | 50 | 15 | | 60 | 18 | | |
| 10 | B | 0.44 | 0.1 | 0.05 | 0.04 | 50 | 60 | 75 | 60 | 72 | 90 | **83** |
| 11 | A | 0.46 | 0.14 | 0.08 | 0.06 | 60 | 18 | | 80 | 24 | | |
| 11 | B | 0.46 | 0.14 | 0.08 | 0.06 | 60 | 72 | 90 | 80 | 96 | 120 | **75** |
| 12 | A | 0.44 | 0.1 | 0.05 | 0.04 | 50 | 15 | | 60 | 18 | | |
| 12 | B | 0.44 | 0.1 | 0.05 | 0.04 | 50 | 60 | 75 | 60 | 72 | 90 | **83** |
| 13 | A | 0.44 | 0.1 | 0.05 | 0.04 | 50 | 15 | | 60 | 18 | | |
| 13 | B | 0.44 | 0.1 | 0.05 | 0.04 | 50 | 60 | 75 | 60 | 72 | 90 | **83** |
| 14 | A | 0.44 | 0.1 | 0.05 | 0.04 | 50 | 15 | | 60 | 18 | | |
| 14 | B | 0.44 | 0.1 | 0.05 | 0.04 | 50 | 60 | 75 | 60 | 72 | 90 | **83** |
| 15 | A | 0.44 | 0.1 | 0.05 | 0.04 | 50 | 15 | | 60 | 18 | | |
| 15 | B | 0.44 | 0.1 | 0.05 | 0.04 | 50 | 60 | 75 | 60 | 72 | 90 | **83** |

***Table C2. Continued.***

| Site Number | Horizon | Saturated Porosity ($m^3/m^3$) | Water content ($m^3/m^3$) (-10kPa) | (-100kPa) | (-1500kPa) | RAW (mm/m) | RAW/horizon | RAW (in 1.5m) | PAWC (mm/m) | AWC/horizon | AWC (in 1.5m) | RAW/PAW * 100 (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 16 | A | 0.44 | 0.1 | 0.05 | 0.04 | 50 | 15 | | 60 | 18 | | |
| 16 | B | 0.44 | 0.1 | 0.05 | 0.04 | 50 | 60 | 75 | 60 | 72 | 90 | **83** |
| 17 | A | 0.48 | 0.19 | 0.11 | 0.08 | 80 | 24 | | 110 | 33 | | |
| 17 | B | 0.53 | 0.25 | 0.19 | 0.15 | 60 | 72 | 96 | 100 | 120 | 153 | **63** |
| 18 | A | 0.44 | 0.1 | 0.05 | 0.04 | 50 | 15 | | 60 | 18 | | |
| 18 | B | 0.5 | 0.24 | 0.19 | 0.15 | 50 | 60 | 75 | 90 | 108 | 126 | **60** |
| 19 | A | 0.53 | 0.25 | 0.19 | 0.15 | 60 | 18 | | 100 | 30 | | |
| 19 | B | 0.5 | 0.24 | 0.19 | 0.15 | 50 | 60 | 78 | 90 | 108 | 138 | **57** |
| 20 | A | 0.44 | 0.1 | 0.05 | 0.04 | 50 | 15 | | 60 | 18 | | |
| 20 | B | 0.44 | 0.1 | 0.05 | 0.04 | 50 | 60 | 75 | 60 | 72 | 90 | **83** |
| 21 | A | 0.44 | 0.1 | 0.05 | 0.04 | 50 | 15 | | 60 | 18 | | |
| 21 | B | 0.44 | 0.1 | 0.05 | 0.04 | 50 | 60 | 75 | 60 | 72 | 90 | **83** |
| 22 | A | 0.44 | 0.1 | 0.05 | 0.04 | 50 | 15 | | 60 | 18 | | |
| 22 | B | 0.44 | 0.1 | 0.05 | 0.04 | 50 | 60 | 75 | 60 | 72 | 90 | **83** |
| 23 | A | 0.44 | 0.1 | 0.05 | 0.04 | 50 | 15 | | 60 | 18 | | |
| 23 | B | 0.44 | 0.1 | 0.05 | 0.04 | 50 | 60 | 75 | 60 | 72 | 90 | **83** |
| 24 | A | 0.44 | 0.1 | 0.05 | 0.04 | 50 | 15 | | 60 | 18 | | |
| 24 | B | 0.44 | 0.1 | 0.05 | 0.04 | 50 | 60 | 75 | 60 | 72 | 90 | **83** |
| 25 | A | 0.44 | 0.1 | 0.05 | 0.04 | 50 | 15 | | 60 | 18 | | |
| 25 | B | 0.44 | 0.1 | 0.05 | 0.04 | 50 | 60 | 75 | 60 | 72 | 90 | **83** |
| 26 | A | 0.44 | 0.1 | 0.05 | 0.04 | 50 | 15 | | 60 | 18 | | |
| 26 | B | 0.44 | 0.1 | 0.05 | 0.04 | 50 | 60 | 75 | 60 | 72 | 90 | **83** |
| 27 | A | 0.54 | 0.32 | 0.24 | 0.19 | 80 | 24 | | 130 | 39 | | |
| 27 | B | 0.63 | 0.39 | 0.3 | 0.26 | 90 | 108 | 132 | 130 | 156 | 195 | **68** |
| 28 | A | 0.63 | 0.39 | 0.3 | 0.26 | 90 | 27 | | 130 | 39 | | |
| 28 | B | 0.63 | 0.39 | 0.3 | 0.26 | 90 | 108 | 135 | 130 | 156 | 195 | **69** |
| 29 | A | 0.62 | 0.41 | 0.32 | 0.27 | 90 | 27 | | 140 | 42 | | |
| 29 | B | 0.63 | 0.39 | 0.3 | 0.26 | 90 | 108 | 135 | 130 | 156 | 198 | **68** |
| 30 | A | 0.54 | 0.32 | 0.24 | 0.19 | 80 | 24 | | 130 | 39 | | |
| 30 | B | 0.54 | 0.32 | 0.24 | 0.19 | 80 | 96 | 120 | 130 | 156 | 195 | **62** |

***Table C2. Continued.***

| Site Number | Horizon | Saturated Porosity ($m^3/m^3$) | Water content ($m^3/m^3$) (-10kPa) | (-100kPa) | (-1500kPa) | RAW (mm/m) | RAW/horizon | RAW (in 1.5m) | PAWC (mm/m) | AWC/horizon | AWC (in 1.5m) | RAW/PAW * 100 (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 31 | A | 0.54 | 0.32 | 0.24 | 0.19 | 80 | 24 | | 130 | 39 | | |
| 31 | B | 0.57 | 0.36 | 0.27 | 0.2 | 90 | 108 | 132 | 160 | 192 | 231 | 57 |
| 32 | A | 0.53 | 0.25 | 0.19 | 0.15 | 60 | 18 | | 100 | 30 | | |
| 32 | B | 0.54 | 0.32 | 0.24 | 0.19 | 80 | 96 | 114 | 130 | 156 | 186 | 61 |
| 33 | A | 0.53 | 0.25 | 0.19 | 0.15 | 60 | 18 | | 100 | 30 | | |
| 33 | B | 0.54 | 0.32 | 0.24 | 0.19 | 80 | 96 | 114 | 130 | 156 | 186 | 61 |
| 34 | A | 0.54 | 0.32 | 0.24 | 0.19 | 80 | 24 | | 130 | 39 | | |
| 34 | B | 0.63 | 0.39 | 0.3 | 0.26 | 90 | 108 | 132 | 130 | 156 | 195 | 68 |
| 35 | A | 0.5 | 0.24 | 0.19 | 0.15 | 50 | 15 | | 90 | 27 | | |
| 35 | B | 0.63 | 0.39 | 0.3 | 0.26 | 90 | 108 | 123 | 130 | 156 | 183 | 67 |
| 36 | A | 0.48 | 0.19 | 0.11 | 0.08 | 80 | 24 | | 110 | 33 | | |
| 36 | B | 0.53 | 0.25 | 0.19 | 0.15 | 60 | 72 | 96 | 100 | 120 | 153 | 63 |
| 37 | A | 0.54 | 0.32 | 0.24 | 0.19 | 80 | 24 | | 130 | 39 | | |
| 37 | B | 0.63 | 0.39 | 0.3 | 0.26 | 90 | 108 | 132 | 130 | 156 | 195 | 68 |
| 38 | A | 0.54 | 0.32 | 0.24 | 0.19 | 80 | 24 | | 130 | 39 | | |
| 38 | B | 0.54 | 0.32 | 0.24 | 0.19 | 80 | 96 | 120 | 130 | 156 | 195 | 62 |
| 39 | A | 0.63 | 0.39 | 0.3 | 0.26 | 90 | 27 | | 130 | 39 | | |
| 39 | B | 0.63 | 0.39 | 0.3 | 0.26 | 90 | 108 | 135 | 130 | 156 | 195 | 69 |
| 40 | A | 0.53 | 0.25 | 0.19 | 0.15 | 50 | 15 | | 100 | 30 | | |
| 40 | B | 0.53 | 0.25 | 0.19 | 0.15 | 50 | 60 | 75 | 100 | 120 | 150 | 50 |
| 41 | A | 0.5 | 0.24 | 0.19 | 0.15 | 50 | 15 | | 90 | 27 | | |
| 41 | B | 0.63 | 0.39 | 0.3 | 0.26 | 90 | 108 | 123 | 130 | 156 | 183 | 67 |
| 42 | A | 0.55 | 0.27 | 0.15 | 0.12 | 120 | 36 | | 150 | 45 | | |
| 42 | B | 0.54 | 0.32 | 0.24 | 0.19 | 80 | 96 | 132 | 130 | 156 | 201 | 66 |
| 43 | A | 0.53 | 0.25 | 0.19 | 0.15 | 50 | 15 | | 100 | 30 | | |
| 43 | B | 0.53 | 0.25 | 0.19 | 0.15 | 50 | 60 | 75 | 100 | 120 | 150 | 50 |

# APPENDIX 3. Wood Property, Climatic and Bioclimatic data

***Table A3. Complete wood property data for SPY, WMD, AA and FL_WM as well as SI data for study sites.***

| Site Number | Estate | Compt. Code | $SI_5$ | WMD ($kg/m^3$) | SPY (%) | FL WM (mm) | AA (%) |
|---|---|---|---|---|---|---|---|
| 1 | Rattrays | RC42 | 23.7 | 395 | 51.54 | 0.82 | 82.14 |
| 2 | Rattrays | RC09 | 21.8 | 428 | 50.48 | 0.77 | 81.58 |
| 3 | Rattrays | RD26 | 16.4 | 412 | 49.49 | 0.69 | 82.10 |
| 4 | False Bay | J20 | 14.2 | 418 | 47.80 | 0.65 | 80.70 |
| 5 | Rattrays | RE41 | 22 | 388 | 50.61 | 0.74 | 80.72 |
| 6 | Teza | TH20 | 17.4 | 435 | 47.27 | 0.65 | 83.64 |
| 7 | Mtunzini | Q05 | 21.68 | 520 | 49.51 | 0.98 | |
| 8 | Salpine1 | D3b | 24.81 | 420 | 51.34 | 0.90 | 83.88 |
| 9 | Salpine2 | H17 | 24.74 | 510 | 50.56 | 0.93 | 71.14 |
| 10 | The Gage | Gage | 24.89 | 500 | 50.96 | 0.95 | 70.93 |
| 11 | Kwambo Timbers | Terra A18 - H9 | 21.8 | | | | |
| 12 | Hluhluwe | L03a | 17 | 457 | 46.94 | 0.64 | 83.28 |
| 13 | Mtunzini | K13f | 20.2 | 590 | 49.80 | 0.87 | 84.68 |
| 14 | Mtunzini | K16a | 22.6 | 493 | 50.00 | 0.84 | 81.58 |
| 15 | False Bay | J06 | 13.4 | 465 | 45.83 | 0.63 | 82.60 |
| 16 | Mfezi | Mfezi | 16.2 | 527 | 46.65 | 0.65 | 85.12 |
| 17 | Mtunzini | K08a | 16.7 | 453 | 49.29 | 0.77 | 80.18 |
| 18 | Mtunzini | K03e | 21.2 | 475 | 49.19 | 0.75 | 81.66 |
| 19 | Mtunzini | G07 | 24.6 | 504 | 51.87 | 0.86 | 85.28 |
| 20 | False Bay | J07 | 16.0 | 510 | 47.51 | 0.73 | 91.26 |
| 21 | False Bay | J11 | 13.3 | 472 | 48.20 | 0.76 | 87.54 |
| 22 | Mavuya | C8 | | 490 | 48.78 | 0.75 | 85.17 |
| 23 | Mtunzini | F17 | | 491 | 48.16 | 0.75 | 87.99 |
| 24 | Rattrays | RE10 | 23.5 | 470 | 51.93 | 0.89 | 79.50 |
| 25 | Mtunzini | H09a | 21.4 | 461 | 49.69 | 0.75 | 82.02 |
| 26 | Teza | TH22B | 17 | 502 | 48.35 | 0.80 | 80.28 |

***Table A3. Continued.***

| Site Number | Estate | Compt. Code | SI5 | WMD ($kg/m^3$) | SPY (%) | AA (%) |
|---|---|---|---|---|---|---|
| 27 | Glenthorpe | F124 | 10.8 | 465 | 47.70 | 91.70 |
| 28 | Glenthorpe | F105 | 14.9 | 418 | 50.80 | 84.70 |
| 29 | Glenthorpe | F122 | 12 | | 49.30 | 81.40 |
| 30 | Glenthorpe | F77 | 20.1 | | 52.70 | 85.10 |
| 31 | Glenthorpe | F146 | 9.6 | 475 | 46.65 | 89.03 |
| 32 | Glenthorpe | B19 | 15.6 | 376 | 49.20 | 89.70 |
| 33 | Glenthorpe | B88a | 20.1 | 369 | 50.68 | 84.84 |
| 34 | Glenthorpe | B17 | 15.2 | | 48.50 | 86.10 |
| 35 | Glenthorpe | B115 | 18.5 | 415 | 51.66 | 80.94 |
| 36 | Glenthorpe | G10c | 19.5 | | 50.40 | 89.20 |
| 37 | Glenthorpe | M35 | 18.3 | 387 | 50.22 | 83.57 |
| 38 | Glenthorpe | A24 | 13.4 | | 50.60 | 73.34 |
| 39 | Glenthorpe | E5 | 24.1 | 422 | 51.41 | 81.87 |
| 40 | Sabey | T4 (D54) | 12 | | 49.20 | 82.02 |
| 41 | Venus | A14 | 24.7 | | 53.70 | 79.80 |
| 42 | Venus | A33 | 24.8 | 439 | 52.20 | 82.90 |
| 43 | Waterhoutboom | H09b | 20 | 395 | 53.10 | 70.86 |

***Table B3. Mean monthly minimum temperature data for study sites as predicted by Anusplin.***

| Site | Estate | Compt. | | | | | Mean Monthly Minimum Temperature | | | | | | | Ave. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Number | | Code | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | MinT |
| 1 | Rattrays | RC42 | 20 | 20 | 20 | 17 | 14 | 12 | 11 | 13 | 15 | 16 | 18 | 19 | 16.3 |
| 2 | Rattrays | RC09 | 20 | 20 | 20 | 17 | 14 | 11 | 11 | 13 | 15 | 16 | 18 | 19 | 16.2 |
| 3 | Rattrays | RD26 | 20 | 20 | 19 | 17 | 14 | 11 | 11 | 13 | 15 | 16 | 18 | 19 | 16.1 |
| 4 | False Bay | J20 | 19 | 19 | 18 | 15 | 12 | 9 | 9 | 11 | 13 | 15 | 16 | 18 | 14.5 |
| 5 | Rattrays | RE41 | 20 | 20 | 19 | 17 | 14 | 11 | 11 | 13 | 15 | 16 | 18 | 19 | 16.1 |
| 6 | Teza (IC118TEZ) | TH20 | 20 | 20 | 19 | 17 | 14 | 11 | 11 | 13 | 15 | 16 | 18 | 19 | 16.1 |
| 7 | Mtunzini | Q05 | 20 | 20 | 19 | 17 | 14 | 12 | 11 | 13 | 15 | 16 | 18 | 19 | 16.2 |
| 8 | Salpine1 | D3b | 20 | 20 | 19 | 17 | 14 | 11 | 11 | 13 | 15 | 16 | 18 | 19 | 16.1 |
| 9 | Salpine2 | H17 | 20 | 20 | 19 | 17 | 14 | 11 | 11 | 13 | 15 | 16 | 18 | 19 | 16.1 |
| 10 | The Gage | Gage | 20 | 20 | 20 | 17 | 14 | 12 | 11 | 13 | 15 | 16 | 18 | 19 | 16.3 |
| 11 | Kwambo Timbers | H9 | 20 | 20 | 20 | 17 | 14 | 11 | 11 | 13 | 15 | 16 | 18 | 19 | 16.2 |
| 12 | Hluhluwe | LO3A | 19 | 19 | 18 | 15 | 12 | 9 | 9 | 11 | 14 | 15 | 17 | 18 | 14.7 |
| 13 | Mtunzini | K13F | 20 | 20 | 20 | 17 | 14 | 12 | 11 | 13 | 15 | 16 | 18 | 19 | 16.3 |
| 14 | Mtunzini | K16A | 20 | 20 | 20 | 17 | 14 | 12 | 11 | 13 | 15 | 16 | 18 | 19 | 16.3 |
| 15 | False Bay | JO6 | 20 | 21 | 20 | 17 | 15 | 12 | 12 | 13 | 15 | 16 | 18 | 20 | 16.6 |
| 16 | Mfezi | ICO72MFZ | 20 | 20 | 20 | 17 | 14 | 11 | 11 | 12 | 15 | 16 | 18 | 19 | 16.1 |
| 17 | Mtunzini | KO8a | 20 | 20 | 20 | 17 | 14 | 12 | 11 | 13 | 15 | 16 | 18 | 19 | 16.3 |
| 18 | Mtunzini | KO3e | 20 | 20 | 19 | 17 | 14 | 12 | 11 | 13 | 15 | 16 | 18 | 19 | 16.2 |
| 19 | Mtunzini | G07 | 20 | 20 | 20 | 17 | 15 | 12 | 12 | 13 | 15 | 16 | 18 | 19 | 16.4 |
| 20 | False Bay | J07 | 19 | 19 | 18 | 15 | 12 | 9 | 9 | 11 | 13 | 15 | 16 | 18 | 14.5 |
| 21 | False Bay | J11 | 19 | 19 | 18 | 15 | 12 | 9 | 9 | 11 | 13 | 15 | 16 | 18 | 14.5 |
| 22 | Trial CSI 02 - Mavuya | C8 | 20 | 20 | 19 | 17 | 14 | 11 | 11 | 13 | 15 | 16 | 18 | 19 | 16.1 |
| 23 | Mtunzini | F17 | 20 | 20 | 20 | 17 | 14 | 12 | 11 | 13 | 15 | 16 | 18 | 19 | 16.3 |
| 24 | Rattrays | RE10 | 20 | 20 | 19 | 17 | 14 | 11 | 11 | 13 | 15 | 16 | 18 | 19 | 16.1 |
| 25 | Mtunzini | H09a | 20 | 21 | 20 | 18 | 15 | 12 | 12 | 13 | 15 | 17 | 18 | 20 | 16.8 |
| 26 | Teza | TH22B | 20 | 20 | 19 | 17 | 14 | 11 | 11 | 13 | 15 | 16 | 18 | 19 | 16.1 |

***Table B3. Continued.***

| Site | Estate | Compt. | | | | | Mean Monthly Minimum Temperature | | | | | | | Ave. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Number | | Code | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | MinT |
| 27 | Glenthorpe | F124 | 17 | 17 | 16 | 13 | 9 | 5 | 5 | 8 | 11 | 13 | 15 | 16 | 12.1 |
| 28 | Glenthorpe | F105 | 17 | 17 | 16 | 13 | 9 | 5 | 5 | 8 | 11 | 14 | 15 | 17 | 12.3 |
| 29 | Glenthorpe | F122 | 17 | 17 | 16 | 13 | 9 | 6 | 6 | 8 | 11 | 13 | 15 | 16 | 12.3 |
| 30 | Glenthorpe | F77 | 17 | 17 | 16 | 13 | 9 | 5 | 5 | 8 | 11 | 14 | 15 | 17 | 12.3 |
| 31 | Glenthorpe | F146 | 17 | 17 | 16 | 13 | 9 | 5 | 5 | 8 | 11 | 13 | 15 | 16 | 12.1 |
| 32 | Glenthorpe | B19 | 17 | 17 | 15 | 12 | 8 | 5 | 5 | 8 | 11 | 13 | 15 | 16 | 11.8 |
| 33 | Glenthorpe | B88 | 17 | 17 | 16 | 13 | 9 | 6 | 6 | 8 | 11 | 13 | 15 | 16 | 12.3 |
| 34 | Glenthorpe | B17 | 17 | 17 | 15 | 12 | 8 | 5 | 5 | 8 | 11 | 13 | 15 | 16 | 11.8 |
| 35 | Glenthorpe | B115 | 17 | 17 | 16 | 13 | 9 | 6 | 6 | 8 | 11 | 14 | 15 | 17 | 12.4 |
| 36 | Glenthorpe | G10 | 17 | 17 | 16 | 13 | 9 | 5 | 5 | 8 | 11 | 14 | 15 | 17 | 12.3 |
| 37 | Glenthorpe | M35 | 17 | 17 | 16 | 13 | 9 | 6 | 6 | 8 | 11 | 13 | 15 | 16 | 12.3 |
| 38 | Glenthorpe | D2B | 15 | 14 | 14 | 11 | 8 | 5 | 5 | 7 | 9 | 11 | 13 | 14 | 10.5 |
| 39 | Glenthorpe | E5 | 16 | 16 | 15 | 13 | 9 | 6 | 6 | 8 | 11 | 13 | 14 | 16 | 11.9 |
| 40 | Sabey | D54 | 16 | 15 | 15 | 12 | 9 | 7 | 7 | 8 | 11 | 12 | 14 | 15 | 11.8 |
| 41 | Venus | A14 | 18 | 18 | 16 | 13 | 9 | 6 | 6 | 8 | 12 | 14 | 16 | 17 | 12.8 |
| 42 | Venus | A33 | 18 | 18 | 17 | 14 | 10 | 6 | 6 | 9 | 12 | 14 | 16 | 17 | 13.1 |
| 43 | Waterhoutboom | H09 | 16 | 16 | 15 | 12 | 9 | 6 | 6 | 8 | 11 | 13 | 15 | 16 | 11.9 |

***Table C3. Mean monthly maximum temperatures for study sites as predicted by Anusplin.***

| Site Number | Estate | Compt. Code | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Ave. MaxT | MAT ANU |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Mean Monthly Maximum Temperature | | | | | | | | | |
| 1 | Rattrays | RC42 | 30 | 30 | 29 | 27 | 26 | 24 | 24 | 25 | 26 | 26 | 27 | 29 | 26.9 | 21.9 |
| 2 | Rattrays | RC09 | 30 | 30 | 29 | 27 | 26 | 24 | 24 | 25 | 26 | 26 | 27 | 29 | 26.9 | 21.9 |
| 3 | Rattrays | RD26 | 30 | 30 | 29 | 27 | 26 | 24 | 24 | 25 | 26 | 26 | 27 | 29 | 26.9 | 21.9 |
| 4 | False Bay | J20 | 29 | 28 | 28 | 26 | 25 | 23 | 23 | 24 | 25 | 26 | 27 | 28 | 26.0 | 22.3 |
| 5 | Rattrays | RE41 | 30 | 30 | 29 | 27 | 26 | 24 | 24 | 25 | 26 | 26 | 27 | 29 | 26.9 | 21.9 |
| 6 | Teza (IC118TEZ) | TH20 | 30 | 30 | 29 | 27 | 26 | 24 | 24 | 25 | 26 | 26 | 28 | 30 | 27.1 | 22.1 |
| 7 | Mtunzini | Q05 | 28 | 28 | 28 | 26 | 25 | 23 | 23 | 24 | 24 | 25 | 26 | 28 | 25.7 | 22.0 |
| 8 | Salpine1 | D3b | 30 | 30 | 29 | 27 | 26 | 24 | 24 | 25 | 26 | 26 | 28 | 30 | 27.1 | 21.8 |
| 9 | Salpine2 | H17 | 30 | 30 | 29 | 27 | 26 | 24 | 24 | 25 | 26 | 26 | 28 | 30 | 27.1 | 21.9 |
| 10 | The Gage | Gage | 30 | 30 | 29 | 27 | 26 | 24 | 24 | 25 | 25 | 26 | 27 | 29 | 26.8 | 22.0 |
| 11 | Kwambo Timbers | H9 | 30 | 30 | 29 | 27 | 26 | 24 | 24 | 25 | 26 | 26 | 27 | 29 | 26.9 | 21.9 |
| 12 | Hluhluwe | LO3A | 29 | 29 | 29 | 27 | 25 | 23 | 23 | 24 | 26 | 26 | 27 | 29 | 26.4 | 22.0 |
| 13 | Mtunzini | K13F | 28 | 28 | 28 | 26 | 25 | 23 | 23 | 24 | 24 | 25 | 26 | 28 | 25.7 | 22.3 |
| 14 | Mtunzini | K16A | 28 | 28 | 28 | 26 | 25 | 23 | 23 | 24 | 24 | 25 | 26 | 28 | 25.7 | 21.9 |
| 15 | False Bay | JO6 | 29 | 29 | 28 | 27 | 25 | 23 | 23 | 24 | 24 | 25 | 26 | 28 | 25.9 | 21.9 |
| 16 | Mfezi | ICO72MFZ | 31 | 31 | 30 | 28 | 26 | 24 | 24 | 25 | 26 | 27 | 28 | 30 | 27.5 | 22.2 |
| 17 | Mtunzini | KO8a | 28 | 28 | 28 | 26 | 25 | 23 | 23 | 24 | 24 | 25 | 26 | 28 | 25.7 | 22.3 |
| 18 | Mtunzini | KO3e | 28 | 28 | 28 | 26 | 25 | 23 | 23 | 24 | 24 | 25 | 26 | 28 | 25.7 | 21.8 |
| 19 | Mtunzini | G07 | 29 | 29 | 28 | 27 | 25 | 23 | 23 | 24 | 25 | 25 | 26 | 28 | 26.0 | 22.0 |
| 20 | False Bay | J07 | 29 | 28 | 28 | 26 | 25 | 23 | 23 | 24 | 25 | 26 | 27 | 28 | 26.0 | 22.3 |
| 21 | False Bay | J11 | 29 | 28 | 28 | 26 | 25 | 23 | 23 | 24 | 25 | 26 | 27 | 28 | 26.0 | 22.3 |
| 22 | Trial CSI 02 - Mavuya | C8 | 30 | 30 | 29 | 27 | 26 | 24 | 24 | 25 | 26 | 26 | 28 | 30 | 27.1 | 22.1 |
| 23 | Mtunzini | F17 | 28 | 28 | 28 | 26 | 25 | 23 | 23 | 24 | 24 | 25 | 26 | 28 | 25.7 | 22.1 |
| 24 | Rattrays | RE10 | 30 | 30 | 29 | 27 | 26 | 24 | 24 | 25 | 26 | 26 | 27 | 29 | 26.9 | 21.9 |
| 25 | Mtunzini | H09a | 29 | 29 | 28 | 27 | 25 | 23 | 23 | 24 | 24 | 25 | 26 | 28 | 25.9 | 22.0 |
| 26 | Teza | TH22B | 30 | 30 | 29 | 27 | 26 | 24 | 24 | 25 | 26 | 26 | 28 | 30 | 27.1 | 22.1 |

***Table C3. Continued.***

| Site Number | Estate | Compt. Code | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Ave. MaxT | MAT ANU |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Mean Monthly Maximum Temperature | | | | | | | | | | | | | |
| 27 | Glenthorpe | F124 | 28 | 28 | 27 | 25 | 24 | 21 | 22 | 24 | 26 | 27 | 27 | 28 | 25.6 | 19.0 |
| 28 | Glenthorpe | F105 | 29 | 29 | 28 | 26 | 24 | 22 | 22 | 24 | 26 | 27 | 27 | 28 | 26.0 | 18.9 |
| 29 | Glenthorpe | F122 | 28 | 28 | 27 | 25 | 23 | 21 | 21 | 23 | 25 | 26 | 26 | 27 | 25.0 | 18.8 |
| 30 | Glenthorpe | F77 | 29 | 28 | 28 | 26 | 24 | 22 | 22 | 24 | 26 | 27 | 27 | 28 | 25.9 | 18.5 |
| 31 | Glenthorpe | F146 | 28 | 28 | 27 | 25 | 24 | 21 | 22 | 24 | 26 | 27 | 27 | 28 | 25.6 | 18.7 |
| 32 | Glenthorpe | B19 | 28 | 28 | 27 | 25 | 23 | 21 | 21 | 23 | 25 | 26 | 26 | 27 | 25.0 | 18.6 |
| 33 | Glenthorpe | B88 | 28 | 28 | 27 | 25 | 23 | 21 | 21 | 23 | 25 | 26 | 26 | 27 | 25.0 | 19.3 |
| 34 | Glenthorpe | B17 | 28 | 28 | 27 | 25 | 23 | 21 | 21 | 23 | 25 | 26 | 26 | 27 | 25.0 | 19.0 |
| 35 | Glenthorpe | B115 | 28 | 28 | 27 | 26 | 24 | 22 | 22 | 24 | 26 | 27 | 27 | 28 | 25.8 | 19.2 |
| 36 | Glenthorpe | G10 | 28 | 28 | 27 | 26 | 24 | 22 | 22 | 24 | 26 | 27 | 27 | 28 | 25.8 | 17.2 |
| 37 | Glenthorpe | M35 | 28 | 28 | 27 | 25 | 24 | 21 | 22 | 24 | 26 | 27 | 27 | 28 | 25.6 | 18.7 |
| 38 | Glenthorpe | D2B | 25 | 25 | 24 | 22 | 20 | 18 | 18 | 21 | 23 | 23 | 23 | 24 | 22.2 | 18.7 |
| 39 | Glenthorpe | E5 | 27 | 27 | 26 | 24 | 23 | 20 | 21 | 23 | 25 | 26 | 25 | 27 | 24.5 | 19.3 |
| 40 | Sabey | D54 | 26 | 26 | 25 | 24 | 22 | 19 | 20 | 22 | 24 | 25 | 25 | 26 | 23.7 | 19.6 |
| 41 | Venus | A14 | 28 | 28 | 27 | 26 | 24 | 22 | 22 | 24 | 26 | 26 | 27 | 28 | 25.7 | 18.2 |
| 42 | Venus | A33 | 28 | 28 | 27 | 26 | 24 | 22 | 22 | 24 | 26 | 26 | 27 | 28 | 25.7 | 18.4 |
| 43 | Waterhoutboom | H09 | 27 | 27 | 26 | 25 | 23 | 21 | 21 | 23 | 24 | 25 | 26 | 26 | 24.5 | 18.5 |

***Table D3. Mean monthly rainfall for study sites as predicted by Anusplin.***

| Site | Estate | Compt. | | | | | Mean Monthly Rainfall | | | | | | | MAP | MAP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Number | | Code | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | ANU | CCWR |
| 1 | Rattrays | RC42 | 121.4 | 130.5 | 120.7 | 72.3 | 58.4 | 47.3 | 40.5 | 50.2 | 65.8 | 95.4 | 98.6 | 106.5 | 1007.5 | 1081.0 |
| 2 | Rattrays | RC09 | 135.7 | 144.6 | 134.9 | 81.9 | 64.2 | 51.6 | 45.4 | 54.7 | 72.7 | 106.1 | 107.0 | 117.1 | 1116.0 | 1065.0 |
| 3 | Rattrays | RD26 | 131.1 | 136.5 | 129.8 | 79.0 | 62.6 | 50.4 | 44.7 | 53.5 | 70.4 | 103.9 | 102.2 | 112.3 | 1076.5 | 1051.0 |
| 4 | False Bay | J20 | 110.6 | 116.4 | 106.6 | 61.0 | 50.3 | 40.8 | 32.8 | 45.5 | 55.4 | 95.0 | 93.1 | 97.7 | 905.2 | 872.0 |
| 5 | Rattrays | RE41 | 137.8 | 146.3 | 137.1 | 84.4 | 67.2 | 54.2 | 47.9 | 57.8 | 74.0 | 107.9 | 108.6 | 118.5 | 1141.7 | 1086.0 |
| 6 | Teza (IC118TEZ) | TH20 | 129.6 | 135.7 | 126.5 | 74.8 | 59.0 | 48.0 | 41.0 | 52.3 | 68.7 | 107.0 | 102.9 | 112.4 | 1057.9 | 980.0 |
| 7 | Mtunzini | Q05 | 145.3 | 153.4 | 144.8 | 87.4 | 84.2 | 61.5 | 63.0 | 60.5 | 88.9 | 121.4 | 127.8 | 136.7 | 1274.9 | 1262.0 |
| 8 | Salpine1 | D3b | 140.5 | 149.9 | 139.9 | 86.8 | 69.7 | 56.4 | 49.9 | 60.3 | 75.6 | 110.0 | 111.3 | 120.8 | 1170.9 | 1113.0 |
| 9 | Salpine2 | H17 | 140.7 | 150.1 | 140.1 | 87.2 | 70.2 | 56.9 | 50.3 | 60.8 | 75.7 | 110.1 | 111.4 | 120.8 | 1174.4 | 1163.0 |
| 10 | The Gage | Gage | 135.7 | 144.6 | 137.8 | 84.9 | 66.4 | 52.6 | 47.0 | 53.7 | 73.1 | 102.0 | 106.8 | 117.1 | 1121.8 | 1058.0 |
| 11 | Kwambo Timbers | H9 | 138.9 | 148.0 | 138.6 | 85.4 | 67.7 | 54.5 | 48.3 | 57.8 | 74.6 | 107.8 | 109.6 | 119.5 | 1150.7 | 1168.0 |
| 12 | Hluhluwe | LO3A | 110.8 | 116.4 | 104.0 | 59.0 | 47.4 | 38.2 | 30.3 | 42.6 | 53.0 | 90.9 | 94.8 | 98.2 | 885.7 | 683.0 |
| 13 | Mtunzini | K13F | 140.2 | 146.5 | 142.9 | 87.8 | 80.9 | 59.7 | 58.2 | 59.4 | 87.3 | 115.8 | 124.6 | 132.3 | 1235.6 | 1248.0 |
| 14 | Mtunzini | K16A | 137.6 | 146.6 | 144.1 | 87.1 | 81.4 | 59.9 | 55.8 | 59.9 | 88.2 | 115.4 | 124.5 | 131.8 | 1232.6 | 1248.0 |
| 15 | False Bay | JO6 | 111.9 | 118.3 | 105.7 | 59.5 | 48.4 | 39.1 | 31.2 | 44.0 | 54.6 | 94.8 | 96.0 | 99.6 | 903.0 | 707.0 |
| 16 | Mfezi | ICO72MFZ | 124.3 | 130.1 | 120.8 | 69.9 | 56.1 | 45.9 | 38.0 | 51.2 | 65.1 | 107.5 | 101.0 | 109.3 | 1019.0 | 881.0 |
| 17 | Mtunzini | KO8a | 139.2 | 145.1 | 142.3 | 87.6 | 80.1 | 59.1 | 57.2 | 59.1 | 86.7 | 114.5 | 123.7 | 131.2 | 1225.8 | 1248.0 |
| 18 | Mtunzini | KO3e | 133.3 | 144.3 | 144.1 | 87.0 | 80.0 | 59.0 | 51.7 | 59.5 | 88.3 | 112.6 | 123.5 | 129.6 | 1212.9 | 1227.0 |
| 19 | Mtunzini | G07 | 140.8 | 165.4 | 154.5 | 101.9 | 87.1 | 65.6 | 62.1 | 65.8 | 94.5 | 119.4 | 133.6 | 138.6 | 1329.2 | 1354.0 |
| 20 | False Bay | J07 | 112.3 | 118.6 | 108.2 | 62.1 | 51.1 | 41.5 | 33.4 | 46.3 | 56.4 | 96.4 | 94.7 | 99.3 | 920.3 | 801.0 |
| 21 | False Bay | J11 | 111.2 | 117.2 | 106.9 | 61.1 | 50.3 | 40.8 | 32.8 | 45.6 | 55.6 | 95.6 | 93.8 | 98.3 | 909.1 | 872.0 |
| 22 | Trial CSI 02 - Mavuya | C8 | 133.4 | 140.6 | 131.6 | 79.7 | 63.7 | 51.8 | 44.9 | 56.0 | 71.1 | 108.0 | 105.8 | 115.2 | 1101.8 | 1064.0 |
| 23 | Mtunzini | F17 | 144.3 | 155.3 | 146.3 | 90.7 | 84.4 | 62.6 | 62.4 | 61.2 | 90.7 | 120.8 | 129.7 | 137.6 | 1286.1 | 1273.0 |
| 24 | Rattrays | RE10 | 139.4 | 148.5 | 138.8 | 85.7 | 68.4 | 55.2 | 48.8 | 58.9 | 74.9 | 108.9 | 110.2 | 119.9 | 1157.6 | 1174.0 |
| 25 | Mtunzini | H09a | 141.1 | 164.9 | 155.1 | 102.7 | 87.9 | 66.4 | 62.1 | 66.4 | 95.0 | 118.6 | 133.5 | 138.9 | 1332.7 | 1361.0 |
| 26 | Teza | TH22B | 129.5 | 135.6 | 126.5 | 74.8 | 59.1 | 48.1 | 41.0 | 52.5 | 68.6 | 107.0 | 102.8 | 112.3 | 1057.7 | 995.0 |

***Table D3. Continued.***

| Site | Estate | Compt. | | | | | | Mean Monthly Rainfall | | | | | | MAP | MAP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Number | | Code | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | ANU | CCWR |
| 27 | Glenthorpe | F124 | 147.6 | 142.5 | 110.6 | 54.9 | 21.8 | 8.9 | 11.4 | 8.9 | 31.7 | 79.7 | 131.5 | 155.5 | 904.9 | 805.0 |
| 28 | Glenthorpe | F105 | 132.7 | 131.4 | 100.3 | 50.3 | 20.8 | 8.2 | 10.4 | 7.7 | 27.9 | 73.3 | 120.0 | 142.1 | 825.0 | 864.0 |
| 29 | Glenthorpe | F122 | 148.6 | 143.6 | 111.1 | 55.2 | 21.8 | 8.9 | 11.5 | 8.9 | 32.0 | 80.2 | 132.5 | 156.8 | 911.1 | 864.0 |
| 30 | Glenthorpe | F77 | 160.8 | 153.3 | 119.9 | 57.5 | 21.6 | 9.1 | 12.5 | 8.7 | 34.2 | 83.4 | 139.2 | 165.2 | 965.4 | 816.0 |
| 31 | Glenthorpe | F146 | 162.9 | 149.8 | 119.7 | 59.7 | 22.9 | 9.8 | 11.9 | 11.1 | 35.5 | 86.6 | 144.0 | 165.1 | 979.0 | 1030.0 |
| 32 | Glenthorpe | B19 | 186.8 | 170.1 | 130.8 | 71.4 | 26.6 | 10.7 | 13.3 | 16.3 | 41.5 | 100.6 | 172.8 | 195.9 | 1136.9 | 988.0 |
| 33 | Glenthorpe | B88 | 174.1 | 158.5 | 123.9 | 63.4 | 23.4 | 9.7 | 12.5 | 13.0 | 36.3 | 90.3 | 155.1 | 174.3 | 1034.6 | 1007.0 |
| 34 | Glenthorpe | B17 | 180.8 | 164.1 | 127.1 | 67.5 | 25.1 | 10.2 | 12.8 | 14.8 | 38.7 | 95.4 | 164.2 | 185.0 | 1085.7 | 834.0 |
| 35 | Glenthorpe | B115 | 138.0 | 133.1 | 102.6 | 46.9 | 18.7 | 7.9 | 11.0 | 7.6 | 27.7 | 71.5 | 119.3 | 136.4 | 820.6 | 866.0 |
| 36 | Glenthorpe | G10 | 159.1 | 153.8 | 118.4 | 54.9 | 20.5 | 8.7 | 12.8 | 8.2 | 32.8 | 80.4 | 136.6 | 161.4 | 947.8 | 821.0 |
| 37 | Glenthorpe | M35 | 143.7 | 130.6 | 103.2 | 50.9 | 18.9 | 8.5 | 10.5 | 10.2 | 27.2 | 74.3 | 124.2 | 133.5 | 835.7 | 1444.0 |
| 38 | Glenthorpe | D2B | 177.5 | 158.1 | 122.2 | 67.5 | 26.0 | 12.3 | 12.8 | 15.6 | 42.0 | 96.5 | 163.7 | 172.2 | 1066.5 | 984.0 |
| 39 | Glenthorpe | E5 | 172.8 | 153.7 | 118.0 | 59.9 | 22.1 | 11.3 | 12.2 | 12.9 | 32.1 | 82.4 | 144.8 | 158.1 | 980.4 | 1420.0 |
| 40 | Sabey | D54 | 175.9 | 159.5 | 123.1 | 65.1 | 24.4 | 9.9 | 12.6 | 14.2 | 36.8 | 91.9 | 159.1 | 178.8 | 1051.3 | 1126.0 |
| 41 | Venus | A14 | 190.5 | 188.8 | 137.1 | 71.8 | 25.6 | 13.8 | 15.7 | 16.8 | 44.0 | 77.4 | 141.7 | 190.0 | 1113.3 | 1151.0 |
| 42 | Venus | A33 | 176.8 | 175.3 | 127.9 | 67.0 | 24.6 | 13.1 | 14.9 | 14.7 | 42.0 | 72.3 | 131.5 | 176.8 | 1036.8 | 1347.0 |
| 43 | Waterhoutboom | H09 | 251.6 | 237.7 | 182.6 | 93.0 | 32.4 | 16.9 | 24.7 | 24.7 | 55.2 | 101.0 | 178.9 | 243.7 | 1442.4 | 1021.0 |

***Table E3. Bioclimatic parameters for study sites as predicted by Bioclim.***

| Site Number | Estate | Compt. Code | MAT | DIUR_RANG | TEMP_SEAS | TEMP_ANN_R | MAP | PREC_SEAS | PREC_WQ | PREC_DQ | TEMP_WQ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Rattrays | RC42 | 21.9 | 8.9 | 0.9 | 17.5 | 1132 | 38 | 425 | 156 | 25.2 |
| 2 | Rattrays | RC09 | 21.9 | 9 | 0.89 | 17.4 | 1116 | 38 | 421 | 151 | 25.1 |
| 3 | Rattrays | RD26 | 21.9 | 9.1 | 0.89 | 17.5 | 1093 | 39 | 413 | 146 | 25.1 |
| 4 | False Bay | J20 | 22.3 | 9.8 | 0.97 | 19.8 | 909 | 41 | 341 | 118 | 25.8 |
| 5 | Rattrays | RE41 | 21.9 | 8.8 | 0.9 | 17.5 | 1142 | 37 | 426 | 159 | 25.2 |
| 6 | Teza (IC118TEZ) | TH20 | 22.1 | 9.5 | 0.91 | 18.4 | 1058 | 39 | 398 | 140 | 25.4 |
| 7 | Mtunzini | Q05 | 22 | 9.7 | 0.96 | 18.9 | 1275 | 34 | 451 | 185 | 25.3 |
| 8 | Salpine1 | D3b | 21.8 | 8.5 | 0.89 | 17 | 1171 | 37 | 435 | 166 | 25.1 |
| 9 | Salpine2 | H17 | 21.9 | 8.5 | 0.9 | 17.1 | 1174 | 36 | 436 | 168 | 25.2 |
| 10 | The Gage | Gage | 22 | 9.1 | 0.91 | 17.8 | 1122 | 38 | 423 | 153 | 25.3 |
| 11 | Kwambo Timbers | H9 | 21.9 | 8.7 | 0.89 | 17.2 | 1151 | 37 | 431 | 160 | 25.1 |
| 12 | Hluhluwe | LO3A | 22 | 9.8 | 0.95 | 18.9 | 886 | 43 | 337 | 110 | 25.3 |
| 13 | Mtunzini | K13F | 22.3 | 9.9 | 0.98 | 19.1 | 1236 | 33 | 436 | 178 | 25.7 |
| 14 | Mtunzini | K16A | 21.9 | 9.6 | 0.94 | 18.7 | 1233 | 34 | 434 | 176 | 25.1 |
| 15 | False Bay | JO6 | 21.9 | 9.7 | 0.94 | 18.7 | 903 | 42 | 342 | 113 | 25.3 |
| 16 | Mfezi | ICO72MFZ | 22.2 | 9.6 | 0.92 | 18.7 | 1019 | 40 | 381 | 134 | 25.5 |
| 17 | Mtunzini | KO8a | 22.3 | 9.9 | 0.98 | 19.4 | 1226 | 34 | 433 | 176 | 25.8 |
| 18 | Mtunzini | KO3e | 21.8 | 9.5 | 0.92 | 18.6 | 1213 | 34 | 427 | 170 | 24.9 |
| 19 | Mtunzini | G07 | 22 | 9.6 | 0.96 | 18.8 | 1329 | 33 | 466 | 194 | 25.3 |
| 20 | False Bay | J07 | 22.3 | 9.7 | 0.96 | 19.6 | 920 | 40 | 345 | 120 | 25.8 |
| 21 | False Bay | J11 | 22.3 | 9.8 | 0.97 | 19.8 | 909 | 41 | 341 | 118 | 25.8 |
| 22 | Trial CSI 02 - Mavuya | C8 | 22.1 | 9.1 | 0.91 | 18.1 | 1102 | 38 | 411 | 152 | 25.4 |
| 23 | Mtunzini | F17 | 22.1 | 9.7 | 0.97 | 19 | 1286 | 33 | 453 | 187 | 25.4 |
| 24 | Rattrays | RE10 | 21.9 | 8.7 | 0.89 | 17.2 | 1158 | 37 | 432 | 162 | 25.1 |
| 25 | Mtunzini | H09a | 22 | 9.6 | 0.96 | 18.7 | 1333 | 33 | 466 | 195 | 25.3 |
| 26 | Teza | TH22B | 22.1 | 9.5 | 0.91 | 18.4 | 1058 | 39 | 397 | 141 | 25.4 |

***Table E3. Continued.***

| Site Number | Estate | Compt. Code | MAT | DIUR_RANG | TEMP_SEAS | TEMP_ANN_R | MAP | PREC_SEAS | PREC_WQ | PREC_DQ | TEMP_WQ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 27 | Glenthorpe | F124 | 19.1 | 13.2 | 1.16 | 23.6 | 905 | 77 | 451 | 29 | 22.8 |
| 28 | Glenthorpe | F105 | 19.3 | 13.4 | 1.17 | 23.9 | 825 | 77 | 411 | 26 | 23.1 |
| 29 | Glenthorpe | F122 | 19 | 13.3 | 1.17 | 23.7 | 911 | 77 | 454 | 29 | 22.8 |
| 30 | Glenthorpe | F77 | 18.9 | 13.1 | 1.15 | 23.5 | 965 | 78 | 485 | 30 | 22.7 |
| 31 | Glenthorpe | F146 | 18.8 | 13.1 | 1.15 | 23.3 | 979 | 77 | 484 | 32 | 22.6 |
| 32 | Glenthorpe | B19 | 18.5 | 12.8 | 1.11 | 22.8 | 1137 | 76 | 563 | 39 | 22 |
| 33 | Glenthorpe | B88 | 18.7 | 13 | 1.13 | 23.1 | 1035 | 77 | 514 | 34 | 22.3 |
| 34 | Glenthorpe | B17 | 18.6 | 12.9 | 1.12 | 22.9 | 1086 | 77 | 539 | 37 | 22.1 |
| 35 | Glenthorpe | B115 | 19.3 | 13.4 | 1.17 | 24 | 821 | 79 | 412 | 26 | 23.1 |
| 36 | Glenthorpe | G10 | 19 | 13.2 | 1.15 | 23.6 | 948 | 79 | 479 | 29 | 22.7 |
| 37 | Glenthorpe | M35 | 19.2 | 13.3 | 1.15 | 23.6 | 836 | 77 | 412 | 29 | 22.9 |
| 38 | Glenthorpe | D2B | 17.2 | 11.4 | 1 | 20.2 | 1066 | 75 | 518 | 39 | 20.3 |
| 39 | Glenthorpe | E5 | 18.7 | 12.5 | 1.07 | 21.9 | 980 | 78 | 490 | 36 | 22.1 |
| 40 | Sabey | D54 | 18.7 | 13 | 1.13 | 23.1 | 1051 | 77 | 523 | 36 | 22.2 |
| 41 | Venus | A14 | 19.3 | 13.4 | 1.17 | 23.6 | 1113 | 77 | 575 | 44 | 23.1 |
| 42 | Venus | A33 | 19.6 | 13.4 | 1.18 | 23.8 | 1037 | 77 | 534 | 41 | 23.4 |
| 43 | Waterhoutboom | H09 | 18.2 | 12.6 | 1.02 | 21.6 | 1442 | 76 | 740 | 63 | 21.5 |

# APPENDIX 4. K-means Cluster Analysis results

### *Cluster 1. Clustering of sites by SI*

| Cluster Membership | | |
|---|---|---|
| Case Number | Cluster | Distance |
| 1 | 1 | 2.1375 |
| 2 | 1 | 1.9625 |
| 3 | 1 | 0.9375 |
| 4 | 2 | 1.411111 |
| 5 | 1 | 3.3375 |
| 6 | 1 | 2.6625 |
| 7 | 2 | 2.088889 |
| 8 | 1 | 2.2625 |
| 9 | 2 | 3.011111 |
| 10 | 2 | 2.011111 |
| 11 | 2 | 3.211111 |
| 12 | 1 | 0.4625 |
| 13 | 2 | 2.588889 |
| 14 | 1 | 0.9375 |
| 15 | 2 | 3.188889 |
| 16 | 2 | 3.288889 |
| 17 | 2 | 1.511111 |

| ANOVA | | | | | | |
|---|---|---|---|---|---|---|
| | Cluster Mean Square | df | Error Mean Square | df | F | Sig. |
| SI | 311.3229493 | 1 | 6.232509 | 15 | 49.95146 | 3.82E-06 |

| Number of Cases in each Cluster | | |
|---|---|---|
| Cluster | 1 | 8 |
| | 2 | 9 |
| Valid | | 17 |
| Missing | | 0 |

***Cluster 2. Clustering of sites by SPY***

| Cluster Membership | | |
|---|---|---|
| Case Number | Cluster | Distance |
| 1 | 1 | 0.725 |
| 2 | 2 | 0.788279 |
| 3 | 1 | 0.875 |
| 4 | 2 | 1.111721 |
| 5 | 1 | 1.775 |
| 6 | 1 | 0.775 |
| 7 | 2 | 0.907212 |
| 8 | 1 | 0.075 |
| 9 | 2 | 0.071721 |
| 10 | 2 | 1.188279 |
| 11 | 2 | 1.368279 |
| 12 | 2 | 0.988279 |
| 13 | 2 | 0.178279 |
| 14 | 1 | 0.775 |
| 15 | 2 | 2.111721 |
| 16 | 2 | 0.611721 |
| 17 | 2 | 1.511721 |

| ANOVA | | | | | | |
|---|---|---|---|---|---|---|
| | Cluster Mean Square | df | Error Mean Square | df | F | Sig. |
| SPY | 38.84811592 | 1 | 1.316385 | 15 | 29.51121 | 6.93E-05 |

| Number of Cases in each Cluster | | |
|---|---|---|
| Cluster | 1 | 6 |
| | 2 | 11 |
| Valid | | 17 |
| Missing | | 0 |

### *Cluster 3. Clustering of sites by WMD*

| Cluster Membership | | |
|---|---|---|
| Case Number | Cluster | Distance |
| 1 | 1 | 5.333333 |
| 2 | 2 | 21.94937 |
| 3 | . | . |
| 4 | . | . |
| 5 | 1 | 15.33333 |
| 6 | 2 | 20.05063 |
| 7 | 2 | 27.05063 |
| 8 | . | . |
| 9 | 2 | 19.30379 |
| 10 | . | . |
| 11 | 2 | 18.05063 |
| 12 | . | . |
| 13 | 2 | 24.94937 |
| 14 | . | . |
| 15 | . | . |
| 16 | 1 | 20.66667 |
| 17 | 2 | 1.050632 |

| ANOVA | | | | | | |
|---|---|---|---|---|---|---|
| | Cluster Mean Square | df | Error Mean Square | df | F | Sig. |
| WMD | 8498.69975 | 1 | 453.5303 | 8 | 18.73899 | 0.002516 |

| Number of Cases in each Cluster | | |
|---|---|---|
| Cluster | 1 | 3 |
| | 2 | 7 |
| Valid | | 10 |
| Missing | | 7 |

### *Cluster 4. Clustering of sites by AA*

| Cluster Membership | | |
|---|---|---|
| Case Number | Cluster | Distance |
| 1 | 1 | 6.480714 |
| 2 | 1 | 0.519286 |
| 3 | 1 | 3.819286 |
| 4 | 1 | 0.119286 |
| 5 | 1 | 3.810714 |
| 6 | 1 | 4.480714 |
| 7 | 1 | 0.379286 |
| 8 | 1 | 0.880714 |
| 9 | 1 | 4.279286 |
| 10 | 1 | 3.980714 |
| 11 | 1 | 1.649286 |
| 12 | 2 | 1.326667 |
| 13 | 1 | 3.349286 |
| 14 | 1 | 3.199286 |
| 15 | 2 | 5.133333 |
| 16 | 1 | 2.319286 |
| 17 | 2 | 3.806667 |

| ANOVA | | | | | | |
|---|---|---|---|---|---|---|
| | Cluster Mean Square | df | Error Mean Square | df | F | Sig. |
| AA | 275.1191934 | 1 | 13.24673063 | 15 | 20.76884 | 0.000378 |

| Number of Cases in each Cluster | | |
|---|---|---|
| Cluster | 1 | 14 |
| | 2 | 3 |
| Valid | | 17 |
| Missing | | 0 |

# APPENDIX 5. Results of t-tests

## *T-test 1: DEPTH_CLAS Clusters*

| Group Statistics | DEPTH_CLAS | N | Mean | Std. Dev. | Std.Err. Mean |
|---|---|---|---|---|---|
| WMD | 0 | 3 | 438.66667 | 54.5 | 31.466 |
| | 1 | 7 | 405.05063 | 25.21 | 9.5284 |
| AA | 0 | 6 | 85.211667 | 6.828 | 2.7873 |
| | 1 | 11 | 82.345455 | 4.57 | 1.3779 |
| SPY | 0 | 6 | 48.658333 | 1.375 | 0.5613 |
| | 1 | 11 | 51.461006 | 1.366 | 0.4117 |
| SI | 0 | 6 | 12.766667 | 2.401 | 0.9804 |
| | 1 | 11 | 20.045455 | 4.127 | 1.2442 |

| DEPTH_CLAS | | Levene's Test for Equality of Variances | | t-test for Equality of Means | | | | | 95% Confidence Interval of the Difference | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | F | Sig. | t | df | Sig. (2-tailed) | Mean Difference | Std. Error Difference | Lower | Upper |
| WMD | Equal variances assumed | 5.0157548 | 0.0554611 | 1.395 | 8 | 0.2005 | 33.6160 | 24.0954 | -21.9480 | 89.1801 |
| | Equal variances not assumed | | | 1.022 | 2.3769 | 0.3992 | 33.6160 | 32.8771 | -88.3777 | 155.6097 |
| AA | Equal variances assumed | 1.6561736 | 0.2176268 | 1.04 | 15 | 0.3146 | 2.8662 | 2.7547 | -3.0054 | 8.7378 |
| | Equal variances not assumed | | | 0.922 | 7.5179 | 0.3853 | 2.8662 | 3.1093 | -4.3847 | 10.1172 |
| SPY | Equal variances assumed | 0.024752 | 0.8770848 | -4.03 | 15 | 0.0011 | -2.8027 | 0.6946 | -4.2832 | -1.3221 |
| | Equal variances not assumed | | | -4.03 | 10.332 | 0.0023 | -2.8027 | 0.6961 | -4.3470 | -1.2584 |
| SI | Equal variances assumed | 1.0775796 | 0.3156847 | -3.94 | 15 | 0.0013 | -7.2788 | 1.8491 | -11.2201 | -3.3375 |
| | Equal variances not assumed | | | -4.6 | 14.835 | 0.0004 | -7.2788 | 1.5840 | -10.6584 | -3.8992 |

### *T-test 2: SI Clusters*

| Group Statistics | SI_CLUS | N | Mean | Std. Dev. | Std.Err. Mean |
|---|---|---|---|---|---|
| MAT | 1 | 8 | 18.65 | 0.644 | 0.2276 |
| | 2 | 9 | 18.988889 | 0.42 | 0.1399 |
| DIUR_RANG | 1 | 8 | 12.8875 | 0.633 | 0.224 |
| | 2 | 9 | 13.1 | 0.343 | 0.1143 |
| TEMP_WQ | 1 | 8 | 22.2375 | 0.873 | 0.3088 |
| | 2 | 9 | 22.644444 | 0.59 | 0.1966 |
| TEMP_SEAS | 1 | 8 | 1.12625 | 0.056 | 0.0197 |
| | 2 | 9 | 1.1322222 | 0.053 | 0.0177 |
| TEMP_ANN_R | 1 | 8 | 22.9375 | 1.172 | 0.4144 |
| | 2 | 9 | 23.188889 | 0.854 | 0.2845 |
| MAP | 1 | 8 | 995 | 107.5 | 38.016 |
| | 2 | 9 | 1019.6667 | 183.9 | 61.295 |
| PREC_SEAS | 1 | 8 | 76.625 | 0.744 | 0.2631 |
| | 2 | 9 | 77.555556 | 1.014 | 0.3379 |
| PREC_WQ | 1 | 8 | 492.875 | 51.59 | 18.24 |
| | 2 | 9 | 515.66667 | 99.14 | 33.045 |
| PREC_DQ | 1 | 8 | 33.375 | 5.041 | 1.7822 |
| | 2 | 9 | 36.888889 | 11.45 | 3.8168 |
| CLAY_B | 1 | 8 | 42.213363 | 19.2 | 6.7882 |
| | 2 | 9 | 41.143333 | 12.42 | 4.1391 |
| OM_A | 1 | 8 | 5.04875 | 2.367 | 0.8367 |
| | 2 | 9 | 4.32 | 1.536 | 0.5119 |
| SOL_RAD | 1 | 8 | 24.770833 | 1.578 | 0.5581 |
| | 2 | 9 | 23.592593 | 2.347 | 0.7823 |
| WMD | 1 | 4 | 433.5 | 45.68 | 22.842 |
| | 2 | 6 | 402.8924 | 26.9 | 10.981 |
| AA | 1 | 8 | 84.74875 | 5.877 | 2.078 |
| | 2 | 9 | 82.12 | 5.034 | 1.678 |
| SPY | 1 | 8 | 48.99375 | 1.385 | 0.4898 |
| | 2 | 9 | 51.785674 | 1.232 | 0.4108 |

| Site Index Cluster | | Levene's Test for Equality of Variances | | t-test for Equality of Means | | | | | 95% Confidence Interval of the Difference | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | F | Sig. | t | df | Sig. (2-tailed) | Mean Difference | Std. Error Difference | Lower | Upper |
| MAT | Equal variances assumed | 0.2510968 | 0.6235771 | -1.3 | 15 | 0.2128 | -0.3389 | 0.2604 | -0.8940 | 0.2162 |
| | Equal variances not assumed | | | -1.27 | 11.814 | 0.2290 | -0.3389 | 0.2671 | -0.9219 | 0.2441 |
| DIUR_RANG | Equal variances assumed | 0.5491278 | 0.470117 | -0.87 | 15 | 0.3955 | -0.2125 | 0.2429 | -0.7303 | 0.3053 |
| | Equal variances not assumed | | | -0.85 | 10.496 | 0.4168 | -0.2125 | 0.2514 | -0.7691 | 0.3441 |
| TEMP_WQ | Equal variances assumed | 0.3318865 | 0.5730934 | -1.14 | 15 | 0.2729 | -0.4069 | 0.3575 | -1.1690 | 0.3551 |
| | Equal variances not assumed | | | -1.11 | 12.087 | 0.2879 | -0.4069 | 0.3660 | -1.2038 | 0.3899 |
| TEMP_SEAS | Equal variances assumed | 0.0140498 | 0.9072192 | -0.23 | 15 | 0.8242 | -0.0060 | 0.0264 | -0.0623 | 0.0503 |
| | Equal variances not assumed | | | -0.23 | 14.554 | 0.8248 | -0.0060 | 0.0265 | -0.0626 | 0.0507 |
| TEMP_ANN_R | Equal variances assumed | 0.0413022 | 0.8416868 | -0.51 | 15 | 0.6176 | -0.2514 | 0.4931 | -1.3024 | 0.7996 |
| | Equal variances not assumed | | | -0.5 | 12.687 | 0.6256 | -0.2514 | 0.5027 | -1.3402 | 0.8374 |
| MAP | Equal variances assumed | 0.4212208 | 0.5261416 | -0.33 | 15 | 0.7447 | -24.6667 | 74.3776 | -183.1987 | 133.8653 |
| | Equal variances not assumed | | | -0.34 | 13.12 | 0.7378 | -24.6667 | 72.1274 | -180.3439 | 131.0106 |
| PREC_SEAS | Equal variances assumed | 1.512476 | 0.2377027 | -2.13 | 15 | 0.0499 | -0.9306 | 0.4364 | -1.8607 | -0.0005 |
| | Equal variances not assumed | | | -2.17 | 14.534 | 0.0468 | -0.9306 | 0.4282 | -1.8459 | -0.0152 |
| PREC_WQ | Equal variances assumed | 0.8882415 | 0.360887 | -0.58 | 15 | 0.5689 | -22.7917 | 39.1259 | -106.1864 | 60.6031 |
| | Equal variances not assumed | | | -0.6 | 12.311 | 0.5569 | -22.7917 | 37.7448 | -104.8004 | 59.2170 |
| PREC_DQ | Equal variances assumed | 2.1508204 | 0.1631443 | -0.8 | 15 | 0.4364 | -3.5139 | 4.3943 | -12.8802 | 5.8524 |
| | Equal variances not assumed | | | -0.83 | 11.257 | 0.4215 | -3.5139 | 4.2124 | -12.7595 | 5.7317 |
| CLAY_B | Equal variances assumed | 1.6147187 | 0.2231847 | 0.138 | 15 | 0.8920 | 1.0700 | 7.7481 | -15.4448 | 17.5848 |
| | Equal variances not assumed | | | 0.135 | 11.751 | 0.8952 | 1.0700 | 7.9505 | -16.2934 | 18.4335 |
| OM_A | Equal variances assumed | 0.4394329 | 0.517454 | 0.762 | 15 | 0.4578 | 0.7287 | 0.9561 | -1.3091 | 2.7666 |
| | Equal variances not assumed | | | 0.743 | 11.777 | 0.4721 | 0.7287 | 0.9809 | -1.4130 | 2.8705 |
| SOL_RAD | Equal variances assumed | 0.6263796 | 0.4410225 | 1.197 | 15 | 0.2497 | 1.1782 | 0.9839 | -0.9189 | 3.2754 |
| | Equal variances not assumed | | | 1.226 | 14.055 | 0.2403 | 1.1782 | 0.9609 | -0.8820 | 3.2385 |
| WMD | Equal variances assumed | 2.4671639 | 0.154889 | 1.349 | 8 | 0.2142 | 30.6076 | 22.6828 | -21.6990 | 82.9142 |
| | Equal variances not assumed | | | 1.208 | 4.4057 | 0.2880 | 30.6076 | 25.3443 | -37.2760 | 98.4912 |
| AA | Equal variances assumed | 0.3660583 | 0.5542043 | 0.994 | 15 | 0.3361 | 2.6288 | 2.6453 | -3.0096 | 8.2671 |
| | Equal variances not assumed | | | 0.984 | 13.925 | 0.3418 | 2.6288 | 2.6709 | -3.1027 | 8.3602 |
| SPY | Equal variances assumed | 0.0032767 | 0.9551075 | -4.4 | 15 | 0.0005 | -2.7919 | 0.6346 | -4.1444 | -1.4394 |
| | Equal variances not assumed | | | -4.37 | 14.175 | 0.0006 | -2.7919 | 0.6392 | -4.1613 | -1.4225 |

## *T-test 3: SPY Clusters*

| Group Statistics | SPY_CLUS | N | Mean | Std. Dev. | Std.Err. Mean |
|---|---|---|---|---|---|
| MAT | 1 | 6 | 18.783333 | 0.232 | 0.0946 |
| | 2 | 11 | 18.854545 | 0.671 | 0.2024 |
| DIUR_RANG | 1 | 6 | 13.05 | 0.187 | 0.0764 |
| | 2 | 11 | 12.972727 | 0.612 | 0.1844 |
| TEMP_WQ | 1 | 6 | 22.416667 | 0.36 | 0.147 |
| | 2 | 11 | 22.472727 | 0.903 | 0.2724 |
| TEMP_SEAS | 1 | 6 | 1.14 | 0.024 | 0.0097 |
| | 2 | 11 | 1.1236364 | 0.064 | 0.0192 |
| TEMP_ANN_R | 1 | 6 | 23.233333 | 0.367 | 0.1498 |
| | 2 | 11 | 22.981818 | 1.216 | 0.3668 |
| MAP | 1 | 6 | 1011.5 | 95.25 | 38.884 |
| | 2 | 11 | 1006.1818 | 175.7 | 52.963 |
| PREC_SEAS | 1 | 6 | 76.833333 | 0.408 | 0.1667 |
| | 2 | 11 | 77.272727 | 1.191 | 0.3591 |
| PREC_WQ | 1 | 6 | 502.33333 | 46.39 | 18.938 |
| | 2 | 11 | 506.36364 | 94.14 | 28.385 |
| PREC_DQ | 1 | 6 | 33.666667 | 4.274 | 1.7448 |
| | 2 | 11 | 36.090909 | 10.79 | 3.2542 |
| CLAY_B | 1 | 6 | 38.899483 | 20.02 | 8.1723 |
| | 2 | 11 | 43.145455 | 13.21 | 3.9831 |
| OM_A | 1 | 6 | 4.465 | 1.92 | 0.7838 |
| | 2 | 11 | 4.7709091 | 2.038 | 0.6145 |
| SOL_RAD | 1 | 6 | 25.25 | 1.129 | 0.461 |
| | 2 | 11 | 23.545455 | 2.23 | 0.6724 |
| WMD | 1 | 3 | 438.66667 | 54.5 | 31.466 |
| | 2 | 7 | 405.05063 | 25.21 | 9.5284 |
| AA | 1 | 6 | 86.658333 | 4.237 | 1.7298 |
| | 2 | 11 | 81.556364 | 5.32 | 1.6039 |
| SPY | 1 | 6 | 48.425 | 1.063 | 0.4339 |
| | 2 | 11 | 51.588279 | 1.187 | 0.358 |

| SPY Cluster | | Levene's Test for Equality of Variances | | t-test for Equality of Means | | | | | 95% Confidence Interval of the Difference | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | F | Sig. | t | df | Sig. (2-tailed) | Mean Difference | Std. Error Difference | Lower | Upper |
| MAT | Equal variances assumed | 2.3972048 | 0.1423891 | -0.25 | 15 | 0.8070 | -0.0712 | 0.2864 | -0.6816 | 0.5392 |
| | Equal variances not assumed | | | -0.32 | 13.551 | 0.7548 | -0.0712 | 0.2234 | -0.5519 | 0.4095 |
| DIUR_RANG | Equal variances assumed | 2.9517813 | 0.1063491 | 0.298 | 15 | 0.7698 | 0.0773 | 0.2593 | -0.4755 | 0.6300 |
| | Equal variances not assumed | | | 0.387 | 12.961 | 0.7050 | 0.0773 | 0.1996 | -0.3541 | 0.5087 |
| TEMP_WQ | Equal variances assumed | 2.2473818 | 0.1545907 | -0.14 | 15 | 0.8873 | -0.0561 | 0.3890 | -0.8851 | 0.7730 |
| | Equal variances not assumed | | | -0.18 | 14.255 | 0.8588 | -0.0561 | 0.3095 | -0.7188 | 0.6067 |
| TEMP_SEAS | Equal variances assumed | 4.5495841 | 0.049856 | 0.599 | 15 | 0.5581 | 0.0164 | 0.0273 | -0.0419 | 0.0746 |
| | Equal variances not assumed | | | 0.761 | 13.914 | 0.4596 | 0.0164 | 0.0215 | -0.0298 | 0.0625 |
| TEMP_ANN_R | Equal variances assumed | 5.0538512 | 0.0400356 | 0.488 | 15 | 0.6326 | 0.2515 | 0.5154 | -0.8470 | 1.3501 |
| | Equal variances not assumed | | | 0.635 | 12.897 | 0.5366 | 0.2515 | 0.3962 | -0.6051 | 1.1081 |
| MAP | Equal variances assumed | 0.6126759 | 0.4459643 | 0.068 | 15 | 0.9465 | 5.3182 | 77.9570 | -160.8433 | 171.4796 |
| | Equal variances not assumed | | | 0.081 | 14.981 | 0.9366 | 5.3182 | 65.7040 | -134.7423 | 145.3786 |
| PREC_SEAS | Equal variances assumed | 3.8022369 | 0.0701296 | -0.87 | 15 | 0.4005 | -0.4394 | 0.5078 | -1.5217 | 0.6429 |
| | Equal variances not assumed | | | -1.11 | 13.518 | 0.2864 | -0.4394 | 0.3959 | -1.2913 | 0.4125 |
| PREC_WQ | Equal variances assumed | 0.7423271 | 0.4024801 | -0.1 | 15 | 0.9236 | -4.0303 | 41.3122 | -92.0851 | 84.0245 |
| | Equal variances not assumed | | | -0.12 | 14.957 | 0.9076 | -4.0303 | 34.1230 | -76.7800 | 68.7194 |
| PREC_DQ | Equal variances assumed | 1.8890333 | 0.1894986 | -0.52 | 15 | 0.6093 | -2.4242 | 4.6445 | -12.3239 | 7.4754 |
| | Equal variances not assumed | | | -0.66 | 14.225 | 0.5220 | -2.4242 | 3.6925 | -10.3321 | 5.4836 |
| CLAY_B | Equal variances assumed | 1.6462616 | 0.2189393 | -0.53 | 15 | 0.6044 | -4.2460 | 8.0233 | -21.3472 | 12.8552 |
| | Equal variances not assumed | | | -0.47 | 7.4475 | 0.6538 | -4.2460 | 9.0913 | -25.4844 | 16.9925 |
| OM_A | Equal variances assumed | 0.0026584 | 0.9595596 | -0.3 | 15 | 0.7672 | -0.3059 | 1.0147 | -2.4687 | 1.8569 |
| | Equal variances not assumed | | | -0.31 | 10.964 | 0.7645 | -0.3059 | 0.9959 | -2.4988 | 1.8870 |
| SOL_RAD | Equal variances assumed | 1.8520235 | 0.1936455 | 1.737 | 15 | 0.1029 | 1.7045 | 0.9815 | -0.3875 | 3.7966 |
| | Equal variances not assumed | | | 2.091 | 14.988 | 0.0540 | 1.7045 | 0.8152 | -0.0332 | 3.4422 |
| WMD | Equal variances assumed | 5.0157548 | 0.0554611 | 1.395 | 8 | 0.2005 | 33.6160 | 24.0954 | -21.9480 | 89.1801 |
| | Equal variances not assumed | | | 1.022 | 2.3769 | 0.3992 | 33.6160 | 32.8771 | -88.3777 | 155.6097 |
| AA | Equal variances assumed | 0.0639024 | 0.8038625 | 2.017 | 15 | 0.0620 | 5.1020 | 2.5300 | -0.2906 | 10.4946 |
| | Equal variances not assumed | | | 2.163 | 12.627 | 0.0504 | 5.1020 | 2.3590 | -0.0098 | 10.2137 |
| SPY | Equal variances assumed | 0.2739804 | 0.6083209 | -5.43 | 15 | 0.0001 | -3.1633 | 0.5823 | -4.4044 | -1.9221 |
| | Equal variances not assumed | | | -5.62 | 11.467 | 0.0001 | -3.1633 | 0.5625 | -4.3953 | -1.9313 |

## *T-test 4: WMD Clusters*

| Group Statistics | WMD_CLUS | N | Mean | Std. Dev. | Std.Err. Mean |
|---|---|---|---|---|---|
| MAT | 1 | 3 | 19.166667 | 0.404 | 0.2333 |
| | 2 | 7 | 18.842857 | 0.431 | 0.1631 |
| DIUR_RANG | 1 | 3 | 13.233333 | 0.153 | 0.0882 |
| | 2 | 7 | 13 | 0.379 | 0.1431 |
| TEMP_WQ | 1 | 3 | 22.933333 | 0.416 | 0.2404 |
| | 2 | 7 | 22.428571 | 0.618 | 0.2337 |
| TEMP_SEAS | 1 | 3 | 1.1633333 | 0.015 | 0.0088 |
| | 2 | 7 | 1.1171429 | 0.056 | 0.021 |
| TEMP_ANN_R | 1 | 3 | 23.566667 | 0.252 | 0.1453 |
| | 2 | 7 | 22.985714 | 0.948 | 0.3582 |
| MAP | 1 | 3 | 973.66667 | 66.16 | 38.198 |
| | 2 | 7 | 1010.8571 | 225.3 | 85.146 |
| PREC_SEAS | 1 | 3 | 77 | 0 | 0 |
| | 2 | 7 | 77.142857 | 1.069 | 0.4041 |
| PREC_WQ | 1 | 3 | 489.66667 | 41.79 | 24.127 |
| | 2 | 7 | 506 | 119 | 44.993 |
| PREC_DQ | 1 | 3 | 34 | 6.245 | 3.6056 |
| | 2 | 7 | 36.142857 | 12.85 | 4.8571 |
| CLAY_B | 1 | 3 | 42.953333 | 13.53 | 7.8118 |
| | 2 | 7 | 40.672414 | 21.94 | 8.293 |
| OM_A | 1 | 3 | 5.8166667 | 0.384 | 0.2215 |
| | 2 | 7 | 3.5085714 | 1.287 | 0.4865 |
| SOL_RAD | 1 | 3 | 24.111111 | 3.713 | 2.1438 |
| | 2 | 7 | 24.809524 | 1.099 | 0.4154 |
| WMD | 1 | 3 | 459.66667 | 18.58 | 10.729 |
| | 2 | 7 | 396.05063 | 22.13 | 8.3632 |
| AA | 1 | 3 | 87.876667 | 4.512 | 2.605 |
| | 2 | 7 | 82.354286 | 5.795 | 2.1902 |
| SPY | 1 | 3 | 48.85 | 2.948 | 1.7022 |
| | 2 | 7 | 51.010152 | 1.225 | 0.463 |

| WMD cluster | | Levene's Test for Equality of Variances | | t-test for Equality of Means | | | | | 95% Confidence Interval of the Difference | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | F | Sig. | t | df | Sig. (2-tailed) | Mean Difference | Std. Error Difference | Lower | Upper |
| MAT | Equal variances assumed | 0.3445775 | 0.5733874 | 1.105 | 8 | 0.3015 | 0.3238 | 0.2932 | -0.3522 | 0.9998 |
| | Equal variances not assumed | | | 1.137 | 4.105 | 0.3174 | 0.3238 | 0.2847 | -0.4587 | 1.1063 |
| DIUR_RANG | Equal variances assumed | 3.8916865 | 0.0839875 | 1.004 | 8 | 0.3446 | 0.2333 | 0.2323 | -0.3024 | 0.7690 |
| | Equal variances not assumed | | | 1.388 | 7.9728 | 0.2026 | 0.2333 | 0.1681 | -0.1545 | 0.6212 |
| TEMP_WQ | Equal variances assumed | 1.5365653 | 0.2502579 | 1.273 | 8 | 0.2387 | 0.5048 | 0.3965 | -0.4095 | 1.4191 |
| | Equal variances not assumed | | | 1.506 | 5.8319 | 0.1843 | 0.5048 | 0.3353 | -0.3214 | 1.3309 |
| TEMP_SEAS | Equal variances assumed | 3.1375647 | 0.1144561 | 1.373 | 8 | 0.2070 | 0.0462 | 0.0336 | -0.0314 | 0.1238 |
| | Equal variances not assumed | | | 2.027 | 7.5933 | 0.0791 | 0.0462 | 0.0228 | -0.0069 | 0.0992 |
| TEMP_ANN_R | Equal variances assumed | 4.0976503 | 0.077544 | 1.014 | 8 | 0.3403 | 0.5810 | 0.5730 | -0.7403 | 1.9022 |
| | Equal variances not assumed | | | 1.503 | 7.5257 | 0.1736 | 0.5810 | 0.3865 | -0.3203 | 1.4822 |
| MAP | Equal variances assumed | 2.1383267 | 0.1818015 | -0.27 | 8 | 0.7922 | -37.1905 | 136.5496 | -352.0745 | 277.6936 |
| | Equal variances not assumed | | | -0.4 | 7.72 | 0.7010 | -37.1905 | 93.3220 | -253.7573 | 179.3764 |
| PREC_SEAS | Equal variances assumed | 3.8167401 | 0.0865032 | -0.22 | 8 | 0.8287 | -0.1429 | 0.6389 | -1.6161 | 1.3304 |
| | Equal variances not assumed | | | -0.35 | 6 | 0.7358 | -0.1429 | 0.4041 | -1.1316 | 0.8458 |
| PREC_WQ | Equal variances assumed | 1.5067357 | 0.2545294 | -0.23 | 8 | 0.8276 | -16.3333 | 72.5860 | -183.7170 | 151.0503 |
| | Equal variances not assumed | | | -0.32 | 7.9698 | 0.7572 | -16.3333 | 51.0533 | -134.1403 | 101.4737 |
| PREC_DQ | Equal variances assumed | 0.4921049 | 0.5028826 | -0.27 | 8 | 0.7950 | -2.1429 | 7.9764 | -20.5364 | 16.2507 |
| | Equal variances not assumed | | | -0.35 | 7.5536 | 0.7328 | -2.1429 | 6.0491 | -16.2370 | 11.9513 |
| CLAY_B | Equal variances assumed | 1.2129343 | 0.3027812 | 0.164 | 8 | 0.8739 | 2.2809 | 13.9186 | -29.8155 | 34.3773 |
| | Equal variances not assumed | | | 0.2 | 6.3569 | 0.8476 | 2.2809 | 11.3928 | -25.2213 | 29.7832 |
| OM_A | Equal variances assumed | 1.7585126 | 0.2214195 | 2.957 | 8 | 0.0182 | 2.3081 | 0.7806 | 0.5081 | 4.1081 |
| | Equal variances not assumed | | | 4.317 | 7.7468 | 0.0028 | 2.3081 | 0.5346 | 1.0683 | 3.5479 |
| SOL_RAD | Equal variances assumed | 13.147778 | 0.006724 | -0.49 | 8 | 0.6406 | -0.6984 | 1.4397 | -4.0183 | 2.6215 |
| | Equal variances not assumed | | | -0.32 | 2.152 | 0.7775 | -0.6984 | 2.1836 | -9.4857 | 8.0889 |
| WMD | Equal variances assumed | 0.7998492 | 0.3972463 | 4.329 | 8 | 0.0025 | 63.6160 | 14.6958 | 29.7274 | 97.5046 |
| | Equal variances not assumed | | | 4.676 | 4.6024 | 0.0067 | 63.6160 | 13.6034 | 27.7189 | 99.5132 |
| AA | Equal variances assumed | 0.0407652 | 0.8450316 | 1.454 | 8 | 0.1839 | 5.5224 | 3.7968 | -3.2331 | 14.2779 |
| | Equal variances not assumed | | | 1.623 | 4.995 | 0.1657 | 5.5224 | 3.4034 | -3.2289 | 14.2736 |
| SPY | Equal variances assumed | 5.1793632 | 0.052412 | -1.72 | 8 | 0.1231 | -2.1602 | 1.2533 | -5.0502 | 0.7299 |
| | Equal variances not assumed | | | -1.22 | 2.3027 | 0.3312 | -2.1602 | 1.7640 | -8.8700 | 4.5497 |

### *T-test 5: AA Clusters*

| Group Statistics | AA_CLUS | N | Mean | Std. Dev. | Std.Err. Mean |
|---|---|---|---|---|---|
| MAT | 1 | 14 | 18.957143 | 0.316 | 0.0843 |
| | 2 | 3 | 18.233333 | 1.05 | 0.6064 |
| DIUR_RANG | 1 | 14 | 13.114286 | 0.26 | 0.0694 |
| | 2 | 3 | 12.466667 | 1.007 | 0.5812 |
| TEMP_WQ | 1 | 14 | 22.628571 | 0.432 | 0.1155 |
| | 2 | 3 | 21.633333 | 1.405 | 0.811 |
| TEMP_SEAS | 1 | 14 | 1.1435714 | 0.03 | 0.0079 |
| | 2 | 3 | 1.0633333 | 0.093 | 0.0536 |
| TEMP_ANN_R | 1 | 14 | 23.342857 | 0.554 | 0.1481 |
| | 2 | 3 | 21.8 | 1.709 | 0.9866 |
| MAP | 1 | 14 | 965.42857 | 98.41 | 26.302 |
| | 2 | 3 | 1207 | 204.9 | 118.28 |
| PREC_SEAS | 1 | 14 | 77.357143 | 0.842 | 0.225 |
| | 2 | 3 | 76 | 1 | 0.5774 |
| PREC_WQ | 1 | 14 | 482.21429 | 49.53 | 13.237 |
| | 2 | 3 | 611 | 115.3 | 66.566 |
| PREC_DQ | 1 | 14 | 32.357143 | 4.814 | 1.2865 |
| | 2 | 3 | 48.666667 | 12.66 | 7.3106 |
| CLAY_B | 1 | 14 | 43.301921 | 15.35 | 4.1015 |
| | 2 | 3 | 33.923333 | 16.43 | 9.4851 |
| OM_A | 1 | 14 | 4.3364286 | 1.684 | 0.4501 |
| | 2 | 3 | 6.1866667 | 2.738 | 1.5808 |
| SOL_RAD | 1 | 14 | 24.47619 | 1.672 | 0.4468 |
| | 2 | 3 | 22.611111 | 3.351 | 1.9349 |
| WMD | 1 | 9 | 417.37271 | 38.2 | 12.735 |
| | 2 | 1 | 395 | . | . |
| AA | 1 | 14 | 85.219286 | 3.465 | 0.9261 |
| | 2 | 3 | 74.666667 | 4.615 | 2.6646 |
| SPY | 1 | 14 | 50.044362 | 1.725 | 0.4611 |
| | 2 | 3 | 52.466667 | 1.644 | 0.9493 |

| AA Cluster | | Levene's Test for Equality of Variances | | t-test for Equality of Means | | | | | 95% Confidence Interval of the Difference | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | F | Sig. | t | df | Sig. (2-tailed) | Mean Difference | Std. Error Difference | Lower | Upper |
| MAT | Equal variances assumed | 7.2172941 | 0.0169101 | 2.355 | 15 | 0.0326 | 0.7238 | 0.3074 | 0.0687 | 1.3789 |
| | Equal variances not assumed | | | 1.182 | 2.078 | 0.3548 | 0.7238 | 0.6123 | -1.8181 | 3.2657 |
| DIUR_RANG | Equal variances assumed | 11.709444 | 0.0037838 | 2.314 | 15 | 0.0353 | 0.6476 | 0.2799 | 0.0510 | 1.2443 |
| | Equal variances not assumed | | | 1.106 | 2.0574 | 0.3811 | 0.6476 | 0.5853 | -1.8046 | 3.0999 |
| TEMP_WQ | Equal variances assumed | 8.2084644 | 0.0118017 | 2.4 | 15 | 0.0299 | 0.9952 | 0.4148 | 0.1112 | 1.8793 |
| | Equal variances not assumed | | | 1.215 | 2.0818 | 0.3442 | 0.9952 | 0.8192 | -2.4001 | 4.3906 |
| TEMP_SEAS | Equal variances assumed | 13.875378 | 0.0020325 | 2.889 | 15 | 0.0112 | 0.0802 | 0.0278 | 0.0210 | 0.1394 |
| | Equal variances not assumed | | | 1.48 | 2.0872 | 0.2721 | 0.0802 | 0.0542 | -0.1440 | 0.3044 |
| TEMP_ANN_R | Equal variances assumed | 7.4292784 | 0.0156323 | 2.995 | 15 | 0.0091 | 1.5429 | 0.5151 | 0.4449 | 2.6409 |
| | Equal variances not assumed | | | 1.547 | 2.091 | 0.2568 | 1.5429 | 0.9976 | -2.5754 | 5.6611 |
| MAP | Equal variances assumed | 4.5046947 | 0.0508595 | -3.21 | 15 | 0.0058 | -241.5714 | 75.2499 | -401.9628 | -81.1800 |
| | Equal variances not assumed | | | -1.99 | 2.2019 | 0.1726 | -241.5714 | 121.1698 | -719.6970 | 236.5542 |
| PREC_SEAS | Equal variances assumed | 0.0017544 | 0.9671424 | 2.467 | 15 | 0.0261 | 1.3571 | 0.5501 | 0.1846 | 2.5296 |
| | Equal variances not assumed | | | 2.19 | 2.6443 | 0.1282 | 1.3571 | 0.6196 | -0.7738 | 3.4880 |
| PREC_WQ | Equal variances assumed | 5.490613 | 0.0333151 | -3.24 | 15 | 0.0055 | -128.7857 | 39.7232 | -213.4537 | -44.1177 |
| | Equal variances not assumed | | | -1.9 | 2.1608 | 0.1886 | -128.7857 | 67.8692 | -400.9374 | 143.3659 |
| PREC_DQ | Equal variances assumed | 9.9419985 | 0.0065647 | -3.98 | 15 | 0.0012 | -16.3095 | 4.0965 | -25.0409 | -7.5781 |
| | Equal variances not assumed | | | -2.2 | 2.1255 | 0.1516 | -16.3095 | 7.4229 | -46.5072 | 13.8882 |
| CLAY_B | Equal variances assumed | 0.0007799 | 0.9780891 | 0.951 | 15 | 0.3565 | 9.3786 | 9.8581 | -11.6334 | 30.3906 |
| | Equal variances not assumed | | | 0.908 | 2.8028 | 0.4353 | 9.3786 | 10.3339 | -24.8573 | 43.6145 |
| OM_A | Equal variances assumed | 1.5583915 | 0.2310352 | -1.56 | 15 | 0.1387 | -1.8502 | 1.1830 | -4.3718 | 0.6713 |
| | Equal variances not assumed | | | -1.13 | 2.3351 | 0.3626 | -1.8502 | 1.6437 | -8.0336 | 4.3331 |
| SOL_RAD | Equal variances assumed | 3.016813 | 0.1028897 | 1.481 | 15 | 0.1594 | 1.8651 | 1.2595 | -0.8195 | 4.5497 |
| | Equal variances not assumed | | | 0.939 | 2.218 | 0.4383 | 1.8651 | 1.9858 | -5.9229 | 9.6530 |
| WMD | Equal variances assumed | . | . | 0.556 | 8 | 0.5937 | 22.3727 | 40.2707 | -70.4917 | 115.2371 |
| | Equal variances not assumed | | | . | . | . | 22.3727 | . | . | . |
| AA | Equal variances assumed | 0.2644102 | 0.6145984 | 4.557 | 15 | 0.0004 | 10.5526 | 2.3156 | 5.6171 | 15.4881 |
| | Equal variances not assumed | | | 3.741 | 2.5067 | 0.0451 | 10.5526 | 2.8210 | 0.4879 | 20.6173 |
| SPY | Equal variances assumed | 0.0612206 | 0.8079318 | -2.22 | 15 | 0.0422 | -2.4223 | 1.0908 | -4.7474 | -0.0972 |
| | Equal variances not assumed | | | -2.3 | 3.029 | 0.1046 | -2.4223 | 1.0553 | -5.7627 | 0.9180 |