A Site Analysis and Classification System for *Eucalyptus grandis* on the Zululand Coastal Plain

by

MARIUS DU PLESSIS

Dip. Forestry (Saasveld), B.Sc. Forestry (Stellenbosch)

Submitted in fulfillment

of the requirements for

the degree of

MASTER OF SCIENCE IN AGRICULTURE

(FORESTRY)

in the

Forestry Programme

Faculty of Science and Agriculture

University of Natal

PIETERMARITZBURG

DECEMBER 2001

FINAL COPY

ABSTRACT

A site analysis for *Eucalyptus grandis* planted on the Zululand coastal plain was carried out. Data from the permanent sample plot program from Mondi Forests was used to derive meaningful site quality relationships.

Although water availability to trees is clearly identified as the single most important factor in forest land use management in South Africa, the matrix of other site factors such as soil, climate, genetic advancement and environmental constraints make timber plantations operationally complex and fascinating for research.

The correlation between environmental parameters influencing tree growth and the yield obtained from a stand of trees is researched in this study. Growth models in the form of mathematical relationships are developed to enable the forest manager to predict tree growth from easily attainable input variables such as age, diameter or clay content of soils.

The Chapman-Richards model was used to define the basic sigmoidal height growth curve over age for a given site. A site index model developed through a non-linear modelling process was constructed from permanent sample plot data. This model proved to be different from the site index model developed for a larger data set of the same physiographic zone. A site quality prediction model estimating site index at reference age five, from soil attributes was constructed. Soil morphology and grid referenced climatic data were found to be of limited value for the prediction of site index, but organic content in the top-soil and clay content in the sub-soil proved to be valuable predictors of site growth potential. For further site analysis studies, soil and climate variables will have to be measured on-site as opposed to using computer simulated figures.

A site classification exercise was carried out by using the statistical technique known as clustering. Clusters were derived for the study area making use of clay content and mean annual precipitation (MAP) as input variables to separate the study area geographically, into meaningful structures on the basis of similarity. Significant clusters were derived using Ward's technique, which proposed three distinct site classification units for the study area. Site index for each of the site classification units was modelled and it was proved that the models predicted significantly different height – age relationships for each unit. From this site classification exercise it is shown that the variance in height growth within each site classification unit (SCU) is sufficiently small for each unit to be regarded as an independent site, uniform in its attributes of soil, climate, topography, water and nutrients status. A methodology for site classification is proposed from this study.

Key words: Eucalyptus grandis, site potential, climatic variables, site quality, site index, prediction, site classification, cluster analysis, regression analysis.

PREFACE

This thesis documents research conducted at the University of Natal and at Mondi Forests from February 2000 to December 2001 under the supervision of Professor Janusz Zwolinski.

I declare that the results contained in this thesis are from my own original work except where acknowledged accordingly. I also declare that these results have not previously in their entirety or in part been submitted in any form for any degree or diploma to any University.

....

Marius du Plessis

March 2002

ACKNOWLEDGEMENTS

The assistance of the following persons and organisations is gratefully acknowledged.

Professor Janusz Zwolinski for guidance, constructive criticism and assistance, as study leader of this scientific work.

Mr W. Groenewald for guidance with statistical analysis.

Mr B. Pienaar from Mondi Forests for assistance with the data collection and the compilation of analysis-ready data sets.

Dr B.J.H. Janse, Ms F. Blakeway, Dr K. Little, Dr C. Smith for advice given with regard to the scientific approach and for many hours of debating these issues that we are passionate about.

Mondi Forests for their financial assistance and support during the study period and for the opportunity granted to become better equipped as a Forest Scientist.

My mother, Mrs M.P. du Plessis (77) and my late father Dr F.B. du Plessis (D.Comm.) for their love and example through the years.

My wife, Eureka, for support, encouragement and showing a tremendous amount of interest in my work, as well as our three children Christof (12), Biermann (9) and Michal (3) for their understanding.

Any others whose names I might inadvertently have omitted.

Finally I wish to thank my Lord Jesus Christ for the talents I received.

TABLE OF CONTENTS

PAGE

ABSTRACT ii

PREFACE iv

ACKNOWLEDGEMENTS v

LIST OF TABLES ix

LIST OF FIGURES xi

LIST OF APPENDICES xii

LIST OF VARIABLES xiii

1. INTRODUCTION 1

2. REVIEW ON SITE QUALITY PREDICTION MODELS. 7

2.1 Introduction. 7

2.2 Other Relevant Studies 14

2.3 Process Based Models 16

3. DESCRIPTION OF THE STUDY AREA. 18

3.1 Location 18

3.2 Climatic Factors important to Forestry in South Africa. 18

3.3 Solar Radiation. 19

3.4 Geology 21

3.5 Lithology of the Zululand Coastal Zone 22

3.6 Geo-hydrology 23

3.7 Soil Factors 24

4. MATERIALS AND METHODS 32

4.1 The Forest Site Classification of the MMRC making use of Geology. 32

4.2 Permanent Sample Plots 33

4.3 The Measurement of Trees. 39

4.4 Description of the Data sets and Preliminary Analysis.............. 44

4.4.1 Mensurational data 44

4.4.2 Soils data. 48

4.4.3 Climatic data. 52

5. DATA ANALYSIS 61

5.1 Selection of Variables. 61

5.2 Descriptive Data Statistics. 62

5.3 Correlation Analysis. 64

6. MODEL CONSTRUCTION. 69

6.1 Site Index Model. 72

6.1.1 Comparing the Zululand MMRC model to the "POOLED model" developed in this study. 77

6.1.2 Predicting site index with site variables. 81

6.1.3 Discussion. 84

6.2 Mean Annual Increment. 86

6.2.1 Predicting mean annual increment with site variables. .. 87

6.2.2 Discussion. 88

7. SITE CLASSIFICATION. 89

7.1 Introduction and Objectives. 89

7.2 Materials and Methods. 90

7.3 Description of each Site Classification Unit. 94

7.4 Verifying the Clusters. 96
7.4.1 Developing a prediction equation for inclusion in a cluster 96
7.4.2 Making use of site index to establish the significance of the site classification units. 96
7.5 Discussion. 98

8. SUMMARY AND CONCLUSIONS. 100

RERERENCE LIST. 104

APPENDICES. 113

LIST OF TABLES

PAGE

TABLE 1. Comparison of the area planted with commercial tree species to the total area of land holdings owned by MMRC in members Mpumalanga and KwaZulu-Natal, for 1996/97. 33

TABLE 2. Description of the study area for 80% of the land using MMRC classification terminology (Kunz and Pallett 2000). 33

TABLE 3. Tree status and stem form. 37

TABLE 4. Plot level variables measured and recorded. 38

TABLE 5. Tree level variables measured and recorded. 38

TABLE 6. Numbers and location of the sample plots. 44

TABLE 7. Summary statistics of growth and yield measured and derived variables for the series of 26 PSPs. 45

TABLE 8. Fit statistics for dummy variable fitted with MAI as dependent variable. 48

TABLE 9. Summary of soils data used in the study. 49

TABLE 10. Summarised climatic data for the 26 plot sites. 52

TABLE 11. Fit statistics for distance from the coast estimated with MAP as dependent variable. 54

TABLE 12. Descriptive statistics for explanatory variables used in this study. 63

TABLE 13. Matrix showing Pearson's correlation coefficients (r) as well as the probability values (p) for the variables in this study. 66

TABLE 14. Fit statistics for the top height (HTOP) and Age relationship for 26 permanent sample plots and modelled SI5 for each plot. 74

TABLE 15. Fit statistics for POOLED model for HTOP and age using the Chapman-Richards equation.. 75

TABLE 16. Correlation coefficients (r) for SI_5 with the site variables of the study area. 76

TABLE 17. Fit statistics for the MMRC model (Kotze, 2000). 77

TABLE 18. Residual mean squares for MMRC and POOLED models. 78

TABLE 19. Statistics for site index (SI_5) fitted with site variables and parameter estimates. 82

TABLE 20. Calculated Mean Annual Increment for each Permanent Sample Plot. 86

TABLE 21. Correlation coefficient (r) and probability of MAI_{peak} correlated site variables of the study area........ 87

TABLE 22. Fit statistics for MAI_{peak} model with organic carbon content. 88

TABLE 23. Descriptive statistics for site classification unit 1,2 and 3. 94

TABLE 24. Correlation coefficient (r) of site index (SI_5) with site variables for each site classification unit. 94

TABLE 25. Site Index (SI_5) models for the three site classification units. 97

TABLE 26. Site Index (SI_5) model statistics for site classification units1, 2 and 3 showing parameters and lower and upper confidence levels........ 98

LIST OF FIGURES

PAGE

FIGURE 1. Development of quadratic mean diameter (D_q) with age by PSP. 46

FIGURE 2. Development of top height (HTOP) with age by PSP. 46

FIGURE 3. Development of volume per hectare (Vol) with age by PSP. 47

FIGURE 4 Monthly median rainfall per permanent sample plot. 53

FIGURE 5. Mean monthly maximum and minimum temperatures per PSP in degrees Celsius. 55

FIGURE 6. Mean monthly A-pan evaporation (mm). 56

FIGURE 7. Effective monthly Langs Climatic Index. 58

FIGURE 8. Monthly water balance. 59

FIGURE 9. Modelled HTOP development with age for each PSP. 75

FIGURE 10. Graphical presentation of MMRC model vs. POOLED model for Zululand coast. 78

FIGURE 11. Predicted vs. observed site index (SI_5) in metres based on Equation 18. 83

FIGURE 12. Clusters separated by MAP and clay percentage in the sub-soil. 92

FIGURE 13. Dendrogram depicting the cluster output showing the three theoretical site classification units (SCU). 93

FIGURE 14. Dominant height vs. age relationships for site classification units (SCU) 1,2 and 3. 97

LIST OF APPENDICES

PAGE

APPENDIX 1. Solar radiation for KZN in selected months (Clemence, 1992 in Schulze, 1997). 114

APPENDIX 2. Map indicating MMRC zones 5,6,7,8 and 9. 115

APPENDIX 3. Map indicating physical location of permanent sample plots. 116

APPENDIX 4. An example of raw measured tree data. 117

APPENDIX 5. An excerpt from plot summary data by measuring period. 120

APPENDIX 6. Soil Data. 122

APPENDIX 7. Monthly median rainfall (mm) estimates for study area by PSP. 126

APPENDIX 8a. Mean monthly maximum temperature per PSP (degrees Celsius). 127

APPENDIX 8b. Mean monthly minimum temperature per PSP (degrees Celsius). 128

APPENDIX 9. Mean monthly A-pan evaporation per PSP (mm). 129

APPENDIX 10. Scatter plots of mean annual increment for selected permanent sample plots. 130

APPENDIX 11. Cluster Analysis output from Ward's technique. 132

APPENDIX 12. Map showing the geographical location of SCUs. 133

LIST OF VARIABLES

Age	Age of trees from establishment
$\beta_0 \ldots\ldots \beta_n$	Parameter estimates
DBH, d	Diameter (cm) at breast height (1,3m) over bark
D_q	Quadratic mean diameter (cm) $= \sqrt{\frac{BA_1 / TPH_1}{\pi / 40000}}$.
HT	Total tree height (m)
HTOP	Regression height of the 20% largest diameter trees
h	Upper stem height (m) to upper stem diameter
d	Upper stem diameter where height = h
BA	Basal Area per hectare (m^2/ha)
MAI	Mean Annual Increment (m^3/ha/yr)
MAP	Mean Annual Precipitation (mm)
MAT	Mean Annual Temperature (°C)
PSP	Permanent Sample Plot
SI	Site Index (m), dominant height at AGE_5
TPH_0	Trees per hectare established, AGE=0
$UVol_n$	Utilisable stem volume (m^3/ha) at reference age, AGE=n
Vol_n	Total stem volume (m^3/ha) at reference age, AGE=n
Vol	Total stem volume per hectare (m^3/ha)
V_t	Total stem volume
Z	A variable denoting site.
ASPECT	Orientation of slope from North 0°
HEAT_UNITS	Cumulative degrees Celsius per annum
LAT	Latitude (degrees South)
LONG	Longitude (degrees East)
ALTITUDE	Altitude above sea level (m)
ERD	Effective rooting depth (cm)

TAW	Total available water in a soil profile (mm water)
Jan_max	Mean maximum temperature for January (°C)
A_PAN	A-pan evaporation potential (mm)
CLAY_PERC_SUB	Clay content in the sub-soil (%)
LCI	Lang's climatic index (MAT/MAP)
OC_PERC	Organic carbon content in the top-soil (%)
DISTANCE	Distance from the coast line (m)
SF_FW	Fernwood soil form

CHAPTER ONE
INTRODUCTION

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.

South Africa is a country of diversity with a rich cultural and historical heritage, and a wealth of fauna and flora which have evolved under a steep gradient of bio-geophysical conditions. The warmer Indian Ocean in the east and the colder Atlantic Ocean in the west characterise the southern sub-region of Africa. Most of the interior plateau (between 1200 m and 1800 m above mean sea level) occupies almost two-thirds of the country's total area of 1 219 912 km^2. The southern and eastern seaboards lie at the foot of the Drakensberg range of mountains, with the North-eastern Plateau dropping sharply through the Great Escarpment into the Lowveld, which joins the flat plains of Mozambique on the east coast. North-west of the sub-region lie two deserts, the Kalahari and Namib.

The rapidly changing topography affects the diversity of climate and soil conditions. Mountain ranges act as barriers to moist air movement from the east in the summer and the west in the winter. Warm moist tropical air flows into the country during the peak of the summer rainfall season from the north. Temperatures are largely affected by altitude, with low lying areas being warmer and higher altitudes having lower mean annual temperatures. Frost occurs frequently on the high lying plateaus. Solar radiation receipts are also influenced by topography; while the southern aspect slopes are generally cooler, a higher temperature is found on the northerly aspects. During the winter months, deep cold fronts moving inland from the south Atlantic can produce snowfalls at medium and high altitudes. The Drakensberg mountains of Lesotho (altitudes > 2500 m) have a permanent snow blanket evident through most of the winter (Schulze, 1997).

Although water availability to trees is clearly identified as the single most important factor in forest land use management in South Africa, the matrix of other relevant factors such as land availability, socio-economic constraints, genetic advancement and environmental awareness make timber plantations operationally complex and fascinating for research (Zwolinski, 2001).

About 35% of the country receives a mean annual precipitation (MAP) of less than 300 mm, while only seven percent has a MAP exceeding 800 mm, which is considered the lowest rainfall suitable for economically viable commercial forestry (Schönau and Grey, 1987; Herbert, 1993, 2000). Soil water availability is often limited while the evaporation demands are usually high (Roberts, 1994). Many of the soils that occur on ancient weathering surfaces are inherently low in fertility particularly where they are associated with high rainfall (Olbrich *et al.*, 1997).

Commonly site is understood as the space occupied by growing trees. As a uniform ecological unit however, a site carries a specific type of vegetation but also possesses specific production capacity capable of delivering a specific quantity of timber. Pressure to apply sustainable forestry land management and on responsible social interrelationships and environmental accountability is increasing, while the cost-effective deployment of genetically improved material and silvicultural technology is affecting international competitiveness. Forestry managers will have to demonstrate a greater understanding of complex environmental resources and processes for producing appropriate fibre resources.

For thousands of years people have benefited from understanding the relationship between biotic and abiotic organisms or features. Schimper (1890 in Schulze, 1997) realised that climatic impact on plant distribution and survival is controlled through basic physiological processes. Much later, Chang (1968) highlighted the benefits of climatic knowledge to crop cultivation, and suggested that the more detailed the knowledge of the climate the more intelligently the land use can be planned on macro and farm scale levels. This is no different today, three decades later. A classification of forestry land with the objective of wise human intervention and utilisation has been part of forestry for more than 100 years. Morozov (1904 in

Zwolinski, 2001) defined bio-climatic classification of forests in Russia, while Cajander (1909) used forest floor flora to distinguish forest sites in Finland.

Three major types of site classification systems have emerged:

a. photocentric – based on a composition of plant communities, or their measurable performance (like diameter height relationship or site index of trees) used by Cajander (1909), Acocks (1975) and Vanclay *et al.*, 1995),
b. geocentric – site attributes such as climate, soil factors, topography, parent material and geomorphology in a forest system, contributing to the specific composition and production rates of forests,
c. a mixture of both.

The use of the geocentric approach usually requires a comprehensive knowledge of factors that are difficult or expensive to study and their interpretation for commercial plantation forestry requires long term experiments, such as the permanent sample plot approach that will be discussed in this thesis.

For practical reasons, site can be described as the collective interactions between climate, topography, geology and soil characteristics. The traditional definition of site used in this thesis needs clarification as the term "site" is used in layman's language to describe a certain place, but it may also be confused with ecological terminology used to describe the environment (Zwolinski, 2001). For example Louw (1999) viewed the forest site type as an integrated complex range of environmental factors within a prescribed area. Grey (1987) used "environmental factors" in a context of site characteristics and classification. In the context of this thesis, the ecosystem that is referred to is dominated by trees, and is a site that is relatively stable in terms of the soils and the longer term climate of which it is a function.

Site can therefore be described as "a holistic biophysical unit where particular vegetation will succeed if, within a specific plant's life requirements, supportive climatic, hydrological and nutritional processes allow a complete physiological cycle of survival, biomass production and reproduction" (Woodward, 1986). Site factors affect in some way the following: suitability of species, growth rates, timber production, forest health, wood properties, operational costs and economic returns.

The use of site quality prediction modelling is based on the empirical testing of relationships between tree performance under defined site conditions. Such a derived model is known as a Site Quality Prediction Model (H. Kotze, *pers comm.*, 2001), often referred to as site-growth models (Grey, 1987; Louw, 1997; Zwolinski, 2001). Such work is predominantly based on the application of empirical mathematical and statistical techniques (Grey, 1987; Louw, 1997; Woollons *et al.*, 1997), without providing much insight into physiological tree functioning as described by Kaufmann and Landsberg (1991), Battaglia and Sands (1997) and Sands *et al.* (2000).

In scientific studies aimed at site and growth relationships, the mathematical regression models explain the observed growth variability in terms of site explanatory variables (Grey 1987; Louw 1997; Woollons *et al.*, 1997). Such studies are frequently evaluated by comparing site factors and their relative contribution to explain variability. The aspiration of a growth modeller is to use site factors and to limit the unexplained sources contributing to variability to a minimum, thus providing a model that can be used to predict tree growth. The statistical modelling of tree growth as a function of the physical site factors allows us to match a particular tree species to the site and to estimate potential timber yields. Information is collected from study plots where site factors are defined, based on a broad understanding of their importance, while tree performance is studied with the traditional inventory and growth modelling techniques. Some explanatory site variables are correlated with growth but may not be readily available. In order to be useful for the practice of forest management and silviculture, the models should be based on easily accessible predictor variables.

It is only when site is well understood, that good silviculture can be practiced.

According to Theron (2000) the following components of good silviculture are of importance:

a. correct site species matching,
b. adequate soil tilth,
c. vigorous, disease free, optimum site-specific genetic material,
d. optimum site occupation and effective stand management,
e. minimum stress or competition factors,
f. feasible economic principles,
g. cost effective implementation of the above principles.

Modellers have worked towards increasing the precision and predictive power of their empirically-derived individual tree and stand level models by attaching some non-essential variables to these. These non-essential variables include time of occurrence of an event e.g. thinning regime, orientation with respect to the sun or aspect, soil type or some form of soil grouping or an indication of the performance of natural vegetation on the same land type (Woollons, *et al.*, 1997). It is well recognised that many other factors such as soil, climatic, physical or physiological in origin contribute to tree growth. While some of these factors have been included in models of growth and yield, they have generally been excluded from empirical systems of site and productivity.

Site quality prediction models have a wide range of uses:

a. they facilitate site-matched plantings, thereby optimising the inherent site potential,
b. they provide meaningful predictions with regard to future growth of trees on a given site for a specific species,
c. they highlight those site parameters that influence the productivity of trees the most, thus allowing silviculturists to manage on a site specific basis,
d. they can be used to determine cost-effective forestry strategies and are useful algorithms to optimise spatially with geographical information systems as a planning tool.

The prospects of hybridising stand level models by mixing empirical and process (eco-physiological) models will not be investigated in the scope of this study. Hybrid models aim to improve on traditional growth models based on age, stand conditions and mensurational inputs, by including growth indices derived from physiological processes (e.g. photosynthesis) or climatic or edaphic inputs (e.g. mean annual rainfall, effective rooting depth, organic carbon, underlying geology, etc).

With this background in mind, the objectives of this study can be formulated as follows:

a. to characterise the respective site conditions in terms of the soil, geo-morphology and climate,
b. to determine site parameters that describe the variation in growth patterns of *Eucalyptus grandis* occurring on the Zululand coastal plain,
c. to develop a production potential model of timber yield for a range of sites,
d. to establish a site classification system for the Zululand coastal belt for afforestation with *Eucalyptus grandis*, based on growth / site relationships.

The study aims at predicting dependent variables such as standing volume, mean annual increment (m^3/ha/yr) or site index (m) with independent site variables of geographical, topographical, soil or climatic origin. All the variables used in this study are readily available through most monitoring procedures of permanent sample plot (PSP) measurement, forest mensuration, site description and routine climatic monitoring. The study evaluates the site characteristics and is directed towards establishing the relationships between these characteristics and subsequent tree growth.

CHAPTER TWO
REVIEW OF SITE QUALITY PREDICTION MODELS

2.1 Introduction

It is known to be expensive and often perplexing to measure many of the site factors in a plantation with sufficient intensity for them to be included with permanent sample plot data in the construction of growth and yield models (Woollons, *et al.*, 1997). However, there are exceptions as demonstrated by Schönau (1987), Louw (1997), Strydom (1999) and Zwolinski, *et al.* (1997), which clearly indicate that it is possible to develop site quality prediction models using site variables.

The development of site quality prediction models must be based on accurate growth data and a thorough investigation of complex site conditions. While PSP derived information is readily available, the detailed site data is normally difficult to get, especially for large scale operational implementation. In reaction, some researchers optimised their study design by collecting transect data (Herbert 1997, 1998) from sampling plots significantly positioned within the range of site conditions.

There are some temporal and spatial variations to overcome when site quality prediction models are being investigated, particularly with short rotation eucalypt crops where annual or even seasonal fluctuation can have a prominent impact on the behavioral growth pattern. The application of PSP data combined with regular climatic information in addition to the "stable" site characteristics should provide for an accurate and practical approach to growth modelling.

These obstacles have not prevented modellers from constructing growth models based on physiological (Battaglia and Sands, 1997) and soil processes (Zwolinski, *et al.*, 1997; Louw, 1997), and driven by the input and calibration of site variables (Zwolinski, *et al.*, 1998).

The process models were initially intended for research purposes to help scientists understand the mechanisms of tree and stand growth, mainly through knowing more about canopy dynamics. This has not deterred scientists from applying them in commercial conditions as management tools, for example (Battaglia and Sands, 1998), and (Kaufmann and Landsberg, 1991).

In some regions of South Africa, it has become possible to use climate data as supplementary input variables in growth model equations, through the availability of excellent long term average weather statistics, obtained from an intensive grid of weather stations (Schulze, 1997; Woollons, *et al.*, 1997; Battaglia and Sands, 1998; Kunz and Smith, 2001). These models are known as hybridised models, purely due to the mixture of origin of predictor variables used.

Hybridised models have become increasingly more popular amongst forest managers. These models use data that are more readily available than pure process based models, which are based on eco-physiological parameters related to canopy dynamics such as photosynthesis, leaf area index, stomatal dynamics, assimilation process, carbon sequestration, etc. (Battaglia and Sands, 1998; Makela and Landsburg, 2000).

Hybrid models require inputs that are of a qualitative, as well as quantitative nature, but which can be readily and cheaply obtained. Site and soil factors such as slope, texture, depth, limiting horizons, total available water (McVicar, *et al.*, 1977; The Soil Classification Working Group, 1991), can be obtained from local knowledge or soil data and topographical map sheets. Climatic factors such as maximum and minimum temperature, heat units, rainfall and evaporation (Schulze, 1997) can be obtained from weather station summary data or electronically published geographical information system coverages (Schulze, 1997).

A summary of hybrid and physiological models from the literature is set out below. Woollons *et al.*, (1997) developed a model with site variables to estimate the basal area or top height utilising climate variables in conjunction with empirical plot measures. Top height was considered as a good indicator of the inherent production ability of a forest site.

Climatic variables, which included solar radiation (MJ/m^2/d), annual rainfall (mm) and mean temperature ($^\circ C$), were estimated for each study plot by making use of surface splining algorithms in conjunction with latitude, longitude, altitude, aspect and slope values. It was shown that the effects of the climate and soil are strongly related and thus partially confounded. Woollons *et al.*, (1997) suggested a pooled model for *Pinus radiata* grown in the Nelson region of New Zealand:

$$G = \exp\left(\log(G_1)\left(\frac{T_1}{T}\right)^{B+\eta\log\left(\frac{N}{10}\right)} + \alpha^*\left(1-\left(\frac{T_1}{T}\right)\right)^{B+\eta\log\left(\frac{N}{10}\right)}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 1$$

and

$$\alpha^* = (\alpha + \delta.mg.\log(rain) + \varepsilon.ehs.\log(rain) + \phi.hfg.solar) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 2$$

where: G = Basal area per hectare, N = Stems per hectare (estimated or modelled), T = Age, Rain = annual total rainfall (mm), Solar = average solar radiation(MJ/m^2/d); Parameter estimates: α =4,6405; β=0,6139; δ=0,4714; ε =0,6904; η=0,1421; ϕ=0,0069.

Equation 1 is a pooled model of the Schumacher formulation (Schumacher, 1939) that predicts future basal area (G) at a selected age (T) from a measured basal area (G_1) at age (T_1) that includes a site parameter derived from site variables (Function 2). Function 2 describes four "dummy" variables representing three distinct edaphic types, (mg = Moutere gravels, ehs = eastern hill soils, hfg = high fertility granites and mc = Mapua clays) similarly to South African soil forms or land types. These soil or dummy variables are in turn coupled with rainfall and solar radiation variables. Set simultaneously to zero, the last term in model 1 collapses, to a predictor of basal area per hectare for the Mapua clays.

To use this model effectively, a "regular" mortality function was included to predict the number of stems per hectare. This basal area model for *Pinus radiata* is considered to be the most precise with the least bias, for the three distinct soil types included in the study (Woollons *et al.*, 1997).

There are several limitations to the proposed methodology. Despite the selection of a large range of altitude classes in this case, with known appreciable differences in temperature, the implementation of such a model is restricted to the study area. Clearly the conditions that are valid for this particular model are atypical for other forestry areas in the sub-region or elsewhere. However, its successful implementation will depend on the existence of long-term and reliable weather stations and quality climatic information.

This and other studies showed that site data need to be stratified into the correct groupings through a statistical process of discriminant analysis, which discriminates between site variables based on hypothetical relationships with growth (Louw, 1997; Woollons *et al.*, 1997; Snowdon *et al.,* 1998, 1999). It can further be noted that the coefficients for the above model are all positively correlated which is expected given the choice of variables used. The model thus predicts a higher basal area with higher rainfall and solar radiation and both these terms have upper asymptotes, thus reaching reasonable limits.

Site growth models are particularly useful to predict tree growth in areas that were not afforested before. There they serve as indicators for the feasibility of timber production.

The study conducted by Zwolinski *et al.,* (1998), deals with the reconstruction of pine growth on various sites of the North Eastern Cape Forests (NECF). The main objective was to model site-growth relationships in order to accurately predict the Mean Annual Increment (MAI_{18}) and Site Index (SI_{18}) both at 18 years of age. The study involved stem analysis of existing trees, detailed surveys of the soils and other site characteristics, monthly measurement of soil water status at some of the sites and detailed data analyses to achieve the set objectives.

In the NECF study, data were collected from on-site inspections and included variables such as tree diameter at 1,3 m (DBH), tree form, stem status such as multiple stems, forks, crookedness, disease cankers, etc. On each plot, 50% of the trees were felled and their heights (HT) measured with a measuring tape, then the stems were cut into one meter sections and annual rings were counted. The HT growth was reconstructed from the ring data per one meter section and from the year ring mapping at 1,3 m stem height.

Climatic profiles were developed for each of the study sites including parameters such as mean annual precipitation (MAP), mean monthly precipitation, mean monthly temperature, heat units and relative potential radiation indices. At each test plot a soil pit was made, soil was classified and its characteristics were defined; leaching index, pH, organic carbon content, macro- and micro-nutrients, water availability and the bulk soil density were determined at five depths. The estimated root zone available water (RAW) was determined with existing models (Hensley, 1996; Zwolinski *et al.,*1998).

The data analysis showed that timber yields were highly dependent on water availability, which was defined as a combination of RAW and annual rainfall. This relationship was characterised with acceptable values of the coefficient of determination, mean square error and probability levels. In the same study, the only species specific model could be developed for *Pinus elliottii*, and only with site index, base age 18 (SI_{18}), as the response variable. The regressors used in this case were heat units and carbon content in the B horizon. These variables are not easily or readily measured in a forest but together with water supply they are important predictors of tree growth.

In another South African study, Louw (1997) described the site growth relationships of *Eucalyptus grandis* in the Mpumalanga escarpment area. Soils of this region are mostly of a granitic origin. The objectives of this particular study were to identify those site factors that can be related to the growth of *Eucalyptus grandis*, as well as to develop a site-growth model for the quantitative evaluation of sites for predicting site index with base age 20 (SI_{20}). An integrated approach was followed using multiple regression analysis (SAS Institute Inc., 1989) and incorporating topographic, soil and climatic factors.

In this study, temporary sample plots of *Eucalyptus grandis* saw-timber were used. The advantage of this approach was the opportunity to establish plots on pre-determined locations to cover the variation of soils and climate more effectively. A wide range of site factors was recorded as independent variables and a measure of tree growth such as site index represented the growth potential for specific sites.

The lack of high resolution climatic data were mentioned as a drawback for these types of studies (Louw, 1997). The accurate extrapolation of climatic data from data collected at existing weather stations has been made possible by using topography and meso- and macroclimatic patterns. Louw (1997) also considered a range of physical soil variables, chemical soil variables and independent physiographic variables.

A highly significant correlation between tree growth and terrain position was found by Louw (1997). This physiographical phenomenon is called topographical wetness, which is a function of the flow of water and nutrient deposition, due to topography. A very low correlation between organic carbon content of the soil and tree grow was recorded. On the Zululand coastal plain however, carbon content was indicated as a highly significant indicator of tree growth (Noble *et al.,* 1991). A very high correlation was also found between tree growth and soil depth. Numerous other authors (James, 1988; Schafer, 1988a, 1998b and 1994; Louw, 1991; Strydom, 1991) have described the positive correlation of effective soil depth and tree growth.

Louw (1997) followed the same approach as Woollons *et al.*, (1997) by grouping soils into units bigger than soil form *per se*. Three soil groups were described: red apedal soils with orthic top-soils, red apedal soils with humic top-soils, and apedal or neocutanic soils underlaid by material with signs of wetness. It is not surprising that these three groups of soils were highly correlated with SI_{20}. The underlying soil processes probably indicate the available water content of the soil.

Louw (1997) concluded that correlation between site variables and tree growth was generally low, but those factors that influenced water available to the trees were most important. Site factors influencing the nutritional status are less important, which is in contrast with the findings of Noble *et al.,* (1991).

Noble *et al.,* (1991) initiated a study in the Zululand coastal plain at a time when mortality of *Eucalyptus grandis* was exceptionally high. Soil pits were dug in a number of poorly performing and thriving stands in the Mtunzini area. Soil samples were collected and submitted for chemical analysis. A transect design was used through all *Eucalyptus* clonal compartments. In addition, foliar samples were taken from nearby trees and analysed for nutrient contents. Soil organic carbon contents of the high performance sites were found to be double that of the poor growing sites. A highly significant linear relationship was observed between organic carbon content of the soil and site index. Another interesting phenomenon was the high correlation between organic carbon content of the soil and the nitrogen content of the tree foliage. According to Noble *et al.*, (1991), organic carbon content can be seen as the most reliable soil parameter to consider when sites are evaluated for their afforestation potential on the Zululand plain. Very low soil organic carbon content soils (<0,3%) have very low cation exchange capacity (CEC) and nutrient supplying ability, which indicates a high risk of stand failure. The trees growing on these sub-optimal sites are often stunted, lack apical dominance and have small crowns lacking ability to effectively photosynthesise. Also a high correlation between clay percentage and site index was observed on the sandy soils. This confirms Louw's (1997) findings that one of the most important factors to consider is the sustained water retention and supply in which soil plays a vital role. This view was also supported by Zwolinski *et al.*, (1995) who recognised relevant soil characteristics and suggested soil amelioration techniques to optimise water supply for best tree growth in the Southern Cape.

It needs to be emphasised that Noble *et al.*, (1991) focussed on chemical properties of the soils only. Therefore further research of physical soil properties and climate should improve the understanding of site growth relationships in Zululand.

2.2 Other Relevant Studies

The following is a summary of site research done elsewhere in the world on subjects directly related to site analysis for predicting growth of forest trees.

Snowdon *et al.* (1999) in a study on *Pinus radiata* in Australia, demonstrated how a Schumacher projection model is substituted with annual indices of climatic or edaphic source as a surrogate of growth potential to act as a basis of stand basal area prediction. "Hybrid models" were developed based on traditional empirical models of forest growth and yield but also incorporating "growth indices" reflecting changing conditions for growth. While a simple index such as annual rainfall is useful, the best indices used to date are derived from process-based models such as BIOMASS, which was developed following a comprehensive study of the effects of water and nutrient availability on the growth of *Pinus radiata* (Snowdon *et al.*, 1999).

Predictions obtained from traditional empirical forest models implicitly assume average climatic conditions. Snowdon *et al.* (1998) points out, that in New South Wales' (NSW) Southern Tablelands running five-year mean rainfall can be as much as 15% above or below the long-term average, and variation from year to year is much greater. A variation of ± 50% in the amount of carbon fixed was found in a NSW pine forests on an annual basis, which indicates large variations in the amount of wood produced. It was also shown by Smith (2001) that the Current Annual Increment (CAI) curve follows the same pattern as the rainfall for a particular period, indicating a fluctuation of ± 44% in tree growth (m^3/ha/yr) depending on annual rainfall.

Hybrid models can help managers interpret growth data from experimental plantings. For example, if measurements have been made in a particularly dry period they are unlikely to reflect long-term growth prospects. Using these measurements as the starting point, together with long-term weather records, a hybrid model should be able to give a more reliable estimate of prospects based on the experimental results (Snowdon *et al.*, 1999).

Traditional forest growth models are sometimes used to update previous inventories, but as these do not take account of year-to-year variations in growing conditions the results can be wide off the mark. If weather conditions in the intervening period are known, hybrid models can be used to update previous inventories more accurately.

In Italy, a study was conducted to establish the environmental factors related to site index of Douglas-fir (*Pseudotsuga menziesii var. menziesii*) (Corona *et al.,*1998). This study aimed to identify the climatic, topographic and edaphic factors that could be used for estimating site index. Only easily assessable factors were considered, and soils factors requiring detailed chemical analysis were avoided. According to Corona *et al.,* (1998), a slight improvement of growth estimation gained by using chemical factors often does not justify the associated increase of work and expense. The approach they used was similar to the one followed by Louw (1997) in that landholdings were stratified into units of uniform site qualities and Douglas-fir trees of roughly 30 years of age were used to coincide with site index base 30.

A linear relationship was used to describe the site growth relationship in this particular study. The best site index models developed for Douglas-fir stands, where exclusively edaphic variables were included, explained only 16% of the variation in site index for this particular study area (Corona *et al.,* 1998). For the same study area, location parameters, such as elevation, natural habitat and species composition, longitude and latitude data were included, which explained 42% of the variation (Corona *et al.,* 1998).

In Douglas-fir plantations, the best coefficient of determination in site growth studies was found to be 45% in Scotland where a mixture of edaphic and climatic variables was used (Corona *et al.,* 1998). The R^2-value was improved in another investigation (Klinka and Carter, 1990) for the same study area to 72% by including factors not readily assessable, such as evapotranspiration in warm summer months and mineralisable nitrogen of the forest floor and the soil.

The best coefficient of determination in South African-based studies also varies considerably. One of the highest coefficients of determination, achieved in a growth study for long rotation *Eucalyptus grandis* was in a model developed by Strydom (1999). By including effective soil depth, position in the terrain and mean annual precipitation into the model, 84% of the growth variation was explained (Strydom 1999).

2.3 Process Based Models

Since the Landsberg and Waring (1997) publication on modelling stand growth on the basis of physiological processes was published, an increasing number of South African scientists have been engaged in the study of process based models (Zwolinski, 2001). The Physiological Principles Predicting Growth – model (3-PG) by Landsberg and Waring (1997), is based on simplified concepts of radiation-use efficiency, carbon balance and partitioning. In principle, the model calculates total carbon fixed from utilisable photosynthetically active radiation adjusted for the effects of drought, atmospheric vapour pressure deficit and frost. The model can input remotely-sensed estimates of leaf area index and basic weather and soils information.

The model known as PROMOD, as described by Battaglia and Sands (1998) predicts growth of a forest following canopy closure. This process model predicts growth from a stand only after the canopy dynamics have stabilised. These models commonly assume biomass production to be proportional to Absorbed Photosynthetic Active Radiation, and consequently process based models are also known as APAR models. Esprey (2001), reviewed PROMOD and found this model too static to predict responses to drought over the whole rotation. The improved version of PROMOD known as PROMOD–*dynamic* predicts biomass of foliage, branch, stem wood, bark, coarse and fine roots and litter fall over time. The model makes provision for the input of silvicultural management regimes such as spacing control and competition management, as well as defoliation due to some stress agent.

The PROMOD process model requires input that forest managers can readily and cheaply obtain, such as: latitude, longitude, altitude, slope and aspect and a classification of the soil depth, texture, stone content, drainage and a rating of soil fertility.

The principal output from this model is Mean Annual Increment (MAI). MAI, however, is a measure of stand productivity that is, unlike site index, severely influenced by the silvicultural treatments a site or stand might have received. In short rotation eucalypt plantations in South Africa, it is known that the number of stems per hectare is one of the most influencing factors affecting MAI (Coetzee, 1997). MAI is not a true indicator of the site potential because silviculture and management can influence stems per hectare or spacing, beyond levels normally associated with the qualitative norms of site potential.

It is alleged by Sands *et al.*, (2000), that the APAR models such as PROMOD could easily be used to screen prospective plantation sites on the basis of readily available input data. This is, however, impossible where canopy dynamics are not known. Therefore before their application in a true commercial sense can be improved, APAR models, will remain research tools to study site classification, establish true commercial gain from genetic improved stock and to determine the exact productivity potential of a series of sites given well defined silviculture .

CHAPTER THREE
DESCRIPTION OF THE STUDY AREA

3.1 Location

The Zululand coastal plain is situated on the eastern seaboard of the KwaZulu-Natal Province of South Africa. The general study area lies approximately between latitudes 28°34' and 28°40' South and longitudes 32°02' and 32°40' East. It forms a part of the open Zululand coastal plain from an elevation of 0 m at sea level to an elevation of 120 m above mean sea level at about 20 km inland.

There are no meaningful topographical barriers to air movement from the Indian Ocean coastline that runs in a northeasterly direction between Port Durnford and Cape St. Lucia (Wolmarans and Du Preez, 1986).

In general the topography is flat to gently undulating, with frequent small to medium drainage lines and open water pans in depressions. Prior to commercial land use programs, the land was characterised by open swamps and typical marsh vegetation. Although the water table has resided considerably over the last number of years, flooding can still occur following large spells of precipitation associated with cyclonical activity in the Mozambique Channel (Wolmarans and Du Preez, 1986).

3.2 Climatic Factors important to Forestry in South Africa

Climate is a primary factor for site quality or the classification of sites in South Africa (Schönau, 1987). The variation in climate is measured regionally using mean annual precipitation (MAP), and mean annual temperature (MAT). MAP is used to characterise the long-term water supply into a region. It further defines the potential of a growing area assuming other factors such as nutrients, light and suitable substrate. MAT is associated with, or is an indication of the amount of heat units available that in turn can be an indication of:

a. the length of the growing season,

b. the potential evapotranspiration to take place,

c. the rate of assimilation (Schulze, 1997).

The main atmospheric conditions that determine growth on a regional and local scale are:

a. light associated with day length,

b. temperature regimes, and

c. available water or moisture, atmospheric or soil bound.

Climatic factors, which when compared with atmospheric conditions, cause the most damage to trees, are droughts, lightning, frost, snow, strong winds and sudden local temperature changes. Drought, and in particular available soil water, is often the most limiting factor in sustained plantation forestry in South Africa. Soil water availability is a function of rainfall and its distribution in time and space. Soil water holding capacity is closely related to soil depth and texture and evapotranspiration potential of a given area. The likelihood that a climate-related constraint will impact on the lifespan of a plantation forest is high.

3.3 Solar Radiation

Solar radiation has an important effect on green growing (photosynthesising) plants. Higher order plants utilise the visible portion of the solar radiation to produce carbohydrates out of water and CO_2. Photosynthesis takes place mainly during the daytime in the green parts of trees that are exposed to sunlight. Eucalypt trees often have a green bark that would also assimilate carbohydrates (Schulze, 1997).
A generalised formula for photosynthesis is;

$$CO_2 + H_2O + energy \longrightarrow (CH_2O) + O_2 ,$$

The resultant product, CH_2O denotes the carbohydrates of plants (i.e. starches, sugars and cellulose), which react in a complex manner (Schulze, 1997).

When water or nutrients are in short supply, a profound daily relationship exists between photosynthesis and solar radiation, especially when a high leaf area index exists. Photosynthesis is a relatively conservative and inefficient process, with a conversion rate of not more than 2,5% of solar energy to assimilated carbohydrates (Monteith, 1977).

Appendix 1 shows the amount of solar radiation, for a few selected months, that KZN receives per day, measured in $MJ/m^2/day$. In the South African context, solar radiation is seldom limiting to plant growth and should therefore be regarded as part of the macro equation of factors contributing to plant production.

The real impact of solar radiation available for photosynthesis becomes eminent when slope and aspect are taken into consideration. The energy budget therefore fluctuates on a micro scale depending on the variation of slope and aspect. Battaglia and Sands (1997) described slope and aspect as key input parameters into the site growth and process based models because the energy budget is important to the development of the canopy and associated stand dynamics.

3.4 Geology

The science devoted to the earth is appropriately known as *Geology* (from the Greek *Gaia* or *Ge,* the ancestral Earth-goddess of Greek mythology, and *logy*, a suffix denoting "knowledge of") (Holmes, 1965). Geology is the science that refers to the earth's crust, the strata that compose it, its mutual relationships and the continual change to which the present conditions and spatial representation are due. Modern geology has as its objective the deciphering of the whole evolution of the earth and its inhabitants from the time of the earliest records that can be recognised in the rocks right down to the present day.

The influence of the geological material on tree growth is important. The influence mainly comes from the effect the soils, which have developed on a specific parent material, might have on tree growth (Ellis, 2000a in Owen, 2000). If the origin of the parent material is known, more accurate predictions regarding characteristics and land use will be possible.

South Africa has a complex geology consisting of hard rock (igneous, sedimentary or metamorphic origin) and loose (unconsolidated) material (Ellis, 2000a in Owen, 2000). The geological material occurring on or near the surface is important to the forester. Some soils are derived from aeolian deposits, such as those of the coastal dune forests of Zululand, Alexandria (Eastern Cape) and Harkerville near Knysna. Others are derived from material deposited by running water (alluvial deposits along riverbanks) and ocean or lake sediments, for example some parts along lake St Lucia. Some soils are formed *in situ* from weathering mother rock such as granite, sandstone, quartzite, dolerite or basaltic origin. Others have developed from organic deposits, as a result of low temperatures, incomplete drainage, and others from soils formed elsewhere and transported to their present position known as colluvial soils. South African forest soils often have their origin in more than one parent material, e.g. the top-soil may be from colluvial drift and the sub-soil from granitic weathered bedrock (Ellis, 2000a in Owen, 2000).

The geology of the northern part of the study area, known as the Nyalazi area, has been mapped at a scale of 1:50 000, but the results were never published. (Jacobs *et al.,* 1989). The geology around Kwambonambi has significance from a geo-hydrological point of view and has been intensively studied for this purpose (Wolmarans and Du Preez, 1986; Jacobs *et al.*, 1989).

3.5 Lithology of the Zululand Coastal Zone

Lithology refers to the mineralogical composition and texture of rocks as parent materials of soil and weathered material utilised by tree roots for water, air and nutrients. Regional lithology can be used as a suitable surrogate where data on physical soil properties as well as on soil fertility and soil chemical properties are lacking (Morris, 1986: in Kunz and Pallett, 2000).

The Northern section (Nyalazi and St. Lucia)

a. The St. Lucia formation comprises richly fossiliferous glauconitic, olive-grey silts and fine sands with large calcareous concretions of marine sediments at various levels. (Wolmarans and Du Preez, 1986; Jacobs *et al.*, 1989). Glauconite, also known as "green sands", is hydrated aluminosilicate of iron and potassium, usually enriched in calcium (Wilde, 1958). This formation is the most important for forestry in this sub-region (Herbert, 1998). It yields poorly drained soils with a clay-loam texture.

b. The Muzi formation occurs mainly in the south-west of the study area, but also isolated in the Kwambonambi area, and consists of mottled, brown, clayey sand related to a vlei or swamp sedimentary environment. Hydromorphic soils are usually formed from this substrate.

c. The Berea formation consists of red, orange and yellow decalcified quartz sands. The grain-size distribution is well sorted with sub-angular to rounded particles. The sand is generally compact due to cementation by kaolinitic clay derived from weathering feldspar and by hydrated oxides. The red sands on the eastern side of Nyalazi, are recognised by a high and relative persistent ridge and are younger than the red sands in and around Kwambonambi.

d. Recent sediments which are

   i) whitish to light grey fine- to very fine-grained, well sorted redistributed sands,

   ii) white wind-blown sands covering the centre parts of the key area and,

   iii) mainly silt and clay that has been deposited by the Nyalazi river in the west. The sands are fine to very fine-grained and well sorted texturally, consisting of almost pure silica; accordingly, they form very sandy soils, frequently in excess of 2 m in depth (Herbert, 1998).

The Southern section (Kwambonambi and south)

a. The Uloa formation occurs closer to Richard's Bay. It consists out of a thin limestone, which is richly fossiliferous.

b. The Bluff formation consists of a pale-brown calcareous sandstone, which essentially is a beach rock and forms the core of the inland dune cordons.

c. The Port Dunford formation consists of mudstone, lignite, clay and sand. This formation has been interpreted as a lagoon barrier complex.

d. The Kwambonambi formation can be regarded as all the recent sands occurring from Nyalazi in the north to Port Dunford in the south and, together with the Berea formation, are the only formations which outcrop in the area (Jacobs *et al.*, 1989).

3.6 Geo-hydrology

Generally, it is believed that the marshes and swamps reflect the main watertable, which is largely continuous throughout the area (Jacobs *et al.*, 1989).

The assumption that vleis and swamps exist because of perched water tables is only partially correct. In north-eastern Zululand it was found that hardpans, like ferricrete, calcrete, silcrete and claypans influence the hydrology (and geo-morphology) and form highly efficient aquifers. It is known that the Uloa formation in and around Kwambonambi, forms aquifers for deeper water extraction. The underlying aquiclude is Palaeocene/Cretaceous siltstone, and is estimated to be between 25 and 60 m deep. This aquifer is semi-confined and gave rise to leakage from the system and developed a number of seepage zones and springs. It was found that perched water tables could exist above shallow discontinuous clays (Jacobs *et al.*, 1989).

The drainage pattern is largely a reflection of this. Initially water percolation is restricted by the compacted Berea-formation causing overland flow and so activates the drainage network during heavy rains. Surface runoff may also occur where grey humus-stained sands cause water repellency. There is evidence that drainage of the Berea formation is improved through the formation of natural pipes (Jacobs *et al.*, 1989).

3.7 Soil Factors

The fluctuation of temperature, expansion of water on freezing, erosive action of wind and raindrops, all contribute to the rupture of rocks into "skeletal" soil material – stones and gravel (Holmes, 1965). Physical weathering is usually accompanied by more profound changes caused by chemical processes such as solution, hydrolysis, carbonation, oxidation and reduction. Weathering is primarily a geological process which may proceed tens of meters below the surface, out of the reach of tree roots, but essentially it is the initial genesis of soils and parent soil material properties that have a decisive influence on the growth of forest trees (Holmes, 1965).

The understanding of forest soils forms the basis of good forestry planning. Soil surveys are important parts of data collection, and form the basis of decision making practises in forestry. In the South African forest industry soil surveys are standardised according to the Forest Soils Data base (FSD) system of systematic data capturing (Erasmus, 1998). The data are almost entirely managed with Geographical Information Systems (GIS).

Following is a short description of the more important parameters measured during soil surveys.

Soil depth

Trees require a minimum soil depth, known as the Effective Rooting Depth (ERD) in which their roots can develop, water and nutrient are absorbed and in which trees anchor themselves. Many soils, however, have some limitations regarding root growth and development. Such limitations include periodic or permanent periods of wetness, abrupt textural changes in the profile and hardened underlying horizons. Soil descriptions should take cognisance of the underlying horizons. For example a pedocutanic B may be more penetrable than a prismacutanic B and should therefore have a greater suitability for tree growth (Ellis, 2000b in Owen 2000).

Wetness

The term wetness refers to the presence of free water occurring during prolonged periods of the year and are within reach of the tree roots. Fundamentally two types of wetness hazards occur in the Kwambonambi area: those that are caused by a perched water table, mostly due to poor drainage in the sub-soil, and those caused by permanent water bodies in the area such as pans, vleis and rivers (Jacobs *et al.*, 1989).

Wetness causes low oxygen levels in soils and increases carbon dioxide levels which inhibits active root respiration. It also causes a reduction of iron compounds, which results in green / blue to grey mottled soil colour. In many cases such discolouration is associated with massive soil structure. In some cases, iron compounds are leached leading to bleached soils of high densities and high strengths in the dry state (Ellis, 2000b).

The FSD deals with wetness by categorising it into 3 classes:
W1 = short periods (mottles on a good background colour)
W2 = long periods (mottles on poor background colour)
W3 = almost year round (gleyed colours throughout with dark cutans and oxidised root channels (Erasmus, 1998).

Soil texture

This term refers to relative size parameters and the arrangement of soils particles (MacVicar *et al.*, 1977). Any abrupt textural change with depth has a detrimental effect on water movement, air motion and root penetration. Alluvial and colluvial derived soils exhibit typical characteristics of textural impeding horizons. The actual obstacle to root, water and air penetration depends on the abruptness of the textural change. The restriction is uplifted fairly successfully with deep ripping in the near dry state.

Another type of textural layering is so-called duplex soils with layers, by definition, of higher permeability in top layers and lower permeability in the lower layers. Stone lines viz. a concentration of gravel or stones in horizontal layers, also pose a real obstacle to tree root development.

The FSD does not give guidelines for the measurement of textural layering. However, all the relevant texture information for the purpose of this study was recorded in-field, e.g. soil form and family, horizon order, associated depth and clay percentage, soil colour, grade, type of structure and depth of limiting material. These qualitative and quantitative elements can be interpreted on a polygon basis to describe textural layering. Such an analysis, using spatial analysis and dissolving GIS layers into one principal sheet for part of the study area, is displayed graphically in Appendix 2.

Soil structure

Structure refers to the natural aggregation of primary soil particles into compound units or peds, which are separated from one another by planes of weakness (MacVicar *et al.*, 1977). Soils with a structure that can be observed with the naked eye are called structured or pedal (Smith, 1995) in contrast with soils that have no apparent cohesion and are called apedal.

Structure is described in terms of three characteristics, namely type (shape and arrangements of peds), their size and distinctness (degree of inter-ped adhesion or grade of structural development). There are furthermore, four primary types of structure: blocky, spheroidal, prismatic or platy (Erasmus, 1998). FSD standards refer to the same principles as discussed above and they make provision for various grades of structure.

Soil colour

Colour is a most useful characteristic when it comes to describing a soil or horizon and is an equally handy tool to distinguish between soils. A good indication can be gained of the soil characteristics from colour, and colour is often diagnostic of soil composition and conditions. Soils' colours are described either as the secular name given to a colour with dark and light shades or, more scientifically, using the Munsell soil colour charts system (Munsell Soil Color Charts, 1988).

The principles in the identification or interpretation of soils by using their colour are:

a. top-soils are usually darker than sub-soils due to organic matter enrichment. Dark colours may also be an indication of a dry climate such as in the case of base rich melanic or vertic top-soils;

b. grey top-soils reflect poor drainage in the sub-soil, sub-soil colour changes from red through to yellow to grey, blue and green (gleyed) when the top-soils get more saturated with water, less aerobic and often more reduced in iron element (Smith, 1995).

FSD uses general soil colours with the option to describe the degree of colour intensity (Erasmus, 1998). The Munsell colour notation is optional and companies may instruct pedologists to use Munsell colour charts.

Soil fertility

Plant nutrients and soil reaction to chemical processes all affect tree growth, particularly the development of the root system. Most chemical imbalances can wholly or at least partially be ameliorated to reduce the restrictions, which such imbalances place on plant development (Noble and Herbert, 1991). The availability of nutrients on a site is largely determined by the interaction of the climate, soil and the forest ecosystem. The inherent nutrient supplying capacity of sites vary due to the differences in soil parent material and organic content, climate, stand dynamics and management prescriptions, for example slash management (Du Toit and Carlson, 2000).

Available soil water

Under South African conditions, the growth rate and health of plantations of commercial tree species are highly related to the variation of soil moisture and water availability (Roberts, 1994). The quantification and evaluation of available soil water and the complex impacts it has on different tree species grown on different sites are vital to the interpretation of results from silvicultural experiments and the development of sound management practices.

In order to identify and understand the opportunity of managing the soil moisture regime through silvicultural techniques, the following factors need to be considered:

a. the potential soil volume the tree's root system will be able to colonise,
b. the quantity of water the soil can hold for use by the trees,
c. the soil water availability at different levels of soil moisture content,
d. soil management principles to improve its capacity to hold enough water to sustain tree growth at optimum levels, and
e. the information on profile re-charge cycles (Roberts, 1994).

It is also important to understand tree specific reaction to available soil water content, specifically with respect to:

a. the rate that soil water is extracted at different times of the year with respect to stand dynamics and at different levels of soil moisture,
b. the correlation between tree growth stress and rate of soil water extraction, and
c. the levels of deficit soil moisture at which tree growth is hampered or become susceptible to insect attacks and other physiological stresses.

Roberts (1994) developed a series of ratio indicators (RATIO) where the mean annual potential evapotranspiration (MAPE) and the mean annual actual evapotranspiration (MAAE) are calculated to determine the success of afforestation above certain threshold values. He also defined variables to indicate the percentage of time where soil moisture levels are below 10%, the average number of occurrences per annum where moisture levels reach field capacity and the frequency of rain spells greater than 30 mm. Further regression modelling was carried out using the RATIO and profile available water supply (PAWS) to explain the variance in MAAE.

The following conclusions were reached from this work (Roberts, 1994):

a. water that enters a soil profile is rapidly used until the profile dries to a point just before wilting point, where the moisture content stabilises,
b. soil profiles with PAWS values of between 65 and 70 mm result in optimum levels of actual evapotranspiration and growth, and the growth rate declines as PAWS deviates on either side of the optimum. The result is that root development is enhanced at high levels of PAWS but cannot be sustained once the PAWS drops back to optimum and lower, and
c. the characteristics of climate at any site tend to be more important than the characteristics of the soil profile within the ranges encountered in forested areas, and the benefits derived from the

amelioration of the soil profile will most likely be greater in areas of more suitable climates.

Organic Carbon Content

Soil organic matter is a term generally used to refer to the readily oxidisable organic matter present in a soil, known as humus, as well as highly condensed, nearly elemental organic carbon such as charcoal, graphite or coal (Jackson, 1962). The soil organic carbon content is calculated as a proportion of soil organic matter. The conventional conversion factor converting carbon to organic matter factor is 1,724 (Jackson, 1962).

There are several ways of determining the organic matter content of a soil. The classic approach is by a wet-oxidation technique known as the Walkley-Black method (Walkley, 1947), and is generally the method against which all other determinations are compared. This technique should be requested whenever accurate determinations of soil organic carbon content are required. In most laboratories it is the only acceptable technique to be used when organic carbon contents are high (>4%).

However, the Walkley-Black procedure is laborious and slow. A rapid method for estimating the soil organic carbon content has been devised for certain southern African conditions using a thermogravimetric loss-on-ignition (LOI) approach (Donkin *et al.*, 1993). The method should only be used for top-soils with relatively low organic carbon contents (< 4%) and is most useful when soils need to be ranked within a set of similar soils. Good results have been obtained using this method for soils with very low organic carbon contents from Zululand (Noble *et al.*, 1991).

It is generally observed that forestry top-soils from Zululand have an organic carbon content of less than 1%, whereas those from the remainder of the forestry regions often have carbon contents substantially greater than 2% (Donkin *et al.*, 1993, 1994).

Soil organic matter was also shown to correlate with nitrogen content and with climate and clay content (Jackson, 1962). Multiplication of the total nitrogen content of the soil by a factor of 20 approximates the organic matter content. Jackson (1962) indicates in his study that the estimation of soil organic matter from the nitrogen content is just as accurate as estimation based on carbon content. It is also suggested that carbon content can be estimated from climatic variables and the clay content of a soil.

Previous studies have indicated that soil organic carbon can be correlated with the relative responsiveness of *Eucalyptus grandis* to nitrogenous inorganic fertiliser application (Noble and Herbert, 1991). This would suggest that the major role of organic matter on a diverse set of soils be in the supply of mineralisable nitrogen. A poor correlation between the sum of exchangeable cations and organic carbon content was observed in the Noble and Herbert (1991) study. Although this was not expected, since the soils are relatively low in clay content, it was foreseen that the organic carbon content would contribute significantly to the supply of CEC. It further emphasises the important role that organic carbon content plays in supplying mineralisable nitrogen into the nutrient pool of a plantation site.

CHAPTER FOUR
MATERIALS AND METHODS

4.1 The Forest Site Classification of the MMRC making use of Geology

The commercial timber companies in South Africa have been researching growth and yield of stands of trees for many years. In the mid 1990s, the Mensuration and Modelling Research Consortium (MMRC) was formed to primarily collate and store the data from growth and yield studies, and to make data available to forest mensurationists for modelling purposes (Morley, 1997). It is important that the mensurational network's sample trees are located on sites representative of all growing conditions that a specific tree species occupies. Permanent sample plots are therefore established in the major physiographic regions of the commercial forestry industry in South Africa (Kunz and Pallett, 2000). Each physiographic region is defined as a unit of land in which the temperature (MAT) and lithology are relatively homogeneous.

The tree growth data collected for this study can be classified and fitted in with the MMRC geology and climate classification system. This will allow for future referencing with a common system and could facilitate the expansion of work done in site quality prediction growth modelling. The forest economic zones showing area planted compared with total area owned by patrons of the MMRC are shown in Table 1.

A breakdown of the Zululand Coastal Zone is shown in Table 2, indicating the geological groupings, geological type and macroclimate that dominate the sub-region.

TABLE 1. Comparison of the area planted with commercial tree species to the total area of land holdings owned by MMRC members in Mpumalanga and KwaZulu-Natal, for 1996/97.

Forest Economic Zone	Planted area (ha)	Total area owned (ha)
Maputuland (Makhatini)	21 514	4 710
Zululand	141 748	194 821
KwaZulu-Natal Midlands	217 740	336 972
Northern KwaZulu-Natal	83 896	227 288
Southern KwaZulu-Natal	112 890	172 311
KwaZulu-Natal (Total)	**577 788**	**936 103**
Eastern Mpumalanga	297 404	367 465
South-eastern Mpumalanga	313 826	456 746
Mpumalanga (Total)	**611 230**	**824 211**
TOTAL (MMRC)	**1 189 018**	**1 760 314**

TABLE 2. Description of the study area for 80% of the land using MMRC classification terminology (Kunz and Pallett, 2000)

1. Physiograpic region	**Zululand Sub-tropical sands**	
2. Geological groupings	A. Sands (65% Zululand total area) 90 000 ha.	B. Basalt and Siltstones (15% of Zululand total area) 21 000 ha.
3. Geological type	Q = Sedimentary Qb = Arenite Qm = Sand	Jl = Basalt Kz = Siltstone
4. MMRC Stratum name	06 - Zululand Subtropical Sands	23 - Zululand Subtropical basalts / siltstones

A colour graphic representing the major physiographic regions of the Zululand Coastal Area and other adjacent MMRC regions is shown in Appendix 2.

4.2 Permanent Sample Plots

The Permanent Sample Plot (PSP) program in Mondi Forests was used as a data source for this study. The author has been instrumental since 1991 in driving a process to establish a credible PSP program in Mondi and previously, in Hunt

Leuchars and Hepburn and this dissertation thus forms part of the culmination of some ten years of research effort.

The PSP programme forms an integral part of the data acquisition strategy in a growth and yield programme. PSP data are used for the following purposes:

a. development of growth and yield models that are used in the forestry planning process, such as the Growth and Yield Simulator (Kotze, 2000),
b. determination of harvesting volumes (Clutter *et al.*, 1983; Avery and Burkhart, 1994; Van Laar and Akca, 1997),
c. management of long term sustainability of the growing stock of a forestry company (Du Plessis, *et al.*, 1997; Chiswell and Pienaar, 1999).

The periodic re-measurement of permanent sample plots is statistically superior to successive independent inventories for evaluating changes in forest conditions (Avery and Burkhart, 1994). When identical sample plots are re-measured, sampling errors relating to differences are inclined to be lower i.e. the precision of "change estimates" is improved.

With the establishment of PSPs, two very important criteria were met:

a. the field plots are representative of the forest area for which the inferences are made,
b. they are subjected to the same silvicultural treatments as the non-sampled portion of the forest (Vanclay *et al.*, 1995).

Sampling design

Stratified sampling is used throughout the placing of PSPs. This ensures that the full range of conditions is represented. Measuring strata can for example include variables related to soils, climate, land types, species, age class or product working circles. The following points are important when the sampling design and data collection strategy is considered:

a. a longer observation period per plot offers a better basis for growth modelling,

b. an initial stratification, based on age, offers a useful shortcut to cover the full age range from the beginning,

c. the PSPs for a given region should be representative of the full geographical spread of the study area (longitude, latitude, elevation, topographical features, etc.),

d. the sample should cover the full range of soil conditions of the study area, and

e. different stand conditions such as variable stand density per hectare should be carefully considered, e.g. poorly stocked areas in a compartment should rather be avoided because the cause of the irregular mortality can be attributed to many factors, which are not easily determined or kept constant in the study.

Plot Size and Shape.

Given below are the major rules applied in the plot selection and layout process:

a. the plot size remains constant throughout the life of a compartment,

b. all plots were fixed area PSPs, consisting of six by six tree rows with 36 measured trees, depending on the initial planting espacement, with long thin plots orientated along the contour with the longest side following the contour to avoid variation caused by the position on the slope,

c. each plot was given a unique number, as were the trees in the plot to allow for successive measurements of exactly the same tree, to increase the accuracy of the sequential data over time (re-measured data),

d. a Global Positioning System (GPS) was used to measure the position (latitude and longitude) of the plot centre.

Plot measurement

Only trained personnel were used for the measuring of PSPs. As a rule these staff were recruited from the commercial cruising teams and had an aptitude for data collection, accuracy and a sense of correctness.

Following are the major rules applied to the measuring of trees:

a. measurements were made annually or bi-annually after establishment. In some cases the intervals were much shorter (three months) to capture seasonal growth differences. According to Chiswell and Pienaar (1999), the interval between re-measurements should be long enough to allow for growth increment that is larger than the standard error of the difference between measurements. The seasonal fluctuation in timber yield was not tested in this study,

b. measuring order and direction of trees were the same for each measurement. The previous records, as well as the plot map were used for in-field reference.

c. diameter of each tree at 1,30 m above ground level (DBH) was measured,

d. the heights to the growing tip (HT) of up to 30 trees per plot were measured,

e. the stem form and condition of each individual tree were assessed as described in Table 3.

TABLE 3. Tree status and stem form.

Variable	Factor	Evaluation	Description
Tree Status	**Stem condition**	0 or 1 or 2 or 3	0 = Alive
			1 = Thinned
			2 = Dead, natural mortality
			3 = Dead, other factors
Stem form	Broken or dead top	0 or 1	0 = absent, 1 = present
	Forked	0 or 1	0 = absent, 1 = present
	Leaning	0 or 1	0 = absent, 1 = present
	Butt sweep	0 or 1	0 = absent, 1 = present
	Foxtail	0 or 1	0 = absent, 1 = present
	Mechanical damage	0 or 1	0 = absent, 1 = present

Closing-off of a PSP

Although it is useful and necessary to collect growth data beyond the normal rotation age of the plantation, PSPs are not the most efficient means of collecting such data - long term trials (such as spacing trials) are more appropriate. Thus, each PSP was concluded when the compartment was harvested. A final re-measurement was made before the trees were felled. In such cases, actual tree volumes were determined for a sample of PSPs when trees were felled. These data supplemented other data collection efforts for determining tree volume and taper, and assisted to monitor whether appropriate total and merchantable stem volume equations were being used to predict standing tree volumes from DBH and height measurements.

A closed PSP was usually re-established in the same compartment as close to the locality of the previous PSP as possible. It is of importance to assess changes in growth on a particular site over more than one rotation. This is particularly important where long term sustainability research forms part of a greater research program. In the data set used for this study some PSPs (5 and 11) were re-measured over more than one rotation.

The variables recorded in every plot are provided in Tables 4a and b. The tree-level variables as measured and recorded are shown in Table 5. An extract of raw tree data are shown in Appendix 4.

TABLE 4. Plot level variables measured and recorded.

Variable	Details / Method
Plot number	Unique number
Estate	Estate code and name
Compartment	Compartment number
Species	Tree species
Stock	Stock code of the planted trees
Working circle	Combination of species, management regime and product
Position on slope	Top, middle or bottom
Soil variables	The variables as per FSD standard
Silvicultural operations	Record what operations were performed and when and giving details of the operations, e.g. 3 m pruning
Planting date	Date when compt was planted
Measure date	Date when plot was measured
Aspect	Dominant facing aspect (degree)
Slope	Measure the slope in the direction of the steepest gradient
Altitude	Elevation above sea level (m) – measured with altimeter
Side lengths, and diagonals or radii	Row plots: sides should be measured in a systematic order, e.g. AB, BC, CD, DA, diagonal AC (in m) Circular plots: radius (m) and steepest slope recorded
Plot co-ordinates	Use a GPS to measure (in degrees, min, sec)

TABLE 5. Tree level variables measured and recorded.

Variable	Details / method	Unit	Accuracy
Tree number	Uniquely identify each tree location within a plot	Integer	Must be constant across Measurements
Stem number	Uniquely identify each stem at each tree position	Integer	Must be constant across Measurements
DBH	Diameter at breast height (1,3 m)	cm	To nearest 0,1 cm
Height	Tree height to the growing tip – measured with a hypsometer or height rods	m	To nearest one cm
Tree status	See codes in TABLE 4		
Stem form	See codes in TABLE 4		
Disease score and impact on utilisable timber	See the booklet *Guidelines for disease impact rating for Eucalyptus species (MMRC)*		

4.3 The Measurement of Trees

The basic growth variables used in this study:

a. Age

The stand age represents the length of time elapsed since planting. Information about stand age is obtained from management plans and from electronic records recorded in years and months.

b. Diameter at breast height (DBH)

DBH was measured in cm, over the outside bark to the closest decimal place, with a tape placed horizontally around the bole at 1,3 m height from the surrounding soil surface.

The data set for this study refers to mean DBH, which is simply the arithmetic mean DBH of a sample size *n* and is described by the following equation;

$$\overline{Dbh} = \frac{\sum_{i=1}^{n} d_i}{n} \qquad \text{..................................3}$$

Equation 3 produces an unbiased estimate of the population mean providing the assumption of random sampling is satisfied (Snedecor and Cochran, 1980). Its usefulness, however, is limited to certain types of experimental studies, such as small plot genetic variation testing and fertiliser trials.

The Quadratic Mean Diameter of the stand represents the tree with the mean basal area. The sample estimator is:

$$D_q = \sqrt{\frac{\sum_{i=1}^{n} d_i^2}{n}} \qquad \text{...............................4}$$

c. Height (HT)

The tree height (HT) is required to determine the Site Index (SI) of the PSP and the HT/DBH relationship, to calculate the volume of the stand and to predict the future tree growth.

The tree height is a useful response variable for the early analysis and evaluation of silviculture trials and tree breeding experiments. The mean height at a specific reference age (5 years in the case of Zululand) is an indication of the site quality. In forest inventories, the mean height of the stand is required to estimate the volume of the mean tree (mean DBH). Since this study is focussed on PSPs only, the total tree height was used on an individual tree basis (DBH-HT pairs). Furthermore, the tree height was used to determine the SI and stem volume.

Height for the purpose of prediction can be calculated from a relationship that exists between HT and DBH. The top height (HTOP) is defined as the regression height of the 20% largest diameter trees The equation most often used for this regression is:

$$\ln(HT) = b_0 + b_1 . \ln(d) \quad \ldots\ldots 5$$

also,

$$\ln(HT) = b_0 + b_1 . \frac{1}{d} \quad \ldots\ldots 6$$

where:

HT = tree height in m

d = DBH in cm

ln = natural log.

d. Trees per hectare (TPH)

TPH was calculated for each plot by using the number of trees counted on a specific plot area.

e. Basal Area (BA)

The basal area of a tree is defined as the cross-sectional area of the stem, usually calculated at DBH (Clutter *et al.*, 1983). The calculation assumes a circular shape of the cross section of the stem. An elliptical cross-section occurs occasionally when there is wind with a prevailing direction during the growing season or throughout the year, trees that are growing on steep slopes or when trees are planted in a rectangular spacing pattern (Van Laar and Akca, 1997).

f. Volume

Stand volume in commercial plantations is the most important stand characteristic. It is a function of the number of trees, basal area, mean height and form of the trees (Clutter *et al.*, 1983). It may be expressed in terms of stem or tree volume, total or merchantable volume, or, over or under bark volume.

The stand volume is usually calculated from the mean diameter and top height of a stand. Volume is sometimes calculated from diameter distribution classes such as the Weibull distribution where there is reason to believe that height per diameter class differs significantly.

For the purpose of this study the individual tree volume calculation was made using the sectional under bark approach for each log section of the tree (Chiswell, 1998). The Schumacher and Hall equation (Schumacher, 1939) as fitted by Chiswell (1998) was used to calculate tree volume.

$$V = B_0 D^{B_1} H^{B_2}$$

$$V_t = \exp\left[B_0 + B_1.\ln(D) + \ln B_2.\ln(H)\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .7$$

(linearized by logarithmic transformation)

where $\beta_0 = -9{,}7722; \beta_1 = 1{,}9584; \beta_2 = 0{,}8500$

with fit statistics $R^2 = 0{,}9799; n = 473$

g. Site index (SI)

In silviculture and forest management, the forest site is commonly described by those edaphic and climatic site characteristics which have an impact on growth and yield of a given tree species on a given site. In South Africa and many other countries, the site index of a stand is usually defined as the mean height of the dominant trees at a reference age, calculated from a subset of tree diameter characteristics, and which is closely linked to the rotation age (Van Laar and Akca, 1997). For the Zululand sub-region this reference age was fixed at 5 years (Coetzee, 1997).

Site, the yield class or the site index, are concepts which serve to describe and quantify the potential of a given site to produce timber of a certain tree species for a given initial planting espacement and specific silvicultural regime. It has to be taken into account, however, that in young stands the prediction of the expected height of trees is uncertain.

The construction of a set of site index curves for a given species, based on regression equations, requires a model which expresses stand height as a function of age. A simple and convenient relationship between height and age was presented by Schumacher (1939) in Van Laar and Akca (1997). The general form is shown below:

$$\ln(H) = B_0 + B_1 \cdot \left(\frac{1}{A}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 8$$

where B_0, B_1 are coefficients to be estimated, H= tree height, A= Age.

The Classical Chapman-Richards 3-parameter guide curve (Brickell, 1969; Pienaar and Kotze, 2000), was used to estimate the Site Index (SI_5) for every PSP in the study. The general form is shown below:

$$HD = \beta_0 \left[1 - e^{(\beta_1 (Age_1))}\right]^{\beta_2} \quad \text{...9}$$

where:

HD = Height of defined group of Dominants

A = Reference Age

$\beta_0, \beta_1, \beta_2$ are parameters to be estimated

The parameters for Zululand coastal area as developed by Kotze (2000) are:

$B_0 = 75{,}0$

$B_1 = -0{,}030791$

$B_2 = 0{,}66672$

Site index should not develop in any meaningful pattern with age. By definition SI should stay constant over age if it is assumed that the production potential of the growing site does not change.

We know that environmental inputs, such as rainfall, number of heat units, fluctuation in soil water potential (Louw, 1997; Woollons *et al.*, 1997; Zwolinski *et al.*, 1998; Roberts, 1994) and other parameters such as changes in chemical composition, (Schönau, 1987; Donkin and Smith 1991) do affect the site index.

Site index will be used as the dependent variable in most of the analyses to follow in this study.

4.4 Description of the Data sets and Preliminary Analysis

4.4.1 Mensurational data

Twenty-six PSPs were selected for this study, all of which were planted with *Eucalyptus grandis* seedlings. These plots are located on Mondi Forests' land. The PSP numbers and their location along the Zululand coastal area, as well as the number of measurements each PSP received are shown in Table 6. The 26 plots were measured 278 times in total, and were made up of 10 081 individual tree measurements. A map is attached (Appendix 3) indicating the physical location of each PSP.

TABLE 6. Numbers and location of the permanent sample plots.

Plot number	Lat.	Long.	Farm Name	Compt	1st survey	Last Survey	Number of surveys
MONEF0001F00	28°35'15"	32°04'28"	Kwambonambi	RF07b	1991	1993	10
MONEF0005F00	28°35'08"	32°04'27"	Kwambonambi	RF07c	1991	1993	4
MONEF0005F01	28°35'08"	32°04'27"	Kwambonambi	RF07c	1996	1998	3
MONEF0011F00	28°43'55"	31°57'21"	Kwambonambi	NC13c	1991	1993	4
MONEF0011F01	28°43'55"	31°57'21"	Kwambonambi	NC13c	1995	1997	3
MONEF0019F00	28°31'15"	32°10'01"	Mtubatuba	TH68	1992	1997	13
MONEF0023F00	28°35'15"	32°11'38"	Kwambonambi	RE10	1992	1998	7
MONEF0032F00	28°59'04"	31°43'48"	Mtunzini	A05	1992	1998	9
MONEF0033F00	28°58'27"	31°42'56"	Mtunzini	B10	1992	1997	7
MONEF0034F00	28°58'23"	31°42'29"	Mtunzini	C03a	1992	1997	7
MONEF0037F00	28°59'12"	31°42'35"	Mtunzini	D13	1992	1996	6
MONEF0038F00	28°59'20"	31°43'42"	Mtunzini	A06	1992	1996	12
MONEF0039F00	28°58'47"	31°43'21"	Mtunzini	B16	1992	1996	6
MONEF0040F00	28°58'48"	31°43'21"	Mtunzini	C13	1992	1996	6
MONEF0041F00	28°58'40"	31°43'53"	Mtunzini	B18	1992	1997	6
MONEF0059F00	28°41'19"	32°02'29"	Kwambonambi	NA18c	1995	1998	4
MONEF0060F00	28°41'54"	32°03'06"	Kwambonambi	NK33	1995	1998	4
MONEF0061F00	28°42'00"	32°01'26"	Kwambonambi	NA06	1995	1998	4
MONEF0062F00	28°39'13"	32°03'50"	Kwambonambi	NL17a	1995	1998	4
MONEF0065F00	29°02'24"	31°39'40"	Mtunzini	K16b	1995	1998	4
MONEF0069F00	28°38'22"	32°05'50"	Kwambonambi	RA37	1995	1998	4
MONEF0070F00	28°35'56"	32°08'06"	Kwambonambi	RC51	1996	1998	3
MONEFGM72F0	28°35'26"	32°04'00"	Kwambonambi	RG37	1995	1998	36
MONEFGM73F0	28°37'27"	32°05'44"	Kwambonambi	RB27	1995	1998	36
MONEFGM74F0	28°39'09"	32°06'31"	Kwambonambi	RB50	1995	1998	36
MONEFGM75F0	28°36'22"	32°10'44"	Kwambonambi	RE25	1995	1999	36

The characterisation of *E. grandis* stands in the Mondi Forests' Zululand coastal plantations based on the 278 PSP surveys is shown in Table 7. An extract of the summarised plot data is shown in Appendix 5.

TABLE 7. Summary statistics of growth and yield measured and derived variables for the series of 26 PSPs.

Variable	Mean	Min	Max	Standard Deviation
Age (years)	6,2	1,88	9,27	1,51
HTOP	24,65	18,20	31,50	2,93
Dbh (cm)	15,7	8,4	21,2	2,0
D_q(cm)	15,8	8,5	21,8	2,0
TPH	1336	1071	1885	164
BA (m^2/ha)	23,7	6,0	46,0	7,57
Vol (m^3/ha)	247,7	6,2	687,4	132,3
MAI (m^3/ha/yr)	57,1	3,2	104,7	19,3

The raw tree data were plotted to visualise the development of tree growth, the variance of certain parameters and the ranges in which the data were limited. The visualisation also helped to indicate the necessity of the mathematical transformation of data.

The relationships between AGE with D_q, HTOP and Volume per hectare (Vol) are shown in Figures 1 to 3. The PSP Interval Data Visualisation (IDV) tool developed by Safcol, (PSP IDV[1] version 1.0, Safcol) was used to graphically display the PSP interval data. Segments of re-measured data are spliced onto the previous measurements; these types of data are known as longitudinal data.

The IDV was developed to plot connected PSP data quickly in order to visualise and explore the PSP data as continuous lines with different rates of development (change over time), for each PSP.

[1] IDV – Interval Data Visualisation tool, developed by D. Vonck, Safcol, 1999.

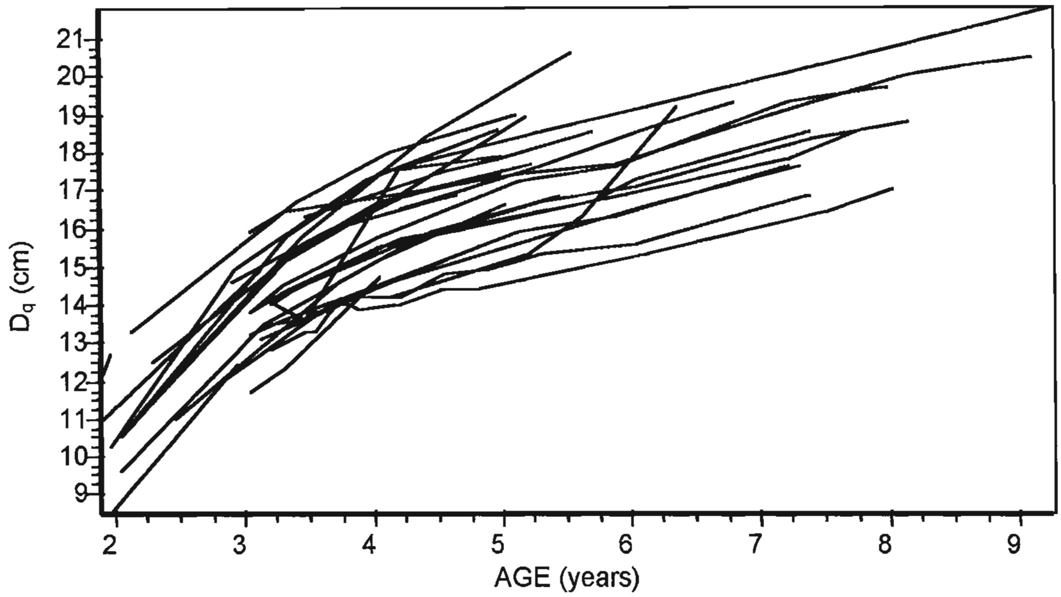


FIGURE 1. Development of quadratic mean diameter (D_q) with age by PSP.

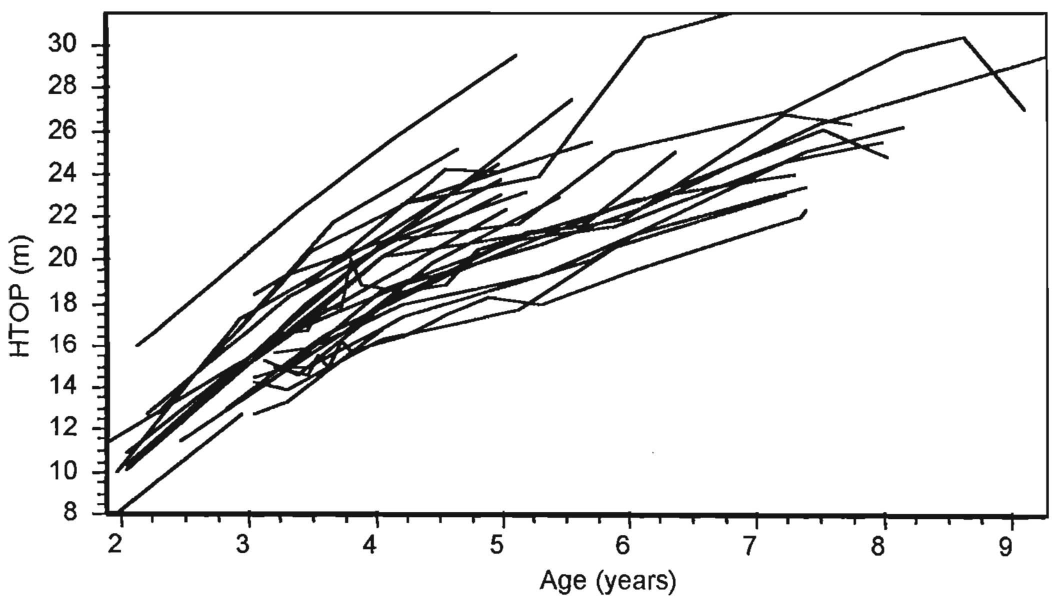


FIGURE 2. Development of top height (HTOP) with age by PSP.

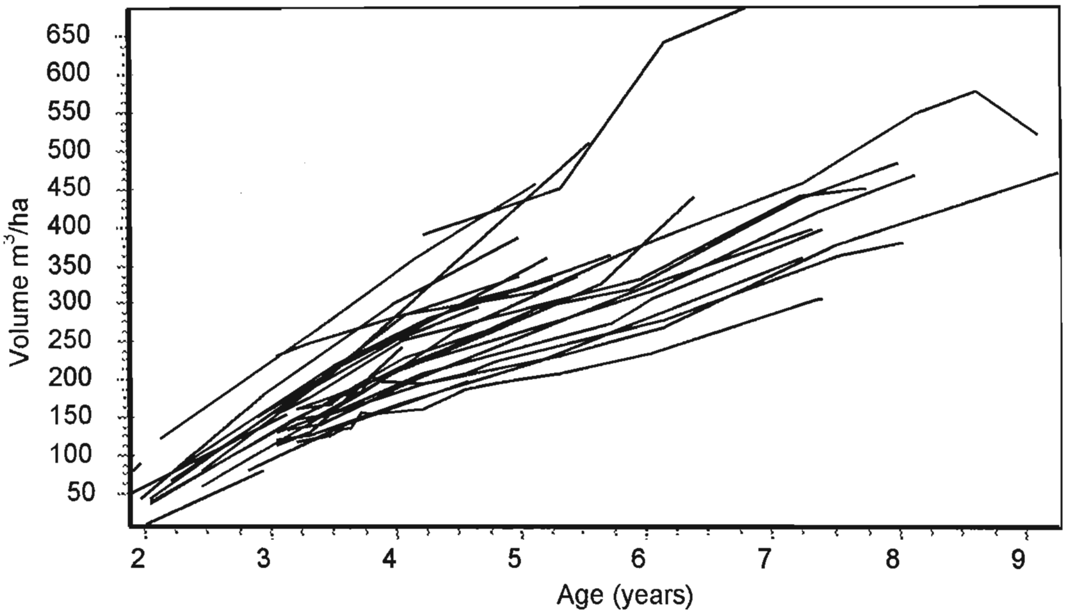


FIGURE 3. Development of volume per hectare (Vol) with age by PSP.

The total stem volume was derived by using models provided by Schumacher and Hall (Schumacher, 1939), while the Demaerschalk model (Demaerschalk, 1972) was used to describe taper of the usable stem.

4.4.2 Soils data

FSD standards were applied to all soils data used in this study. Identification of soils to the family level was undertaken according to "Soil Classification: A taxonomic system for South Africa", (The Soil Classification Working Group, 1991). Soils were sampled by auger on a 150 x 150 m grid and described up to a depth of 150 cm. Stone lines were penetrated and the underlying material was documented. Soil pits were also used in some cases.

A description of the soil form and family for all PSPs is shown in Appendix 6a. Furthermore, the detailed information for each distinct soil horizon per PSP is shown in Appendix 6, Table 2.

The organic carbon percentage in the top-soil was estimated in-field and classified into four classes.

Further to the organic carbon content, a soil productivity potential was developed for each PSP (indicated in Appendix 3 on the map). This is a pedological index expressing the soil potential from empirical variables such as clay content (%) in the sub-soil, effective rooting depth, water holding capacity, drainage potential and position in the landscape (Erasmus, 1998). This estimation is a class or categorical variable. A simple regression analysis with these categorical variables or "dummy variables" was performed with MAI as the dependent variable. The low potential category was set as 0, medium = 1, medium-high = 2 and high = 3. The fit statistics are shown in Table 8.

TABLE 8. Fit statistics for dummy variable fit with MAI as dependent variable.

Model:	MAI=17,4215+2,3288 (Potential)				
Fit statistics:	df (1;25)	R^2 = 57%,	RMSE=1,84	F=32,2406	P<0,001

From the regression statistics in Table 8, particularly the R^2 value of 0,57 and the significance of the fit (p-value < 0,001), it is clear that "growth potential" required further research with respect to collecting accurate information on organic carbon content. It was decided to sample each plot independently, to obtain an empirical, laboratory-derived value for organic carbon. The Walkley-Black method as a wet oxidation technique was used to determine organic carbon content (OC%) for each PSP.

A summary of the soil data is shown in Table 9.

TABLE 9: Summary of soils data used in the study.

Variable	Mean	Minimum	Maximum
Effective rooting depth (ERD) cm.	>150	>150	>150
Total Available Water (TAW) (mm)	150,2	118	164
Clay content in top soil (%)	22,57	5,0	45,0
Organic carbon content (%)	0,45	0,25	0,90
Soil types represented (The Soil Classification Working Group, 1991)	Hu2200, Hu2100 Vf2220, Fw1210, Fw1110 Oa1110 Gf2100		

The effective rooting depth across the study was found to be more than 1,5 m. Soils of the study area are thus all deep and should not impose any physical impediment to tree growth. For the purpose of explaining variation in growth, ERD cannot be used in regression analysis because of the lack of variance in the data.

For simulation and hydrological modelling purposes the water retention parameters may be derived from a knowledge of soil texture, organic matter content and bulk density (e.g. Hutson, 1986). However, available water capacity (AWC) as defined by Hutson (1986) is a variable obtained from multiple regression analysis and was found not to take cognisance of the influence of soil bulk density on water retention (Smith *et al.*, 2001). Furthermore, Hutson (1986) described the AWC as a function of the textural breakdown of the soil as defined in the Soil Classification : A Binomial System for South Africa (MacVicar *et al.*, 1977). The textural soil data for the PSP plots were classified according to the Taxonomic System for South Africa (The Soil Classification Working Group, 1991). The classification guidelines for texture are different between these two classification systems and AWC was therefore found to be inadequate for inclusion as soil parameter for this study. It is suggested by Smith *et al.* (2001) that textural classes are used to determine AWC from the soil texture, but the PSP soils data lack these textural breakdown classes and it was decided to use the TAW values as suggested by Erasmus (1998).

The following equation was used to determine TAW:

$$TAW = \left(\frac{A-B}{100}\right) \times HorizonDepth(cm) \quad \text{.......................} 10$$

where A, B are estimated from equations 11 or 12.

For clay content $\leq$ 15%. 11

$$A = 0{,}1387 + (0{,}00416 \times Clay\%) \times 100$$
$$B = 0{,}0344 + (0{,}00381 \times Clay\%) \times 100$$

For clay content > 15%. 12

$$A = 0{,}0943 + (0{,}00428 \times Clay\%) \times 100$$
$$B = 0{,}0344 + (0{,}0381 \times Clay\%) \times 100$$

The TAW index was calculated from the ERD and clay percentage values for each horizon as surveyed and captured in the data set. The values for TAW listed in Appendix 6, Table 1 compare favourably with the AWC held at pressures -10 to – 1500 kPa found by Smith *et al.* (2001) for soil texture classes of loamy sand and sandy loam.

One of the soil forms and families represented in the study area is from the Oxisol group (USDA, 1975 in Van der Watt and Van Rooyen, 1990), locally referred to as Hutton form (Soil Classification Working Group, 1991). Both the families that occur in the study area are mesotrophic in the B1 horizon, with the distinction that one is non-luvic while the other is luvic. The luvic criterion is used to distinguish between soils where the sub-soil (B-horizon) has significantly more clay than the A-horizon. These characteristics come into consideration when the soil water retention capacity of the site is studied. These soils are well-drained and associated mainly with the Berea clay ridges.

The Zululand coastal soils are often referred to as the Zululand sands. The Fernwood soil form, that is classified under the Entisol soil order from the USDA Soil Taxonomy (1975 in Van der Watt and Van Rooyen, 1990), is characteristic of these sands. The Fernwood-forms represented in the Zululand-area are distinctively light coloured A horizon soils with an E horizon in the grey or yellow colour groups, when observed under moist conditions. The Fernwood soils that are described both have lamellae present in the E horizon and are enriched with organic matter, sesquioxides or aluminosilicatic clays.

4.4.3 Climatic data

The climate data provided by Schulze (1997) were used. Electronic point data, based on the latitude and longitude of each PSP, were obtained from the CCWR.[2] The summarised climate data for the 26 sites of interest in the study area are provided in Table 10.

TABLE 10. Summarised climatic data for the 26 plot sites.

Precipitation (mm)	**Mean**	**Minimum**	**Maximum**
Mean Annual Precipitation (MAP)	1158,5	1015	1295
Wettest month (March)	116,4	101,6	132,2
Driest month (July)	35,7	13,5	43,6
Median annual rainfall	1118,8	969,9	1255,5
20^{th} percentile	439		
80^{th} percentile	1100		
Temperature ($^{\circ}C$)			
Mean Annual Temperature (MAT)	21,3	19,4	21,8
Mean max. hottest month (January)	29,2	27,2	30,1
Mean max. coldest month (July)	23,3	21,7	23,8
Mean min. hottest month (January)	20,2	18,0	20,5
Mean min. coldest month (July)	11,6	9,1	12,5
Evaporation (mm)			
Total Annual Evaporation	1766,9	1725,9	1796,5
Mean monthly A-pan evaporation	147,24	83,8 (June)	200,2 (Dec,)
Langs' climatic index (mm/$^{\circ}C$)	54,3	46,6	61,4

Precipitation

Precipitation estimates were obtained from the CCWR for each of the 26 individual PSPs. A summary of these estimates is shown in Appendix 7. A graphic representation of the median monthly rainfall of each PSP is shown in Figure 4.

[2] CCWR: Computing Centre for Water Research, Department of Agricultural Engineering, University of Natal, Pietermaritzburg.

Figure 4 shows that the average monthly distribution is very similar for all sites, viz. a summer peak between November and March, with a steady monthly decrease thereafter to a winter low between June and August.

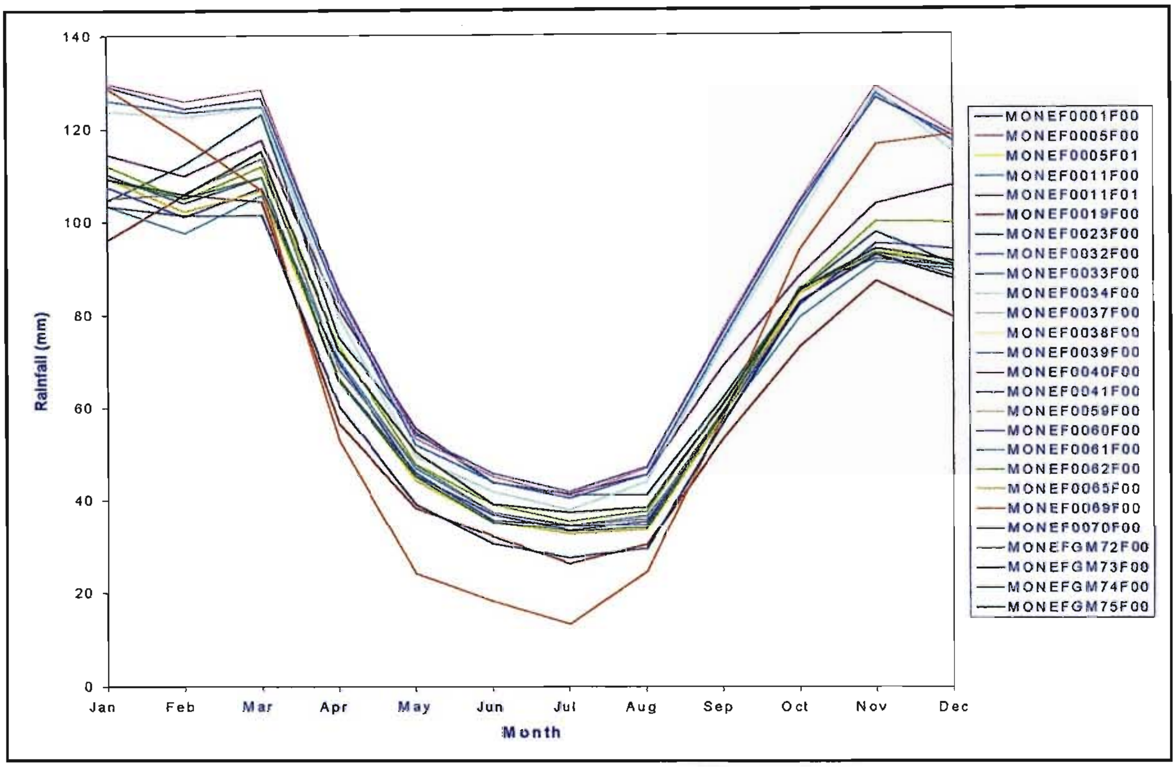


FIGURE 4. Monthly median rainfall per Permanent Sample Plot.

The monthly distribution pattern is unique to summer-rainfall sites in Southern-Africa, as even reasonably good sites have between 20 and 40 mm per month during winter. Another distinguishing factor is that the higher precipitation sites have consistently higher monthly precipitation over the year.

From the estimated data it is assumed that distance from the east coast has a significant influence on precipitation (MAP), which is in strong contrast with other forestry areas where altitude is a stronger influencing factor with regard to both MAP and MAT. In this particular sub-region the MAP tapers off from the coast to the inland (Herbert, 1998; Gardner *et al.*, 2001). A simple regression analysis tested this assumption and showed it to be correct. The null hypothesis that rainfall does not taper off from the coast to the inland was rejected. Details of this analysis are shown in Table 11.

TABLE 11. Fit statistics for distance from the coast, with MAP as dependent variable.

Model:	MAP=1308,7549 - 0,0148 * (Distance from coast)				
Fit statistics:	df (1;25)	R^2 = 84%,	RMSE=42,72	F=125,4861	P<0,001

From the data, it is evident that precipitation varies according to latitude, probably in response with the coastline's orientation. In this regard, the coast north of Cape St. Lucia is orientated north-south, and thus the precipitation system changes at a different rate with distance from the coast when compared with the Kwambonambi area. Generally, the highest precipitation in the sub-region occurs at Port Durnford and tapers off in both a westerly and a northerly direction. The variables MAT and MAP are primary climatic factors affecting tree growth conditions and become less favourable as one moves further away from the coast and / or more northwards. This implies that MAP may be used as a variable to meaningfully distinguish between forestry sites on the Zululand coastal plain.

Gardner *et al.* (2001) showed a very small relative difference between rainfall stations, which indicates the rainfall received in the sub-region emanates from the same precipitation system.

Observed data from a number of local weather stations were used to augment the rainfall data obtained from the CCWR. No meaningful differences were observed between the CCWR and the augmented data set (du Plessis and Pienaar, 1999).

Temperature

Long term estimated temperature data were also obtained from the CCWR at the Department of Agricultural Engineering (DAE), University of Natal. The long-term maximum, mean and minimum values are shown in Appendix 8a (mean monthly maximum) and Appendix 8b (mean monthly minimum).

The mean monthly maximum and mean monthly minimum temperatures per PSP are shown in Figure 5. The difference between the maximum and minimum per experimental site follow the same pattern for all PSPs, with the absolute differences between these two values not being very high.

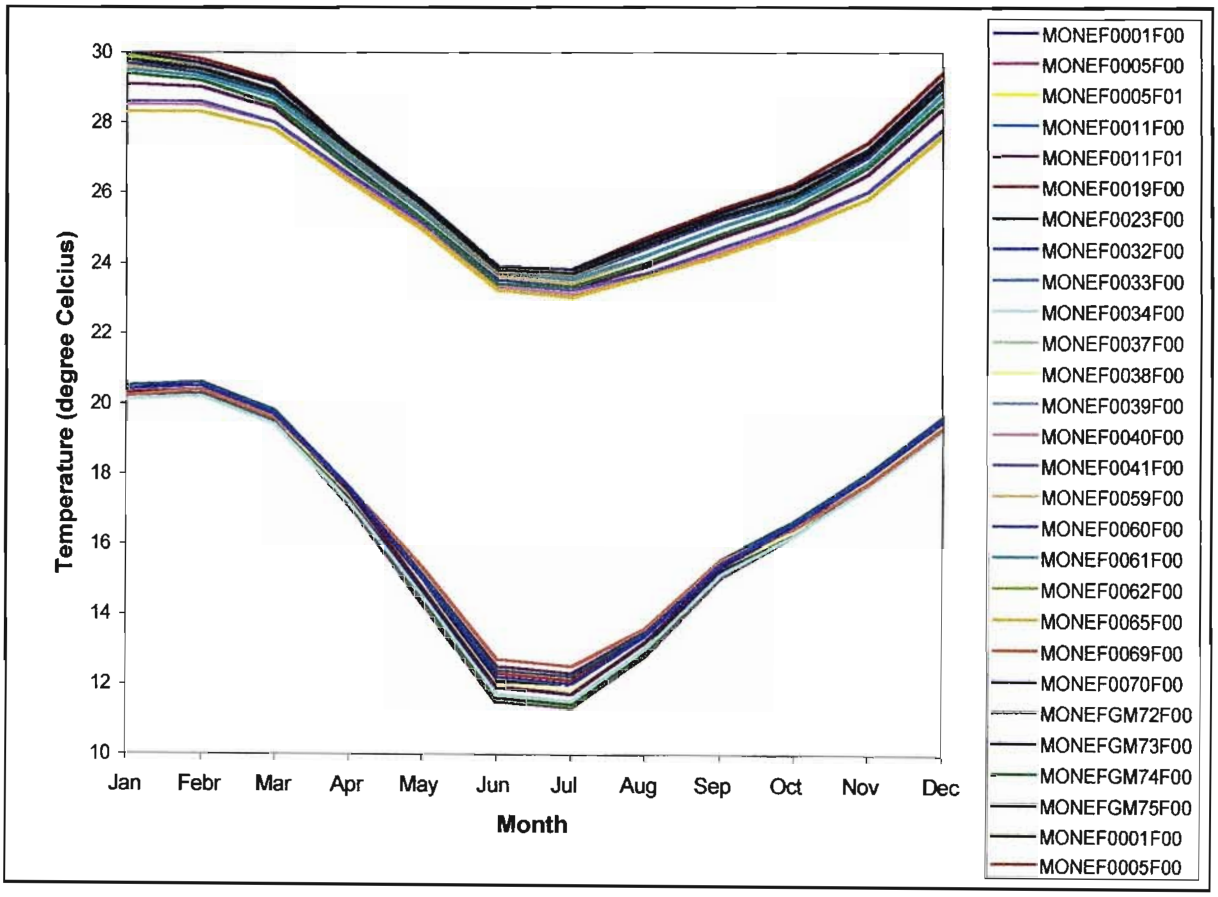


FIGURE 5. Mean monthly maximum and minimum temperatures per PSP in degrees Celsius.

Herbert (1998) describes a method whereby the maximum temperature for the hottest month (January) and the minimum temperature for the coldest month (July) are correlated with altitude to establish a prediction for any given point in the study area of interest. From the computer generated CCWR data, it is clear that there are relationships between distance from the coast and maximum and minimum temperatures, as defined in the statistically highly significant (P < 0,01) equations shown below:

$$Min.\,AT(^\circ C) = 17{,}0978 - (0{,}039798 * Altitude(m))[n = 38; r = 0.95] \quad \ldots\ldots\ldots\ldots 13$$

and

$$Max.\,AT(^\circ C) = 25{,}9924 + (0{,}043964 * Altitude(m))[n = 38; r = 0.90] \quad \ldots\ldots\ldots\ldots 14$$

These equations are useful for estimating temperatures at any point in the study area, and may be used to determine the optimum limits of tree species and hybrid genotypes for compartments in the Kwambonambi area (Herbert, 1998).

Potential evapotranspiration

Potential evaporation can be considered as the equivalent of evaporation from an open pan. The University of Natal DAE's A-pan evaporation model has proven to be relatively accurate across a wide range of sites (Schulze, 1997; Herbert, 1998). Estimated values for each PSP are included in Appendix 9 and in Figure 6.

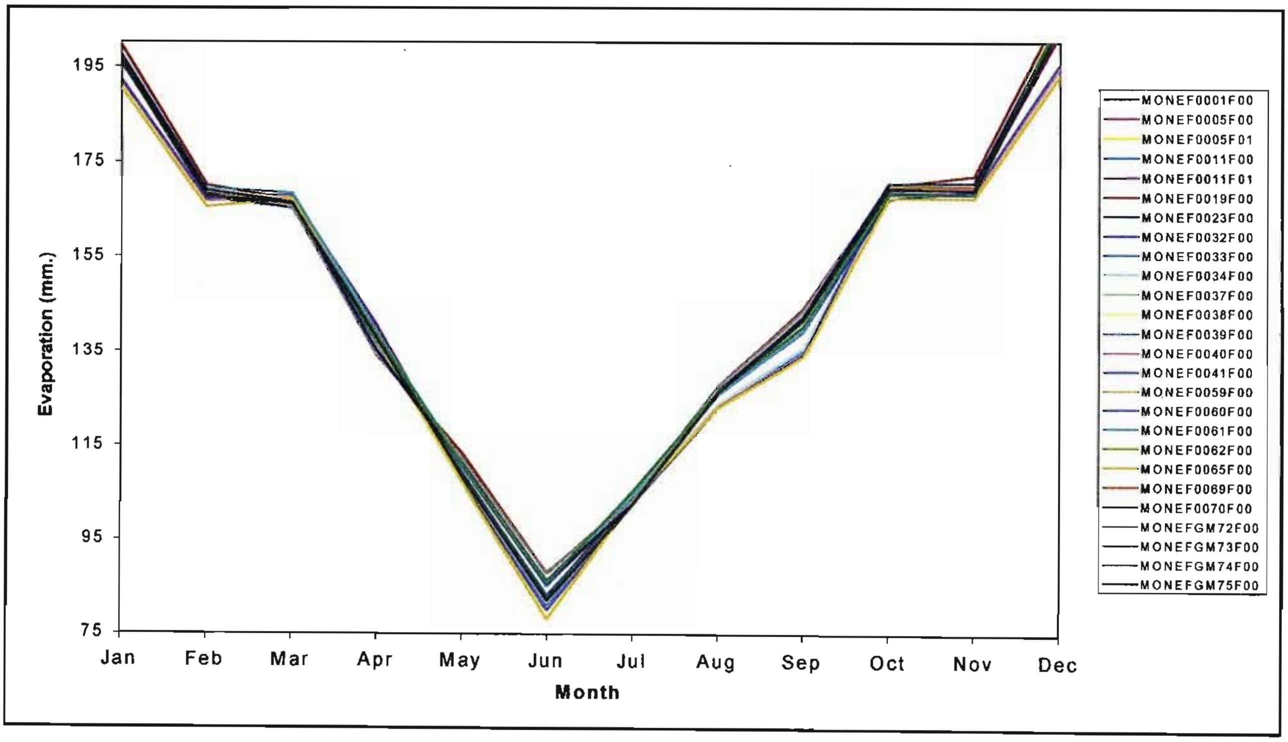


FIGURE 6. Mean monthly A-pan evaporation (mm).

It is clear that evaporation peaks in December- January at 185 – 206 mm per month, and reaches a low of 78 mm per month in June of every year. Two other features are notable, viz. an upturn in March and again in October. These might be due to a loss of cloud cover in late summer, which leads to greater radiation and hot berg winds in spring which cause evaporation to increase. It can be noticed in Figure 6 that an increase of evaporation towards the coast is present, although very small in value. While coastal humidity may be higher, there is also a prevailing wind present on almost a daily basis closer to the coast line. By implication, sites that are exposed to wind on the Zululand coastal plain are more likely to have higher rates of evaporation that sheltered sites.

Effective precipitation and water balance

Lang (1926) used the ratio of MAP to MAT to determine the suitability of climate for temperate forestry, known as the Lang's Climatic Index (LCI) and expressed as follows:

$$LCI(mm/{}^\circ C) = MAP(mm) / MAT({}^\circ C) \qquad 15$$

Schönau (1969) found a highly significant correlation between LCI and Site Index (SI) for black wattle and, similarly to Lang (1926) considered 50 mm/°C to be a general minimum value for commercially viable forestry. In the recent past the use of LCI has proven to be most useful and relative to MAI it constitutes a measure of effectiveness of rainfall in supplying in the plants' requirements (Herbert, 1998).

It can be argued from general observation that trees growing in cooler climates require comparatively less rainfall than those in warmer climates, through less evapotranspiration and greater water storage. Warm sites, although allowing for potentially high rates of physiological activity and growth rate, require a high and well distributed rainfall if drought stress is to be avoided. LCI should therefore be refined to monthly ratios in order to take some seasonal fluctuations into consideration (Herbert, 1997, 1998).

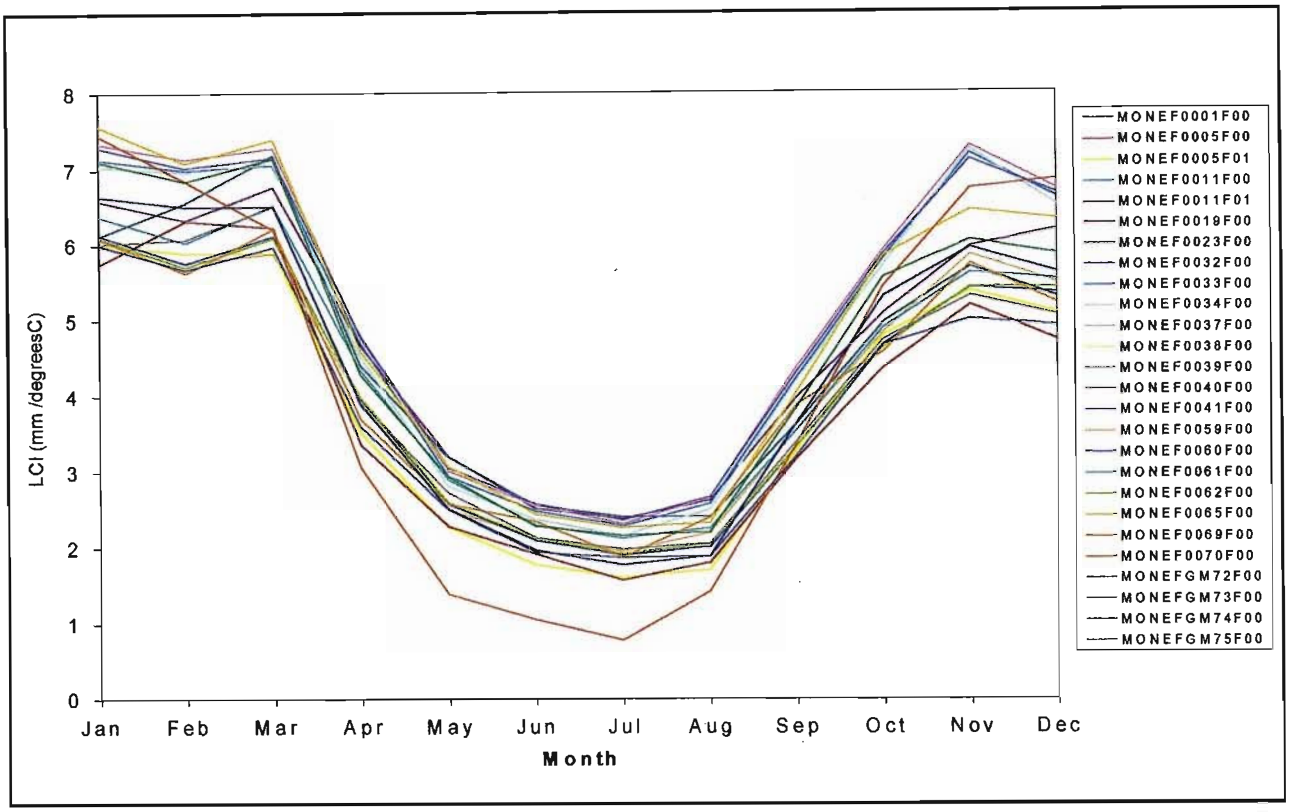


FIGURE 7. Effective monthly Langs Climatic Index.

The monthly ratio of MAP to MAT for every PSP is given in Figure 7. From this figure it can be observed that PSP number 69 has the highest effective precipitation and PSP number 70 has the lowest effective precipitation throughout the year. Herbert (1998) suggested maximum growth can take place when an equivalent of 65 LCI mm/°C per annum is achieved and also that minimal growth takes place when LCI is estimated to be 38 mm/°C or less per annum. From Figure 7 it can be seen that a very low monthly LCI is prevalent during April to September and growth probably only takes place when there is sufficient ground water or water from a saprolitic aquifer available.

When the Potential Evapotranspiration (PET) is compared with the monthly rainfall data for every plot, the water balance is studied. It either indicates a deficit for a given period or a surplus. Such a comparison is shown in Figure 8. On average PET exceeds precipitation each month of the year with the deficit being the greatest between August and January, and with the peak being in December.

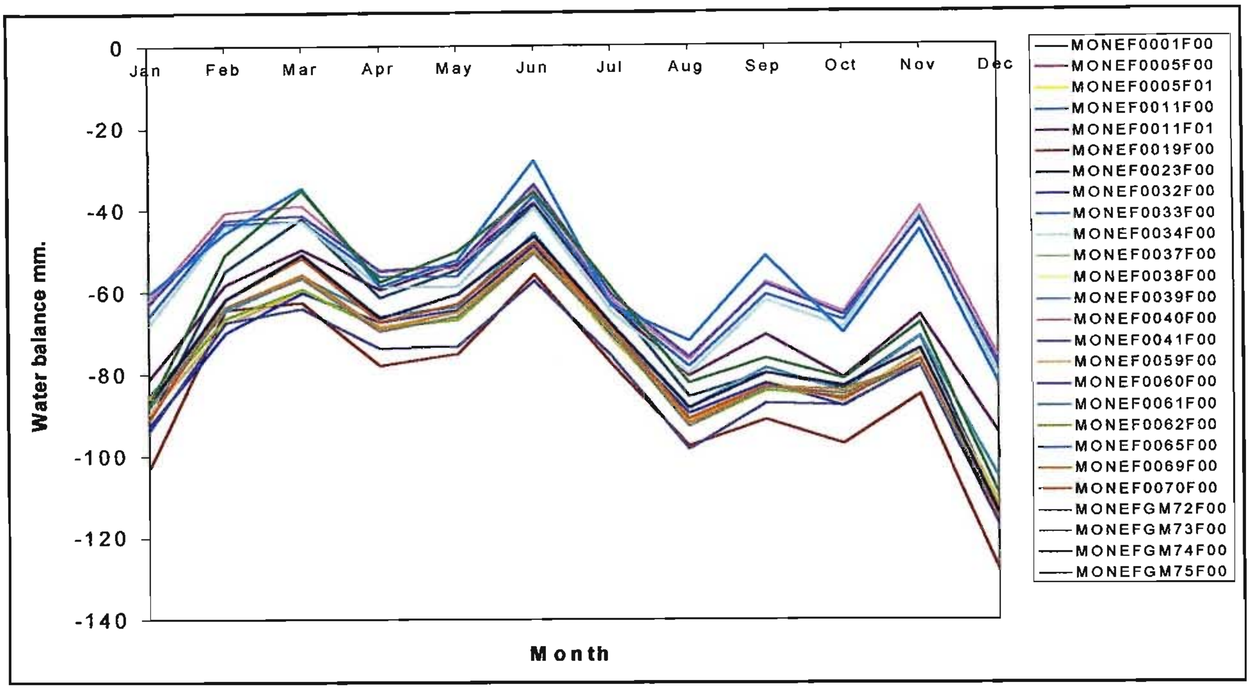


FIGURE 8. Monthly water balance.

The deficit for PSP19 is the greatest (1015 mm) and the least for PSPs 39 & 40 (664 mm). It constitutes a variance of 351 mm or 34% in potential water storage ability for the particular site. For December and January the deficit is quite high and growth can be affected negatively particularly on low clay soils, or soils with no intermediate water supply. In particular newly planted seedlings can suffer under these conditions, which may not only be the result of the water deficiency, but also due to high temperatures in Zululand during these months.

The effect of drought, available water and particularly the turning point in conditions making soils suitable for afforestation, using percentage survival, can be studied using the Palmer drought models (Anon, 1985; Zwolinski, 1997). The Palmer Drought Severity Index (PDSI) is a meteorological drought index, which reflects weather changes on a monthly basis. The one contradictory outcome of this index is that when the weather changes from dry to normal, the meteorological drought ends immediately, despite the fact that the soils moisture and the reservoirs or rivers may still be significantly lower than normal levels. This shortcoming has led to the development of the Palmer Hydrological Drought Index (PHDI) which reflects the water availability to the plant in a better way and is being used more often in the agricultural sector.

Zwolinski (1997) made use of nine consecutive planting seasons' data from the USA, indicating how the PDSI and PHDI can be used to explain 73% of the variation in the survival of plantation trees. It is further indicated that PHDI can facilitate operational decisions to improve the phasing of planting when high mortality is expected due to poor hydrological conditions. Preventative action may be taken when PHDI indicates dry conditions. These actions could include better quality planting stock, deep planting, planting with water and/or superabsorbents. Under extreme shortage of water planting should be stopped. This action can take place when the monthly water balance, as discussed and indicated in Figure 8, is also taken into account.

CHAPTER FIVE
DATA ANALYSIS

5.1 Selection of Variables

In this section the variables and data accumulated for growth - site monitoring are discussed and evaluated. A correlation analysis precedes further analyses to aid in selecting the relevant variables.

The dependent variables selected for this study are site productivity orientated, expressed mainly by SI_5 (m) and MAI (m^3/ha/yr).

The independent variables can be classed into four distinct groups:

a. continuous variables measured at enumeration as descriptors of tree growth e.g. DBH,
b. derived variables, also describing tree growth e.g. HTOP which is calculated as the regression height of the 20% largest diameter trees,
c. environmental variables, measured or derived from e.g. A-pan evaporation, MAT, MAP and heat units, and
d. categorical or "dummy" variables, which assume the dichotomous form in an analysis that have the ability to default a model to a pre-selected value if certain conditions are met.

The next section is a discussion of the variables used in the analysis and some of their characteristics and the reasons for their inclusion are revealed.

Aspect is included in the study as a variable to describe the orientation of slope, as a part of the topography for the Zululand coastal area. Taking that North represents 0°, in each PSP, the aspect as an indicator of the expected moisture and temperature gradients associated with the PSP and associated yield were measured. Slope was also measured but not included because of the generally flat terrain.

Heat units expressed as "degree days", were calculated for every PSP. The threshold limit for growth was set at 10 °Celsius. No upper limit for temperature was set and it was assumed that trees in Zululand grow optimally at all temperatures higher than 10° Celsius.

Latitude, longitude and altitude as measured variables were included in the analysis because of their discriminate ability to describe the relative position of each PSP from a geographical point of view.

Measured variables such as age, top height, effective rooting depth, soil form, clay percentage in the sub-soil, organic carbon content in the top soil, distance from the coast and estimated or modelled parameters such as TAW, MAP, MAT, monthly mean maxima and minima, LCI, estimated A-pan evaporation, were all included in the analysis.

5.2 Descriptive Data Statistics

All the independent variables collected in this study were included in a PROC Univariate (SAS Institute Inc., 2000) analysis for producing the descriptive statistics and testing of the data for normality. Tests for normality are particularly important because the commonly used capability indices are difficult to interpret unless the data are at least approximately normally distributed (Snedecor and Cochran, 1980). Most parametric tests assume an underlying normal distribution for the population of data analysed. If the data do not meet the normality criteria, it is recommended to use nonparametric analysis.

The Kolmogorov-Smirnov test was used to test the distribution of the data around normality (Snedecor and Cochran, 1980; Van Laar, 1991). The Kolmogorov-Smirnov statistic measures the maximum deviation of the Empirical Distribution Function (EDF) within the classes from the pooled EDF. This deviation serves as an indication of the distribution around the mean representing the normality of the distribution. Most of the variables used for analysis in this study were found to be normally distributed and thus fit for inclusion in further analyses.

Shown in Table 12 are descriptive statistics for variables used in this study.

TABLE 12. Descriptive statistics for explanatory variables used in this study.

Variable	Mean	Minimum	Maximum	Std Deviation	Kolmogorov -Smirnov	Probability
ASPECT (°)	157	0	330	116	0,14296	>0,1500*
HEAT_UNITS	4162	3832	4300	107,33	0,229102	<0,0100
LAT (dms)	28°46'76"	28°31'15"	29°02'24"	15'16"	0,237565	<0,0100
LONG (dms)	31°80'07"	31°39'40"	32°11'25"	30'72"	0,331754	<0,0100
ALTITUDE (m)	56	16	102	26,67	0,110077	>0,1500*
AGE (yr)	6,28	1,88	9,27	1,51	0,188601	0,0182
HTOP (m)	24,65	18,20	31,50	2,93	0,121495	>0,1500*
ERD (cm)	151	151	151	.	.	.
TAW (mm)	149,8	116,0	164,0	13,75	0,268888	<0,0100
MAP (mm)	1158	1015	1295	106,89	0,151026	0,1287*
MAT (°C)	21,40	21,00	21,80	0,24	0,229133	<0,0100
Jan_max (°C)	29,26	28,30	30,10	0,61	0,210077	<0,0100
A_PAN (mm)	1769	1734	1797	17,56	0,203923	<0,0100
CLAY_PERC_SUB (%)	22,57	5,00	45,00	16,00	0,207212	<0,0100
LCI (mm/°C)	54,14	46,65	61,37	5,50	0,163182	0,0746*
OC_PERC (%)	0,45	0,25	0,90	0,15	0,117262	>0,1500*
DISTANCE (m)	10290	723	18813	6722	0,195024	0,0119

*significant at 95% level

From Table 12 it is evident that the variables such as aspect, altitude, age, top height, MAP, LCI and organic carbon content in the top soil, are normally distributed and can be used and analysed by applying parametric statistics. It is further noted that ERD cannot be used in any analysis since soil depth was measured only to 1,5 m, and no differences in ERD could be defined.

5.3 Correlation Analysis

A correlation matrix was drawn up between all the input variables (Table 13). The Pearson Correlation Coefficient (r) was used to calculate the correlations (SAS Institute Inc., 2000). Correlation measures the strength of the linear relationship between two variables, the correlation coefficient is a numerical measure that quantifies the strength of linear relationships (Van Laar, 1991). A correlation of 0 means that there is no linear association between two variables. A correlation of 1 (-1) means that there is an exact positive (negative) linear association between the two variables. From the latter, a high value of the correlation coefficient implies a high degree of linear association between two variables, but does not necessarily mean that a causal relationship exists between these variables, since both might be related to a third variable.

It is appropriate here to explain the basic difference that exists between regression analysis and correlation analysis. These two techniques are closely related with one essential difference. Regression analysis assumes that the independent variable (X) is fixed and measured without error and that the dependent variable (Y) is expressed as a linear relationship with predictor variables X_1, X_2 .... X_n. On the other hand, correlation analysis assumes that the two variables involved have a joint, bivariate normal distribution, which leads to a linear relationship between the two variables. Regression analysis' goal is to predict Y from X_1, X_2 .... X_n, while the correlation analysis quantifies the degree of association between X_i and X_j (Van Laar, 1991).

In the two-variable regression analysis, the total sum of squares of Y is partitioned into a regression component and a component expressing unexplained variance. The regression sum of squares, when calculated as a fraction of the total sum of squares, reveals the proportion of the variance of Y, explained by X. When this proportion is high, it is concluded that X is a good predictor variable. This cannot occur unless X and Y are closely associated (correlated) (Van Laar, 1991) .

The degree of association between two random variables, X_1 and X_2, is numerically expressed as Pearson's dimensionless product-moment correlation coefficient (r). This association between random variables selected for this study is shown in Table 13.

The purpose of the correlation analysis is mainly to define variables which correlate with tree growth variables for parameter selection, also to identify those independent variables that could be used in regression analysis for the construction of site prediction growth models.

TABLE 13. Matrix showing Pearson's correlation coefficients (r), as well as the probability values (p) for the variables in this study.

	Aspect	Heat_U	Lat.	Long.	Altitude	Age	HTOP	TAW	MAP	MAT	A_Pan	Clay%	LCI	OC%	Distance
Aspect	1,0000	0,0553 0,7883	0,0303 0,8830	0,0808 0,6945	-0,3047 0,1301	-0,1455 0,4780	0,0157 0,9392	0,4139 0,0355	-0,0267 0,8967	0,0109 0,9577	-0,0632 0,7587	-0,2659 0,1891	-0,0247 0,9047	0,0036 0,9858	-0,2069 0,3105
Heat_ Units	0,0553 0,7883	1,0000	-0,9434 <0,0001	0,8791 <0,0001	0,08791 0,6693	-0,2809 0,1645	0,1311 0,5230	0,5231 0,0061	0,7105 <0,0001	0,9418 <0,0001	0,8831 <0,0001	-0,5733 0,0022	-0,7540 <0,0001	0,4066 0,0392	0,7211 <0,0001
Lat.	0,0303 0,8830	-0,9434 <0,0001	1,0000	-0,8074 <0,0001	-0,30566 0,1289	0,2412 0,2351	-0,1102 0,5920	-0,4654 0,0166	0,7084 <0,0001	-0,8204 <0,0001	-0,8784 <0,0001	0,4266 0,0297	0,7386 <0,0001	-0,4154 0,0348	-0,7707 <0,0001
Long.	0,0808 0,6945	0,87913 <0,0001	-0,8074 <0,0001	1,0000	0,3401 0,0891	-0,4316 0,0277	0,1667 0,4157	0,4229 0,0314	-0,8680 <0,0001	0,9458 <0,0001	0,8929 <0,0001	-0,4992 0,0094	-0,8975 <0,0001	0,5129 0,0074	0,7850 <0,0001
Altitude	-0,3047 0,1301	0,0879 0,6693	-0,3056 0,1289	0,3401 0,0891	1,0000	-0,3145 0,1176	-0,0805 0,6958	-0,2280 0,2625	-0,5736 0,0022	0,1272 0,5355	0,4174 0,0338	0,2931 0,1461	-0,5363 0,0047	0,3551 0,0750	0,6276 0,0006
Age	-0,1455 0,4780	-0,2809 0,1645	0,2412 0,2351	-0,43160 0,0277	-0,3145 0,1176	1,0000	0,4670 0,0162	-0,1645 0,4217	0,4900 0,0111	-0,3891 0,0494	-0,4674 0,0161	0,3005 0,1358	0,4914 0,0108	-0,4455 0,0225	-0,5792 0,0019
HTOP	0,0157 0,9392	0,1311 0,5230	-0,1102 0,5920	0,1667 0,4157	-0,0805 0,6958	0,4670 0,0162	1,0000	0,1472 0,4728	-0,0053 0,9793	0,1162 0,5716	-0,0124 0,9517	-0,0932 0,6504	-0,0190 0,9262	0,4120 0,0365	-0,1226 0,5505
TAW	0,4139 0,0355	0,5231 0,0061	-0,4654 0,0166	0,4229 0,0314	-0,2280 0,2625	-0,1646 0,4217	0,1472 0,4728	1,0000	-0,1745 0,3939	0,4023 0,0416	0,2662 0,1886	0,8259 <0,0001	-0,2076 0,3088	0,2456 0,2264	0,1051 0,6091
MAP	-0,0267 0,8967	-0,7105 <0,0001	0,7084 <0,0001	0,8680 <0,0001	0,5736 0,0022	0,4900 0,0111	-0,0053 0,9793	-0,1754 0,3939	1,0000	-0,7838 <0,0001	-0,9090 <0,0001	0,2688 0,1842	0,9973 <0,0001	-0,4915 0,0108	-0,8945 <0,0001
MAT	0,0109 0,9577	0,9418 <0,0001	-0,8204 <0,0001	0,94580 <0,0001	0,1272 0,5355	-0,3891 0,0494	0,1162 0,5716	0,4023 0,0416	-0,7838 <0,0001	1,0000	0,8872 <0,0001	-0,5549 0,0033	-0,8268 <0,0001	0,4527 0,0202	0,7514 <0,0001
A_Pan	-0,0632 0,7587	0,8831 <0,0001	-0,8784 <0,0001	0,8929 <0,0001	0,4174 0,0338	-0,4674 0,0161	-0,0124 0,9517	0,2662 0,1886	-0,9090 <0,0001	0,8872 <0,0001	1,0000	-0,3901 0,0488	-0,9277 <0,0001	0,4818 0,0127	0,9341 <0,0001
Clay%_ Sub_Soil	-0,2659 0,1891	-0,5733 0,0022	0,4266 0,0297	-0,4992 0,0094	0,2931 0,1461	0,3005 0,1358	-0,0932 0,6504	0,8259 <0,0001	0,2688 0,1842	-0,5549 0,0033	-0,3901 0,0488	1,0000	0,3104 0,1227	-0,3320 0,0975	-0,2446 0,2284
LCI	-0,0247 0,9047	-0,75404 <0,0001	0,73864 <0,0001	-0,8975 <0,0001	-0,5363 0,0047	0,4914 0,0108	-0,0190 0,9262	-0,2076 0,3088	0,9973 <0,0001	-0,8268 <0,0001	-0,9277 <0,0001	0,3104 0,1227	1,0000	-0,5008 0,0091	-0,8994 <0,0001
OC%	0,0036 0,9858	0,4066 0,0392	-0,4154 0,0348	0,5129 0,0074	0,3551 0,0750	-0,4455 0,0225	0,4120 0,0365	0,2456 0,2264	-0,4915 0,0108	0,4527 0,0202	0,4818 0,0127	-0,3320 0,0975	-0,5008 0,0091	1,0000	0,5416 0,0043
Distance	-0,2069 0,3105	0,7211 <0,0001	-0,7706 <0,0001	0,78503 <0,0001	0,6276 0,0006	-0,5792 0,0019	-0,1226 0,5505	0,1052 0,6091	-0,8945 <0,0001	0,7514 <0,0001	0,9341 <0,0001	-0,2446 0,2284	-0,8994 <0,0001	0,5416 0,0043	1,0000

The following conclusions were derived from the correlation analysis:

a. Aspect is not significantly correlated with any of the variables. The terrain in Zululand is flat and the influence that aspect might have elsewhere, is negligible under these conditions.

b. HEAT_UNITS as a variable is strongly correlated with latitude, longitude, MAP, MAT, A_PAN, LCI, DISTANCE from the coastline and TAW. HEAT_UNITS are derived from MAT and this correlation can be expected, similarly HEAT_UNITS are associated with LCI. As expected, HEAT_UNITS are also closely correlated with distance from the coast which implies that there are more heat units further from the coast, but it is also understood from Table 13 that DISTANCE is negatively correlated with MAP implying that it is dryer further away from the coast (less clouds). The effect of this correlation is that growth conditions are more favourable closer to the seaboard.

c. HTOP is significantly correlated with organic carbon content (OC%). The higher the organic carbon content, the higher the HTOP. This correlation fact is researched later on in this thesis in more detail, and it was described in earlier studies by Noble *et al.* (1991).

d. Total available water is significantly correlated with MAT and clay content in the sub-soil. TAW is as expected strongly correlated with clay content in the sub-soil, which implies that higher clay levels hold more water in the soil profile. It is known for the sandy Zululand soils that water drains through the profile quickly, but from the geology study earlier in this document it is evident, that the lithology gives rise to perched water tables due to clay pans, and that there are deep aquifers from which water is extracted. Therefore the available water in the soil profile can also be associated with other factors like humus and the presence of other organic components.

e. MAP is significantly correlated with latitude and longitude ($p<0,05$). From the correlation analysis for variables DISTANCE and LONGITUDE, it is clear that the more western locations are the dryer sites. It is also shown that MAP is positively correlated with latitude, which implies that it becomes dryer if one moves from south (Port Durnford) to north (Teza, Nyalazi).

f. MAT is also significantly correlated with latitude and longitude. Moving away from the coastline and further north, it gradually becomes warmer. It is interesting to note that MAT is negatively correlated ($p<0,05$) with MAP, in other words, it is slightly wetter where it is cooler, which along the coast is due to ocean mist and the influence of cyclonic weather systems that frequent this area. It is also dryer in areas where it is generally hotter.

g. A-pan evaporation (A_PAN) is negatively correlated ($p<0,05$) with latitude and positively correlated with longitude. Generally where there is more moisture available closer to the sea. Conversely, where there are prevailing winds and high temperature, the evaporation will be higher.

h. Clay content is correlated with latitude (more clay in the southern end of the study area and *vica versa*) and for this study positively correlated with longitude, which means more clay is found to the east than the west. These correlations however are poor ($r < 0,5$).

i. Organic carbon content (OC%) in the top-soil is negatively correlated with MAP ($r < 0,5$) which implies higher OC% occurs on the slightly dryer sites. This is a bit surprising, as it is generally assumed that higher organic carbon contents are found on the wetter sites. Also, OC% seems to be slightly higher where sites are warmer.

In a small sample area, correlations may appear to be contradictory due to small variances in the data, but when seen in a bigger context, they are normally logical. By using a larger data- set, or a stratified sampling technique for specific variables such as organic carbon %, a different picture for the correlation statistics could have emerged. From the above correlation analyses, variables were identified for use in regression analyses for the explanation of the dependent variables.

CHAPTER SIX
MODEL CONSTRUCTION

Constructing a growth model is not easy, even if suitable data are available (Vanclay, 1994). Before any model is constructed it is important to clarify a few questions such as what the model will be used for, what inputs and outputs will be required, the data available to fit the model and the resources available to construct, test and implement the model.

There are many techniques available for fitting equations to data, and the appropriate one to use depends on the relationships chosen to represent the system, the nature of the data, and on the resources available to fit the model. There may be only one guideline that holds for many approaches and that is to plot the data, the fitted model and the residuals, and to compare them. The data were already described and briefly examined in Chapter 4, section 4.4.1 (mensuration data), and plotted with the IDV tool.

Regression analysis and analysis of variance were used the further analyses of the data. Following is a short introduction to further the understanding of these techniques.

Linear regression techniques imply that explanatory variables enter the objective function in a linear or additive way (i.e. $\hat{Y} = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots\ldots \beta_j X_j$). It does not imply however, that the resulting relationships are straight lines. This form of regression is widely used for fitting equations to data.

Non-linear regression on the other hand is used to fit models where the estimated parameters do not enter the model in a linear additive manner. A typical forestry example is the Chapman-Richards equation. Typically these models have associated asymptotic values, like the height growth of trees, which increases to a certain top limit, known as the asymptote. While non-linear regression allows for great flexibility in formulating models to ensure sensible extrapolation, it does have limitations. One problem is that, unlike linear regression, non-linear regression does not necessarily provide an unique best unbiased solution for a given set of variables. Non-linear solutions are determined iteratively, and may be influenced by the estimation method and the starting conditions specified by the user. Reparameterisation is a technique used in non-linear regression to redefine variables with other variables in order to linearise the equation as much as possible (Van Laar, 1991; Vanclay, 1994).

There are certain statistical assumptions underlying the concept of regression analysis (Snedecor and Cochran, 1980). Linear regression and other least square methods, such as non-linear regression, are normally robust enough to give good estimates of the chosen dependent variable. It is important to understand the assumptions implicit in the method to realise the consequences of breaking the "rules". Linear regression assumes that the dependent (response) variable (Y) can be predicted from the independent (explanatory) variable (X) with an element of error (ε) which reflects natural variation and factors not included in the model. It is about this error (ε), that the managing of regression technique centres. The underlying assumptions are:

a. the errors are independently and identically normally distributed with zero mean and constant variance,
b. the errors are assumed to have identical distribution,
c. outliers are observations that deviate greatly from the mean or trend and may have a big influence on the least square methodology, but may not be deleted from the data set unless solid ground exists for doing so,
d. the explanatory variables are assumed to be independent (Snedecor and Cochran, 1980).

If two or more variables are correlated, multi-collinearity may exist which may lead to numerical problems in parameter estimation. The absolute value of the estimated parameters may be too large, the sign may be wrong, and parameter estimates may change substantially after the addition or omission of a single data point (Van Laar, 1991). The tolerance level is 1- R^2 for the regression of a particular independent variable on all the other independent variables, ignoring the dependent variable, is an indication of the correlation between independent variables in the model and should be as far removed from 1,0 as possible. This test for multi-collinearity was carried out throughout this analysis.

The aim of model building is to achieve a high R^2 and low SE, matching predicted to measured SI_5 or MAI as closely as possible by using the smallest number of easily measured, readily comprehendible, independent variables. A regression model should preferably contain only those variables with the highest possible level of significance. Significance levels ranging from 10% – 25% are often used as exclusion criterion in regression models in preference to standard significance levels of 1% to 5% (Schutz, 1990). Deciding which significance level to use therefore involves a compromise between including meaningful explanatory variables and increasing the Type I error of the model. For this study a 5% significance level was used.

In this section regression models are presented, showing the regression coefficients, their standard deviations, the t-values of the regression coefficients and significance levels. The coefficient of multiple determination (R^2) and standard error of estimate (SE) for the models are also shown.

6.1 Site Index Model

As indicated earlier in this study, height attained by trees referenced at a specific age is a good indicator of the productivity of a stand. Height growth from the 26 PSPs were modelled with age by using the Chapman-Richards 3-parameter equation (Brickell, 1969), to represent a height-age relationship. For each PSP then, height was calculated at 5 years, as the site index (SI_5).

Finally, SI_5 was identified as the response, or dependent variable that was modelled by explaining the variance with independent site variables.

For non-linear regression models, the Taylor linearisation method, the method of the steepest descent and Marquardt's method to estimate the parameters are used most frequently (Van Laar, 1991; Vanclay, 1994). PROC NLIN (SAS Institute Inc., 2000) was used to model SI_5 making use of the Marquardt algorithm (Marquardt, 1963). Marquardt's method is equivalent to performing a series of ridge regressions and is useful when the parameter estimates are highly correlated or the objective function is not well approximated by a quadratic (SAS Institute Inc., 2000).

Often, in non-linear functions the difficulty arises not because of non-linearity in the predictor variables, but because of non-linearity in one or more of the parameters such as: α, β, γ (Snedecor and Cochran, 1980).

The PROC NLIN method does not always converge successfully for a given set of data, particularly if the starting values for the parameters are not close to the least-squares estimates. The delta, or starting value for the 3-parameter Chapman-Richards equation selected for this study was fixed at 75 m (Kotze, 2000), which is believed to be the absolute maximum height growth for trees in Zululand and also the highest asymptotic value that height growth can assume under the given conditions. Fitting non-linear equations is an iterative process, and in this study the maximum iterations allowed for the statistical fit was 500.

Each point of measurement was regarded as an observation, with HTOP as the variable dependent on age. HTOP was calculated to present the 20% largest DBH at the age of measurement, based on the relationship of height and diameter defined earlier in this document.

The 3-parameter Chapman-Richards equation was used as the non-linear function fitted with PROC NLIN.

$$HTOP = \beta_0 \left[1 - e^{(\beta_1(Age))}\right]^{\beta_2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 16$$

Summary of the statistics for fitting a HTOP – Age relationship for every PSP is presented in Table 14.

TABLE 14. Fit statistics for top height (HTOP) and Age relationship for 26 permanent sample plots and modelled SI_5 for each plot.

Note: B_0 is 75,0 in all cases.

Plot number	B_1	B_2	Number Obs.	F-Value	Probability	R^2	SI_5
01F00	-0,0407	0,6992	10	1739,77	<0,0001	69,58	22,97
05F00	-0,0245	0,6301	4	1203,41	0,0008	90,75	19,22
05F01	-0,0527	0,9060	3	1497,10	0,0183	98,68	19,93
11F00	-0,0366	0,6804	4	1192,22	0,0008	93,55	22,21
11F01	-0,0350	0,7121	3	21864,6	0,0048	99,94	20,38
19F00	-0,00715	0,4040	13	4504,17	<0,0001	92,03	19,38
23F00	-0,0183	0,5546	7	8129,93	<0,0001	99,15	19,41
32F00	-0,00591	0,3621	9	1457,95	<0,0001	88,40	20,84
33F00	-0,0175	0,5770	7	7660,72	<0,0001	98,98	17,93
34F00	-0,0256	0,6496	7	4634,29	<0,0001	98,71	18,93
37F00	-0,0204	0,5944	6	1721,68	<0,0001	96,87	18,73
38F00	-0,0113	0,5230	13	13954,2	<0,0001	98,06	16,44
39F00	-0,0172	0,5863	6	8821,80	<0,0001	99,19	16,92
40F00	-0,0199	0,6359	6	2014,76	<0,0001	97,09	16,75
41F00	-0,0178	0,5519	6	1341,63	<0,0001	95,95	19,25
59F00	-0,0536	0,9212	4	7912,61	<0,0001	99,74	19,76
60F00	-0,0631	0,7694	4	62910,5	<0,0001	99,96	27,43
61F00	-0,0772	1,0467	4	1323,11	0,0008	98,94	22,77
62F00	-0,0744	1,0307	4	1049,85	0,0010	98,64	22,47
65F00	-0,0391	0,7289	4	1302,88	0,0008	98,14	21,27
69F00	-0,0501	0,7749	4	329,54	0,0030	93,04	23,33
70F00	-0,0597	0,8370	3	635,88	0,0280	96,17	24,13
GM72F00	-0,0794	1,1689	36	9384,63	<0,0001	97,08	20,35
GM73F00	-0,0437	0,6750	36	5022,81	<0,0001	89,03	24,98
GM74F00	-0,0690	0,9211	35	6104,64	<0,0001	94,17	24,11
GM75F00	-0,0908	1,1344	36	9379,69	<0,0001	96,09	23,90

From Table 14 it is evident that all the PSPs submitted in the study have met the convergence criterion and that the F-statistic and R^2 -values are sufficiently large to accept the Chapman-Richards 3-parameter model as fitting the data sufficiently well. The modelled top height development over age for each of the PSPs is shown in Figure

9. Figure 9 shows that more than one grouping of HTOP curves are present. These are potentially site differences between PSPs and will be tested for later on in this study.

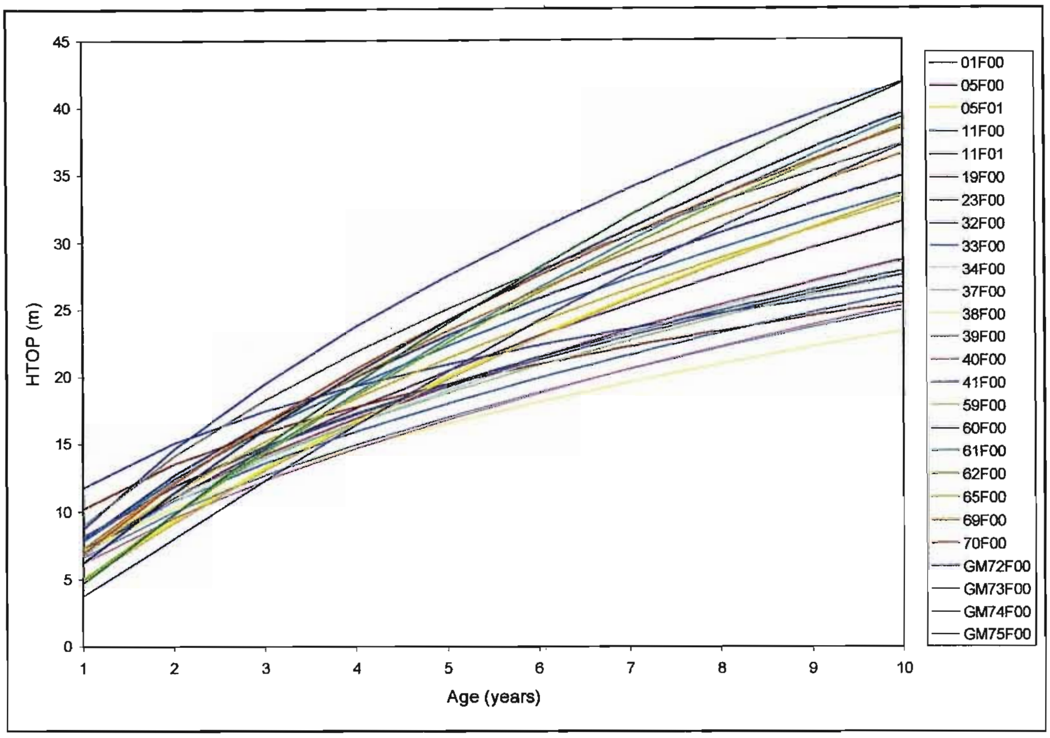


Figure 9. Modelled HTOP development with age for each PSP.

Similarly to the height–age relationship models developed for every single PSP, a pooled model, using all the plot data (26 plots, 278 observations in total) and covering the complete study area, was developed. Given below are the fit statistics for the POOLED model:

TABLE 15. Statistics for the POOLED-model for HTOP over age fitting the Chapman-Richards equation.

Source	**DF**	**Sum of Squares**	**Mean Square**	**R^2**
Regression	2	97000,3966	485000,1983	64%
Residual	276	1917,9696	6,9491	
Uncorrected total (Corrected total)	278 277	98918,3662 5231,7381		
Parameter	**Estimate**	**Asymptotic Std Error**	**Asymptotic 95% Confidence Interval**	
			Lower	**Upper**
B1	-0,021348	0,0028956	-0,027049	-0,015648
B2	0,566102	0,0301809	0,506687	0,625516

The resultant equation for the study area is:

$$HTOP = 75,0 * \left[1 - e^{(-0,0213*(AGE))}\right]^{0,5661} \quad \ldots\ldots 17$$

The SI_5 for the whole study area was calculated to be 20,51 m, making use of Equation 17. A correlation matrix for each of the individual plot-models (Table 14) with site variables are shown in Table 16.

TABLE 16. Correlation coefficients (r) of SI_5 with site variables of the study area.

Variable	Aspect	Heat_Units	Latitude	Longitude	Altitude	TAW
r p	0,18048 n.s.	0,46837 *	-0,36333 n.s.	0,59765 **	0,10482 n.s.	0,37890 n.s.
MAP	**MAT**	**A_PAN**	**CLAY%_S**	**LCI**	**OC%**	**Distance**
-0,49282 **	0,56306 **	0,47925 **	-0,52999 **	-0,51419 **	0,70148 ***	0,45731 *

From Table 16 it can be seen that organic carbon content is highly correlated (r =0,7) with SI_5. This relationship indicates that a higher organic carbon content will give rise to a higher SI_5. The following variables were also found to be correlated with SI_5:

a. distance from the coastline has a positive influence on SI_5, which means the PSPs further away from the coast have higher SI_5. The correlation however is weak (r<0,5) and probably a result of the small variance in the data.

b. SI_5 is significantly (p<0,01), correlated with MAT (r<0,5). This indicates a higher SI_5 where MAT increases.

c. SI_5, is also significantly correlated with LCI and MAP. However the correlation coefficient is small (r<0,5) and negative. This does however, imply that higher SI_5 values are achieved where rainfall is lower. Not too much value should be attached to this occurrence because the hydrology is complex and water supply is not exclusively dependent on rainfall in Zululand.

6.1.1 Comparing the Zululand MMRC model to the "POOLED model" developed in this study

The question is asked whether this POOLED model differs significantly from the MMRC model developed specifically for the Zululand coastal zone (Kotze, 2000). It is important to understand the similarity or disparity between the two models for the sake of the MMRC high level site classification system (Kunz and Pallet, 2000) as an indicator of underlying variance within a particular zone. The consequence of this may have an impact on the forest planning system.

The significance of the POOLED model (Equation 17) and the HTOP – age relationship modelled by the MMRC (Kotze, 2000) is tested below. The fit statistics for the MMRC model (Kotze, 2000) is shown in Table 17, while a graphical comparison of the two models is given in Figure 10.

TABLE 17. Fit statistics for the MMRC model (Kotze, 2000).

Source	**DF**	**Sum of Squares**	**Mean Square**	**R^2**
Regression	2	218458,3886	109229,1943	78,9%
Residual	399	4148,7213	10,3978	
Uncorrected total	401	222607,1100		
(Corrected total)	400	19672,8536		
Parameter	**Estimate**	**Asymptotic Std Error**	**Asymptotic 95% Confidence Interval**	
			Lower	**Upper**
B1	-0,030791	0,001984	-0,026889	-0,034692
B2	0,66672	0,022611	0,622262	0,711168

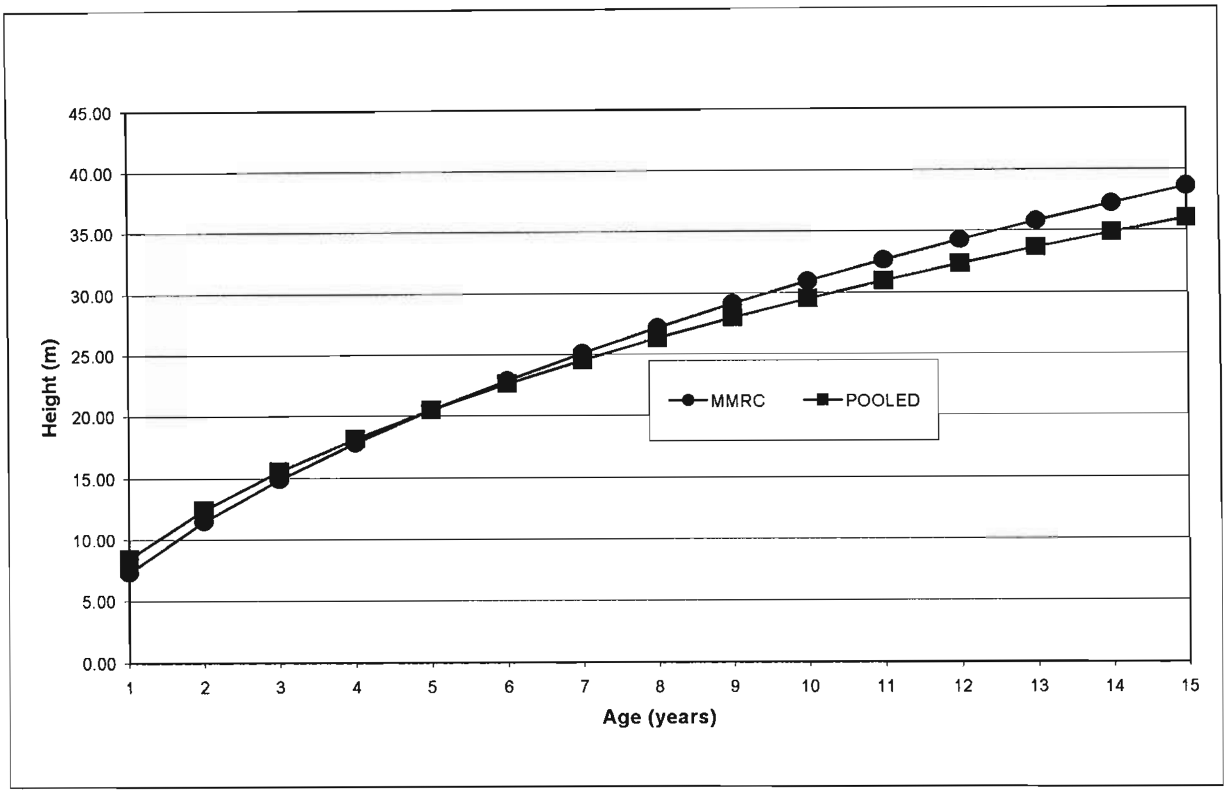


FIGURE 10. Graphical presentation of MMRC model vs. POOLED model for Zululand coast.

From figure 10, it seems that the POOLED model over-estimates in the early years with reference to the MMRC model and under-estimates in the later years.

In evaluating the results from more than one model for the same region or a model fitted to a subset of the data, the question arises as to whether the regression lines of the two models can be regarded as the same. Snedecor and Cochran (1980) suggested to test the hypothesis that the slopes and the deviations mean squares are homogenous. The significance of the deviations of the residual mean squares are tested below. The residual mean squares for the two models are shown in Table 18.

TABLE 18. Residual mean squares for MMRC and POOLED models.

	Deviations (residual) from regression		
	Df	**SS**	**MS**
MMRC	399	4148	10,40
POOLED	276	1917	6,95
TOTAL	675	6065	17,35

Both tests are discussed below as an analysis of the hypothesis.

a. The two-tailed F-test was used to compare the deviations of the residual mean squares denoted by σ_1^2, σ_2^2.

For this comparison:

$$H_0 : \sigma_1^2 = \sigma_2^2$$
$$H_{a1} : \sigma_1^2 \neq \sigma_2^2$$
$$H_{a2} : \sigma_1^1 > \sigma_2^2$$

Reject H_o if the observed F value (F_{obs}) exceeds the tabulated F value ($F_{0,05}$) for $a = \alpha$, $df_1 = n_1 - 1$, and $df_2 = n_2 - 1$

For this study F_{obs} =1,49 with df 399 and 276 respectively.

From the F-distribution table (Snedecor and Cochran, 1980) the F-distribution at the 5% alpha level is 1,26.

Thus,

$$F_{obs} > F_{tabular}$$

and the null hypothesis must be rejected. This implies that the two regression lines differ significantly at the 95% confidence level.

b. The alternative technique was also used to establish if two models were significantly different by comparing the numeric value of the β_1, β_2-parameter of the MMRC model (Kotze, 2000) and the POOLED model at the 95% confidence levels.

The population mean is a particularly informative measure of the central tendency of the observed variable if it is reported along with its confidence intervals. The confidence interval gives a range of values around the mean where the "true" mean is located with a given level of certainty and the variable is assumed to be normally distributed.

The respective parameters for the two models are as follows:

For the MMRC model: $\beta_0 = 75, \beta_1 = -0{,}030791, \beta_2 = 0{,}66672, n = 401$

For the POOLED model: $\beta_0 = 75, \beta_1 = -0{,}021348, \beta_2 = 0{,}566102, n = 278$

The confidence intervals for parameters based on the asymptotic normality of the parameter estimators were used for this comparison. The 95% confidence intervals for the MMRC model are:

$$\beta_1 : -0{,}0268 \leftrightarrow -0{,}03469$$
$$\beta_2 : 0{,}62226 \leftrightarrow 0{,}711168$$

The estimated β_1, β_2-parameters of the POOLED model fall outside of the 95% confidence intervals of the MMRC model, which in essence indicates that the two models are significantly different from one another.

A similar test procedure was performed for every PSP in the study for comparison with the POOLED model. In most cases no evidence was present to reject the null hypothesis of a different $\sigma_1^2, or \sigma_2^2$. From these tests it can be concluded that the individual PSP SI_5 models and the POOLED model do not differ significantly.

6.1.2 Predicting SI_5 with site variables.

PROC REG (SAS Institute Inc., 2000) selection method was used to regress SI_5 against any combination of 14 independent site variables included in the study. Although the R^2 value was apparently higher in some combinations, it showed numerous incidences of multicollinearity and in many cases a non-significant contribution to the model ($p>0,05$). Organic carbon content was so strongly affecting the regression analysis that a stepwise regression was also done with the exclusion of this variable.

Categorical ("dummy") variables were designed for the various soil forms and included in the analysis. Categorical variables such as soil colour or soil form are normally qualitative observations. In a regression analysis, categorical variables are re-coded in a number of separate dichotomous variables, which have the ability to be "switched on" or "switched off" when the regression is performed. The presence of the Fernwood soil form, together with organic carbon content significantly explained 60% variation of SI_5 (R^2= 0,5983) with significance at the 95% level and a low mean square error. However, it was decided that a continuous, quantitative variable would be more meaningful to include in the regression.

When a predictor variable X is nearly a linear combination of other predictor variables in the model, the affected estimates are unstable and have high standard errors. This problem is called *collinearity* or *multicollinearity* (Van Laar, 1991). For this multiple regression the multicollinearity was tested by using the tolerance statistic. It can be expected that multicollinearity is part of the model if the value is lower than 0,2. Multicollinearity is also associated with high error of estimates of regression coefficients, which makes the regression unstable. From Table 13, it can be seen that the correlation between organic carbon content and clay content in the sub-soil is -0,3320 and the probability is 0,0975. This also serves as an indication that multicollinearity is highly unlikely because of the weak correlation between these two predictor variables. When independent variables are correlated by a factor of 0,9 and higher, then they should not be used in the same regression of Y, because multicollinearity will almost certainly exist (Van Laar, 1991; SAS Institute Inc., 2000).

Organic carbon content in the top-soil in combination with the clay content in the sub-soil proved to be the two independent variables explaining most of the variance in SI_5 and contributing significantly to the model (Table 19). This observation confirms the findings of Noble *et al.* (1991).

TABLE 19. Statistics for site index (SI_5) fitted with site variables and parameter estimates.

Analysis of Variance					
Source	**DF**	**Sum of Squares**	**Mean Square**	**F-value**	**Pr>F**
Model	2	110,40476	55,20238	16,64	<0,0001
Error	23	76,31647	3,31811		
Corrected Total	25	174,72123			
	Root MSE	1,82157	R-square	0,6319	
	Dep. Mean	20,93653	Adj R-Sq	0,6157	
	Coeff. Var				

Parameter Estimates						
Variable	**DF**	**Parameter Estimate**	**Standard Error**	**T Value**	**Pr> t**	**Tolerance**
Intercept	1	17,40246	1,47404	11,81	<0,0001	
OC_PERC	1	10,71437	2,56365	4,18	0,0004	0,88978
CLAY_PERC_ SUB	1	-0,05702	0,02413	-2,36	0,0270	0,88978

The Kolmogorov-Smirnov test was applied on the residuals to test for normality. The null hypothesis of the normality test is that there is no significant departure from normality. The value for this study was: p >0,1500, which implies the null hypothesis could not be rejected and residuals were thus normally distributed. Also, the means of the residuals should theoretically be zero, or very close. In this study having run the PROC UNIVARIATE it was shown that the mean for residuals was $\approx$ 0.

The model derived from Table 19 can be implemented by using the following equation:

$$SI_5 = 17{,}4024 + 10{,}71437(OC\%) - 0{,}05702(Clay\%\_subsoil) + \varepsilon \quad \ldots\ldots 18$$

where: OC% = organic carbon content in top soil

Clay%_subsoil = clay content measured in the sub-soil (%)

Mean bias is an indication of the predictive ability of a model. Bias was calculated as (predicted – observed) for SI_5. The mean bias and mean absolute bias for this model were calculated to be –0,0172 m and 1,342 m respectively. This indicates that Equation 18 over-predicts the mean value of SI_5 by only (1,72 cm) when applied to input data that fall within the boundaries of this study. The standard deviation of these biases have shown to be sufficiently small to accept the model to have a high predictive ability.

A graphical distribution of observed vs. predicted values for SI_5 is shown in Figure 11.

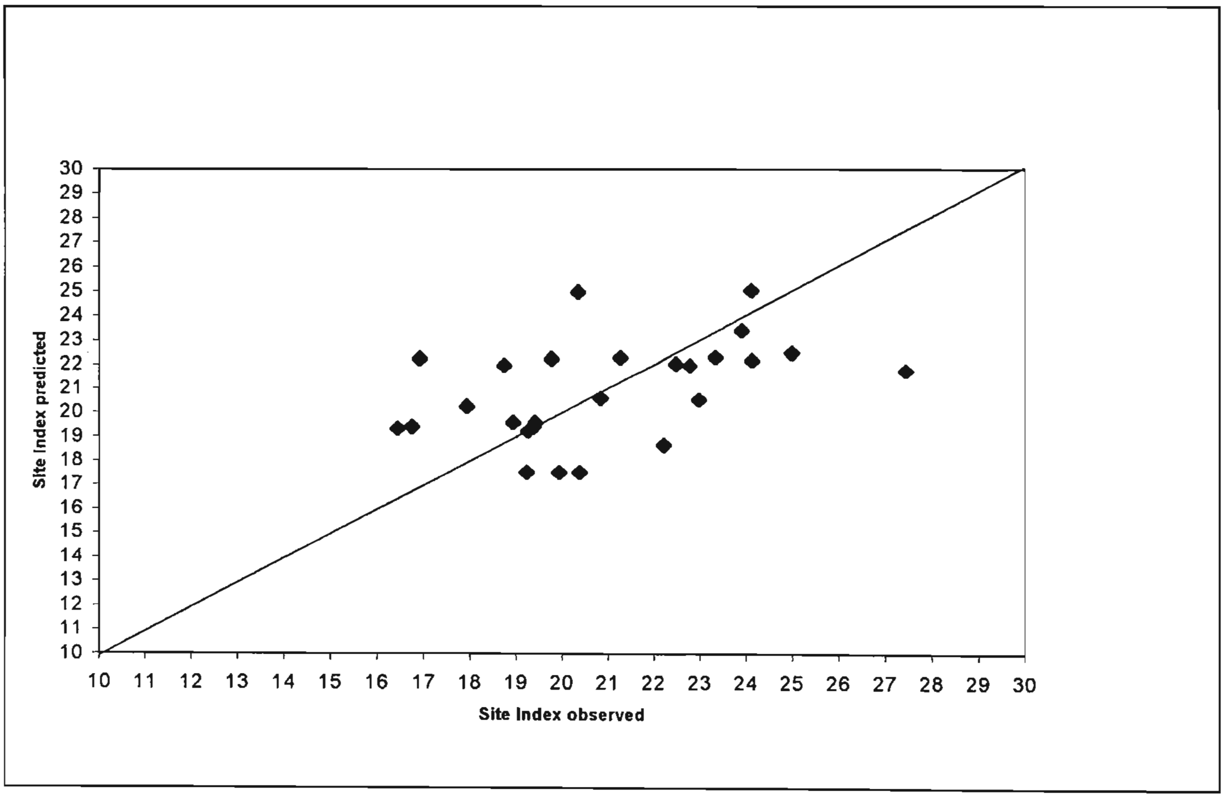


FIGURE 11. Predicted vs. observed site index (SI_5) in metres based on Equation 18.

6.1.3 Discussion

The POOLED model was developed and used to calculate SI_5, which was entered into the correlation analysis. The correlation analysis identified the significant variables for the construction of a site quality prediction model. It should be noted that the location variables played a significant role, emphasising the importance of the geographical location of forestry in the Zululand coastal region for predicting growth and yield. It is secular knowledge that closer to the coast the rainfall is high and that it is warmer in the north of the study area. It has now been proven that there are significant correlations between SI_5 and longitude, MAP, MAT, LCI, A-pan evaporation and distance from the coast. The negative correlations found between SI_5 and LCI or MAP are difficult to explain. It may be that the scale of climate interpolation algorithms used by the CCWR, is not precise enough for the relatively small study area. On-site weather monitoring for site analyses purposes, would be more acceptable than the modelled data from large scale climatic research.

It is somehow surprising that some of the soil variables, apart from organic carbon content, did not play a bigger role in the prediction of site potential. For soil classification purposes, only the first 1,5 m from the surface is surveyed and recorded, and it is postulated that much more useful information, such as water table and recharge dynamics of the aquifers, can be found below the 1,5 m cut-off. TAW and ERD were non-contributing variables in the models, although literature suggests they should be highly significant (Roberts, 1994). This is a direct consequence of the FSD data not being suitable for this kind of site analysis.

It was somehow expected that the POOLED model of SI_5 would differ significantly from the MMRC model. The POOLED-model is derived effectively from a subset of the MMRC data, but representing only 33% of the timber plantation area owned by the MMRC members. As the tendency for growing trees on sites geographically different from that of Mondi Forests increases, it becomes important to know which model to use, since it may provide strategic insights for expansion and optimised management.

It is pleasing that the site quality prediction model for SI_5 yielded statistically significant results of R^2 = 63%, p<0,0001 and MSE=1,82157, with little bias in the prediction.

The organic carbon content information was derived from a laboratory analysis and it is likely that if clay content data in the sub-soil had also been derived from laboratory analysis, the coefficient of determination would have been even better. When sampling any of these variables for site analysis purposes, a stratified sampling approach should be followed to ensure the variance in the data has been captured. The PSP system is not ideally suited to capture variance in soil variables and it is likely that if a sampling strategy had been exclusively designed to capture soil variables, that a far better statistical fit would be achieved.

6.2 Mean Annual Increment

MAI is the average annual increase in volume of individual trees or stands defined at a specific age. The MAI changes with different growth phases in a tree's life, being highest in the middle years and then slowly decreasing with age. The point at which the MAI peaks is commonly used to identify the biological maturity of the stand and its readiness for harvesting.

The volume of each PSP plot for every measurement was calculated by applying the equation provided by Chiswell (1998), earlier defined as Equation 7. The MAI_{peak} for every PSP was determined and used as dependent variable (Y) in subsequent regressions. A summary of the calculated MAI per PSP is shown in Table 20.

TABLE 20. Calculated Mean Annual Increment for each Permanent Sample Plot.

PLOTID	Frequency	MAI_PEAK	MAI_MIN	MAI_MEAN	MAI_LAST	Converged
01F00	10	74,09	62,51	69,90	70,97	Y
33F00	7	43,51	40,35	42,05	43,43	Y
34F00	7	51,69	40,66	47,46	51,56	N
37F00	6	41,22	34,01	38,46	40,32	Y
38F00	13	38,31	32,18	35,14	35,13	Y
39F00	6	46,57	42,41	44,55	46,57	N
40F00	6	42,05	36,42	39,00	42,05	N
41F00	6	48,96	41,85	44,48	45,74	Y
59F00	4	45,15	25,21	38,32	45,15	N
60F00	4	70,23	50,04	64,08	70,23	N
61F00	4	55,49	22,33	44,63	52,81	Y
62F00	4	47,43	20,66	38,87	45,99	Y
65F00	4	52,52	26,35	42,07	52,52	N
69F00	4	50,61	32,11	44,81	47,60	Y
70F00	3	49,60	42,60	46,62	48,10	Y
GM72F00	36	42,39	11,32	28,32	38,74	Y
GM73F00	36	62,31	35,68	54,20	49,27	Y
GM74F00	35	67,98	22,58	50,41	60,02	Y
GM75F00	36	75,29	26,11	50,56	68,21	Y
05F00	4	62,11	42,99	48,53	62,11	N
05F01	3	33,80	24,37	29,91	33,80	N
11F00	4	50,12	46,65	48,02	47,37	Y
11F01	3	41,45	25,96	36,73	41,45	N
19F00	13	45,27	35,44	40,32	36,44	Y
23F00	7	60,89	55,78	57,82	57,42	Y
32F00	9	61,51	42,89	52,24	42,89	Y

From Table 20 it can be seen that certain plots have reached their MAI_{peak} already and some not. The plots that have peaked (from a silvicultural point of view) have reached their period of maximum volume production and in a commercial environment they would be ready for harvesting.

Examples of the MAI scatter plots of age and MAI_{peak} are shown in Appendix 10. It can be seen in Appendix 10 that GM73F00 has reached its MAI_{peak}, GM72F00 and GM74F00 display a flattening curve, and that GM75F00 is still in the upward phase.

6.2.1 Predicting mean annual increment with site variables.

The correlation coefficients (r) were determined in an effort to establish which independent variables that should be used for predicting for MAI_{peak} (Table 21).

TABLE 21. Correlation coefficient (r) and probability of MAI_{peak} with site variables of the study area.

Variable	**Aspect**	**Heat_Units**	**Latitude**	**Longitude**	**Altitude**	**TPH**	**TAW**
r	0,00296	0,28627	-0,22242	0,40833	0,03892	-0,04211	0,30510
p	n.s.	n.s.	n.s.	*	n.s.	n.s.	n.s.
MAP	**MAT**	**A_PAN**	**CLAY%_S**	**LCI**	**OC%**	**Distance**	**SF_FW**
-0,20092	0,33481	0,22391	-0,29175	-0,22329	0,52936	0,14515	0,41362
n.s.	n.s.	n.s.	n.s.	n.s.	**	n.s.	*

From this correlation analysis it is clear that organic carbon content (OC%) and the categorical variable Fernwood soil form are significantly correlated with MAI_{peak}. A short discussion follows:

a. OC% and MAI_{peak} are positively correlated (r=0,52) indicating that higher MAI_{peak} is to be expected where the OC% is higher. This meaningful correlation will be investigated with regression techniques.

b. The Fernwood soil form, which occurs in abundance in the growing area, is also positively correlated (r= 0,41) with MAI_{peak}. No split for a categorical variable was made between Fw1210 and Fw1110. The other soil forms, Griffin, Oakleaf and Hutton, are all negatively correlated with MAI_{peak}, all at non-significant levels.

A larger data set for this analysis might have proven other soil types to be better correlated with MAI_{peak}, but the correlation of OC% is seen as meaningful, even with larger data sets.

MAI_{peak} was entered in a regression analysis, as the dependent variable to establish its relationship with site variables. A PROC REG, making use of the r-square step-wise selection method, with all 15 independent variables was carried out with the data. No useable models came forth from the analysis. Shown in Table 22 are regression statistics from the regression performed.

TABLE 22. Fit statistics for MAI_{peak} model with organic carbon content.

Model:	MAI_{peak}=34,52991 + 39,5639 (OC%)				
Fit statistics:	df (1;25)	R^2 = 35%,	RMSE=95,69	F=9,2333	P<0,05

6.2.2 Discussion

MAI is a measure of stand productivity that is, unlike site index, severely influenced by the silvicultural treatments a stand might have received. In short rotation eucalypt plantations in South Africa, it is known that the number of stems per hectare is one of the most influencing factors affecting MAI, but is also one of the main options to the silviculturist to alter stand composition with regards to rotation age, tree size and possibly, wood quality.

Plant physiology process-modellers are achieving some success predicting the mean annual increment, as an indication of the rate of biomass accumulation, by modelling processes such as photosynthesis-dynamics and soil water processes with tree growth as dependent variable (Woollons *et al.*, 1997; Battaglia and Sands, 1998; Esprey, 2001).

CHAPTER SEVEN
SITE CLASSIFICATION

7.1 Introduction and Objectives

A shortage of suitable land for commercial timber plantations through pressures of water-use and land re-distribution, force growers to intensify production through deployment of appropriate genetic material best suited to site conditions, and the application of site specific silviculture. The process of cloning also poses a higher risk of failure where a precise site-genotype matching is not implemented. The process of understanding forest site requires an intensive site classification effort from commercial forestry. Efforts to classify forestry land into homogenous units has been focussed in the past on high level classification systems (Kunz and Pallett, 2000), with very little advantage to the forestry manager wanting to make decisions at an operational level. The importance of site classification to the commercial enterprise is immense. Following are a few advantages with the implementation of a sound classification system:

a. it allows for accurate site species matching, particularly if the genetic improvement programme focuses on tree breeding and uses the same set of site classification attributes to test new species and clones,
b. the boundaries of site units are known and demarcated into distinct production classes,
c. it facilitates uniform silvicultural management over an area where the site variation is kept to a minimum and prioritises the production of high value products on high potential sites through site specific silviculture, and
d. allows for a focussed modelling approach through modelling growth and yield per dominant site class (Du Plessis, 1998).

A Site Classification Unit (SCU) can be defined as a unit of land sufficiently uniform in its attributes of soil, climate, topography, water and nutrients status, to sustain uniform growth of trees. In order to effectively manage such a unit, forest managers need a mechanism to delineate land into basic ecological units and to establish the inherent characteristics and capability of each unit. In this chapter it is attempted to devise a site classification system that can be applied at the operational level in a commercial enterprise. The data collected and models developed in the previous sections were used as the basis for the development of site classification units for the Zululand coastal plain.

7.2 Materials and Methods

Cluster Analysis

A multivariate technique that organises observed data into meaningful structures on the basis of similarity, known as cluster analysis, was used for this study. The application of clustering is restricted to surveys where large number of variables are involved, where the focus of interest is to detect a natural grouping of these variables, for which purpose a measure of similarity is needed (Van Laar, 1991; SAS Institute Inc., 2000). This technique allows the modeller to identify clusters before a meaningful description of the differences between members of each cluster are available. The significance of the clusters can then be tested with a known, reliable variable such as SI_5.

Using tree-clustering or block-clustering means joining objects together into successfully larger clusters by making use of some measure of similarity or distance. As a result more and more objects are linked together and larger and larger clusters of increasingly dissimilar elements are aggregated. Depending on the stage of which the respective elements of clusters were linked together, one can read off their criterion distance. When the data contain a clear structure in terms of clusters of objects that are similar to each other, one can interpret these clusters in order to obtain a meaningful description of their difference.

Cluster analysis differs in one important point from discriminate analysis in that this method allocates unknown individuals, like permanent sample plots, into pre-determined groups in order to classify the unknown entities into clusters or zones of similarity. In cluster analysis the number of groups and their composition is unknown. Diagnostic statistics, which will be demonstrated later in this chapter, are used to determine a "logical" number of groupings. Through this clustering analysis, it is expected that the grouping might reveal an interpretable partition of the population which was unknown prior to the cluster analysis.

Selecting the variables to determine the clusters

More specific for this study, one or more distinct site classification units may be described. The SI_5 –variable, as indicator of site, was used to examine their within-groups and between-groups covariance structure. This information was used to classify unknown individuals like plantation compartments, into known classes of site uniformity.

All previously identified site variables were tested in the clustering procedure. The fitness of any variable to stand a chance to be selected for the clustering was done through a PROC GLM (SAS Institute Inc., 2000). The cluster analysis was performed using MAP and CLAY_PERC_SUB as input variables. These variables were selected on the basis of the R^2 value, their relative low variance, and significance at the 0,05 level in the ANOVA, also because they are easily estimated in a forest environment.

There are no real assumptions underlying cluster analysis since hypothesis testing is involved. However, the variables used in the cluster analysis have different scales (MAP is measures in mm, while CLAY_PERC_SUB is measured in %). Therefore those variables with greater variance and stronger structure will dominate the clustering. The unstandardized variance for MAP and CLAY were, respectively found to be: 11427,0154 and 256,09385 and differ vastly from each other. These variables were subsequently standardised to a mean of one, using PROC STDIZE (SAS Institute Inc., 2000) by subtracting a location measure and dividing by a scale measure and put forward to the cluster analysis.

Deriving the clusters

Ward's minimum variance technique (SAS Institute Inc., 2000) was used as the clustering method since this method gave the best overall performance.

The three criteria that performed best in these simulation studies with a high degree of error in the data were a pseudo F statistic developed by Calinski and Harabasz (1974), that can be transformed into a pseudo t^2 statistic, and the cubic clustering criterion (CCC). The pseudo F statistic and the CCC are displayed by PROC FASTCLUS. These two statistics and the pseudo t^2 statistic, which can be applied only to hierarchical methods, are displayed by PROC CLUSTER. A summary output for PROC CLUSTER (SAS Institute Inc., 2000) is shown in Appendix 11. Consensus was sought among the three statistics; local peaks of the CCC, pseudo *F* statistic combined with a small value of the pseudo t^2 statistic and a larger pseudo t^2 for the next cluster fusion.

A local peak in the CCC occurs between 2,22 and 17,6 (Appendix 11). The cubic clustering criterion (CCC) is used for crude hypothesis testing and estimating the number of population clusters. A local peak also appears between the third and the fourth cluster (327 and 730) and the pseudo t^2 value is sufficiently low around these two cut-off points (366). At this point, the clusters are declared significantly different from the rest of the observations and they are accepted as site classification units (SCU) and are displayed in Figure 12. The authenticity of the three distinct clusters are verified in the next section.

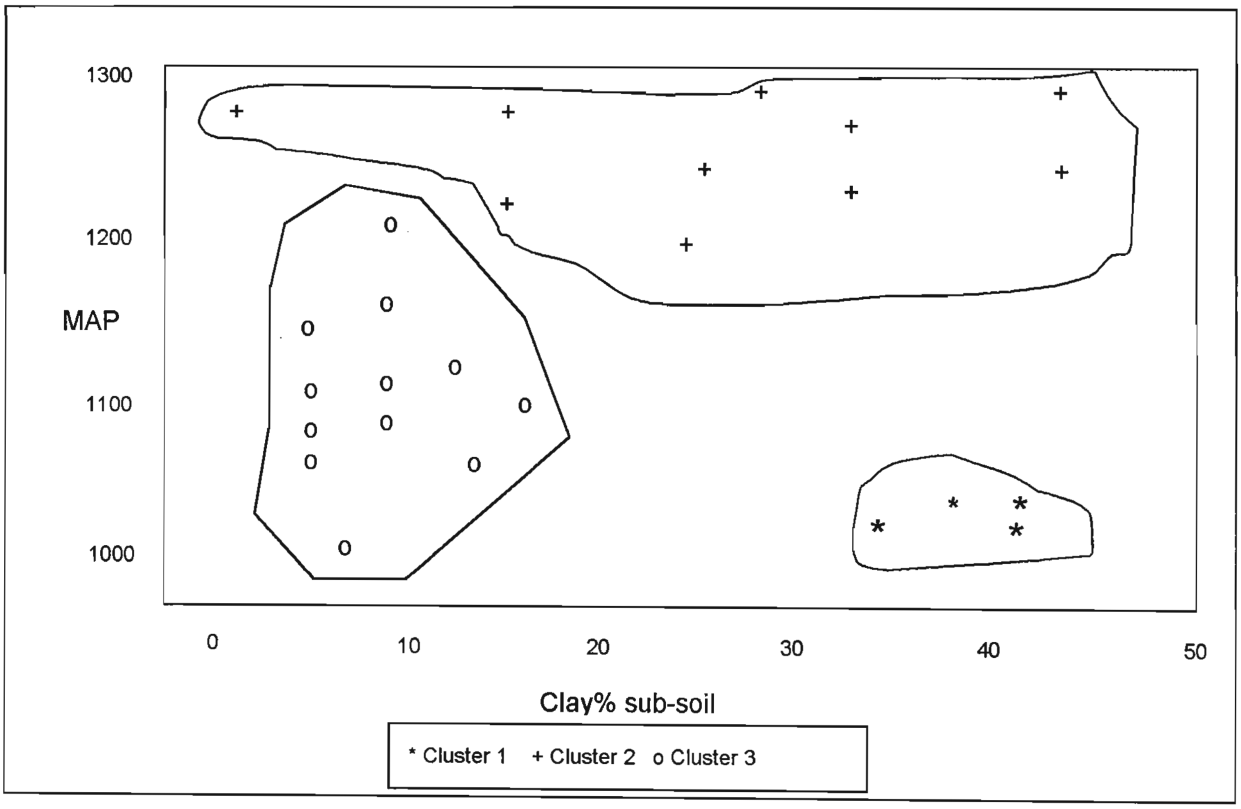


FIGURE 12. Clusters separated by MAP and clay percentage in the sub-soil.

Results

Tukey's Studentized Range (HSD) test was used to establish the significance of each of the clusters with the input variables MAP and clay content in the sub-soil. From the output generated by PROC GLM (SAS Institute Inc., 2000), it was established that for

MAP, the three clusters differ significantly on the alpha (0,05) level. For clay content in the sub-soil, clusters three and one were not significantly different, but three and one were significantly different from cluster two (Figure 12). These variables gave a good separation and it can be seen from Figure 12 that the clustering worked well. Along the MAP axis, there are two clusters – one above the 1200 mm mark and one below. Along the CLAY axis, there are also two distinct classes separated at a value of around 20%.

A dendrogram indicating the distribution of the three clusters is shown in Figure 13. The CCC criterion was applied and three groups of PSP plots are clearly visible.

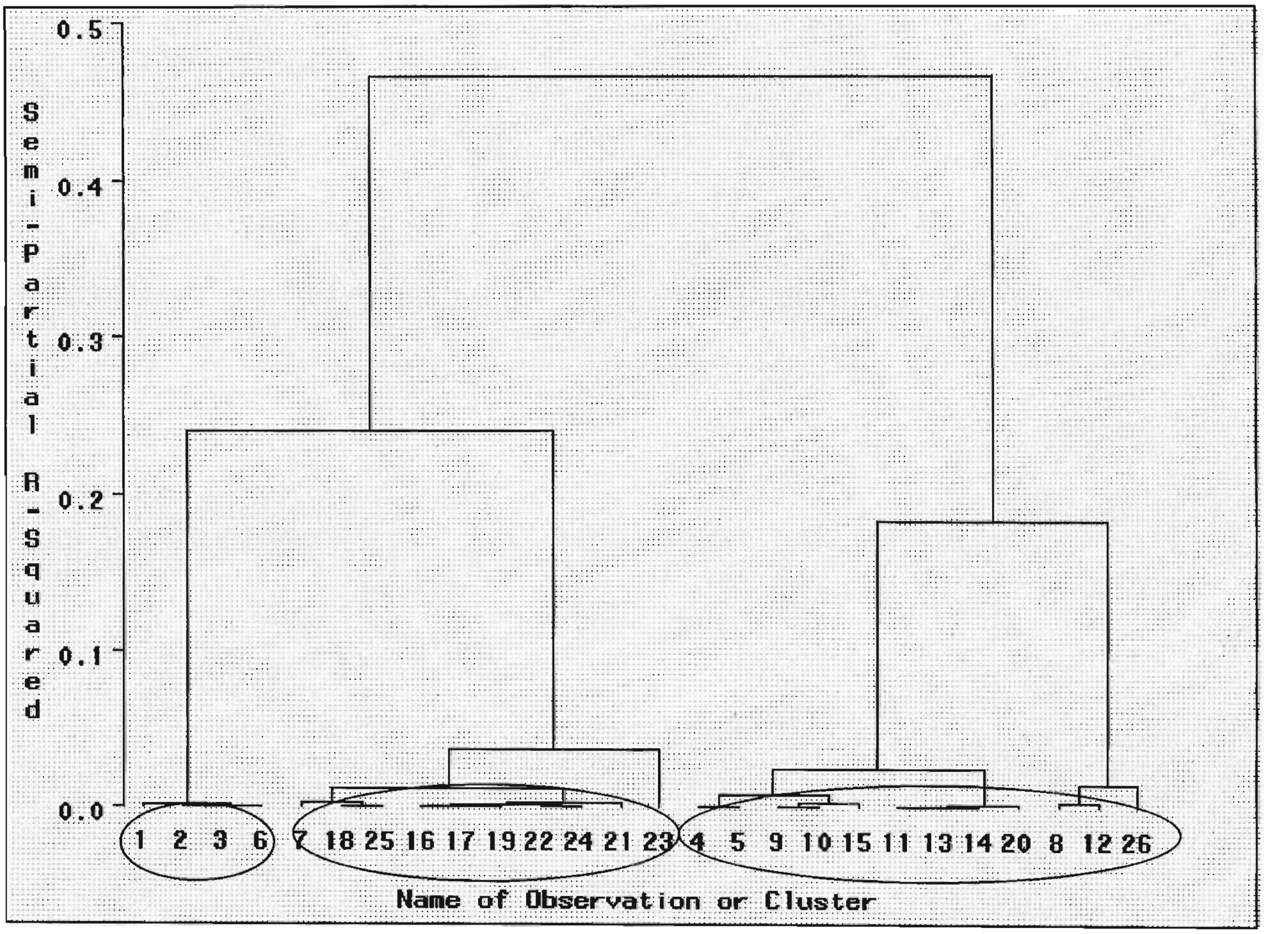


FIGURE 13. Dendrogram depicting the cluster output showing the three theoretical site classification units (SCU).

A spatial representation of the physical location of these plots is shown as a map in Appendix 12. It is very meaningful to note the specific geographical locations of the clusters as it almost verifies what was casually referred to as "good sites" and "poor sites".

7.3 Description of each Site Classification Unit

The three groupings from the clustering process are regarded and tested as three distinctive SCUs. The descriptive statistics for each SCU, with standard deviation in brackets, are shown in Table 23.

TABLE 23. Descriptive statistics for site classification unit 1,2 and 3.

Variable	SCU 1 Teza	SCU 2 Kwambonambi	SCU 3 Mtunzini
Observations (no. plots)	4	10	12
MAP	1015,5 (73,87)	1140,80(84,32)	1275,71(24,06)
MAT	21,57(0,150)	21,50(0,175)	21,08(0,069)
Clay_perc_sub	38,75(2,50)	10,13(6,75)	40,00(6,45)
Heat_Units	4228(48,05)	4208(63,20)	4025(87,06)
OC%	0,507(0,236)	0,492(0,112)	0,325(0,073)
Distance (m)	18219(484)	11947(5181)	2205(684)
HTOP	25,17(4,95)	24,56(3,02)	24,52(1,42)
Age	6,44(1,43)	5,77(1,56)	7,28(0,98)
SPH	1325(202)	1109(110)	1245(83)
MAI	53,82(17,82)	54,58(11,30)	46,65(4,57)
SI_5	20,37(1,75)	22,17(2,70)	18,61(1,47)

The correlation coefficients and probability values are shown in Table 24.

TABLE 24. Correlation coefficient (r) of site index (SI_5) with site variables for each site classification unit.

SCU 1: The Teza unit

Variable	Aspect	Heat_Units	Latitude	Longitude	Altitude	TAW
r p	-0,52809 n.s.	-0,37497 n.s	0,39014 n.s.	-0,37348 n.s.	0,37497 n.s.	0,27792 n.s.
MAP	**MAT**	**A_PAN**	**CLAY%_S**	**LCI_square**	**OC%**	**Distance**
-0,37497 n.s.	-0,37497 n.s.	-0,37497 n.s.	-0,98476 **	0,37497 n.s.	0,98322 **	0,32835 n.s.

SCU 2: The Kwambonambi unit

Variable	Aspect	Heat_Units	Latitude	Longitude	Altitude	TAW
r	-0,43257	0,49111	-0,49532	0,52914	0,13684	0,14965
p	n.s.	n.s.	n.s.	*	n.s.	n.s.
MAP	**MAT**	**A_PAN**	**CLAY%_S**	**LCI_square**	**OC%**	**Distance**
-0,48687	0,49528	0,45380	-0,03955	-0,51502	0,64124	0,32934
n.s.	n.s.	n.s.	n.s.	*	**	n.s.

SCU 3: The Mtunzini unit

Variable	Aspect	Heat_Units	Latitude	Longitude	Altitude	TAW
r	-0,40388	-0,73927	0,79598	-0,80176	0,24145	-0,60867
p	n.s.	n.s.	*	*	n.s.	n.s.
MAP	**MAT**	**A_PAN**	**CLAY%_S**	**LCI_square**	**OC%**	**Distance**
-0,59901	-0,37565	-0,68920	-0,11315	-0,61483	0,66600	0,01538
n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

7.4 Verifying the Clusters

7.4.1 Developing a prediction equation for inclusion in a cluster

Logistic regression may be performed to assess whether a subject belongs to a cluster or not. Logistic regression is used when the dependent is a dichotomy e.g. a site classification unit and the independents are continuous variables (MAP and clay percentage in the sub-soil), categorical variables (Fernwood soil form), or both (SAS Institute Inc., 2000).

This type of analysis reveals which variables contributed most to the cluster analysis. In addition, it yields an equation for predicting inclusion in specific clusters e.g. (SCUs), for additional subjects such as PSPs or compartments. A relationship between the clusters and the variables was derived by using logistic regression. Such an analysis would provide a prediction equation to indicate which SCU-cluster a plot would fit into and it could be used as a commercial site classification tool.

A problem in estimation arises when there is some linear combination of the explanatory variables that perfectly predict the dependent variable. With categorical explanatory variables in logistic regression this problem is called complete separation. It happens when all or most of the responses at one of the levels of the categorical variable are successes and all or most of the responses at another level are failures. A prediction equation for inclusion in a defined cluster could therefore not be developed.

7.4.2 Making use of site index to establish the significance of the site classification units

A Site Index model was developed for every SCU. The Chapman-Richards 3-parameter equation was used. The same process that was followed earlier, making use of non-linear regression and the Marquardt algorithm, was used to derive the three SI_5 models. The model parameters are given in Table 25, while Figure 14 shows the dominant height and age relationships for each of the site classification units.

TABLE 25. Site Index (SI_5) models for the three site classification units.

CLUSTER	B_0	B_1	B_2	F-Value	P	R^2	SI_5
SCU1	75,0	-0,0585	0,9099	1447,04	<0,0001	92,94	21,52
SCU2	75,0	-0,0222	0,5635	4086,06	<0,0001	95,25	21,06
SCU3	75,0	-0,0171	0,5287	1704,75	<0,0001	95,11	19,98

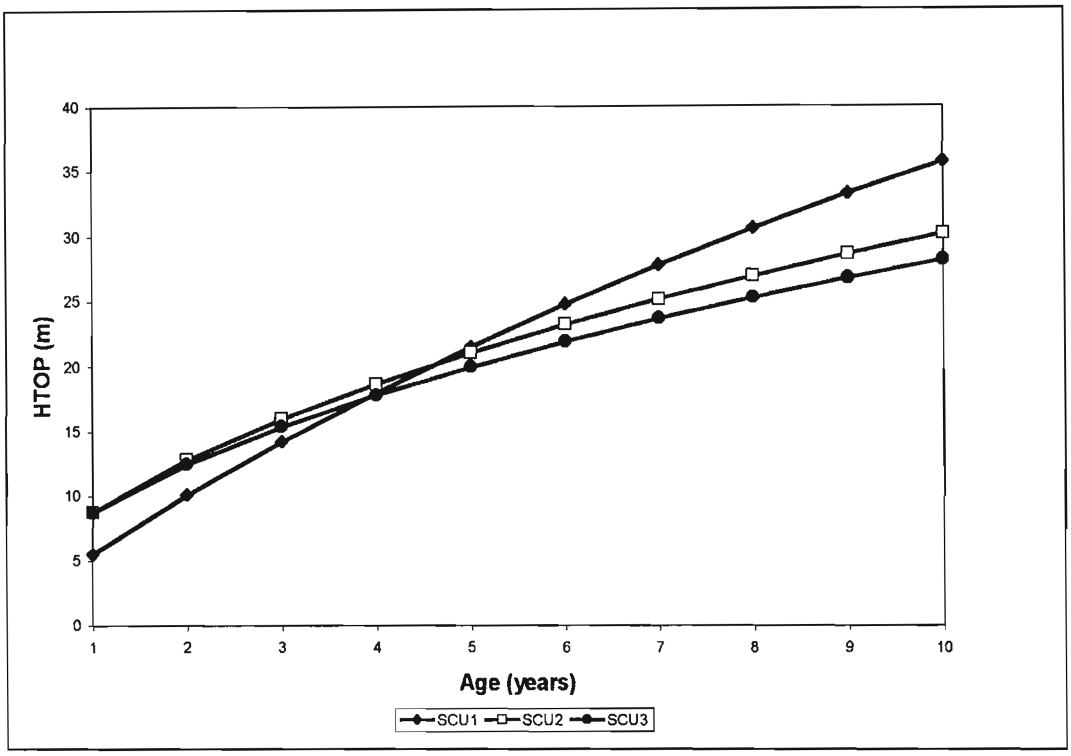


FIGURE 14. Dominant height vs. age relationships for site classification units (SCU) 1,2 and 3.

The F-test was used to determine whether the three models differed significantly at the 95% confidence level. Table 26 shows the parameter estimates with the 95% confidence intervals.

TABLE 26. Site Index (SI_5) model statistics for site classification units1, 2 and 3 showing parameters and lower and upper confidence levels.

SCU	Parameter	Value	95% LL	95% UL
1	B_1	-0,0585	-0,0360	-0,0810
	B_2	0,9099	0,6877	1,1320
2	B_1	-0,0222	-0,0140	-0,0303
	B_2	0,5635	0,4823	0,6447
3	B_1	-0,0171	-0,00689	-0,0272
	B_2	0,5287	0,4105	0,6469

From the 95% confidence interval range test, the following results are concluded:

a. Model SCU1 differs significantly from models SCU2 and SCU 3

b. Model SCU 2 differs significantly from models SCU1 but not from SCU3

c. Model SCU 3 differs significantly from models SCU 1 but not from SCU2.

7.5 Discussion

Cluster analysis is a very exciting tool to use in site classification research. Logistic regression is just as exciting and selection of data should be such that complete separation does not occur (Section 7.4.1).

It should be borne in mind that the successful clustering achieved here is a result of the vast differences between the three locations. Zululand appears to be yielding uniform growth for plots closer to each other than further apart. If the plots were selected not so far apart from a geographical point of view, or rather as a continuous geographical gradient, the cluster analysis would have been more difficult in distinguishing between the clusters than was the case here.

Trends in correlation analysis have shifted, e.g. in SCU1 (Teza) the correlation is still significant for organic carbon content and clay content, similar to those used for the clustering procedure. However, for SCU2 (Kwambonambi) the significant correlations with SI_5 are now with Longitude, LCI and organic carbon content, and for SCU3 (Mtunzini) the significant correlations are with SI_5 are only Latitude and Longitude. From the correlation coefficients for all three units it is clear that different variables are correlated significantly with SI_5 in each of the SCUs. The variance in SI_5 in each of the units has become so small that the same trend that was examined for the study area as a whole, is not so apparent any more.

From the correlation coefficient examination, a regression analysis within each SCU was performed to explain some of the variation of SI_5 (Section 7.4.2) which is summarised below:

a. for SCU1, organic carbon content and clay content in the sub-soil explained most of the variation in SI_5, (r^2=0,98, p<0,05),
b. but for SCU2 (latitude and longitude explained most variance in the ANOVA: (r^2=0,45, p=0,0322) while in
c. SCU3 (longitude explained most variance in the ANOVA: r^2=0,28, p=0,0425).

When a site prediction growth model was developed for each of the SCUs it became apparent that none of the variables identified through the correlated analysis (Table 24), explained any variance in a proposed model, at a significant level. The variation in SI_5 was basically eliminated through the development of uniform clusters. Each SCU is thus sufficiently uniform in its characteristics of soil, climate, topography, water and nutrients status, to sustain uniform growth of trees (per definition).

It can be concluded from the above argument that the SCUs are in fact different site units by definition of uniformity in environmental parameters and the sustainable growth they support. Further research is necessary to understand which different silvicultural management options should be implemented to optimise growth and yield in each of the SCUs.

Site classification units have successfully been established.

CHAPTER EIGHT
SUMMARY AND CONCLUSIONS

In some of the previous chapters results were discussed in detail and conclusions drawn. This chapter therefore is aimed at providing a general overview of the study, to list the general conclusions that were drawn and to make suggestions for future research.

The objectives set out in the beginning of the study were:

a. to characterise the respective site conditions in terms of the soil, geomorphology, climate and associated growth of trees,
b. to determine site variables that describe the variation in growth patterns of *Eucalyptus grandis* occurring on the Zululand coastal plain,
c. to determine a timber production potential model for a range of sites,
d. to establish a site classification for the Zululand coastal plain for afforestation with *Eucalyptus grandis*, based on growth / site relationships that may exist.

Site conditions for the Zululand coastal zone have been described making use of climate and soil variables. The climate in the sub-region was found to be very uniform. Neither rainfall nor temperature was found to be useful in any of the regressions performed, nor were any of the derived climatic variables like heat units or LCI. However, rainfall was used together with clay content to establish the site classification units in the study area. Climatic variables MAT and MAP were derived from a grid coverage and proved too broad to effectively explain the variation in tree growth.

The location variables of longitude and latitude were effective in understanding the climatic pattern of the sub-region and through correlation analysis with MAP and MAT confirmed the facts that it is wetter along the coast and drier towards the inland and wetter in the south and drier and warmer in the north. It was found that SI_5 as an indicator of site quality, was correlated with geographical attributes such as longitude and latitude, but not altitude, due to the flat terrain.

General soil observations according to the FSD standards were insufficient to explain variation in growth. Only empirically established variables such as organic carbon content in the top-soil played a meaningful role in the analysis and to some extent clay content in the sub-soil that was measured infield by the pedologist. These two variables are best measured through laboratory analysis. The deep Fernwood sands in Zululand have a higher geo-hydrological complexity, than what can be described within the first 1,5 m of the soil profile. Total Available Water did not correlate with SI_5 or MAI_{peak} at all. Only the Fernwood-soil if used as a categorical variable, correlated significantly with growth potential. This association is meaningful, and supports the hypothesis that geo-hydrological processes are important to study if the role of soil and water in site growth modelling is to be understood.

Site index models were developed for each PSP, as well as for the combined data set. A POOLED site index model was compared with the model developed by the MMRC and the SI_5 predictions of these two models were found to be significantly different. This finding shows that Zululand is not as uniform as is sometimes assumed. By excluding 122 data points (Safcol Ltd. and Sappi Forests' eucalypt PSPs), and retaining the Mondi Forests data (278 points), a different set of growth curves was obtained with different growth potentials.

A significant site quality (SI_5) prediction model was developed. SI_5 is accurately predicted with organic carbon and clay content in the soil profiles. Once again, FSD soil data, with the exception of clay content, at this level of site analysis, were found to be insufficient. Furthermore, the FSD information is at the wrong scale, with some of the true indicators of soil productivity not being measured at all. Detailed surveys with relevant variables will have to be conducted for accurate site analysis.

A range of sites on the Zululand coastal plain was effectively classified in distinct units from easily obtained variables, such as clay content and MAP. Cluster analysis was used to derive three distinct site classification units. Clustering worked extremely well. SCUs were proved to be significantly different from one another, making use of SI_5 and testing F-values and probabilities. The SCUs, being such distinctive units, showed complete separation, fouling the effort to use logistic regression techniques to predict, by using the classification variables in which SCU a particular plot or compartment should belong to. However, the positioning of the SCUs is geographically unique and it is obvious in which SCU a commercial compartment belongs to. Correlation analysis within each SCU indicated non-significant correlations between site variables and SI_5. It is suggested that the variation in SI_5 data were effectively managed with the clustering process, to such low levels that it was difficult to explain with correlation or regression techniques. By definition that is the characterisation of a SCU, being a unit of land where growth is sufficiently uniform to be regarded as a homogenous system. As the classification technique worked well, further research to employ this technique over MMRC zones might prove to be a worthwhile exercise.

All yield and productivity predictions involve developing and using models – whether an internal conceptual model based on experience, an empirically based mensurational computer model, or a hybridised simulation model that includes some process-based simulation. All these models are inevitably inaccurate, to some extent, because they are all merely abstract representations of real forest growth. Thus, evaluation of models should be based less on whether they are "right" or "wrong", than on whether they are accurate enough for their intended purpose. We should use the model that gives predictions of the desired level of accuracy and reliability at the lowest cost and greatest ease of use (Kimmins and Sollins, 1986).

Traditional empirical yield models have sufficed in the past because the rate of change in management practices and growing conditions was slow enough to use the records of past growth as both a satisfactory predictor, and also as the best available predictor of future growth. However, increasing demands on the forest and rapid changes in the atmosphere and climate have resulted in the need for yield models that are flexible enough to account for changing future conditions.

Although the mechanistic approach of process-based simulation (Landsberg and Waring, 1997; Battaglia and Sands, 1998) does not offer a satisfactory alternative, a hybrid model (Woollons *et al.*, 1997), combining the empirical approach with the process simulation based approach, may appear to offer the most useful improvements.

Site growth prediction modelling or the hybrid modelling route proves to be the desired approached to follow, where both yield prediction and site classification are primary objectives. However, it stands firmly that the process of data collection for site variables will have to be designed to facilitate higher accuracy. This implies that on-site monitoring of climatic variables will become necessary. A review of the FSD standards is necessary to examine their usefulness for modelling and classification purposes, alternatively, for the compilation of site quality prediction models, edaphic variables should be collected outside the FSD system.

REFERENCE LIST

1. ACOCKS, J.P.H., 1975. The Veld Types of South Africa. *Memoirs of the Botanical Survey of South Africa* 40, 128 pp.
2. ANON, 1985. Atlas of monthly Palmer Drought Severity Indexed (1931-1938) for the contiguous United States. *Historical Climatology Service* 3-11. National Oceanic and Atmospheric Administration, National Environmental Satellite Data and Information Service, National Climatic Data Centre, Ashville, N.C., pp i-xii.
3. AVERY, T.E. and BURKHART, H.E., 1994. *Forest Measurements*. McGraw-Hill, Inc. New York. 408 pp.
4. BATTAGLIA, M. and SANDS, P.J., 1997. Process-based forest productivity models and their application in forest management. *Forest Ecology and Management* 102: 13 -32. Elsevier Science B.V.
5. BATTAGLIA, M. and SANDS, P.J., 1998. Modelling Site Productivity of *Eucalyptus globulus* in Response to Climatic and Site Factors. *Australian Journal of Plant Physiology* (24): 831 – 850.
6. BRICKELL, J.E., 1969. Site index curves for engelmann spruce in the northern and central Rocky Mountains. *USDA For. Res. Note* INT-42. 8 pp.
7. CAJANDER, A.K., 1909. Über Waldtypen. *Acta Forest Fennica* 1:1-175.
8. CALINSKI, T. and HARABASZ, J., 1974. A Dendrite Method for Cluster Analysis, *Communications in Statistics*, 3: 1 -27.
9. CHANG, J-H, 1968. *Climate and Agriculture: An ecological Survey*. Aldine publishing Co. Chicago IL, USA. PP 304.
10. CHISWELL, K.E.A., 1998. Volume and taper equations for *Eucalyptus grandis*. *Unpublished report*. MMRC, Pietermaritzburg, 13 pp.
11. CHISWELL, K.E.A. and PIENAAR, B., 1999. Policy: Establishment, management and measurement of Permanent Sample Plots. *Research Document*. Mondi Forests, Pietermaritzburg, 6 pp.
12. CLEMENCE, B.S.E., 1992. An attempt at estimating solar radiation at South African sites which measures air temperature only. *South African Journal of Plant and Soil*, 9: 40-42.

13. CLUTTER, J.L., FORTSON, J.C., PIENAAR, L.V., BRISTER, G.H. and BAILEY, R.L., 1983. *Timber management: A Quantitative Approach*. John Wiley & Sons, Inc., USA. 333 pp.

14. COETZEE, J., 1997. The estimated mining timber yield from a good site. *ICFR Bulletin Series 07/97*. ICFR, Pietermaritzburg, South Africa.

15. CORONA, P., SCOTII, R and TARCHIANI, N., 1998. Relationship between environmental factors and site index in Douglas-fir plantations in Italy. *Forest Ecology and Management* 110: 195 – 207.

16. DEMAERSCHALK, 1972. Converting volume equations to compatible taper equations. *Forest Science*, 18 (3): 241-245.

17. DONKIN, M.J., 1994. A Multivariate Reappraisal of a Site Evaluation Study in *Acacia mearnsii* De Wild. *South African Forestry Journal* 169:1-10.

18. DONKIN, M.J., PEARCE, J. and CHETTY, P.M., 1993. Methods for routine soil analysis in the ICFR laboratories. *ICFR Bulletin 06/93*. ICFR, Pietermaritzburg, South Africa.

19. DU PLESSIS, M., 1998. Research note on site classification. *Research Document*. Mondi Forests, Pietermaritzburg, 4 pp.

20. DU PLESSIS, M., PIENAAR, B. and CHISWELL, K.E.A., 1997. Criteria for the inclusion of permanent sample plots in the Mensuration and Modelling Research Consortium – v.1,0. ICFR, Pietermaritzburg, South Africa.

21. DU PLESSIS, M. and PIENAAR, B., 1999. A climate and soil investigation for conversion of former Safcol sites to *Eucalyptus*. *Research Document*. Mondi Forests, Pietermaritzburg, 25 pp.

22. DU TOIT, B and CARLSON, C., 2000. Timber Plantation Silviculture. Fertilization of Commercial Forest stands. In: D.L. Owen (Ed.) South African Forestry Handbook, Vol 1. *The Southern African Institute of Forestry*, Pretoria, 734 pp.

23. DWAF, 1998. Report on commercial timber resources and primary roundwood processing in South Africa 1996/1997. Report compiled by the Directorate Forestry Development. Department of Water Affairs and Forestry, Pretoria, South Africa. pp 128.

24. ELLIS, F., 2000a. Timber Plantation Silviculture: Geology. In: D.L. Owen (Ed.) South African Forestry Handbook, Vol 1. *The Southern African Institute of Forestry*, Pretoria, 734 pp.

25. ELLIS, F., 2000b. Timber Plantation Silviculture: Soils. In: D.L. Owen (Ed.) South African Forestry Handbook, Vol 1. *The Southern African Institute of Forestry*, Pretoria, 734 pp.

26. ERASMUS, D. (Ed.), 1998. Forest Industry Soils Database (FSD) Co-operative. Soil Survey Standards for Consultants. Ver 1.3. FSD, Pietermaritzburg, 22 pp.

27. ESPREY, L.J., 2001. Process-based modelling in forestry: a report on a visit to the CRC-SPF and CSIRO, Australia (April – May 2001). *ICFR Bulletin 14/2001*. ICFR, Pietermaritzburg, South Africa.

28. GARDNER, R.A.W., OSCROFT, D.O. and NTOMBELA, K.A., 2001. Final report on the 1992 Zululand site-species interaction trial series SGE.32 to SGE.34. *ICFR Bulletin Series 17/2001*. ICFR, Pietermaritzburg, South Africa.

29. GREY, D.C., 1987. A study of the relationship between environmental factors and mensurational parameters in *Pinus radiata*. (D. Don.). Ph.D. thesis, University of Stellenbosch, 130 pp.

30. HENSLEY, M., 1996. Forestry site and soil characterisation at North Eastern Cape Forests. *Internal report*. ISCW, Glen, South Africa. 44 pp.

31. HERBERT, M.A., 1993. Site requirements of exotic hardwood species. In: H.A. Van der Sijde (Ed.) Forestry Handbook. *The Southern African Institute of Forestry*. 846 pp.

32. HERBERT, M.A., 1997. Report on site evaluation study on portions of the Numbi section White River Area, Mpumalanga. *Research Document*. Mondi Forests, Pietermaritzburg, 77 pp.

33. HERBERT, M.A., 1998. Report on site evaluation study on portions of Rattrays estate, Kwambonambi Area, Zululand. *Research Document*. Mondi Forests, Pietermaritzburg, 75 pp.

34. HERBERT, M.A., 2000. Eucalypt and Wattle species. In: D.L. Owen (Ed.) South African Forestry Handbook, Vol1. *The Southern African Institute of Forestry*. Pretoria, Vol. 1, pp. 85-94.

35. HOLMES, A., 1965. *Principles of Physical Geology*. Thomas Nelson (printers) Ltd. London, Great Britain. 1288 pp.

36. HUTSON, J.L., 1986. Water retentivity of some South African soils in relation to particle size criteria and bulk density. *South African Journal of Plant & Soil*. 3, 150-155.

37. JACKSON, M.L., 1962. *Soil Chemical Analysis.* Constable & Co. Ltd., London. 498 pp.

38. JACOBS, E.O., SCHAFER, G.N., ROBERTSON, T.A., 1989. The classification of Forest Sites: Zululand Key Area. *South African Forestry Research Institute*, Report No. S89/3, 37pp.

39. JAMES, D.B., 1988. Prediction of tree growth from soil parameters in the Tsitsikamma key area. *Proceedings of the Forest Site and Nutrition Research Working group. Eighth meeting. Stellenbosch. pp. 16-18.*

40. KAUFMANN, M.R., LANDSBERG, J.J., (Eds.), 1991. Advancing towards closed models of forest ecosystems. Tree Physiol., 9, 1 – 324.

41. KIMMINS, J.P. and SOLLINS, 1986. FORCYTE in forestry: the need for a systems approach in forestry education, yield prediction and management. In: *The E.B. Eddy distinguished lecture series,* 1-25 Toronto, Ont.: Faculty of Forestry, University of Toronto. pp 202-220.

42. KLINKA, K and CARTER, R.E., 1990. Relationships between site index and synoptic environmental factors in immature coastal douglas-Fir stands. *Forest Science* 36, 815-830.

43. KOPRA, M.I.,(1988). Ph.D.thesis, München.

44. KOTZE, H. (Ed.), 2000. Regional PSP-based growth and yield models for *Eucalyptus grandis.* Proceedings from MMRC Technical Committee Workshop, October 2000. *Unpublished memo.* ICFR, Pietermaritzburg, South Africa.

45. KUNZ, R. and PALLETT, R., 2000. A stratification system based on Climate and Lithology for locating commercial forestry permanent sample plots. *ICFR Bulletin 01/2000.* ICFR, Pietermaritzburg, South Africa.

46. KUNZ, R. and SMITH, C.W., 2001. An initial assessment of drought risk for the forestry areas in the summer rainfall region of southern Africa. *ICFR Bulletin 15/2001.* ICFR, Pietermaritzburg, South Africa.

47. LANDSBERG, J.J. and WARING, R.H., 1997. A generalised model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. Forest Ecology and Management 95:209-228.

48. LANG, R., 1926. *Forstliche Standortsslehre.* Paul Parey, Berlin.

49. LOUW, J.H., 1991.The relationship between site characteristics and *Pinus radiata* growth on the Tsitsikamma Plateau. *South African Forestry Journal* 158 : 37 - 45.

50. LOUW, J.H., 1997. A site-growth study of Eucalyptus grandis in the Mpumalanga Escarpment Area. *South African Forestry Journal* 180 : 1 - 15.

51. LOUW, J.H., 1999. A review of site-growth studies in South Africa. *South African Forestry Journal* 158 :37 - 45.

52. MACVICAR, C.N., DE VILLIERS, J.M., LOXTON, R.F., VERSTER, E., LAMBRECHTS, J.J.N., MERRYEWETHER, F.R., LE ROUX, J., VAN ROOYEN, T.H. and VON M. HARMSE, H.J., 1977. *Soil Classification: A Binomial system for South Africa.* Dept. of Agric. Tech. Services, Science Bulletin 390. Pretoria. 150 pp.

53. MAKELA, A. and LANDSBERG, J., 2000. Process-based models for Forest Management. *Tree Physiology.*, Vol 20 (5/6): 289 – 299. Heron Publishing, Victoria, Canada.

54. MARQUARDT, D.W., 1963, "An Algorithm for Least-Squares Estimation of Nonlinear Parameters," *Journal for the Society of Industrial and Applied Mathematics*, 11, 431 - 441.

55. MONTEITH, J.L., 1977. Climate and the efficiency of crop production in Britain. *Philosophical Transactions of the Royal Society*, London, Series B, 281: 277-294

56. MORLEY, T., 1997. Mensuration and Modelling Research Consortium (MMRC). *ICFR Newsletter May 1997.* ICFR, Pietermaritzburg, South Africa.

57. MOROZOV, G.P., 1904. O tipach nasazhdenij i ich znaczenie v losovodstve (On stand types and their importance in forestry). *Lesnoi Journal* 42: 843-871.

58. MORRIS, A., 1986. Soil fertility and long term productivity of *Pinus patula* in Swaziland. *Unpublished PhD thesis.* University of Reading, England.

59. MUNSELL SOIL COLOR CHARTS, 1988. Munsell Color. Macbeth Division of Kollmorgen Instruments Corporation. Maryland USA.

60. NOBLE, A.D., 1992. Zululand Sands Project. Institute for Commercial Forestry Research. *ICFR Bulletin 14/92.* ICFR, Pietermaritzburg, South Africa.

61. NOBLE, A.D., DONKIN, M.J. and SMITH, C.W., 1991. The importance of Soil Properties as Indicators of Site Quality for *Eucalyptus grandis* on the Zululand Coastal Plain. *Proceedings of IUFRO Symposium on Intensive Forestry: The role of Eucalyptus. 2-6 September 1991.* Vol I: 433 – 443.

62. NOBLE, A.D. and HERBERT, M.A., 1991. Influence of soil organic matter content on the responsiveness of *Eucalyptus grandis* to nitrogen fertiliser. *South African Forestry Journal* 156 : 23-27

63. OLBRICH, K., CHRISTIE, S.J., EVENS, J., EVERARD, D., OLBRICH B., and SCHOLES, R.J., 1997. Factors influencing the long term sustainability of the South African forest industry. *South African Forestry Journal* 178 53-55.

64. PIENAAR, B. and KOTZE, H., 2000. Growth and Yield Functions. MMRC: Technical Committee Report. *Unpublished memo*. ICFR, Pietermaritzburg, South Africa.

65. ROBERTS, P.J.T., 1994. Variation in soil moisture availability in South African Plantations: Initial results of parameter sensitivity tests of model Wetness. *ICFR Bulletin 8/94*. ICFR, Pietermaritzburg, South Africa.

66. SANDS, P.J., BATTAGLIA, M. and MUMMERY, D., 2000. Application of processed-based models to forest management: experience with PROMOD, a simple plantation productivity model. *Tree Physiology* 20: 383 – 392.

67. SAFCOL, 1999. PSP Interval Data Visualization Tool Ver 1.0. Compiled by H. Kotze and D. Vonck.

68. SAS INSTITUTE Inc., 1989. SAS/STAT User's Guide, Version 6, Fourth Edition, Volume 1, Cary, NC, USA. 943 pp.

69. SAS INSTITUTE Inc., 2000. SAS Online Documentation Version 8. SAS Institute Inc., Cary, NC, USA. HTML Format.

70. SCHAFER, G.N., 1988a. A Site growth model for *Pinus pinaster* in the Southern Cape. *South African Forestry Journal* 146: 18 –22.

71. SCHAFER, G.N., 1988b. A Site growth model for *Pinus elliottii* in the Southern Cape. *South African Forestry Journal* 146: 12-17.

72. SCHAFER, G.N., 1994. *Pinus radiata* growth model for the Southern Cape and Tsitsikamma. *CSIR report* : FOR-DEA/816 12 pp.

73. SCHIMPER, A.F.W., 1890. *Pflanzengeographie auf Physiologischer Grundlage.* Jena Germany.

74. SCHöNAU, A.P.G., 1969. A site evaluation study in black wattle (*Acacia mearnsii* de Wild) *Annals University of Stellenbosch*, 44(A2), 214 pp.

75. SCHöNAU, A.P.G., 1987. Problems in using vegetation or soil classification in determining site quality. *South African Forestry Journal* 141: 28 - 34

76. SCHöNAU, A.P.G. and GREY, D.C., 1987. Site requirements of exotic tree species. Forestry Handbook 1987. *The Southern African Institute of Forestry*, pp 82-94.

77. SCHULZE, R.E., 1997. South African atlas of agrohydrology and –climatology. Department of Agriculture Engineering, *Water Research Commission*. Report TT86/96. 276 pp.

78. SCHUMACHER, F.X., 1939. A new growth curve and its application to timber yield studies. *Journal of Forestry* 37: 819-820.

79. SCHUTZ, C.J., 1990. Site relations for *Pinus patula* in the Eastern Transvaal escarpment. Unpublished Ph.D. (Agric) thesis. Univ. of Natal, Pietermaritzburg, South Africa.

80. SMITH, C.W., 1995. Introduction to Forest Soils of the Summer Rainfall Regions of South Africa. *ICFR Bulletin 4/95.* ICFR, Pietermaritzburg, South Africa.

81. SMITH, C.W., 2001. A Visit to Zululand Spacing and Nutrition trials. ICFR Field day, November 2001. 14 pp. ICFR, Pietermaritzburg, South Africa.

82. SMITH, C.W., JOHNSTON, M.A. and LORENTZ, S.A., 2001. The effect of soil compaction on the water retention characteristics of soils in forest plantations. *South African Journal of Plant and Soil.* 18 (3) 87 – 97.

83. SNEDECOR, G.W. and COCHRAN, W.G., 1980. *Statistical Methods.* The IOWA State University Press, Iowa, USA. 505 pp.

84. SNOWDON, P., WOOLLONS, R.C. and BENSON, M.L., 1998. Incorporation of annual climatic indices into models of *Pinus radiata* in a spacing experiment. *New Forests* 16: 101 – 123.

85. SNOWDON, P., JOVANOVIC, T. and BOOTH, T.H., 1999. Incorporation of indices of annual climatic variation into growth models for *Pinus radiata.* CSIRO. *Forest Ecology and Management* 117 (1999) 187 – 197. Elsevier Science B.V.

86. STRYDOM, H.L., 1991. 'n Groeiplekmodel vir Pinus elliotii in die Sabie omgewing. FORESTEK (CSIR). Internal report 900 90275/07 16 pp.

87. STRYDOM, H.L., 1999. A site classification and evaluation of a Geographical Information System platform for forestry. *Unpublished M. Tech. Dissertation*. Dept. of Forestry, Port Elizabeth Technikon, South Africa.

88. THE SOIL CLASSIFICATION WORKING GROUP. MACVICAR, C.N. and DE VILLIERS, J.M. (Convenors), 1991. *Soil Classification. A Taxonomic System For South Africa.* Department of Agriculture Development, Pretoria. 257 pp.

89. THERON, J.M., 2000. Timber Plantation Silviculture. Preface. In: D.L. Owen (Ed.) South African Forestry Handbook, Vol 1. *The Southern African Institute of Forestry*, Pretoria, 734 pp.

90. USDA Soil Survey Staff, 1975. Soil Taxonomy – a basic system of soil classification for making and interpreting soil surveys. *U.S. Dept. Agric.* Washington Handbook No. 436: U.S. Govt. Printing Office.

91. VANCLAY, J.K., 1994. *Modelling Forest growth and Yield* : Applications to mixed Tropical Forests. CAB International, Wallingford, UK. 312 pp.

92. VANCLAY, J.K., SKOVSGAARD, J.P. and HANSEN, C.P., 1995. Assessing the quality of permanent sample plot databases for growth modelling in forest plantations. *Forest Ecology and management* 71 (1995) 177 – 186. Elsevier Science B.V.

93. VAN DER WATT, H.v.H. and VAN ROOYEN, T.H., 1990. A Glossary of Soil Science. *The Soil Science Society of South Africa*, Pretoria. 356 pp.

94. VAN LAAR, A., 1991. *Forest Biometry.* University of Stellenbosch, Stellenbosch. 589 pp.

95. VAN LAAR, A. and AKCA, A., 1997. *Forest Mensuration.* Cuvillier Verlag, Gottingen, Germany. 418 pp.

96. WALKLEY, A., 1947. A critical examination of a rapid method for determining organic carbon in soil - effect of variations in digestion conditions and of inorganic constitutes. *Soil Sci.* 63: 251-264.

97. WILDE, S.A., 1958. *Forest Soils: Their properties and relation to Silviculture.* The Ronald Press Company, New York. 537 pp.

98. WOLMARANS, L.G. and DU PREEZ, J.W., 1986. *The geology of the Saint Lucia Area.* Mineral and Energy Affairs, 42 pp.

99. WOODWARD, F.I., 1986. *Climate and Plant distribution.* Cambridge university Press, Cambridge, UK, 174 pp.

100. WOOLLONS, R.C., SNOWDON, P. and MITCHELL, N.D., 1997. Augmenting empirical stand projections with edaphic and climatic variables. *Forest Ecology and Management* 98 (1997) 267 - 275. Elsevier Science B.V

101. ZWOLINSKI, J.B., 1997. Palmer Drought Indices and their Application to Plantation Establishment Strategies. *South African Forestry Journal* 178: 9-13.

102. ZWOLINSKI, J.B., 2001. The relevance of site analysis for tree breeding in South Africa. *Unpublished me*mo, University of Natal, Pietermaritzburg, 14 pp.

103. ZWOLINSKI, J.B., DONALD, D.G.M., VAN LAAR, A. and VAN DER MERWE, L., 1995. Water retention in cultivated Forest Soils of the Southern Cape Province. *South African Forestry Journal* 174: 1 – 8.

104. ZWOLINSKI, J.B., HENSLEY, M., GERISCHER, G.F.R., MONNIK, K.A. and GROENWALD, W, 1997. Growth and Timber Properties of Mature Pine stands on Various Sites at the North Eastern Cape Forests. NECF Internal Report, Ugie, South Africa. 33 pp.

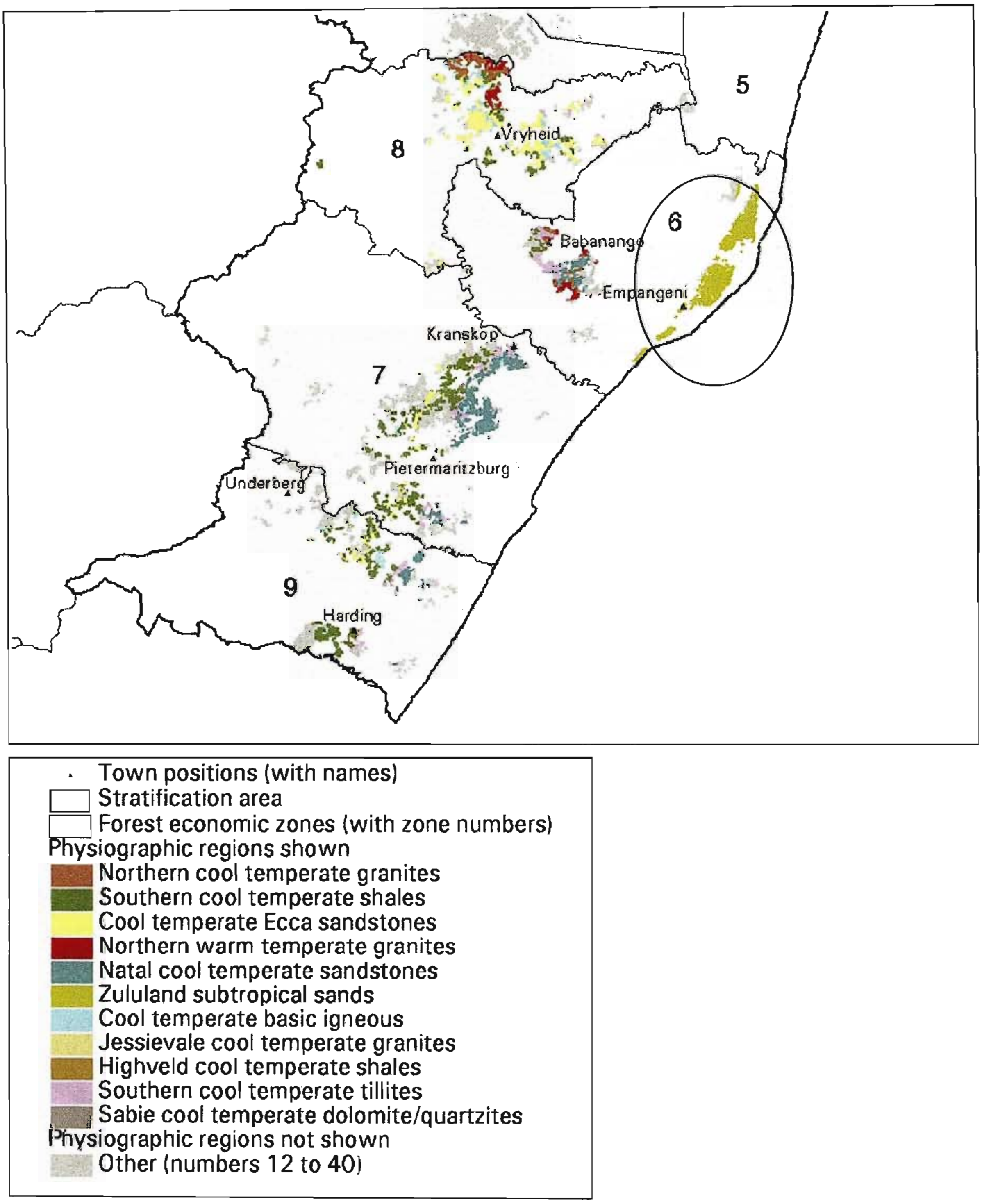
105. ZWOLINSKI, J.B., HENSLEY, M. and MONNIK, K.A., 1998. Site conditions and growth of pines at the North Eastern Cape Forests. *South African Forestry Journal* 183: 1 – 16.

APPENDICES

APPENDIX 1: Solar radiation for KZN in selected months (Clemence, 1992 in Schulze, 1997).

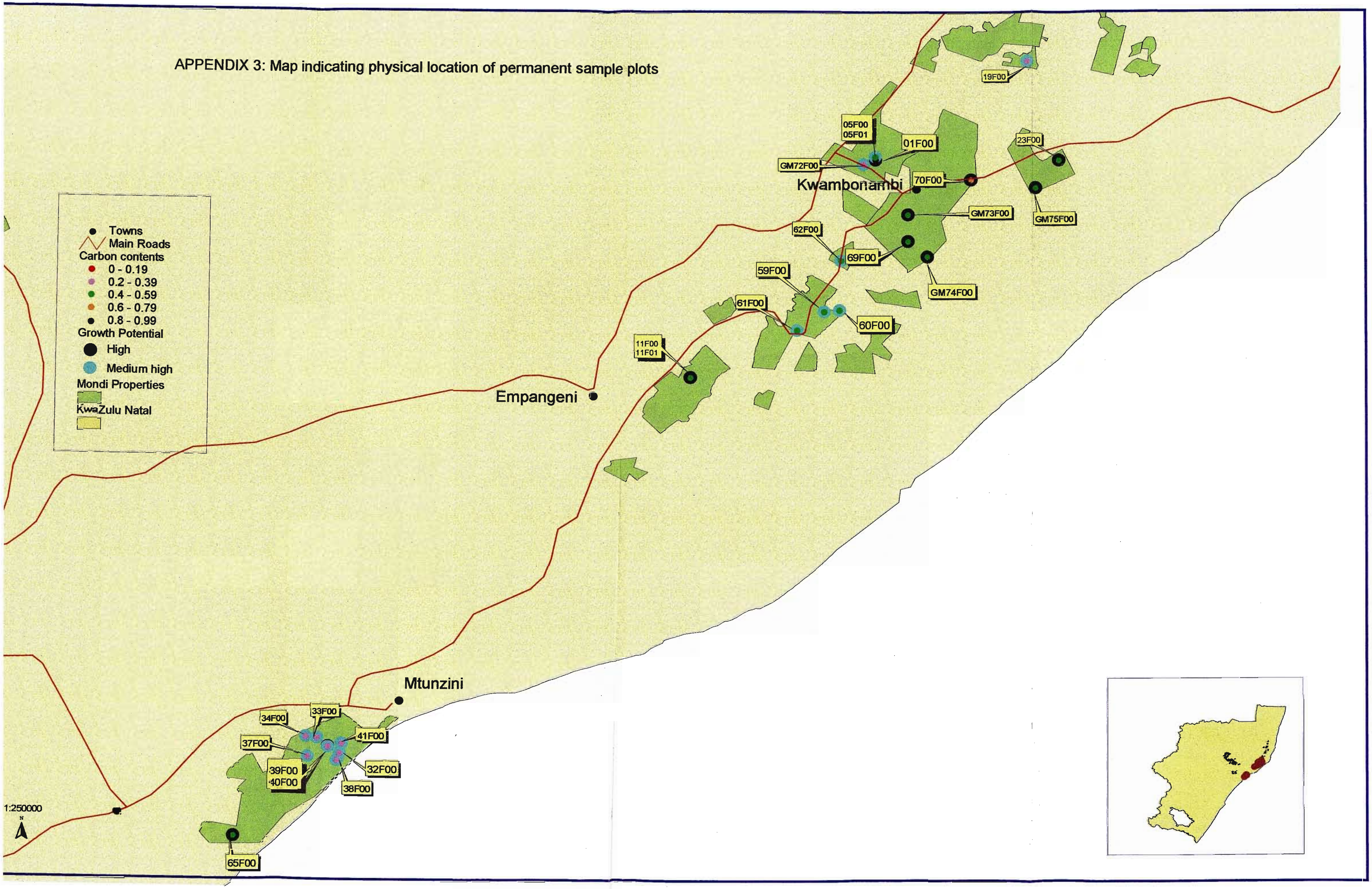
Solar Radiation MJ/m²/day¹, in selected months							
Month	Mean Value	CV (%)	Maximum Value	Minimum Value	Exceedence probability		
					20%	50%	80%
January	27,8	7	43,4	21,0	34,9	31,8	28,0
July	15,9	6	17,9	11,6	16,9	16,0	15,1
October	25,9	8	32,8	18,4	27,7	26,2	24,0
December	28,7	7	36,8	20,9	30,6	28,9	26,8

APPENDIX 2: Map indicating MMRC zones 5,6,7,8 and 9.



APPENDIX 3: Map indicating physical location of permanet sample plots.

APPENDIX 3: Map indicating physical location of permanent sample plots



APPENDIX 4: An example of raw measured tree data.

Plotid	Myear	Mmonth	Mday	Stump	Stem	dbh	ht	Status
MONEF0005F00	1991	4	1	1	1	14,9	0,0	0
MONEF0005F00	1991	4	1	2	1	13,2	17,9	0
MONEF0005F00	1991	4	1	3	1	15,5	0,0	0
MONEF0005F00	1991	4	1	4	1	14,2	18,0	0
MONEF0005F00	1991	4	1	5	1	13,1	0,0	0
MONEF0005F00	1991	4	1	6	1	15,2	18,2	0
MONEF0005F00	1991	4	1	7	1	15,3	0,0	0
MONEF0005F00	1991	4	1	8	1	15,2	17,6	0
MONEF0005F00	1991	4	1	9	1	14,6	0,0	0
MONEF0005F00	1991	4	1	10	1	16,1	18,3	0
MONEF0005F00	1991	4	1	11	1	14,5	0,0	0
MONEF0005F00	1991	4	1	12	1	15,3	0,0	0
MONEF0005F00	1991	4	1	13	1	14,6	0,0	0
MONEF0005F00	1991	4	1	14	1	14,9	17,0	0
MONEF0005F00	1991	4	1	15	1	12,1	0,0	0
MONEF0005F00	1991	4	1	16	1	13,1	16,2	0
MONEF0005F00	1991	4	1	17	1	13,1	0,0	0
MONEF0005F00	1991	4	1	18	1	9,9	17,4	0
MONEF0005F00	1991	4	1	19	1	12,9	0,0	0
MONEF0005F00	1991	4	1	20	1	16,9	0,0	0
MONEF0005F00	1991	4	1	21	1	13,9	0,0	0
MONEF0005F00	1991	4	1	22	1	7,6	0,0	0
MONEF0005F00	1991	4	1	23	1	14,3	0,0	0
MONEF0005F00	1991	4	1	24	1	14,7	17,9	0
MONEF0005F00	1991	4	1	25	1	12,9	17,0	0
MONEF0005F00	1991	4	1	26	1	11,9	0,0	0
MONEF0005F00	1991	4	1	27	1	15,6	18,1	0
MONEF0005F00	1991	4	1	28	1	14,9	0,0	0
MONEF0005F00	1991	4	1	29	1	10,8	15,2	0
MONEF0005F00	1991	4	1	30	1	8,9	0,0	0
MONEF0005F00	1991	4	1	31	1	15,5	0,0	0
MONEF0005F00	1991	4	1	32	1	14,3	16,4	0
MONEF0005F00	1991	4	1	33	1	15,4	0,0	0
MONEF0005F00	1991	4	1	34	1	18,9	20,1	0
MONEF0005F00	1991	4	1	35	1	15,5	0,0	0
MONEF0005F00	1991	4	1	36	1	15,2	18,0	0
MONEF0005F00	1992	5	1	1	1	16,5	22,1	0
MONEF0005F00	1992	5	1	2	1	14,6	20,1	0
MONEF0005F00	1992	5	1	3	1	17,2	20,6	0
MONEF0005F00	1992	5	1	4	1	15,5	20,4	0
MONEF0005F00	1992	5	1	5	1	14,1	19,2	0
MONEF0005F00	1992	5	1	6	1	17,0	20,4	0
MONEF0005F00	1992	5	1	7	1	16,6	21,2	0
MONEF0005F00	1992	5	1	8	1	16,7	21,2	0
MONEF0005F00	1992	5	1	9	1	16,1	21,1	0
MONEF0005F00	1992	5	1	10	1	18,1	21,2	0
MONEF0005F00	1992	5	1	11	1	15,7	19,2	0
MONEF0005F00	1992	5	1	12	1	16,3	21,0	0
MONEF0005F00	1992	5	1	13	1	15,9	21,2	0
MONEF0005F00	1992	5	1	14	1	15,7	21,4	0
MONEF0005F00	1992	5	1	15	1	15,7	20,2	0
MONEF0005F00	1992	5	1	16	1	12,7	18,1	0
MONEF0005F00	1992	5	1	17	1	14,1	19,3	0
MONEF0005F00	1992	5	1	18	1	9,9	15,1	0
MONEF0005F00	1992	5	1	19	1	13,4	18,1	0
MONEF0005F00	1992	5	1	20	1	18,1	21,4	0
MONEF0005F00	1992	5	1	21	1	14,9	18,2	0
MONEF0005F00	1992	5	1	22	1	7,5	12,2	0
MONEF0005F00	1992	5	1	23	1	15,8	20,2	0
MONEF0005F00	1992	5	1	24	1	16,0	21,1	0

Plotid	Myear	Mmonth	Mday	Stump	Stem	dbh	ht	Status
MONEF0005F00	1992	5	1	25	1	13,7	18,3	0
MONEF0005F00	1992	5	1	26	1	12,5	17,2	0
MONEF0005F00	1992	5	1	27	1	17,3	21,2	0
MONEF0005F00	1992	5	1	28	1	16,4	21,2	0
MONEF0005F00	1992	5	1	29	1	10,9	17,1	0
MONEF0005F00	1992	5	1	30	1	8,9	14,1	0
MONEF0005F00	1992	5	1	31	1	16,9	21,1	0
MONEF0005F00	1992	5	1	32	1	15,8	20,6	0
MONEF0005F00	1992	5	1	33	1	17,1	22,1	0
MONEF0005F00	1992	5	1	34	1	16,2	22,2	0
MONEF0005F00	1992	5	1	35	1	16,8	20,1	0
MONEF0005F00	1992	5	1	36	1	16,7	20,3	0
MONEF0005F00	1992	10	1	1	1	17,4	21,3	0
MONEF0005F00	1992	10	1	2	1	15,1	19,2	0
MONEF0005F00	1992	10	1	3	1	18,0	20,1	0
MONEF0005F00	1992	10	1	4	1	16,3	20,1	0
MONEF0005F00	1992	10	1	5	1	14,6	19,2	0
MONEF0005F00	1992	10	1	6	1	17,6	20,1	0
MONEF0005F00	1992	10	1	7	1	17,3	21,2	0
MONEF0005F00	1992	10	1	8	1	17,3	20,2	0
MONEF0005F00	1992	10	1	9	1	16,5	20,1	0
MONEF0005F00	1992	10	1	10	1	18,9	22,1	0
MONEF0005F00	1992	10	1	11	1	16,2	20,3	0
MONEF0005F00	1992	10	1	12	1	16,9	21,2	0
MONEF0005F00	1992	10	1	13	1	16,7	21,2	0
MONEF0005F00	1992	10	1	14	1	17,0	21,1	0
MONEF0005F00	1992	10	1	15	1	14,8	20,1	0
MONEF0005F00	1992	10	1	16	1	14,4	19,2	0
MONEF0005F00	1992	10	1	17	1	9,9	15,1	0
MONEF0005F00	1992	10	1	18	1	13,6	18,1	0
MONEF0005F00	1992	10	1	19	1	19,2	22,1	0
MONEF0005F00	1992	10	1	20	1	15,5	19,3	0
MONEF0005F00	1992	10	1	21	1	7,6	12,2	0
MONEF0005F00	1992	10	1	22	1	16,5	20,1	0
MONEF0005F00	1992	10	1	23	1	0,0	0,0	2
MONEF0005F00	1992	10	1	24	1	16,5	21,1	0
MONEF0005F00	1992	10	1	25	1	0,0	0,0	2
MONEF0005F00	1992	10	1	26	1	14,0	18,1	0
MONEF0005F00	1992	10	1	27	1	12,6	17,2	0
MONEF0005F00	1992	10	1	28	1	18,1	20,3	0
MONEF0005F00	1992	10	1	29	1	17,0	19,4	0
MONEF0005F00	1992	10	1	30	1	11,1	16,2	0
MONEF0005F00	1992	10	1	31	1	17,4	20,1	0
MONEF0005F00	1992	10	1	32	1	16,8	21,2	0
MONEF0005F00	1992	10	1	33	1	17,9	21,1	0
MONEF0005F00	1992	10	1	34	1	22,7	23,1	0
MONEF0005F00	1992	10	1	35	1	17,7	21,1	0
MONEF0005F00	1992	10	1	36	1	17,4	20,4	0
MONEF0005F00	1993	7	1	1	1	13,7	20,5	0
MONEF0005F00	1993	7	1	2	1	0,0	0,0	2
MONEF0005F00	1993	7	1	3	1	16,2	22,5	0
MONEF0005F00	1993	7	1	4	1	21,5	24,5	0
MONEF0005F00	1993	7	1	5	1	0,0	0,0	2
MONEF0005F00	1993	7	1	6	1	16,5	20,5	0
MONEF0005F00	1993	7	1	7	1	15,1	21,0	0
MONEF0005F00	1993	7	1	8	1	26,2	26,0	0
MONEF0005F00	1993	7	1	9	1	20,4	24,5	0
MONEF0005F00	1993	7	1	10	1	23,0	24,5	0
MONEF0005F00	1993	7	1	11	1	16,3	21,5	0

PlotId	Myear	Mmonth	Mday	Stump	Stem	dbh	ht	Status
MONEF0005F00	1993	7	1	12	1	23,0	24,5	0
MONEF0005F00	1993	7	1	13	1	0,0	0,0	2
MONEF0005F00	1993	7	1	14	1	0,0	0,0	2
MONEF0005F00	1993	7	1	15	1	19,2	24,5	0
MONEF0005F00	1993	7	1	16	1	14,5	19,5	0
MONEF0005F00	1993	7	1	17	1	0,0	0,0	2
MONEF0005F00	1993	7	1	18	1	9,2	17,0	0
MONEF0005F00	1993	7	1	19	1	18,6	23,5	0
MONEF0005F00	1993	7	1	20	1	21,0	25,0	0
MONEF0005F00	1993	7	1	21	1	21,7	23,5	0
MONEF0005F00	1993	7	1	22	1	0,0	0,0	2
MONEF0005F00	1993	7	1	23	1	21,8	24,0	0
MONEF0005F00	1993	7	1	24	1	0,0	0,0	2
MONEF0005F00	1993	7	1	25	1	19,7	24,0	0
MONEF0005F00	1993	7	1	26	1	21,3	24,0	0
MONEF0005F00	1993	7	1	27	1	20,7	24,5	0
MONEF0005F00	1993	7	1	28	1	9,8	14,5	0
MONEF0005F00	1993	7	1	29	1	20,9	26,0	0
MONEF0005F00	1993	7	1	30	1	19,5	23,0	0
MONEF0005F00	1993	7	1	31	1	17,4	21,0	0
MONEF0005F00	1993	7	1	32	1	20,1	25,0	0
MONEF0005F00	1993	7	1	33	1	18,1	24,0	0
MONEF0005F00	1993	7	1	34	1	19,8	23,5	0
MONEF0005F00	1993	7	1	35	1	0,0	0,0	2
MONEF0005F00	1993	7	1	36	1	21,8	24,5	0

APPENDIX 5: An excerpt from plot summary data by measuring period.

Plotid	AGE	TPH0	TPH2	Psurv	Spplot	MIN_DBH	MEAN_DBH	DQ	STD_DBH	HTOP80	TreeVol	Vol_Ha	MAI	BA
MONEF0001F00	4,21	1579	1579	100,0	36	10,2	16,4	16,5	1,8	22,6	0,247	389,3	92,5	33,8
MONEF0001F00	5,29	1579	1579	100,0	36	10,2	17,4	17,6	2,4	23,9	0,284	448,5	84,7	38,3
MONEF0001F00	5,71	1579	1579	100,0	36	10,3	18,1	18,3	2,7	26,0	0,333	526,0	92,1	41,4
MONEF0001F00	5,80	1579	1579	100,0	36	10,9	18,2	18,4	2,6	29,5	0,379	598,1	103,2	42,0
MONEF0001F00	5,88	1579	1579	100,0	36	10,3	18,1	18,3	2,7	28,7	0,371	585,7	99,6	41,6
MONEF0001F00	5,96	1579	1579	100,0	36	10,4	18,4	18,6	2,8	27,7	0,361	570,5	95,7	42,7
MONEF0001F00	6,05	1579	1579	100,0	36	10,4	18,4	18,6	2,8	29,7	0,396	624,6	103,3	42,9
MONEF0001F00	6,13	1579	1579	100,0	36	10,4	18,4	18,6	2,8	30,4	0,406	641,3	104,7	43,0
MONEF0001F00	6,46	1579	1579	100,0	36	10,5	18,7	18,9	3,0	29,0	0,399	630,5	97,6	44,4
MONEF0001F00	6,80	1579	1579	100,0	36	11,1	19,0	19,3	3,0	31,5	0,435	687,4	101,2	46,0
MONEF0005F00	4,12	1558	1558	100,0	36	7,6	14,0	14,2	2,2	18,2	0,149	218,9	53,1	24,6
MONEF0005F00	5,21	1558	1558	100,0	36	7,5	15,1	15,3	2,5	21,3	0,201	295,8	56,8	28,6
MONEF0005F00	5,63	1558	1472	94,5	34	7,6	16,1	16,3	2,8	21,5	0,228	325,3	57,8	30,7
MONEF0005F00	6,37	1558	1212	77,8	28	9,2	18,8	19,2	3,9	25,0	0,363	439,4	68,9	35,1
MONEF0005F01	2,82	1121	1121	100,0	36	5,7	11,9	12,0	1,5	13,0	0,072	78,5	27,9	12,6
MONEF0005F01	3,60	1121	1121	100,0	36	6,0	13,8	13,9	1,8	16,6	0,128	139,7	38,8	17,0
MONEF0005F01	4,56	1121	1121	100,0	36	6,1	15,0	15,2	2,1	19,4	0,181	197,2	43,2	20,3
MONEF0011F00	3,46	1091	1061	97,3	35	11,1	16,2	16,3	1,9	18,9	0,198	209,8	60,6	22,1
MONEF0011F00	4,55	1091	1061	97,3	35	11,3	17,3	17,5	2,4	24,2	0,285	301,9	66,4	25,5
MONEF0011F00	4,96	1091	1061	97,3	35	11,3	17,6	17,8	2,5	24,1	0,299	316,6	63,8	26,4
MONEF0011F00	5,71	1091	1061	97,3	35	11,5	18,3	18,5	2,8	25,5	0,342	362,4	63,5	28,5
MONEF0011F01	1,88	1121	1090	97,2	35	6,2	10,7	10,9	1,6	11,4	0,055	49,7	26,5	10,1
MONEF0011F01	3,12	1121	1090	97,2	35	8,7	14,8	14,9	1,9	15,9	0,144	152,6	48,8	19,0
MONEF0011F01	3,88	1121	1090	97,2	35	8,7	15,9	16,0	2,0	18,2	0,191	202,3	52,2	22,0
MONEF0019F00	3,21	1429	1389	97,2	35	9,7	13,5	13,5	1,1	16,6	0,116	161,5	50,3	19,9
MONEF0019F00	3,46	1429	1389	97,2	35	9,8	13,6	13,6	1,1	16,8	0,120	166,6	48,1	20,3
MONEF0019F00	3,55	1429	1389	97,2	35	9,9	13,8	13,8	1,2	17,8	0,130	180,1	50,8	20,8
MONEF0019F00	3,63	1429	1389	97,2	35	9,9	13,8	13,8	1,1	17,7	0,129	179,1	49,3	20,8
MONEF0019F00	3,72	1429	1389	97,2	35	10,0	14,0	14,0	1,1	17,8	0,133	185,3	49,9	21,4
MONEF0019F00	3,80	1429	1389	97,2	35	10,6	14,0	14,0	1,1	20,0	0,147	204,8	53,9	21,4
MONEF0019F00	3,88	1429	1389	97,2	35	9,8	13,9	13,9	1,2	18,9	0,142	197,4	50,9	21,2
MONEF0019F00	4,21	1429	1389	97,2	35	9,7	14,0	14,0	1,2	18,5	0,139	193,0	45,8	21,5

Plotid	AGE	TPH0	TPH2	Psurv	Spplot	MIN_DBH	MEAN_DBH	DQ	STD_DBH	HTOP80	TreeVol	Vol_Ha	MAI	BA
MONEF0019F00	4,55	1429	1389	97,2	35	10,0	14,3	14,4	1,3	18,9	0,150	207,7	45,7	22,5
MONEF0019F00	4,80	1429	1389	97,2	35	10,1	14,3	14,4	1,4	20,5	0,161	223,5	46,6	22,6
MONEF0019F00	6,13	1429	1389	97,2	35	10,0	15,2	15,3	1,7	22,8	0,200	278,3	45,4	25,5
MONEF0019F00	7,52	1429	1389	97,2	35	10,9	16,3	16,4	2,1	26,1	0,260	361,0	48,0	29,4
MONEF0019F00	8,03	1429	1389	97,2	35	11,4	16,9	17,0	2,2	24,8	0,274	380,3	47,4	31,5
MONEF0023F00	3,21	1457	1093	75,0	27	0,1	12,2	14,1	7,3	16,5	0,191	147,2	45,8	17,2
MONEF0023F00	3,46	1457	1215	83,4	30	0,1	11,1	13,6	7,9	17,0	0,201	154,8	44,7	17,6
MONEF0023F00	4,21	1457	810	55,6	20	7,1	17,3	17,6	3,1	18,9	0,250	192,5	45,7	19,6
MONEF0023F00	5,30	1457	810	55,6	20	9,2	18,3	18,5	3,1	20,7	0,287	232,7	44,0	21,8
MONEF0023F00	6,13	1457	810	55,6	20	9,7	18,9	19,2	3,3	22,5	0,331	268,3	43,8	23,3
MONEF0023F00	7,49	1457	850	58,3	21	7,1	19,8	20,3	4,7	26,3	0,464	375,8	50,2	27,6
MONEF0023F00	9,27	1457	850	58,3	21	7,7	21,2	21,8	5,2	29,4	0,578	468,0	50,5	31,7
MONEF0032F00	3,04	1324	1250	94,4	34	5,3	15,7	15,9	3,1	18,4	0,197	231,6	76,1	25,0
MONEF0032F00	3,30	1324	1213	91,6	33	7,7	16,2	16,4	2,5	19,3	0,211	247,9	75,2	25,6
MONEF0032F00	4,04	1324	1213	91,6	33	7,7	16,6	16,8	2,6	20,9	0,241	283,1	70,0	27,0
MONEF0032F00	5,13	1324	1213	91,6	33	8,0	17,2	17,4	2,7	21,7	0,268	314,8	61,4	28,9
MONEF0032F00	5,88	1324	1213	91,6	33	8,1	17,5	17,7	2,9	25,0	0,313	367,8	62,6	30,0
MONEF0032F00	7,23	1324	1213	91,6	33	9,2	18,9	19,1	3,3	26,9	0,377	457,1	63,3	34,9
MONEF0032F00	8,14	1324	1213	91,6	33	9,8	19,7	20,0	3,6	29,7	0,450	545,9	67,1	38,1
MONEF0032F00	8,62	1324	1213	91,6	33	10,2	20,0	20,3	3,7	30,3	0,474	575,5	66,8	39,4
MONEF0032F00	9,10	1324	1213	91,6	33	10,4	20,1	20,5	3,9	27,0	0,427	518,2	56,9	39,9
MONEF0033F00	3,21	1385	1346	97,2	35	4,8	13,9	14,1	2,6	15,6	0,123	160,7	50,0	21,0
MONEF0033F00	3,46	1385	1346	97,2	35	5,1	14,3	14,5	2,6	15,9	0,135	176,3	50,9	22,4
MONEF0033F00	4,21	1385	1308	94,4	34	11,0	15,5	15,6	2,3	17,9	0,171	224,2	53,2	25,0
MONEF0033F00	5,30	1385	1308	94,4	34	11,5	16,5	16,7	2,5	19,3	0,213	278,6	52,6	28,6
MONEF0033F00	6,04	1385	1308	94,4	34	11,5	16,9	17,1	2,6	21,2	0,241	315,1	52,1	29,9
MONEF0033F00	7,38	1385	1308	94,4	34	12,0	18,1	18,3	3,0	25,0	0,320	418,8	56,7	34,4
MONEF0033F00	8,14	1385	1308	94,4	34	12,6	18,6	18,8	3,1	26,2	0,356	465,9	57,3	36,3
MONEF0034F00	3,04	1385	1192	86,1	31	10,3	13,8	13,8	1,3	14,5	0,109	130,0	42,7	17,9
MONEF0034F00	3,30	1385	1192	86,1	31	10,3	14,4	14,5	1,5	14,9	0,125	148,7	45,1	19,7
MONEF0034F00	4,04	1385	1192	86,1	31	11,5	15,7	15,8	1,7	18,6	0,181	215,8	53,4	23,3
MONEF0034F00	5,13	1385	1192	86,1	31	13,3	17,1	17,2	2,0	21,0	0,247	294,2	57,4	27,8
MONEF0034F00	5,88	1385	1192	86,1	31	13,9	17,5	17,6	2,0	21,6	0,268	319,2	54,3	29,1

APPENDIX 6: Soils Data.

TABLE 1. General soils data per PSP used in this study.

Plotid	Soil form & family	ERD (mm)	Carbon Content	TAW (mm)	Growth Potential
MONEF0001F00	Hu2200	151	m	143	H
MONEF0005F00	Vf2220	151	lm	146	Hm
MONEF0005F01	Vf2220	151	lm	146	Hm
MONEF0011F00	Hu2200	151	m	139	H
MONEF0011F01	Hu2200	151	m	139	H
MONEF0019F00	Oa1110	151	m	118	Mh
MONEF0023F00	Fw1210	151	lm	161	H
MONEF0032F00	Hu2200	151	lm	163	Hm
MONEF0033F00	Hu2200	151	lm	139	hm
MONEF0034F00	Vf2220	151	m	152	hm
MONEF0037F00	Oa1110	151	m	134	hm
MONEF0038F00	Fw1210	151	lm	160	mh
MONEF0039F00	Hu2200	151	lm	135	h
MONEF0040F00	Hu2200	151	lm	149	hm
MONEF0041F00	Vf2220	151	lm	147	hm
MONEF0059F00	Hu2100	151	m	161	hm
MONEF0060F00	Fw1210	151	lm	160	hm
MONEF0061F00	Fw1210	151	lm	160	hm
MONEF0062F00	Fw1210	151	lm	160	hm
MONEF0065F00	Hu2200	151	m	116	h
MONEF0067F00	Hu2100	151	m	161	hm
MONEF0069F00	Fw1110	151	lm	164	h
MONEF0070F00	Fw1110	151	lm	161	h
MONEFGM72F00	Gf2100	151	lm	160	hm
MONEFGM73F00	Fw1110	151	lm	161	h
MONEFGM74F00	Fw1110	151	lm	161	h
MONEFGM75F00	Fw1210	151	lm	162	h

TABLE 2. Soil properties per horizon for every PSP data set used in this study.

Plotid	HORIZON	DEPTH	HORIZORDER	CLAY_PCENT	SANDGRADE	COLOUR	MUN_COLOUR	STRUCTURE	WETNESS
MONEF0001F00	A	40	1	5	M	BR	5YR43	sg	
	B1	90	2	12	M	RB	25YR34	sg	
	B2	151	3	35	M	R	25YR36	a	
MONEF0005F00	A	30	1	5	M	PB	5YR43	sg	
MONEF0005F01	E	100	2	5	M	PBR	75YR54	sg	
	B	151	3	40	M	R	25YR48	wb	
MONEF0011F00	A	30	1	5	M	B	5YR44	sg	
MONEF0011F01	B1	85	2	15	M	RB	25YR46	a	
	B2	151	3	25	M	R	25YR46	a	
MONEF0019F00	A	40	1	35	M	B	10YR31	a	
	B	151	2	40	M	MYB	10YR56	a	
MONEF0023F00	A	20	1	5	M	PBG	10YR52	sg	
	E1	70	2	5	M	PGB	10YR53	sg	
	E2	151	3	8	M	PY	10YR54	sg	
MONEF0032F00	A	25	1	5	M	PBR	5YR44	sg	
	B	151	2	12	M	R	25YR48	a	
MONEF0033F00	A	20	1	5	M	PBR	5YR53	sg	
	B1	80	2	6	M	R	5YR44	sg	
	B2	151	3	35	M	R	5YR44	wb	
MONEF0034F00	A	30	1	12	M	B	75YR42	a	
	E	120	2	5	M	PB	5YR53	sg	
	B	151	3	35	M	RMB	25YR36	m	

Plotid	HORIZON	DEPTH	HORIZORDER	CLAY_PCENT	SANDGRADE	COLOUR	MUN_COLOUR	STRUCTURE	WETNESS
MONEF0037F00	A	45	1	10	M	B	75YR42	sg	
	B	151	2	45	M	R	25YR36	wb	
MONEF0038F00	A	40	1	5	M	PB	75YR42	sg	
	E	151	2	5	M	PYR	75YR54	sg	
MONEF0039F00	A	50	1	5	M	BR	5YR46	sg	
	B	151	2	45	F	R	25YR48	a	
MONEF0040F00	A	20	1	5	M	PYB	5YR55	sg	
	B1	100	2	9	M	RP	5YR44	sg	
	B2	151	3	45	M	R	25YR46	wb	
MONEF0041F00	A	25	1	5	M	PB	75YR52	sg	
	E	110	2	5	M	P	75YR64	sg	
	B	151	3	30	M	MPR	5YR66	m	
MONEF0042F00	A	15	1	6	M	BG	10YR42	sg	
	E	140	2	5	M	P	10YR63	sg	W1
	B	151	3	12	M	MGBR	10YR52	m	W1
MONEF0059F00	A	35	1	5	M	PBR	5YR42	sg	
	B	110	2	8	M	RP	5YR46	sg	
	C	151	3	5	M	PPR	5YR64	sg	
MONEF0060F00	A	25	1	5	M	PBG	10YR42	sg	
	E	151	2	5	M	PY	10YR54	sg	
MONEF0061F00	A	25	1	5	M	PB	10YR53	sg	
	E	151	2	5	M	PY	10YR54	sg	

Plotid	HORIZON	DEPTH	HORIZORDER	CLAY_PCENT	SANDGRADE	COLOUR	MUN_COLOUR	STRUCTURE	WETNESS
MONEF0062F00	A	30	1	5	M	PBG	10YR42	sg	
	E	151	2	5	M	PPY	10YRP54	sg	
MONEF0065F00	A	35	1	25	M	BR	25YR46	a	
	B1	100	2	35	M	R	25YR48	a	
	B2	151	3	45	M	R	25YR8	wb	
MONEF0067F00	A	30	1	5	M	BRP	5YR54	sg	
	B	100	2	7	M	RBP	5YR44	sg	
	C	151	3	5	M	PR	5YR53	sg	
MONEF0069F00	A	40	1	8	M	BP	10YR42	sg	
	E1	80	2	10	M	P	10YR52	sg	
	E2	151	3	15	M	PPY	10YR53	a	
MONEF0070F00	A	30	1	5	M	PBG	10YR52	sg	
	E	151	2	8	M	PG	10YR62	sg	
MONEFGM72F00	A	40	1	5	M	PB	5YR43	sg	
	B1	120	2	5	M	YRP	75YR56	sg	
	B2	151	3	6	M	R	5YR56	sg	
MONEFGM73F00	A	35	1	5	M	PBG	10YR52	sg	
	E	151	2	8	M	P	10YR53	sg	W1
MONEFGM74F00	A	40	1	5	M	PB	10YR42	sg	
	E	151	2	8	M	P	10YR53	sg	
MONEFGM75F00	A	20	1	5	M	PBG	10YR42	sg	
	E1	60	2	5	M	PPY	10YR63	sg	
	E2	151	3	12	M	PY	10YR54	a	

APPENDIX 7: Monthly median rainfall (mm) estimates for the study area by PSP.

Plot number	Latitude	Longitude	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec	TOTAL
MONEF0001F00	283515	320428	103,5	101,4	101,6	60,5	39,1	30,6	27,6	29,5	56,4	82,5	92,6	87,5	**812,8**
MONEF0005F00	283508	320427	103,5	101,4	101,6	60,5	39,1	30,6	27,6	29,5	56,4	82,5	92,6	87,5	**812,8**
MONEF0005F01	283508	320427	103,5	101,4	101,6	60,5	39,1	30,6	27,6	29,5	56,4	82,5	92,6	87,5	**812,8**
MONEF0011F00	284355	315721	114,5	110	117,6	81	55,5	43,8	41,4	45,5	68,9	88,2	103,7	107,6	**977,7**
MONEF0011F01	284355	315721	114,5	110	117,6	81	55,5	43,8	41,4	45,5	68,9	88,2	103,7	107,6	**977,7**
MONEF0019F00	283115	321001	96,1	105,9	104,4	56,4	38,3	32,1	26,3	30,3	53	73	87	79,3	**782,1**
MONEF0023F00	283515	321125	104,7	112,4	123,1	75,4	54,6	43,8	41,2	41,2	62	84,9	97,5	90,6	**931,4**
MONEF0032F00	285904	314348	129,1	124,3	126,6	84,9	54	45,7	41,9	47,2	76,1	103,9	126,1	118,1	**1077,9**
MONEF0033F00	285827	314256	126	123,5	124,7	82,9	51,9	43,9	40,4	45,5	74,5	102,6	127,1	116,9	**1059,9**
MONEF0034F00	285823	314229	123,8	122,5	124,5	79,4	49,4	41,8	37,9	43,9	73,6	100,5	127,7	114,6	**1039,6**
MONEF0037F00	285912	314235	129,6	125,9	128,4	84,1	53,1	45,1	40,8	46,9	76,9	104,4	128,7	118,8	**1082,7**
MONEF0038F00	285920	314342	129,1	124,3	126,6	84,9	54	45,7	41,9	47,2	76,1	103,9	126,1	118,1	**1077,9**
MONEF0039F00	285847	314321	129,6	125,9	128,4	84,1	53,1	45,1	40,8	46,9	76,9	104,4	128,7	118,8	**1082,7**
MONEF0040F00	285848	314321	129,6	125,9	128,4	84,1	53,1	45,1	40,8	46,9	76,9	104,4	128,7	118,8	**1082,7**
MONEF0041F00	285840	314353	129,1	124,3	126,6	84,9	54	45,7	41,9	47,2	76,1	103,9	126,1	118,1	**1077,9**
MONEF0059F00	284119	320229	107,7	101,1	107,4	69,6	45,3	36,9	33,4	35,3	58,3	82	95,2	93,9	**866,1**
MONEF0060F00	284154	320306	103,5	97,7	105,8	70,4	46,9	37,3	34,4	36,6	57,2	79,3	91,1	89,6	**849,8**
MONEF0061F00	284200	320126	112,2	104,9	112	73,2	47,7	39	35,3	37,6	61	85,1	99,8	99,5	**907,3**
MONEF0062F00	283913	320350	109,4	102,3	106,8	66,3	44,2	35,2	32,6	33,6	58,1	84,3	93,2	91,4	**857,4**
MONEF0065F00	290224	313940	129,7	119,7	132,2	78,6	54,9	49,9	39,9	51,1	82,3	97,3	122,2	111	**1068,8**
MONEF0069F00	283822	320550	110,3	104,2	109,7	66	45,9	35,7	34,3	34,7	58,7	85,6	91,8	90,2	**867,1**
MONEF0070F00	283556	320806	105,1	106,2	113,7	68,2	47,6	37,3	34,5	35,9	59,1	82,7	92,8	88,3	**871,4**
MONEFGM72F0	283526	320400	103,5	101,4	101,6	60,5	39,1	30,6	27,6	29,5	56,4	82,5	92,6	87,5	**812,8**
MONEFGM73F0	283727	320544	109,3	105,2	109,8	65,7	45,1	35,2	33,2	34	58,9	85,4	93	90,2	**865**
MONEFGM74F0	283909	320631	109,3	105,9	115,2	72,2	50,4	39,2	37,3	38,5	60,6	85	94	91,4	**899**
MONEFGM75F0	283622	321044	108,7	116,9	130,8	80,1	58,3	45,9	43,6	44,1	65,5	88,3	101,3	94,6	**978,1**
		Mean	**114,42**	**111,72**	**116,41**	**73,67**	**48,82**	**39,83**	**36,37**	**39,75**	**65,58**	**90,28**	**106,00**	**100,67**	
		Min	**96,10**	**97,70**	**101,60**	**56,40**	**38,30**	**30,60**	**26,30**	**29,50**	**53,00**	**73,00**	**87,00**	**79,30**	
		Max	**129,70**	**125,90**	**132,20**	**84,90**	**58,30**	**49,90**	**43,60**	**51,10**	**82,30**	**104,40**	**128,70**	**118,80**	

APPENDIX 8a: Mean monthly maximum temperature per PSP (degrees Celsius).

PSP number	Lat.	Long.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
MONEF0001F00	283515	320428	29,8	29,6	28,9	27,1	25,5	23,7	23,6	24,5	25,3	26	27,1	29,1
MONEF0005F00	283508	320427	29,8	29,6	28,9	27,1	25,5	23,7	23,6	24,5	25,3	26	27,1	29,1
MONEF0005F01	283508	320427	29,8	29,6	28,9	27,1	25,5	23,7	23,6	24,5	25,3	26	27,1	29,1
MONEF0011F00	284355	315721	29,1	29	28,4	26,7	25,2	23,4	23,2	23,9	24,7	25,4	26,5	28,4
MONEF0011F01	284355	315721	29,1	29	28,4	26,7	25,2	23,4	23,2	23,9	24,7	25,4	26,5	28,4
MONEF0019F00	283115	321001	30,1	29,8	29,2	27,3	25,7	23,9	23,8	24,7	25,5	26,2	27,4	29,4
MONEF0023F00	283515	321138	29,7	29,4	28,8	27,1	25,5	23,7	23,6	24,4	25,2	25,8	27	29
MONEF0032F00	285904	314348	28,6	28,6	28	26,5	25,1	23,4	23,2	23,7	24,4	25,1	26	27,8
MONEF0033F00	285827	314256	28,5	28,5	28	26,5	25	23,3	23,1	23,7	24,4	25	26	27,8
MONEF0034F00	285823	314229	28,5	28,5	28	26,4	25	23,3	23,1	23,7	24,4	25	26	27,8
MONEF0037F00	285912	314235	28,5	28,5	28	26,4	25	23,3	23,1	23,7	24,3	25	26	27,8
MONEF0038F00	285920	314342	28,6	28,6	28	26,5	25,1	23,4	23,2	23,7	24,4	25,1	26	27,8
MONEF0039F00	285847	314321	28,5	28,5	28	26,4	25	23,3	23,1	23,7	24,3	25	26	27,8
MONEF0040F00	285848	314321	28,5	28,5	28	26,4	25	23,3	23,1	23,7	24,3	25	26	27,8
MONEF0041F00	285840	314353	28,6	28,6	28	26,5	25,1	23,4	23,2	23,7	24,4	25,1	26	27,8
MONEF0059F00	284119	320229	29,6	29,3	28,7	26,9	25,4	23,6	23,4	24,2	25	25,7	26,8	28,8
MONEF0060F00	284154	320306	29,4	29,2	28,5	26,8	25,2	23,5	23,3	24	24,8	25,5	26,7	28,6
MONEF0061F00	284200	320126	29,5	29,3	28,7	27	25,4	23,7	23,5	24,2	25	25,7	26,8	28,8
MONEF0062F00	283913	320350	29,9	29,7	29,1	27,3	25,7	23,9	23,8	24,6	25,4	26,1	27,2	29,2
MONEF0065F00	290224	313940	28,3	28,3	27,8	26,3	24,9	23,2	23	23,6	24,2	24,9	25,8	27,6
MONEF0067F00	290036	311910	27,2	27,5	26,8	25,3	23,7	21,7	21,7	22,8	23,6	24,2	25	26,8
MONEF0069F00	283822	320550	29,8	29,5	28,9	27,2	25,6	23,8	23,7	24,5	25,3	26	27,1	29
MONEF0070F00	283556	320806	29,7	29,5	28,9	27,1	25,5	23,7	23,6	24,4	25,2	25,9	27	29
MONEFGM72F00	283526	320400	29,8	29,6	28,9	27,1	25,5	23,7	23,6	24,5	25,3	26	27,1	29,1
MONEFGM73F00	283727	320544	30	29,7	29,1	27,3	25,7	23,9	23,8	24,6	25,4	26,1	27,2	29,2
MONEFGM74F00	283909	320631	29,4	29,2	28,5	26,7	25,2	23,4	23,3	24	24,8	25,5	26,7	28,6
MONEFGM75F00	283622	321044	29,8	29,5	28,9	27,2	25,6	23,8	23,7	24,5	25,3	25,9	27,1	29

APPENDIX 8b: Mean monthly minimum temperature per PSP (degrees Celsius).

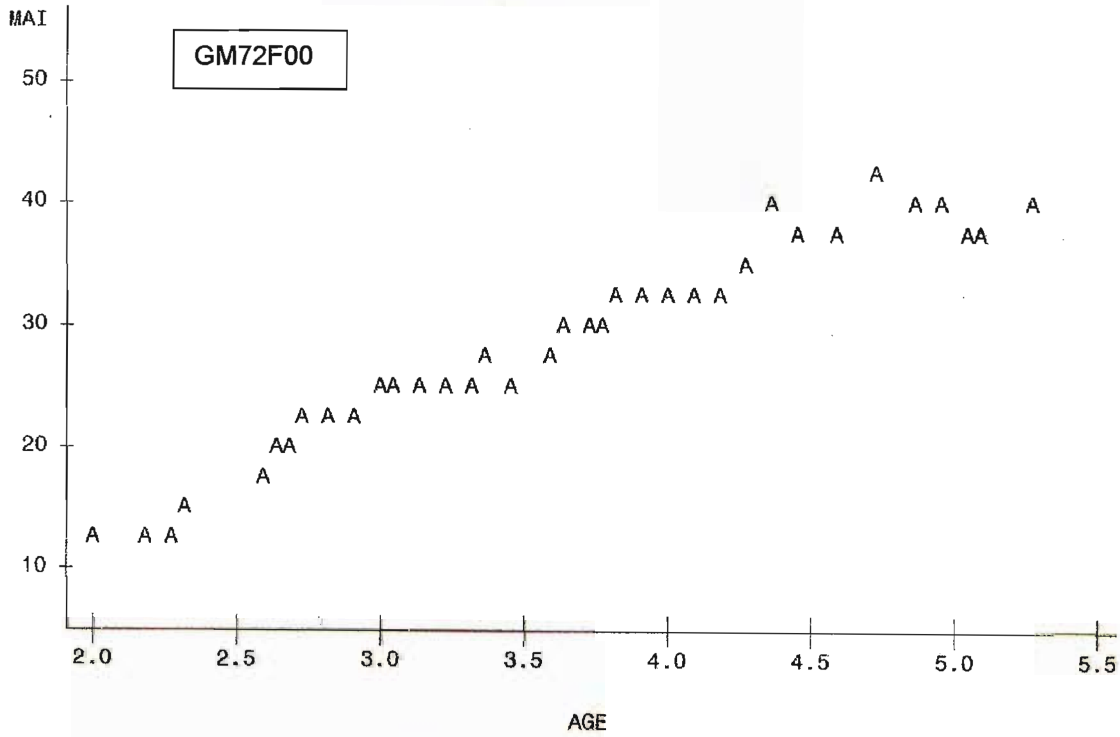
Plot ID	Jan	Feb	March	April	May	June	July	August	Sept	Oct	Nov	Dec
MONEF0001F00	20,1	20,2	19,4	17,2	14,5	11,7	11,5	13	15,1	16,2	17,6	19,2
MONEF0005F00	20,1	20,2	19,4	17,2	14,5	11,7	11,5	13	15,1	16,2	17,6	19,2
MONEF0005F01	20,1	20,2	19,4	17,2	14,5	11,7	11,5	13	15,1	16,2	17,6	19,2
MONEF0011F00	20,2	20,3	19,5	17,3	14,8	12,1	11,9	13,2	15,2	16,3	17,7	19,3
MONEF0011F01	20,2	20,3	19,5	17,3	14,8	12,1	11,9	13,2	15,2	16,3	17,7	19,3
MONEF0019F00	20,3	20,5	19,7	17,5	14,8	12	11,9	13,3	15,4	16,4	17,9	19,5
MONEF0023F00	20,3	20,4	19,6	17,5	15	12,3	12,1	13,4	15,4	16,4	17,8	19,4
MONEF0032F00	20,4	20,6	19,7	17,4	14,6	11,7	11,5	13	15,2	16,5	18	19,6
MONEF0033F00	20,3	20,4	19,6	17,2	14,4	11,6	11,4	12,9	15,1	16,4	17,8	19,4
MONEF0034F00	20,2	20,3	19,5	17,1	14,3	11,5	11,3	12,8	15	16,3	17,7	19,3
MONEF0037F00	20,3	20,4	19,6	17,2	14,4	11,6	11,4	12,9	15,1	16,3	17,8	19,4
MONEF0038F00	20,4	20,6	19,7	17,4	14,6	11,7	11,5	13	15,2	16,5	18	19,6
MONEF0039F00	20,3	20,4	19,6	17,2	14,4	11,6	11,4	12,9	15,1	16,3	17,8	19,4
MONEF0040F00	20,3	20,4	19,6	17,2	14,4	11,6	11,4	12,9	15,1	16,3	17,8	19,4
MONEF0041F00	20,4	20,6	19,7	17,4	14,6	11,7	11,5	13	15,2	16,5	18	19,6
MONEF0059F00	20,4	20,5	19,7	17,6	15,1	12,4	12,2	13,5	15,5	16,5	17,9	19,5
MONEF0060F00	20,3	20,4	19,7	17,6	15,1	12,5	12,3	13,5	15,4	16,4	17,8	19,4
MONEF0061F00	20,5	20,6	19,8	17,6	15,1	12,4	12,2	13,5	15,5	16,6	18	19,6
MONEF0062F00	20,4	20,5	19,7	17,4	14,7	11,9	11,7	13,2	15,3	16,4	17,9	19,5
MONEF0065F00	20,2	20,3	19,5	17,1	14,3	11,5	11,3	12,8	15	16,2	17,7	19,3
MONEF0067F00	18	18,1	17,2	14,8	12	9,2	9,1	10,7	12,8	14,1	15,5	17,1
MONEF0069F00	20,3	20,4	19,6	17,4	14,7	11,9	11,8	13,2	15,3	16,4	17,8	19,4
MONEF0070F00	20,2	20,4	19,6	17,4	14,8	12	11,8	13,2	15,3	16,3	17,8	19,4
MONEFGM72F00	20,1	20,2	19,4	17,2	14,5	11,7	11,5	13	15,1	16,2	17,6	19,2
MONEFGM73F00	20,4	20,5	19,7	17,5	14,7	11,9	11,7	13,2	15,3	16,5	17,9	19,5
MONEFGM74F00	20,2	20,4	19,6	17,6	15,3	12,7	12,5	13,6	15,5	16,4	17,7	19,3
MONEFGM75F00	20,4	20,5	19,7	17,6	15	12,2	12	13,4	15,4	16,5	17,9	19,5

APPENDIX 9: Mean monthly A-pan evaporation per PSP (mm).

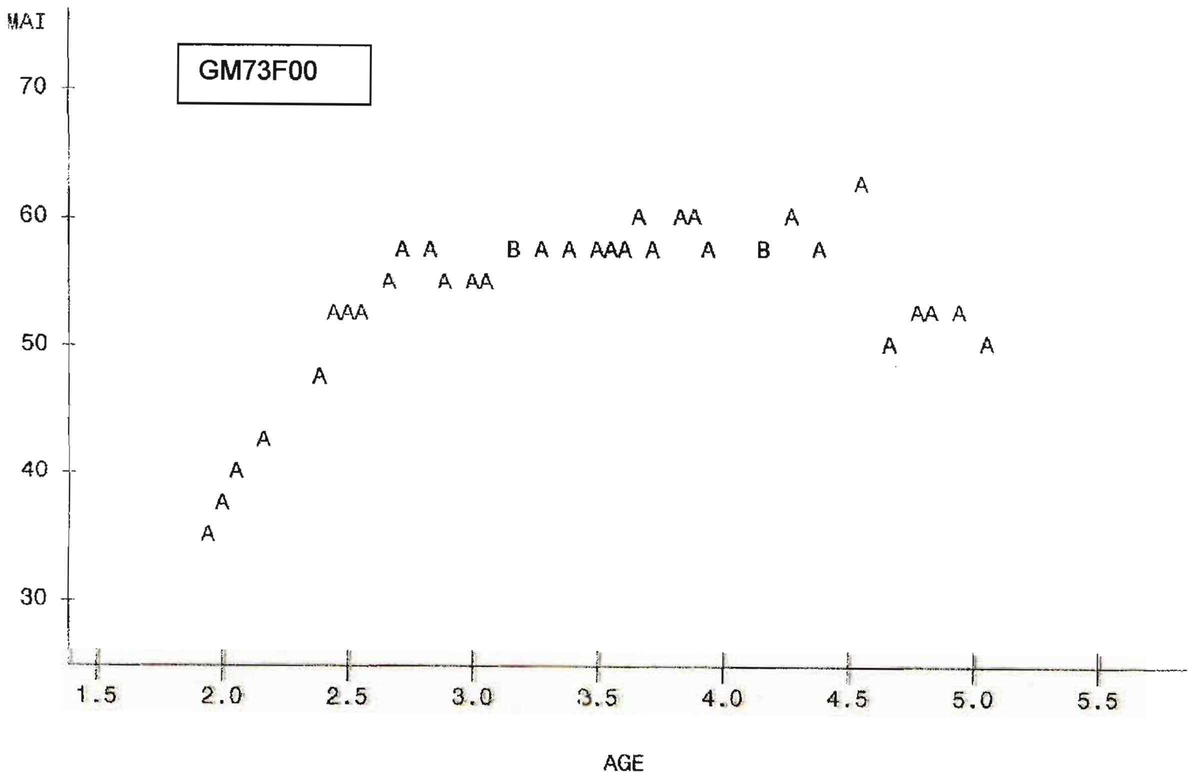
PSP number	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
MONEF0001F00	197,3	168,8	165,5	134,3	112,3	88,1	103,4	127,8	143,7	170,3	170,8	204,3
MONEF0005F00	197,3	168,8	165,5	134,3	112,3	88,1	103,4	127,8	143,7	170,3	170,8	204,3
MONEF0005F01	197,3	168,8	165,5	134,3	112,3	88,1	103,4	127,8	143,7	170,3	170,8	204,3
MONEF0011F00	195,7	168,2	167,3	140,6	108,8	82,4	104,6	126,1	139,5	169,2	169,5	202
MONEF0011F01	195,7	168,2	167,3	140,6	108,8	82,4	104,6	126,1	139,5	169,2	169,5	202
MONEF0019F00	199,4	170,1	166,9	134,2	113,4	87,9	103,8	127,9	144,2	170	172,2	206,9
MONEF0023F00	195,9	167,3	165,3	136,9	109,4	83	103,1	126,9	142	168,7	168,5	203,7
MONEF0032F00	192,2	167,1	168,1	139,8	107,6	79,8	102,8	123,2	134,5	169,8	168,9	195,5
MONEF0033F00	192,1	167	167,6	139,3	108	80,7	103	123,7	135,5	169,7	168,9	195,1
MONEF0034F00	192	166,9	167,4	138,3	108,3	81,5	102,9	123,9	135,9	169,4	168,8	195
MONEF0037F00	191,7	166,7	167,5	139,4	107,5	80	102,9	123,5	134,8	169,6	168,5	194,9
MONEF0038F00	192,2	167,1	168,1	139,8	107,6	79,8	102,8	123,2	134,5	169,8	168,9	195,5
MONEF0039F00	191,7	166,7	167,5	139,4	107,5	80	102,9	123,5	134,8	169,6	168,5	194,9
MONEF0040F00	191,7	166,7	167,5	139,4	107,5	80	102,9	123,5	134,8	169,6	168,5	194,9
MONEF0041F00	192,2	167,1	168,1	139,8	107,6	79,8	102,8	123,2	134,5	169,8	168,9	195,5
MONEF0059F00	197,3	168,8	167,3	138	111,7	86,2	104,8	126,3	140,4	168,9	170,3	205,2
MONEF0060F00	196,1	167,5	166	137,8	111,4	86,2	104,9	126,2	139,7	167,3	168,9	204,4
MONEF0061F00	197,4	169,3	168,4	139	111,3	85	104,5	125,9	139,7	169,7	170,8	204,7
MONEF0062F00	196,7	168,7	166,2	135	111	85,9	102,6	126,5	142,3	170,2	170,9	203,7
MONEF0065F00	190,4	165,4	167	137,4	107,3	78	103,4	123,2	133,9	167,5	167,6	193,2
MONEF0067F00	185,4	160,9	157,3	128,8	110,5	92,1	104,1	128,1	142,4	165,5	163,5	187,3
MONEF0069F00	196,1	167,8	165,6	134,9	110,8	85,9	102,8	126,7	142,2	169,8	170	203,2
MONEF0070F00	196,2	167,9	165,4	135,5	110,7	85,5	103,2	127	142,2	169,1	169,5	203,6
MONEFGM72F00	197,3	168,8	165,5	134,3	112,3	88,1	103,4	127,8	143,7	170,3	170,8	204,3
MONEFGM73F00	197,3	169	166,5	135,2	111,2	86,1	102,8	126,8	142,5	170,6	170,9	204,3
MONEFGM74F00	196,4	167,7	166,2	138,6	111	85,9	105,3	126,8	140,5	168,2	168,2	205,2
MONEFGM75F00	196,2	167,9	166,2	137,8	108,6	81,9	102,8	126,5	141,8	169,7	169,1	203,7

APPENDIX 10: Scatter plots of mean annual increment for selected permanent sample plots.

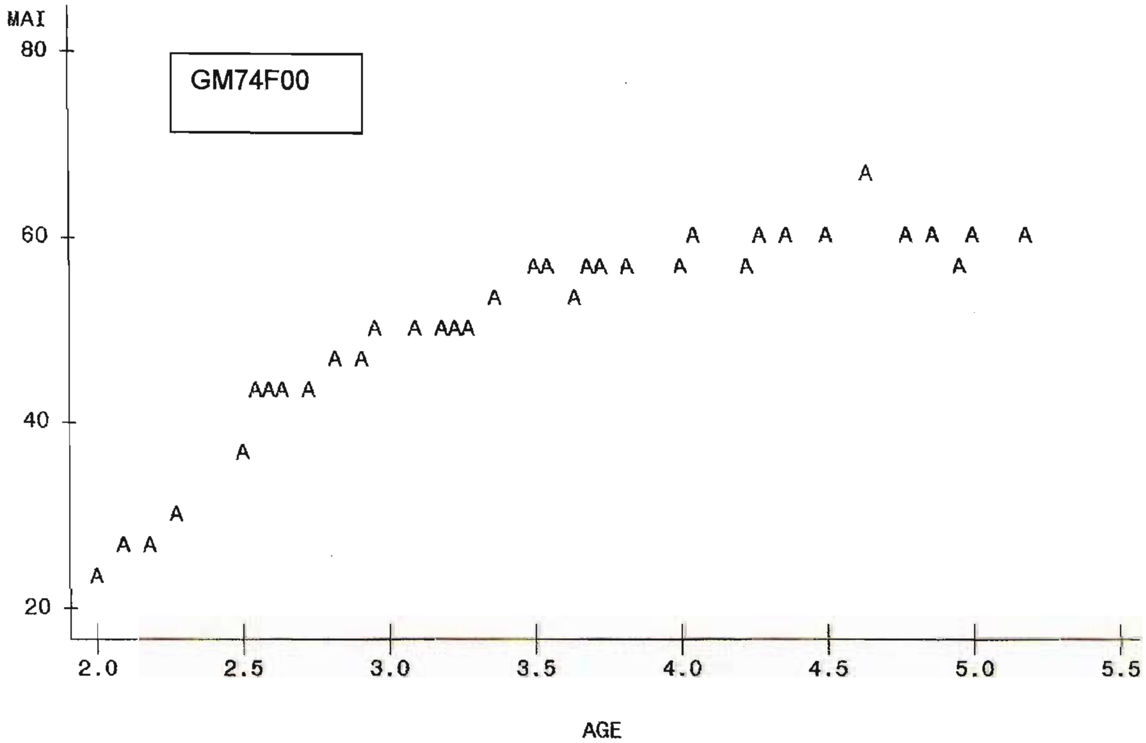
Plot of MAI*AGE. Legend: A = 1 obs, B = 2 obs, etc.



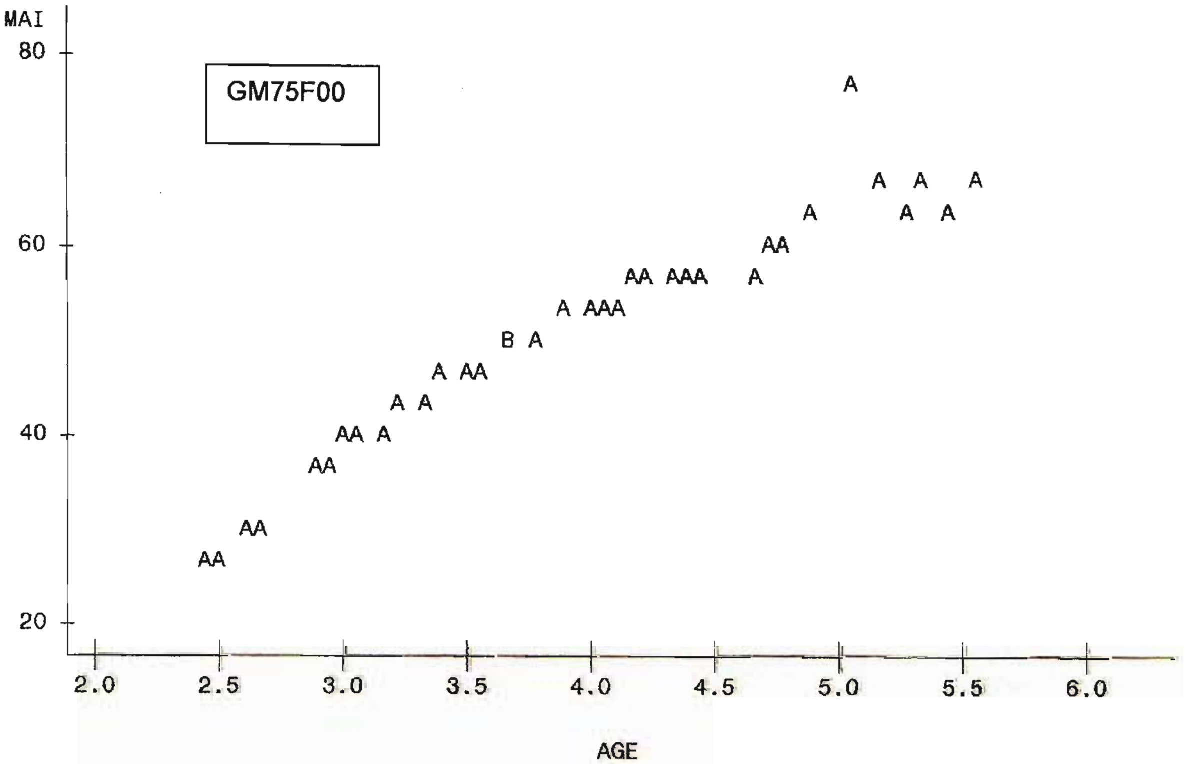
Plot of MAI*AGE. Legend: A = 1 obs, B = 2 obs, etc.



Plot of MAI*AGE. Legend: A = 1 obs, B = 2 obs, etc.



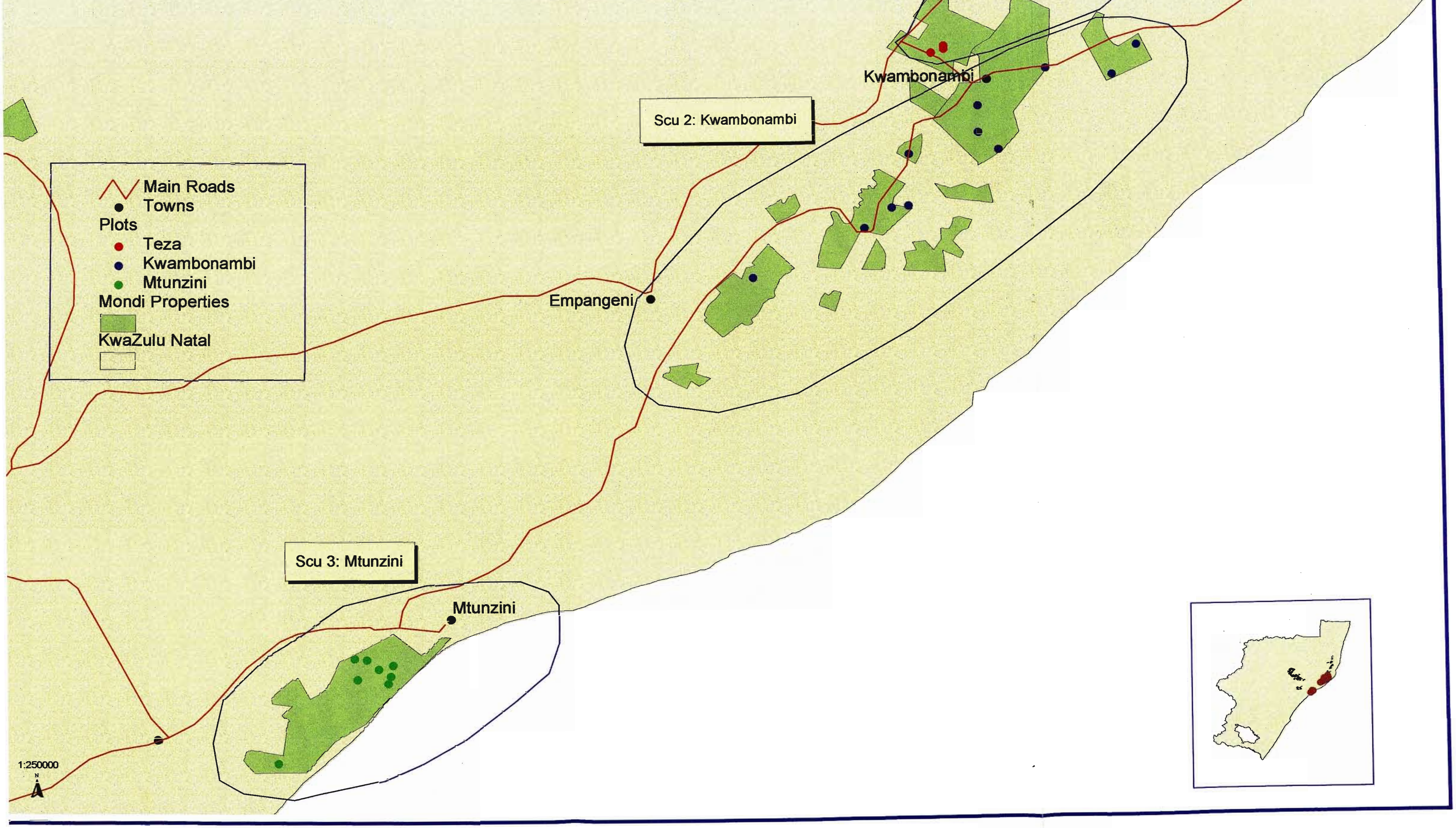
Plot of MAI*AGE. Legend: A = 1 obs, B = 2 obs, etc.



APPENDIX 11: Cluster Analysis output from Ward's technique.

NCL	------Clusters Joined------ Tie			FREQ	SPRSQ	RSQ	RSQ	CCC	PSF	PST2	
25	2		3	7	0,0000	1,00	,968	.	.	.	T
24	4		5	7	0,0000	1,00	,966	.	.	.	T
23	11		13	12	0,0000	1,00	,965	.	.	.	T
22	CL23		14	18	0,0000	1,00	,963	.	.	.	
21	CL25		6	20	0,0000	1,00	,961	163	39E5	.	
20	17	19	8	0,0000	1,00	,958	121	34E4	.		
19	22	24	39	0,0001	1,00	,956	107	14E4	.		
18	16	CL20		12	0,0001	1,00	,953	93,9	68E3	34,1	
17	18	25	39	0,0004	,999	,950	78,2	27E3	.		
16	9	10	14	0,0004	,999	,946	70,8	18E3	.		
15	CL18	CL19		51	0,0010	,998	,942	59,7	9188	233	
14	CL22		20	22	0,0013	,997	,938	52,2	5942	.	
13	1	CL21		30	0,0016	,995	,932	47,2	4398	14E3	
12	CL16		15	20	0,0020	,993	,926	42,9	3398	94,0	
11	CL15		21	55	0,0021	,991	,919	40,3	2884	88,2	
10	8	12	22	0,0024	,989	,910	38,2	2525	.		
9	7	CL17		46	0,0028	,986	,899	36,8	2293	330	
8	CL24	CL12		27	0,0076	,978	,885	31,7	1699	78,6	
7	CL9	CL11		101	0,0114	,967	,868	27,0	1291	176	
6	CL10		26	58	0,0141	,953	,844	24,0	1076	324	
5	CL8	CL14		49	0,0246	,928	,812	20,4	866	101	
4	CL7	23	137	0,0377	,890	,763	**17,6**	**730**	284		
3	CL5	CL6		107	0,1834	,707	,681	**2,22**	**327**	**366**	
2	CL13	CL4		167	0,2401	,467	,469	-0,12	238	693	
1	CL2	CL3		274	0,4668	,000	,000	0,00	.	238	

APPENDIX 12: Map showing the geographical location of site classification units



APPENDIX 12: Map showing the geographical location of SCUs.