An Investigation into Estimating Productivity, Above Ground Biomass and Leaf Area Index of *Eucalyptus grandis* Using Remotely Sensed Data and a Process-Based Model.

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Declaration

The work described in this dissertation was carried out in the CSIR and the School of Environmental Sciences, University of KwaZulu-Natal from August 2004 to August 2006, under the supervision of Dr Fethi Ahmed and co-supervised by Dr Luke Esprey.

I hereby certify that the research work reported in this dissertation is the result of my own original investigation except where acknowledged.

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Abstract

South Africa depends largely on afforestation programs for its timber supplies due to the great demands for fiber and wood products. This has brought discomfort to other water users who have advocated that the effects of afforestation on water resources are detrimental to the country as a whole since South Africa is known as a water scarce country. This study has undertaken to integrate a process-based model and remote sensing data to estimate water use and productivity of *Eucalyptus grandis* in the Zululand areas of South Africa.

The remote sensing techniques and recently developed “process based model” that is 3PG-S were used to estimate water use and productivity of *Eucalyptus grandis*, an economically important plantation species grown in the summer rainfall areas of South Africa. The study utilized monthly Landsat Thematic Mapper datasets and climatic data as inputs into the 3PG-S model, determined the Leaf Area Index (LAI) and Specific Leaf Area (SLA) through direct (destructive sampling) and indirect measurements (LiCor- 2000) and assessed the relationships between various vegetation indices (VI’s) using correlation and regression analyses.

The results suggest that all the indices, except the ratio VI, correlated significantly with LiCor-determined and destructively measured LAI values with both normalized difference vegetation index (NDVI) and Ratio Vegetation Index (RVI) ($r=0.86$, $p < 0.01$) correlating the highest followed by transformed normalized difference vegetation index (TNDVI) ($r=0.85$, $p < 0.01$). These indices can therefore be used to estimate LAI in the study area. All the indices showed significant correlations with SLA, with vegetation index (VI_3) giving the highest correlation ($r=0.95$, $R^2= 0.90$, $p < 0.01$), followed by TNDVI ($r=0.88$, $R^2= 0.86$, $p < 0.01$), NDVI ($r=0.98$, $R^2= 0.83$, $p<0.01$) and RVI ($r=0.98$, $R^2= 0.84$, $p < 0.01$). The relationships between SLA and vegetation indices suggest that SLA can be derived from vegetation indices in the study area, using regression analysis with great confidence.

The 3PG-S was validated using four trial sites in Zululand. The results showed a relative consistency between the observed and predicted above ground biomass (AGB) and net primary productivity (NPP) data hence its robustness in predicting both parameters. The literature on water use suggest that commercial forestry reduces runoff and reduces streamflow, therefore a balance need to be found between forestry and other water users. There needs to be further field-based research on water use of *Eucalyptus grandis* using 3PG-S.

In conclusion, LAI can be estimated from NDVI, TNDVI and RVI with high degrees of confidence whilst the SLA can be estimated fairly accurately from all the indices tested in this study. The regression equation between LiCor-2000 measurements and destructively sampled LAI was found to have a generally high degree of association between the two variables and can be used to calibrate the LiCor-2000 readings. The 3PG-S model have potential to be used to predict the productivity of *Eucalyptus grandis* in locations similar to the study area where trees have not been grown and can be used to explore the effects of environmental constraints on growth.

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List of Abbreviations and Acronyms

3-PG	Physiological Principles Predicting Growth
3PG-S	Physiological Principles Predicting Growth (Spatial version)
α	Canopy Quantum Efficiency Coefficient
AGB	Above Ground Biomass
ANOVA	Analysis of Variance
aPAR	Absorbed Fraction of Photosynthetically Active Radiation
aPARu	Utilizable Absorbed Fraction of Photosynthetically Active Radiation
APS	Afforestation Permit System
AVHRR	Advanced Very High Resolution Radiometer
ARVI	Atmospherically Resistant Vegetation Index
CO2	Carbon Dioxide
CSIR	Council for Scientific and Industrial Research
DBH	Diameter at Breast Height
DWAF	Department of Water Affairs and Forestry
ET	Evapotranspiration
FOREST-BGC	Forest-Bio-Geo-Chemical
GDP	Gross Domestic Product
GIS	Geographical Information Systems
GPP	Gross Primary Productivity
GPS	Global Positioning System
ICFR	Institute for Commercial Forestry Research
LA	Leaf Area
LAI	Leaf Area Index
MAP	Mean Annual Precipitation
MAR	Mean Annual Runoff
MAT	Mean Annual Temperature
MSAVI	Modified Soil-Adjusted Vegetation Index
MVP	Marginal Value Product

NDVI	Normalized Difference Vegetation Index
NIR	Near Infrared
NOAA	National Oceanic and Atmospheric Administration
NPP	Net Primary Production
PAI	Plant Area Index
PAR	Photosynthetically Absorbed Radiation
PBM	Process-Based Model
PCA	Plant Canopy Analyzer
pET	Potential Evapotranspiration
R	Red
RS	Remote Sensing
RSR	Reduced Simple Ratio
RV	Residual Value
RVI	Ratio Vegetation Index
SAC	Satellites Application Centre
SAVI	Soil-Adjusted Vegetation Index
SARVI	Soil-Adjusted Ratio Vegetation Index
SE	Standard Error of Estimation
SFRA	Stream Flow Reduction Activity
SLA	Specific Leaf Area
SPOT	Systeme Pour l'Observation de la Terre
SR	Simple Ratio
TDLM	Total Dry Leaf Mass
tDM/ha	Ton Dry Matter per Hectare
TM	Thematic Mapper
Tmin	Minimum Temperature
TNDVI	Transformed Normalized Difference Vegetation Index
Tmax	Maximum Temperature
VI	Vegetation Index
VPD	Vapour Pressure Deficit

CHAPTER1: INTRODUCTION

1.1 Introduction

Commercial forestry is a major economic force that contributes 1.8% to the country's gross domestic product (GDP), and employs approximately 124000 people 25% in saw milling, 38% in the pulp and paper industries and 37% directly in plantations (DWAF, 1997). The latest Figures suggest an increase in Figures to R12 billion in contributions to the GDP and 170 000 jobs created by the commercial forestry sector (Chamberlain *et al.*, 2005, Tewari, 2005). It is a significant industry, uniquely positioned to assist in bringing about a change in employment and economy (Olivier, 1997). An increase in demand for forest products and strong income incentives for downward wood processing industries influence the economic significance of commercial forestry in South Africa. It is, therefore, important to effectively manage the commercial forests in South Africa to ensure its sustainability as a renewable resource.

The detailed knowledge of forest serves as an important component for forest resource managers, which in turn empowers the officials to recognize the need to create practical indicators for forest sustainability. Forest ecosystems are not only important components of terrestrial vegetation but also require that an understanding of processes such as the cycling of carbon, water and nutrients through these systems be gained (Lucas and Curran, 1999). Such an understanding is attained through process based models that attempt to describe these forest processes. These process based models increase basic understanding of the dynamic behaviour of these forest processes and how they react to natural and anthropogenic pressures.

1.2. Afforested Areas in South Africa

The area conducive to forests plantation is mainly influenced by climate and those parts of the country with mean annual rainfall and mean annual temperature above 850mm and 14°C respectively are suitable. These weather patterns i.e. high temperatures and good rainfall are conducive to fast growing trees such as *Eucalyptus* species. These areas where the South African plantations are located in areas which were either grasslands or otherwise but did not carry forests. Forest plantations in South Africa are currently limited to areas located on the eastern side of South Africa that is Mpumalanga, KwaZulu-Natal and Eastern Cape (Dye and Olbrich, 1992, Tewari, 2005).

1.3 Importance of Commercial Forestry

The forest industry plays a crucial role in society because it influences the lives of more than a million people through direct and indirect employment (DWAF, 1997). It is also involved in other roles such as recreation, aesthetics, energy utilization and so forth. The forest industry is known for encouraging participation of communities as stakeholders through small-growers schemes. Most small growers have entered into contracts with timber companies as this is seen as the only way to return to viable farming (Gandar, 1994). These schemes are seen as important because even the previously socially disadvantaged groups such as women are encouraged to participate.

Afforestation has been shown to be the only resource by which the growing shortfalls in wood supply can be met (Nambiar, 1999). Besides being important for economic growth and employment provision, forest plantations are important as land uses that can contribute to “solutions of environmental problems caused by land degradation, biodiversity loss and climate change” (Nambiar, 1999). The basic services commercial forests render to the environment are replenishment of the air, conserving the soil thus maintaining its fertility, store water and serve as a habitat for wildlife. The commercial forests are assets to communities as they provide the necessary wood and fiber products that contribute to a nation’s development and regulate the climate through carbon sequestration. They are therefore consequential to the economic, social and environmental health of all nations.

1.4. Forest Productivity and Water Use

The various factors that control plant growth and productivity such as climate, topography and geology of areas determine the potential of an area to be used for commercial forestry. Various models that incorporate growth determining factors for the prediction of forest growth, productivity and water use at both local and regional scales, exist. Examples of such models include FOREST –BGC (Running and Coughlan, 1988; Running and Gower, 1991), BIOMASS (McMutrie *et al.*, 1992; McMutrie *et al.*, 1994), ProMod (Battaglia and Sands, 1997; Sands *et al.*, 2000) and 3-PG Landsberg and Waring (1997). The estimation of commercial forest productivity is crucial because forest managers require accurate forest inventories to make appropriate management decisions. The forest managers therefore use a wide array of empirical growth and yield models to facilitate inventory update. Researchers have been creating mechanistic, process based models to incorporate ecological and physiological understanding into predictions of forest productivity and water use by commercial forestry across variable environmental conditions (Henning and Burk, 2004).

The problem exists with continued afforestation because South Africa is known to be a water scarce country and therefore there is a need to manage the resources efficiently in order to meet the rising demand for water by agricultural, urban and industrial sectors (Dye *et al.*, 2004). Accordingly, Van Der Zel (1995) points at major declines of water catchments water yields due to forest plantations, because they remain physiologically active seasonally. Therefore, the implementation of process-based model could help with estimating the amount of water used by the commercial forestry. Commercial afforestation has been declared a *stream flow reduction activity* (SFRA) that is dryland agricultural crops using more water than the natural vegetation which would otherwise grow there (e.g. dryland sugarcane), regulated by means of a SFRA Water-use Licensing System in terms of Chapter 4, Section 36 of the National Water Act (No. 36 of 1998) (Government Gazette 20615, 1999).

Plantations tend to have their highest relative impact on stream flow reduction during dry periods or in water-stressed catchments and when plantations enter the riparian zone. Armstrong and Scott-Shaw (1998), Nambiar (1999) and Everson, (1993) concurred that water usage by trees is more than the grasslands that they often replace particularly during winter when "the grasses would normally die back and halt transpiration". Exotic plantations use more water than indigenous vegetation because their growth rates, and therefore their evapotranspiration, are higher (Versfeld, 1994). Cornish and Vertessy (2001) studied forest-age induced changes in evapotranspiration and water yield in a eucalypt forest. They found that more water is used as forest growth increases. They further mentioned that maximum water use is likely to take place at an age when a combination of high leaf areas, high photosynthetic rates and high conducting areas occurs.

Studies by Dye *et al.*, *(*2001) have revealed that forest water use is affected by factors such as range of weather, forest stand and site factors. They further argue that the ability to extrapolate from few research sites for an entire forest area remains limited. In order to obtain optimum growth, the tree crop needs a balance of resources such as light, water and nutrients. Therefore water is one of the important factors which encourage growth and hence high economic returns. It is therefore imperative to monitor such balance of resources, more especially water use by forest plantations so as to ascertain a healthy growth and therefore obtain high economic returns (Du Toit, 2002).

The productivity and water use of *Eucalyptus grandis* using a forest growth and yield model represent the development of tree crops as they increase in age, or as time changes. The statistically derived or empirical models have in the past been used to a varying degree. These models, although they produced satisfactory results, lacked "generality in that they are limited to regions and management scenarios for which they were originally developed and cannot respond to dynamic changes in the environment" Esprey (2005). The need to incorporate varying environmental conditions into the growth of commercial forestry saw development of process-based models. Process-based models (PBM's) were initially intended for research purposes and help with the understanding of the mechanisms of tree and strand growth, mainly knowing more about canopy dynamics. PBM's usefulness include risk assessments, selection of plantation sites or site specific species and identification of site limitations to productivity (Esprey and Sands, 2004).

According to Stapper (1986), the general structure of a model is defined to be (i) its spatial and temporal resolution (ii) the number of state variables, processes and parameters in the model (iii) the balance between empiricism and phenomenology in the manner in which processes are presented, (iv) the detail of the inputs required for it to run and (v) the nature of its outputs; is correlated largely with the intended use of the model. PBM's, for instance 3-PG has been applied in various countries such as Brazil, Canada, Australia, New Zealand and South Africa (Coops and Waring, 2001, Almeida *et al.*, 2001; Dye *et al.*, 1997 and Dye *et al.*, 2004). The disadvantage of many process-based models has been that they are point based and only applicable to smaller areas rather than large areas (Coops *et al.*, 1998, 2001; Coops and Waring, 2001). A spatial approach integrating spatially-distributed growth influencing factors in a GIS environment is necessary if a model is to be applied operationally across large areas. This project aims at estimating water use and productivity of *Eucalyptus grandis* over large areas using the spatial version of 3-PG.

1.5. Aims and Objectives

Plantation growth and yield modelling has always been at the centre of planning in the forestry industry. The economic returns of commercial forestry depend largely on the amount and quality of timber harvested and as such accurate predictions of growth of commercial forestry plantations through process based models are important. These predictions will help with the development of improved understanding of the complex interactions between site factors and forest productivity; water used by forestry plantations and also future accurate site-species matching (Louw, 1999). The benefits for South African forestry industry using process-based models are huge.

The water use of forest plantations remains a topical subject in the light of recent changes to Water Act (Dye *et al.*, 2001) and also the continuing debate over the hydrological impacts of various types of land uses remains one of the thorny issues between foresters and environmentalists. Forestry is believed to consume more water than other land uses and therefore this dissertation seeks, as the main aim to estimate net primary productivity (NPP), aboveground biomass (AGB) and leaf area index (LAI) of *Eucalyptus grandis* in the Zululand areas of South Africa using remotely sensed data and a process-based model.

The specific objectives of this study are:

1. To determine leaf area index of *Eucalyptus grandis* using various vegetation indices derived from remotely-sensed Landsat TM imagery.
2. To determine the LAI and specific leaf area (SLA) through direct and indirect measurements.
3. To assess the relationships between the various VIs obtained from remotely sensed imagery and LAI estimates determined through direct destructive sampling and indirect (optical instruments) field-based measurements on *Eucalyptus grandis.*
4. To predict aboveground biomass and productivity of *Eucalyptus grandis* using the 3PG-S model.
5. To validate the 3PG-S estimated aboveground biomass and productivity and develop a predictive models for future use.

1.6. Structure of the Thesis

The first chapter of the thesis has introduced the rationale of undertaking this study by looking at importance of commercial forestry, relevance and significance of estimating water use and productivity taking into consideration the Water Act of 1998. A brief of work on process-based models quantifying water use and productivity at stand level has also been looked at, identifying the gaps and hence justifying this study. Chapter two reviews the literature on the importance of afforestation, empirical and process-based models taking into account advantages and disadvantages of each. Furthermore, the chapter gives in depth reviews on 3-PG and 3PG-S. Chapter three describes the study area in terms of geographical location, climate, topography, and geology. Chapter four provides detailed descriptions of all the materials and methods used in this study. The results obtained from destructive sampling, remote sensing and 3PG-S model are presented and discussed in chapter five. Chapter six deals with the conclusions and recommendations formulated during this study.

CHAPTER 2: LITERATURE REVIEW

2.1. Leaf Area Index

Leaf area index (LAI) is defined as the total one-sided area of all leaves in the canopy within a defined region (that is m^2 of leaf per m^2 of ground) (Chen and Black, 1992; Gong *et al.*, 2003). LAI is one property being measured in remote sensing using vegetation indices and is an effective variable in determining the quantity of water transpired by the vegetation and is highly correlated with productivity and yield rates. Franklin *et al.*, (1997) and Pu *et al.*,(2003) believe that LAI is a common input variable in models predicting evapotranspiration because it "influences energy absorption and interception of rainfall" Cornish and Vertessy, (2001) whilst Gong *et al.*,(2003) see LAI, owing to its direct relationship with plant functions, as an important parameter because it "quantifies the energy and mass exchange characteristics" of the terrestrial ecosystem such as photosynthesis, respiration, transpiration and "subsequently stand growth" (Ares and Fownes, 1999; Pierce and Running, 1988).

Ever since leaf area index was developed, many studies have been conducted to correlate it with vegetation productivity and evapotranspiration through models (Running and Coughlan, 1988). Various studies also correlate remotely sensed data and regional estimates of a number of forest ecosystem variables such as LAI, absorbed fraction of photosynthetically active radiation (APAR) and canopy chemistry. These variables that form both the biological and physical processes within the terrestrial ecosystem have been assessed and obtained with some accuracy and cheaply using imagery from various sensors (Franklin *et al.*, 1997).

Regression analysis has been the method used to estimate LAI values due to the relationship that exist between LAI values measured *in situ* and those of particular vegetation indices computed from remote sensing data. The other methods besides remote sensing, which have been used to determine the LAI are the theoretical approach using leaf water and energy balance and the modular estimation technique which is based upon measuring true LAI of a few clumps or modules in a tree foliage and scale up (Gong *et al.*,2003). Megown *et al.*, (1999) believe that the mostly commonly used satellites for LAI determination are SPOT, NOAA, AVHRR and Landsat TM.

The majority of studies on destructive and non-destructive methods of estimating leaf area have been conducted on forest canopies, orchards and agricultural row crops (Norman and Welles, 1983; Lang and Yuequin, 1986, Norman and Campbell, 1989; Lang and McMutrie, 1992). The indirect methods for determining LAI include the use of allometric equations, hemispheric photographs and gap fraction analysis (Marshall and Waring, 1986; Neumann *et al.*, 1989; Martens *et al.*, 1993). The indirect methods that are based on the coupling between light penetration and canopy structure are to be a good alternative in homogeneous stands (Gong *et al,* 2003; Pontailler *et al*, 2003). McPherson and Pepper, (1998) used five methods to estimate and compare the LAI of open-grown deciduous trees. These methods included the LiCor-2000, logarithmic regression equations, Accupar Ceptometer, CI-100 Plant Canopy Analyser and Image Processing with the Agvision system. Leaf area can also be investigated in the field by sampling ground cover or litter fall (leaves, twigs, branches fallen from trees). Further, calculations of tree basal area against leaf area, based upon measurements by portable instruments, can be used to calculate LAI for any site (Pierce and Running, 1988).

2.2. Plant Canopy Analyzer (PCA)

A LiCor – 2000 is an easy to use, portable plant canopy analyzer that has been used successfully in other studies of LAI (Battaglia *et al.*, 1998) and is based on the amount of canopy light transmittance measured across a hemispherical field by five concentrically nested sensors which are varying in angle from the vertical (Welles and Norman, 1991; Birkhead *et al.*, 1997). Chen and Cihlar (1996) believe that the contamination due to self-shading at the levels of needle to shoot, branch and canopy and stand results in an "effective LAI" being obtained. That is also confirmed by studies conducted by Nemani *et al.*, (1993), who also found the drawback of the system to be that branches and stems are also included in the final LAI value and therefore that should be referred to as plant area index (PAI). This LAI value will be useful for LAI studies when a calibration curve for every species is determined and that is accomplished by using the LiCor-2000 and destructive sampling of trees in parallel.

The instrument requires two measurements to estimate LAI that is above canopy and below canopy readings. The former's light reading is utilized to determine the intensity of the radiation without the influence of the canopy whilst the latter's reading measures the attenuation of light through the canopy. The general mode of operation is such that readings are taken consistently early in the morning or under overcast conditions also referred to as "under diffuse sky conditions" (Cosmopoulos and King, 2004). This measuring device offers only the feasible, non-destructive and cost-effective means of documenting changes in the LAI which is consistent with the findings of Dye and Olbrich (1992) who found that LAI measured using LiCor-2000 was consistently lower than that estimated by leaf stripping in *Eucalyptus* trees. Remotely sensed vegetation indices have proved useful in estimating the temporal and spatial distribution of LAI (Peddle *et al.*, 2000).

2.3. Vegetation indices

The vegetation indices have been used to characterize the canopy using remote sensing gathered through radiometric measurements of vegetation (Xavier and Vettorazzi, 2004). Vegetation indices use knowledge of plant physiology to maximize the information extractable from the imagery. The studies of forest ecosystem with remote sensing data have indicated that the most commonly used vegetation indices (VI) are derived from a relationship based on the red and infrared bands (Cleavers, 1988; Turner *et al.*, 1999).The reflectances in these bands have been used to formulate various VI's as indicators of surface vegetation conditions. Numerous indices are available for detection of vegetation from remote sensing. In its simplest form, the division of the near infrared band by the red band correlates to vegetation density and health (greenness) (Locke *et al.*, 1998).

Amongst the various VI's, the ratio-based normalized difference vegetation index (NDVI) and the simple ratio vegetation index are according to Gong *et al.*, (2003) the most "frequently used to correlate with LAI and other canopy structure parameters from airborne and spaceborne remote sensing data". This is despite the shortcomings of NDVI that it could only predict LAI to within 0.8% of actual LAI (30% cover), because it includes even stems, branches and leaves, as compared to SARVI and ARVI's 0.4% (15% cover) (Huete *et al.*,1998). Jordan (1969) was the first author to use NDVI to assess biomass and LAI. Since then, NDVI has been broadly used to estimate vegetation characteristics such as biomass, LAI, percent cover, leaf water content, crop yield, and leaf nitrogen content, among others (Cusack *et al.*, 1999).

The estimation of NDVI from remote sensing is a well-established procedure and studies conducted have shown that there exists "a strong positive correlation between NDVI and vegetation cover or LAI" in a range of environments (Franklin *et al.*, 1996; Danson *et al.*, 2003). The NDVI is probably the most widely used index for the analysis of vegetation because it utilizes radiances or reflectances in the NIR and Red spectral regions therefore enhancing the contrast between the soil and vegetation. Tucker (1979) argues that the satisfactory estimates of NDVI and hence LAI provide relevance to photosynthesis and carbon balance studies because it considers the green parts of the plant only. Although widely used for vegetation parameter assessments, NDVI is according to Nemani *et al.*, (1993) site specific, scale and calibration tasks dependent.

Danson *et al.*, (2003) noted some problems that exist when using the vegetation indices to estimate the biophysical properties of the crops as follows:

1. Lack generality that is they are unsuitable for multitemporal, multisite or multisensor conditions due to the requirement of new equations should a crop type or measurement condition change.
2. Lack consistency that is variability of the 'best' VI with the measurement conditions.
3. Reliability on experimental data that is defining relationship with the desired biophysical property, normally demands field measurements.
4. Use data in two or three spectral wavebands therefore is difficult to include data in other wavebands.
5. Makes little of *a priori* knowledge that is does not use already known information.

2.3.1. Factors Affecting LAI and VI

The performance of ratio-based VI's is good only if the soil background reflectance is relatively constant but that is hardly the case since external variables such as solar position and sensor view angle add some complexities. Therefore, relationship between the VI's and crop biophysical properties (i.e. the form and strength) is largely dependent on many factors including soil spectral variation, canopy architecture which varies from crop to crop, illumination and viewing geometry that may vary diurnally or seasonally and leaf optical properties which may vary spatially and temporally in crops (Danson *et al.*,2003).

LAI was found by Nemani *et al.*, (1993) to vary with microclimate and soil water conditions in mixed forests in Montana. The variations were such that hill tops had lower LAI due to less available water hence water stress in those areas, whilst the bottom hill slopes which had more water, less stress, high temperatures and possibly more nutrients depicted higher values. The seasonal changes in percentage canopy cover cause the NDVI to be less sensitive and therefore cannot distinguish between various attributes such as canopy greenness, green LAI, chlorophyll and foliar N content as a result; the LAI is affected by this insensitivity. This according to Gamon *et al.*, (1995) is due to vegetation indices being poor indicators of total canopy biomass.

"Canopy closure is a key spatial variable governing the scene brightness in conifer canopies, because it controls the fractions of understory and overstory visible to the sensor" (Franklin, 1986). Studies conducted by Price and Bausch (1995) have shown that the density of vegetation cover largely affects the estimation of leaf area. This implies that light absorption and reflectance by canopy are affected by the denseness of cover that is multiple layers of leaves, branches, and trunks. It then follows that thick vegetation canopy can mean a very high leaf area index; therefore, the density of a canopy must be considered when LAI studies are performed.

The areas which cover several kilometres result in problems when using the vegetation indices, due to several climatic zones covering such areas. Matheson and Ringrose (1994) point out that indices apply the same association across climatic zones, and that variation in green vegetation cover may not be detected due to lack of flexibility in the indices. Generally, most vegetation indices are ratios that eliminate shadowing effects through highlighting the difference in reflectance between two image bands. Removal of shadow and albedo effects from vegetation indices can offer improvements in classification (Qi *et al.*, 1995). Another important plant trait i.e. specific leaf area (SLA) has been estimated using the vegetation indices in the same way as LAI and the results were promising (Leo *et al.*, 2000).

2.4. Specific Leaf Area (SLA)

Specific leaf area that is the light capturing area per dry mass of leaf (Westoby *et al.*,2000), also known as leaf mass per unit area; specific leaf mass or leaf specific mass, is defined as the leaf area per unit of dry leaf biomass. According to Pierce and Running (1994), SLA is an important link between plant carbon and water cycles because it describes the distribution of plant biomass relative to leaf area within a plant canopy. Studies (Pierce *et al.*, 1994) have also found SLA to be related to leaf structure, positively and strongly correlated to nutrient concentrations, growth, net photosynthesis and hence used in simulation models to estimate leaf area. Even though the leaf area and specific leaf area are important parameters in many agronomic and ecological processes such as photosynthesis, transpiration and field energy balance, they are difficult and expensive to measure (Reich *et al.*, 1997; Li *et al.*, 2005).

2.5. Afforestation

Afforestation is the planting of trees for commercial purposes (plantations and woodlots); usually on a land supporting non-forest veld types e.g. grasslands and Fynbos. The main objectives of commercial forest plantations are production of industrial round wood, wood for fuel, non-wood forest products, enhancement of environmental benefits such as protection of watershed, protection against desertification and improved quality of life through poverty alleviation programmes. Nambiar (1999) believes that the main objective when planting a forest is producing high quality wood on a commercial basis but emphasized that, it should be within the prescribed guidelines of environmental care (Ahmed and Drew, 2005).

South Africa being a semi-arid country is facing a dilemma of whether to continue afforestation programs or lose water due to runoff and streamflow reduction activity. The importance of water in the growth of trees such as pine, wattle and gum has been published in many research outputs but these trees uses a lot of water through evapotranspiration (loss of water from open water, soil and plant surfaces) leading to reduced runoff of streamflow (Hemakumara *et al.*, 2003). The loss of water from plant surfaces is largely influenced by leaf area and as such *Eucalyptus grandis* plantations are known to draw water from the groundwater therefore leading to reduction in streamflows. Teskey and Sheriff (1996) used heat pulse technique and observed that large trees hence bigger leaf areas used more water than small trees, smaller leaf areas. Also fluctuations in environmental factors such as soil water availability and amounts of rainfall could lead to large differences in daily to monthly water use by trees. The problem that has been foreseen in commercial forestry water use is the new impact (increase transpiration values) that it introduce to the environment relative to original land cover it replaces.

2.5.1. Water, Plant Growth and Productivity (Yield)

The water supply is the most important environmental factor because it determines amongst other things growth of forest and species distribution and composition. It has been further suggested by Dury and Manjunath (1992) that water supply affects mineralization, nitrogen uptake, leaf area index (LAI), canopy photosynthesis and the duration of annual active growth. The availability of soil water at a site affects growth, and is impractical to measure due to factors such as, differing rooting depths, highly variable stoniness, depth to bedrock and uncertainty over lateral soil water flow (Dye *et al.*, 2001). Rapidly growing plants require large quantities of water, far in excess of that found in the plant for synthesis of new materials.

Most growing plants contain about 90% water. Water is the medium for transfer within the plant and is the solvent system of the cell. Water abundance increases growth rate and stomatal conductance to gaseous exchange which both suffer under stress brought about by drought (Jackson, 1986). The reaction of plants to drought / limitations of insufficient water represent an integral response to "one or more morphological and physiological adaptations" (Ares and Fownes, 1999). These adaptations are found in the stems, leaves and roots that form a core of the living tree. Amongst these adaptations are rapid stomatal closure, few and sunken stomata and heavy wax deposition on leaf surfaces. The ability of the roots to extend deep (that is high root to shoot ratio) and twig and stem photosynthesis is some of the drought tolerant techniques explored by roots and stems respectively. The trees with deeply penetrating and branching roots best present an efficient water absorbing system to avoid desiccation

A tree experiences water stress if there is a decrease or increase in water content and deficit respectively. Jackson (1986) has described vegetation stress as any disturbance that adversely influences growth. Stress can be simplified as not enough water to the plants, or a water potential that is too negative. A growing plant is said to absorb water from the soil and gives it off in transpiration. CO_2 enters the plant through a film of water that surrounds the leaf and as the film evaporates it is replenished by the plant. The transpirational loss of water in exchange for CO_2 is necessary for plant growth. Transpiration leads to moisture stress if moisture is not readily available to the roots. Warm dry air has a high evaporative capacity, increasing the rate of transpiration. Equally important is the increase in leaf temperature resulting from high light intensity, which raises the rate of transpirational loss, and hence water stress occurs. A great deal of the research on the onset and progression of plant water stress using remote sensing has been aimed at documenting the effects of water stress on the growth of plants (Simpson, 1981, Danson *et al.*, 1992., Moran *et al.*, 1994; Moran *et al.*, 1995).

Water deficits develop readily in forest trees, even in trees growing in wet conditions due to excess transpiration over absorption of water (Van Laar, 1982 and Berliner *et al.*, 1990). Armstrong and Scott-Shaw (1998) mentioned that water use rates of plantations decline during times of soil water deficit and therefore trees do not require water pumped out of rivers like many other land uses. Moisture stress is generally detrimental to plant growth reducing both yield and quality of the crop. The degree and duration of the stress will determine how severely growth is reduced, however, yields may never return to the level it was before the stress. The stage of growth when moisture stress occurs is also important. Moisture stress at the time of flower initiation may significantly reduce yield. Severe stress leads to premature flower, leaf and fruit drop (Nambiar, 1999). Remote sensing provides ways of distinguishing between healthy and stressed plants through vegetation indices (VI's).

LAI is a key physiological variable which affects growth and yield of commercial forest species. The leaf area of a plant is increased by high fertility; nutrient content and carbon assimilation rates which in turn increase amongst other things whole-plant growth. The forest productivity is largely limited by nutrient and water, which are both factors that can be alleviated by intensive management practices. The favourable water availability "provides a bulk-flow pathway for nutrient uptake and maintains turgidity for growth and higher stomatal conductance for photosynthesis" (Coyle and Coleman, 2005). The other critical process, which regulates growth during the nutrient and water stress, is uptake of these resources by root systems.

In the past, the growth and yield of commercial forestry has been predicted using empirical models. These models have been known to be insensitive to major influential factors which influence growth rates strongly such as management strategies and environmental factors such as rainfall. The development of process-based models introduced the simulation of growth in terms of the underlying physiological process or mechanisms that govern net primary productivity and the way stands are affected by the physical conditions to which trees are subject to, and with which they interact (Landsberg and Gower, 1997, Landsberg *et al.*, 2001).

Net Primary Productivity (NPP) is the net amount of energy a plant accumulates during a time period (Foley *et al.*, 1996 and Kucharik *et al.*, 2000). A direct relationship exists between the energy that a plant accumulates and the mass of the plant and therefore NPP could be thought of, as the amount of mass a plant gains over some period of time. NPP is calculated by taking the gross primary productivity (GPP: the total amount of energy/mass taken in by the plant) and subtracting the plant's respiration (the total amount of energy/mass lost by the plant as it breathes). Net primary production (NPP) is a key component of the terrestrial carbon cycle and it accounts for most of the annual carbon fluxes between the atmosphere and biosphere compared to other pools and fluxes that make up the cycle Hazarika *et al.*, (2005). NPP helps the scientists make predictions quantifying the amounts of carbon dioxide the plant will pull out of the atmosphere and hence pursue the climate change studies with a certain degree of confidence. The importance of accurate estimation of forest NPP in regional and global scales is widely related to studies of global changes for instance assessing carbon balance hence playing a role in demonstration of compliance with the Kyoto protocol on greenhouse gas reductions (Zhou *et al.*, 2002).

NPP is a function of above-ground biomass (AGB – amount of living matter; leaves, twigs, stems produced by plants or trees), conditions and stand age of forest. Accurate estimation of biomass is required for carbon stock accounting and monitoring in an ecosystem (Brown, 2002; De Jong *et al.*, 2003; Rosenqvist *et al.*, 2003). Many ecological and environmental applications for regional and global ecosystem models require biomass and LAI as some of the input variables. Attempts to estimate above-ground biomass (AGB) like NPP and LAI have been investigated in several studies at various spatial scales and environments (Spanner *et al.*, 1994; Nemani *et al.*, 1993; Chen and Cihlar, 1996; Fassnacht *et al.*, 1997; Brown *et al.*, 2000, Brown, 2001). The South African forestry industry has now embarked on research for improved predictions of growth (NPP and AGB) and water use by commercial forestry as per water Act of 1998 in order to avoid conflict with other water users.

2.5.2. Forestry Related Conflicts

South Africa is known to be a water scarce country. The scarcity of this commodity is largely due to man-made factors such as progressive human civilization and to a lesser extent to natural factors. These man-made factors have put a strain on water resources by desiccating the landscape therefore reducing the accessibility of water. The aridity (low rainfall over a long period) or droughts (failure of rain for a period of over five years) are the natural phenomena, which can lead to scarcity (Tewari, 2003).

South Africa's mean annual total rainfall is estimated to be 497mm, which is well below the world average of 860mm and Tewari (2003) believes that this "is further aggravated by uneven distribution of rainfall across the country that is coastlines receive more rain than the interior and western portions of the country". The remaining portions of the country are therefore arid or semi-arid due to 65% of the country receiving less than 500mm whilst the other 35% or so gets less than 200mm of rainfall. It is estimated that about 7.9% of the total water is utilized by forestry both as an important and limiting factor of production and therefore Gandar (1994) regarded afforestation as a "highly efficient user of water".

The evapotranspiration and streamflow reduction are the two forms of water usage by commercial forestry. The industry requires no water supply infrastructure such as irrigation, since it takes only what it needs and wastes none. A "history of insufficient knowledge on the impact of afforestation on runoff, coupled with inadequate planning and control over the expansion of afforestation has caused a conflict between forestry and other water users" (Gandar, 1994). The industry has therefore been labelled as an excessive water user and thus unsound, uses water indiscriminately and preferentially takes no consideration for other users.

A controversy about the effects of afforestation on water supplies began in the 1920s which was a drought period, and continues today. According to Calder *et al.*, (1992), Scott *et al.*, (1998) and Dye *et al.*,(2001) the controversy has risen in many parts of the world over the environmental and social effects of large-scale afforestation for industrial and social applications. This led to the implementation of controls on afforestation that have been applied through the afforestation permit system due to criticism that afforestation have negative impacts on both the quality and quantity of water resources. The criticism grew very strong after the 1994 democratic transition of South Africa, where forestry was accused of not accounting for environmental damages and costs. The debate is said to be between the two groups or coalitions: firstly, the environmental advocacy coalition which advocates that commercial forestry should pay for damaging the environment, especially for water it uses. Secondly, the commercial forestry advocacy coalition which wants to maximize profits with some concerns for the environment (Tewari, 2003)

The basis for arguments about forest water use has been around the 8% for longer periods. There have been dissenting views to the 8% approximation due to various reasons. Jewitt (2002) argues that the 1995 Green Paper on Sustainable Forest Development in South Africa found that the estimated available surface water reduction value was about 3.5% which is equal to about 7.6% of the current demand. Justifiably, questions have been raised about 8% given what was on the Green paper and after 8% seemed to appear from nowhere in the White paper. In the South African Yearbook of 2001/2002, DWAF gave 560 000 million m^3 / annum the country's water availability from which 89 % constitutes runoff and other 11% from groundwater resources. "Given the ongoing and sustained research into the water use of commercial forestry in South Africa; an allowance should be made for more accurate estimates of runoff and water use once research has been completed" (Jewitt, 2002).

The forested areas are known to have first option on water resources because forests mostly intercept water and draw water from the soil and groundwater. It is perceived that most water used by the forests is unavailable to other water users by virtue of having short root systems. The position of the forests on most catchments that is upper parts are such that rainfall is highest and therefore there is no reason to utilize runoff. The forests areas are criticized for drawing water automatically from rain events and the saturated zones surrounding nearby perennial streams during dry periods. The studies conducted in the then Eastern Transvaal proved that *Eucalyptus* trees were capable of drawing water resources from depths far in excess of eight meters during dry periods when there is insufficient water in the soil to meet demands (Gandar, 1994).

Calder (1992) believes that the commercial forest plantations affect the hydrological cycle by influencing the balance between evapotranspiration, interception, runoff, storage and percolation and therefore stormflows. "A major environmental concern has been the depletion of soil and ground water by plantations of fast-growing trees" (Harding *et al.*, 1992). Evidence suggests that forestry does not necessarily use significantly more water than other forms of agricultural activity (Chamberlain *et al.*, 2005). Tewari (2003) found that irrigation is using more water (52.2%), followed by ecological (17%), municipal and domestic use (9.3%) and forestry only uses 7.9% of the total. Gandar (1994) categorize afforestation's impact on runoff resources into two: namely (i) consumption of water by commercial tree species reduces the total volume of water that drains from a catchment's area and (ii) a major impact on the low flow regimes of rivers, particularly during dry season or periods of drought. This water usage creates a problem for downstream water users. That was attested to by Van der Zel (1995) where farmers downstream from Worcester forests in the Cape complained about decreased runoff from the plantations as early as 1915.

There are several studies that had been undertaken and whose findings indeed prove that afforestation is linked with depleted water resources. The fears of the hydrological effects of afforestation were also expressed in India by Shiva *et al.*, (1982), where the *Eucalypts* tree species were seen as voracious consumers of water and most likely to deplete water resources. Calder (1992) found that the *Eucalyptus* was utilized in Australia as water pumps to deliberately lower the water table in areas suffering from salinity problems. Studies have also shown that conversion of grasslands to *Eucalyptus* plantations has demonstrated a marked reduction in streamflow (Van Der Zel, 1995). There is therefore a concern over the effects of plantation forests on water resources which according to Van Lille *et al.*, *(*1980) "is widespread, highlighting the need for information on the magnitude of the water use".

In South Africa, there is evidence of depletion or reduction of the amounts of water flowing into the river systems immediately after the afforestation process has resumed substituting the native grassland or Fynbos (Van Der Zel, 1995). The reductions have been in the overall order of about 30% or 100 to 200mm equivalents of rainfall. The severity is believed to be dependent on the hydrological processes in the catchment, plantation species, growth rates, rotation lengths and management systems. Other impacts by the afforestation programmes include the disturbance of the ecological rich communities which supports a variety of species and animals. These species tend to lose their habitat once the grasslands have been converted to commercial forestry plantations. The loss is further aggravated by the single species typically established during afforestation programmes (Ahmed and Drew, 2005)

Studies conducted have presented planting of forests as a dual process of growing wood whilst at the same time improving soil and water quality of agriculturally degraded land because it is believed that trees enhance the improvements of physical environments and bio-diversity of farms. That will in the long run ensure that there is sustainable utilisation of land where the development of plantations to suit one or more land use objectives is encouraged. There is a huge positive impact ecologically because of the interaction between the afforestation programmes and hydrological processes. The planting of trees on the previously compacted land, could increase the infiltration rates due the breaking up of soil aggregates and structure to allow water to infiltrate, therefore improving the land for further afforestation programmes. It has been suggested that the improved water recharge may in some cases be sufficient to compensate for the increased evapotranspiration from the trees (FAO, 1989).

2.5.3. Social Impacts of Forestry

Commercial forestry in South Africa was born out of the need to alleviate the growing demand on limited natural resources. It therefore acts as a source of employment, foreign exchange and facilitates a number of downstream processing activities. Gandar (1994) have observed that once a large-scale afforestation project has been completed, there has been an exodus from certain rural areas looking for job opportunities in newly developed projects, resulting eventually in the withdrawal of services, closure of schools and post offices and the decline of rural communities. On the contrary, silvicultural practices such as coppice reduction provide fuel wood for the rural livelihoods. These pruned tree-lets are normally used by the rural communities for different purposes e.g. fencing, erection of huts and kraals.

2.5.4. Afforestation and the Water Act

Under the Water Act of 1998, water is allocated to users according to availability after making allowance for the ecological and social reserves. In South Africa, commercial plantation forestry is designated as a *stream flow reducing activity* (SFRA) and is regulated on this basis and this is seen as the key negative impact characteristic of commercial forestry. Commercial forestry is regulated by means of a SFRA Water-use Licensing System in terms of Chapter 4, Section 36 of the National Water Act (No. 36 of 1998). Stream flow reduction is based on the net increase in water use due to a switch from natural vegetation to plantations (DWAF, 2004; Chamberlain *et al.*, 2005).

Legislation governing future afforestation restricts the establishment of plantations as they are regarded as serious water users in South Africa. All new afforestation requires a permit. In addition, a charge is levied for stream flow reduction activities, which includes plantation forestry, based on planted area (Ahmed and Drew, 2005). The data required for a decision on granting a permit comprises the minimum flow requirements of downstream users, which the afforestation permit system (APS) has divided the South African catchments into three categories: Class 1 pertains to catchments where no more afforestation is possible due to large demands for other purposes such that any more afforestation could be permitted. Class 2 catchments are permitted to have afforestation to the extent that it does not reduce mean annual runoff (MAR) by more than 5% from existing level of precipitation. The priority is given to water needs of other sectors such as irrigation. Class 3 catchments allow up to a 10% reduction in MAR (Gandar, 1994; Van der Zel, 1995; Tewari, 2003).

These water use controls are seen only to be applicable to forestry when other crops with high water usage were not subjected to similar regulation. These controls omit the economics thereof in relation to other competing water uses and also do not consider on other runoff reducing land use such as farm dams and dry land crops (Tewari, 2003). The APS is believed to be a temporary measure until scientific research produces the necessary data for a more defensible system of control. Studies conducted have found the possibility of APS underestimating the impact of afforestation on mean annual runoff reductions, where the reductions were more than 20%. Van der Zel (1995) has criticized the APS for only favouring large companies as compared to resident farmers because they could afford the capital to expand plantations over a large number of catchments (Gandar, 1994; Dye and Bosch, 2000).

The APS has limited afforestation since its inception and has been successful in ensuring that the riparian zones remain intact such that forest plantations do not exist in riparian zones and also ensuring the clearing of all self-sown alien species. The APS has been seen to be at the forefront of integrated catchment management systems of all water and land uses where equitable sharing of water resources is encouraged. It has helped in the production of an economically efficient industry in the country because it has not hindered the economics and markets of tree growing business (Tewari, 2003).

2.6. Remote Sensing (RS)

Remote sensing has been defined as the science and art of obtaining information about an object, area or phenomena through the analysis of data acquired by a device that is not in contact with that object, area or phenomena under investigation (Cracknell and Hayes, 1991; Pu *et al.*, 2003). Van Laar, (1974) has further defined remote sensing as the study of objects from great distances by photographic (applicable in many sectors e.g. forestry etc) as well as non-photographic sensors and "includes both photographic and digital sensing devices ranging from detailed aerial photography to ultra small scale meteorological satellite imagery" Thompson and Whitehead (1992). The principle which governs remote sensing is obtaining data of an object without necessarily having to be in contact with that object. Van der Zel (1985) stated that South African forestry is one of the spheres of activity amongst other land use applications that are being investigated using remote sensing. Kätsch and Vogt (1999) confirmed that a number of studies have been conducted in South Africa where remotely sensed data have been applied for a variety of purposes and recently have been used for determining water use and growth of forest species in conjunction with process-based models (Dye *et al.*, 2002 and Ahmed, 2005).

Remote sensing is a cost efficient source of information for forest inventory and monitoring purposes (Pekkarinen, 2002) and Pu *et al.*, *(*2003) describe RS as an important driver to some ecosystem models applied at landscape to global scales. Studies conducted by Cosmopoulos and King (2004) confirmed the usefulness of both the airborne and satellite imagery in modelling variables such as LAI, basal area etc. even though the forest management information needs for inventory could be or are met using aerial photography. Remote sensing techniques have the potential to provide forest managers with a rapid and economical method of acquiring plantation information related to forest productivity (Ghebremicael *et al.*, 2004). As such, there is an operational requirement for forest stand mapping and quantification of various forest parameters, which require continuous updating. These parameters include LAI, crown closure, tree height, tree density, leaf and canopy density, etc. The thematic maps of rates of photosynthesis, transpiration etc. could be produced from the above parameters (Anselmi *et al.* 2004).

The combination of remote sensing and modelling techniques is seen as a potential source of information describing structural and functional properties of vegetation at broad spatial and temporal scales that after proper calibration will enable changes over extensive vegetated areas to be feasibly assessed. Anselmi *et al.*,(2004) provide evidence of time consuming and expensiveness of some technologies used for forestry inventory data collection, which are based on field based measurements such as destructive sampling. It is believe that this is further aggravated by measurements, which are to be made over large areas and at frequent intervals. The situation therefore has led to the birth of new technologies such as remote sensing coupled with modelling techniques which enable much quicker detection of environmental changes in terrestrial ecosystems.

2.6.1. Remote Sensing and Growth and Yield Models

A model is an abstraction or a simplified representation of some aspect of reality whilst modelling is about making a good representation. Growth models assist forest researchers and managers in many ways e.g. ability to predict future yields and to explore silvicultural options. Models provide an efficient way to prepare resource forecasts, but a more important role may be their ability to explore management options and silvicultural options.

(Vanclay, 1994; Coops *et al.*, 2005). These models are classified according to the relationship types they represent; the level of detail incorporated and intended model uses. Also, using the conceptual underpinning and internal structure of the model, one can broadly differentiate between empirical, and process or mechanistic growth and yield models (Tharakan *et al.*, 2000).

Empirical models are descriptive by nature whilst the process-based models are explanatory. Recent publications have focused on advantages and limitations of both the empirical and process approaches for instance empirical models primarily use statistical analyses to collate and describe data on growth and biomass production in a large number of forest stands or plantations, using which, predictions about other stands growing under similar conditions can be made, whilst process-based models predict the behaviour of a system such as a forest stand based on a set of functional components and their interactions with each other and the system environment (Mohren and Burkhart 1994; Korzukhin *et al.*,1996; Makela *et al.*, 2000; Corona *et al.*, 2002).

A growth model is a synthesis of dynamic inventory data indicating growth and change in the forest. Used to advantage and in conjunction with other resources and environmental data, growth models can be used to make predictions, formulate prescriptions and guide forest policy and management prescriptions, and that supplementary data and adequate testing are also required. Growth models are of limited use on their own, and require ancillary data to provide useful information. With suitable inventory and other resource data, growth models provide a reliable way to examine silvicultural and harvesting options, to determine the sustainable timber yield, and examine the impacts of forest management and harvesting on other values of the forest. A number of process-based models aimed at calculating forest productivity exist for an example FOREST–BGC (Running and Coughlan, 1988; Running and Gower, 1991), BIOMASS (McMutrie *et al.*, 1992), ProMod (Battaglia and Sands, 1997) and 3-PG (Landsberg and Waring, 1997). 3-PG is a simple PBM requiring easily obtained input data and species-specific parameter values, has also been intensively tried and validated under different environments and it provides answers to questions relevant to both researchers and forest managers (Johnsen *et al.*,2001; Sands and Landsberg, 2002 ; Almeida *et al.*, 2004).

2.6.2. 3-PG

Landsberg and Waring (1997) developed a simple process-based forest growth model called 3-PG (Physiological Principles for Predicting Growth) that generates a number of growth variables that are relevant to forest managers such as estimates of diameter at breast height (DBH), stand volume and biomass and projected leaf area index (LAI). 3-PG is a stand-level model of forest growth but needs to be parameterized for individual species (Sands and Landsberg, 2002). The model simplifies application because it requires only a few parameters that can be derived from literature or from field measurements. The monthly time step of the model requires values for total short-wave incoming radiation, monthly mean vapour pressure deficits (VPD), total monthly rainfall, and an estimate of soil water storage capacity and soil fertility (Coops *et al.*, 2001; Esprey and Sands, 2004; Coops *et al.*,2005).

The 3-PG model is based on the fraction of photosynthetically active radiation absorbed by the forest canopy, and consists essentially of two sets of calculations; biomass production, and subsequent allocation of biomass between the components of the tree (Campion *et al,* 2005). Absorbed photosynthetically active radiation (APAR) is estimated from global solar radiation, derived from an established empirical relationship based on average maximum and minimum temperatures. The utilized portion for each month ($APAR_u$) is calculated by reducing APAR by an amount determined by a series of modifiers that is (take values between 0 system shutdown and 1 no constraints); derived from constraints that cause partial to complete stomatal closure: subfreezing temperatures, high daytime atmospheric vapour pressure deficit (VPD) and depletion of soil water reserves. A soil water balance is calculated as the difference between total monthly rainfall, plus available soil water stored from previous month, and losses through interception and transpiration define the limits on soil water availability (Landsberg and Waring, 1997; Coops *et al.*, 2001).

Gross primary productivity (GPP) is calculated by multiplying APARu by a canopy quantum efficiency coefficient (α), with a maximum value set by the soil fertility ranking and reduced monthly when mean temperatures are suboptimal for photosynthesis and growth. 3-PG's major simplification is that it does not require calculation of respiration or root turn over, but assumes that total net primary productivity (NPP) in temperate forests approximates a fixed fraction (0.45± 0.05) of GPP. The 3-PG was according to Coops *et al.*, (1998), modified to allow remotely sensed observations to be used as inputs and thus became 3PG-S where the S symbolises the use of spatial version data in the model framework. The introduction of satellite driven observations to 3-PG model to be utilized as inputs to it, led to a spatial version of 3-PG that is 3PG-S.

2.6.3 3 PG-S

The utility of process-based models to predict forest growth variables at specific stand ages, and their capacity to be extrapolated across the landscape using GIS technology, now offers operational potential for use in routine forest management and planning (Battaglia *et al.*, 1998). The 3PG-S (Physiological Principles Predicting Growth Spatial version) developed by Coops *et al.*, (1998) is a simplified version of the original implementation of the 3-PG model and is driven primarily by vegetation light absorption, which determines the potential physiological rates. 3PG-S is a simple process-based forest growth model which uses a monthly time step and requires values for total short-wave incoming radiation, monthly mean VPD, total monthly rainfall, an estimate of soil water storage capacity, and some estimates of DBH, stand volume and biomass and projected leaf area index (LAI).

The 3PG-S has been successfully used in Australia and New Zealand to assess growth and water use of a wide range of forests based on remotely sensed data and a number of established biophysical relationships and constants (Coops *et al.*, 1998). The model requires few parameters which can be derived from field measurements (Appendix A). It uses allometric relationships to estimate the amount of carbon allocated to roots, stem and branches. A fertility rating describes the influence of nutrients on carbon assimilator and allocation strategy. Self-thinning of forest stands is predicted using -3/2 power law, while water use is calculated using the Penman-Montheith equation (Landsberg and Waring, 1997).

The forest characteristics such as LAI, above-ground biomass and duration of water deficiency are reflected in the remotely sensed attributes e.g. vegetation indices. The biomass production results from the conversion of radiant energy that is absorbed by canopies. The advantage of integrating remotely sensed data with process based models is that it can help monitor and map large areas of the earth surface at both local and regional scales. It therefore substitutes the intensive field data sampling which is costly and time consuming due to its high spatial coverage and resolution on a long term basis.

2.7 Site Quality / Index

Site quality indicates the productive capacity of a specific area of land for a particular species. In the forestry environment, site quality can be defined as the potential of the site to produce timber given a particular species or forest type. It is therefore a collective of various characteristics which influence growth of that particular area for that particular plant species. This collection of characteristics renders site quality a difficult component to assess due to interacting and interdependent factors of the site and the plants themselves thus making it difficult to assign cause and effect relationships (MacFarlane *et al*., 2000).

There is no single measure of site quality that has been found to be entirely satisfactory. The environmental factors that influence growth include soil factors such as physical and chemical properties, available soil moisture content; topographic factors, for instance slope, elevation, aspect; climatic factors, that include air temperature, humidity, radiant energy, precipitation; and competitive factors, for an example other trees and lesser vegetation, animals and man.

The most commonly used measure of potential site productivity is site index which is a mean height of upper crown class trees that have been free to grow in an even-aged stand at a specified index age (Harrington, 1986; MacFarlane *et al*., 2000). Height growth is accepted as the more stable, directly measured stand growth statistics; has been used as a measurement of site quality because of existence of correlation between volume and dominant height growth. Harrington (1986) further argue about the difficulty or impossible accurate assessment of site index in stands that are of uneven aged, mixed species, very young or very old, or on sites where the species of interest is not growing.

Summary

This chapter has outlined the importance of forestry in South Africa and hence employment opportunities and its contribution to the country's GDP. It has also looked at the need for afforestation programmes, conflicts with other water users, the impacts of forestry on water resources and therefore the need to use process based models to predict yield and water use of forest species taking into consideration the Water Act of 1998. The process based model as integrated with remotely sensed data is of vital importance as it has the potential for predicting growth and water use over large areas as compared to point based models. This study aims at investigating the use of remotely sensed data and a process-based model to estimate productivity, above ground biomass and LAI of *Eucalyptus grandis* in Zululand.

CHAPTER 3: STUDY AREA.

3.1. Introduction

The study was conducted in commercial forestry plantations in the Zululand region of KwaZulu-Natal province (Figure 3.1) of the Republic of South Africa. Ten study sites (*Eucalyptus grandis* compartments*)* were selected for this study. These sites were divided into two groups i.e. four sites were used as an independent data for model calibration and all are Institute for Commercial Forestry Research (ICFR) research trial sites whilst the other six are commercial forestry estates in Zululand. These sites lie between 28°19'.28"and 28°42'.23" South and between 32°08'.20" and 32°20'.20" East. The criteria used to choose the sites was based on the following : age of trees must be greater than 2 years representing pre-canopy closure, sites must have 70% of stocking rate and must have contrast in climate and water hence productivity. An effort was made to select stand which represented varying productivity potentials so as to provide a full range of estimated LAI values for the calibration and correlations of the different LAI estimation methods. These stands had *Eucalyptus grandis* stands of different age groups.

Plots of 15m x 15m representative of variation within the compartment, were delineated to represent the whole compartment, each varied in size (4 ha to 5 ha), the uniformity of the canopy, condition of the understory vegetation and tree condition were taken into consideration during site selection. The plots were chosen such that diseased, forked and infested trees were avoided. The sites had varying understory vegetation consisting of little or no weed. The sites were of high planting density with a spacing of 2.7m and an initial stocking of 1667 trees per hectare. The general descriptions of the study sites are shown in Table 3.1.

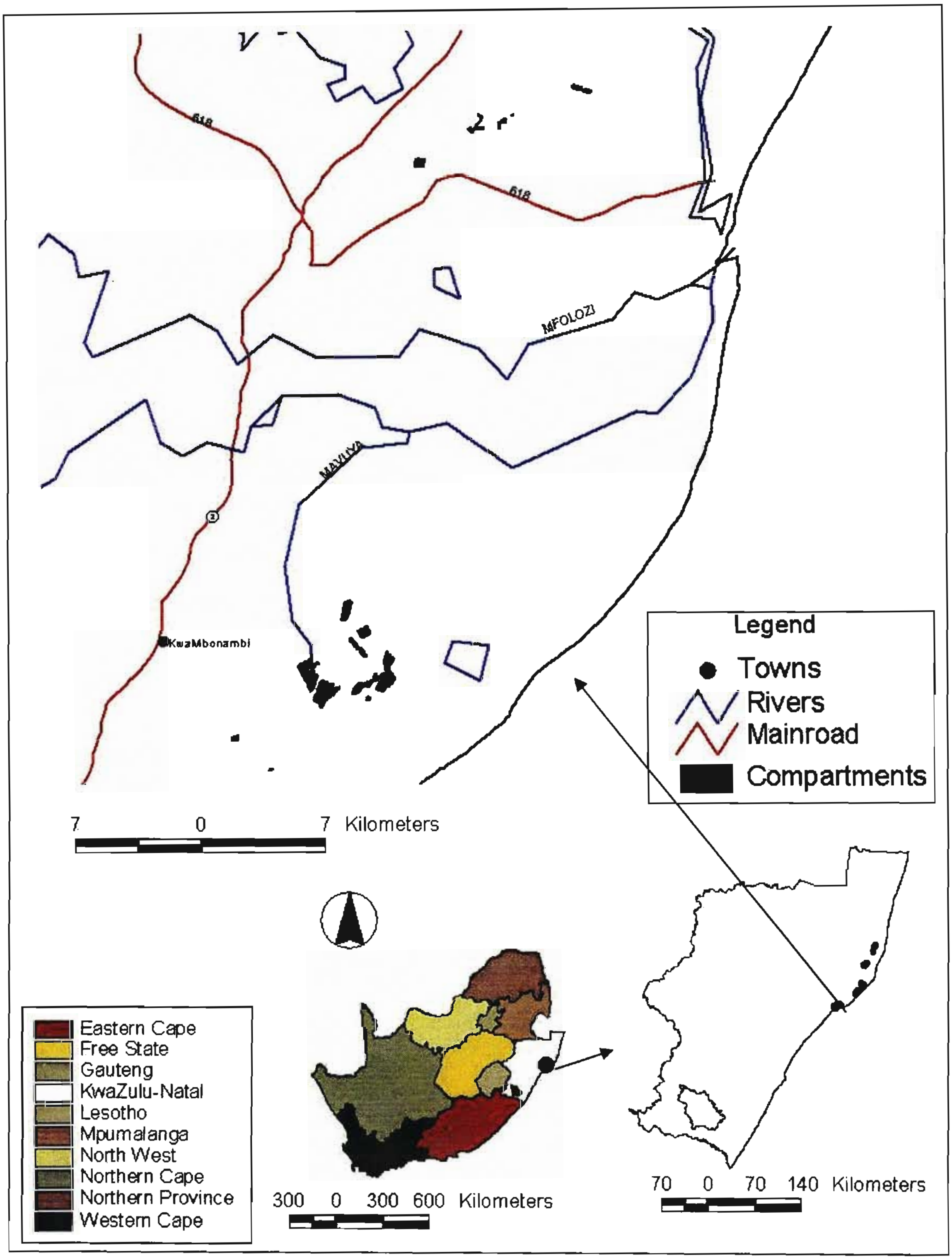


Figure 3.1. Map of study area

Table 3.1. General description of study sites

Plots	Site Index	Age	Average DBH (cm)	Stocking (Stems/ha)	Latitude	Longitude	Comments
E34A	17.4	3.6	12.9	1387	28°19'.28"	32°20'.20"	Weed-free, easy access, pine stumps from previous rotation visible, 7%slope.
J1B	20.2	5	16.6	1544	28°35'.51"	32°12'.25"	7% slope, previous rotation was pines, clean and easily accessible.
F9	20.2	4	15.2	1620	28°37'.14"	32°10'.55"	Weedy, dead branches on the ground, 6% slope, no diseased or dead trees
A63	16.4	4	9.9	1587	28°32'.43"	32°14'.39"	A little weedy, healthy tree, 6.5% slope, few stumps.
F18	16.6	4	15.5	1560	28°37'.10"	32°12'.00"	Fern plants present, little weedy, pine stumps from previous rotation visible.
C14	20.2	3	12	1666	28°42'.23"	32°08'.20"	5% slope, weed free, healthy trees.

3.2. Topography

Topography introduces variations in the radiance detected by the remote sensing sensor and this effect has been researched in many studies. The study area consists of flat to gently undulating topography, 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 (Wolmarans and Du Preez, 1986; Jacobs *et al.*, 1989).

3.3. Climatic Factors

Climate is a primary factor for site quality or classification of sites in South Africa (Schönau and Grey, 1987). Mean annual precipitation (MAP) and mean annual temperature (MAT) are the two used regionally to measure variation in climate. MAP characterises long-term water supply into the region and hence defines the potential of a growing area assuming other factors such as nutrients, available light and suitable substrate. MAT is associated with the amount of heat units available that in turn can be an indication of length of a growing season, the potential evapotranspiration to take place and the rate of assimilation The growth conditions on a regional or local scale are determined by light associated with day length, temperature regimes and available soil water or moisture, atmospheric or soil bound. The hottest mean maximum temperature is around 30 °C whilst mean annual temperature is 22 °C for KwaZulu-Natal north coast. The mean annual rainfall decreases from an average of 1200 to 1400mm along the coast to an average of 650mm inland. Mean annual temperature decreases from 22 °C to 16 °C from the coast to 20km inland respectively (Schulze, 1997).

3.4 Geology and Soils

The influence of the geological material is important because most soils conducive to tree growth are derived from specific parent material. If the origin of the parent material is known, more accurate predictions regarding characteristics and land use will be more possible than if the origin is unknown. The coastal sand dunes found in Zululand are derived from Aeolian deposits whilst the inland soils are derived from material deposited by running water (alluvial deposits along the river banks) and ocean and lake sediments e.g. some parts along St. Lucia. The soils suitable for agriculture are found along the coast belt area and are derived from sand stone, shale and mudstone whilst the low potential soils are found along the portions of Mhlathuze River (Jacobs *et al.*, 1989).

The St. Lucia formation is comprised of rich fossiliferous glauconitic, olive grey silts and fine sands with large calcareous concretions of marine sediments at various levels. Glauconitic sand or green sands as they are known, are hydrated with aluminosilicate of iron and potassium, usually calcium enriched. Forestry is suited with this formation as it is poorly drained with clay-loam texture. Mottled, brown, clayey sand related to vlei or swamp sedimentary environment characterises the KwaMbonambi area. This substrate usually forms hydromorphic soils with Uloa formation occurring close to Richards Bay and is rich fossiliferously and limestone (Jacobs *et al.*, 1989).

3.5. Hydrology

The climatic conditions in Zululand largely influence the hydrological processes and hence the water quantity and quality in the area. Severe storms common during the past decade has led to sufficient storm events contributing largely to water quality trends and hydrological water paths. The degradation of water resources of Zululand in the past decade has caused detrimental sediment deposits. These sediments largely contain pollutants from commercial agricultural sites (Kelbe and Germishuyse, 1999).

3.6 Natural vegetation

Vegetation is a prime determinant of ecosystem types (Peters, 1992). The dominant Bioresource groups are moist forest, thornveld and palm veld. The vegetation in Zululand is diverse, comprising of numerous community types (Raal and Burns, 1996; Camp, 1997). The natural vegetation of Zululand consists of a mosaic of climax dune forest, secondary grassland, Dwarf shrubland, saltmarsh, mangroves, swamp forest and Cirque vegetation and are considered as high conservation priority (Fairbanks and Benn, 2000 ; Wassenaar, *et al.*,2005).

CHAPTER 4: MATERIALS AND METHODS

4.1 Introduction.

As it has been highlighted before, the aim of this project was to estimate water use and productivity of *Eucalyptus grandis* using remotely sensed data and a process-based model. Both direct (destructive sampling) and indirect use of optical (that is LiCor-2000) methods were used to estimate *Eucalyptus grandis* LAI values. This chapter will then briefly describe the direct and indirect field based methods of estimating LAI. A description of how the processing of satellite imagery was undertaken and methods used in calculating the different VI's is clearly laid out. Describing the statistical analyses undertaken concludes this chapter.

4.2 LAI Determination using Destructive Sampling

The sampling procedure was based on that described by Ghebremicael *et al.*, (2004) and Esprey (2006, *per. comm.).* Trees to be harvested were selected based on age and location (that is to fall within the path 167 row 80 of Landsat TM). That was essential in order to capture the variation in leaf area. Within the compartments, a plot of 15m x 15m was delineated. These compartments were such that they are on near-level terrain to minimize the topographic effects.

The diameter at breast height (DBH that is 1.3m from the ground) was measured using the DBH measuring tape for all the trees in these demarcated plots and the DBH values grouped according to small, medium, large and very large distributions. Five trees were selected based on the DBH distribution from each of the plots. Each tree was felled as close as possible to the ground using the chainsaw. The tree height and height to the first live branch were measured and the difference between the two measurements that represent the crown length was determined. The crown length was divided into three zones *viz.* upper, middle and lower zones of equal length. Appendix E shows all the plot measured parameters.

In the field, the leaves of the whole crown were stripped by hand and their fresh weight determined using a 30kg spring balance having an accuracy of ±1g. Three sub-samples of leaves from each zone were collected, taken back to the laboratory in a cooler box and fresh weights measured using a more precise laboratory balance. These sub-samples were then oven dried overnight for 24 hours at constant temperature of 65 °C. In order to avoid absorption of moisture by leaves, their dry weight was quickly determined after removing them from the oven. For each sample, a ratio of oven-dry –to- fresh-weight was calculated and an average ratio taken. An estimate of dry weight of each component was obtained by multiplying the total fresh weight of the component by the corresponding oven-dry-to-fresh –weight.

4.2.1 LA and LAI Determinations

A sub-sample of leaves was used for the determination of SLA because SLA was required to relate foliage dry mass to a LA. The expression which relates the two is:

SLA (cm^2/kg) = LA (cm^2)/ Leaf Dry Matter (kg)

Leaves were randomly selected from each of the three zones of the crown. The leaves were put in zip-lock bags and labelled. These bags were then placed in cooler-boxes whilst the leaves were pressed in books to preserve their shape and flatness. A Li-3100 leaf area meter was used to scan the leaves for leaf area and oven dried to constant weight at 65 °C. The leaves were then cooled in the desiccators and weighed to obtain their dry mass. The leaf area meter (that is Li-3100) used was calibrated in $0.1mm^2$ to correct the LA for each sample. SLA was calculated on a projected LA or single side basis. After calculating the leaf area of different zones, they were summed for individual trees to give tree leaf area. The LAI was therefore calculated using the following expression:

LAI (m^2/m^2) = LA / Plot Area.

Above ground biomass is the sum of all the components i.e. leaves, branches, bark and stem. Appendix F shows sample trees biomass determination in detail.

4.2.2. Scaling- Up

The scaling-up was done based on a direct relationship between LA and DBH (Battaglia *et al.*, 1998). The relationship is such that an increase in LA leads to an increase in DBH. This relationship is used because it is not realistic to destructively sample all the trees in a compartment and therefore it is practical to use the data on felled trees where it is possible using regression equations. Therefore, regression analysis was used to develop relationships between the DBH and LA in each study site. LA and DBH have a direct relationship i.e. an increase in LA leads to an increase in DBH (Battaglia *et al.*, 1998; Ghebremicael, 2003).The LA of the plot trees was calculated by expressing the DBH as LA for each in the plot measured. Finally, LAI was computed as the sum of the tree LA's for each plot per ground area covered by the trees.

4.3. LAI Determination using LiCor-2000

The plant canopy analyzer (LiCor-2000) is known for providing "reasonable estimates of LAI" (Battaglia *et al.*, 1998 and Welles and Norman, 1991). This instrument measures the estimates of LAI using measures of canopy photosynthetically active radiation (PAR, between 400-700 nm) as inputs to equations which derive the LAI as a function of PAR detected below the canopy. The above canopy readings were obtained by taking measurements in the open space outside the stands. The instrument consists of 80 individual light sensors placed at 1mm spacing along the probe and was held at breast height during operation.

The instrument was programmed to take twelve set of readings that is first one was on the above canopy (calibration) and next four were below canopy, two above canopy again, four below canopy and last one above canopy. The readings were taken whilst pointing the instrument in the direction away from the sun. The measurements were taken early in the morning under clear sky. The calibrating readings were taken on the open field close to each forest stand before and after the measurement readings. The LAI-2000 data file viewer (FV2000 software) was used to download the data from the LiCor-2000 instrument.

Studies by Pierce and Running (1998) used the same sampling strategy because it is believed to give a good spatial coverage of the study area.

4.4. Image Processing

4.4.1 Plots Location

The x and y co-ordinates of the point on the nearest road to the plots were captured using the GeoExplorer Global Positioning System (GPS) (Trimble, 1994), and the distances from the road to the delineated plots measured. These points (GPS co-ordinates) were then entered into ArcGIS 9.1 (ESRI, 2000) to overlay them with the polygon boundaries of the compartments. That was done in order to ascertain the exact positions of the study plots within compartments. Due to different projections of the vector files (shapefile) to those of satellite images, they were imported into Arc Coverage format and therefore reprojected to Transverse Mercator projection, Clarke 1880 Cape Datum and a central meridian of lo 31° in ERDAS Imagine 8.7 (ERDAS Imagine Inc., 1999). These projected and accurate digital coverages were then used to clip or extract the satellite data pertaining to the study compartments and hence maps of the study compartments produced.

4.4.2. Image Data

The Landsat TM images (path 167 row 80) used in the study were acquired from the Satellite Application Centre (SAC). The seasonal distribution of the images was taken into consideration when selecting capture dates and as a result four images were used in this study. The images were captured in February, April, July and September 2006. Figure 4.1 depicts the April subscene and image specifications are included in Appendix B. The images were cloud free and were in Transverse Mercator projection and Clarke 1880 Cape Datum. The images were both geometrically and radiometrically corrected by SAC. The image processing was done using ERDAS Imagine 8.4.

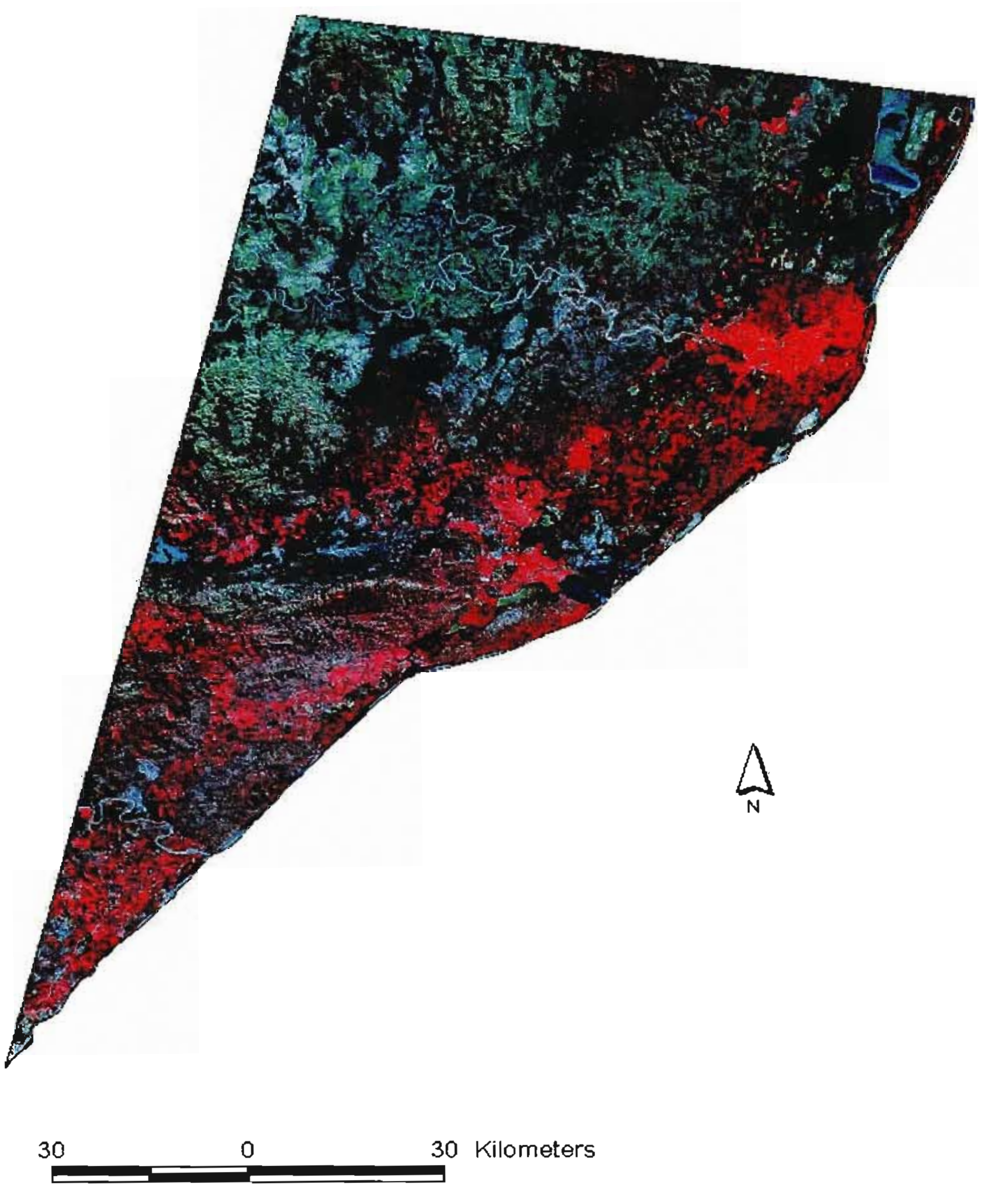


Figure 4.1. A Composite of Landsat TM (path 167, row 80), April 2006

4.4.3 Image Analysis.

Image analysis consisted of orthorectifying the image, subsetting the fields of interest and calculating various indices. The relationships between image data and plot-level forest data were easily obtained through image sub-setting. The different plots were cleaned and had their topology built as polygon features.

4.4.4 Calculating Various Vegetation Indices

The vegetation indices were calculated using Erdas 8.7 model maker, since it provides an option to build or use the already existing models, thus enabling processing of the clipped compartment images for calculating of different vegetation indices. The indices that were chosen for the study were NDVI, TNDVI, RVI and VI_3. The models for different indices were run using appropriate plot subset images as inputs and output thematic maps depicting estimated vegetation indices values throughout the compartment were then computed.

4.4.5. LAI Estimation

A sound model is required to estimate LAI values from vegetation indices. This study used a regression-based model (empirical) instead of deterministic models. The regression-based model describes the relationship between vegetation indices and LAI estimates and has been shown to be valid for a wide range of scenes and sensors (Xavier and Vettorazzi, 2004).

4.5. 3PG-S Model

The 3PG-S model was run on the ArcGIS 8.3 (ESRI, 2000), data such as the site data (that is latitude, fertility rating, soil class, maximum and minimum available soil water), duration data (that is start age, end year, year and month planted), climatic data (T_{min}, T_{max}, vapour pressure deficit (VPD), solar radiation, frost and LAI values derived from NDVI);

were used for predicting NPP for the chosen compartments. Figure 4.2 shows a flow diagram of how the model works.

4.6. Statistical Analyses

Correlation and regression analyses was undertaken using SPSS in order to ascertain the relationships between various parameters such as LiCor-measured LAI values; LAI values determined true destructive sampling (Actual LAI), vegetation indices, SLA. Regression analysis was used to build models that can be used to predict LAI across compartments. The correlation coefficients were also tested for their significance. Similarly the predicted NPP and AGB was validated using the independent data made available by ICFR i.e. (it is data observed during destructive sampling exercise) by means of statistical analysis, where different models e.g. linear, logarithmic, power and exponential were applied to obtain the best fit between the variables. Figure 4.3. Summarises the flow of methods used in this study.

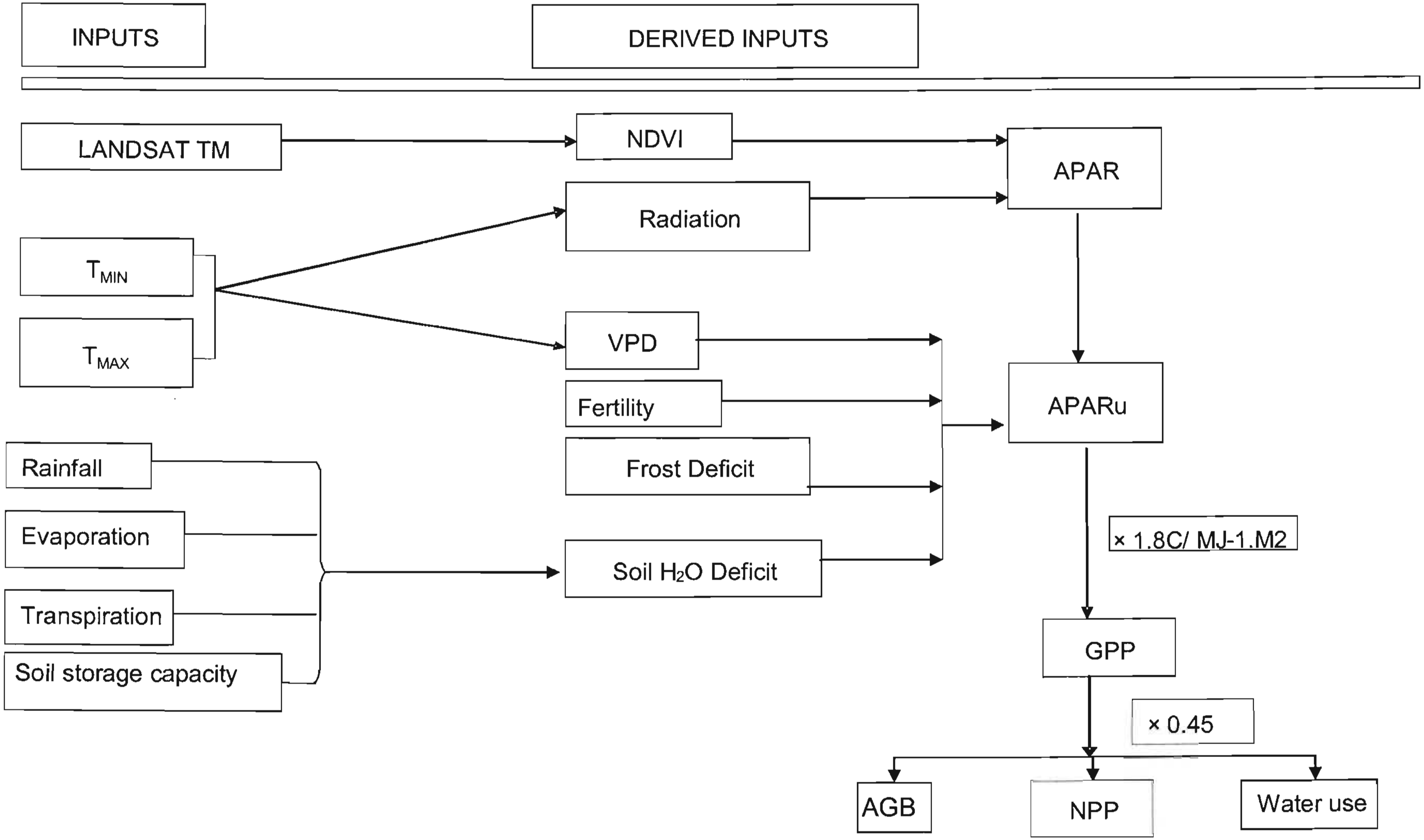
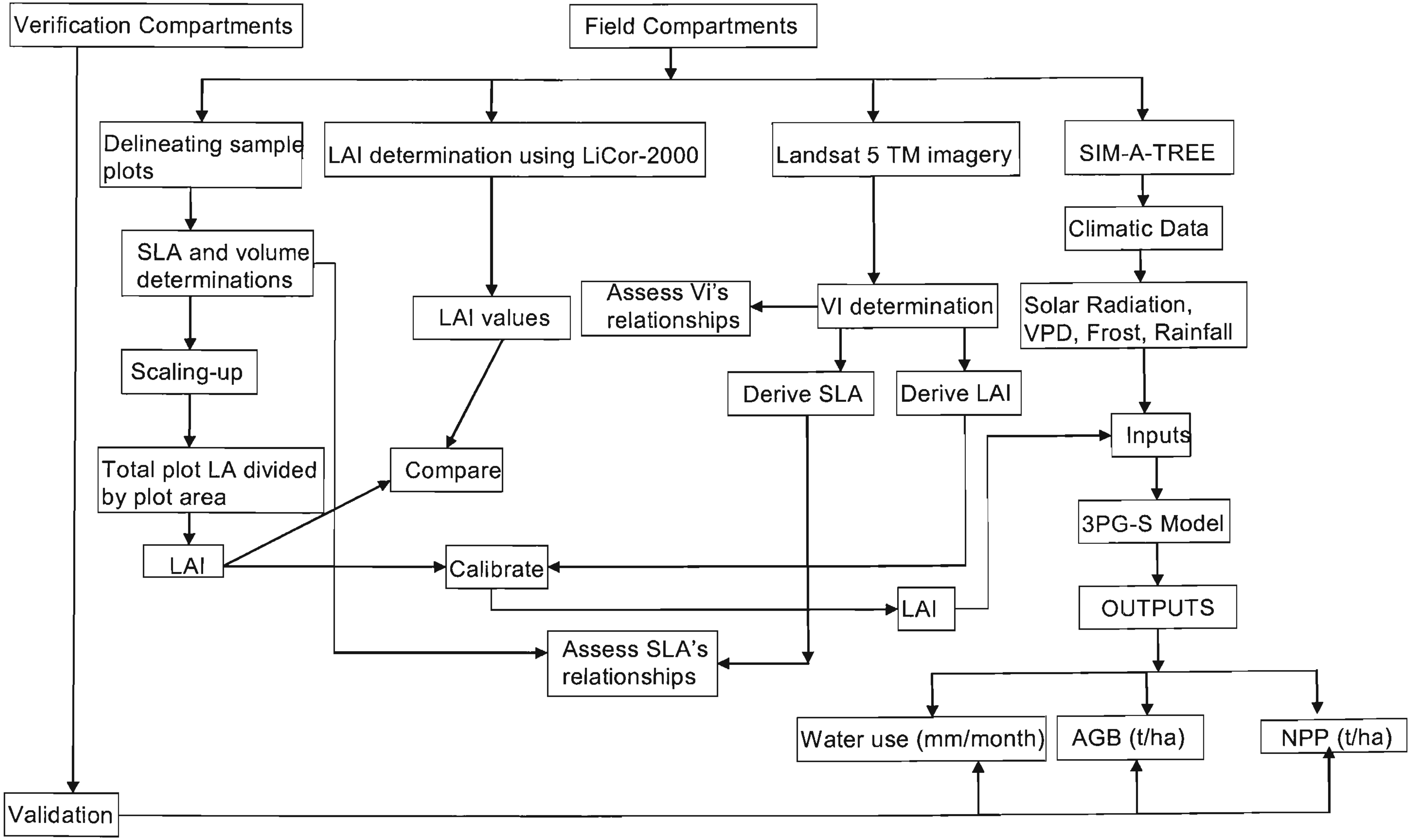


Figure 4.2. The 3PG-S flow diagram



Where, NPP = Net Primary Productivity, AGB= Aboveground Biomass, SLA= Specific Leaf Area, LA= Leaf Area, LAI= Leaf Area Index, VI's = Vegetation Indices, VPD= Vapor Pressure Deficit

Figure 4.3 Flow chart of methodology used in the study.

CHAPTER 5: RESULTS AND DISCUSSION

5.1. Introduction

The previous chapters have outlined in detail the introduction, literature review, description of study sites and materials and methods used in the study. This chapter will present the results obtained followed by their discussion.

5.2 Leaf Area Index

The leaf area index was obtained through both the direct (destructive sampling) and indirect field based methods, where the optical instrument LiCor-2000 was used. As stems and branches also intercept sunlight, a correction applicable to *E.grandis* trees in Zululand was used to estimate the true LAI of the canopy alone. The correction (Dovey and du Toit, 2006) takes the form: LAI = 1.0594 (PAI)-0.892, where PAI represent the entire plant area index as measured by the same instrument. Destructively sampled LAI (Actual LAI) was calculated by dividing the total LA of trees in the sample plot by the plot area. These LAI values which were obtained through destructive sampling and LiCor-2000 are shown in Table 5.1.

Table 5.1 LAI values measured using destructive sampling and LiCor-2000

Compartment	Total Plot LA (m^2)	Plot Area (m^2)	LAI through destructive sampling (Actual)	LiCor- LAI
E34A	505.351	225	2.24	1.46
J1B	299.452	225	1.33	2.27
F9	90.208	225	0.40	0.47
A63	234.394	225	1.04	0.91
F18	1028.308	225	4.57	3.32
C14	209.577	225	0.93	1.14

There was a significant correlation between the actual LAI values and those obtained from LiCor-2000 ($r=0.88$, $p<0.05$). The regression relationship between LiCor-LAI and actual LAI is a significant relationship with an R^2 of 0.78 (Figure 5.1). This relationship can be safely used to predict actual LAI values of *Eucalyptus grandis* in the study area within the measured range of LiCor-LAI. From the diagram (Figure 5.1), it is clear that the LiCor instrument underestimates true or actual LAI values, as evidenced by the slope of the regression equation.

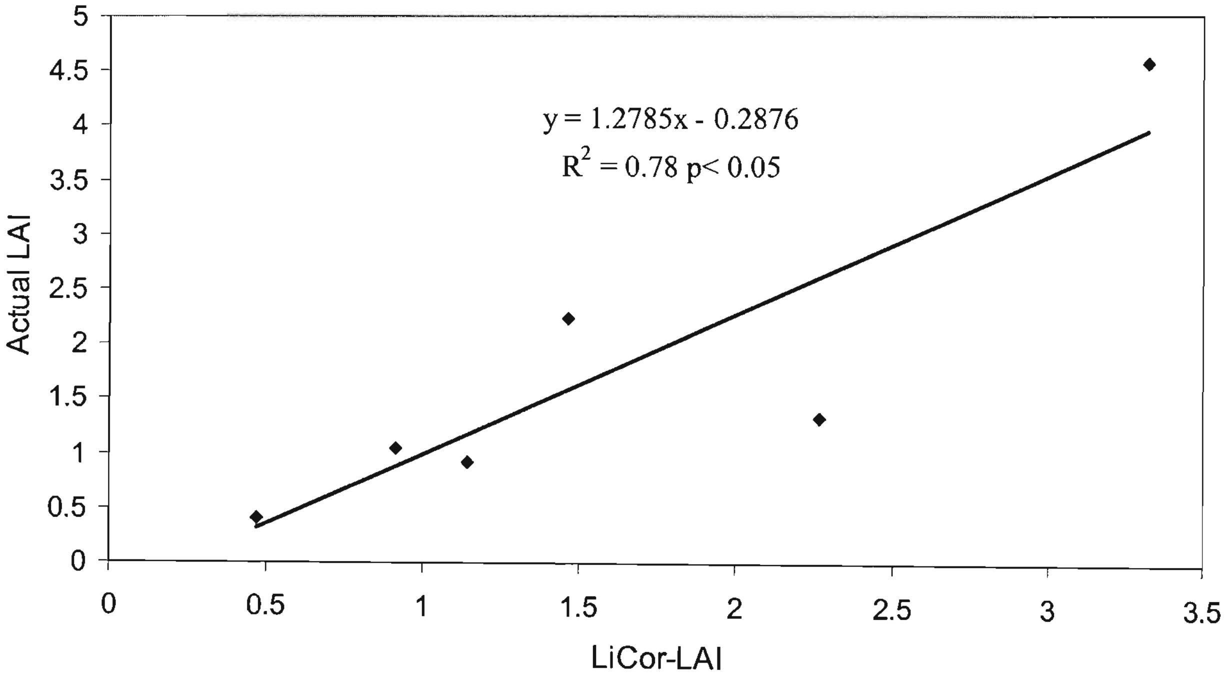


Figure 5.1 Relationship between LAI values from different sampling methods

Previous studies (e.g. Chason *et al.*,1991; Smith *et al.*,1993; Stenberg *et al.*,1994; Chen, 1996) have also observed the LiCor-LAI was actually less than the actual LAI. It has further been suggested that underestimation happens due to clumping of foliage at high leaf areas. LiCor-LAI underestimated actual LAI by 43% and 62% in Scots pine and Douglas-fir stands respectively (Smith *et al.*, 1993 and Stenberg *et al.*, 1994). Wang *et al.*, (1992) observed that apart from LAI obtained by destructive sampling, LiCor-LAI even underestimates PAI values derived from hemispherical photographs by 15%.

5.3 Specific Leaf Area (SLA)

The SLA values of all sampled trees in the study are presented in Appendix C. The summary of the SLA values are depicted in Table 5.2. The SLA is one parameter in 3-PG and 3PG-S that is age dependent. The measured SLA values ranged from 9.0 to 10 m^2/kg with ages from 3 to 5 years.

Table 5.2 SLA of sample plots estimated by destructive sampling.

Compartment No:	Tree Age (years)	SLA (m^2/kg)
E34A	3.6	10.467
J1B	5	10.018
F9	4	10.284
A63	4	9.578
F18	4	9.437
C14	3	10.409

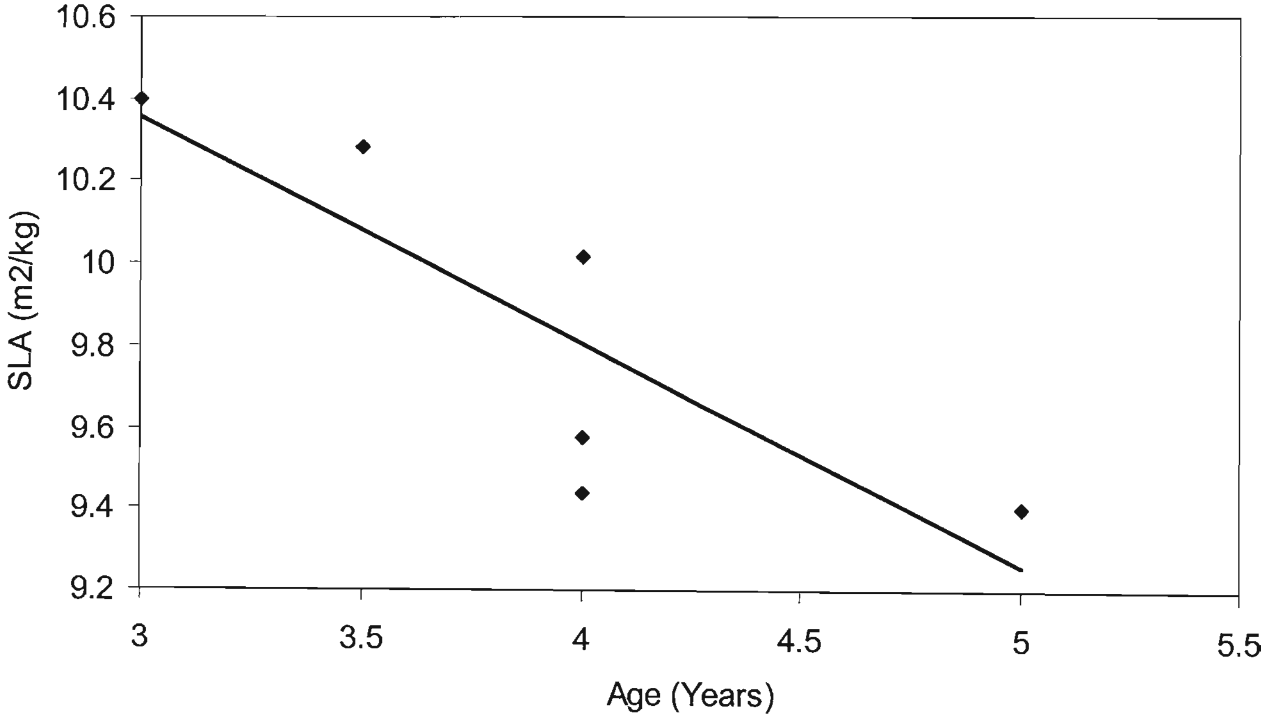


Figure 5.2 Relationship between SLA and age

The SLA for Zululand was done by Esprey and Sands (2004) and they found that it is age dependent i.e. trees at younger age have higher SLA than older trees. Similar trend was observed where SLA showed a decline from 10.467 m^2/kg to 9.437 m^2/kg for stands aged between three and five years (Figure 5.2).

SLA indicates leaf thickness which according to Vile *et al.*, (2005) is a crucial role player in leaf and plant functioning such as strategies of resource acquisition and use; good indicator of the strength of photosynthetic tissue and can be related to leaf structure, growth and net photosynthesis (Barden, 1977 cited by Awal *et al.*, 2004 and Ghebremicael *et al.*, 2004). It can also be used in conjunction with LA to estimate leaf mass for nutrient balance calculations and growth estimates. SLA has been positively correlated to light use efficiency and together with other parameters such as photosynthesis, transpiration, growth rate and yield, are closely related to leaf area and leaf mass. The SLA is largely modified by environmental factors such as light and temperature and therefore the amount that penetrates the canopy depends on the degree of closure of that canopy. It is therefore expected that SLA differ according to the position of the leaf on the plant (Awal *et al.*, 2004).

SLA is directly correlated with net photosynthesis, LAI, aboveground NPP, leaf nitrogen content and leaf water content (Reich *et al.*, 1998) and thus is an important variable in ecological functions (Körner, 1991; Reich *et al.*, 1992; Ganier *et al.*, 2001). SLA has been determined from remotely sensed data in a manner similar to LAI. The most practical and easy way adopted in these studies, was to use regression equations. Leo *et al.*,(2000), estimated canopy – average SLA using Landsat TM and obtained good correlations between SLA and red, near Infrared and mid-infrared reflectances; NDVI, RVI and SARVI. Leo *et al.*, (2000), suggested that these vegetation indices could be used to estimate SLA with a high degree of confidence. In this study, SLA was regressed against NDVI, TNDVI, RVI and VI derived from Landsat TM data. The results are shown in Table 5.3. A general significant and high degree of correlation was obtained between SLA and these vegetation indices.

Table 5.3. Correlation Coefficients between indices and SLA

	NDVI	TNDVI	RVI	VI_3	SLA
NDVI	1				
TNDVI	0.964**	1			
RVI	0.969**	0.968**	1		
VI_3	0.354	0.477	0.255	1	
SLA	0.981**	0.883**	0.989**	0.951**	1

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

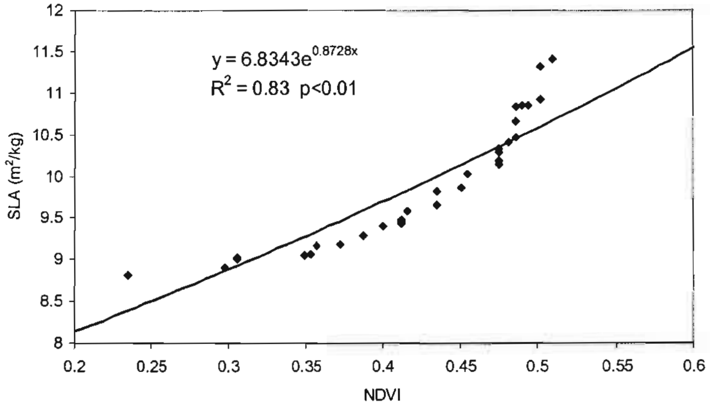
Table, 5.4 shows the regression analysis between SLA and the vegetation indices. The results show a significant correlation between SLA and TNDVI (R^2= 0.86, $p< 0.01$), SLA and RVI (R^2= 0.84, $p< 0.01$), SLA and NDVI (R^2=0.83, $p< 0.01$) and SLA and VI_3 (R^2 = 0.90, $p< 0.01$), Figures 5.5., 5.6. , 5.3 and 5.4, respectively. The relationship between SLA and NDVI was observed to be almost similar to that of SLA and RVI. Similar findings were observed by Xavier and Vettorazzi, (2004). These results suggest that SLA can be estimated from the vegetation indices successfully.

The strongest relationship was obtained between SLA and VI_3 with an R^2 of 0.90, $p< 0.05$. It would therefore be possible to obtain a rough estimate of SLA of *Eucalyptus grandis* in Zululand using vegetation indices derived from LANDSAT TM. Different vegetation indices represent vegetation cover differently based on calculations using different bands. SLA can therefore be calculated from the regression models in Table, 5.4.

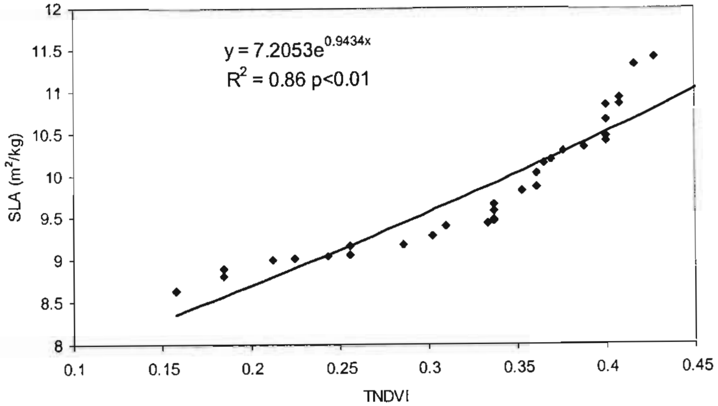
Table 5.4. Equations for predicting SLA from VI's

Vegetation Index	Equation	R^2	Correlation Coefficient (r)
NDVI	SLA = 6.8343e0.8728x	0.83	0.981**, n=32
RVI	SLA=7.2818e0.7892x	0.84	0.989**, n=32
TNDVI	SLA=7.2053e0.9434x	0.86	0.883**, n=32
VI_3	SLA=5.9351e1.0321x	0.90	0.951**, n=32

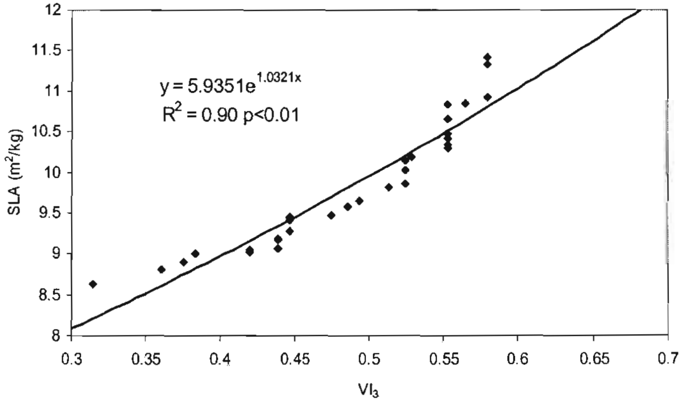
** Correlation significant at 0.01 level (2-tailed)



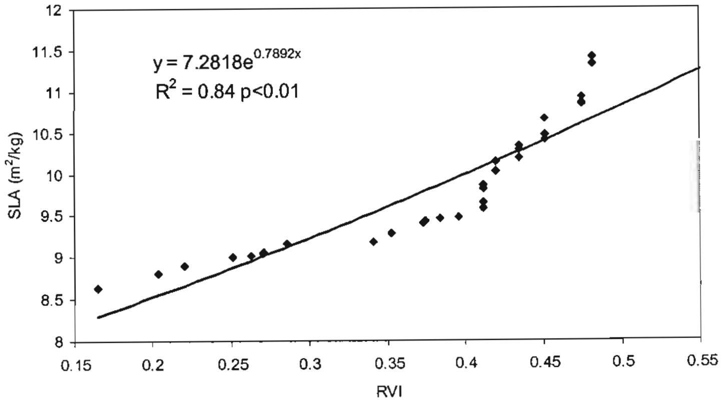
Figure, 5.3 Regression analysis between NDVI and SLA



Figure, 5.5 Regression analysis between TNDVI and SLA



Figure, 5.4 Regression analysis between VI$_3$ and SLA



Figure, 5.6 Regression analysis between RVI and SLA

5.4. Leaf Area

Allometric equations Battaglia *et al.*, (1998) were used to describe the relationships between LA and DBH of different sampling plots because it is difficult realistically to destructively sample all the trees in a compartment. The mean and total LA of each plot are shown in Table 5.5. The correlation between the LA and DBH of all the sample sites was found to be significant (r=0.74, p< 0.01, n=25). The findings suggested a non-linear regression or exponential relationships for all the sites. The relationships between LA and DBH of all the sites in the study are shown in Figure 5.7.

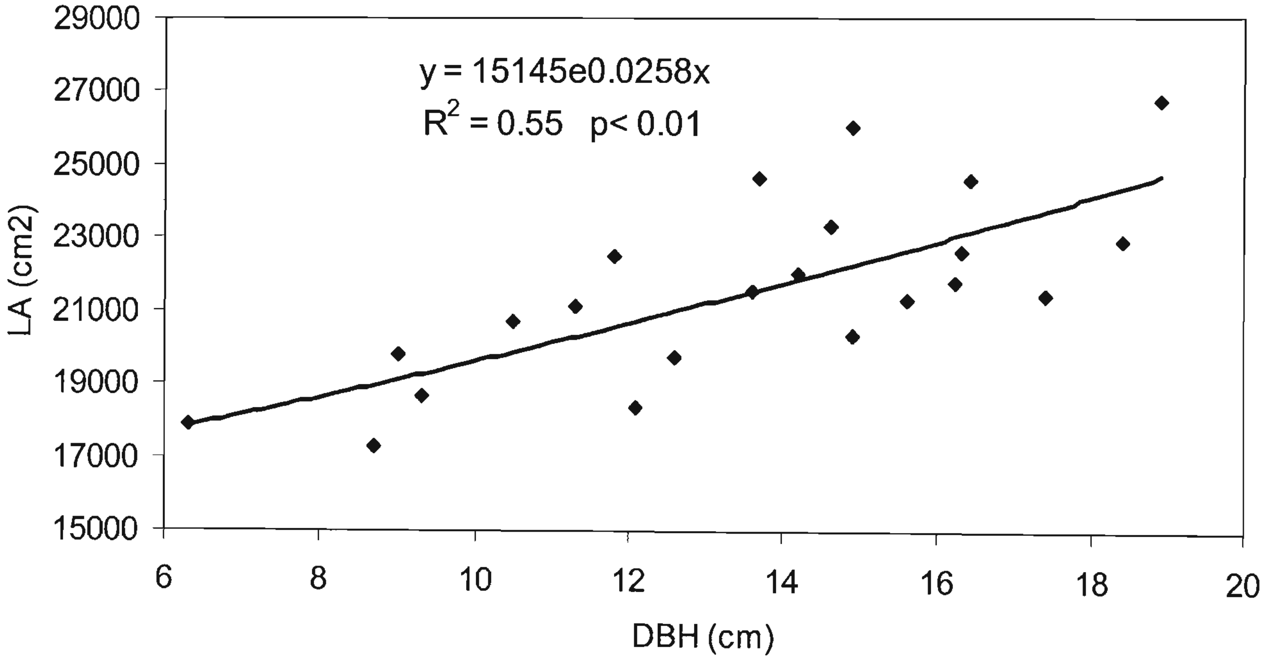


Figure 5.7 Relationships between LA and DBH

Table 5.5, Destructively sampled total LA of sample plots.

Compartment No:	Tree Age (years)	Mean LA (m^2)	Total Plot LA (m^2)
E34A	3.6	10.313	505.351
J1B	5	6.371	299.452
F9	4	2.374	90.208
A63	4	5.451	234.394
F18	4	23.371	1028.308
C14	3	4.192	209.577

Total leaf area has been seen as a key ecophysiological trait, involved in photosynthesis and aboveground biomass production. Total leaf area serves as an indicator of potential prospective dry mass production or plant productivity, be it assessed at forest stand or large regions. According to Köstner *et al.*, (2002) Arwal *et al.*, (2004), Bhatt and Chanda (2003) and Gamper (2005), leaf mass is important for nutrient balance calculations and growth estimations. In this study, the relationship between leaf area and total dry leaf mass was evaluated and a significant ($p < 0.01$) linear relationship between leaf area and total leaf dry mass was obtained (Figure 5.8). The correlation ($r=0.98$) between the two variables was found to be significant at $p < 0.01$. These findings were similar to those obtained by Arwal *et al.*, (2004).

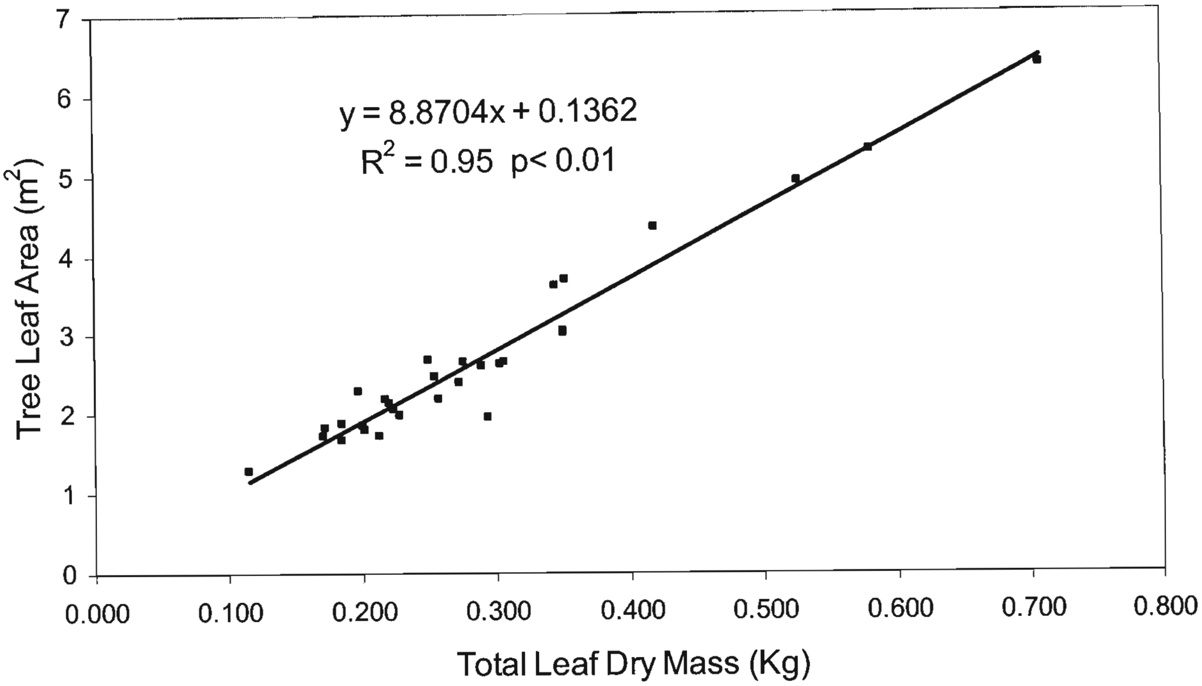


Figure 5.8 Relationship between tree leaf area and total leaf dry mass for all the sites.

This means that large leaf area represent more leaf mass whilst the SLA remains constant during stages of plant development. An increase in leaf area would result in an increase in its dimensions such as thickness, width and length and therefore its mass / aboveground biomass is expected to increase.

5.5 Remotely-sensed Vegetation Indices

In estimating LAI from remotely sensed data, the first step was to transform the imagery into vegetation indices. The VI's chosen in this study were NDVI, TNDVI, RVI and VI_3. The statistical descriptive of the compartment's vegetation indices i.e. means, standard deviations and standard error are shown in Appendix D.

5.5.1 Relationship between LAI, VI's and destructively sampled LAI

Many of the physical and biological processes and models related to vegetation dynamics depend largely on LAI as a structural vegetation parameter. Therefore accurate measurements of LAI are critical if such models are to be acceptable and valid. This study will utilized LAI as an input into 3PG-S for estimation of productivity and water use of *Eucalyptus grandis*.

Studies (Peddle *et al.*, 2000; Xavier and Vettorazzi, 2004 and Cherry *et al.*, 1998) have shown that remotely sensed data are useful for retrieving LAI at both its spatial and temporal distribution. The results of all these studies showed promising results. Table 5.6, depicts a matrix of the correlations between vegetation indices and LAI derived from LiCor-2000 and destructive sampling.

Table 5.6 Correlation Coefficients between vegetation indices, PAI and actual LAI

	NDVI	TNDVI	RVI	VI_3	PAI	Actual -LAI
NDVI	1					
TNDVI	0.964**	1				
RVI	0.969**	0.968**	1			
VI_3	0.354	0.477	0.252	1		
PAI	0.859**	0.849**	0.859**	0.439	1	
Actual-LAI	0.568*	0.553*	0.568*	0.384	0.88**	1

** Correlations significant at the 0.01 level (2-tailed)

* Correlations is significant at the 0.05 level (2-tailed)

The results shown a significant correlation between actual LAI and LAI obtained using LiCor-2000 ($r=0.88$, $p < 0.01$). PAI was more strongly correlated with NDVI and RVI ($r=0.86$, $p<0.01$) than TNDVI ($r= 0.85$, $p<0.01$), whilst it is non-significantly, less correlated with VI_3 ($r= 0.44$). The actual LAI was strongly correlated with both the NDVI ($r=0.57$, $p<0.05$) and RVI ($r= 0.57$, $p < 0.05$) and also less correlated with TNDVI ($r=0.55$, $p<0.05$) when compared with the two above-mentioned vegetation indices. There was no significant correlation between actual LAI and VI_3 ($r=0.38$).

The comparison between the indices showed that the strongest correlation was obtained between NDVI and both TNDVI and RVI ($r=0.96$, $p< 0.01$), ($r=0.97$, $p<0.01$) respectively, whilst it had a non-significant correlation with VI_3 ($r=0.35$). VI_3 was observed to have no significant correlation with other vegetation indices. In general there were significant correlations between all the indices with PAI and actual-LAI, except the VI. These comparisons agreed with those of Lu *et al.*, (2005), who found good relationships between the measured LAI and the different vegetation indices in most cases.

5.5.2 Derivation of LAI from Vegetation Indices

Regression analyses were undertaken in order to find out if any relationships exist between vegetation indices and LiCor-2000. The various indices for the sampling plots obtained were plotted against LiCor LAI values after it was calibrated with destructively sampled LAI. Various regression models i.e. linear, logarithmic, power or exponential in SSPS statistical package were used to determine the relationships using the curve estimation mode and the one with the best strength of correlation picked. The developed regression equations are shown in Table 5.7

Table 5.7 Regression of LiCor-LAI and VI's

Independent Variable (VI)	Equations	Correlation Coefficient (r)	R^2
NDVI or RVI	LAI= 0.097*NDVI + 0.248	0.86	0.72**
NDVI or RVI	LAI= 0.183 Ln (NDVI) – 1.180	0.87	0.75**
TNDVI	LAI= 0.1*TNDVI + 0.168	0.85	0.70**
TNDVI	LAI= 0.218 Ln (TNDVI)- 1.436	0.87	0.74**
VI_3	LAI= 0.089 Ln (VI) – 0.588	0.40	0.09
VI_3	LAI= 0.069 + 0.530	0.43	0.13

** Significance at $p<0.01$

Research has previously been conducted to gauge the performance of VI's when related to biophysical characteristics especially LAI. These investigations into the relationship between ground-measured LAI and spectral indices have always been attractive and had yielded varying results. Xavier and Vettorazzi (2004) observed that LAI- NDVI (R^2 =0.72, $p < 0.05$) correlation was not statistically different from LAI- SR correlation (R^2 = 0.70, p

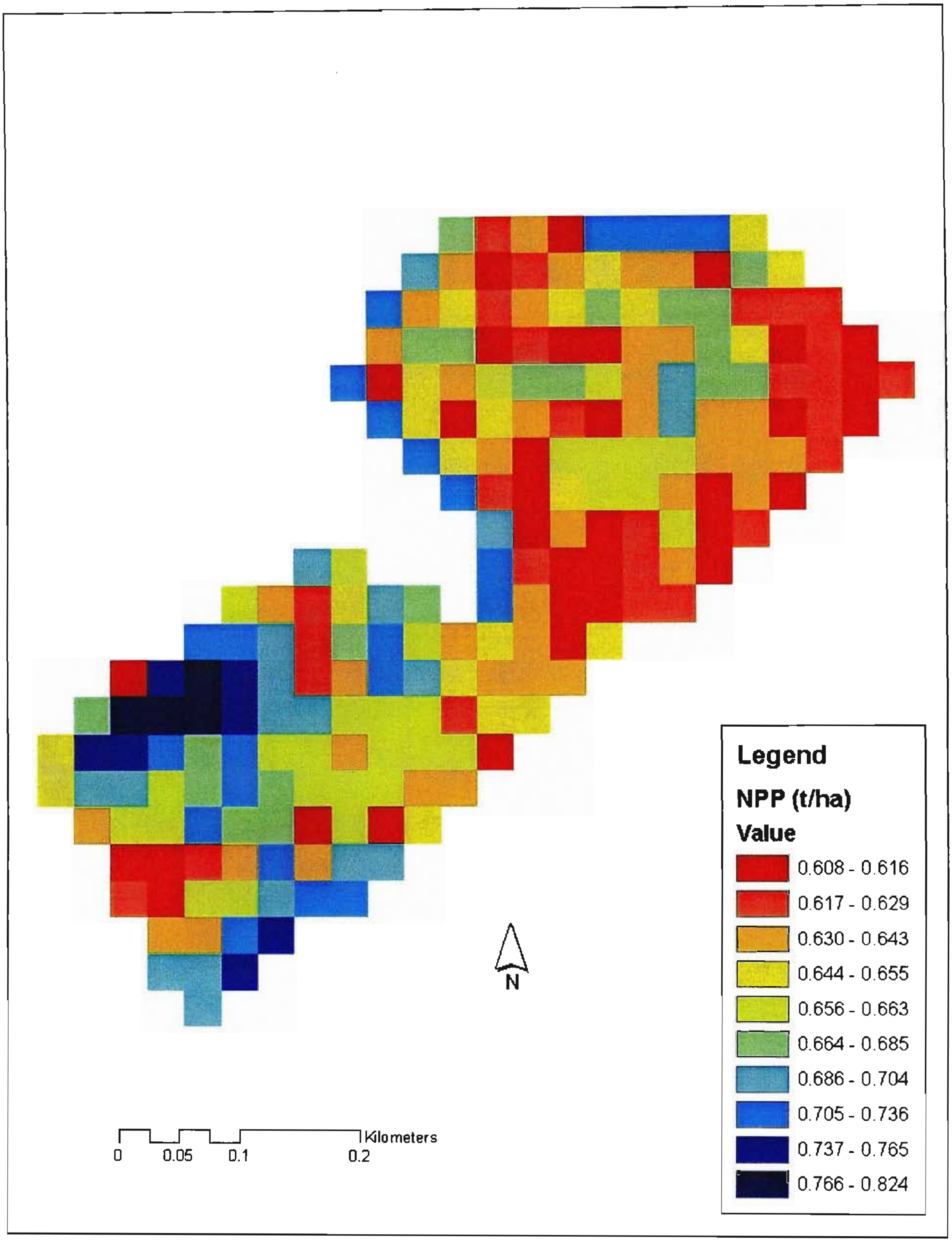
<0.05) whilst the worst was obtained by LAI – SAVI ($R^2 = 0.56$, $p<0.05$). Lu *et al.*, (2005) studied the relationship between ground-measured LAI and vegetation indices in an alpine meadow, North-West China. Among the vegetation indices that is NDVI, SR and MSAVI studied, it was found that although the relationship between ground measured LAI and the vegetation indices had positive correlations, NDVI elicits the strongest correlation with an $R^2 = 0.56$, $p< 0.05$ and hence the best/ promising estimator for extraction of LAI for the Alpine Meadow.

Spanner *et al.*, (1994) found that the logarithmic regressions between RVI and LAI better explained the variation in LAI in stands in the Oregon Transect Ecosystem Research project, whilst Lu *et al.*, (2005) attributed the non-linear and exponential deviations to the errors associated with instrument operations conducted by different people in the field and errors associated with cloudiness and wind conditions in the measurement times. Coops *et al.*, (1997) however, found linear relationships to be appropriate when relating NDVI ($R^2 = 0.71$) and SR ($R^2 = 0.53$) to the LAI data. In contrast, Herwitz *et al.*, (1990) reported that neither SR nor NDVI were significantly related to LA of pine (*Pinus strobes* L.) and red pine (*Pinus resinota* Ait) plantations in Central Massachusetts.

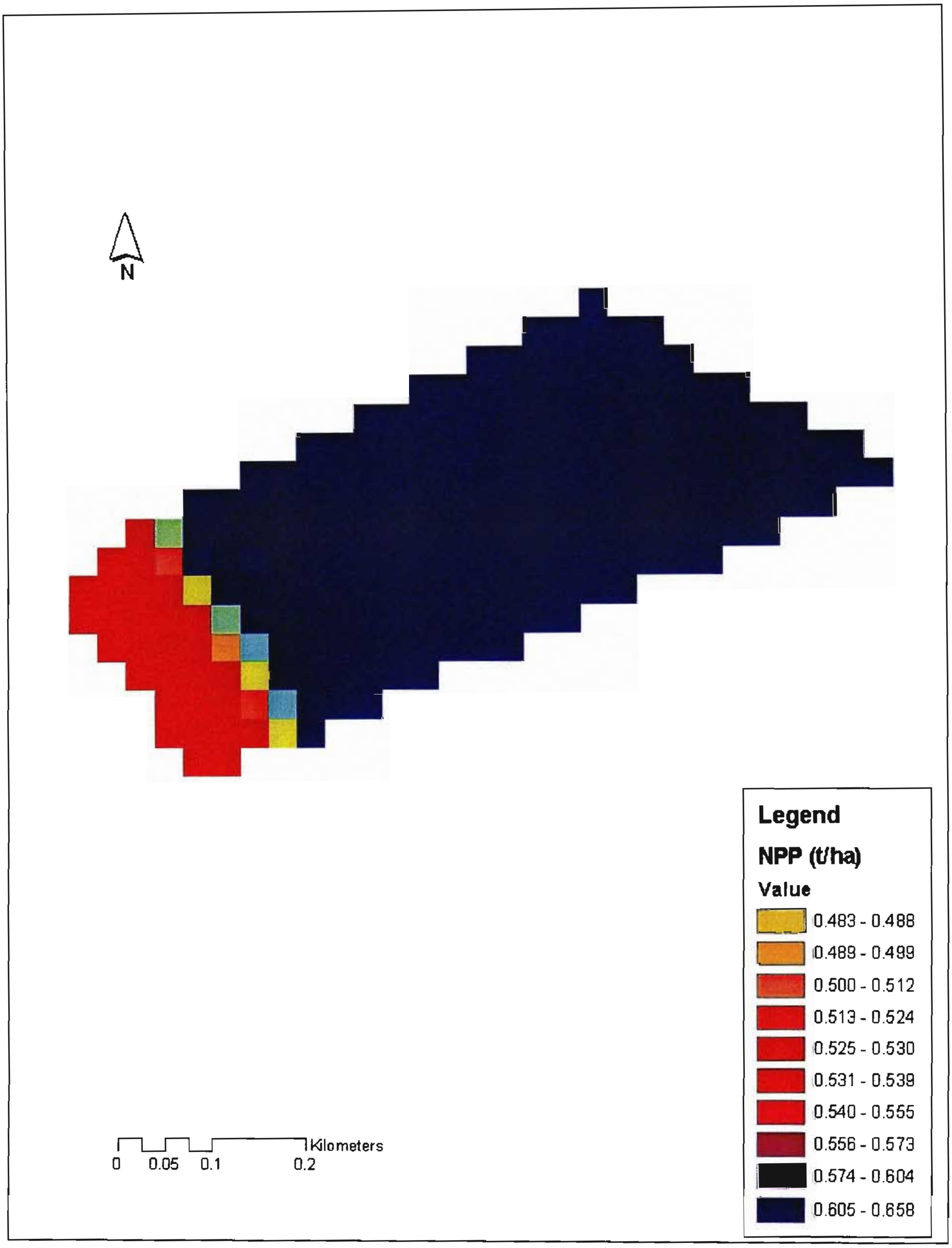
Stenberg *et al.*, 2004) found that Reduced Simple Ratio (RSR) was more strongly correlated with LAI ($R^2 = 0.63$) than NDVI and SR ($R^2 = 0.55$ and 0.52), respectively. The relationship between NDVI and LAI ($R^2= 0.28$) was found (Boyd *et al.*, 1999) to be weaker than VI_3 and LAI ($R^2 = 0.62$) for the boreal forest canopy. About 76% of the variation in the field estimation of LAI was accounted for by VI_3 as compared to 46% when using NDVI. Curran *et al.*, (1992) showed that there is seasonal variation in the relationship between NDVI and LAI. The relationship was found to be $R^2 = 0.35$, 0.75, and 0.86, for February, September and March for control and slash pine (*P. elliottii* Engelm.) sites in Florida.

5.6 Estimation of Net Primary Productivity from 3PG-S Model

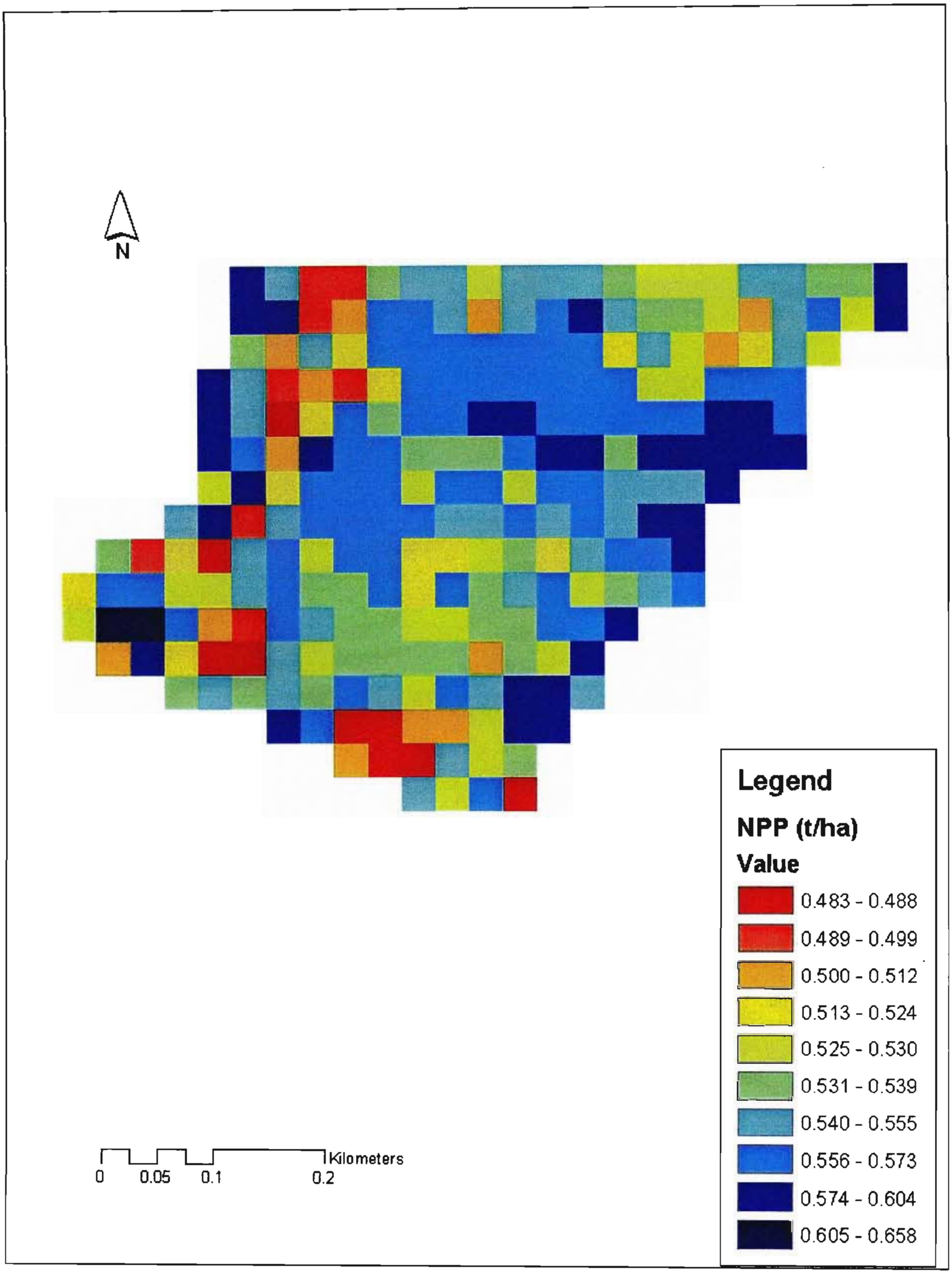
The 3PG-S model was used to simulate net primary productivity (NPP) of the four sites in Zululand. The simulations were completed on a computer using ArcGIS 8.3 together with 3PG-S ArcTool box V2.5. The appropriate weather data (T_{min}, T_{max}, VPD, solar radiation, Frost and LAI values derived from NDVI), site factors, and parameter values as inputs were used to simulate NPP of the four sites that is ND07, C17, D4 and D20. Figures 5.9, 5.10, 5.11 and 5.12 below, show NPP maps for the above-mentioned sites.



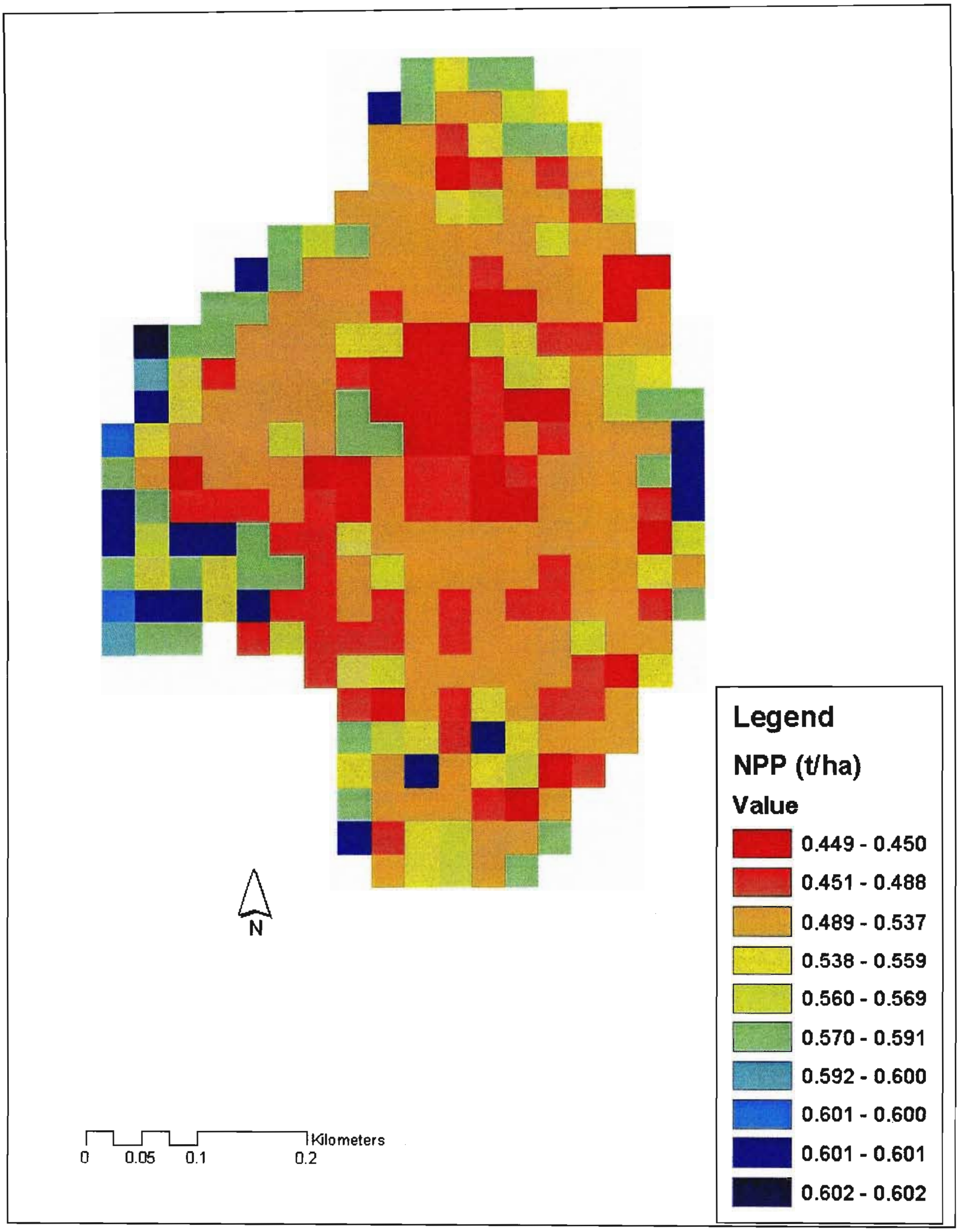
Figures 5.9 Map of net primary productivity for plot ND07



Figures 5.10 Map of net primary productivity for plot C17



Figures 5.11 Map of net primary productivity for plot D20



Figures 5.12 Map of net primary productivity for plot D4

5.7 Validation of Productivity

The model outputs (NPP and AGB i.e. predicted data) were validated using the data collected in the field, obtained from ICFR trial sites i.e. observed data. The above-ground NPP and AGB predicted by the model was compared with the observed above-ground stemwood volume and above-ground biomass derived from four sites of different productivity capacity in Zululand that is ND07, C17, D4 and D20 Table 5.8 below. Table 5.9 shows the mean, maximum, minimum, standard error and standard deviation of NPP and AGB for all the plots.The model validation is important in order to determine how robust the model can predicts NPP.

Table 5.8. Productivity capacity of the validation sites.

Plot	Age (years)	Initial stocking	Final stocking	T_X (^{0}C)	T_N (^{0}C)	MAT (^{0}C)	MAP (mm)	Productivity class
NDO7	7	1600	1342	27.2	16.4	21.8	860	Medium
D20	8	1389	972	26.6	16.6	21.6	1174	High
C17	6	1600	1144	25.8	16.4	21.1	1403	High
D4	7	1600	1216	26.8	16.9	21.6	11068	High

Table 5.9. Descriptives Statistics of all plots' NPP and AGB

		ND07	D4	D20	C17
Net Primary Productivity (t/ ha)	Min NPP	0.607	0.448	0.483	0.484
	Max NPP	0.824	0.602	0.658	0.658
	Mean NPP	0.682	0.559	0.539	0.569
	Standard Deviation	0.053	0.052	0.041	0.052
	Standard Error	0.008	0.010	0.007	0.009
Above Ground Biomass (t / ha)	Min AGB	10.250	11.345	9.228	21.261
	Max AGB	15.360	16.498	14.812	30.193
	Mean AGB	11.701	14.220	11.104	25.287
	Standard Deviation	1.196	2.021	1.731	2.630
	Standard Error	0.182	0.540	0.285	0.465

5.7.1 Plot ND07

The net primary productivity of the plot was found to vary that is there was uneven productivity, with values ranging from low to medium productivity dominating the plot as compared with high values (Figure 5.9). The comparison of the observed NPP and predicted NPP for compartment ND07 show a highly significant correlation (r= 0.94, $p<0.001$) between the two. Furthermore, a significant exponential regression relationship ($R^2 = 0.90$, $p<0.001$, SE= 0.021 t/ ha) against stemwood volume was obtained as shown by Figure 5.13. There is also an over-prediction of NPP at high observed stemwood values as shown by points around observed stemwood volume of 0.05 t/ha.

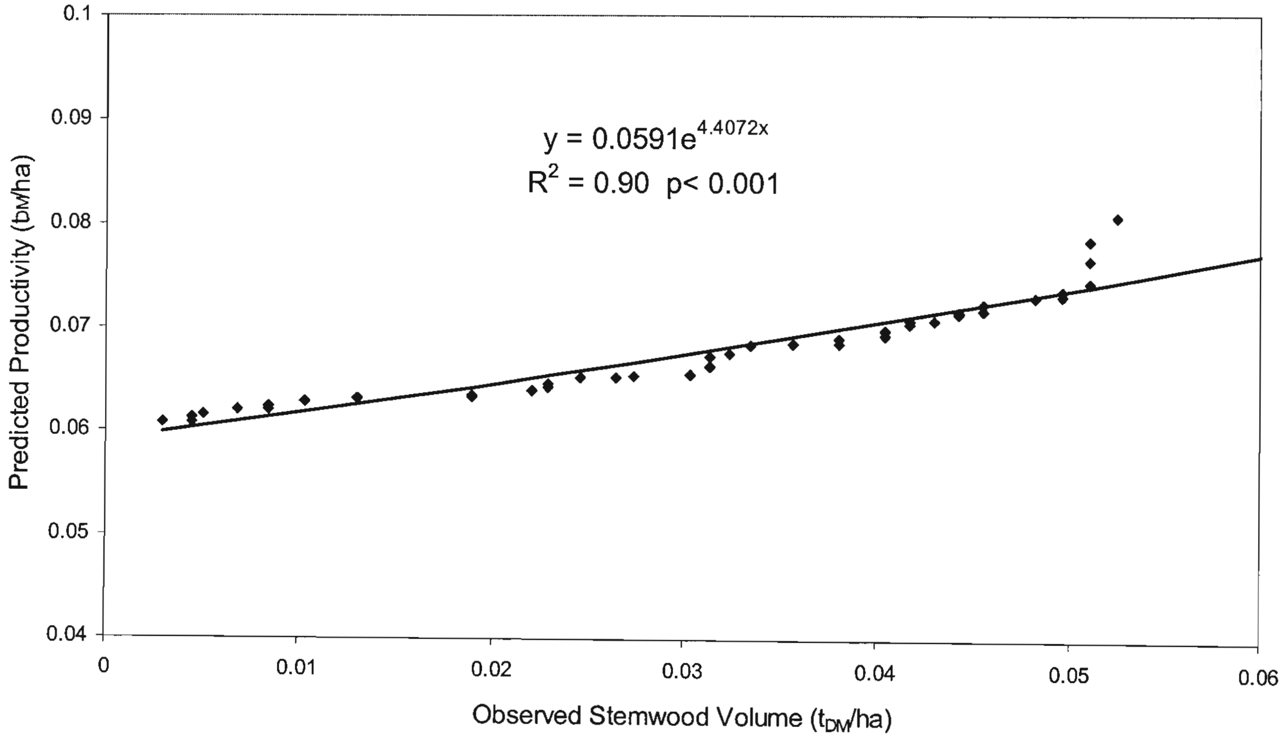


Figure 5.13 Relationship between stemwood volume and 3PG-S NPP.

5.7.2. Plot D4

The centre of the plot is dominated by medium to low NPP values whilst the outer boundary is dominated by high values (Figure 5.12). A significant correlation relationship

($r = 0.88$, $\rho<0.001$) explains the relationship between observed and predicted NPP. A logarithmic significant regression relationship was found ($R^2 = 0.91$, $\rho<0.001$, SE=0.002) between the 3PG-S NPP and the stemwood volume, as shown by Figure 5.14.

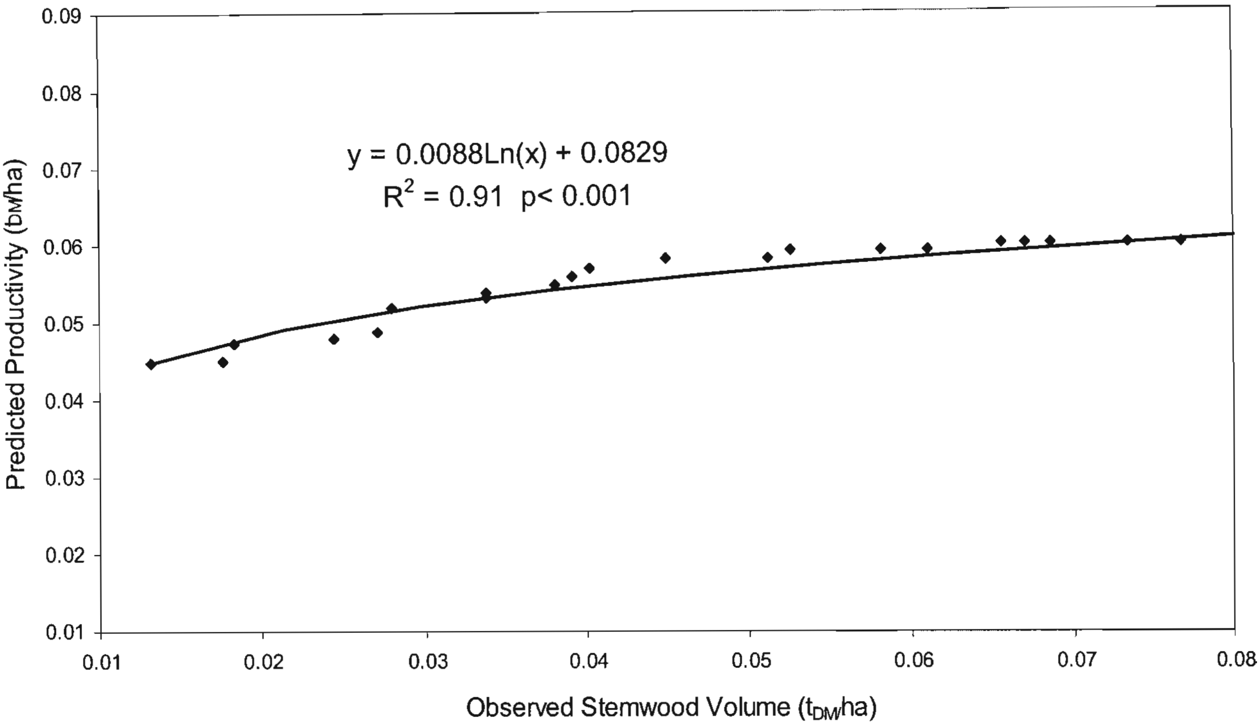


Figure 5.14. Relationship between stemwood volume and 3PG-S NPP

5.7.3 Plot D20

The results for plot D20 show a significant ($r = 0.93$, $\rho<0.001$) relationship between the observed NPP and predicted values of NPP. A significant exponential regression relationship ($R^2 = 0.82$, $\rho<0.001$, SE= 0.024) was obtained between the two variables (Figure 5.15). The predicted net primary productivity of the plot shows less high values with the medium to low NPP values dominant (Figure 5. 11).

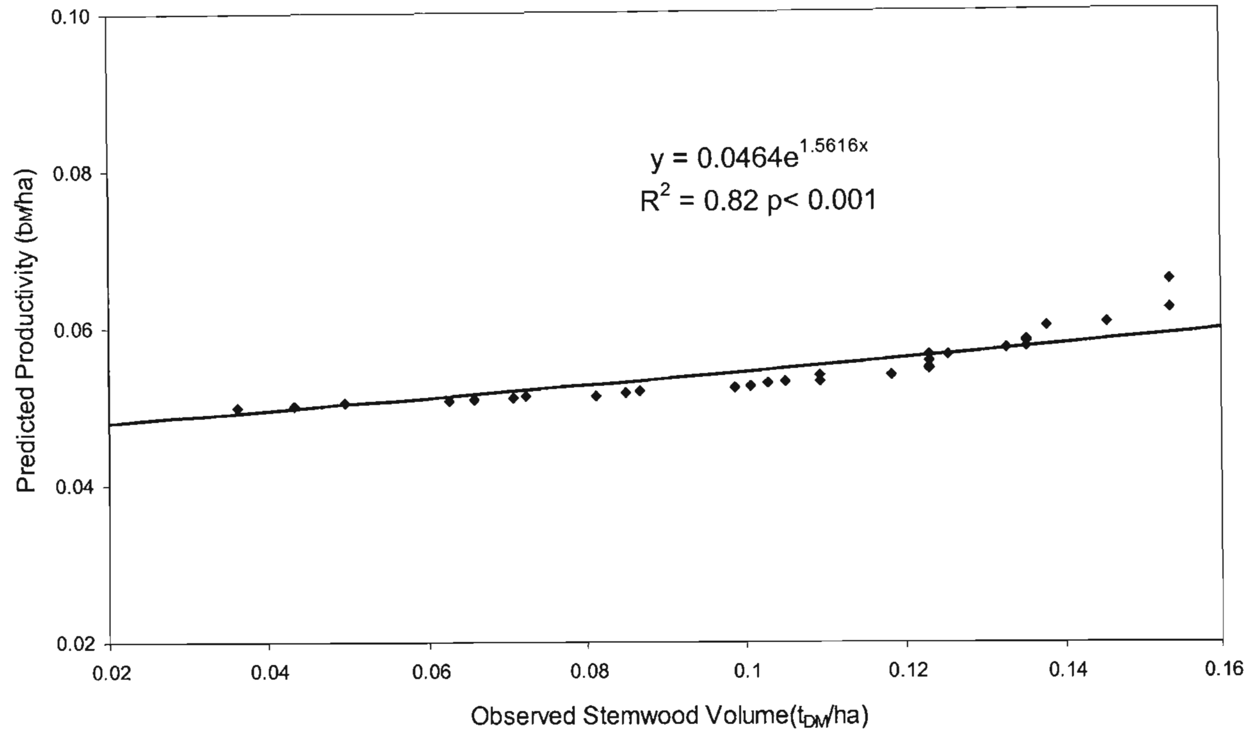


Figure 5.15. Relationship between stemwood volume and 3PG-S NPP

5.7.4. Plot C17

The dominant NPP values in the plot are high NPP values compared to medium and low values (that is almost three quarter of the plot is dominated by high NPP values) Figure 5.10. A significant correlation relationship (r =0.96, ρ<0.001) was obtained between the observed and model predicted NPP for plot C17. The significant exponential regression relationship (R^2 = 0.89, ρ<0.001, SE= 0.024) was obtained between 3PG-S NPP and stemwood volume Figure 5.16.

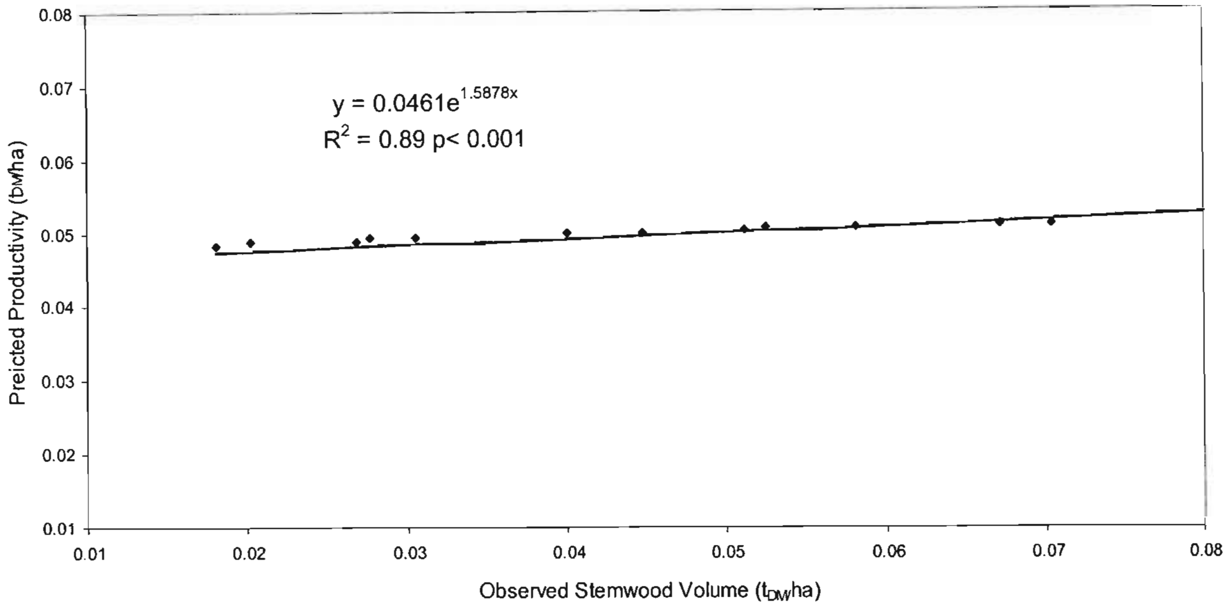


Figure 5.16 Relationship between stemwood volume and 3PG-S NPP

5.7.5. Global NPP Model

An attempt was made in this study to combine the data from each plot to obtain a global model for predicting NPP in Zululand and the results were promising. Figure 5.17 shows a significant correlation relationship between observed NPP and predicted NPP values ($r= 0.95$, $n=144$, $p< 0.01$, $SE = 0.032$). Furthermore, an exponential regression ($R^2 =0.94$, $p< 0.01$) explains the relationship between the two variables.

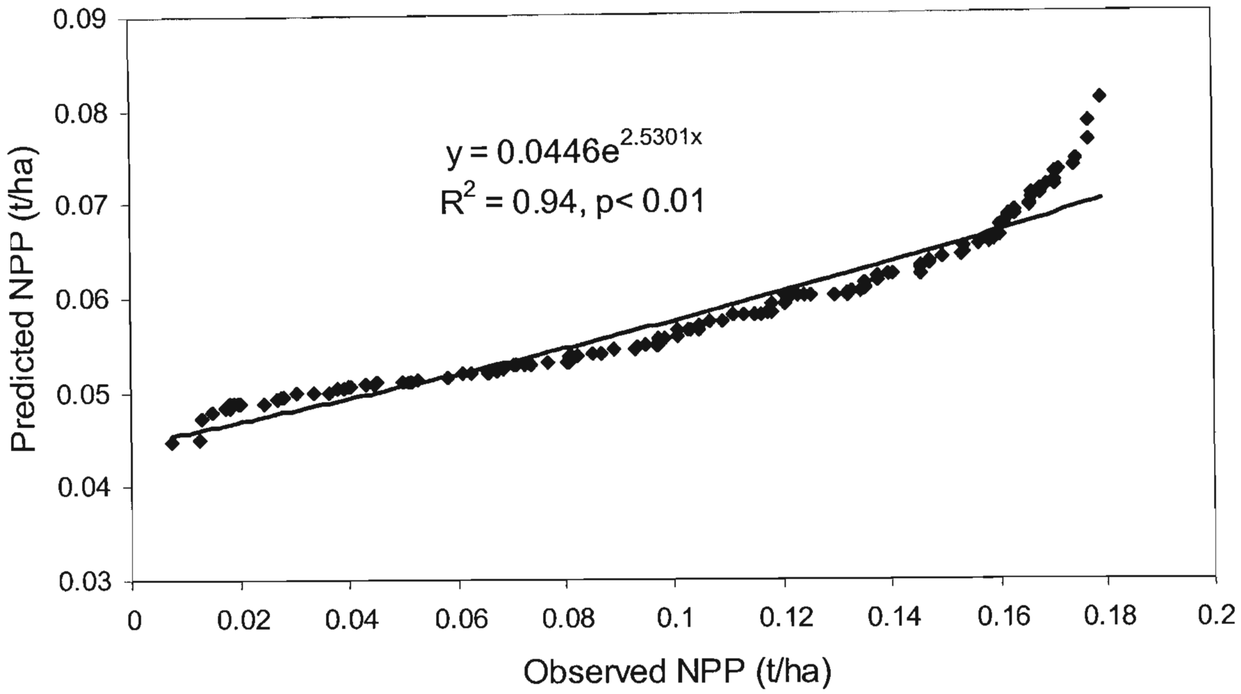


Figure 5.17 Relationship between observed stemwood volume and 3PG-S NPP for Zululand

In general, the 3PG-S model performed robustly with the observed stemwood volume for all the sites irrespective of its productivity capacity that is all the sites except ND07 (medium productive site) where high productivity sites and the model performed well with all the sites. The 3PG-S model outputs showed very good relationships between measured (ground based measurements) and simulated (modelled) values by significant (ρ<0.001) coefficient of determination (r) more than 0.8 suggesting that they were in near 1:1 agreement with Coefficient of determination.

Assessing forest productivity in Australia and New Zealand using a physiological based model driven with averaged monthly weather data and satellite derived estimates of canopy photosynthetic capacity, Coops *et al.*,(1998) found a linear, highly associated (R^2 = 0.82) relationship between predicted NPP and measured wood production. Also comparing the accumulated above ground biomass predicted by the model was compared with biomass data from discrete stands in a 2,265-ha *Pinus radiata* plantation in southern New South Wales, Australia, Coops (1999) found a linear relation between predicted and measured wood production with an R^2 of 0.84. Coops and Waring, (2001), further found model predictions of maximum annual aboveground growth compared to those derived from forestry yield Tables based on height-age relationship, had a significant ($\rho<0.01$) and a promising association ($R^2= 0.76$) between the two variables. Similarly, it has also been shown that the model performed better using seasonal variables instead of fixed values. Coops *et al.*, (2001) managed to improve the linear relationship of predicted and observed values of P_G and NPP_A from $R^2 = 0.85$ to $R^2 = 0.92$ after adjusting the quantum efficiency and available soil water storage capacity to all sites, to match seasonal variation instead of using fixed values of quantum efficiency and soil water storage capacity (f=0.04 mol C/MJ APAR) (θ=226 mm), respectively.

5.8 Validation of Aboveground Biomass

5.8.1 Plot ND07

Figure 5.19 shows distribution of AGB for plot ND07. The comparison of the observed AGB and predicted AGB for compartment ND07 show a highly significant correlation (r= 0.86, ρ<0.01, n = 43, SE= 0.626) between the two variables. Furthermore, a significant exponential regression relationship (R^2 = 0.73, ρ<0.01) was obtained as shown by Figure 5.18.

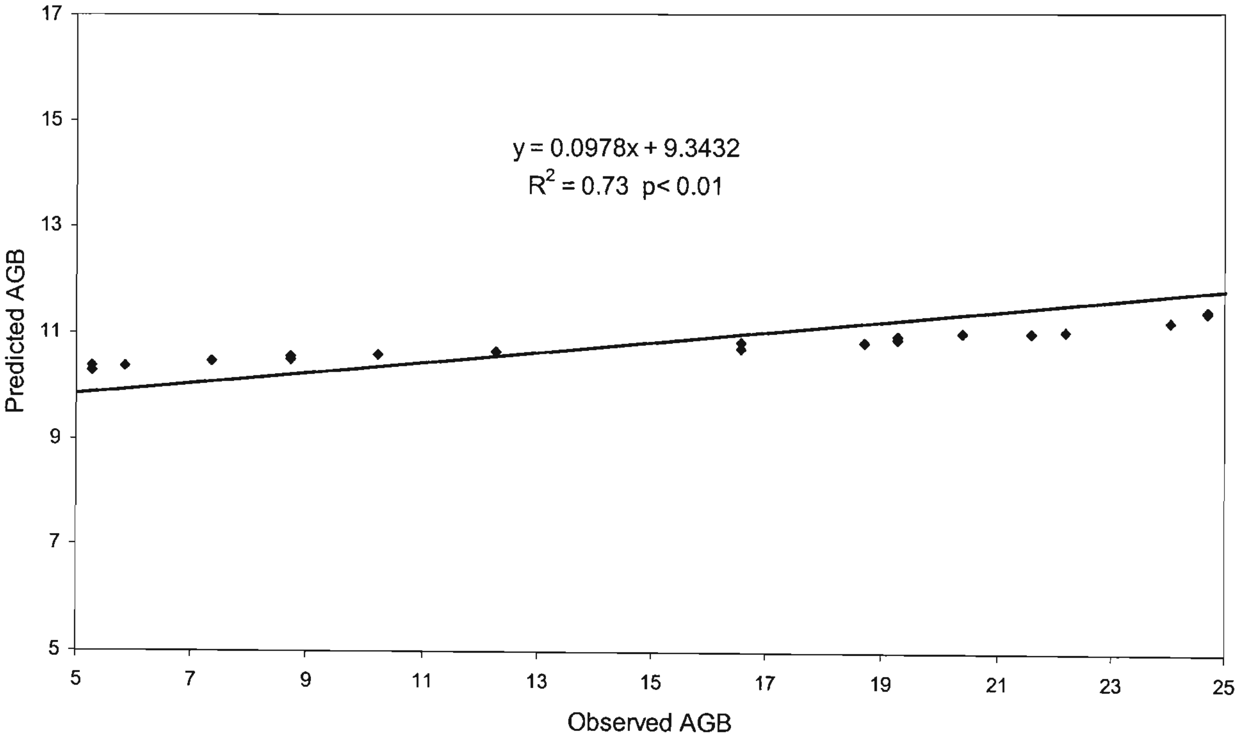


Figure 5.18 Relationship between observed ABG and 3PG-S ABG.

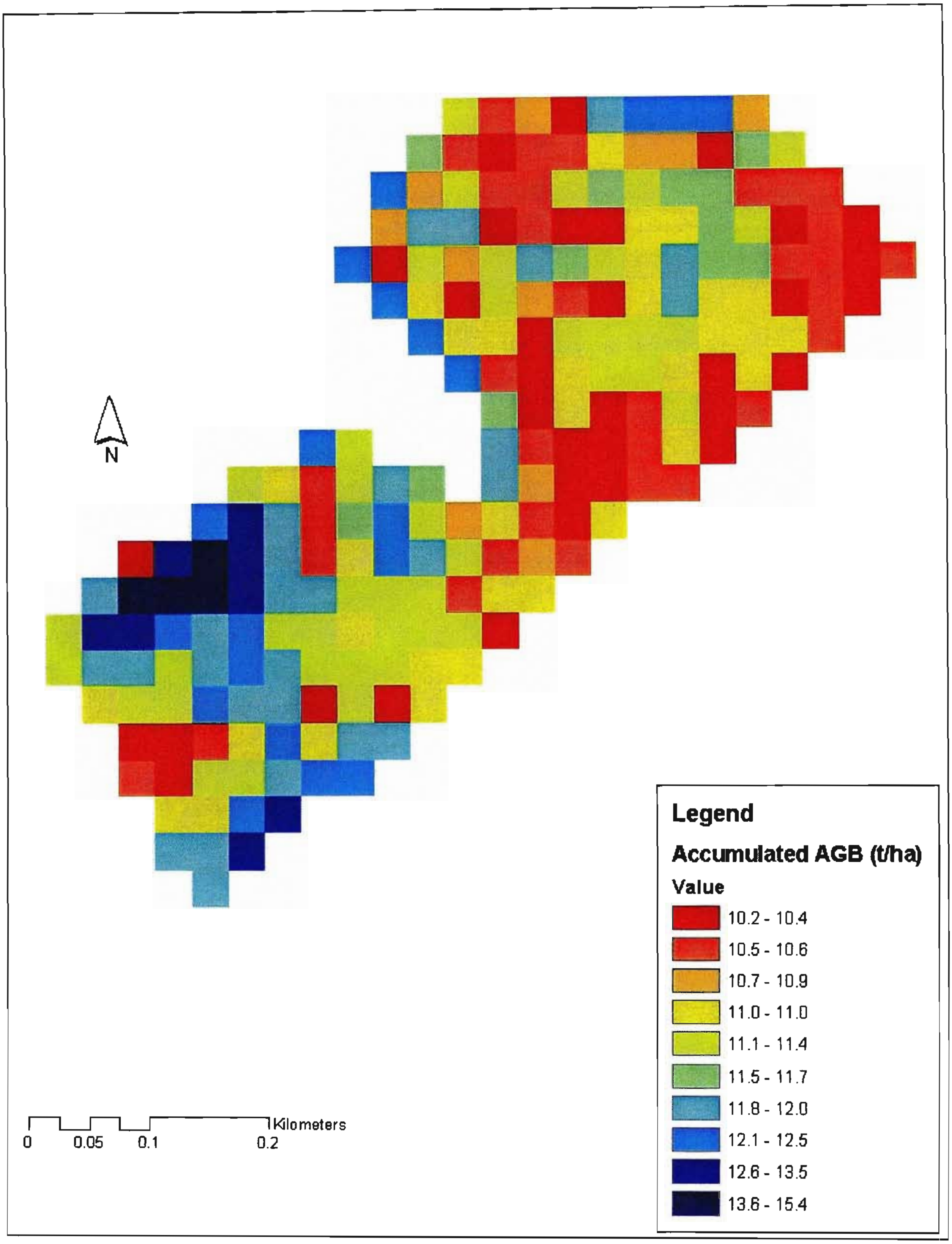


Figure 5.19Map of Aboveground Biomass for plot ND07.

5.8.2 Plot D4

A significant correlation relationship (r= 0.96, ρ<0.01) explains the relationship between observed AGB and predicted AGB. A significant regression relationship was found (R^2 = 0.95 ρ<0.01, n=34, SE= 0.486 between the 3PG-S AGB and observed AGB, as shown by Figure 5.20. Figure 5.21 shows AGB values distribution for plot D4.

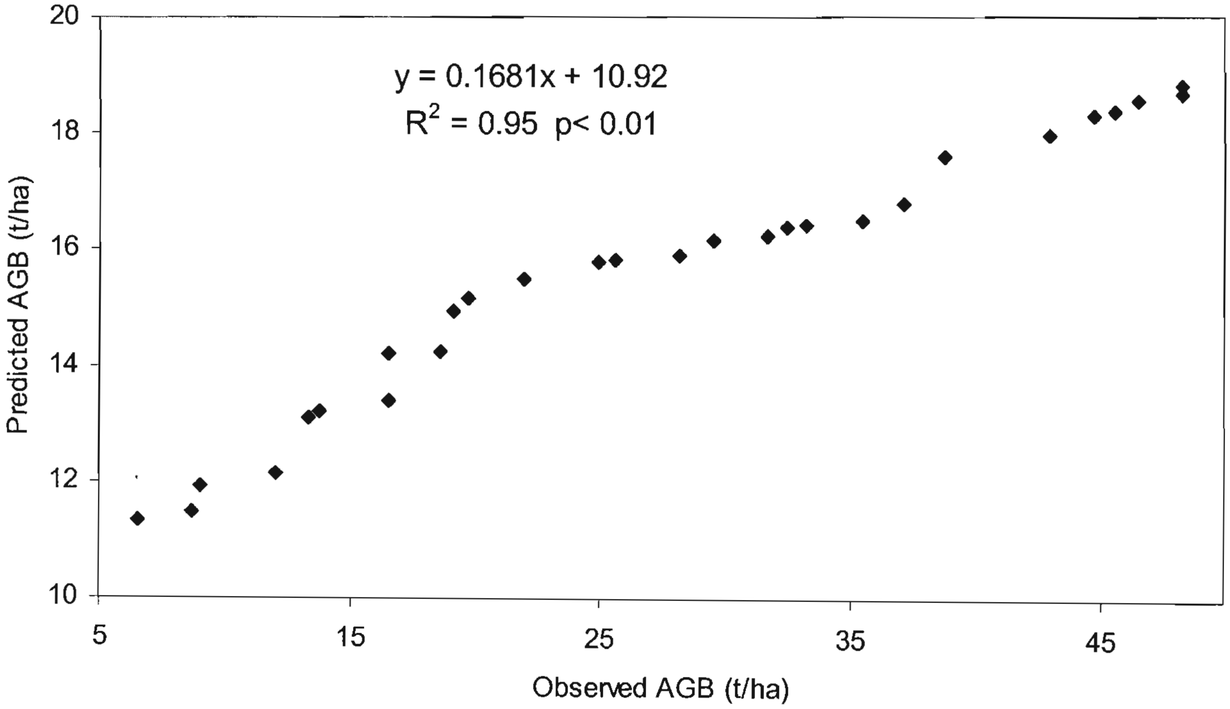


Figure 5.20 Relationship between observed ABG and 3PG-S ABG

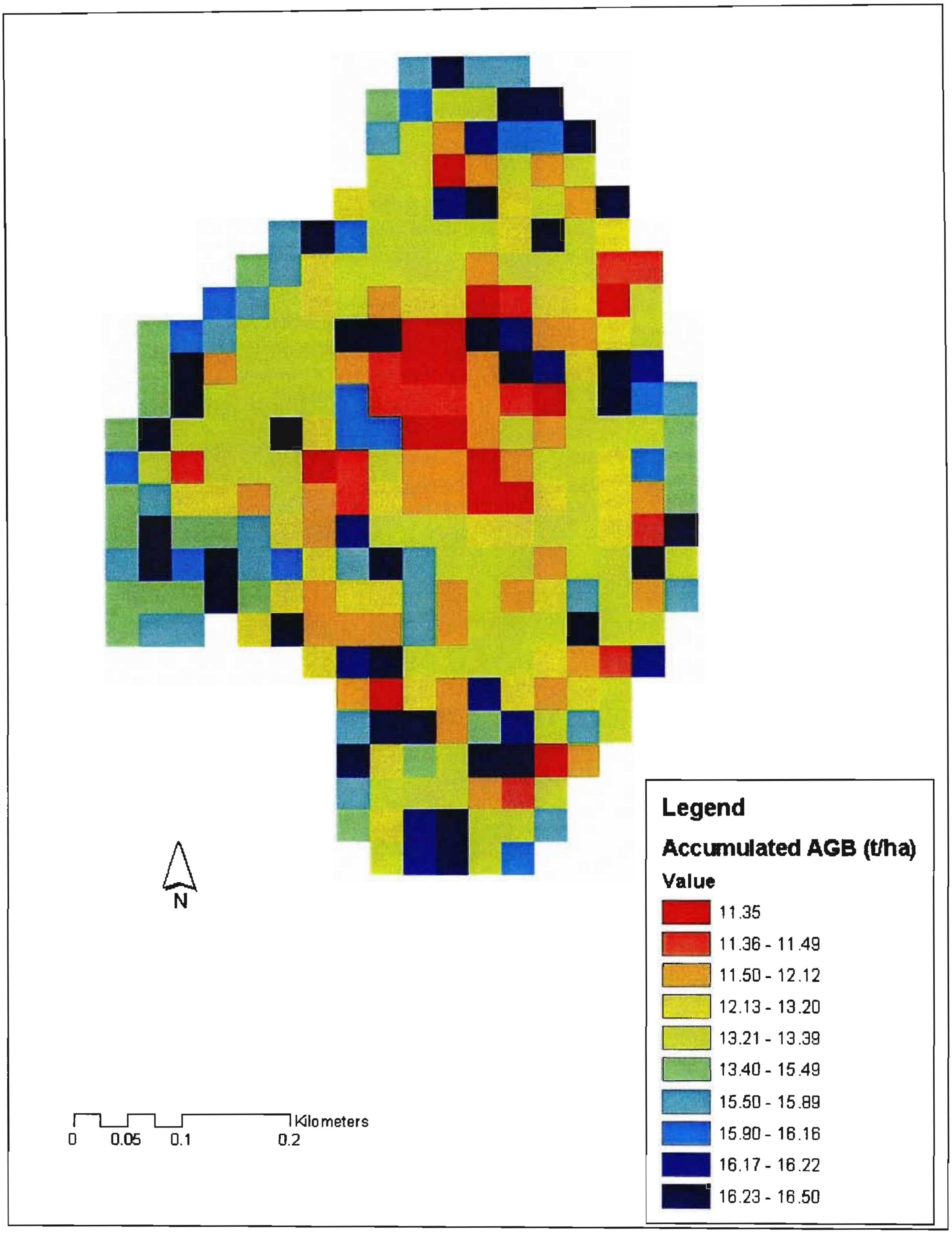


Figure 5.21 Map of Aboveground Biomass for plot D4

5.8.3 Plot D20

The results for plot D20 show a highly significant (r =0.96, ρ<0.01, n = 32, SE=0.125) relationship between the observed AGB and predicted values of AGB. A significant linear regression relationship (R^2 = 0.92, ρ<0.01) was obtained between the two variables (Figure 5.22). A spatial map of AGB is shown in Figure 5.23

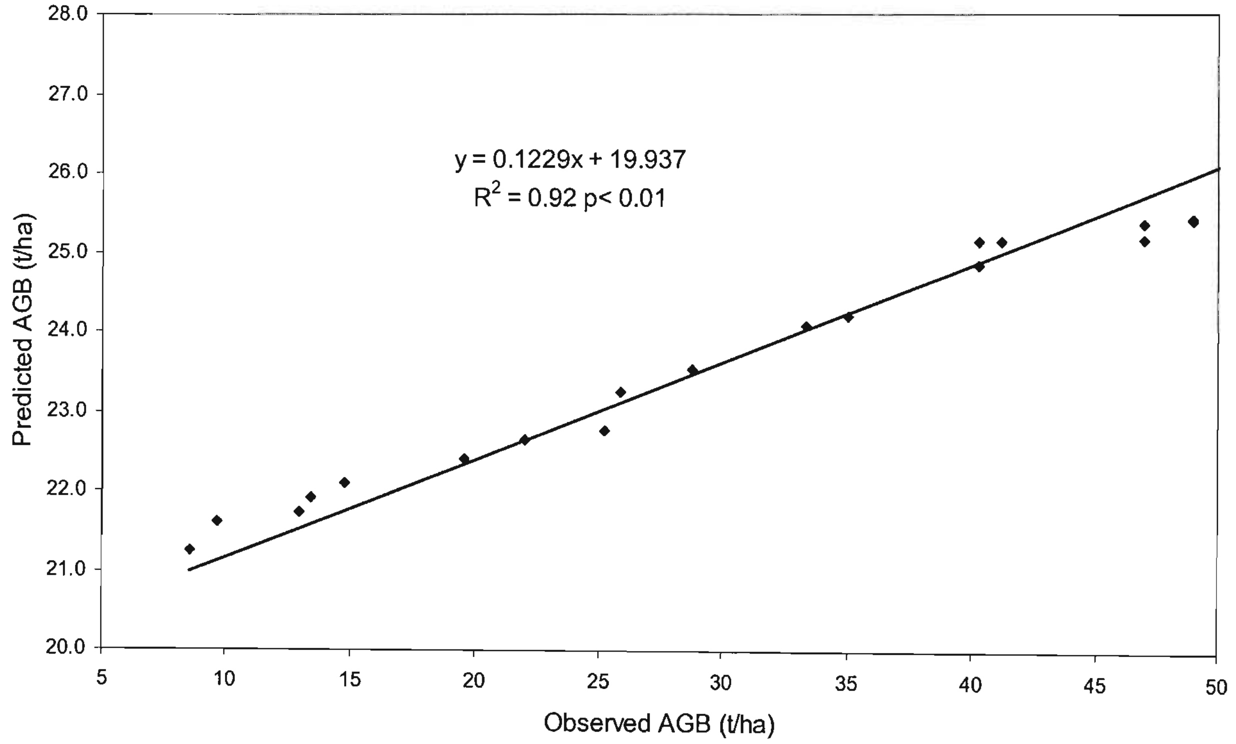


Figure 5.22 Relationship between observed ABG and 3PG-S ABG

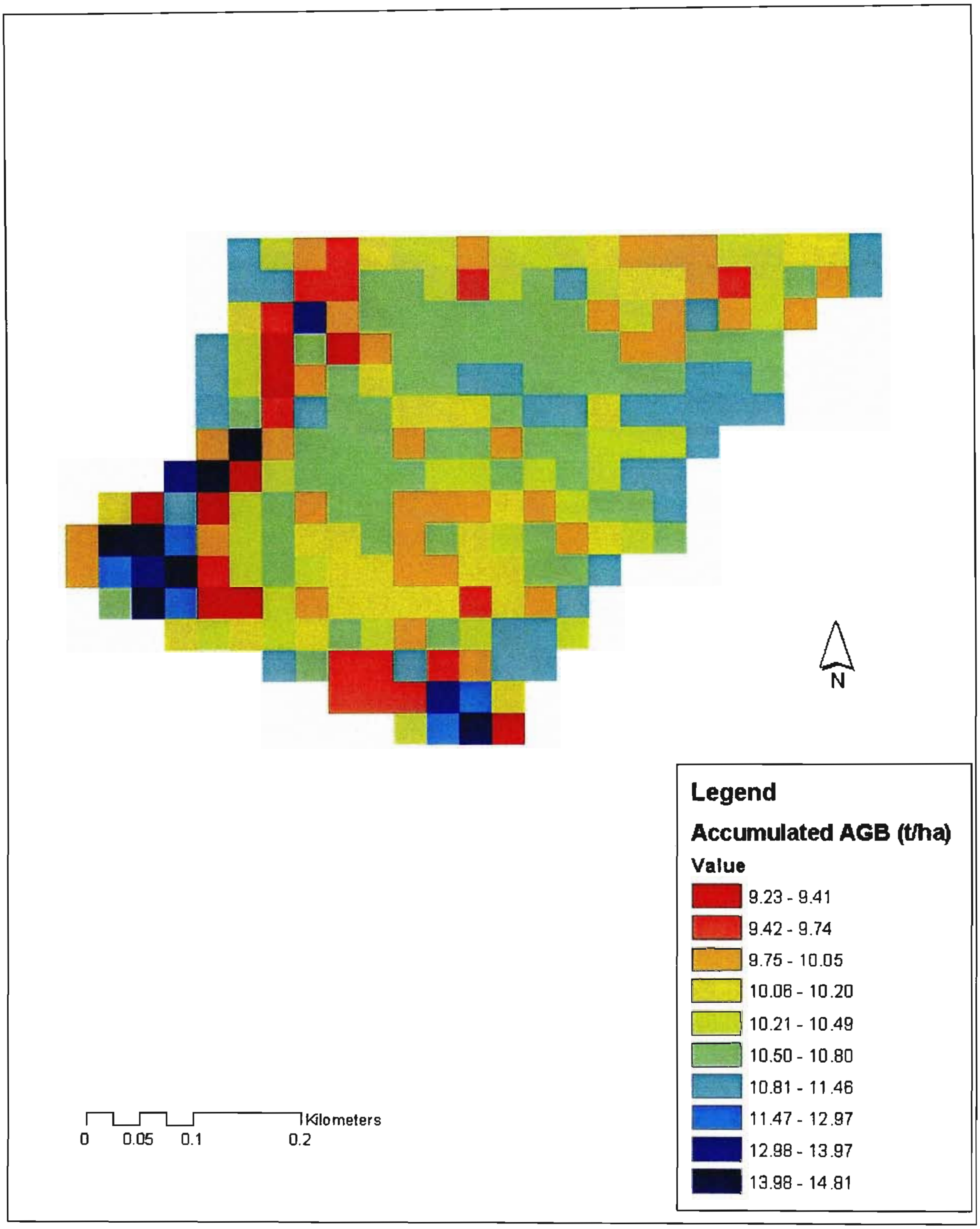


Figure 5.23 Map of Aboveground Biomass for plot D20

5.8.4 Plot C17

A significant correlation relationship (r =0.86, ρ<0.01, n = 37, SE= 5.906) was obtained between the observed and model predicted AGB for plot C17. The significant linear regression relationship (R^2 = 0.95, ρ<0.01) was obtained between 3PG-S AGB and observed AGB Figure 5.24. A map of accumulated AGB for plot C 17 is shown in Figure 5.25.

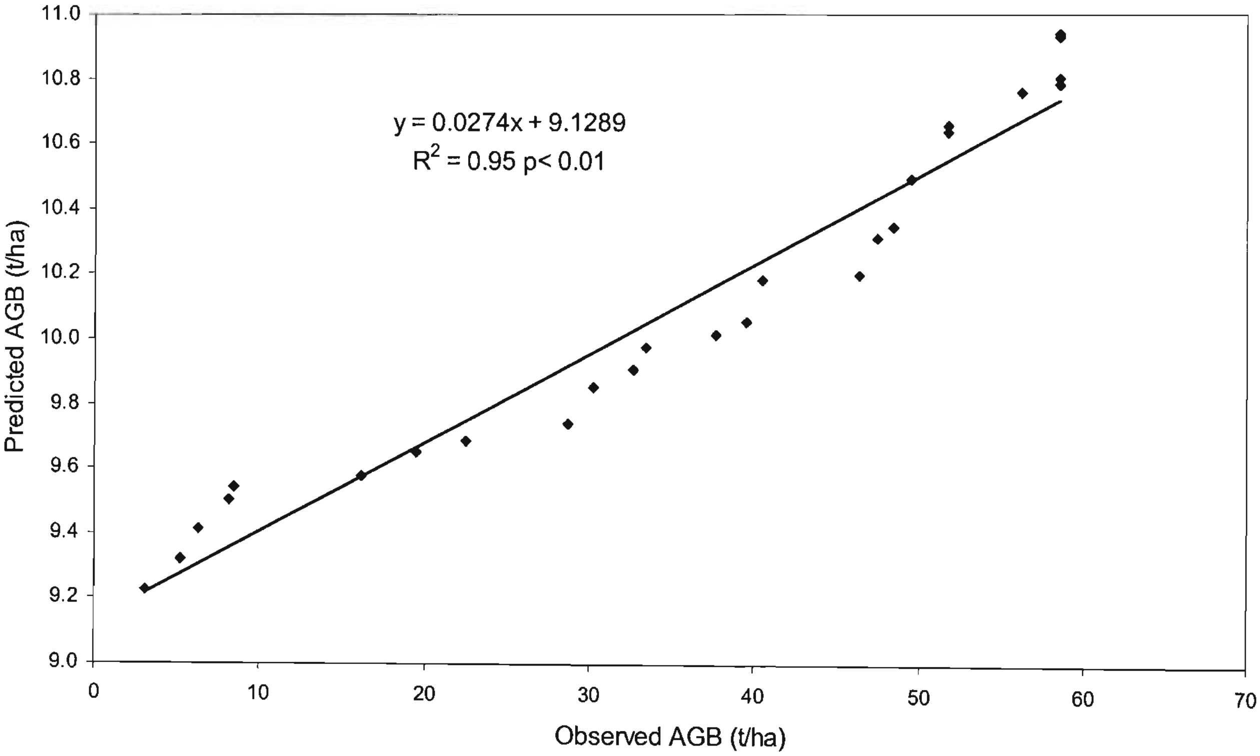


Figure 5.24 Relationship between observed ABG and 3PG-S ABG

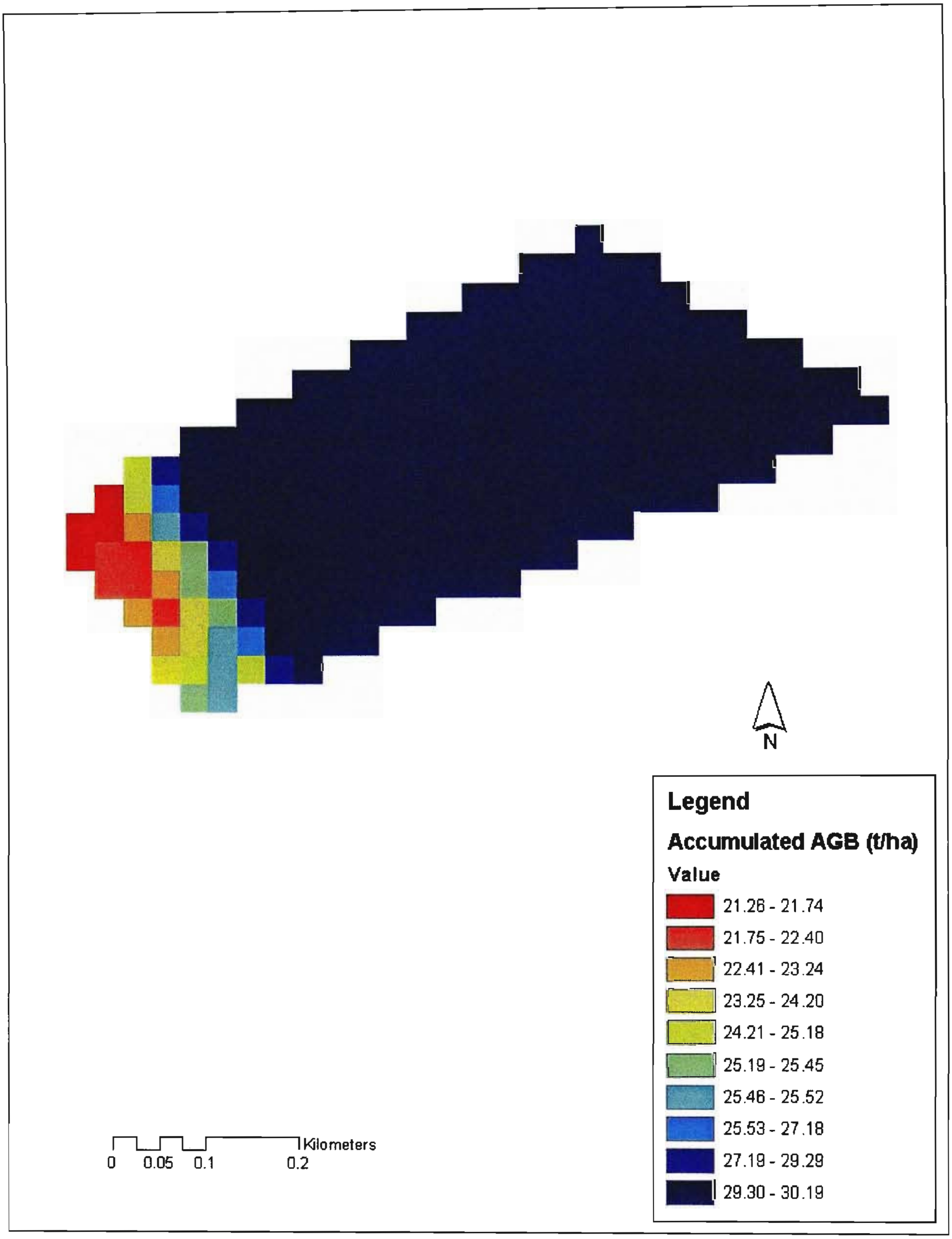


Figure 5.25 Map of Aboveground Biomass for plot C17.

5.8.4 Global AGB Model

The overall results for the combined plots show a highly significant (r= 0.93, n=115, p< 0.01, SE = 0.116) relationship between the observed AGB and predicted values of AGB. The significant exponential regression relationship (R^2 = 0.91, ρ<0.01) was obtained between 3PG-S AGB and observed AGB Figure 5.26.

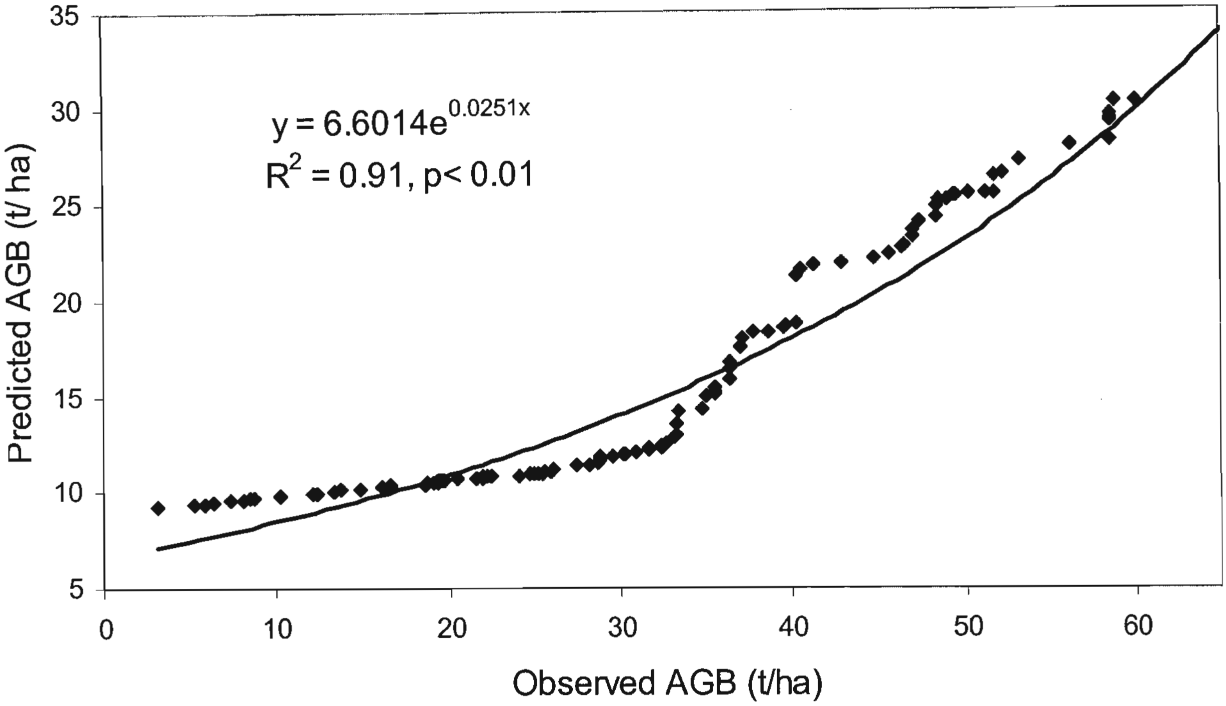


Figure 5.26 Relationship between observed AGB and 3PG-S AGB in Zululand

Above-ground biomass is a good indicator for the volume stored in the ecosystem and therefore there is a need for producing spatial maps of AGB for large areas and hence reflection of productivity. AGB could also be used to indicate degraded state of ecosystems. In general, the 3PG-S model performed robustly with the observed above ground biomass for all the sites irrespective of its productivity capacity. The 3PG-S model outputs showed very good relationships between measured (ground based measurements) and simulated (modelled) values by significant (ρ<0.01) coefficient of determination (r) more than 0.85 suggesting that they were in near 1:1 agreement with Coefficient of determination.

Baccini *et al.*, (2000) estimated forest biomass over regional scales using multisource that is Random Forest Model which utilizes Moderate Resolution Imaging Spectroradiometer (MODIS), precipitation and elevation data and the results proved effective. They found that the regression coefficient (R^2) ranged between 0.68 and 0.75 with about 78% of values falling within ± 50 t/ ha of the root mean square error. Studying the spatial distribution of forest biomass in the Brazilian Amazon, Houghton *et al.*, (2001) found the best agreement between observed biomass and spatial interpolated biomass with a correlation coefficient of 0.99. Estimating aboveground biomass using Landsat 7 ETM+ data across a managed landscape in northern Wisconsin in the United States, Zheng *et al.*, 2004) found the estimates to correspond well ($R^2 = 0.67$) with previously reported estimations of AGB in that region. Heiskanen, (2006) estimated aboveground tree biomass and leaf area index in a mountain birch forest using ASTER satellite data and found strong correlation ($r = 0.91$, $p < 0.05$) between estimated biomass and observed biomass. Also there were strong significant correlations between biomass and vegetation indices derived from ASTER data.

In summary, this chapter has presented results of the study as a whole. The LiCor-2000 results were calibrated using the LAI obtained from destructive sampling. The study also presented the SLA values obtained both from direct and indirect field based measurements and hence produced algorithms which can be used to obtain SLA from VI's. The relationship between LA and DBH was also looked at and promising results were obtained. The relationship/s between VI's amongst themselves and also LAI were investigated and hence LAI equally as SLA can be deduced from vegetation indices. This study mapped the NPP and AGB predicted using 3PG-S for four different sites and hence validated the predictions using the observed values. The results were shown to be highly correlated and very close to 1:1 relationship. Finally, literature on water use was explored to further clarify water used by forestry, especially in the Zululand region. The next chapter would formulate conclusions from this study and therefore draw some recommendations and problems encountered during the study and proposed solutions.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Remote sensing techniques are useful for acquiring data over large areas especially commercial forestry given the spatially heterogeneous nature of these forests. Goetz *et al.*, (2000); Prince and Goward, (1995) and Running *et al.*, 2000) further mentioned that remote sensing techniques allow scientists to examine properties and processes of ecosystems and their interannual variability at multiple scales because satellite observations can be obtained over large areas of interest with high revisitation frequency and are timely with precise data at a lower cost .

Collection of field data to estimate biomass and productivity involves destructive sampling, which is time consuming and expensive and as a results data for AGB and NPP is relatively rare and when present, tend to be representative of small areas and local conditions (Schroeder *et al.*,1997; Brown 2002). Remote sensing provides one important technique for monitoring the status of trees and hence determining the role they play, not only on local and regional levels, but also on a global scale.

Leaves are the primary site of energy and mass exchange within the forest environment (Pierce and Running, 1988). Studies of forest productivity, modelling of canopy structure and aboveground biomass estimation depends largely on the knowledge of plantations actual LA and LAI (Van Laar, 1984 and Borghetti and Vendramin, 1986). Cherry *et al.*, (1998) and Xavier and Vettorazzi, (2004) have shown that remotely sensed data are useful for retrieving LAI. LAI has been described by Pu *et al.*, 2003) as an important driver of some ecosystem models applied at landscape to global scales since it is related to productivity of forest stands. This study estimated LAI using three methods: destructive sampling, LiCor-2000 and remotely sensed imagery. The role of destructive sampling is crucial when dealing with LiCor-2000 because LiCor-2000 is said to overestimate LAI values due to its failure to distinguish between leaves, branches and stems, therefore needs to be calibrated all the time. The calibration of LiCor-2000 LAI by destructive sampling showed an overestimation of the *Eucalyptus grandis* plot's LAI.

The relationship / calibration of LiCOR-2000 using destructive sampling served to provide an important relationship between the two parameters. This relationship will save time and money and also cut out tedious and laborious work of destructive sampling. The LiCor-2000 measurements taken in the same area would be calibrated using the relationship created in this study with high confidence and hence more reliable data will be obtained. The relationship between the two variables was significant with good association between them. The coefficient of determination (R^2) assessed the ability to predict LAI from the above-mentioned methods. The relationships deduced from these methods are useful across the range of compartments sampled despite the small sample size. The correlations between PAI and Actual LAI and the vegetation indices found NDVI, RVI and TNDVI to have good strength whilst VI had non-significant relationships with the two. The possibility of estimating forest LAI from satellite sensors data has been intensively investigated by many researchers. The relationships between VI's and LAI estimates have found to be affected by various factors such as canopy closure, understory vegetation and soil reflectance.

In this study, the utility of LANDSAT TM data to estimate LAI was undertaken. The results showed different logarithmic and linear equations explaining the existing relationships between LAI and vegetation indices. The vegetation indices from which LAI could be estimated with high levels of confidence were found to be NDVI, RVI and TNDVI whilst VI didn't show any significant relationships with LAI. The conclusions that can be drawn from these results are that forest managers can now be able to estimate LAI from the above indices and over large areas and also emphasise the importance of remote sensing as tool in forest management. The spatial LAI maps are needed in the estimation of productivity, aboveground biomass and water use of forest stands using process-based models.

The critical importance of SLA as a plant attribute, other than being the main parameter towards estimating LAI; is that it can be incorporated into ecological and biogeochemical models predicting net-primary productivity in a similar way to LAI. It can now be estimated over large areas in the same way as it has been done for LAI, through its relationships with vegetation indices. All of the vegetation indices used in this study showed good relationships with the SLA and different models were established from which SLA can be estimated using satellite imagery.

The advantage of estimating LAI from vegetation indices is that they (VI's) can be related to leaf area, standing biomass and productivity of forest species. The net primary productivity (NPP) is defined as gross primary production (GPP) minus autotrophic respiration (Zhong *et al*., 2002), is a key descriptor of the carbon cycles of ecosystems. According to Zhou *et al*., (2002) "NPP of a forest is a function of the biomass, conditions and stand age of forest". The use of spatial databases is important if the potential of a process-based model is to be realized. Remote sensing data integrated with process models, primarily using simulations of ecophysiological processes of plants and ecosystems, are useful tools to estimate NPP at a variety of scales due to the spatial nature of remotely sensed. The 3PG-S model was used to predict net primary productivity and above ground biomass of forest compartments in Zululand.

The 3PG-S outputs (maps) show variation (that is both the net primary productivity and above ground biomass were not uniform across each chosen plots) within the compartments for net primary productivity and above ground biomass, except plot C 17 where high values of NPP and AGB dominated the plot. The validation of predicted data with observed data shows that the coefficient of determination (R^2) for all the NPP estimates of various plots show good relationships between observed data and predicted data. Results presented show that the 3PG-S model is robust and reliable and can be used with confidence to predict growth in areas where trees have not been grown that is the model can be used to estimate site productivity. It can also be used to explore the effects of changing environmental conditions on tree growth and productivity by varying factors such climate and therefore observe how such variation affect net primary productivity. "It is important that actual rather than average weather data are used when the model is used to evaluate the impact of variations in weather or management options on productivity across a large estate" Almeida *et al.*, (2004).

Changes in extent of plantation cover from original type to commercial forestry have been shown to be directly related to streamflow reduction activity. Water tables have been found to drop substantially as the commercial forestry stands developed. Literature on water use by commercial forestry species have shown massive evapotranspiration and streamflow reductions in areas previously planted with grass that have recently been introduced with afforestation programmes.

6.2. Recommendations

This study achieved all of its planned objectives and the following recommendations are based on the findings of work undertaken in this study and could be used for further research.

- The net primary productivity of sites planted with *Eucalyptus grandis*, with different weather conditions, productivity potentials and different locations should be explored in order to get a better understanding of the role played by environmental factors.
- The 3PG-S should be used to predict NPP and AGB of different forest species e.g. pines, wattle and eucalypts after parameterisation for each species has been undertaken.
- A study of chemical bioassays such as nitrogen, carbon and photosynthesis, which drives growth of forest species, should be undertaken through Hyperspectral data in order to compare between them and predicted productivity that is the effects of chemical bioassays on productivity should be considered.
- Water use estimates should be validated against water use values undertaken on various plots.
- The methodology used in this study need to be tested over a period of time and on more study sites rather than the only four sites used in this study.

- Effects of SLA on productivity should be tested and also its variation with height and environmental factors that is weather, pre-planting preparations needs further research; since SLA is related to leaf structure, positively and strongly correlated to nutrient concentrations, growth and net photosynthesis.
- The remotely sensed data used in this study had a spatial resolution of 30m x 30m. There is a need to investigate the use of higher spatial resolution imagery and such imagery is likely to provide more spatial accuracies of LAI estimates.
- Effects of soil and understory vegetation on the relationships between LAI and vegetation indices needs further research.

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Appendix A: Parameters used in 3PG-S

Temporary Species definition file generated by 3-PGS Toolbox	Parameter value
Foliage:stem partitioning ratio @ D=2 cm	0.75
Foliage:stem partitioning ratio @ D=20 cm	0.11
Constant in the stem mass v. diam. relationship	0.044
Power in the stem mass v. diam. relationship	2.771
Maximum fraction of NPP to roots	0.6
Minimum fraction of NPP to roots	0.25
Minimum temperature for growth	3
Optimum temperature for growth	23
Maximum temperature for growth	35
Days production lost per frost day	1
Moisture ratio deficit for fq = 0.5	0.7
Power of moisture ratio deficit	9
Value of 'm' when FR = 0	0
Value of 'fNutr' when FR = 0	1
Power of (1-FR) in 'fNutr'	0
Maximum stand age used in age modifier	30
Power of relative age in function for fAge	4
Relative age to give fAge = 0.5	0.95
Maximum litterfall rate	0.001
Litterfall rate at t = 0	0.075
Age at which litterfall rate has median value	24
Average monthly root turnover rate	0.015
Maximum canopy conductance	0.02
LAI for maximum canopy conductance	3.33
Defines stomatal response to VPD	0.05
Canopy boundary layer conductance	0.2
Max. stem mass per tree @ 1000 trees/hectare	300
Power in self-thinning rule	1.5

Appendix A: (Cont'd)

Fraction mean single-tree foliage biomass lost per dead tree	0
Fraction mean single-tree root biomass lost per dead tree	0.2
Fraction mean single-tree stem biomass lost per dead tree	0.2
Specific leaf area at age 0	13
Specific leaf area for mature leaves	7.7
Age at which specific leaf area = (SLA0+SLA1)/2	2.25
Extinction coefficient for absorption of PAR by canopy	0.5
Age at canopy cover	2
Maximum proportion of rainfall evaporated from canopy	0.15
LAI for maximum rainfall interception	0
Canopy quantum efficiency	0.064
Ratio NPP/GPP	0.47
Branch and bark fraction at age 0	0.6
Branch and bark fraction for mature stands	0.131
Age at which fracBB = (fracBB0+fracBB1)/2	1.945
Minimum basic density - for young trees	0.53
Maximum basic density - for older trees	0.32
Age at which rho = (rhoMin+rhoMax)/2	5.66
Intercept of net v. solar radiation relationship	-90
Slope of net v. solar radiation relationship	0.8
Molecular weight of dry matter	24
Conversion of solar radiation to PAR	2.3

Where, FR= Fertility Rating , fAge= Age Modifier SLA0= SLA at Age 0 , SLA1= SLA for mature leaves , FracBB=Fraction of Branch and Bark FracBB0= Age 0 , FracBB1= Mature stands

Appendix B: Image Specifications

PRODUCT	06179003775
WRS	167/080F
ACQUISITION DATE	20060427
SATELLITE	L5
INSTRUMENT	TM10
PRODUCT TYPE	MAP ORIENTED
PRODUCT SIZE	FULL SCENE
TYPE OF GEODETIC PROCESSING	SYSTEMATIC
RESAMPLING	CC RAD
GAINS/BIASES	+0.6024/-1.5000 +1.1749/-2.8000 +0.8059/-1.2000 +0.8145/-1.5000 +0.1081/-0.3700 +0.0552/+1.2378 +0.0570/-0.1500
TAPE SPANNING FLAG	1/1
START LINE	1
LINES PER VOL	6888
ORIENTATION	0.00
PROJECTION	UTM
USGS PROJECTION	1 USGS
MAP ZONE	36
USGS PROJECTION PARAMETERS	0.637813700000000D+07

0.635675231400000D+07	0.000000000000000D+00
0.000000000000000D+00	0.000000000000000D+00
0.000000000000000D+00	0.000000000000000D+00
0.000000000000000D+00	0.000000000000000D+00
0.000000000000000D+00	0.000000000000000D+00
0.000000000000000D+00	0.000000000000000D+00
0.000000000000000D+00	0.000000000000000D+0

```
EARTH ELLIPSOID                                  WGS 84
SEMI-MAJOR AXIS                                       6378137.000
SEMI-MINOR AXIS                                  6356752.314
 PIXEL SIZE                                      30.00
PIXELS PER LINE                                  7560
LINES PER IMAGE                                  6888
UL 0311837.0280E 275539.3630S   333738.531  6909669.000
UR 0333654.1571E 275611.7384S   560508.562  6909669.000
LR 0333734.0374E 294804.9479S   560508.562  6703059.000
LL 0311647.5012E 294729.9908S   333738.531  6703059.000
BANDS PRESENT                                    1234567
BLOCKING FACTOR                                  1
RECORD LENGTH                                    7560
SUN ELEVATION                                    36
SUN AZIMUTH                                      41
CENTER     0322726.4248E   285212.2227S  447078.594  6806289.500
3780 3444
OFFSET                                           0 REVB
```

Appendix C: SLA of all the compartments in the study

Tree	DBH	Field tare (kg)	Field sub mass (kg)	Total wet mass	Dry tare (kg)	Dry mass (kg)	Dry:wet ratio	Total DM	Leaf area of sample (cm2)	Leaf area of sample (m2)	Leaf area of tree (m2)	SLA of sample (m2/kg)	SLA of tree
E34A													
4	11.4	0.012	5.6	0.6302	0.012	0.5272	0.092	0.058	48800	4.880	0.550	9.472	9.472
29	13.4	0.012	8.4	0.507	0.012	0.3444	0.040	0.020	36058	3.606	0.218	10.848	10.848
37	12.7	0.012	8.2	0.8388	0.012	0.7086	0.085	0.071	61400	6.140	0.629	8.814	8.814
47	15.8	0.012	13	0.6218	0.012	0.5809	0.044	0.027	52787	5.279	0.253	9.279	9.279
52	16.3	0.012	12	0.6647	0.012	0.4188	0.034	0.023	56651	5.665	0.314	13.926	13.926
													10.468
J1B													
37	18	0.01	18	0.4275	0.012	0.2742	0.015	0.006	26600	2.660	0.063	10.145	10.145
29	12.1	0.01	4	0.3851	0.012	0.1725	0.040	0.015	18322	1.832	0.177	11.416	11.416
10	14.9	0.01	9	0.406	0.012	0.1705	0.018	0.007	17317	1.732	0.078	10.926	10.926
47	21.1	0.01	19	0.4056	0.012	0.2928	0.015	0.006	19526	1.953	0.042	6.954	6.954
20	16.2	0.01	10.4	0.3442	0.012	0.2165	0.020	0.007	21787	2.179	0.072	10.654	10.654
													10.019

Appendix C: continued

F9													
38	10.5	0.011	4	0.3105	0.012	0.2227	0.053	0.016	20669	2.067	0.161	9.810	9.810
25	14.2	0.011	3.7	0.3334	0.012	0.256	0.066	0.022	21993	2.199	0.199	9.014	9.014
23	18.4	0.011	21	0.4097	0.012	0.1965	0.009	0.004	22900	2.290	0.045	12.412	12.412
32	15.6	0.011	11.6	0.2962	0.012	0.2003	0.016	0.005	18560	1.856	0.047	9.857	9.857
43	17.4	0.011	18	0.3079	0.012	0.2191	0.012	0.004	21400	2.140	0.037	10.333	10.333
													10.285
A63													
41	8.7	0.012	4	0.4553	0.012	0.3025	0.073	0.033	26278	2.628	0.300	9.046	9.046
47	6.3	0.012	1.2	0.3847	0.012	0.2012	0.159	0.061	17891	1.789	0.579	9.456	9.456
23	13.6	0.012	18.2	0.6214	0.012	0.3506	0.019	0.012	30131	3.013	0.103	8.899	8.899
4	9	0.012	3.2	0.4753	0.012	0.2276	0.068	0.032	19768	1.977	0.295	9.169	9.169
34	11.8	0.012	9.5	0.4267	0.012	0.2488	0.025	0.011	26814	2.681	0.121	11.323	11.323
													9.579
F18													
18	12.6	0.01	6.4	0.3599	0.012	0.1841	0.027	0.010	16609	1.661	0.094	9.651	9.651
4	14.6	0.01	6.6	0.5285	0.012	0.3048	0.044	0.023	26554	2.655	0.213	9.069	9.069
47	15.2	0.01	16	0.4626	0.012	0.3518	0.021	0.010	36799	3.680	0.106	10.830	10.830
11	18.9	0.01	18	0.3741	0.012	0.2125	0.011	0.004	17300	1.730	0.036	8.628	8.628
25	16.3	0.01	14	0.3825	0.012	0.35	0.024	0.009	30452	3.045	0.083	9.009	9.009
													9.437
C14													
23	16.4	0.011	23	0.2461	0.012	0.1151	0.004	0.001	12800	1.280	0.014	12.415	12.415
53	9.3	0.011	5.8	0.3179	0.012	0.184	0.030	0.009	18665	1.867	0.102	10.852	10.852
42	14.9	0.011	11.8	0.4955	0.012	0.2882	0.023	0.012	25987	2.599	0.109	9.409	9.409
12	11.3	0.011	8	0.4757	0.012	0.2722	0.033	0.015	23906	2.391	0.142	9.188	9.188
50	12	0.011	8.4	0.4499	0.012	0.2541	0.029	0.013	24652	2.465	0.132	10.183	10.183
													10.409

Appendix D: Statistical Descriptives

E34A				
	NDVI	RVI	TNDVI	VI_3
Mean	0.634	0.628	0.629	0.645
Standard Error	0.027	0.032	0.030	0.020
Median	0.692	0.688	0.688	0.669
Mode	0.722	0.725	0.722	0.686
Standard Deviation	0.170	0.203	0.192	0.124
Sample Variance	0.029	0.041	0.037	0.015
Kurtosis	0.559	0.054	0.168	0.363
Skewness	-0.986	-0.637	-0.720	-0.658
Range	0.718	0.843	0.815	0.541
Minimum	0.192	0.157	0.165	0.314
Maximum	0.910	1.000	0.980	0.855
C14				
	NDVI	RVI	TNDVI	VI_3
Mean	0.893	0.893	0.836	0.794
Standard Error	0.007	0.007	0.010	0.009
Median	0.890	0.890	0.827	0.792
Mode	0.878	0.878	0.812	0.792
Standard Deviation	0.046	0.046	0.066	0.056
Sample Variance	0.002	0.002	0.004	0.003
Kurtosis	0.021	0.021	-0.224	0.227
Skewness	-0.560	-0.560	-0.429	-0.536
Range	0.192	0.192	0.270	0.243
Minimum	0.773	0.773	0.671	0.655
Maximum	0.965	0.965	0.941	0.898
F18				
	NDVI	RVI	TNDVI	VI_3
Mean	0.815	0.726	0.757	0.716
Standard Error	0.025	0.030	0.028	0.020
Median	0.851	0.757	0.788	0.765
Mode	0.851	0.757	0.788	0.765
Standard Deviation	0.156	0.187	0.178	0.129
Sample Variance	0.024	0.035	0.032	0.017
Kurtosis	3.733	1.771	2.270	2.875
Skewness	-1.874	-1.251	-1.448	-1.789
Range	0.702	0.816	0.780	0.577
Minimum	0.298	0.184	0.220	0.290
Maximum	1.000	1.000	1.000	0.867

Appendix: D Cont'd

F9				
	NDVI	RVI	TNDVI	VI$_3$
Mean	0.797	0.715	0.739	0.718
Standard Error	0.015	0.019	0.018	0.018
Median	0.816	0.733	0.761	0.714
Mode	0.839	0.765	0.788	0.714
Standard Deviation	0.097	0.119	0.113	0.114
Sample Variance	0.009	0.014	0.013	0.013
Kurtosis	5.325	2.788	3.122	0.433
Skewness	-1.358	-0.606	-0.751	0.548
Range	0.584	0.690	0.659	0.514
Minimum	0.416	0.310	0.341	0.486
Maximum	1.000	1.000	1.000	1.000
J1B				
	NDVI	RVI	TNDVI	VI$_3$
Mean	0.796	0.737	0.743	0.710
Standard Error	0.026	0.035	0.031	0.026
Median	0.867	0.808	0.827	0.745
Mode	0.937	0.945	0.914	0.855
Standard Deviation	0.167	0.221	0.197	0.164
Sample Variance	0.028	0.049	0.039	0.027
Kurtosis	0.509	-0.163	0.133	-0.755
Skewness	-1.203	-0.893	-1.021	-0.601
Range	0.623	0.788	0.733	0.576
Minimum	0.353	0.212	0.251	0.361
Maximum	0.976	1.000	0.984	0.937
A63				
	NDVI	TNDVI	RVI	VI$_3$
Mean	0.607	0.546	0.608	0.774
Standard Error	0.029	0.033	0.029	0.021
Median	0.520	0.445	0.520	0.765
Mode	0.475	0.400	0.475	0.682
Standard Deviation	0.186	0.206	0.185	0.135
Sample Variance	0.035	0.042	0.034	0.018
Skewness	0.660	0.749	0.673	-0.198
Range	0.643	0.714	0.627	0.525
Minimum	0.357	0.286	0.373	0.475
Maximum	1.000	1.000	1.000	1.000

Where, NDVI = (NIR – RED) / (NIR + RED)

RVI= NIR / RED

TNDVI= NIR / RED

VI$_3$ = NIR - RED

Appendix E: Plot Measured parameters

Plot	Tree no:	DBH	Height (m)	Height to First live branch (m)	Crown Depth (m)	Mass of leaves (kg)
E34A	4	11.4	13	9.6	3.4	5.60
	29	13.4	14.6	10.87	3.73	8.40
	37	16.3	14.5	9.6	4.9	8.20
	47	12.7	13.7	9.2	4.5	13.00
	52	15.8	13.9	9.2	4.7	12.00
J1B	10	14.9	16.7	3.4	13.3	9.00
	20	16.2	17.2	3.7	13.5	10.40
	29	12.1	15.6	2	13.6	4.60
	37	18	18.3	4.4	13.9	18.00
	47	21.1	20.2	6.1	14.1	19.00
F9	23	18.4	18.2	5.3	12.9	21.00
	25	14.2	14.3	2.7	11.6	3.70
	32	15.6	16.9	5.5	11.4	11.60
	38	10.5	14.1	3.4	10.7	4.00
	43	17.4	17.8	5.6	12.2	18.00
A63	4	9	9.4	2	7.4	3.20
	23	13.6	14.1	6.12	7.98	18.20
	34	11.8	12.9	4.8	8.1	9.50
	41	8.7	10.1	3.7	6.4	4.00
	47	6.3	10.2	2.2	8	1.40
F18	4	14.6	16.6	4.7	11.9	6.60
	11	18.9	17.2	5.5	11.7	18.00
	18	12.6	15.9	3.2	12.7	6.40
	25	16.3	16.8	6.4	10.4	14.00
	47	15.2	16.7	5.5	11.2	16.00
C14	12	11.3	10.6	3.3	7.3	8.20
	23	16.4	12	6.3	5.7	23.00
	42	14.9	11.5	3.9	7.6	11.80
	50	12	11.1	3.9	7.2	8.40
	53	9.3	10.1	3.1	7	5.80

Appendix F: Biomass Determination.

The biomass determination procedure was as follows:

The sample trees were felled as close to the ground as possible using a chainsaw. Then, tree height up to a pulpable diameter i.e. 5cm and height to the first limb carrying live foliage were measured with a 50-meter measuring tape. The crown length is obtained from the difference of the two heights. Diameter at breast height (DBH) and stem diameter at the base of the crown were measured using a DBH tape and in some cases callipers depending on the diameter of the tree. The crown length was divided into three equal parts as upper, middle and lower crown zones. The following parameters were measured:

A. Leaves

All leaves were stripped off by hand. The leaves were collected and placed in a plastic bag (of known weight) and the fresh weight was taken with the spring balance. A small leaf sample representative of the whole canopy was taken and placed in a zip-lock bags and fresh weight determined. This small leaf sample was taken to the laboratory for leaf area determination in a cooler box. The LICOR-2000 leaf area meter was used to take leaf area of samples. The samples were then oven dried to a constant mass in an oven at 65 °C and the specific leaf area was determined. The leaves were then cooled in the desiccators and weighed to obtain their dry mass.

B. Branches

All the branches both dry and live branches were cut from the stem, separated i.e. dry from live and weighed using a 30kg spring balance in the field. Three sub-samples were taken from both dry and live branches using pruners of different sizes. These samples were weighed in the field using the 5kg balance, placed in plastic bags and stored in cooler boxes. These samples were taken back to the laboratory for drying and the ratios of wet to dry mass calculated. The calculated ratios were used to scale up for branches on that particular tree by multiplying the total wet branch weight from the field with the ratio of the sample branches.

C. Bark

Each sample tree was debarked up to the pulpable part of the stem i.e. up to 5cm diameter. Three sub-samples were taken, weighed, placed in zip-lock bags and transported to the laboratory in cooler boxes. These samples were then dried in the laboratory to a constant weight at 65 °C and weighed; hence ratio of dry to wet mass of the sample barks will be calculated. The ratio of wet to dry mass was used to scale up for tree weight bark by multiplying the total wet bark mass by the ratio.

D Stem

The stem circumference overbark and underbark was measured for every weighable chunk. The fresh weight of stem chunks up to the diameter of 5cm was taken in the field. The discs were then taken back to the laboratory in plastic bags and dried to a constant weight. Ratios of dry to wet mass of discs will be calculated