ESTIMATING LEAF AREA INDEX (LAI) OF GUM TREE (*EUCALYPTUS GRANDIS X CAMALDULENSIS*) USING REMOTE SENSING IMAGERY AND LiCor-2000

By

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DECLARATION

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These studies represent original work by the author and have not otherwise been submitted in any form for any degree or diploma to any University. Where use has been made of the work of others it is duly acknowledged in the text.

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Abstract

The use of remotely sensed data to estimate forest attributes involves the acquisition of ground forest data. Recently the acquisition of ground data (field based) to estimate leaf area index (LAI) and biomass are becoming expensive and time consuming. Thus there is a need for an easy but yet effective means of predicting the LAI, which serves as an input to the forest growth prediction models and the quantification of water use by forests. The ability to predict LAI, biomass and eventually water use over a large area remotely using remotely sensed data is sought after by the forestry companies. Remotely sensed LAI values provide the opportunity to gain spatial information on plant biophysical attributes that can be used in spatial growth indices and process based growth models. In this study remotely sensed images were transformed into LAI value estimates, through the use of four vegetation indices (Normalized Difference Vegetation Index (NDVI), Corrected Normalized Difference Vegetation Index (NDVIc), Ratio Vegetation Index (RVI) and Normalized Ratio Vegetation Index (NRVI). Ground based measurements (Destructive Sampling and Leaf Canopy Analyzer) relating to LAI were obtained in order to evaluate the vegetation indices value estimates. All four vegetation indices values correlated significantly with the ground-based measurements, with the NDVI correlating the highest. These results suggested that NDVI is the best in estimating the LAI in *Eucalyptus grandis x camaldulensis* in the Zululand region with correlation coefficients of 0.78 for destructive sampling and 0.75 for leaf canopy analyzer. Visual inspection of scatter plots suggested that the relations between NDVI and ground based measurements were variable, with R^2 values of 0.61 for destructive sampling and 0.55 for Leaf Canopy analyzer. These LAI estimates obtained through remotely sense data showed a great promise in South African estimation of LAI values of *Eucalyptus grandis x camaldulensis*. Thus water use and biomass can be quantified at a less expensive and time-consuming rate but yet efficiently and effectively.

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LIST OF ABBREVIATIONS

CCWR	Computer Center for Water Research
CSIR	Council for Scientific and Industrial Research
DBH	Diameter at Breast Height
GIS	Geographic Information System
LAI	Leaf Area Index
Landsat 7	Satellite used to gather information over land
MIR	Middle Infrared
MTA	Mean Tip Angle
NDVI	Normalized Difference Vegetation Index
NDVIc	Corrected Normalized Difference Vegetation Index
NRVI	Normalized Ratio Vegetation Index
NIR	Near Infrared
PCA	Plant Canopy Analyzer
RVI	Ratio Vegetation Index
SAC	Satellite Application Center
SEM	Standard Error of MTA
SEL	Standard Error of LAI
SI	Site Index
SLA	Specific Leaf Area
SMP	Number of Sample Pairs Used
SPSS	Statistical package for the Social Sciences
VI	Vegetation Index
3PG	Physiological Processes Predicting Growth Model

Chapter 1

Introduction

1.1 Introduction

The aim of this study is to evaluate the integrated system of remote sensing and geographic information systems (GIS) in providing the necessary information that aid in the study of the physiological characteristics of the gum tree (*Eucalyptus grandis x comedulensis),* and for the subsequent determination of water consumption capability of this species. This is to assist in the quantification of the influence of *Eucalyptus grandis x comedulensis* on water resources, particularly its impact on reducing stream flow. The negative impact of forestry in general, and *Eucalyptus* in particular, on water resources has recently been documented. *Eucalyptus* consumes on average, 25 liters of water per day (Megown *et al,* 1999). The influence of plants on water resources is largely determined by their annual rate of evapotranspiration, a highly variable quantity that changes from year to year and from site to site in response to a wide range of weather, site and plant factors.

The key to determination of the physiological or growth characteristics of forestry stands is the estimation of leaf area index (LAI). This can be measured through destructive sampling of trees. Recently one of the vegetation indices obtained from remotely sensed data to calculate LAI values for large areas have been reported. In this study, estimates of LAI of *Eucalyptus grandis x camaldulensis* species were obtained through satellite remote sensing, ground observations by destructive sampling and through LiCor-2000. This was undertaken in the commercial forestry region of KwaZulu-Natal.

1.2 Leaf Area Index (LAI)

In studies of the Earth's ecosystems and their interaction with climate, it is frequently necessary to know the leaf area index (LAI) of vegetation cover. LAI can be defined as one half of the total leaf area per unit ground surface area. LAI determines the productivity of the surface and hence affects physical and biophysical interactions between the surface and the atmosphere.

Since direct measurements of LAI of forests are time consuming and destructive in nature, indirect methods are often used. These methods include the use of optical instruments and allometric relationships of their operating instrument. Allometric relationships such as that between LAI and sapwood area or tree trunk diameter are often stand specific, i.e. they depend on species, season, age, stand density, tree crown size, and other stand attributes. Optical instruments are therefore very attractive to many investigators because of the speed and nondestructive nature of the measurements. Optical instruments measure the amounts of direct or diffuse radiation penetrating the canopy from which the LAI is derived. For large areas, reflected spectral radiances that are remotely sensed from airborne and space borne platforms have been used to derive LAI.

1.3 Remote Sensing and its Forestry Applications

The revolutionary merger of remote sensing and GIS has generated tremendous interest and application over a wide range of disciplines including forestry. It has brought new understanding of the natural world and the processes operating on our planet. Furthermore, it has shed light on the impacts of human kind on earth's resources (Lillesand and Kiefer, 1994). Relative to ground surface sampling, remotely sensed satellite images have improved spatial coverage that can help study, map, and monitor the earth's surface at local and/ or regional scales. Advantages offered by remotely sensed image data include, a synoptic/regional view, cost effectiveness, high spatial and temporal resolution coverage compared to ground sampling.

Satellite remote sensing is a technique that is developing and improving every year. With the development and the application of vegetation indices, users can have access to updated data on vegetation (Campbell, 1987; Lillesand and Kiefer, 1994).

A forest stand is characterized by several attributes that include species composition, crown closure, height, age class, etc. The extent to which stand structure can be detected, classified and mapped determine the informational value of classified airborne images in the inventory, necessary database development and management, and modeling of the forest resources (Leckie *et al,* 1995; Magnussen and Boudewyn, 1997).

One view that limits the use of remote sensing in forestry, however, is that results of digital image analysis should be comparable, or even superior, to the inventory results generated from existing analogue methods e.g. aerial photography. In addition, image analysis methods employed must be relatively simple, well understood and readily accessible to managers responsible for development and implementation of resource management plans within a framework of ecological, socio-economic and environmental considerations (Franklin *et al,* 1997).

1.4 Vegetation Indices (VI)

Healthy canopies of green vegetation have a very distinctive interaction with energy in the visible and near-infrared regions of the electromagnetic spectrum. In the visible regions, plant pigments (most notably chlorophyll) cause strong absorption of energy, primarily for the purpose of photosynthesis. This absorption peaks in the red and blue areas of the visible spectrum, thus leading to the characteristic green appearance of most leaves. In the near infrared, however, a very different interaction occurs.

Energy in this region is not used in photosynthesis, and it is strongly scattered by the internal structure of most leaves, leading to a very high apparent reflectance in the near infrared. It is this strong contrast, then, most particularly between the amount of reflected energy in the red and near infrared regions of the electromagnetic spectrum, that has been the focus of a large variety of attempts to develop quantitative indices of vegetation condition using remotely sensed imagery (Thiam and Eastman, 2000).

Vegetation indices are derived from multipectral data based on the differences in absorption, transmittance and reflectance of energy by vegetation in the red and near-infrared bands. The vegetation indices are measures of biomass or vegetation vigor and have been useful in revealing the physiological conditions and patterns of green vegetation distribution (Azzali and Meneti, 2000).

There are numerous vegetation indices including ratio vegetation index (RVI), normalized difference vegetation index (NDVI), perpendicular vegetation index (PVI), soil adjusted vegetation index (SAVI), transformed soil adjusted vegetation index (TSAVI) and tasseled cap greenness index (Fung and Siu, 2000 and Lyon *et al,* 1998). These vegetation indices can be used in a number of ways amongst others the determination of leaf area index (LAI). The study by Perry and Lautenschlager (1984) indicated the similarity in information in most of these vegetation indices. Among them, the NDVI is the most commonly adopted one.

1.5 Aim and Objectives

The aim of this study is to develop a practical methodology to optimize the relationship between the LAI derived from the Vegetation Indices determined from the remotely sensed data, direct (destructive methods) and indirect measurements (through the use of optical instruments) of LAI. The results thereof, will assist in providing inputs to models such as the spatial version of Physiological Processes Predicting Growth (3-PG) developed by Landsberg and Waring (1997). This model assists in the quantification of the influence of crops on water resources. It is also hoped that this study will contribute towards the fulfillment of some articles of the South African Water Act of No.36 of 1998 which makes provisions for the classification of various crops and land use practices as stream flow reduction activities, which are then subject to controls to ensure equity in water allocation.

The following are the specific objectives of the study

- To measure LAI of different *Eucalyptus grandis x comedulensis* stands in the various environmental settings of Hluhluwe and KwaMbonambi areas using LiCor-2000 (optical instrument) and destructive sampling.

- To determine LAI using remotely sensed imagery of Landsat 7 through various vegetation indices.
- To calibrate / optomise remote sensing based LAI measurements with LAI estimates from the LiCor-2000 (optical instrument) and from destructive sampling.

Chapter 2

Literature Review

2.1 Remote Sensing Techniques

Remote sensing is the examination, measuring and analysis of an object without being in contact with it (Graetz, 1987). It requires a signal usually electromagnetic (EM) radiation. The majority of remote sensing is done with passive sensors. These sensors rely on existing forms of energy sources normally the sun. Active sensors provide their own source of energy, for example Radar. Radar emits its own signal, measures the amount of that signal which reflects back to it.

Specifically, remote sensing has been more associated with interaction between earth surface materials and electromagnetic energy, which could be achieved through the use of satellites (Lillesand and Kiefer, 1994). The satellite remotely sensed data is usually collected in two dimensions either as a photographic image carried on the space or as an array of digital data.

There are numerous applications of remote sensing ranging from weather predictions, mineral explorations, crop forecasting to pollution detection, rangeland monitoring and commercial fishing. As this process is relatively new, its status continues to change as new and improved spacecraft are introduced into orbit. Therefore, satellite remote sensing has had a fundamental impact in conceiving earth as a system.

2.2 Vegetation Indices

The distribution of vegetation is largely associated with climate, terrain characteristics and human activity. According to Graetz (1987), vegetation cover is basically characterized by three measures: *physiognomy* (vegetation structure and phenology) where the vegetation structure includes micrometeorological aspects, *dynamics* (vegetation change in space and in time in response to climatic and landscape factors), whose main components are the rhythms of phonological changes and distribution events, *taxonomy* (photogenetic affinities and botanical characterization of plants). In a functional contest, taxonomy has a relatively small value compared to the other two. Satellite data provide the opportunity to monitor continuously the physiognomy as well as the dynamics of vegetation, its changes and its impact on the environment (Azzali and Menenti, 2000).

The vegetation indices (VI) are applicable to both low and high spatial resolution satellite images, such as NOAA AVHRR, Landsat TM and MSS, SPOT HRV/XS, and any others similar to these that sense in the red and near-infrared regions. They have been used in a variety of contexts to assess green biomass and as a proxy to overall environmental change, especially in the context of drought (Massom, 1991 and Goward *et al* 1985) and land degradation risk assessment. As a consequence, special interest has been focused on the assessment of green biomass in arid environments where soil background becomes a significant component of the signal detected.

VI can be classified into groups, (Jackson and Huete, 1991). The two groups that are discussed in this report are the *slope based* and *distance based* VI's. To appreciate this distinction, it is necessary to consider the position of vegetation pixels in a two-dimensional graph (or *bi-spectral plot*) of red versus infrared reflectance. The slope based VI's are simple arithmetic combinations that focus on the contrast between the spectral response patterns of vegetation in the red and near infrared portions of the electromagnetic spectrum. They are so named because any particular value of the index can be produced by a set of red / infrared reflectance values that form a line emanating from the origin of a bi-spectral plot. Thus different levels of the index can be envisioned as producing a spectrum of such lines emanating from the origin that differ in their slope.

2.2.1 The Slope Based VI's

The slope based VI's are a combinations of the visible red and the near infrared bands and are widely used to generate vegetation indices. Both these values give status and abundance of green vegetation cover and biomass. The slope based VI's include the Ratio Vegetation Index (RATIO), the Normalized Difference Vegetation Index (NDVI) (Rouse *et al*, 1974), the Ration Vegetation Index (RVI) (Richardson and Wiegand, 1977), the Normalized Ration Vegetation Index (NRVI)

(Baret and Guyot, 1991), the Transformed Vegetation Index (TVI), the Corrected Transformed Vegetation Index (CTVI) (Perry and Lautenschlager, 1984) and the Thiam's Transformed Vegetation Index (TTVI) (Thiam, 2000).

The RATIO was proposed by Rouse *et al.* (1974) to separate green vegetation from soil background using Landsat MSS imagery. Simply by dividing the reflectance values contained in the near infrared band by those contained in the red band i.e produces the RATIO VI.

$$\text{Ratio} = \text{NIR/RED} \tag{2.1}$$

The result clearly captures the contrast between the red and infrared bands for vegetated pixels, with high index values being produced by combinations of low red (because of absorption by chlorophyll) and high infrared (as a result of leaf structure) reflectance. In addition, because the index is constructed as a ratio, problems of variable illuminations as a result of topography are minimized. However, the index is susceptible to division by zero errors and the resulting measurement scale is not linear. As a result, RATIO VI images do not have normal distributions, making it difficult to apply some statistical procedures.

The NDVI was introduced by Rouse *et al.* (1974) in order to produce a spectral VI that separates green vegetation from its background soil brightness using Landsat MSS digital data. It is expressed as the difference between the near infrared and red bands normalized by the sum of those bands i.e.

$$\text{NDVI} = (\text{NIR-RED}) / (\text{NIR + RED}) \tag{2.2}$$

This is the most commonly used VI as it retains the ability to minimize topographic effects while producing a linear measurement scale. In addition, divisions by zero errors are significantly reduced. Furthermore, the measurement scale has the desirable property of ranging form -1 to 1 with 0 representing the approximate value of no vegetation. Thus negative values represent non-vegetated surfaces. NDVIc was derived from NDVI by Megown *et al* (1999).

NDVIc is expressed as the difference of one with the difference between the near infrared and red bands normalized by the sum of those bands i.e.

$$NDVIc = \{1-(NIR-RED) / (NIR + RED)\} \tag{2.3}$$

The simple RVI was suggested by Richardson and Wiegand (1977) as graphically having the same strengths and weakness as the TVI, while computationally being simpler than the TVI. RVI is clearly the reverse of the standard simple ratio (RATIO) as shown by its expression.

$$RVI = RED / NIR \tag{2.4}$$

The NRVI is a modification of the RVI by Baret and Guyot (1991) whereby the result of RVI-1 is normalized over RVI+1.

$$NRVI = RVI - 1 / RVI + 1 \tag{2.5}$$

This normalization is similar in effect to that of the NDVI, i.e., it reduces topographic, illumination and atmospheric effects and it creates a statistically desirable normal distribution.

2.2.2 The Distance Based VI's

In contrast to the slope-based group, the distance based group measures the degree of vegetation present by gauging the difference of any pixel's reflectance from the reflectance of bare soil. A key concept here is that a plot of the positions of bare soil pixels of varying moisture levels in a bi-spectral plot will tend to form a line (known as a *soil line*). As vegetation canopy cover increases, this soil background will become progressively obscured, with vegetated pixels showing a tendency towards increasing perpendicular distance from this soil line. All of the members of this group (such as the Perpendicular Vegetation Index- PVI) thus require that the slope and intercept of the soil line be defined for the image being analyzed. To these two groups of vegetation indices, a third group can be added called *orthogonal transformation* VI's.

The Tasseled Cap transformation is perhaps the most well known of this group, all of which undertake a transformation of the available spectral bands to form a new set of de-correlated bands within which a green vegetation index band can be defined.

The distance based VI is a group of vegetation indices that is essentially derivative of the Perpendicular Vegetation Index (PVI). The main objective of these VI's is to cancel the effect of soil brightness in case where vegetation is sparse and pixels contain a mixture of green vegetation and soil background. This is particularly important in arid and semi-arid environments.

The procedure is based on the soil line concept. The soil line represents a description of the typical signatures of soils in a red / near - infrared bi-spectral plot. It is obtained through linear regression of the near-infrared band against the red band for a sample of bare soil pixels. Pixels falling near the soil line are assumed to be soils while those far away are assumed to be vegetation.

Distance based VI's using the soil line require the slope and intercept of the line as inputs to the calculation. Unfortunately, there has been a remarkable inconsistency in the manner in which this soil line has been developed in varying implementations of this logic to produce a VI. One group requires the red band as the independent variable and the other requires the near-infrared band as the independent variable for the regression.

The distance based VI's include the Perpendicular Vegetation Index (PVI)(Richardson and Wiegand, 1977), the Ashburn Vegetation Index (AVI), the Soil-Adjusted Vegetation Index (SAVI) (Huete 1994), the Transformed Soil-Adjusted Vegetation Index (TSAVI) (Baret *et al.* 1988), the Modified Soil-Adjusted Vegetation Index (MSAVI) (Qi *et al.* 1994) and the Weighted Difference Vegetation Index (WDVI) (Richardson and Wiegand 1977, and Clevers, 1978)

2.3 Leaf Area Index (LAI)

Leaf area Index is a dimensionless index used to quantify the total single sided vegetation leaf area per unit area on the ground (Watts *et al,* 1976). The determination of leaf area index is currently of great importance to various scientists e.g. climatologists who wish to model energy and mass exchange by plant canopies over landscapes and forest managers who are investigating the usefulness of leaf area as a measure of forest structure for monitoring changes in forest productivity.

2.3.1 Importance of LAI

Tree leaf area regulates many forest processes, including canopy light interception (Running *et al.* 1995), evapotranspiration (Grier and Running, 1977), and photosynthesis (Beadle *et al,* 1998 and Running *et al,* 1989). Consequently, leaf area is related to stand productivity (Waring, 1983 and Oren *et al,* 1987) and is a crucial component in studies of regional and global phenomena such as acid rain and global warming (Running *et al,* 1989). Foliar biomass is closely correlated with leaf area and is related to many of such processes. Leaf area is generally a preferred measure because the ratio of leaf surface area to mass (specific leaf area, SLA) varies seasonally and changes from the upper to the lower canopy (Borghetti *et al,* 1986 and Jurik, 1986). Estimates of foliar biomass, however, are required in carbon allocation studies for determining the construction and maintenance costs of foliage (Chung and Barnes, 1977 and Kinerson *et al,* 1977). Similarly, in studies of nutrient cycling and retranslocation at the stand level, foliar biomass estimates are needed to convert foliar nutrient concentrations to contents (Ostman and Weaver, 1982). A common method of estimating a tree's leaf area or foliar biomass is through the use of allometric equations (Borghetti *et al,* 1986; Ruark *et al,* 1987; Long and Smith, 1988). Stand leaf area that is commonly expressed in terms of leaf area index (LAI) has also been estimated using direct harvests (Jurik *et al,* 1985), litter traps (Madgwick and Olson, 1974), and measurements of canopy transmittance (Pierce and Running,1988).

Foliar area and biomass may be sensitive to stressing agents such as acid deposition. Waring (1985) suggested that reductions in canopy leaf area should accompany the chronic stress induced by air pollution. Aber *et al.* (1995) theorized that an initial response of forestry to chronic nitrogen deposition would be a gradual increase in foliar biomass, which would be followed ultimately by a decrease in foliar biomass as forest decline occurred.

Susceptibility to insect attack in lodge pole pine (*Pinus contorta Dougl.*) increased as growth efficiency in healthy Norway spruce (*Picea abies* (L) Karst.) than in nearby declining spruce having an acid deposition induced imbalance of nitrogen and magnesium (Waring and Pitman 1985). Accurate estimates of leaf area are required if changes in leaf area or growth efficiency resulting from acid deposition are to be detected. Year to year variation in leaf area (Miller, 1967) and reductions in leaf area resulting from stochastic events (Grier, 1988) must be accounted for before the effects of air pollution can be determined (Burton *et al*, 2000).

One approach to estimating LAI has been the application of canopy radiation models to assess the image expression of forest canopies (Wulder *et al.* 1997). Such models consider the effects of the viewing geometry on the sensor in relation to the solar elevation. They estimate the response of direct and diffuse radiation to various levels of LAI. Researchers have also shown that the area occupied by various gray tones within the image can be related to an overall estimate of LAI since the gradient of gray levels in forest images represents a gradient of leaf area (Seed and King, 1997). High illuminated portions of the canopy are represented by bright areas in the image and correspondence to areas of highest LAI is lowest. The total area of a specific gray tone within an image represents the summation of the total amount of leaf area corresponding to that gray tone, and the summation of the different gray levels will therefore give an estimate of the total amount of leaf area within the image. The total leaf area divided by the area of the scene gives an estimate of the average leaf area per unit area on the ground (LAI) for the image.

This canopy radiation modeling approach has been shown to be particularly effective at estimating LAI locally with the use of high resolution imagery where the spatial variation of gray levels can be captured at the crown or sub crown level (Seed and King, 1997). A second approach to estimating LAI at local scales has been through the use of spectral reflectance models (Wulder *et al*, 1997).

The amount of radiation that is absorbed or reflected is relative to the amount of biomass that is being imaged. A denser canopy layer will absorb more radiation in the red region of the electromagnetic spectrum and reflect more in the near infrared (NIR). Many vegetation indices make use of the information in the different mechanisms of reflectance between red and NIR.

The amount of radiation that is absorbed or reflected in these two bands can be detected by remote sensing and relate through the use of vegetation indices to the thickness of the vegetation layer or LAI. In global vegetation monitoring, satellite imagery has provided adequate LAI estimations using this approach (Nemani *et al,* 1993). However, the low spatial resolution of current satellite sensors has not allowed spatial information to be extracted at the crown level. Much higher spatial resolution is required. Also, spectral reflectance is dependent on species composition, topography and atmospheric effects, which can make it difficult to isolate LAI information. Another problem associated with the use of spectral reflectance models for the estimation of LAI has been the saturation of vegetation indices above the canopy does not change dramatically when leaf area exceeds 3 - 4 per unit area on the ground. Incident radiation from above does not penetrate significantly through 3 - 4 leaf layers, and of the small amount of radiation that does penetrate these layers, little is reflected back towards the sensor.

2.3.2 Potential for texture in the estimation of LAI

The limitations of spectral reflectance models can be overcome to some extent through the incorporation of spatial information in high-resolution imagery for the estimation of LAI. Since texture is a measure of the spatial distribution of variations in tone, it possesses spatial information and therefore can be used to quantify various parameters of forest structure related to LAI. Each level or stratum in the canopy has a distinct spectral reflectance when viewed from above.

Reflectance is related to stratum depth from the canopy generally represents a certain level of leaf area, with lower leaf area occurring in lower strata of the canopy. Variations in spectral reflectance can therefore be attributed to the texture of the canopy itself, with greater texture occurring in areas of longer spatial variation in LAI. The average texture within a window in a forest image or a subscene can represent the spatial distribution of horizontal strata within the forest, each stratum having a different spectral reflectance, and each one representing an area of different LAI.

However, in conifer canopies, the spatial positions of shoots are confined within tree crowns and branches and are not random. Chen and Black (1992) found that such nonrandomness of shoot positions reduces indirect measurements of LAI by approximately 35% for a Douglas fir canopy.

In their case, the indirect measurement of LAI with the Plant Canopy Analyzer (PCA) is only 31% of a direct measurement through destructive sampling. Clumping of needles within shoots accounts for the rest of the difference between the indirect and the direct measurements. Because LAI measurements based on the gap fraction principle inevitably suffer from errors due to nonrandom foliage spatial distributions, attempts to utilize the canopy gap-size information have been made. Gap size refers to the physical dimensions of gaps. It differs from the gap fraction because for the same gap fraction, there can be different gap-size distributions. Using hemispherical photographs of a deciduous canopy, Neumann *et al,* (1989) derived a correction for LAI from a conditional probability of rays, separated by a distance *d*, passing through the same gap in the canopy. In this approach, the conditional probability increases with the size of the gap but is very sensitive to the choice of *d*. They found it difficult to provide justification for the particular values used. In another study, Chen and Black (1992) quantified the effect of foliage clumping at scales larger that the shoots (elements) with an element clumping index.

Using measurements of the transmitted radiation at 12 cm spacing along a tram transect near the forest floor in a Douglas fir stand, Chen and Black (1992) obtained canopy gap size distributions from which an element-clumping index was derived. From a gap size distribution, they also derived several canopy architectural parameters that are of interest for modeling radiation regimes in plant canopies. An important assumption used in their analysis is the random spatial distribution of clumps (tree crowns).

This assumption may be good for open natural forest stands, where the spatial distribution of tree crowns is close to random. However, in plantations, where trees are regularly or artificially spaced, the assumption is violated and the usefulness of their gap size analysis method becomes limited. In the recent papers a new theory is developed to derive the element-clumping index from a canopy gap size distribution. This theory eliminates the need for assumptions of spatial distribution patterns of foliage elements and clumps and can be applied to all types of plant canopies. A prototype Sunfleck LAI instrument named Traing Radiation and Architecture of Canopies (TRAC) has been developed at the Canada Center.

TRAC was developed for Remote Sensing by the senior author for measurement of Sunflects along straight transects beneath the canopy to obtain the canopy gap size information from which to calculate LAI and canopy architectural parameters. The instrument has been tested in two conifer plantations. Sunflacks on the ground result from gaps in the overlying canopy in the Sun's direction. From the Sunflecks, a distribution of the canopy gap size can therefore be obtained after considering the penumbra effects. If a canopy is homogeneous at large scales, Sunflacks measurements on a transect in any direction that are more than 10 times longer than the average tree spacing can statistically represent the canopy in accuracy of 95% according to Poisson probability theory. Otherwise, Sunflack measurements represent only part of the canopy measured. Naturally, gaps along the transect, vary irregularly in size (Chen and Cihlar, 1995).

2.3.3 Plant Canopy Analyzer (LiCor-2000)

The Plant Canopy Analyzer (PCA) (LiCor-2000, 1992) detects the penetrating diffuse radiation to five angles simultaneously and hence avoids the need for knowing the foliage angle distribution. The Demon (Center for Environmental Mechanics, Canberra, Australia; see Lang and Xiang (1986)) and the Sunfleck Ceptometer (Decagon Device, Pullman, Washington) make use of the transmitted direct radiation. A minimum of half a clear day is required to obtain multiangular measurements in determining LAI for canopies with an unknown foliage angle distribution. The percentage of direct or diffuse radiation transmitted through the canopy at a given angle is proportional to the canopy gap fraction at that angle. Hence these optical instruments essentially measure the canopy gap fraction, which is the percentage of sky seen from underneath the canopy. To invert from gap fraction to LAI, an assumption must be made on the spatial distribution of the foliage elements.

One obvious problem in using these instruments in conifer stands is that needles are grouped together in shoots and the amount of needle area in a shoot can not be detected, especially when the shoot is too dense to allow much light penetration (Deblonde and Penner, 1994). Gower *et al* (1999) proposed a simple correction of the PCA measurements of LAI that uses the ratio of leaf area in a shoot to the shoot area. The underlying assumptions for this simple correction are that shoots are firstly the basic foliage units and secondly randomly distributed in the canopy.

The output of the LiCor-2000 is an effective leaf area index (LAI_e) rather than a LAI (Chen and Black 1992). It would thus, be useful to quantify the contributions of the woody parts to the calculation of LAI_e. LAI_e is related to LAI according to the equation (Chen, 1996).

$$LAI = ((1 - \alpha)\, LAI_e\, (\gamma_E / \Omega_E)) \qquad (2.6)$$

Where α is the ratio of woody surface area to total surface area; γ_E is the shoot clumping factor; Ω_E is the clumping index quantifying the effect of foliage clumping at larger scales than the shoot and γ_E / Ω_E is the total stand clumping index (Ω) and equals unity when foliage distribution is random (Barclay *et al,* 2000).

The LAI of a forest canopy is defined as the one-sided area of leaves per unit area of ground (Curran 1987). In a number of investigations broad spectral wavebands remotely sensed data have been used to calculate vegetation indices that have been related to forest LAI. For example, both the simple ratio (SR) and the normalized difference vegetation index (NDVI) have been correlated with LAI. However, when canopy cover is low and there is spatial variation in the understorey, this relationship may no longer hold (Spanner *et al,* 1990). Subsequently, a number of indices were developed such as the Soil Adjusted Vegetation Index (Huete, 1994) and an improved NDVI (incorporating middle-infrared data) to minimize the effect of understorey on the NDVI: LAI relationship (Baret and Guyot, 1991; Gong *et al,* 1995; Nemani *et al,* 1993; Vane and Goetz, 1993; Gong *et al,* 1992 and Baret *et al,* 1988).

2.4 Soil Effect

Soil has a number of effects on the remotely sensed data. According to Huete (1997) soil reflectance on remote assessment of vegetation conditions. Baret and Guyot (1991) have used the SAIL model (Verhoef 1984) to evaluate the sensitivity of several vegetation index formulas to approximations the soil reflectance and leaf inclination. Pery and Lauenschlager (1984) had described the mathematical relationship among a number of vegetation indices.

In this mathematical relationships there are two cases, which are called the 'field' case and 'mixed pixel' case. In the field case, assumptions are made that vegetation cover is uniform within an instrumental field of view so that spatial inheterogeneity may be neglected, and treat the canopy as a spatially uniform layer above the soil. This case generally applies to LANDSAT and SPOT observations. In the mixed pixel case, spatial variability is assumed, corresponding to an AVHRR observation of a number of fields with varying amounts of vegetation and bare soil, but with details of individual fields unknown. Throughout this the question of atmospheric transmittance is ignored and angular effects, which require additional formulations (Holben and Tustice, 1980 and Price, 1992).

2.5 Physiological Processes Predicting Growth (3PG) Model

A recently developed spatial forest model has been successfully used in Australia and New Zealand to assess the growth and water use of a wide range of forests based on remotely sensed data (Coops, 1999). The assessment is based on a process based forest growth and water use model, Physiological Processes Predicting Growth (3-PG), with the introduction of a spatial component then the (S) is added (3-PGS) (Landsberg and Gower, 1997). The model was based on a number of established biophysical relationships and constants. The model requires few parameters and these can be derived from the field measurements.

The model has a monthly time step and requires mean daily short wave incoming radiation, mean vapor pressure deficits, temperature extremes, total monthly rainfall and estimates of soil water storage capacity and fertility and remotely sensed data.

The remotely sensed data reflects forest characteristics such as above ground biomass, leaf area index and the extent and duration of water stress. In summary this model calculates the radiant energy absorbed by forest canopies and converts it into biomass production. The efficiency of radiation conversion is modified by the effects of nutrition, soil drought, atmospheric vapor pressure deficit and stand age.

Relative to surface sampling remotely sensed data have improved spatial coverage that can help study, map, and monitor the Earth's surface at local and or regional scales. The advantages offered by remotely sensed data compared to ground sampling are cost effectiveness, high spatial resolution and coverage and relatively high temporal coverage on a long-term basis. Remote sensing technology may be appropriate for quantifying stream flow reduction activities over large areas in that it is cost effective.

The aim of this study is to optimize the relationship between the LAI estimates derived from Landsat 7 satellite imagery, direct (destructive sampling) and indirect measurement through the use of LiCor-2000 of *Eucalyptus grandis x camaldulensis* study in KwaZulu-Natal. It is hoped that such information will help in provision of accurate LAI value and subsequently be used in quantifying the impact of forestry particularly *Eucalyptus grandis x camaldulensis* on stream flow in the study area and possibly other similar areas.

Through this thesis the relationship between vegetation indices and LAI will be optimized to determine the water consumption capabilities of *Eucalyptus grandis x comedulansis.* This investigation is aimed at the determination of the use of vegetation indices in predicting LAI with high accuracy (VI that is suitable for *Eucalyptus grandis x comedulansis* and which fit the South African (Zululand region) environmental conditions). The various vegetation indices that will be derived from Landsat imagery will be evaluated to determine the most appropriate one for use in the forest plantations in South Africa. The latter will then be compared with the ground measurements to determine the accuracy of the satellite results.

Chapter 3

Materials and Methods

3.1 Study Areas

3.1.1 Introduction

The sites chosen for this study are located along the east coast of Northern KwaZulu-Natal (Figure 3.1). The sites are at KwaMbonambi and Hluhluwe study areas. These study areas were chosen because they are part of the heavy afforested regions in KwaZulu-Natal and the plantations are typical of commercial forestry developments found throughout the country.

3.1.2 Site Location and Description

Six-sites/forest stand were chosen from each study area. These sites were planted with *Eucalyptus grandis x camaldulensis*. The planting density of the trees is very high (up to one tree every 2.5-3 meters). Most trees were planted on a flat or gently sloping land. These sites were chosen because they cover large areas with homogeneous forest at least 30 x 30 meter, approximating the resolution of the Landsat 7 satellite dataset. It was noted that there was difference in trees of the same stand, this confirms Coops *et al* (1998) observation that there is an "extensive variation in species composition, growth rates, soil fertility and terrain within each stand", thus to minimize this cells in each stand were centered:

a) over the largest number of field measurement sites possible,
b) where the terrain was relatively uniform,
c) over areas (as much as possible) completely covered by forest".

These sites were visited and were visually evaluated by a plant physiologist and two foresters, for their suitability in this study. The species chosen for this study was ideally chosen because they have been numerous published work on *Eucalyptus* species and was better understood. In each region different age classes were chosen see Table 3.2 (a and b).

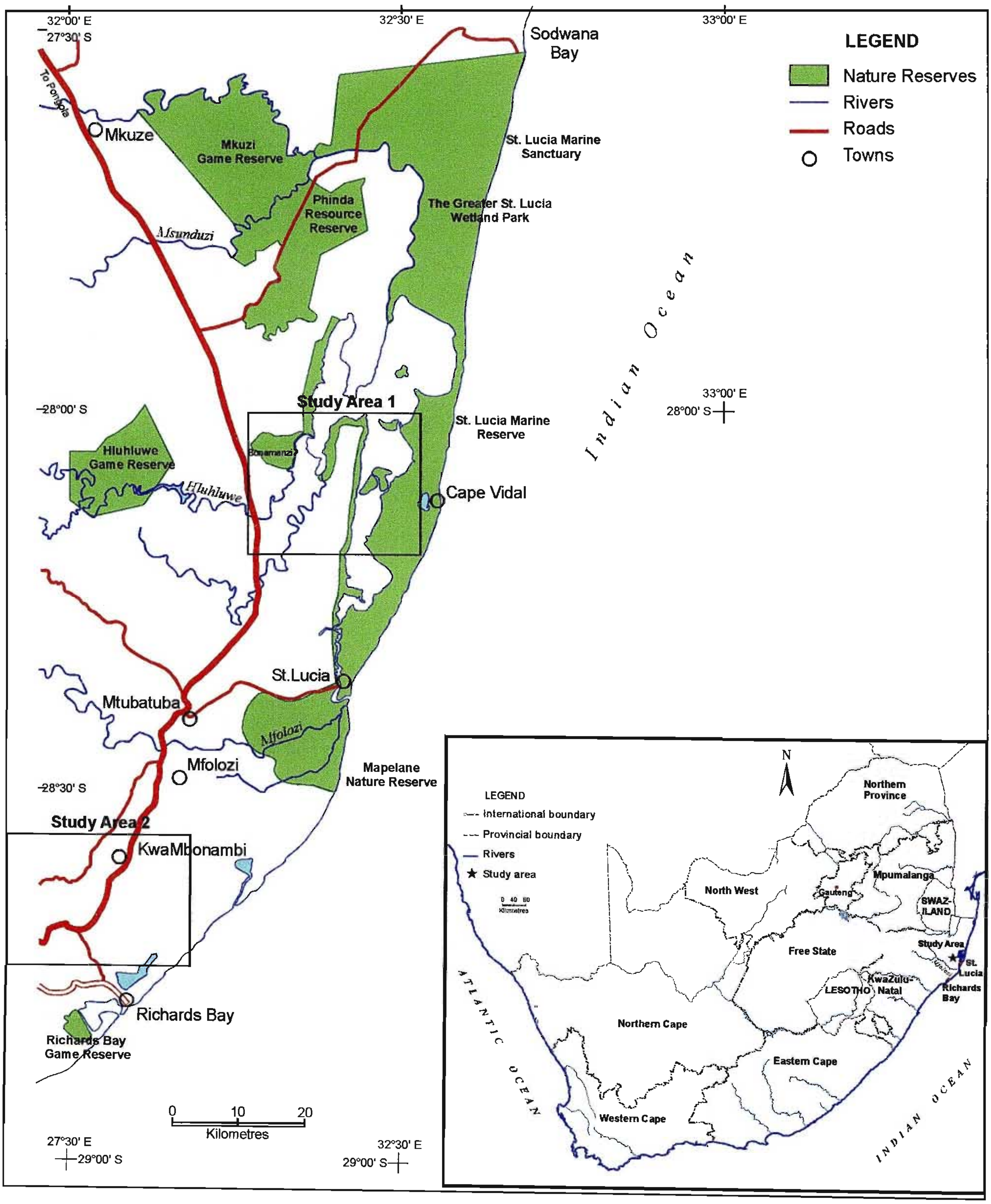

Figure 3.1: Study Areas

Within each age class, two sites of differing site quality were chosen. Tables 3.1 and 3.2 present all the considerations and description of the sites selected, with Table 1 representing the evaluation performed on each site and Table 2 showing the description of each site.

Table 3.1: Sites Evaluation

Planted Clones	Because it is currently the most widespread hybrid across the age ranges required, the species chosen was *Eucalyptus grandis-x-camaldulensis.* This was checked according to Mondi records, and visually according to obvious characteristics such as bark appearance and leaf shape.
Site Index (SI)	Site index is a measure of site quality. It is defined as the collective characteristics of a site that influences plant growth. It is therefore a function of temperature, radiation, moisture and nutrients as well as species (Mcleod and Running, 1987). Site Index is usually calculated using different methods. The Mondi SI function has been used for the study areas.
Understorey vegetation	This ranged from none to a reasonably thick covering of grass with occasional shrubs (*Lantana camara, Chromelina species* and indigenous species for the most part). No sites were found to be inaccessible because of thick understorey vegetation; most sites had little or none.
Brokenness" of compartment	A minimum area of 4 ha was required, with no gaps in the canopy. If the compartment was split by a major road, or had a loading zone in the middle rendering it smaller than 4 ha of unbroken canopy it was deemed unsuitable. In some cases, the compartments were 4 ha or greater in size, but were particularly narrow (in some cases narrower than 75 m).
Accessibility	This was considered in terms of the ability of the group's 4X2 Colt pick-up to reach the site on existing forest roads. Fortunately, in most cases the sites were easy or very easy to reach, or near main roads.
Tree condition	Signs of disease or stress of any sort would make a site unsuitable. No sites exhibited such signs.
Slope	It was desired that only sites with slopes of less than 7% be used in the study. All slopes were found to be less than 7%.
Tree spacing	Actual tree spacing in the field was considered to ensure that no sites with extremely high or extremely low spacing were included in the data set. Every site had spacing of 3 X 2.5 m (roughly 1333 stems per hectare).

Table 3.2 (a). Sites description (Hluhluwe)

Description	Hluhluwe					
Compartment /Sites	A05C	F05	B04	A05A	A04C	A10B
Site Index	17.1	18.3	18.0	20.5	19.0	21.1
Age (years)	7.0	7.0	5.0	5.0	3.0	2.5
Average DBH (cm)	13.6	12.6	12.8	14.7	10.1	10.0
Average height (m)	19.3	17.3	16.8	19.0	11.8	11.8
Stocking (stems ha^{-1})	1357	1456	1352	1455	1392	1615
Latitude	28^{0}06'37''	28^{0}07'19''	28^{0}07'05''	28^{0}06'39''	28^{0}10'9''	28^{0}15'10''
Longitude	32^{0}01'46''	32^{0}40'30''	32^{0}150'06''	32^{0}45'22''	32^{0}50'25''	32^{0}20'55''

Table 3.2 (b). Sites description (Kwambonambi)

Description	Kwambonambi					
Compartment /Sites	NP20B	NH01	RG20B	NK25	NP23	NA24B
Site Index	21.9	23.7	21.1	26.7	21.3	23.8
Age (years)	7.0	7.0	6.0	5.0	3.0	3.0
Average DBH (cm)	18.2	16.2	15.8	15.5	11.8	11.4
Average height (m)	23.0	23.1	21.8	23.3	14.0	15.6
Stocking (stems ha^{-1})	1325	1456	1312	1313	1456	1545
Latitude	28^{0}21'04''	28^{0}34'22''	28^{0}26'15''	28^{0}36'22''	28^{0}42'09''	28^{0}28'12''
Longitude	32^{0}00'54''	32^{0}56'12''	32^{0}48'13''	32^{0}45'39''	32^{0}45'46''	32^{0}15'36''

KwaMbonambi is geographically located along the east coast of Northern KwaZulu-Natal, South Africa. It falls between 28^{0}06`39`` and 28$^{0}$40`26``S and 32^{0}18`00`` and 32$^{0}$00`36`` E. Hluhluwe is located on the east coast of Northern KwaZulu-Natal, South Africa. It is on the west of Lake St Lucia. It falls between 28^{0}06`39`` and 28$^{0}$40`04`` S and 32^{0}18`00`` and 32$^{0}$00`36`` E.

3.1.3 Physical Environment

i) Meteorological Data

Meteorological data was averaged over each of the 30 x 30 meter cells encompassing each study area. The study areas are located in a sub-tropical climate with warm, moist summers and mild, dry winters. Table 3.3 shows annual minimum, mean and maximum temperature pattern in the two study areas. According to Kelbe and Rawlins (1992) the summer rainfall of these regions is usually greater that the winter rainfall, although on average there is a uniform distribution of rainfall throughout the year. On average there is 61 % of rainfall in summer and 23 % in winter. These regions are however, prone to fluctuations in rainfall from season to season and from year to year. Table 3.3 shows the rainfall pattern in the two study areas. The water table in the study areas is relatively very high (CCWR, 1999).

Table 3.3: Meteorological data for both study areas

Parameters	Study area 1	Study area 2
Min Temperature (^{o}C)	14.47 - 16.69	14.47 - 16.69
Mean Temperature (^{o}C)	19.99 - 22.64	19.99 - 22.64
Max Temperature (^{o}C)	24.90 - 27.90	24.90 - 27.90
Rainfall (mm)	801.00 - 1000.00	1001.00 - 1200.00

ii) Geology, Landforms and Soils

An estimate of the maximum available soil water storage capacity was essential to note in the sites. This was dependant on the water holding characteristics of the soil and the rooting depth of the trees. The soil was noted to be sand, and sand is generally characterized as well-drained soils. The soils are generally of poor nutrient status, which suggest that there was the use of fertilizers in the *Eucalyptus grandis x camaldulensis* stands. The general soil description is red and yellow massive or weak structured soils with low to medium base status. Several underlying geological formation form both Hluhluwe and KwaMbonambi regions. The dominant geology under all of the study areas is sandstone, shale, rhyolite and basalt (CCWR, 1999).

3.2 Data Collection and Processing

3.2.1 Field Point Location

The field sites were located in the North coast in the Zululand region. The x and y coordinates of all sites were determined using a GPS (Magellan). The GPS points were then located on a South African 1:50 000 map (topographic map) and were then entered into an Arc/Info and used to generate point coverage. Information pertaining to each point (i.e. LAI, mean DBH and mean tree height) was attached to the relevant points. Maps of the study sites were then produced using Arc View. Other attributes to the maps were taken form the meta-data provided by the CSIR.

3.2.2 Ground Survey

The field data was collected within six days i.e. collection of the information about leaf area index (destructive sampling and using LiCor-2000), understorey biomass, plantation tree height, tree species, soil moisture levels and tree diameter at breast height. The ground survey of 12 forest stands was carried out from 16 - 21 September 2000. Every effort was made to select study plots across the study area at random, but in practice survey locations were influenced by accessibility and planting regimes (i.e. certain ages of plantations could only be found in certain areas). Stand age was determined from Mondi forest maps.

i) Destructive Sampling

Destructive sampling was carried out so as to obtain true LAI values for individual sites. In each site three trees were felled to determine their true mass and height. Each tree was weighed (i.e. the weight of leaves, dry and wet branches and stem). A 25 kg spring balance was used to weigh the stems and branches, and a 5 kg spring balance was used to weigh the leaves. The weigh of the roots was determined using the standard method as described by the CSIR (2000).

Diameters at breast height (DBH) and height of a 25 x 25 meters plot of trees were taken using DBH measuring tape and a vertex measuring tape respectively. The results thereof, were then to be used to determine mean DBH and height of the trees for each site.

Sub-samples of leaves, dry and wet branches, and stems were taken. A step-by-step destructive procedure (Biomass determination) is presented in appendix 1. All sub-samples were re-weighted in the laboratory using a laboratory scale to correct for both spring balances and dried to constant mass at 75 degrees Celsius, with the exception of leaves. Leaf sub-samples were used to get the leaf area using a LiCor leaf area meter, they were then dried to constant mass in an oven at 75 degrees Celsius then, the specific leaf area (SLA) was determined. This was used to determine the leaf area of the entire site canopy and LAI of the entire stand. The dried samples of all sub-samples were used to scale up the measurement to the whole tree and to the stand; this gave an estimate of the total biomass of the tree. In addition, the presence or absence of Molinia/Calluna vegetation on the forest floor (hereafter termed understorey vegetation) was determined visually as a surrogate variable for canopy closure.

ii) Scaling up

Leaf area and the diameter at breast height (1.3m; DBH) have a direct relationship (the increase in leaf area leads to an increase in DBH), this relationship has been used in other studies e.g. Battaglia *et. al*, (1998). This relationship was found to be the same for all study sites. Appendix 3 and 4 shows the entire plot DBH and leaf area measured in the field and which were used.

To determine the scaling up process the area of the entire plot was determined firstly, then the leaf area of individual trees was determined and the sum of all the leaf areas within a plot was determined (Appendix 3). There were on average 80 trees per 30 m x 30 m plot and from the stoking density table 3.2 (b) there should be 80 trees per plot therefore, only this number of trees is shown in appendices and was used for analysis of results. Because the area meter used was calibrated in 0.1 mm^2 all readings had to be divided by 10 to get the correct value. Therefore, to calculate the LAI the plot leaf area was divided by the plot size (with m^2 converted to mm^2). In this case the LAI of the plot was used as a representative of the whole site e.g. NP23 with LAI of 2.85. Taking into cognizance that each stratum within the forest compartment has a different spectral reflectance and each one represents an area of different LAI. The difference in LAI within the compartment was found to be within the region of 0.1 to 1.0. i.e. the difference between pixels.

iii) LAI Estimation using LiCor-2000

In this study the LiCor-2000 plant canopy analyzer was used as it has been shown to provide reasonable estimates of LAI in other studies (Welles, 1990 and Battaglia *et al,* 1998). The LiCor-2000 instrument measures the estimate of LAI using measures of canopy photosynthetically active radiation (PAR, 400-700nm) for input to equations which derive the LAI as a function of PAR detected below the forest canopy; measurements obtained in nearby clearings served as above canopy measurements of PAR. The LiCor-2000 is made of 80 individual light sensors placed at 1cm spacing along a probe, which was held horizontal at a height of 1.3m by a field operator.

The instrument probe was programmed to take a series of 8 consecutive measurements scans per second. The instrument then averages the 8 readings to give one final reading. The readings were taken with the instrument pointing in the direction away from the sun. All the measurements were taken in early morning (7 - 8 am) under a cloudy sky. A 45-degree Celsius mask was used for all readings. Calibrating readings were taken at the open cloudy sky close to each forest stand, before and after the measurement readings. Within each of the study plots measurements of below canopy PAR were taken over an approximately 30m x 30m plot, with one plot per site. Eight measurements were randomly taken within the measured plot. This sampling strategy provides a good spatial coverage of the study site (Pierce and Running, 1988).

LiCor-2000 have been used by Barclay *et al,* (2000) in assessing bias from boles in calculation of leaf area index in mature Douglas fir. Measurements using a LiCor-2000 portable leaf canopy analyzer were taken in twelve plots representing the four extreme treatments at Zululand namely the three low rainfall low site index, high rainfall low site index, Low rainfall high site index and high rainfall high site index.

To maximize the efficiency of the LiCor-2000 the LAI readings acquired in each region were taken under uniformly cloudy sky to minimize the error on readings. Therefore, in all site measurements in each region were taken within an hour and these were in the early morning hours (7:00-8:00am). The taking of the readings at early morning hours minimized the effect of changing solar zenith angle on PAR measurements.

3.2.3 Remotely Sensed Data

Landsat 7 imagery for this study were acquired from Satellite Application Center (SAC). The data was recorded on the 17 September 2000 between 13:00 and 13:00 hours GMT at a flying height of 1000000 m above ground level across a swath width of 1000000 m and with a normal 10000 m ground resolution. The 17 September 2000 was the closest day of the satellite pass and the week of field data collection. The other passes before or after the field data collection weeks were covered by clouds, thus potentially introducing an error to the data. A total of 100 flight lines provided full coverage of the study area. The flight lines were in a North-South direction as close as possible to midday to minimize the effect of canopy shadow; this has been done also by Spanner *et al*, (1990) and Lucas *et al,* (2000).

The data (imagery) was geometrically, radiometrically and atmospherically corrected. The images were co-registered with a digital terrain model by SAC. The orbit of the Landsat 7 satellite allows a 16-day orbital overpass to produce full earth coverage.

i) Landsat 7 Bands

The Landsat 7 bands used in this project were: Red, Near-Infrared and Mid-Infrared bands. These bands are the most useful for vegetation discrimination and VI calculations. In the ERDAS Imagine Software, these bands are allocated to numerical bands and the colors red, green and blue assigned to it. Normally, the red band is represented by number 1 (red), NIR by 2 (green) and MIR by 3 (blue). This combination shows the greatest difference among plantation species, different ages and different levels of stress. The software allows the choice of which colors represent the different bands.

ii) Image Interpretation

The remotely sensed imagery was interpreted through an image enhancement, unsupervised, semi-supervised and supervised classification techniques in the ERDAS-Imagine (Image processing package). This step produced areas under afforestation for the effective VI determination. The imagery was further manipulated through different vegetation indices, to produce a spatial map depicting LAI values throughout the study sites. Four vegetation indices were used and these were, NDVI, NDVIc, RVI and NRVI. Two methods were followed for this; firstly an existing model from the examples in ERDAS using Explorer was used (this was used to run the NDVI). Secondly, to create the new model (this was used for the other three VI's). To make or view a model a modeler was used in ERDAS dropdown menus. To create a new model, model maker was used.

iv) LAI Estimation

The graphic model creator allows the user to place images, functions, tables, links etc. on the Model Maker page using the Tool Palette. To produce an image of meaningful LAI values, the NDVIc vs. LiCor portable leaf canopy analyzer regression equation was entered into MODEL MAKER in ERDAS Imagine using the NDVIc image as an input into the model.

This image was then converted to a GRID in Arc Info and then displayed in Arc View by classifying the LAI values into predetermined classes. Values below 2 and greater than 5 were excluded as these are beyond the range of the data from the test sites.

Landsat 7 is one of the satellites that can be used to estimate LAI. Landsat 7 offers information in the visible and infrared regions of the spectral spectrum (Schrader and Pouncey, 1997). Vegetation indices have been developed to utilize different bands of remotely sensed imagery; this can work in both satellite and airborne sensors. These indices estimate vegetation parameters, one of which is LAI (Baret and Guyot, 1991). Using ERDAS package though four VI performed this estimation. This was performed through the textural analysis of the imagery that added valuable information to LAI estimate. Texture is the measure of the spatial distribution of variations in grey tone.

The bands that were used for this estimation were green, blue and red; these also make up the visible spectrum of remotely sensed imagery. According to Megown *et al* (1999) the radiation absorption is stronger in the red and blue bands than in the green band. Atmospheric effects are greater in blue than in the red (Fassnacht *et al*, 1997). The red band also has a wider dynamic range over green and NIR bands and is therefore better to use in texture analysis (Orthof and King, 1997). Vegetation indices are mainly based on the red and NIR bands. The MIR may be added to reduce errors caused by understorey and soil types (Nemani *et al*, 1993).

The four Vegetation Indices chosen for determination of LAI, were NDVI, NDVIc, RVI and NRVI. These vegetation indices were produced through the use of ERDAS Imagine modeler in model maker. ERDAS Imagine provides an option for choosing one of the models built into the package or building a new model. The NDVI model was chosen from the ERDAS Imagine and is shown in Figure 3.2. The models for the other vegetation indices were created in the modeler. Figure 3.3 provides a flow diagram that summarizes the methods used in this study.

3.2.4 Statistical analyses

To establish the relationship between LAI values estimated from destructive sampling, LiCor-2000 and from vegetation indices, correlation and regression analysis were undertaken as described by Earickson and Harlin, (1994).

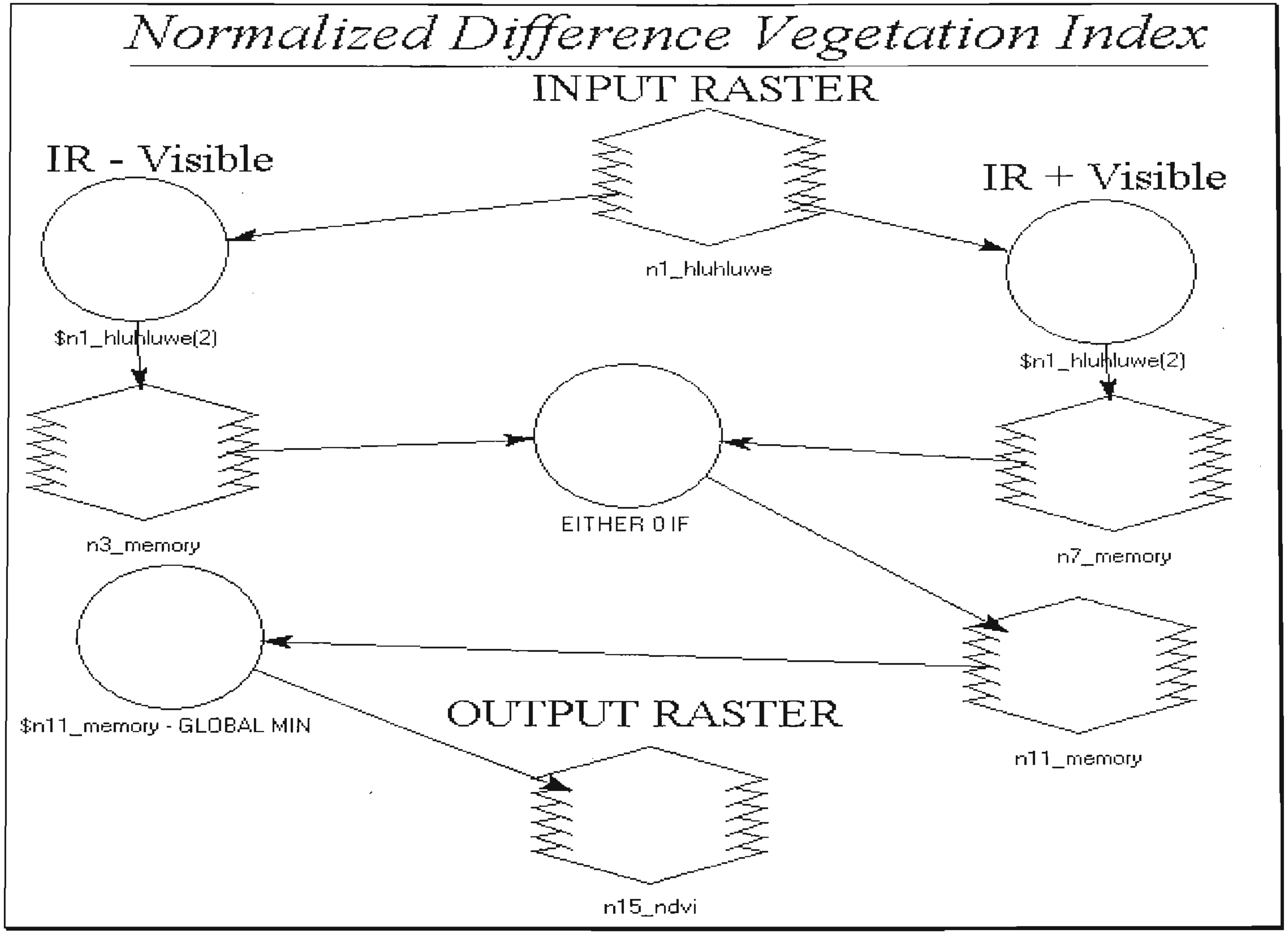

Figure 3.2: NDVI Model used to produce NDVI Image

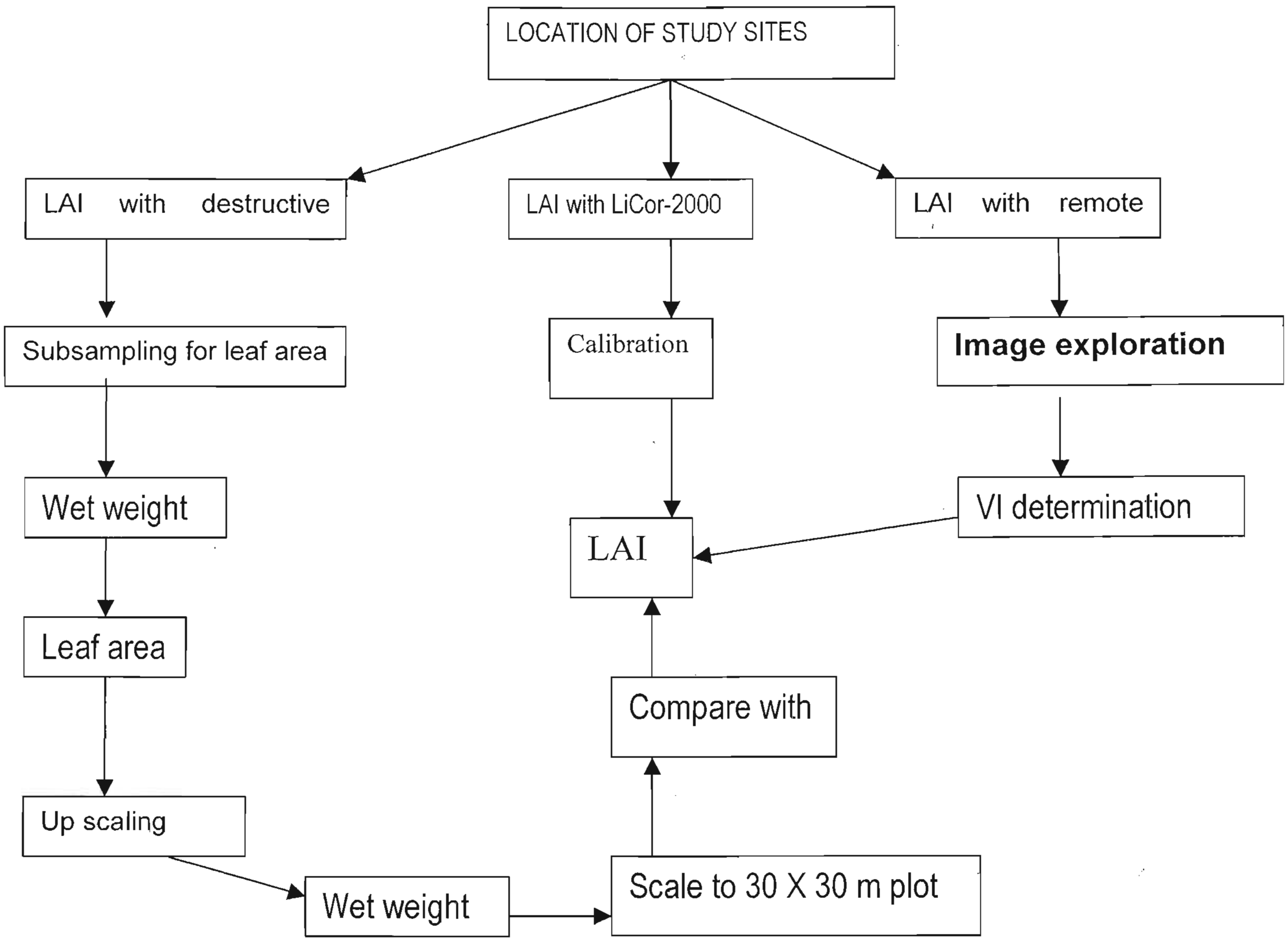

Figure 3.3: Diagrammatical representation of methodology for determining LAI.

Chapter 4

Results and Discussion

4.1 Estimation of LAI by LiCor-2000

The LAI values found in the study sites detected using LiCor-2000 showed some variation (Table 4.1), with very low standard errors (SEL).

Table 4.1: LAI values using LiCor-2000

SITES	AGE GROUP (YEARS)	LAI AVERAGE	STD ERROR OF LAI (SEL)	MEAN TIP ANGLE (MTA)	STD ERROR OF MTA (SEM)	NUMBER SAMPLE PAIRS USED (SMP)
SITE (HLUHLUWE)						
A05C	7.0	2.95	0.03	55	4	8
F05	6.0	3.12	0.02	64	2	8
B04	5.0	1.85	0.02	63	2	8
A05A	2.5	1.68	0.02	63	5	8
A04C	3.0	1.68	0.04	50	4	8
A10B	5.0	2.35	0.07	58	6	8
(KWAMBONAMBI)						
NP20B	7.0	2.78	0.06	59	4	8
NH01	7.0	2.42	0.06	59	2	8
RG20B	6.0	1.98	0.04	62	5	8
NK25	5.0	1.88	0.02	56	2	8
NP23	3.0	2.85	0.03	63	10	8
NA24B	3.0	1.99	0.03	62	3	8

In both KwaMbonambi and Hluhluwe, the stands that were of the same age did not share similar LAI readings, suggesting variation in canopy structures within each site, plot and study area. Relatively the older stands had tree crowns height and diameter smaller than the mid age (3-6 years). According to Battaglia *et. al,* (1998) *Eucalyptus* plantations LAI increase as stands develop and then tend to stabilize or decline slowly, effectively achieving a steady state or equilibrium. Table 4.1 indicates the LAI measurements were not far out of the range from 1.5 to 3.5, as the SEL is having a difference of 0.05. The SEL is largely affected by the tip angle with a high tip angle giving a lower SEL of LAI measurement. This observation was mainly on stand characteristics than on technique used to derive LAI. The MTA had little or no effect on the readings as all of the MTA readings are above 50%, suggesting certain accuracy in the procedure that is taking LAI.

4.2 LAI Measurement by Destructive Sampling

LAI values measured by means of destructive sampling were obtained to give true values that can be used to correct for the readings provided by LiCor-2000 and those based on Vegetation Indices. This was done through a process of calculation firstly of specific leaf area (SLA), by using the following equation:

$$\text{Leaf area / Leaf dry matter = Specific Leaf Area (mm}^2\text{/g)} \qquad (4.1)$$

Leaf area was determined from a LiCor-2000 leaf area meter. SLA was calculated for comparative study with LAI, from which there was no clear direct relationship observed. **Appendix 1 and 2** show the numerical values obtained per tree sampled and tree leaf area, scaling up from a sub-sample using an arithmetic equation as both sub-sample wet weight and tree wet weight were measured in the field and sub-sample area was measured in the laboratory using an area meter.

$$\text{(Tree wet leaf area (mm}^2\text{) x Sub-sample leaf area (mm}^2\text{)) / Wet Sub-sample leaf area (mm}^2\text{)}$$
$$\text{= Leaf Area (mm}^2\text{).} \qquad (4.2)$$

Scaling up from sub-sample leaves to the entire plot was made easer-using DBH (Figure 4.1) and leaf area. DBH and leaf area of three trees in each plot was used to determine its compartment LAI. A sub-sample of felled trees had been used to establish the relationship between leaf area and DBH. The equation produced is $Y=5.17X^{4.19}$, Y and X being the leaf area and DBH respectively and the relevant R^2 is 0.99. The leaf area of a tree was obtained substituting the *x* (DBH of the trees within an approximately 30m x 30m plot) in the equation. To scale up to the plot the averaged results of three trees were multiplied by the plot size. To get the compartment size the plot results were multiplied by the compartment size.

4.3 Remotely Sensed LAI

The images where the VI were derived from were enhanced through piecewise contrast enhancement method for increasing contrast between different vegetation types. The image enhancements applied to the images increased the difference between the vegetation classes that is forestry boundaries were more visible and different vegetation types could be easily identified.

One of the important factors that have to be taken into consideration is the forest understorey vegetation. It can easily be classified as part of the forest signature. In this study care was taken that firstly the sites were not over grown with understorey vegetation. The main understorey species present in these sites were Chromolaena and several different grass species. The sites used were middle age (2.5-3 years) to old (6-7 years as most forest get harvested at 7 years old in the Zululand area) thus, understorey vegetation was not such a problem.

According to Puhr and Donoghue (2000) the understorey vegetation cannot survive beneath fully closed conifer canopies mainly due to insufficient light availability, and that as a result, this type of vegetation should be completely absent under fully closed forest canopies. This seemed to be the case in some stands, which had full closed canopy, but not all stands had full closed canopy. This was apparent and can be seen from Table 4.2 showing the percentage of understorey vegetation.

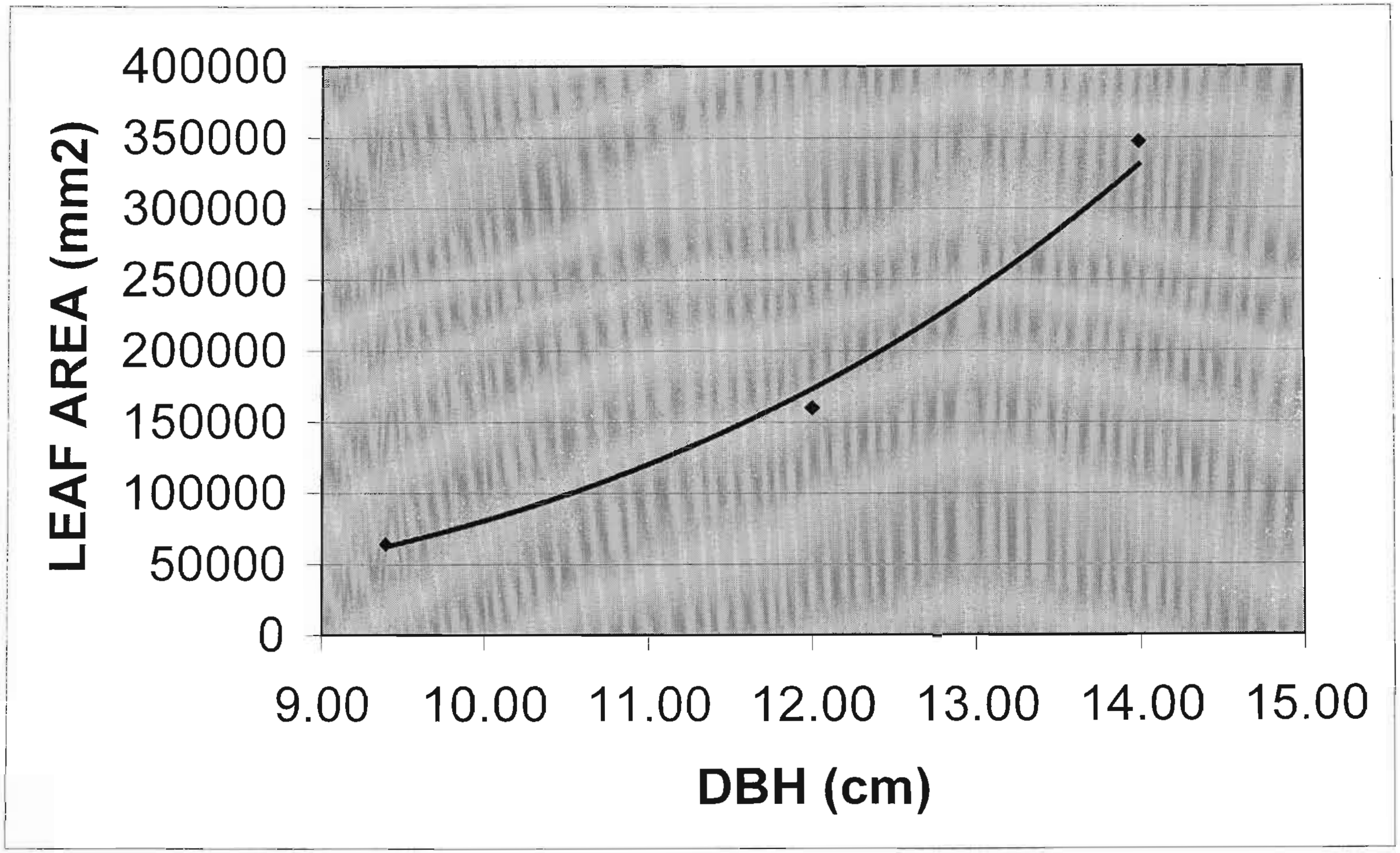

Figure 4.1: Leaf area and DBH to quantify the compartment leaf area

Table 4.2: Understorey vegetation percentages in the study sites

Study areas	Site	Percentage groundcover estimate
Hluhluwe	A10B	0-10% Chromolaena and grass species
	A04C	0-10% Chromolaena and grass species
	B04	0-10% Chromolaena and grass species
	A05A	0-10% Chromolaena and grass species
	F05	None
	A05C	60-70% grass species and 0-10% Chromolaena species
KwaMbonambi	NP20B	None
	NK25	70-80% grass species and 0-10% Chromolaena species
	RG20B	10-20% thick hedges of Chromolaena species and <10% grass species
	NH01	0-10% Chromolaena species and 50-60% grass species
	NA24B	0-10% grass species
	NP23	0-10% grass species

4.4 Correlations

Using the remotely sensed imagery and the field estimates of LAI (using LiCor-2000 and destructive sampling), two approaches to predicting LAI were tested and compared.

- That is whether the use of remote sensing imagery is the accurate predictor of LAI or LiCor-2000 and
- To investigate the various vegetation indices that can be derived from Landsat Satellite Imagery and determine the best one for use in the forestry plantations in South Africa.

Remotely sensed LAI estimates are typically simple statistical relationships between LAI and VI derived from remote sensing data (Gong *et al,* 1995). To study the relationship between Vegetation Indices and LAI (determined from destructive sampling and LiCor-2000) the values were entered into a spreadsheet in Microsoft Excel as shown in Table 4.4 above. This allowed the data to be interpreted through correlation matrix and regression analysis.

It is clear from Table 4.3 that the LiCor-2000 under estimate LAI compared with destructive sampling method. This was also observed by Megown *et al.* (1999) on a similar study in Mpumalanga using *Eucalyptus* species. The direct relationship between LAI and age was also observed with the LAI decreasing with increase in age suggesting a decline in leaf area as the tree get older confirming the observation by Battaglia *et. al*, (1998).

The LAI values from LiCor-2000 and Destructive Sampling method was correlated with the Vegetation Indices values, Table 4.4 (a and b) based on the VI and LAI values provided in Table 4.3 (a and b).

Table 4.3: LAI values determined from Vegetation Indices, LiCor-2000 and Destructive Sampling

Study area	SITE	Age (years)	NDVI	NDVIc	NRVI	RVI	Destructive Sampling	LAI-2000
Hluhluwe	A05C	7	187	137	219	7	2.45	2.95
	F05	6	121	159	219	8	2.9	3.12
	B04	5	199	138	224	7	1.08	1.85
	A05A	5	216	169	227	7	1.64	2.35
	A04C	3	213	153	224	7	1.11	1.68
	A10B	2.5	220	176	232	10	1.2	1.68
KwaMbonambi	NP20B	7	170	148	230	5	2.63	2.78
	NH01	7	187	145	227	8	2.24	2.42
	RG20B	6	171	126	219	7	1.81	1.98
	NK25	5	202	164	232	10	1.58	1.88
	NP23	3	111	152	213	10	2.52	2.85
	NA24B	3	203	152	227	8	1.82	1.99

Correlation analysis was performed between the leaf area indices and the vegetation indices to investigate the direction and the strength of the relationship between these two variables. The analysis was conducted for the leaf area indices that were obtained using both LirCor-2000 and destructive sampling. The results of this analysis are shown in table 4.4, and they suggest that there exist a negative relationship between leaf area and vegetation indices.

The NDVI's correlation coefficient for the LiCor-2000 was found to be -0.745 ($p < 0.05$), whereas that for the destructive sampling was found to be -0.783 ($p < 0.05$). Both these coefficients are closer to unity suggesting a strong relationship between the analysed variables. In the results for the destructive sampling procedure RVI had the lowest correlation coefficient, and in the LiCor-2000 results NDVIc had the lowest coefficient.

Table 4.4: Correlation coefficients (r) of LAI values (VI's, LiCor-2000 and Destructive Sampling) for Both Study Sites (n=12)

	NDVI	*NDVIC*	*NRVI*	*RVI*	*Destructive Sampling*	*LiCor-2000*
NDVI	1					
NDVIC	0.24	1				
NRVI	0.73	0.504	1			
RVI	-0.107	0.504	-0.002	1		
Destructive Sampling	-0.783	-0.189	-0.442	-0147	1	
LiCor-2000	-0.745	-0.146	-0.520	-0.199	0.942	1

4.5 Regression analysis

Linear regression analysis ($p < 0.05$) was performed for both LiCor-2000 and destructive sampling using the leaf area indices as dependent variables and vegetation indices as the independent variable. This analysis was performed to investigate the nature of the relationships that exist between the leaf area indices and the vegetation indices. The results of this analysis are presented in tables 4.5 and 4.6. These results show that for both LirCor-2000 and destructive sampling results, the values of the leaf area indices will decline when those for the vegetation indices increase. The coefficients of determination (R^2) for NDVI were the largest for both samples at 55% and 61%, respectively. These values are interpreted as meaning that 55% of the variation in the leaf area indices can be explained by NDVI for LiCor-2000, whereas 61% of the variation in the leaf area indices can be explained by NDVI for destructive sampling. In LiCor-2000 NDVIc had the lowest R^2 value, suggesting that the predictive power of this equation is very poor. The destructive sampling results however, show that it was RVI that had the least predictive power. All the estimated equations were significant at 5% confidence limit.

Table 4.5: Linear Regressions of VI's with LAI (LiCor-2000) for Both Study Sites

Variable (VI)	Constant	Coefficient	Significance	R^2	Sample Size (n)
NDVI	4.308	-0.011	0.005*	0.55	12
NDVIc	3.105	-0.00535	0.651*	0.021	12
NRVI	12.573	-0.0458	0.083*	0.27	12
RVI	2.826	-0.0679	0.536*	0.040	12

Note: * indicates significance at 5% confidence level

Table 4.6: Linear Equation with R^2 of VI's with LAI (Destructive Sampling) for Both Study Sites

Variable (VI)	Constant	Coefficient	Significance	R^2	Sample Size (n)
NDVI	4.45	-0.0139	0.003*	0.61	12
NDVIc	3.179	-0.00834	0.556*	0.039	12
NRVI	12.395	-0.0467	0.151*	0.195	12
RVI	2.388	-0.0604	0.647*	0.022	12

Note: * indicates significance at 5% confidence level

Both correlation and regression make identical assumptions that relationships are linear. Furthermore, correlation coefficients (r) and coefficients of determination (R^2) are used to indicate how well the regression line fits the data. The results presented in tables 4.4 to 4.6 agree with the above statements, because when the correlation coefficient is high (i.e. close to unity) the coefficient of determination is also higher than 50%. As an example, in table 4.4 the correlation coefficient (r) for NDVI and Licor-2000 is –0.745, whereas in table 4.5 the coefficient of determination (R^2) for the same variable is 0.55.

Moreover, the signs for the correlation coefficients and the regression coefficients (presented as the linear equation variables in the tables above) correspond. Figure 4.2 (a and b) shows the linear regression of VI's with LAI from LiCor-2000 and destructive sampling in both Study Areas

Both the LiCor-2000 and destructive sampling techniques gave comparable results, for example in both, the leaf area indices decreased with increasing NDVI. Other studies suggest a linear relationship between LAI and NDVI, however these studies have found a positive linear relationship (Carlson and Ripley, 1997; Nemani et.al., 1993; and Baret and Guyot, 1991). The results of the regression relationships between LAI (destructive sampling) and LAI from satellite data could be used by forest managers with caution, as the study used a relatively small sample size.

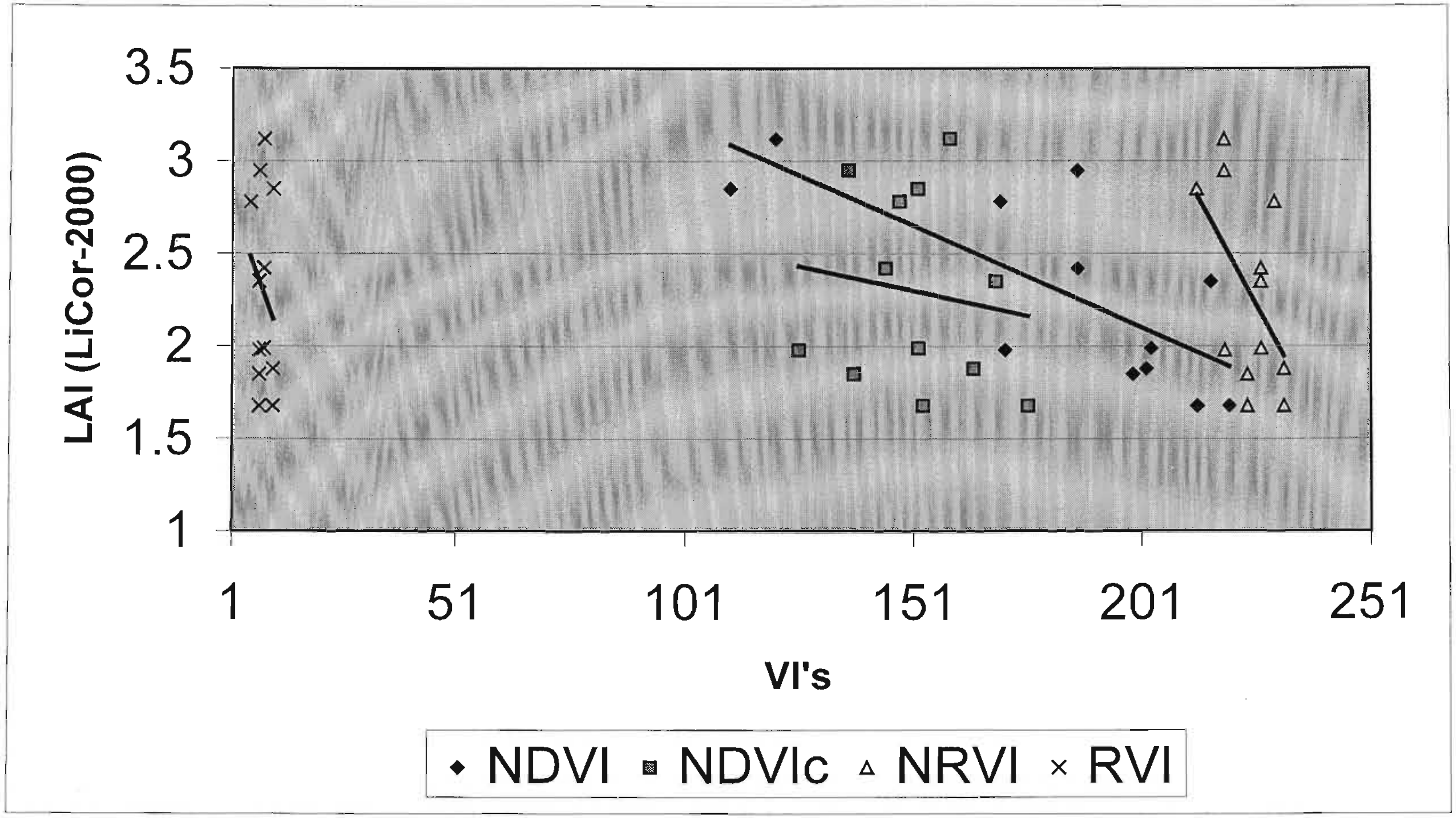

Figure 4.2 a): Linear regression of VI's with LAI from LiCor-2000 in both Study Areas

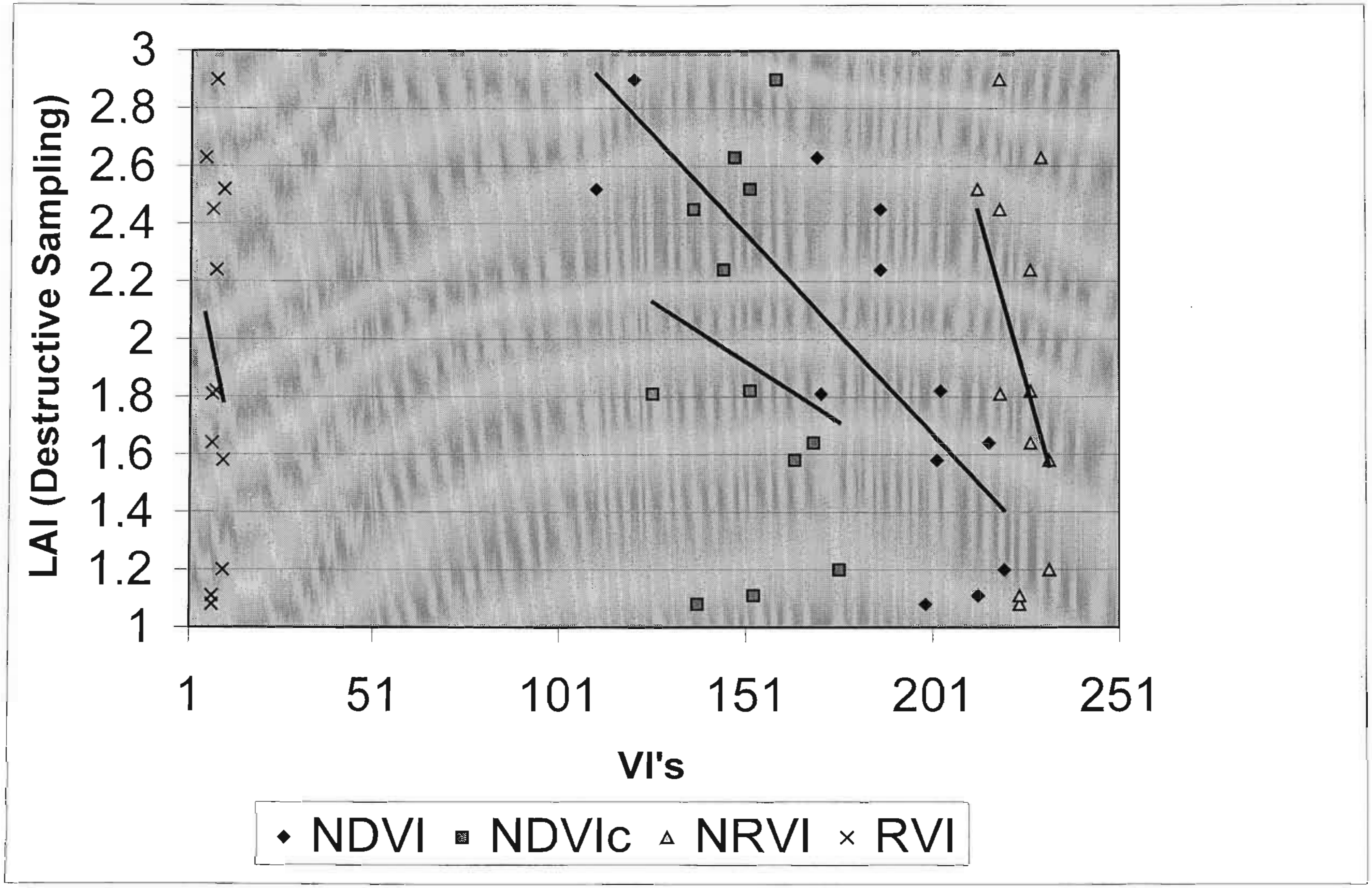

Figure 4.2 b): Linear regression of VI's with LAI from Destructive Sampling in both Study Areas

The application with early LANDSAT MSS images found that NDVI had significant correlation with the amount of green leaf biomass (Tucker 1979). The use of NDVI technique has extended to many other remotely sensed data.

An important applicational development is the use of NDVI derived from NOAA AVHRR to map vegetation distribution and explore the temporal variation of vegetation for large regions ((Gutman *et al,* 1994 and Eidenshink and Faudeen, 1994) and at global scale (Townshend, 1991). Townshed and Justice (1986) also noted NDVI derived from SPOT data was suitable for monitoring vegetation dynamics. Lyon *et al,* (1998) found that NDVI could provide better change detection results compared with other vegetation indices using LANDSAT MSS images. Applying NDVI to a study of quality of life in a country of Georgia, USA. Um and Wright (2000) demonstrated that NDVI as a biophysical variable not only correlated to the percentage of urban land use but also provided the linkage to socioeconomic data.

Since NDVI have a number of reported successes (whether through Landsat TM or NOAA or SPOT) and in this study it also out weighted other VI thus, was employed for the evaluation of LAI in KwaZulu-Natal.

The NDVI where respectively NIR and RED are spectral radiance measurements in the near-infrared and red spectral ranges is related to the amount of active photosynthetic biomass present on the ground. Reed and Waring (1994) described a detailed list of NDVI metrics and their phonological significance. Attributes of plant canopies such as: permanence of aboveground live biomass, leaf longevity and leaf type are related to NDVI (Running, 1994; Nemani and Running 1989; Loveland and Belward 1997).

NDVI derived products have provided an essential tool for characterizing and mapping land cover properties on regional and continental scale. Many examples can be found in literature (Goward *et al,* 1985; Tucker *et al,* 1985; Townshend, 1980; Houghton *et al,* 1980).

Due to variable light interaction within forest stands and spatial variability in forest canopies different LAI estimates can be obtained within the same stand. Although, LiCor-2000 was highly correlated with Destructive Sampling with 98% in both regions, it is affected by a number of environmental conditions e.g. sparse clouds. LiCor-2000 is limited by environmental conditions, which has to be kept at minimal effect to the results. Although, the environmental settings of both study areas were different LAI of different *Eucalyptus grandis x comedulensis* stands were derived and through the use of various vegetation indices LAI estimates were determined from remotely sensed imagery of Landsat 7 and the better VI was determined. Through the correlation matrices the relationship was determined between the remotely sensed based LAI measurements and LAI estimates from the LiCor-2000 (optical instrument) and from destructive sampling.

Chapter 5

Conclusion and Recommendations

The premise of this study is that efforts towards an ecosystem based approach to resource management, may be aided by the increasing availability of image processing software on the 'desktop' that can be easily integrated with geographic information systems (GIS). As Leckie *et al.* (1995) have pointed out: 'Use of digital high-resolution (less than 1m) multispectral imagery as an alternate to aerial photography for forest inventory mapping is a possible revolutionary innovation'. Previous studies in Canadian forests (Smith, 1993 and Franklin *et al*, 1991) and elsewhere (e.g., Baulies and Pons, 1995), have indicated that digital image processing methods applied to airborne images can aid in forest inventory, but that much effort is required before these procedures can replace or even replicate existing inventories for a wide variety of reasons e.g. costing of such an exercise. In the long term, it is also now apparent that more widespread use of digital remote sensing may occur simply because new applications, such as an assessment of stand productivity, can be accomplished.

Leaf Area Index (LAI) is an important structural attribute of ecosystems and forest stands that is related to productivity thus, there is a need for easier reliable means of estimating LAI other than time consuming Destructive Sampling or LiCor-2000 and a need to get the spatial view of forestry therefore, remotely sensed data is important for this purpose. Although, remotely sensed data is useful in estimating LAI as observed in this study it also has shortfalls when the forest stands have high understorey vegetation, which might be classified as part of the forest signatures. Remotely sensed data is timely, easily available and gives reliable information, for LAI estimation. The use of such technology can result in greater opportunities to develop new remote sensing applications.

Structurally, the forest stands surveyed in this study broadly represent the entire spectrum of *Eucalyptus* stands at KwaMbonambi and Hluhluwe regions. Three methods of estimating LAI were used the LiCor-2000, Destructive Sampling and Remotely Sensed Imagery. The ability of all three to predict LAI was assessed according to the magnitude of the linear regression coefficient of determination (r^2).

The correlation between LAI estimates obtained through destructive sampling, LiCor-2000 and satellite data was variable but that between satellite data and determined destructively was good. The NDVI was correlated significantly with LAI that was obtained through destructive sampling with a correlation coefficient of –0.783. This means that an increase in NDVI results in an increase in the estimated LAI. Scatter plots suggested that the relation between NDVI and Destructive Sampling was variable, this was confirmed by R^2 values, and the relationship was almost linear. The use of conventional least squares linear regression analysis was thus suitable. The conclusion that can be drawn from these and other studies is that forest managers can use remotely sensed imagery to estimate LAI for the plantation, using NDVI. The results of this study, although differing from other studies, possibly due to the small sample size used, has further reinforced the suggestion that it is possible to employ remote sensing as a critical tool in forest management.

It is important to choose plantations that are easily identified on the satellite image and to choose plantations that have a far more homogeneous pattern i.e. the same clone species. In this study despite the homogeneity of the stands particular attention was paid to choose stands for survey that could be very clearly identified on the Landsat 7 image with an accuracy of 1 to 2 pixels therefore, errors associated with the size of survey plots were eliminated.

It was observed through this research that the advantages of using the vegetation indices to estimate LAI is that, vegetation indices can be related to green leaf area, standing biomass, percent ground cover, amount of photosynthetically active tissue, photosynthetic activity and productivity through further research these can be explored in details (Justice and Townshed 1981). There are uncertainties in LAI calculated from vegetation indices these uncertainties arise from several sources, including foliage architecture (which affects radiation interception by the foliage and the angular distribution of the reflected radiances), the effects of the understorey,

soil background and to a considerable extent the quality of ground truth LAI data obtained from both direct and indirect methods (Welles, 1990). However, these were not the hindrances to this research nor did they pose any threat to the findings.

The disadvantages of using VI in LAI estimation is that, VI can be affected by cloud effects and sun position as LAI estimates area affected by canopy closure, understorey vegetation and background reflectance e.g. if the broad leaves of the understorey has an outsized effect on the reflectance in the NIR and moderate effects in the red, or if darker soils typically result in higher vegetation index values.

The following are the future work that emerged from this research

- The imagery may need to be corrected deeper for atmospheric effects to improve slightly the LAI estimation. This can be done through intensive image enhancement.
- LAI values found from this work need to be fed into the forest water predicting models. This model can then quantify the accurate amount of water that the forest uses.
- The results of this study need to be tested against other areas of the country since they were only for one
- Larger study areas need to be used with more than twelve stands for statistical analysis in to obtain results that are more comparable to other studies already conducted.
- To develop a generic methodology, based on the integration of plantation characteristics derived from remotely sensed data, GIS and process-based models. This methodology then, can be applied to evaluate stream flow-reducing activities of different crops in the context of catchments management.
- The methodology will also assist with the determination of catchments water use as stated in the New Water Act.

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Appendices

Appendix 1:

Biomass determination

Three trees, representative of the stand in terms of diameter at breast height measurements were felled and their height measured with a 50 meter measuring tape.

A) Leaves

1. All leaves were stripped off from branches by hand.
2. The leaves were collected and placed in a plastic bag (of known weight) and the fresh weight was taken with a spring balance.
3. A small leaf sample representative of the whole canopy, was taken and placed in a zip-lock bags, and fresh weight determined.
4. This small leaf sample was taken to the laboratory for leaf area determination in a cooler bag.
5. The leaf area of the samples leaves was taken with a LiCor-2000 leaf area meter.
6. The samples were then dried to constant mass in an oven at 75 degrees Celsius and the specific leaf area (SLA) was determined. This was used to determine the leaf area of the entire canopy and LAI of the site. The scaling up involved taking the DBH of the 30 m x 30 m plot and scaling up using the DBH of the felled trees as base.

B) Branches

1. Dry and wet branches were weighted using a spring balance (model), after being cut from the stem using a chain saw.
2. A sub-sample was taken for both dry and wet branches using a garden prunner.
3. Sub-samples were placed in zip-lock bags and taken into the laboratory for drying, which the dry weight was used to scale up for branches on that particular tree, thus scale up to a plot.

C) Stem

1. The stem was cut (using a chain saw) into weighable chunks and weighted using a spring balance (model).
2. Disc's at 5%, 15%, 1.5 m, 35% and 65 % of a palpable tree (height to 7 cm diameter of the tree stem from ground) were cut using a chain saw.
3. Disc's were placed in zip-lock bags and placed in a cooler bag.
4. Disc's were taken to the laboratory for drying and the results were used to scale up to the compartment.

D) Instrument Used

1.	To weight leaves	a spring balance (model).
2.	To weight branches and stem	a spring balance (model).
3.	To get area of laves	a LiCor-2000 area meter.
4.	To cut the trees, stems and branches	a Chain saw.
5.	To cut the branches sub-samples	a Garden prunner.
6.	To store sub-samples	Zip-lock bag.
7.	To carry sub-samples	Cooler bag.
8.	To dry sample	Oven (model).

Appendix 2 (a):

Sampled tree parameters of KwaMbonambi stands

Stands	Tree Number	Leaf Area (mm^2)	Leaf dry Mass (g)	SLA (mm^2/g)	Whole Tree Leaves Wet Weight (g)	Wet leaves Sub-sample (g)	Whole Tree Leaf Area (mm^2)	DBH (cm) (Felled trees)
NP23	1	10221.93	146.10	7.15	2360.00	376.00	64158.92	9.40
	2	12171.15	203.70	7.27	7600.00	578.00	160035.84	12.00
	3	11689.61	147.00	9.30	11700.00	394.00	347128.13	14.00
NA24B	1	13126.83	171.80	10.03	2800.00	457.60	80321.48	9.70
	2	12137.92	156.60	9.41	4800.00	436.00	133628.48	12.00
	3	13884.42	153.00	12.60	8900.00	412.00	299930.39	14.70
NK25	1	9824.09	111.90	8.62	1800.00	324.00	54578.28	12.80
	2	10323.20	130.40	8.17	4500.00	362.40	128185.42	16.00
	3	7359.30	104.00	5.21	8000.00	281.20	209368.45	19.00
RG20B	1	6535.98	78.20	5.46	3000.00	202.10	97021.01	13.00
	2	9096.41	125.20	6.61	4200.00	303.50	125881.15	16.00
	3	10115.42	150.40	6.80	13000.00	357.80	367524.86	20.00
NP20B	1	10147.80	121.90	8.45	7000.00	332.00	213959.64	19.00
	2	17536.53	124.30	24.7	15300.00	317.60	844801.30	22.20
	3	11244.06	160.90	7.86	10290.00	396.30	291953.99	17.60
NH01	1	9842.80	116.70	8.30	3000.00	323.10	91390.87	15.10
	2	14227.80	150.20	13.48	9000.00	377.20	339475.51	18.00
	3	10073.87	141.90	7.15	10550.00	349.10	304438.16	20.70

Appendix 2 (b):

Sampled tree parameters of Hluhluwe stands

Compartment	Tree Number	Leaf Area (mm^2)	Dry Leaf Mass (g)	SLA (mm^2/g)	Whole Tree Leaves Wet Weight (g)	Wet leaves Sub-sample (g)	Whole Tree Leaves Area (mm^2)	DBH (cm) (Felled trees)
A10B	1	11662.84	174.32	9.65	80161.00	502.50	195868.72	9.50
	2	15556.19	194.70	12.43	8400.00	531.70	245762.62	9.00
	3	11763.71	162.40	8.52	7050.00	444.10	186746.51	10.40
A04C	1	15094.63	228.30	9.98	5230.00	554.60	142345.70	9.20
	2	18045.85	221.00	14.74	6270.00	538.40	210155.09	10.50
	3	18113.61	226.40	14.49	4600.00	541.60	153845.28	11.40
B04	1	13196.08	176.50	9.87	3170.00	475.50	87973.87	10.20
	2	15239.22	227.60	10.20	5810.00	580.00	152654.94	12.40
	3	15385.30	240.80	9.83	6860.00	618.50	170643.76	14.30
A05A	1	16959.76	218.20	13.18	3430.00	564.60	103032.20	11.10
	2	15114.11	248.80	9.18	4770.00	613.50	117513.11	13.30
	3	13351.99	226.10	7.88	9270.00	545.70	226815.00	16.00
F05	1	12531.68	150.20	10.46	2000.00	389.20	64397.11	11.20
	2	8431.39	124.70	5.70	3600.00	303.20	100108.84	13.00
	3	11327.50	155.00	8.28	4750.00	377.30	142606.99	15.30
A05C	1	9736.67	135.90	6.99	1830.00	350.20	50879.81	11.00
	2	11317.35	170.10	7.53	4050.00	445.00	103000.56	13.80
	3	13820.73	217.80	8.77	7100.00	553.00	177445.13	16.30

Appendix 3:

DBH measurements of the plot.

DBH of the comp. (cm)											
NP23	NA24B	NK25	RG20B	NP20B	NH01	F05	A05C	A10B	A04C	B04	A05A
8.50	12.50	13.50	15.50	18.00	15.20	13.50	13.00	7.00	9.50	13.00	11.00
7.00	11.50	15.00	16.50	18.50	12.00	10.00	15.20	8.00	12.00	12.50	17.00
8.00	9.50	15.00	16.00	20.00	19.50	11.50	13.00	8.00	10.00	12.50	16.00
7.50	10.00	16.50	16.00	21.00	21.00	13.50	15.20	8.50	11.50	14.00	13.00
7.50	12.50	18.50	16.00	20.50	16.50	11.00	14.50	8.50	9.00	13.50	8.00
9.00	11.00	16.00	17.00	20.00	19.00	14.00	12.50	8.50	9.50	6.50	13.00
9.00	10.00	13.00	12.00	17.00	16.00	12.50	13.70	7.50	7.00	14.50	17.50
9.50	11.50	18.00	16.50	19.50	20.50	13.00	14.70	8.50	10.50	12.50	16.50
10.00	12.50	14.50	15.50	15.00	9.50	13.50	13.20	9.00	12.00	14.50	14.50
10.00	11.50	14.00	15.50	19.00	18.00	14.00	15.20	9.50	11.50	14.00	11.50
10.00	14.50	7.50	15.50	19.00	20.50	14.00	15.50	9.50	9.00	13.00	11.00
12.00	11.50	18.00	16.00	17.00	15.00	11.50	14.20	10.00	11.50	12.50	16.00
9.50	12.00	17.00	17.00	17.50	19.00	14.00	16.33	12.00	10.00	12.50	14.00
12.50	12.50	18.50	5.00	18.50	19.50	14.50	13.00	9.00	10.50	13.00	15.50
11.00	11.50	12.50	17.50	17.00	13.50	13.00	15.00	9.00	11.00	6.50	17.00
11.00	13.50	18.00	16.00	16.00	20.00	12.50	16.20	9.00	11.00	14.50	17.00
11.00	12.00	15.50	17.00	17.00	12.00	14.00	13.70	9.00	8.50	13.00	16.50
11.00	13.00	16.00	17.00	14.00	19.50	12.50	9.70	9.00	9.00	13.50	15.50
11.00	15.00	12.50	17.50	18.00	18.50	11.50	13.50	9.00	11.50	12.50	15.50
11.00	10.00	18.50	18.00	18.50	15.00	14.00	13.00	9.50	9.00	13.50	15.00
11.00	11.00	12.50	17.50	17.00	15.00	13.00	15.50	9.50	9.00	14.00	11.00
11.00	9.50	16.00	12.50	17.50	18.00	14.50	14.10	9.50	11.50	13.00	16.00
11.00	10.50	18.50	17.50	19.00	10.00	14.00	13.50	9.50	12.00	12.50	14.50
11.00	13.00	19.50	15.00	16.50	14.00	11.00	14.30	9.50	9.50	13.50	16.00
11.50	13.00	17.50	17.00	16.00	10.50	14.00	13.50	9.50	11.50	11.50	16.50
11.00	10.00	5.00	16.50	16.50	19.50	16.00	14.90	9.50	9.50	14.00	14.00
11.50	14.50	16.50	13.50	19.00	22.00	13.50	13.00	9.50	10.00	13.00	17.00
10.50	4.50	17.00	16.50	16.50	16.00	13.00	14.70	10.00	10.50	13.00	16.50
11.50	10.00	15.00	16.50	18.00	18.00	14.00	14.50	10.00	10.00	14.00	17.00

Appendix 3 (continue): DBH measurements of the plot.

12.50	12.50	21.50	16.50	7.50	20.50	12.50	13.00	10.00	10.50	13.50	15.00
12.00	11.50	17.00	18.00	17.50	11.50	12.50	16.20	10.00	11.00	13.00	12.00
12.00	15.50	12.50	12.00	18.50	13.50	4.00	15.20	10.00	9.50	12.50	16.50
12.00	11.00	14.00	19.00	13.50	12.50	15.00	13.60	10.00	11.00	13.00	15.50
12.00	10.00	20.00	19.50	17.00	19.00	14.50	15.00	10.00	9.50	11.00	16.50
12.00	9.00	15.00	14.00	17.00	8.50	12.00	16.20	10.00	10.00	12.50	14.50
12.00	11.00	17.50	15.50	17.00	12.50	12.50	16.20	10.00	11.00	13.50	17.50
12.00	11.50	18.00	16.00	17.50	22.50	13.00	13.90	10.00	9.00	13.50	15.50
12.00	11.00	16.00	16.50	16.50	20.50	14.00	7.00	10.00	10.50	12.50	16.00
12.00	11.00	19.50	16.50	10.50	18.00	12.00	13.20	10.50	10.00	13.00	12.00
12.00	10.00	15.00	16.50	21.00	16.50	12.50	13.10	10.50	9.00	13.50	15.50
12.00	11.50	9.50	10.00	19.00	19.00	16.50	13.60	10.50	10.00	14.00	17.00
12.00	12.00	17.50	16.00	20.50	14.50	13.50	15.00	10.50	9.00	11.00	16.00
13.00	9.50	14.50	15.50	17.50	11.50	8.50	15.40	10.50	11.00	13.00	17.00
13.00	11.50	10.50	15.00	18.00	19.50	13.00	13.70	10.50	9.00	12.50	16.00
13.50	9.50	9.00	17.50	15.50	18.00	14.00	14.30	10.50	9.00	12.00	15.50
11.00	15.50	20.00	20.00	19.00	12.50	15.50	7.90	10.50	9.00	13.00	14.00
12.50	12.00	18.00	19.50	20.50	20.00	13.50	15.50	10.50	9.00	13.00	16.50
12.50	12.00	14.00	17.50	17.00	13.50	14.00	15.00	10.50	11.00	13.00	16.00
12.50	12.50	16.50	13.00	14.00	20.00	11.50	15.00	10.50	9.50	13.00	16.00
12.50	12.00	16.50	16.50	17.50	20.50	14.00	12.60	10.50	10.50	6.00	7.50
12.50	12.00	17.00	15.50	20.50	16.50	13.50	14.90	10.50	9.50	12.50	10.50
11.50	10.00	17.00	15.50	19.50	13.00	12.00	14.00	9.00	10.50	13.50	11.00
12.00	11.50	12.00	17.00	17.00	14.00	15.50	14.30	10.50	10.00	14.00	7.00
13.50	9.50	10.00	16.00	16.50	22.00	12.00	14.00	10.50	11.00	13.00	18.00
13.00	10.00	10.50	13.50	17.00	16.50	14.00	15.00	12.50	11.00	13.50	12.50
13.00	12.50	15.50	17.00	21.50	23.00	12.50	15.00	11.00	9.50	12.50	6.50
13.00	12.00	11.00	15.50	18.50	19.00	13.50	14.50	11.00	11.50	13.50	15.50
13.00	11.00	13.00	16.50	13.50	19.00	12.50	13.70	11.00	8.00	13.50	14.00
13.00	11.50	16.50	13.00		19.00	15.00	14.90	11.00	11.00	12.50	17.50
13.00	10.00	17.00	15.50		21.00	13.00	15.20	11.00	9.00	13.50	17.50
13.00	14.00	16.50	18.50		19.50	15.00	14.00	11.00	11.50	14.00	16.50
13.00	13.00	17.50	17.00		20.50	11.50	15.40	11.00	10.00	13.50	16.00
13.00	11.50	17.00	13.50		20.00	13.50	14.50	11.00	10.00	14.00	17.50

Appendix 3 (continue): DBH measurements of the plot.

13.00	11.50	16.50	15.00		16.50	14.50	14.10	11.00	10.00	14.50	9.50
13.00	11.50	10.50	13.00		13.00	12.50	14.50	11.00	10.50	13.00	7.50
13.00	10.50	16.00	15.50		21.00	15.00	15.00	11.00	9.00	13.00	15.00
13.00	12.00	16.00	14.50		21.00	13.00	14.50	11.00	11.00	11.50	17.50
12.50	7.50	16.50	16.50		16.50	15.00	15.00	11.00	9.00	13.00	15.00
12.00	6.50	18.50	17.00		7.00	13.00	14.50	11.50	9.00	13.50	17.00
13.50	11.00	18.50	16.00		13.00	13.50	12.50	11.50	10.00	14.00	14.50
13.50	12.50	14.00	15.00		8.00	13.50	15.50	11.50	8.50	12.50	14.50
13.50	17.50	17.50	17.00		8.00	13.00	15.50	9.00	12.00	13.50	13.50
13.00	11.00	17.00	15.50		5.00	12.00	13.20	9.50	10.00	13.50	12.00
14.00	9.50	14.50	15.50		16.50	14.00	12.00	12.00	11.50	11.50	16.50
14.00	11.50		15.50		8.00	14.00	15.00	12.00	10.00	13.50	17.00
14.00	10.00		14.50		5.00	14.00	15.00		10.00	12.00	14.00
14.00	13.50		17.50		16.50	15.50			11.00	14.00	16.50
14.00	10.50		15.00			12.00			10.50	13.00	15.50
12.00	6.00					17.50			10.50	12.50	
14.50									10.00	7.50	

Appendix 4:

Showing the tree / plot leaf areas: KwaMbonambi Region

omp. Leaf rea (mm^2)											
P23	NA24B	NK25	RG20B	NP20B	NH01	F05	A05C	A10B	A04C	B04	A05A
0794.77	37.91	67299.66	147045.27	246837.95	113284.81	291210.25	191225.90	43223.51	67438.94	96096.61	50672.36
8072.64	130389.72	96538.43	178638.89	284623.03	44335.97	203474.48	210210.06	56548.00	111787.70	86975.25	201637.34
1637.29	71253.16	96538.43	162320.74	426856.84	304458.25	240447.12	191225.90	56548.00	75353.12	86975.25	166356.50
4136.07	83803.50	133795.40	162320.74	550091.35	408557.01	291210.25	210210.06	63885.01	101955.08	116023.85	86088.55
4136.07	169737.91	197964.39	162320.74	485322.32	156895.48	228011.97	204294.93	63885.01	59994.86	105775.63	18449.81
1843.84	113287.78	120414.55	196036.07	426856.84	274637.01	304140.67	186738.87	63885.01	67438.94	16491.08	86088.55
1843.84	83803.50	59140.79	66288.73	183386.15	138859.48	265630.93	197394.95	49660.95	34833.88	126852.62	221060.54
5037.00	130389.72	180235.59	178638.89	374216.34	371296.28	278372.72	205996.25	63885.01	83741.37	86975.25	183416.44
0644.00	169737.91	85957.42	147045.27	95672.74	17543.71	291210.25	193001.58	71672.32	111787.70	126852.62	121732.02
0644.00	130389.72	76224.95	147045.27	326947.79	221602.34	304140.67	210210.06	79910.24	101955.08	116023.85	58347.02
0644.00	271426.98	8992.56	147045.27	326947.79	371296.28	304140.67	212712.11	79910.24	59994.86	96096.61	50672.36
73221.90	130389.72	180235.59	162320.74	183386.15	107483.94	240447.12	201725.48	88599.08	101955.08	86975.25	166356.50
5037.00	149177.91	148196.23	196036.07	213211.74	274637.01	304140.67	219536.75	127869.11	75353.12	86975.25	108906.68
05562.95	169737.91	197964.39	4343.52	284623.03	304458.25	317161.28	191225.90	71672.32	83741.37	96096.61	150416.35
20266.32	130389.72	51708.26	214548.73	183386.15	70754.65	278372.72	208531.20	71672.32	92607.47	16491.08	201637.34
20266.32	216518.41	180235.59	162320.74	133812.15	336637.84	265630.93	218477.03	71672.32	92607.47	126852.62	201637.34
20266.32	149177.91	108009.95	196036.07	183386.15	44335.97	304140.67	197394.95	71672.32	53016.76	96096.61	183416.44
20266.32	192155.84	120414.55	196036.07	66838.15	304458.25	265630.93	160161.09	71672.32	59994.86	105775.63	150416.35
20266.32	302149.03	51708.26	214548.73	246837.95	247056.57	240447.12	195645.32	71672.32	101955.08	86975.25	150416.35
20266.32	83803.50	197964.39	234213.44	284623.03	107483.94	304140.67	191225.90	79910.24	59994.86	105775.63	135555.09
20266.32	113287.78	51708.26	214548.73	183386.15	107483.94	278372.72	212712.11	79910.24	59994.86	116023.85	50672.36
20266.32	71253.16	120414.55	75271.29	213211.74	221602.34	317161.28	200864.25	79910.24	101955.08	96096.61	166356.50
20266.32	97787.15	197964.39	214548.73	326947.79	21504.30	304140.67	195645.32	79910.24	111787.70	86975.25	121732.02
20266.32	192155.84	237069.92	132776.31	157024.75	81739.98	228011.97	202584.32	79910.24	67438.94	105775.63	166356.50
44909.33	192155.84	163661.34	196036.07	133812.15	26098.47	304140.67	195645.32	79910.24	101955.08	70358.30	183416.44
20266.32	83803.50	2243.33	178638.89	157024.75	304458.25	356739.89	207688.46	79910.24	67438.94	116023.85	108906.68
44909.33	271426.98	133795.40	95648.36	326947.79	491393.95	291210.25	191225.90	79910.24	75353.12	96096.61	201637.34
3952.13	6705.14	148196.23	178638.89	157024.75	138859.48	278372.72	205996.25	88599.08	83741.37	96096.61	183416.44
44909.33	83803.50	96538.43	178638.89	246837.95	221602.34	304140.67	204294.93	88599.08	75353.12	116023.85	201637.34
05562.95	169737.91	331192.08	178638.89	2605.46	371296.28	265630.93	191225.90	88599.08	83741.37	105775.63	135555.09
73221.90	130389.72	148196.23	234213.44	213211.74	37445.94	265630.93	218477.03	88599.08	92607.47	96096.61	66781.95

ɔpendix 4 (continue): Showing the tree / plot leaf areas: KwaMbonambi Region

3221.90	335167.80	51708.26	66288.73	284623.03	70754.65	68097.44	210210.06	88599.08	67438.94	86975.25	183416.44
3221.90	113287.78	76224.95	277145.90	55324.55	52133.01	330269.57	196521.40	88599.08	92607.47	96096.61	150416.35
3221.90	83803.50	258540.12	300487.38	183386.15	274637.01	317161.28	208531.20	88599.08	67438.94	62838.56	183416.44
3221.90	60053.15	96538.43	107113.71	183386.15	11283.00	252987.96	218477.03	88599.08	75353.12	86975.25	121732.02
3221.90	113287.78	163661.34	147045.27	183386.15	52133.01	265630.93	218477.03	88599.08	92607.47	105775.63	221060.54
3221.90	130389.72	180235.59	162320.74	213211.74	537231.81	278372.72	199134.52	88599.08	59994.86	105775.63	150416.35
3221.90	113287.78	120414.55	178638.89	157024.75	371296.28	304140.67	131458.22	88599.08	83741.37	86975.25	166356.50
3221.90	113287.78	237069.92	178638.89	14980.64	221602.34	252987.96	193001.58	97739.13	75353.12	96096.61	66781.95
3221.90	83803.50	96538.43	178638.89	550091.35	156895.48	265630.93	192115.07	97739.13	59994.86	105775.63	150416.35
3221.90	130389.72	20203.65	37579.28	326947.79	274637.01	370097.60	196521.40	97739.13	75353.12	116023.85	201637.34
3221.90	149177.91	163661.34	162320.74	485322.32	93953.79	291210.25	208531.20	97739.13	59994.86	62838.56	166356.50
2309.67	71253.16	85957.42	147045.27	213211.74	37445.94	167569.04	211880.23	97739.13	92607.47	96096.61	201637.34
12309.67	130389.72	28462.26	132776.31	246837.95	304458.25	278372.72	197394.95	97739.13	59994.86	86975.25	166356.50
33857.70	71253.16	16788.95	214548.73	113453.30	221602.34	304140.67	202584.32	97739.13	59994.86	78399.80	150416.35
20266.32	335167.80	258540.12	325128.37	326947.79	52133.01	343463.18	141445.40	97739.13	59994.86	96096.61	108906.68
)5562.95	149177.91	180235.59	300487.38	485322.32	336637.84	291210.25	212712.11	97739.13	59994.86	96096.61	183416.44
)5562.95	149177.91	76224.95	214548.73	183386.15	70754.65	304140.67	208531.20	97739.13	92607.47	96096.61	166356.50
)5562.95	169737.91	133795.40	85046.05	66838.15	336637.84	240447.12	208531.20	97739.13	67438.94	96096.61	166356.50
05562.95	149177.91	133795.40	178638.89	213211.74	371296.28	304140.67	187641.86	97739.13	83741.37	13454.14	15033.78
05562.95	149177.91	148196.23	147045.27	485322.32	156895.48	291210.25	207688.46	97739.13	67438.94	86975.25	43719.37
44909.33	83803.50	148196.23	147045.27	374216.34	60912.94	252987.96	200000.61	71672.32	83741.37	105775.63	50672.36
73221.90	130389.72	44962.58	196036.07	183386.15	81739.98	343463.18	202584.32	97739.13	75353.12	116023.85	12078.33
83857.70	71253.16	24083.02	162320.74	157024.75	491393.95	252987.96	200000.61	97739.13	92607.47	96096.61	241727.61
42309.67	83803.50	28462.26	95648.36	183386.15	156895.48	304140.67	208531.20	138816.55	92607.47	105775.63	76016.07
42309.67	169737.91	108009.95	196036.07	621668.91	586195.28	265630.93	208531.20	107330.64	67438.94	86975.25	9547.67
42309.67	149177.91	33377.35	147045.27	284623.03	274637.01	291210.25	204294.93	107330.64	101955.08	105775.63	150416.35
42309.67	113287.78	59140.79	178638.89	55324.55	274637.01	265630.93	197394.95	107330.64	46500.31	105775.63	108906.68
42309.67	130389.72	133795.40	85046.05		274637.01	330269.57	207688.46	107330.64	92607.47	86975.25	221060.54
42309.67	83803.50	148196.23	147045.27		408557.01	278372.72	210210.06	107330.64	59994.86	105775.63	221060.54
42309.67	242912.87	133795.40	255066.89		304458.25	330269.57	200000.61	107330.64	101955.08	116023.85	183416.44
42309.67	192155.84	163661.34	196036.07		371296.28	240447.12	211880.23	107330.64	75353.12	105775.63	166356.50
42309.67	130389.72	148196.23	95648.36		336637.84	291210.25	204294.93	107330.64	75353.12	116023.85	221060.54
42309.67	130389.72	133795.40	132776.31		156895.48	317161.28	200864.25	107330.64	75353.12	126852.62	31825.45
42309.67	130389.72	28462.26	85046.05		60912.94	265630.93	204294.93	107330.64	83741.37	96096.61	15033.78
42309.67	97787.15	120414.55	147045.27		408557.01	330269.57	208531.20	107330.64	59994.86	96096.61	135555.09
242309.67	149177.91	120414.55	119477.76		408557.01	278372.72	204294.93	107330.64	92607.47	70358.30	221060.54

Appendix 4 (continue): Showing the tree / plot leaf areas: KwaMbonambi Region

05562.95	33735.99	133795.40	178638.89		156895.48	330269.57	208531.20	107330.64	59994.86	96096.61	135555.09
73221.90	21454.87	197964.39	196036.07		5221.52	278372.72	204294.93	117373.89	59994.86	105775.63	201637.34
83857.70	113287.78	197964.39	162320.74		60912.94	291210.25	186738.87	117373.89	75353.12	116023.85	121732.02
83857.70	169737.91	76224.95	132776.31		8870.29	291210.25	212712.11	117373.89	53016.76	86975.25	121732.02
83857.70	492002.38	163661.34	196036.07		8870.29	278372.72	212712.11	71672.32	111787.70	105775.63	97038.85
42309.67	113287.78	148196.23	147045.27		1373.69	252987.96	193001.58	79910.24	75353.12	105775.63	66781.95
30621.26	71253.16	85957.42	147045.27		156895.48	304140.67	182180.43	127869.11	101955.08	70358.30	183416.44
30621.26	130389.72		147045.27		8870.29	304140.67	208531.20	127869.11	75353.12	105775.63	201637.34
30621.26	83803.50		119477.76		1373.69	304140.67	208531.20		75353.12	78399.80	108906.68
30621.26	216518.41		214548.73		156895.48	343463.18			92607.47	116023.85	183416.44
30621.26	97787.15		132776.31			252987.96			83741.37	96096.61	150416.35
73221.90	16656.23					397048.17			83741.37	86975.25	
83033.29									75353.12	23728.96	