Remote sensing and GIS application for Monitoring forest management operations

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Dedicated to my parents,

Daya Ekanayake
and
Adelaide Ekanayake

and my family

Pemadasa , Chinthaka and Nisala

ABSTRACT

Satellite data potentially provide a useful tool for estimating forest cover and monitoring changes. Traditional forest surveying methods involve time consuming measurements of a large number of trees. Remotely sensed data may enable forest cover changes to be estimated very rapidly over large areas and with a minimum of ground data collection. At present the role of forest management in Britain is expanding, so that looking at forest cover changes is extremely useful for management purposes.

The main task of this study was to detect plantation forest cover change information especially on thinned and clear cut areas. These changes were estimated using Normalised Difference Vegetation Index (NDVI) derived from SPOT HRV data, compared with Forestry Commission (FC) records and field investigations. To detect whether areas have been thinned and felled during the period of concern (1994-1997), three fundamental aspects were considered. First the pattern of forest cover was identified by using FC records and field investigations. This pattern was linked to SPOT data using NDVI. At this stage relationships between forest cover and structural variables (age, top tree height, mean diameter and basal area) were also examined. Second, changes over time were analysed by using NDVI measurements (1994-1997) and change detection methods, particularly to identify the pattern of felling. Third, pixel based forest cover changes in selected compartments were related and compared to FC thinning records and information collected by forest managers.

A number of points about the ability of remote sensing techniques to provide an estimate of forest cover for management operations emerged from this study. First, it was found that NDVI changed spatially with different forest cover; spatial patterns were mainly identified in areas where major management operations (thinning and felling) were carried out. Second, temporal patterns of forest cover change, mainly due to felling operations were identified. Finally with a detailed analysis of thinned compartments, this study recognised changing patterns of forest cover, which were related to management operations.

These findings should be very useful for operational planning in plantation forests. In particular, knowledge of spatial and temporal changes of forest cover may be useful in management operations where the availability of ancillary information is unreliable. These results appear to be sufficient for the initial stages of operational planning. However further investigations need to be undertaken to better understand a number of factors related to changes of forest cover.

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CHAPTER ONE

INTRODUCTION

1.1 INTRODUCTION

Effective management of plantation forest requires detailed local information on the status of the forest. However, the traditional method of ground based surveys to obtain such detailed inventory data is currently both expensive and time consuming. Although ground surveyed inventory data is usually available for Britain's Forestry Commission plantations forests, it is generally based on a 2% to 3% sample by area (Forestry Commission, 1999). Remote sensing and Geographic Information System (GIS) analyses have great potential for providing relatively cheap data to assist in the efficient management of plantations. An additional reason for considering the value of remote sensing for forest management is its potential in the developing world, where ground based surveys are too expensive or difficult to put into practice.

The optimal and efficient management of forest resources calls for reliable technologies with provision to store, update, retrieve and analyse data (Franklin, *et al.,* 2000). Tools like remote sensing and GIS have been used for decision making and to derive meaningful outputs for forest management. In recent years, continued progress made in the field of digital image processing has provided improved capabilities for forest management (Franklin, 2001). More specifically these new technologies have a positive impact on the monitoring and planning activities related to management, providing the potential to map forest types and condition.

Vegetation indices are by far the most popular quantitative method for extracting forest green cover information from satellite imagery (Peterson & Running, 1989). These indices are combinations of red and near-infrared reflectance. The Normalised Difference Vegetation Index (NDVI) has been used extensively to obtain information on vegetation cover (Jensen, 2000). "NDVI has been found to be related to green leaf activity and as such provides a useful means of monitoring the vegetation canopy/ phenology." (Roy and Joshi, 2002, p.4893).

Fewer studies have been carried out on plantation forest than on semi-natural boreal forest, although the potential problems with an inventory based on the remote sensing of plantation forest are readily apparent (Danson and Curran 1993; Brockhaus and Khorram 1992). Plantation forests occupy approximately one third of the forest area of Great Britain (Forestry Commission, 2001) and are among the most productive in the country. Plantation forests tend to be those where growth rates are high, wood volumes are large and the canopy may close well before maturity. The forest canopy, particularly leaf surface area, is important as the surface energy and mass exchange are functionally related to the forest growth (Wulder, *et al.,* 1998). It is therefore extremely useful to examine detailed information on spatial and temporal patterns of forest cover for management purposes.

1.2 BACKGROUND OF THE SUBJECT AREA

Forests cover approximately 4000 million ha. (30%) of the Earth's land surface and are one of the most important components of the terrestrial ecosystem. Though we often take trees in the forest for granted, every aspect of our lives is dependent on them. They feed us, cloth us, absorb carbon dioxide, provide with oxygen and give us building materials and medications (Sri Lanka Ministry of Agriculture, Lands and Forestry, 1995). Timber remains one of the most important raw materials. Forests are among our most valuable natural assets, although other than their timber value many attributes are difficult to price in monetary terms. Forests can help to meet the threat of global warming by absorbing carbon dioxide and releasing oxygen into the atmosphere through the natural process of photosynthesis. (Sri Lanka Ministry of Agriculture, Lands and Forestry, 1995). A young tree growing in a properly managed forest is a more effective vehicle for carbon dioxide absorption than a mature forest. Forests may be particularly important for biodiversity, since they are among the most diverse natural habitats (Hart, 1991).

Forest cover in Great Britain was estimated at just over two million hectares in 1989 and by 2001 it had increased to 2.7 million hectares, an increase of over 370,000 hectares in the past 12 years. It is approximately 9.4% of the total land area (Forestry Commission, 2001). Nearly 900,000 hectares are under plantation forests. The Forestry Commission manages 30% of the total area.

The Forestry Commission, which was established in 1919, is responsible for managing the national forest (both natural and plantation). The management responsibilities include the development of afforestation and production, conducting forestry research and the administration of government forestry acts (Hart, 1991). The Commission, through these various responsibilities, has an interest in all forms of woodland survey, from the detailed survey of commercial forest plantations to the collection of data on forest stands. Detailed information on forest locations and crop distribution is collected by a regular survey on a fifteen-year cycle with local annual updating (Haines-Young and Watkins, 1996). Data collection for the Commission's requirements has been met up to now by a combination of aerial and ground surveys. The fine resolution of aerial photographs meets many of the current needs of forest cover sample surveys. However, the effects of weather on data acquisition, the cost of photography over large areas and the high input of skilled labour needed for interpretation cause practical problems.

The resource information needs for forestry are mainly required for two types of management planning activities, namely strategic and operational planning

(Hart, 1991). Strategic planning is needed to define key measures of forestry policy. The information required for strategic planning generally consists of forest area, tree growth, and health/mortality by stratum. Strata are usually defined by tree species composition, age-class, size class and site types. This thesis is primarily concerned with operational planning which is an instrument for forest management used on a medium or short-term basis. At this level, there is an obvious need for spatial analysis. It helps management to determine where, when and how much to cut, and what areas should be left for environmental purposes. An essential part of the information required for operational planning is provided by forest maps, which define the location, shape and area of each operative unit (sub-compartment or stand). A complete cover database should be maintained, including frequent monitoring of forest resources. Remote sensing information could contribute to better planning decisions through improved data quality at the stand level (Yatabe & Leckie, 1995).

The extraction of forest cover information from aerial photographs has been extensively used, but it has posed problems of data acquisition due to weather and through the need for highly skilled personnel for interpretation (Lillesand and Kiefer, 1994). Therefore remote sensing satellites such as LANDSAT, SPOT, and NOAA have to be considered to help overcome the problems of data acquisition. The use of LANDSAT and SPOT satellites is valuable in many respects for the extraction of forestry information on a regional scale, because these satellites have circular, near-polar orbits, which provide repetitive coverage of an area over a period of time. At a global scale, information can be obtained at lower resolution from weather satellites such as NOAA (AVHRR), which has a ground resolution of 1.1 km at nadir for Local Area Coverage (LAC) or 5 by 3 km resolution for Global Area Coverage (GAC) (Lillesand & Kiefer, 1994).

The Systeme Pour l' Observation de la Terre (SPOT) program that this study uses consists of a series of optical remote sensing satellites with the primary mission of obtaining Earth imagery for land use, agriculture, forestry, geology, cartography, regional planning, water resources and GIS applications (Jensen, 2000). The SPOT system provides global coverage between the latitudes of 87 degrees north and 87 degrees south. These satellites carry two High Resolution Visible (HRV) sensors, constructed with multilinear array detectors, operating in a cross-track direction. The position of each HRV entrance mirror can be commanded by ground control to observe a region of interest not necessarily vertically beneath the satellite. Thus, each HRV offers an oblique viewing capability. This off-nadir viewing enables the acquisition of stereoscopic imagery and provides for short revisit intervals of 1 to 3 days. Both HRV instruments operate in two imaging modes - panchromatic (P) and multispectral (XS). Panchromatic imaging is performed with a single spectral band, and supplies black and white images with a pixel width of 10m. Multispectral imaging contains three spectral bands. The bands are XS1 (green), XS2 (red) and XS3 (near infrared). By combining the data recorded in these bands, colour composite images can be produced with a pixel size of 20 meters (Lillesand & Kiefer, 1994). In this study, a series of four multispectral images is used.

In this thesis, the focus is on the use of optical remote sensing. It would have been possible to use radar, which is reviewed in Chapter 2, but this data is not available historically. Another possibility would have been to use lidar but this is not yet widely available. Optical data, by contrast, are widely available and the historical images can be used to assess forest change over time.

1.3 AIM AND OBJECTIVES

Accurate forest cover estimation is an important requirement for the planning of management operations. The aim, of this thesis is to assess the value of optical remotely sensed data for monitoring and planning forest management. In order to fulfil this aim, the study attempts to meet the following specific objectives:

1) To detect forest canopy cover changes spatially by age class using NDVI derived from SPOT HRV multispectral data.
2) To evaluate the use of NDVI to determine selected structural variables such as tree top height, mean diameter and basal area by comparing NDVI with forest stand parameters derived from compartment records supplied by the Forestry Commission.
3) To test the use of change detection techniques for detecting and monitoring changes of forest canopy cover over a four-year period.

The study site was chosen because:

a) It had a simple stand structure, which would allow the analysis to concentrate on the use of remote sensing to detect management operations such as felling and thinning.
b) The Kings Forest is on relatively flat terrain typical of many plantation forests in southern England. It is therefore, less affected by topographical effects. It also typical of lowland forest in UK especially on those sandy soil.
c) There were suitable management records from the Forestry Commission, which would allow the changes detected by remote sensing to be cross-referenced with management operations in the years concerned.

1.4 PLAN OF THE THESIS

This thesis is organised in seven chapters. The initial chapters introduce the background information on the study area and the theoretical techniques. The results of the study are presented and discussed in the following chapters and the conclusions derived from this study along with a few recommendations for further research are presented in the final chapter. A brief summary of each chapter is provided below:

Chapter I introduces the background of the present study, and explains its aims and objectives followed by an overview of the thesis.

Chapter II reviews studies concerned with remote sensing applications in forest research. It highlights the applicability of remote sensing and related techniques to different types of forestry study.

Chapter III describes the basic principles of remote sensing for forest studies. It contains two main sections. The first section reviews the characteristics of remote sensing data in the optical region of the electromagnetic spectrum and explains how these data have been used to study forest cover changes. Then leaf structure and spectral characteristics of vegetation and their effects on the quantitative analysis of forest cover are discussed. The second section deals with characteristics of forest management. The first subsection explains what forest management is; the second describes some of the needs and methods of data collection for forest management; the third deals with planning; and the final part describes the operations of forest management.

Chapter IV describes the data sources and methodology used for the present study. A description of the study area (The Kings Forest) and the study site (The North-Western quadrant of the Kings Forest) are included in this chapter. This chapter also discusses the pre-processing and processing of satellite data and the change detection methods used in this study. Statistical methods and methods of GIS are also described at the end of the chapter.

Chapter V initially analyses spatial changes of forest canopy cover using satellite-derived values of the Normalised Difference Vegetation Index (NDVI). In the first part of the analysis, statistical relationships of near-infrared reflectance to the red reflectance for different age groups of pine trees in the study site are considered. The analysis focuses on NDVI changes in different types of stand within the same site, rather than changes of the same site over a long period of time. The final part of this chapter discusses the relationship between NDVI and selected forest stand parameters, such as tree height, mean diameter and basal area. **Chapter VI** analyses temporal changes of forest cover using NDVI and change detection methods. The first part of this chapter presents temporal changes of forest cover utilising multi-temporal NDVI data. The second part deals with change detection analysis using the vegetation index differencing method.

Chapter VII highlights how remote sensing can be useful for forest management practices by testing the ability to detect forest cover changes for forest management operations.

Chapter VIII summarises all the previous chapters with the conclusions drawn from the research. It reviews the potential applications of remote sensing of forest management, highlighting the particular contributions made by this thesis. The chapter ends with proposals for future work that can be pursued as a continuation of this study in Britain and developing countries such as SriLanka.

CHAPTER TWO

REVIEW OF SATELLITE REMOTE SENSING FOR FOREST MANAGEMENT

2.1 INTRODUCTION

This chapter is a general review to assess the value of a range of remote sensing techniques in forest management. Since 1972, earth observation satellites have been providing images with reasonably high ground resolutions. These images provide earth cover information continuously and many researchers are trying to use these images to assist in environmental planning. For surveying large areas, the information retrieved from satellite remote sensing is less expensive than that collected in other ways. It also gives better information globally. Besides efforts to launch and operate the satellite systems, substantial funds have been allocated for the development of applications (Lillesand and Kiefer, 1994).

Forestry is one of the disciplines that benefits from these research programmes. Therefore, the popularity of satellite remote sensing in forestry research over the past decades appears to be due to the availability of satellite information and the funds provided by environmental funding agencies. The development and implementation of digital remote sensing techniques with other information sources, through the use of Geographic Information Systems (GIS) and remote sensing interpretations with forest management systems and practices, has also altered the premises for these research programmes.

Because this study mainly focuses on pine plantations using SPOT data, this review of satellite remote sensing within the field of forestry is limited to coniferous forest in temperate and boreal regions (Canada, USA and Eurasia). The first part of this review explains how different kinds of satellites and sensors have become increasingly important for mapping and monitoring forest resources and management operations. It goes on to review recent important research and applications of remote sensing for forest studies.

2.2 BACKGROUND INFORMATION

Satellite based remotely sensed digital data have been used to map forest resources since the inception of the LANDSAT satellite programme in 1972. Such satellites provide synoptic images and homogeneous data, which can be geographically registered over time and which can be therefore an efficient tool for providing high quality forest management information. Since the 1980s, with the availability of scanners, improvements in computer software and development of image processing algorithms, there have been many studies of remote sensing applications in forestry (Franklin, 1986; Danson, 1987; De Wulf *et al.*, 1990; Ulaby, 1990; Herwitz, 1990; Danson and Curran, 1993; Ripple *et al.*, 1991; Derrien *et al.*, 1992; Nilson and Peterson, 1994; Collin and Woodcock, 1994; Cohen *et al.*, 1996; Coppin and Bauer, 1996; Gholz *et al.*, 1996; Ranson *et al.*, 1997; Luckman *et al.*, 1997; Cohen and Fiorella, 1998; Bertrand *et al.*, 2000; Wilson and Sader, 2002). The Multi Spectral Scanner (MSS) onboard LANDSAT -1-2 and-3 (launched on July 23rd of 1972, January 22nd of 1975, and March 5th of 1978 respectively) was the first global monitoring system capable of producing high-resolution multi spectral data in a digital format. The LANDSAT -4 and -5 satellites (launched on July 16th 1982 and March 1st 1984 respectively) included both MSS and the Thematic Mapper (TM) instruments. The TM is a more advanced sensor than MSS incorporating a number of spectral improvements including the acquisition of data in seven bands instead of four (Table 2.1), with new bands in the visible, mid-infrared and thermal portion of the spectrum. Furthermore, these bands are more finely tuned for vegetation discrimination than those of MSS. The green and red bands of the TM are narrower than the combined bands of the MSS and are centred in a region of maximum sensitivity for plant vigour. Therefore, LANDSAT TM imagery has been used extensively to collect forestry information (Horler and Ahern, 1986; Franklin, 1986; Clark, 1990; Brockhuns and Khorram, 1992; Nel *et al.*, 1994; Gemmell, 1995; Nilson and Olsson, 1995).

The next generation of land resource satellites SPOT -1, -2 &-3 (launched on Feb. 21st 1986, Jan. 21st 1990 and Sep. 25th 1993 respectively) increased the potential frequency of coverage. The SPOT system consists of two identical High Resolution Visible (HRV) imaging systems. Each HRV is designed to operate in either of two modes of sensing. They are:

1) A 10 m. resolution panchromatic mode over the band range 0.51 to 0.73μm.
2) A 20 m. resolution multi-spectral mode over the band range 0.50 to 0.59, 0.61 to 0.68 and 0.79 to 0.89μm (Table 2.1)

The SPOT HRV camera can be targeted, providing an opportunity for viewing a given area almost every day if required. Forest applications often require repeated observations on these types of time frames. The use of SPOT data for various interpretative purposes in forestry is facilitated by the system's combination of multi spectral sensing with excellent spatial resolution (Table 2.1). SPOT – 4 was launched in 1997 and operated until 2002. The programme was designed to provide long-term continuity of data, with the addition of a 20 m. resolution band in the mid IR portion of the spectrum. This band 1.58 – 1.75μ was intended to improve vegetation monitoring. Another instrument on SPOT -4 is a wide field-of-view sensor called the Vegetation Monitoring Instrument (VMI). While designed primarily for large-scale vegetation monitoring, the VMI is also useful in a range of applications where frequent, large area coverage at 1 km. resolution is important (Lillesand and Kiefer, 1994).

Table 2.1: Spectral bands of LANDSAT and SPOT systems (source: Lillesand and Kiefer, 1994)

LANDSAT (MSS & TM)

Spectral bands	MSS Band	TM Band
0.5 – 0.6 µm 0.45 – 0.52 µm (blue)	1	1
0.6 –0.7 µm 0.52 – 0.60 µm (green)	2	2
0.7 –0.8 µm 0.63 – 0.65 µm (red)	3	3
0.8 – 1.1 µm 0.85 – 1.01 µm (near infrared)	4	4
1.55 – 1.75 µm (near mid infrared)		5
10.4 – 12.5 µm (thermal infrared)		6
2.08 – 2.35 µm (mid infrared)		7

SPOT

	SPOT 1,2,3,	SPOT 4&5
Spectral bands	HRV Band	HRVIR Band
0.50 – 0.59 µm (green)	1	1
0.61 – 0.68 µm (red)	2	2
0.79 – 0.89 µm (near infrared)	3	3
1.55–1.75 µm (near mid infrared)		4

The National Oceanic Atmospheric Administration (NOAA) series 6-12 missions contained the Advanced Very High Resolution Radiometer (AVHRR). These data from these satellites have been used extensively for large area vegetation monitoring (Goward, *et al.*, 1991; Chilar *et al.*, 1991; Derrien *et al.*, 1992; Fazakas and Nilsson, 1996; Potter and Brooks, 1998; Fernandez, 2000). Typically, the spectral bands used for this purpose have been the channel 1, visible band and the channel 2, near infrared band. Various mathematical combinations of the AVHRR channel 1 and 2 data have been found to be sensitive indicators of the presence and condition of green vegetation. These combinations are often referred to as vegetation indices. Two such indices calculated from AVHRR data are the simple Vegetation Index (VI) and Normalised Difference Vegetation Index (NDVI) defined as follows:

$$VI = Ch2 - Ch1 \tag{2.1}$$

$$NDVI = \frac{Ch2 - Ch1}{Ch2 + Ch1} \tag{2.2}$$

Previous investigators have related the NDVI to several vegetation phenomena, ranged from seasonal vegetation dynamics at global and continental scales, to forest clearance, leaf area index measurement, biomass estimation, percentage ground cover determination and the estimation of photosynthetically active radiation. These vegetation attributes are used in various models to study photosynthesis, carbon budgets, water balance and related processes (Goward *et al.*, 1991).

An increasing amount of vegetation information is acquired by Synthetic Aperture Radar (SAR) sensors that operate in the microwave portion of the electromagnetic spectrum (1 mm - 1m). The SAR sensor sends and receives waves in the microwave region of the electromagnetic spectrum, which pass directly through the atmosphere. This region is made of the P, L, S, C, X, K, Q, V and W bands (Table 2.2).

Table 2.2: Microwave spectrum with wave bands (source: Lillesand and Kiefer, 1994)

Bands	Frequencies (GHz)	Wavelength (cm)
P	0.23 – 0.39	133 – 76.90
L	0.39 – 1.55	76.90 – 19.3
S	1.55 – 4.20	19.3 – 7.1
C	4.20 – 5.75	7.1 – 5.2
X	5.75 – 10.90	5.2 – 2.7
K	10.90 – 36.00	2.7 – 0.83
Q	36.00 – 46.00	0.83 – 0.65
V	46.00 – 56.00	0.65 – 0.53
W	56.00 – 100.00	0.53 – 0.30

The application of microwave remote sensing techniques to forestry has been studied for more than three decades (Morain *et al.*, 1967). It has been widely used for forestry using mathematical modelling over the last decade (Nelson *et al.*, 1988; Dobson *et al.*, 1992; Ranson *et al.*, 1996; Harrell *et al.*, 1997; Luckman *et al.*, 1997). In 1971, a very large mapping project called RADAM (Radar of the Amazon) was undertaken in Brazil. More than 160 radar mosaic sheets covering an area in excess of 8,500,000 sq. km were completed. Foresters used these mosaics as base maps in many studies for timber inventory. In remote and cloud covered areas of the world, radar imagery is a prime source of inventory information about forest resources (Lillesand & Kiefer, 1994).

One of the important features of radar waves is that they interact with vegetation canopies as a group of volume scatters composed of a large number of discrete plant components such as leaves, stems, stalks, limbs etc. In turn, the vegetation canopy is underlain by soil that may result in surface scattering of the energy that penetrates the forest canopy. When the radar wavelength approximates to the mean size of plant components, volume scattering is strong and, if the plant canopy is dense, there will be strong backscatter from the vegetation. In general, shorter wavelengths (2-6 cm) are best for sensing tree leaves (Lillesand and Kiefer, 1994). At these wavelengths, volume scattering predominates and surface scattering from the underlying soil is minimal. Longer wavelengths (10-30 cm) are best for sensing tree trunks and limbs. In addition to plant size and radar wavelength, many other factors affect radar backscatter from trees.

Vegetation with a high moisture content returns more energy than dry vegetation. Most of the energy returning to the antenna has the same polarisation as the transmitted pulse. This energy is recorded as parallel-polarized imagery and is designated HH (horizontal transmit, horizontal return) or VV (vertical transmit, vertical return). But some radar systems have a second antenna element that receives the depolarised energy vibrating at right angles to the plane of the transmitted pulse. The resulting imagery is termed cross-polarised and may be either HV (horizontal transmit, vertical return) or VH (vertical transmit, horizontal return). Likewise, more energy is returned from trees having their rows aligned in the azimuth direction than from those aligned in the range direction of radar sensing. Also the incidence angle has a significant effect on radar backscatter from vegetation. Recent studies have investigated the capabilities of SAR for estimating forest structural parameters, including above ground biomass. These studies have shown high correlation of backscatter with biomass for different forest stands (Dobson *et al.*, 1992; Ranson *et al.*, 1997; Harrell *et al.*, 1997; Luckman *et al.*, 1997).

2.3 FOREST COVER INFORMATION

Studies carried out by many researchers (Franklin, 1986; Danson, 1987; De Wulf *et al.*, 1990; Ulaby, 1990; Herwitz, 1990; Danson and Curran, 1993; Ripple *et al.*, 1991; Derrien *et al.*, 1992; Nilson and Peterson, 1994; Collin and Woodcock, 1994; Cohen *et al.*, 1996; Coppin and Bauer, 1996; Gholz *et al.*, 1996; Ranson *et al.*, 1997; Luckman *et al.*, 1997; Cohen and Fiorella, 1998; Bertrand *et al.*, 2000; Wilson and Sader, 2002) have shown that remote sensing can be applied to several forest characteristics, which can be useful for management purposes. Therefore, this section reviews those studies under the following sub headings.

1) Forest inventories and monitoring.
2) Classification of forest cover and mapping.
3) Detecting forest cover changes.
4) Structural characteristics.
5) Forest productivity.
6) Forest management practices.

2.3.1 Forest Inventories and Monitoring

Estimations of forestry data such as age, basal area, diameter and tree volume are important for forest management planning. Aerial photography has been routinely used for several decades to collect and map the condition of forest areas. Recently, along with the emergence of concepts such as ecosystems in managing forests, has come a significant shift in the emphasis from finer to coarser spatial scales and the widespread use of Geographical Information Systems (Lillesand and Kiefer, 1994). These developments have precipitated an increasing need for vegetation information derived from satellite imagery. There has been much speculation about application of the satellite data to natural resource inventory (Heath, 1975; McKim *et al.*, 1975 and Latham; McCarty, 1972). The possibilities in forestry are well documented (Laboratory for applications of Remote Sensing, USA, 1974).

In the initial stage, forest inventory studies were carried out only for collecting and monitoring forest information. In Britain, the Agrispine project of 1982 (Horne, 1984) used the Space Informatics Network Experiment (SPINE) to test the rapid transmission of LANDSAT data for forestry and agricultural study. This study showed that the possibility of using digital data to improve collection of forest stand parameters and to automate checking procedures was thought worth of investigation. For these reasons, project work concentrated on testing development of forest cover monitoring applications. A joint project was carried out with the Department of Environment (DoE) and the Isle of Wight was chosen for the initial trials. The study identified different forest classes, and then compared the results with the latest forest data. To monitor forest cover they used different temporal scenes (1976 June, 1978 Aug., 1979 May, 1978 Nov., 1981 Feb.) of the island to see what effect different times of the year would have on features identified from the 1975 July scene. Provisional results of the Isle of Wight test areas were extended to Hampshire. Grid sampling of the MSS cover type classes to the map showed that 79% of forest cover was correctly identified. A total of 11% of forest failed to classify but most of the missed points were associated with small blocks and woodland edges. (Townshend *et al.*, 1992)

Danson (1987) used SPOT – 1 HRV data to collect information on forest stand parameters. In his study, image data were correlated with five forest stand parameters: mean percentage canopy cover, tree density, mean tree diameter at breast height (DBH), mean tree height and sub-compartment age. The field site selected was Clipstone Forest located near Mansfield, England. The results of the correlation analysis between remotely sensed data and forest parameters showed that near-infrared wave bands were all significant at the 99% confidence level. The correlation coefficients for the red and green wave bands were lower. This study indicated that the low correlation between visible bands and percentage canopy cover or tree density might be attributed to the asymptotic nature of the relationship between red and green radiance and amount of vegetation at relatively low biomass levels. The unexpected high correlation with the other stand parameters was possibly due to the effects of canopy shadow. It was concluded that more detailed investigation of image data combined with field surveys is required for the accurate inventory of forest stand parameters.

Brockhaus and Khorram (1992) also tried to conduct inventory studies of forest resources. They used SPOT and LANDSAT data and attempted to evaluate detailed forest conditions such as forest type, basal area and age class information. The data were collected from a managed experimental forest in North Carolina, USA. Comparison of two types of data with sample site information showed that the SPOT NIR band and TM 2,3,4,5, and 7 bands were significantly correlated with basal area. Age class was not found to be significantly correlated with the three SPOT bands, but TM bands, 3,4,5, and 7 were significantly correlated with age class. The study finally identified six forest cover types in the area.

In the last decade many authors have reported on the utility of TM data for estimating coniferous timber volume and noted significant correlations between TM data and timber volume (Ripple *et al.*, 1991; Ardö, 1992; Ahern *et al.*, 1992; Gemmell, 1995). Most of the studies have been carried out in the USA and Canada. These reports are encouraging because of the importance of accurate knowledge of timber volume distribution in efficient forest management. Ripple *et al.*, (1991) found significant inverse relationships between timber volume and both TM and SPOT near-infrared bands for a site in Oregon, dominated by Douglas fir. They suggested that canopy shadowing caused these relationships possibly in combination with the extent of the bright deciduous understory exposed to the sensor. Ahern (1992) found a significant correlation between the timber volume and a ratio of TM Bands 7/4 for a site in eastern Canada. Volume estimation using LANDSAT TM band 5 has also been carried out in the Southern Sweden (Ardö, 1992). This study investigated the relationship between spectral radiance and the timber volume (m^3 ha^{-1}) of forest compartments. It also evaluated regression estimates of timber volume of forest compartments. The correlation coefficient between observed volume and estimated volume was 0.83 and the standard error of estimate was 46.5 m^3 ha^{-1}. It was found that there was a stronger relationship between spectral radiance and volume for compartments with small volumes than for compartments with large volumes.

More recently, research has been involved with validation of data collection and application of satellite remote sensing for forestry. A study carried out in Southern Sweden (Fazakas and Nilsson, 1996) presented and validated an extended field inventory across a large region. Total wood volume and the volume for different tree species were estimated in a calibration area using field data, digital map information and a partial LANDSAT Thematic Mapper (TM) Scene. Forest cover information was obtained from digital maps of the same area. The TM estimates and the forest cover information were then listed by regression analysis to determine the statistical relations between these parameters and the spectral signature of NOAA-AVHRR pixels covering the same location. The regression equations developed from the calibration area were then applied to a much larger area covering southern Sweden to estimate the forest parameters of interest. The work demonstrates that the methods developed in this study could be successfully used to generate regional estimates and small-scale maps of forest cover. To improve the LANDSAT TM estimates, it is important to locate the field plots with higher accuracy than the Swedish study has used. For this purpose, the use of the Global Positioning System (GPS) could be useful. On the other hand, the volume estimates would be more accurate if the volumes measured in the field were updated to the year of TM data acquisition. Use of better digital map information would also contribute to better accuracy. In addition, it was shown that all satellite acquisitions should be from the active vegetation period when the tree crowns are in full leaf. All the satellite data, used in this thesis, were acquired in June, which is the period of full crown cover.

2.3.2 Classification of forest cover and mapping:

Knowledge of forest cover classification and mapping is important for many planning and management activities. Therefore, this section explains some research based on classification and mapping of forest features which are directly related to this thesis. The location and measurement of forest types, regeneration areas or clear-cut areas of forest stress or any other related features are important in forest management. Some of the earliest work on remote sensing applications for forest research considered forest classification. Dodge and Bryant (1976) using LANDSAT data produced generalised forest maps of two counties in New Hampshire by a simple cover type classification. First, they chose a training site within the LANDSAT coverage and identified signatures for forest types, and then applied these signatures to a test area. Secondly they applied the same signatures to an entire county and determined different types of forest classes. They also compared Forest Service data with their computer based measurements and found that computer classified data provided more detail and greater accuracy than the currently available regional forest statistics.

Different methods have been applied to derive vegetation maps at regional or global scale from AVHRR images. Derrien *et al.,* (1992) mapped the vegetation cover of France with a 4 km spatial resolution using NOAA-11/AVHRR data from March 1990 to February 1991. They computed the Normalised Difference Vegetation Index (NDVI) over the whole period using visible and near-infrared reflectance corrected for atmospheric effects and applying automatic cloud detection. Monthly NDVI values were obtained for each point of the area by selecting the maximum value. These annual profiles were classified with the clustering algorithm. The final results were in the form of an atlas, which mapped vegetation into 20 classes.

Classification of forest cover and mapping with digital remote sensing data has involved general land cover mapping and the separation of land use and structural class. Classification of multispectral images involves the accurate assignment to pixels of labels describing the ground features. Standard classification algorithms involve supervised and unsupervised methods (Mather, 1987, 1998; Lillesand and Kiefer, 1994; Jensen, 1996; Gibson and Power, 2000). Unsupervised classification commonly relies upon statistical clustering to separate pixels into groups based on the similarity of their multispectral values. Subsequent to definition of statistical clusters, labels can be applied to the clusters based on knowledge of the scene from ground data, field visits or air photos. Fiorella and Ripple (1993) used unsupervised classification of TM imagery with an ERDAS topographic relief image calculated from a Digital Elevation Model (DEM) to classify successional stages from clear cut to old growth in Douglas-fir forests in USA with an overall accuracy of 78.3%. Use of the topographic relief image improved classification accuracy for younger stands, but not for later successional stages. They found that an index based on a linear combination of all TM bands, were strongly correlated with each other and stand age, except on poorly regenerated sites. Ripple (1994) mapped percentage conifer cover on 10.9 million ha of forest in Oregon (USA) using AVHRR imagery. The analysis was based on a regression relationship between LANDSAT MSS and coregistered AVHRR band values and found that the correlation between the AVHRR conifer cover map and observations from U-2 air photos was 0.90. Cohen *et al.,* (1996) also used TM data to map forest cover over 1.24 million ha in Western Oregon. They separated four forest cover classes: open (<30%), semi open (30-85%), closed canopy of mixed conifer-hardwood (>85%) and closed conifer canopy (>85%) based on unsupervised classification. Their primary interest was distinguishing between successional stages within the closed canopy conifer class. Thus, for this class, regression analysis was used to explore relationships between the Tasselled Cap Vegetation Index (brightness, greenness and wetness), topography and stand age. Topography strongly influenced the responses of brightness and greenness, but not of wetness. A regression model for predicting forest age from wetness was developed and applied to predicted forest age in three classes: young (<80 years), mature (80-200 years) and old growth (>200 years) with an accuracy of 75%.

Supervised classification requires the use of “training sets” which are groups of pixels of a known type. The training sets are used to define statistically the known classes in spectral terms. Using some statistical decision rule, such as maximum likelihood, or a learning procedure such as an artificial neural network, the multispectral values of each pixel in the image to be classified are compared to the training data to determine which class the pixel is most like, and the pixel is labelled accordingly (Mather, 1999).

Yool *et al.*, (1986) classified natural vegetation using image-processing algorithms. This research considered the relative capacities of a variety of popular image processing algorithms to discriminate different types of forest in Southern California. The study analysed the performance of wave band ratios, statistical filtering and principal component algorithms using LANDSAT MSS data. Overall, the results suggest that processed spectral variables from

LANDSAT data may be less sensitive to spectral differences between the vegetation classes than original unprocessed LANDSAT variables. Furthermore, it indicated that certain processing algorithms might be better suited to classification of certain forest types, based on the differential performance of some of the spectral variables by class.

The most commonly applied forest classification procedure is the maximum likelihood procedure. it is a statistical decision rule that examines the probability of a pixel in relation to each class with assignment of the pixel to the class with the highest probability (Lillesand and Kiefer, 1994). Decision tree, stratified or layered classifiers have also been utilised to simplify classification computations and maintain classification accuracy.

2.3.3 Detecting forest cover changes

The main objective of this thesis is detect forest canopy cover changes over time. Therefore, this section explains frequently used change detection methods and studies related to forest cover changes using change detection techniques. Several studies have attempted to use digital satellite data to detect changes in land cover (Singh, 1989; Mather, 1992; Collin and Woodcock, 1994; Coppin and Bauer, 1994; Cohen and Fierella, 1998). Coppin and Bauer (1996) wrote a comprehensive review of change detection techniques specifically related to forest ecosystems. Their research had two major components. First they summarised the different perspectives from which the variability in the change event has been approached. The appropriate choice of digital imagery acquisition dates and interval length for change detection was discussed. In the second part, pre-processing routines to establish a more direct linkage between digital remote sensing data and biophysical phenomena, and the actual change detection methods were reviewed and critically assessed. In their review of change detection, they grouped all the change detection algorithms in the literature by early 1995 into 11 distinctly different categories. They noted that only seven methods are frequently used for monitoring vegetation canopies. Others are less common or remain in an experimental stage. They also noted that a number of recent and expected advancements, such as improvement of sensing systems, computer and image processing systems, ecosystem management models and remote sensing algorithms, will increase the accuracy and effectiveness of change detection with digital satellite data. They concluded that:

1) "Vegetation indices are more strongly related to changes in the scene than the responses of a single band.
2) Accurate registration of multidate imagery is a critical prerequisite of accurate change detection.
3) Some form of radiometric calibration is recommended to eliminate exogenous differences, due to differing atmospheric conditions between image acquisitions.
4) Image differencing and linear transformations appear to perform generally better than the other methods of change detection.
5) The capability of using remote sensing imagery for change detection will be enhanced by the improvements in satellite data that will become available over the next several years and by integration of remote sensing and GIS techniques."(Coppin and Bauer, 1996 p.926)

Cohen and Fiorella (1998) carried out research on methods for detecting conifer forest change with LANDSAT TM data. In their study, three methods for detecting changes in a conifer forest environment (image differencing, change vector analysis and composite analysis) were compared. Their analysis involved a simple test of the three methods and included some comparisons with and without a reference image to determine its value in change detection. The importance of the Tasselled Cap wetness features in conifer forest change detection were also evaluated.

The most important finding of Chen and Fiorella's study was that the use of a reference image is extremely important for accurate characterisation of forest change. Another finding was that image differencing performed better than

Change Vector Analysis (CVA), even in combination with the reference image. They concluded that CVA did not compare well to composite analysis, with the disparity between them increasing as the number of cover change classes increased. If only a brightness difference image is used in change detection, the forest clear cuts are readily separable from other change classes, but all other classes are nearly impossible to separate accurately along a brightness difference axis. They also concluded that the "tasselled-cap" wetness features are important for separating different classes of conifer forest.

2.3.3.1 Digital change detection methods

This section discusses the most frequently used digital change detection methods because this thesis uses Vegetation Image Differencing and classification based change detection methods to analyse changes in forest canopy cover. Digital change detection comprises the quantification of temporal phenomena from multidate imagery that are commonly acquired by the satellite based multispectral sensors. Visual or manual change detection is difficult to carry out, because different interpreters produce different results. Apart from offering consistent and repeatable procedures, digital methods can also be more efficient in incorporating features from infrared and microwave parts of the electromagnetic spectrum.

A wide variety of digital change detection methods have been developed over the last two decades. There are three broad categories:

1) Direct comparison methods.
2) Transformation based methods.
3) Classification based approaches.

The three most frequently used direct comparison procedures, are found in the literature are:

a) Image differencing.
b) Normalised image differencing.
c) Image ratioing.

There are many transformation procedures found in the literature of remote sensing analysis. The most widely used methods are:

a) Principal Components Analysis (PCA)
b) Tasselled Cap Analysis (TCA)
c) Vegetation Index Differencing (VID)
d) Change vector analysis (CVA)

Two commonly used classification based approaches are:

a) Post classification
b) Direct multi-date classification

Detailed reviews and examples of these techniques can be found in Mather (1999) and comprehensive reviews of the techniques, specifically related to forest ecosystems can be found in Coppin and Bauer (1996).

2.3.3.1.1 Direct comparison methods

Direct comparison methods involve arithmetic manipulation of image pairs acquired at different times (Watanabe & Hatamura, 1981; Banner & Lynham, 1981) or band by band, (Park *et al.,* 1983; Mukai *et al.,* 1987; Fung, 1990) to produce a change image. In this method, a subtraction operation is often carried on a pair of co-registered images of the same area taken at different times. The degree of change that has taken place between the dates of imaging can be then assessed. The differences are calculated on a pixel-by-pixel basis. Pixels showing small changes will be black in the new image, while those pixels with large differences will be white.

2.3.3.1.1.1 Image differencing

Image differencing is probably the most widely applied change detection algorithm for a variety of geographical environments (Singh, 1989). It requires two co-registered remote sensing data sets of the same format and size. The value of each new pixel is subtracted from the corresponding old pixel of the reference image. Mathematically this technique can be expressed as equation 2.3:

$$\Delta\rho^{k}_{(i,j)} = \rho^{k}_{(i.j)}(\text{image}_1)-\rho^{k}_{(i.j)}(\text{image}_2)+ \text{c} \quad (2.3)$$

$\Delta\rho^{k}_{(i.j)}$ = Change of image

$\rho^{k}_{(i.j)}$ = the surface reflectance of the pixel (*i.,j*) in spectral band *k*

c = constant

The results of the change may have either a positive or a negative value, where a zero value indicates no change. For an 8-bit image, the range of resulting pixel values is from –255 to 255. Therefore a constant c, normally 255, is added to transform the data into positive values, which may be then be divided by 2 to convert to a 0-255 range.

2.3.3.1.1.2 Normalised image differencing

The Normalised image differencing technique is a modified version of image differencing. This technique is a combination of image differencing and image ratioing. The image ratioing method requires two co-registered images at different dates ratioed band by band with the results compared on a pixel-to-pixel basis (equation 2.4). This method is introduced in order to solve problems of identical values in the change image.

$$\Delta\rho^{k}_{(i.j)} = \frac{\rho^{k}_{(i,j)}(image_1) - \rho^{k}_{(i,j)}(image_2)}{\rho^{k}_{(i,j)}(image_1) + \rho^{k}_{(i,j)}(image_2)} * 100 \quad (2.4)$$

The calculated results would be in the range 100 to +100.

2.3.3.1.1.3 Image ratioing

Image ratioing is especially useful for change detection when several dates of imagery are used in an analysis. It can reduce the effect of environmental and system multiplicative factors. In this method, two co-registered images acquired at different dates are ratioed or divided band by band and the results are compared on a pixel-to-pixel basis. It is one of the simplest and quickest change detection methods. The mathematical expression of the ratio function is stated in equation 2.5

$$\Delta\rho^{k}_{(i,j)} = \frac{\rho^{k}_{(i,j)}(t_1)}{\rho^{k}_{(i,j)}(t_2)} \qquad (2.5)$$

$\Delta\rho^{k}_{(i,j)}$ = change pixel value

$\rho^{k}_{(i,j)}\ (t_1)$ = pixel value at line i, column j, and band k at time 1

$\rho^{k}_{(i,j)}\ (t_2)$ = pixel value at line i, column j, and band k at time 2

Areas of change in the multiple date imagery having a value either higher or lower than 1.0 are displayed in either light or dark tones that are directly proportional to the spectral intensity of the change that took place. Therefore, the lighter or darker a pixel appears, the more the digital value has changed between the two dates. On the other hand, the areas that have not changed will have a value of 1.0. As with the image differencing method, the critical elements of this method are the selection of appropriate threshold values in the upper and lower tails of the distribution that represent significant change in pixel values.

2.3.3.1.2 Transformation-based methods

Transformation of image bands is an important tool in image analysis. Two frequently used transformation techniques applied to multi-date imagery are Principal Components Analysis (PCA) and Tasselled Cap Analysis (TCA) (Mather, 1999). These two techniques are similar in nature in that the axes of the original multi-spectral image data representing the original bands are rotated to new orthogonal positions. The difference between these two techniques lies in the method used to derive the transformation coefficients. PCA uses image data statistics whereas TCA uses external data where knowledge of the nature of the ground data is essential for deriving the transformation axes. Apart from these two methods, Vegetation Index

Differencing and Change Vector analysis (CVA) also lie under transformation methods, because these methods involve transformation techniques.

2.3.3.1.2.1 Principal Component Analysis (PCA)

PCA is a multivariate technique that views multispectral image data in a principal axis reference system. Multi-spectral data exhibit high inter-band correlations, which imply a certain degree of redundancy or repetition of information. PCA is designed to reduce such redundancies in multi- spectral data. The procedure compresses most of the information in the original data set into a few components. The principal component data values are simply linear combinations of the original data values where the principal component axes have been chosen to maximise the information content. This technique has been used in a number of application areas such as data compression; data enhancement and land cover change detection. PCA can be performed using either standardised or non-standardised data. In the standardised approach, the radiometric values of each spectral band are treated as having an equal variance. On the other hand, the non-standardised approach is justified by possible differences in the radiometric resolution between spectral bands. Singh (1984, 1986) used both standardised and non-standardised PCA for tropical forest change detection. However, Fung and LeDrew (1987) found that standardised principal components computed from the eigenvectors of the correlation matrix provide more accurate information for change detection than the non-standardised principal components derived from the covariance matrix. Land cover changes are normally detected using statistical data extracted from the entire study area rather than using sub-set or sample data, with the lower order Principal Components typically relating to changes in brightness and greenness. Byrne *et al.,* (1980) used PCA for identification of land cover changes and mapping of bush fires and subsequent regeneration respectively.

2.3.3.1.2.2 Tasselled Cap Analysis (TCA)

The Gramm-Schmidt Orthogonalisation (GSO) technique was used to derive the coefficients of the Tasselled Cap transformation by Kauth and Thomas (1976). This method defines a new co-ordinate system, with the co-ordinates named as “brightness”, “greenness”, “yellowness” and “nonesuch” (Mather, 1999). The last two functions have not been widely used in the Tasselled Cap transformation; brightness and greenness functions, however, have often been used for vegetation analysis.

A slightly modified approach was used by Collins and Woodcock (1994) to detect changes of forest status using multi-temporal image data. They used the first three of the TCA components as stable components and derived the fourth component to represent change based on the GSO technique.

2.3.3.1.2.3 Vegetation Index Differencing (VID)

The operational procedure of Vegetation Index Differencing is similar to direct comparison methods. But prior to subtraction, this method requires each single date data set to be transformed into a vegetation index image using the near-infrared and red bands. Therefore, this method comes under transformation methods. This technique is used in this thesis, so a more detailed critical assessment is given in chapter 6.

2.3.3.1.2.4 Change vector analysis (CVA)

Change Vector Analysis was developed at the Environmental Research Institute of Michigan in the late seventies (Cohen and Fiorella, 1998). When the forest stand undergoes a change, its spectral appearance changes accordingly. The vector describes the direction and magnitude of spectral changes. The decision that a change has occurred is made if the magnitude of the computed spectral change vector exceeds a specified threshold criterion. The direction of the vector contains information about the type of change. This method is a combination of the Tasselled Cap transformation to greenness – brightness, with image segmentation into spatially contiguous pixel groups or "blobs", and a characterisation of the movement of the individual segments in spectral space in terms of magnitude and direction (Malila, 1980). It is based on the assumption that any change in the surface features between successive satellites overpasses results in a displacement of the pixel position in multi-dimensional space. The difference in position can be described by the change of vector in equation 2.6.

$$c\,(i) \;= \rho\,(i,\, t_1) - \rho\,(i,\, t_2) \qquad (2.6)$$

Where $\rho(i,t)$ is the multispectral reflectance of pixel i at time t, represented as vector and $c(i)$ is the change vector of pixel i between t_1 and t_2. While the relative utility of the technique to assess the type of change was not clear, this method performed well for automated change indication (Coppin and Bauer, 1996).

2.3.3.1.3 Classification-based approach

Changes between two multi-temporal data sets can also be identified using classification-based methods. These techniques use clustered data instead of radiance values on a pixel-by-pixel basis. Two popular classification-based methods are post-classification comparison and direct multi-date classification.

2.3.3.1.3.1 Post-classification comparison

This method was used by Howarth and Wickware (1980) to monitor vegetation change in the Peace-Athabasca Delta, northern British Colombia. The method of change detection is based on the comparison of separately produced classified images. It needs properly coded classification results for t_1 and t_2 and it can be used to produce change maps, which show a complete matrix of changes between classes. Furthermore selective classification allows the users to observe any subset of changes. Prior to the analysis of change categories, cover types should be predetermined and a classification legend constructed.

Training samples under each category should be selected from the images. Then the image classification routine can be performed on the entire data set. Detailed classification techniques can be found in Mather (1999). This method holds promise because if data from the two dates are separately classified, which minimises the problem of data normalisation for atmospheric and sensor differences between the two dates. Wiesmiller *et al.* (1977) found that this method reliably identified areas of change without the use of any coincident ground information for comparison purposes.

2.3.3.1.3.2 Direct multi-date classification

In order to identify areas of change, this method is based on a single analysis of a combined data set of two or more dates. These data sets may be analysed in either supervised or unsupervised classification mode. In the supervised approach, with reference to a predetermined classification legend, the training samples should be selected from the two available multi-temporal data sets by overlaying them as a colour composite on the image display system. Then the selected training samples of the change and no change areas can be derived statistically from the classification routine.

In the unsupervised approach, inspection of a small area of the image where known changes have occurred is used to derive classes by cluster analysis. This method is attractive because it requires only a single classification, but it is very complex. If there are several bands, some will be redundant in information content. Also the cluster labelling is usually difficult. Classification-based techniques have significant limitations because comparison does not allow the detection of subtle changes in land surface features as the number of classification categories limits it (Lambin and Strahler, 1994). However in this thesis a classification based technique with a single band was considered suitable for monitoring forestry operations.

2.3.4 Estimation of forest canopy parameters

Although this study uses optical data for the main analysis to monitor forest management operations, an understanding of the relationship between spectral reflectance and forest structural, variables such as LAI and above ground biomass, is also included in this review. The spectral response of the forest is closely linked with canopy parameters. In this section, the following three main canopy parameters are reviewed because estimation of these parameters is closely linked with NDVI.

1) Leaf Area Index.
2) Above ground biomass.
3) Stand characteristics.

2.3.4.1 Estimation of Leaf Area Index (LAI) using Vegetation Indices

An extremely important structural characteristic of the forest is LAI. It quantifies the amount of foliage area per unit ground surface area. It is therefore an important parameter controlling many biological and physical processes associated with vegetation on the Earth's surface, such as photosynthesis, evapo-transpiration, rainfall interception and canopy light interception. LAI is generally defined as the one-sided green leaf area per unit ground area in broadleaf canopies and as either projected or total green leaf area per unit ground in needle canopies (Myneni, 1997). There are direct methods to measure the leaf area and calculate the leaf area index, but these direct measurements are labour intensive and difficult in practice. The use of satellite imagery may offer a practical means to measure LAI on a landscape scale or above (Running *et al.*, 1986) However, in comparison to agricultural and grassland ecosystems, few experiments have attempted to study relationships between tree and forest LAI and satellite data. The majority of studies have been conducted on mature coniferous stands, with little work on young coniferous plantations. Although LAI is not measured directly in this study, an understanding of the relationship with spectral reflectance, as determined from the literature is important in the interpretation of this study results.

Some previous literature has shown spectral vegetation indices such as NDVI to be related to the forest LAI, and has tried to find the relationship between LAI and various vegetation indices. Running *et al.* (1986) reported that NDVI was useful for estimating the LAI of 18 coniferous forests along the west to east transect in Oregon, USA with the Airborne Thematic Mapper (ATM). ATM has seven spectral bands, three visible and four IR. A linear regression between LAI and a ratio of IR/red wavelengths as measured by ATM, provided an r^2 value of 0.76 with a standard error of 0.38. NDVI was less successful with $r^2 = 0.55$ and a standard error of 0.132. However, when Peterson *et al.* (1987) examined the relationship between remotely sensed red and NIR reflectance and LAI in the same Oregon forest site, although they found a negative relationship between LAI and red reflectance, they found no relationship between LAI and NIR reflectance.

Curran *et al.* (1992) also examined the relationship between LAI and NDVI. They mainly focused on seasonal variation in the LAI of young slash pine plantation (15-20 years old) in Northern Florida. The leaf area index of most forest canopies varies throughout the year; therefore it is difficult to estimate anything more detailed than an annual average LAI. So their estimate of the seasonal LAI of forest is useful for determining the seasonal exchange of energy and material between the forest canopy and atmosphere. The study compared field measurements of LAI with NDVI values, using LANDSAT TM data, for fertilised and control slash pine plots on three dates. They derived linear relationships between NDVI and LAI with r^2 values of 0.35, 0.75 and 0.86 for February 1988, September 1988, and March 1989, respectively. Once the relationships between NDVI and LAI had been obtained, they could be extrapolated spatially with LANDSAT TM imagery and thus used to derive seasonally sensitive ecosystem models over a number of years.

Carlson *et al.* (1997) expanded the study of relationships between NDVI and LAI. They applied a simple radiative transfer model with vegetation, soil and atmospheric components to illustrate how the NDVI, LAI and fractional vegetation cover are dependent. The model showed

1) That the customary variation of NDVI with LAI can be largely explained by a variation in fractional vegetation cover.
2) That NDVI increases much less rapidly with LAI when the fractional vegetation cover reaches 100%.
3) That scaling the NDVI between values for bare soil and for 100% vegetation cover factors out most of the atmospheric effect.

A study conducted in the temperate coniferous forest in Western USA aimed to establish the relationship between LAI and TM spectral bands (Spanner *et al.*, 1990). They found that the relationships between LAI of coniferous forests and TM spectral bands, ratios and transforms were affected by canopy closure, understory vegetation and background reflectance. They concluded that the strong inverse curvilinear relationship between LAI and TM bands 3 and 5 was a result of relatively high reflectance of the understory vegetation and background in open stands of lower LAI, and decreased reflectance of the conifer overstory in closed stands with high LAI. A strong positive relationship was observed between LAI and TM band 4 radiance in stands with greater than 89% canopy closure.

Another study investigated the relationship between satellite data from the LANDSAT 5 TM and estimated LAI of hardwood and mixed coniferous forest in North-Central Wisconsin (Fassnacht *et al.*, 1997). LANDSAT 5 TM data were used to estimate mIR min (mid infrared minimum) and mIR max (mid-infrared maximum). These values were used with data from each of the study sites to calculate a correlation with canopy cover. The NDVI was also tested. The utility of the TM data for estimating LAI was ascertained using two methods. The general linear model, Y = a LAI +b was investigated, where Y considered vegetation indices or individual reflective bands, LAI was treated as the independent variable to determine if multiple independent variables improved the fit over the single variable model. This study found that LAI ranged from 1.4 – 8.4 for different types of forest: e.g. in evergreen conifer forest, LAI ranged from 1.4 to 2.5, in broad leafed deciduous forest from 4.4 – 8.4 and in mixed conifer forest from 1.6 – 4.4. Then they tested separately the relationship between vegetation index and LAI, or individual bands and LAI in different types of forest, and found that multiple variable models provided better estimates of LAI than single variable regression. These results are not directly useful in this present thesis, but understanding of the relationship between vegetation index and LAI is useful to interpretation of NDVI and canopy cover.

2.3.4.2 Above ground biomass estimation with SAR data:

Above ground biomass is an important parameter for describing the function and productivity of forested ecosystems. Estimates of above ground forest biomass (mass per unit area) are important for determining the amount of organic matter that is stored in the forest ecosystem and give an indication of forest productivity and /or successional stage (Christensen *et al.* 1990). Recent studies have shown that Synthetic Aperture Radar (SAR) data can be used to estimate forest biomass (Dobson *et al.,* 1992; Rignot *et al*., 1994; Ranson and William, 1994; Ranson *et al.,* 1995a; Harell *et al.*, 1997; Ranson *et al.*, 1997; Luckman *et al.*, 1997). These studies relied on extensive ground truth measurements to construct relationships between biomass and SAR backscatter. Although radar backscatter from forest is influenced by structural properties (Imhoff, 1995), many studies have demonstrated useful relationships between backscattering coefficient and the aerial density of above ground biomass within particular types of forest (Le Toan *et al.*, 1992; Baker *et al.*, 1994; Imhoff, 1995).

A variety of approaches have been developed to assess aboveground biomass using Synthetic Aperture Radar (SAR) data (Dobson *et al.,* 1992; Kasichke *et* *al.*, 1995). SAR backscatter measurements improved the biomass estimation when compared with ground truth measurements using different stand components such as height, basal area and crown or branch biomass (Harrell *et al.*, 1997). Radar devices are sensitive to vegetation structure at the scale of the wavelength. The shorter X-band wavelength results in direct backscatter from foliage and is sensitive to leaf density and crown shape (Figure 2.1). Multiple interactions between vegetation and soil occur with C-band. The L–band provides direct backscatter from the soil surface, as well as interactions with boles and large branches. Radar backscattering comes from different parts of the trees. The orientation and size of branches, leaves and needles are important parameters for backscatter along with the tree height and age. On the other hand, different objects backscatter to different degrees, and this is described by the "backscatter coefficient". The amount of backscatter determines the tone of an image. For example, as it produces little backscatter towards the radar a flat surface produces a dark tone.

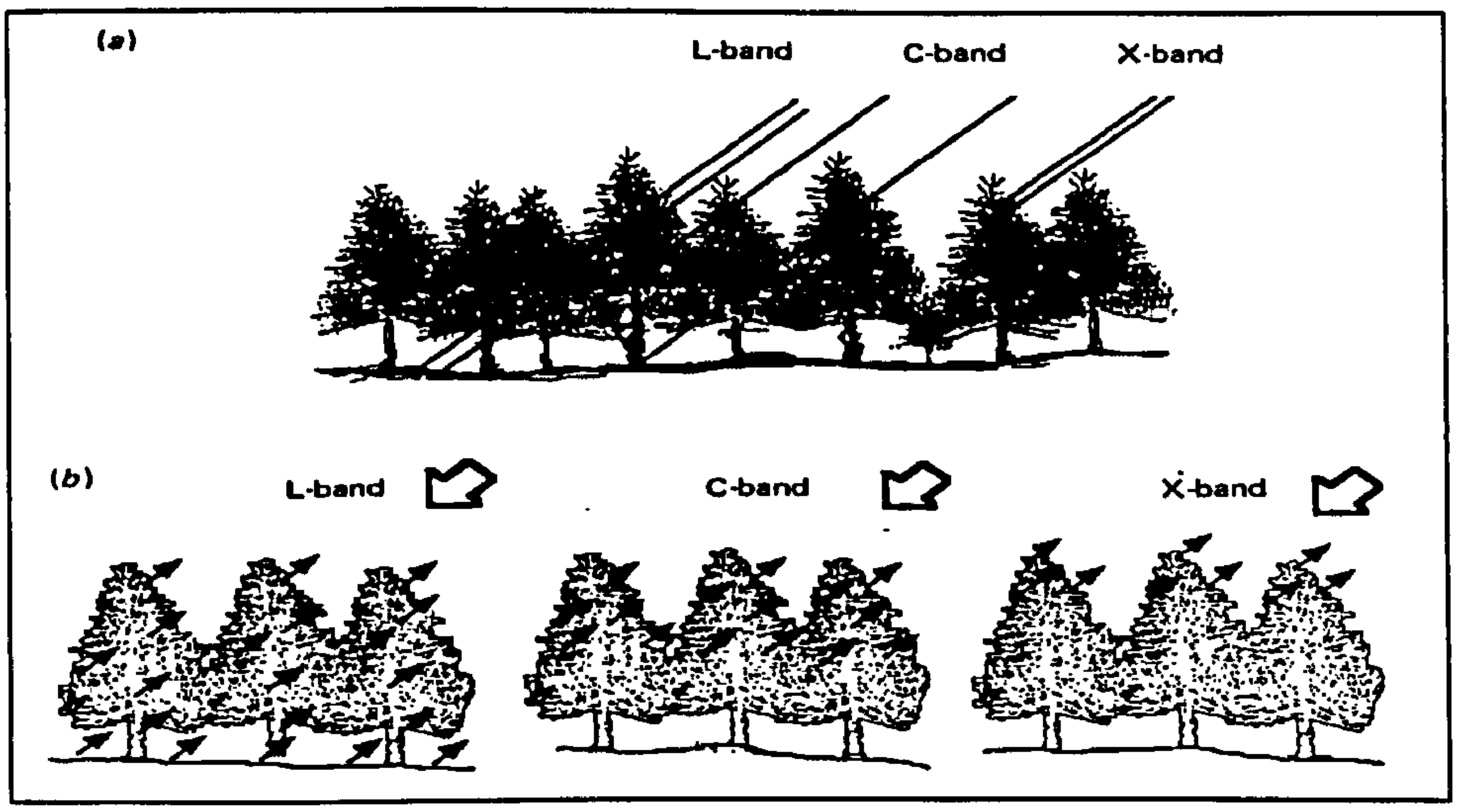


Figure 2.1: Interaction of different forest canopy layers with radar wavelengths

(a) The different wavelengths of radar sensors interact with different parts of a canopy.
(b) The penetration depth of different wavelength radar results in backscattering from different level within the canopy: X-band = 3 cm; C-band = 6 cm; L-band 23 cm (Ranson and Williams, 1992).

Forest and cropland give a medium tone and rough surfaces such as built up areas make a light tone (ESA, 1996). It has been found that cross-polarised backscatter is more strongly correlated with above ground biomass than co-polarised. Cross-polarised backscatter originates from multiple scattering within the tree canopy and is less influenced by surface condition than co-polarised returns, although this is influenced by incidence angle. Wu and Sader (1987) found, in a study of 13 pine stands, that the highest correlation coefficient for total tree biomass was obtained using L-band VH polarisation ($r = 0.768, p< 0.05$). A significant relationship between pine-dominant stands and backscatter was also observed by Sader (1987) using quad-polarised L-band SAR data. He found that the HV return gave the highest and most significant correlation coefficient for green biomass ($r = 0.76, p< 0.05$). No significant relationships were observed using HH or VV polarisation, or for hardwood sites using any polarisation. This later observation may have been due to significant differences between pine and hardwood canopy structure. Wu, (1987) however found all three L-band polarisations HH ($r = 0.744$), VH ($r = 0.888$) and especially VV ($r = 0.894$) gave estimates of total tree biomass of a slash pine plantation that were significant at the 95% level of confidence. After a multiple regression analysis, it was found that a combination of aircraft SAR VV and SIR- A HH channels provided the best estimator of total tree biomass ($r = 0.905, p < 0.05$).

Christensen *et al.*, (1990) observed positive correlations between L-band HH and VV backscatter and the above ground biomass of Loblolly pine forests up to levels of 100 tons ha^{-1}. These levels corresponded to the early stages of natural regeneration from abandoned agricultural land. A reason why backscatter should saturate whilst the average pine tree biomass increased throughout the life of tree stand appears to be change in stand structure. For example, pine density was constantly decreasing whilst the average pine tree biomass throughout the life of the stand was increasing. Other explanations suggested were a change in the tree geometry, variations of the local soil condition and the increasing importance of hardwoods in the pine stand.

The strength of relationship between backscatter, forest biomass and the biomass levels at which saturation occurs vary as a function of forest environment and SAR wavelength, polarisation and incident angle. The availability of multi-wave band/multi- polarisation SAR data has enabled these relationships to be explored in more detail in recent years. Kasischke *et al.* (1995) examined the dependence between calibrated backscatter and above ground biomass of loblolly pine stands as a function of wavelength using bands P- L- and C- of the NASA/JPL AIRSAR and ERIM/ NADC P- 3 SAR systems. All three bands showed a positive relationship, but correlations were insignificant in C-band, because interactions at C-band occur predominantly in the top levels of the canopy rather than sub-canopy components, such as trunks and lower branches. As wavelength increases, the amount of penetration through the forest canopy generally increases and interactions then occur with those components of the trees that are accumulating biomass. Hence the positive relationships were strongest for HH and HV polarisation in L- and P-bands.

Le Toan *et al.* (1992) and Beaudien *et al.* (1994) in a study involving a plantation of maritime pines in Les Landes, France confirmed that there is a strong correlation between L-band cross-polarised backscatter and total biomass. However, the use of P-band HV polarisation data increased the strength of correlation with trunk biomass ($r = 0.97$, $p < 0.01$). Kasischke and Christensen (1995) found C-band VV polarised ERS- 1 SAR data useful for monitoring areas of young Loblolly pine forest for biomass changes up to 60 tons ha^{-1} in Durham, USA. Linear correlation coefficients were significant at the 99% level of confidence or better between various components of biomass and SAR backscatter, with r values ranging from 0.87 to 0.93. They stated that C- band has the potential for monitoring biomass changes during the early successional stages in coniferous forests and throughout later stages in coniferous forests with low overall biomass.

Although these radar studies are not directly related to this thesis, they provide use full ideas to interpret the relationship between spectral reflectance and forest canopy cover.

2.4 FOREST PRODUCTIVITY MODELS USING NDVI DATA

The general term 'forest productivity' may be considered as the primary production or the rate of production of organic matter. It is based on the annual growth of all living plants within an ecosystem and it can be defined in two ways as follows.

1) Net primary production (NPP)
2) Gross primary production (GPP)

NPP is the production that can actually be measured in the field. GPP excludes production losses by respiration and is not directly measurable but it can be stated as a theoretical basis for production. Effects on primary production are an important aspect of any operational test of management scenarios. To understand gross primary productivity, more factors, particularly ecosystem processes such as energy intake, photosynthesis and respiration, need to be taken into account. Measuring the productivity of an ecosystem is not an easy task, particularly in forests where biomass resides in both the above and below ground portions of overstory trees. Therefore, scientists have used models to estimate the production of the forest. To estimate the production of forests at the regional level, two methods are available:

1) Field measurements: This approach is based on measuring tree heights, diameter at breast height (dbh) weight of leaves, branches, bole wood and sometimes roots, and is a very labour intensive task. Most foresters who have used field data to predict forest productivity have done so with the help of a yield model (Edwards, 1981).
2) Modelling plant productivity: Models are used to understand and explain why we observe what we observe. Models can be built at different levels of

abstraction. As far as research on forest productivity is concerned, three types of models are used:

1) Statistical models
2) Parametric models
3) Ecosystem simulation models

2.4.1 Statistical models:

Statistical models are used to express the form and function of environmental systems using inferential statistical techniques, such as correlation and regression. These models have random components and represent unpredictable fluctuations in field data, which may arise from measurement error and the inherent variability of the objects being measured.

Initial studies used a direct statistical approach to estimate forest standing biomass or other input parameters such as dbh, tree height and wood volume. The relationships between these parameters and satellite data have been examined using linear regression analysis, non-parametric line - fitting, and N-dimensional, K-neighbour classification approach. Most authors consider that there is a linear relationship between spectral response and biological variables of canopy (De Wulf *et al.*, 1990; Ahern *et al.*, 1991; Danson and Curran 1993). However, Franklin (1986) found a logarithmic relationship between the spectral response and biomass or basal area, since the spectral reflectance has a progressively weakening dependence on the variation of these two biological parameters when the degree of crown cover nears 100%. For LAI, the relationship with the near-infrared reflectance saturates more slowly than with the red reflectance and hence can be considered linear over larger range of LAI (Peterson *et al.*, 1987; Spanner *et al.*, 1990a). The relationship with the infrared/red ratio or with NDVI has been treated as linear (Asrar *et al.*, 1991; Curran *et al.*, 1992; Gholz *et al.*, 1996) or curvilinear (Peterson *et al.*, 1987; Spanner *et al.*, 1990b)

2.4.2 Parametric models

Parametric models use precise input parameters with an empirical relationship between the efficiency of the absorption of solar radiation by vegetation canopies and the vegetation index. Remote sensing data are processed to retrieve a vegetation index as close as possible to surface values.

Previous studies on the use of remotely sensed data to estimate forest parameters such as LAI indicate that the most commonly used models are light interception models. Such models can be used to validate earth observation data and simplify the problem, and make them easier to apply on large-scale satellite data. The light interception model is a simplification of the radiative balance equation in which the transmittance of the radiation through the canopy is modelled by the Bouguer-Lambert-Beer law as equation 2.7 (Varlet-Grancher *et al.*,1993)

$$\varepsilon_l = \varepsilon_{l,\infty} * (1 - \exp(-k^l * \mathrm{LAI}) \qquad (2.7)$$

ε_l = light interception efficiency

$\varepsilon_{l\infty}$ = light interception efficiency when LAI is infinite

k^l = extinction coefficient for light interception

$\varepsilon_{l\infty}$ depends mainly on the optical properties of the plant canopy elements. It is a function of the illumination geometry and canopy architecture as well as of the optical properties of the background and of the plant and woody elements (Pierce and Running, 1988). Direct measurement of $\varepsilon_{l,}$ is not possible and ε_l is calculated from the radiation transmitted through the canopy. A closed canopy, because of the negligible scattering of visible radiation, intercepts most of the visible incident radiation, which is not transmitted. The transmitted radiation is directly measured with radiometers. Many authors have used indirect measurements of ε_l. The value of ε_l depends on the optical properties of the canopy elements and in general it is functionally linked to the biomass production of the forest canopies, since the latter is the result of photosynthesis, through which a fraction of the intercepted incident solar reflectance energy is converted to biomass.

Another form of parametric model is based on the approach of Kumar and Monteith (1981) who considered instantaneous Net Primary Productivity - NPP (called P in the formulae) as a fraction of the incoming solar energy stored into organic dry matter, equation 2.8:

$$P(t) = e(t) * f(t) * S_0(t) \tag{2.8}$$

t = time

S_0 = incoming Photosynthetically Active Radiation (PAR)

f = equivalent to ε_1 in equation 2.7

e = the conversion efficiency of absorbed radiation into organic dry matter

According to Jarvis and Leverenz (1983), the fraction f of PAR absorbed by the canopy is determined by the following properties:

1) The direction of incoming radiation.
2) The proportion of diffuse radiation in global radiation and its hemispheric distribution.
3) The spectral properties of the optical elements (leaves) in the PAR.
4) The spatial distribution of these elements.
5) The structure of the canopy (LAI, leaf angles).

According to Kumar and Monteith (1981), the conversion efficiency e, is a relatively conservative value among plants of the same metabolic type. It can however vary with phenological stage, climatic conditions such as incoming radiation, temperature and water stress (Jarvis and Leverenz, 1983). A first step towards the introduction of environmental effects on the conversion efficiency of absorbed radiation into organic dry matter, has been made by considering that a mean e per major ecosystem type integrates the effects of environmental parameters such as mean temperature, water budget and interspecies variation

Conversion efficiency *e,* can be derived from the literature with respect to vegetation class. For seasonal estimates of growth, an average conversion efficiency (e_a) can be defined as the ratio of aboveground NPP to absorbed or intercepted radiation during the growing season. Absorption efficiency f is estimated through the use of remotely sensed radiance, while the incoming PAR (S_0) is derived from the climatic model.

Research indicates that f, the fraction of incoming PAR absorbed by the canopy, can be related to various combinations of red (R) and near infrared (NIR) surface reflectance of the canopy (Huemmrich and Goward, 1997). It can be also linearly related to the NDVI defined as in equation 2.9

$$NDVI = \frac{NIR - R}{NIR + R} \tag{2.9}$$

To retrieve the canopy absorption efficiency from remotely sensed reflectance, a linear relationship between f and NDVI is assumed: (equation 2.10)

$$f = \mathrm{a} + \mathrm{b} * \mathrm{NDVI} \tag{2.10}$$

Various authors have also used models of radiative transfer within the canopy to correlate the outputs concerning NDVI and f for various input data sets such as optical properties of soil, leaves, canopy structure etc. (De Wulf *et al.*, 1990; Ahern *et al.,* 1991; Danson and Curran, 1993). For most input sets and varying leaf area indices, non-linear relationships are found. However, when the inputs of the model run for several input sets are plotted on the same graph relatively good linear correlation coefficients are found (Gholz *et al.*, 1991; Asrar *et al.*, 1991; Curran *et al.*, 1992). Conversion efficiency (e_a) is defined as the ratio of aboveground NPP to absorbed or intercepted radiation during the growing season.

2.4.3 Ecosystem Simulation Models:

Simulation models express ideas about components and processes deemed to be important in a system, and some preliminary thoughts on how the components and processes are connected. They can give deep understanding of the dynamics of the environmental system, and increase understanding and predictions of ecological systems and components (Running *et al.*, 1988). Simulation modelling tends to be characterised by the use of simple mathematics applied using computers.

Ecosystem simulation modelling allows the investigation of responses and feedback of processes operating at a range of scales, with the ultimate objective of increasing the accuracy of predictions and understanding biosphere - atmosphere interactions. They can be used to calculate the carbon, water and nitrogen cycles through a forest ecosystem. These models can also be used to estimate potential Net Primary Production (NPP) using GIS data with information on species, soils, topography and climate. Remote-sensing input of forest leaf area into such models can provide estimates of current actual net primary production. Leaf area estimates are obtained from satellite imagery through correlation with physiologically based vegetation indices such as the Normalised Difference Vegetation Index (NDVI) (Running *et al.*, 1986).

Running *et al.* (1986, 1988) developed a general model of forest ecosystem processes for regional applications. In their research, they tried to couple satellite data with computed daily growth and development with the aid of a computer simulation model. The research suggested that the Normalised Difference Vegetation Index calculated from the AVHRR sensors is directly related to photosynthesis, transpiration and above-ground net primary production of terrestrial vegetation. This model FOREST-BGC (Bio-Geo-Chemical Cycles) deals with canopy interception and evaporation, transpiration, photosynthesis, growth and maintenance respiration, carbon allocation above and below ground, litter fall, decomposition and nitrogen mineralisation. The model uses Leaf Area Index to quantify the forest structure with the help of daily incoming short wave radiation, air temperature, dew point and precipitation as driving variables. The model was used to simulate the annual hydrologic balance and the net primary production of a hypothetical forest stand in seven contrasting environments across North America. This model is designed to be particularly sensitive to LAI, and LAI is used as the principal independent variable for calculating canopy interception, transpiration, respiration, photosynthesis, carbon allocation and litter fall.

The research by Running *et al.* (1988) used weekly NDVI data from 1983-1984 for seven sites of diverse climate in North America. Meteorological data from ground stations were retrieved to drive the FOREST – BGC, and the model calculated daily canopy photosynthesis, transpiration and net primary productivity of a hypothetical forest stand for the corresponding period at each site. Daily records of maximum and minimum air temperature, dew point and precipitation were retrieved from compiled records. Incoming solar radiation was derived using the climatological variables. The atmospheric transmission coefficient was computed based on the site elevation. Cloud cover was estimated based on daily maximum and minimum air temperature. Finally the daily transmission coefficient was multiplied by the potential radiation to give an actual incident radiation in kj/m^2/day. For data analysis, seven-day summaries of photosynthesis and transpiration to match the weekly NDVI composite were scaled to the NDVI data and plotted with them to aid in visual comparison of seasonal trends. Finally, the model for each site is calculated as an estimate for net primary productivity. A high correlation was found for annual integrated NDVI across all sites for both years with annual photosynthesis (r^2 = 0.87), annual transpiration (r^2 = 0.77) and annual net primary productivity (r^2 = 0.72).

2.5 FOREST MANAGEMENT OPERATIONS

Forest management requires up-to-date and accurate information about management operations such as thinning and felling. Clear felled areas are relatively easy to detect and delineate from satellite images (Yatabe and Leckie, 1995; Fransson *et al.*, 1999). Thinned areas can also be recognised (Herwitz *et al.*, 1990), but due to the background effect are less easy to detect.

However several studies have tried to determine thinning using satellite images.

2.5.1 Thinning Operations

Most forest stands in pine plantations will be thinned several times before the final cutting (felling). Thinning is the removal of a proportion of the trees in a stand. It has the twin purposes of providing income and giving space to improve the quality of the remaining trees, by accelerating individual tree growth. Normally 20% to 50% basal area in a stand is removed by total thinning (Hamilton, 1980). Usually for commercial plantations, records are maintained of the thinning and volume of timber removed. It should be possible therefore, to test whether satellite remote sensing can measure whether thinning has occurred. But the reflectance changes caused by thinning cuttings have received relatively little attention and are not yet well understood.

Herwitz *et al.* (1990) made a multitemporal study of the change caused by thinning of pine plantations in the United States. The main objective of their study was to determine whether LANDSAT TM data could be used to detect differences and changes in the leaf area of thinned and unthinned pine plantations in central Massachusetts. They determined that stand characteristics such as density, basal area and LAI of the particular pine plantation had decreased after thinning. The thinning treatment represented a canopy LAI reduction of 28%. They also measured the radiance differences in Band 3 and Band 4. Band 3 radiance increased significantly, whereas there was a 3.1% decrease in Band 4 radiance. But when they calculated the Band 4/3 ratio and NDVI (4-3)/(4+3), the band 4/3 ratio decreased by 23% and the NDVI by 7.1%. However, the decrease in the band 4/3 ratio was similar to that observed in nearby unthinned plantations. They concluded that the changes in the reflectance of the unthinned stands might be attributable to a moderate natural reduction in leaf area.

Nilson *et al.* (1992) investigated the reflectance change in 13 thinned Scots pine stands in Estonia. In these stands, around 50% of the stems were thinned because they were damaged. In the near infrared, a non-significant reduction was observed, but they found the best bands for discrimination were the middle infrared bands TM 5 and TM 7 and the thermal band TM 6. They also used a forest reflectance model, which showed that the influence of the ground layer was greater with increased thinning grade. The study, concluded that modelled reflectance change in a particular band due to thinning could be either negative or positive, depending on the assumed reflectance of the canopy and the ground layer. Their model also predicted that the reflectance as a function of tree density per hectare should be a non-linear function with a minimum point that is dependent on the solar elevation. To these analytical results they added that, in real thinning cuttings, the reflectance change might be influenced by the cutting debris that becomes red-brown during the first years after cutting.

Reflectance changes caused by thinning have been investigated using multi-temporal LANDSAT TM data in Sweden (Olsson, 1994). Information on thinning was obtained from local forest management staff. The mean changes in Digital Numbers (DN) for the thinned stands were obtained as the difference between the measured mean DN values after thinning and values from an earlier image. These DN residuals were then scaled to changes in reflectance by use of a radiative transfer code. The results showed that thinning caused an increased reflectance in all reflective TM bands except TM4. The increase was most significant in TM5, TM7 and TM3.

2.5.2 Clear felling

Identification of clear felled areas within a forest using satellite images is one of the most useful areas of research for forest management. Yatabe and Leckie (1995) evaluated and compared the ability of three satellite-borne SAR systems to discriminate clear cuts from different test areas of three main cover types: forest stands, wetlands and open fields. Their observations were made visually, by analysing plotted digital values, and confirmed through statistical separability measurement. They concluded that detectability of clear cuts increases with the sparseness of the vegetation. They also identified that JERS-1 and Almaz images are superior to ERS-1 images in discriminating between clear felled and forest areas, because clear cuts cannot be consistently detected in ERS-1 images, particularly where there is rugged terrain. The backscatter of the clear cuts in the ERS-1 images appears to be related to environmental conditions during the acquisition of the images.

Fransson *et al.* (1999) analysed the separability of recent clear felled areas and forested areas using Almaz-1 SAR data from two subsequent years in combination with optical data (SPOT-panchromatic). The first objective of this study was to develop methods for detecting recently clear felled forested areas by using multi-temporal SAR data with the segmentation of the forest into relatively homogeneous areas based on optical remotely sensed data. The second objective was to calculate the accuracy with which clear felled areas could be separated from forest areas. In this study optical imagery was used to segment the forested areas into homogenous regions. Then for each segment, statistical features based on the first and second order histogram were computed in the two radar images. The changed areas were identified by linear discriminant analysis with cross-validation. They found that using the segment mean values, 61.4% of the clear felled areas were correctly classified under the premise of equal errors of omission and commission.

Bertrand *et al.* (2000) used LANDSAT imagery for change detection over an eleven year time period (1988-1999) to explore the effect of clear-cut and partial cut harvesting patterns. During this period, they found that the number of clearcuts as well as the mean size of clearcuts decreased. On the other hand, the percentage of area that experienced partial cutting remained constant, with a decrease in the number of partial cuts and an increase in size. They also concluded that change maps had overall accuracies between 90% and 94% and distinguished between clear cuts and partial cuts over four year periods. This study recognised that satellite images covering large areas of land have the potential to monitor forest change, and contribute to forest inventory and management goals in a cost-effective manner.

Wilson and Sader (2002) detected levels of forest harvest using a simple and relatively accurate technique of classifying time series LANDSAT TM imagery. This study utilised time series satellite imagery to detect levels of harvest disturbance in a forest stand. The main objective was to compare the success of different satellite remote sensing techniques to detect forest harvest intensity over time in an industrial forest site in Maine USA. Initially the study compared two vegetation indices, the normalised difference vegetation index (NDVI) and the normalised difference moisture index (NDMI) for detecting harvested areas. NDMI is calculated by equation 2.11 where NIR is LANDSAT TM band 4 and the mid- infrared (MIR) is LANDSAT TM band 5.

$$\mathrm{NDMI} = \frac{(near - \inf rared) - (mid - \inf rared)}{(near - \inf rared) + (mid - \inf rared)} \tag{2.11}$$

They found that the NDMI method produced significantly higher accuracies (ranging from 79% to 96%) than the NDVI method for detecting clear cuts. However, detecting partial harvesting was less accurate (55%-80%). These results are interesting because the less common NDMI (using the reflected middle infrared band), out-performed the more popular NDVI. They concluded that NDVI change detection classification applied to LANDSAT TM imagery collected every 2-3 years appears to be a promising technique for monitoring forest harvesting and other disturbances that do not remove the entire overstorey canopy.

2.6 SUMMARY

The aim of this chapter was to review literature relevant to the research presented in this thesis. The fundamentals of remote sensing application for forest research were summarised and discussed under different sub headings. A number of points that are relevant to this thesis emerge from this literature review.

The application of satellite data to forest resource inventory is very important for management planning. Most of the earlier studies were carried out for collecting and monitoring forest data. They used mainly SPOT and LANDSAT optical data to evaluate forest stand variables. Mapping forest cover information is one of the efficient tools of forest management. Satellite based remotely sensed data have been used to map forest data since 1972. These data provide an opportunity for viewing a given area at intervals down to successive days. Improvement of computer software and development of image processing algorithms in recent years has provided high quality map information for forest management. Classification of multi-spectral images has also promoted separation of different types of forest features. Recent advances in remote sensing systems and computer based image processing systems with digital satellite data has also increased the accuracy and effectiveness of detection of changes in forest cover. This area of study, especially digital change detection methods, was used to analyse forest cover changes temporally.

It is well established that forest cover information can be detected by a variety of methods of analysis using satellite images. It can be found in the review that forest inventories, classification and mapping performed reasonably in certain situations. But forest cover monitoring using change detection application is the most appropriate for management activities. Although satellite data have shown a good capability for mapping broad forest types, they are not suitable for management inventories. However, a large variety of change detection methods provide good estimates of forest cover increase and decrease separately. This method may be very useful and can be efficiently integrated into the forest management decision making process. Incorporation of this information into computer aided decision support systems will assist forest management activities, such as thinning and felling operations.

CHAPTER THREE

PRINCIPLES OF REMOTE SENSING FOR FOREST MANAGEMENT

3.1 INTRODUCTION

Remote sensing instruments acquiring radiation at different wavelengths have been widely used to measure different variables in forest stands, such as canopy, crown, and trunk. Optical sensor systems measure reflected solar radiation in one or more discrete wavebands located in the spectral range 400-3000 nm, whereas active Synthetic Aperture Radar (SAR) systems measure backscattered microwave radiation at wavelengths between 1 and 1000 cm (Lillesand and Kiefer, 1994). The optical remote sensing systems provide information on canopy cover in forested areas, whereas microwave systems provide information on woody biomass and forest structure. Because the optical wavelengths are much smaller than the leaves, needles and branches of the forest canopy, radiation may be absorbed and scattered by these components. Whereas the longer microwave wavelengths energy may penetrate the canopy to interact with trunks and the ground (Danson, 2000).

The amount and the spectral distribution of radiant flux leaving from the vegetation canopy is influenced by the type and amount of vegetation present. For example, young pine tree canopies with less than 100% canopy closure reflect energy differently from a mature pine tree canopies with more canopy closure. With 100% canopy closure, the understorey and soil beneath are not visible through the canopy whereas canopies with less than 100% canopy closure allows parts of the understorey or soil to reflect back to the sensors. The spectral reflectance of a continuous canopy cover gives basic information on the distribution and, density of green cover of the vegetation present. In the field of remote sensing applications, scientists have developed vegetation indices for evaluating vegetation cover quantitatively using spectral measurements (Pearson and Miller, 1972; Rouse *et al.,* 1974; Huete, 1988; Baret *et al.*, 1991; Bannari *et al.,* 1995).

This chapter contains two main sections. The first section reviews the characteristics of remote sensing data in the optical region of the electromagnetic spectrum and describes how these data have been used to study forest cover changes. Then it discusses leaf structure and spectral characteristics of vegetation and their effects on the quantitative analysis of forest cover. The second section deals with characteristics of forest management under four sub-headings: the nature of forest management; needs and methods of data collection for forest management; planning and forest management operations.

3.2 BASIC CONCEPT OF REMOTE SENSING

Remote sensing is a scientific technology that can be used to measure and monitor important characteristics and activities on the Earth. It can be defined as the acquisition and recording of information about an object without being in direct contact with the object (Gibson, 2000). Very specific information about an object or the geographic extent of a phenomenon is obtained using variety of sensors. The sensors that are currently in use for recording information are divided in two groups: active and passive systems. The active sensors generate and transmit signals towards the object, then receive and record the returned signals after its interaction with the object. The passive sensors do not generate or transmit signals but detect and record the natural electromagnetic energy reflected and/or emitted from an object (Gibson, 2000).

3.2.1 Electromagnetic radiation

Electromagnetic radiation is the source of all signals collected by remote sensing instruments and satellite-borne sensors measure this electromagnetic energy. Electromagnetic radiation refers to all energy that moves with the velocity of light in a harmonic wave pattern. Most systems rely on the sun to generate all the EM energy needed to image terrestrial surfaces. These systems are called passive sensors. Other sensors called active sensors generate their own energy, and transmit that energy in a certain direction and record the portion reflected back by features within the signal path.

The detection of the properties of objects by remote sensing is based on the processing of electromagnetic energy, which spans a wide spectrum of wavelengths ranging from 10^{-10} to 10^{+10} micrometers (μm). The most used portions of the Electromagnetic Spectrum (EMS) are the range of optical wavelengths from 0.3 μm to 15.0 μm and the microwave wavelength from 1 mm to 1 meter (Figure 3.1). This range is usually subdivided into the following regions:

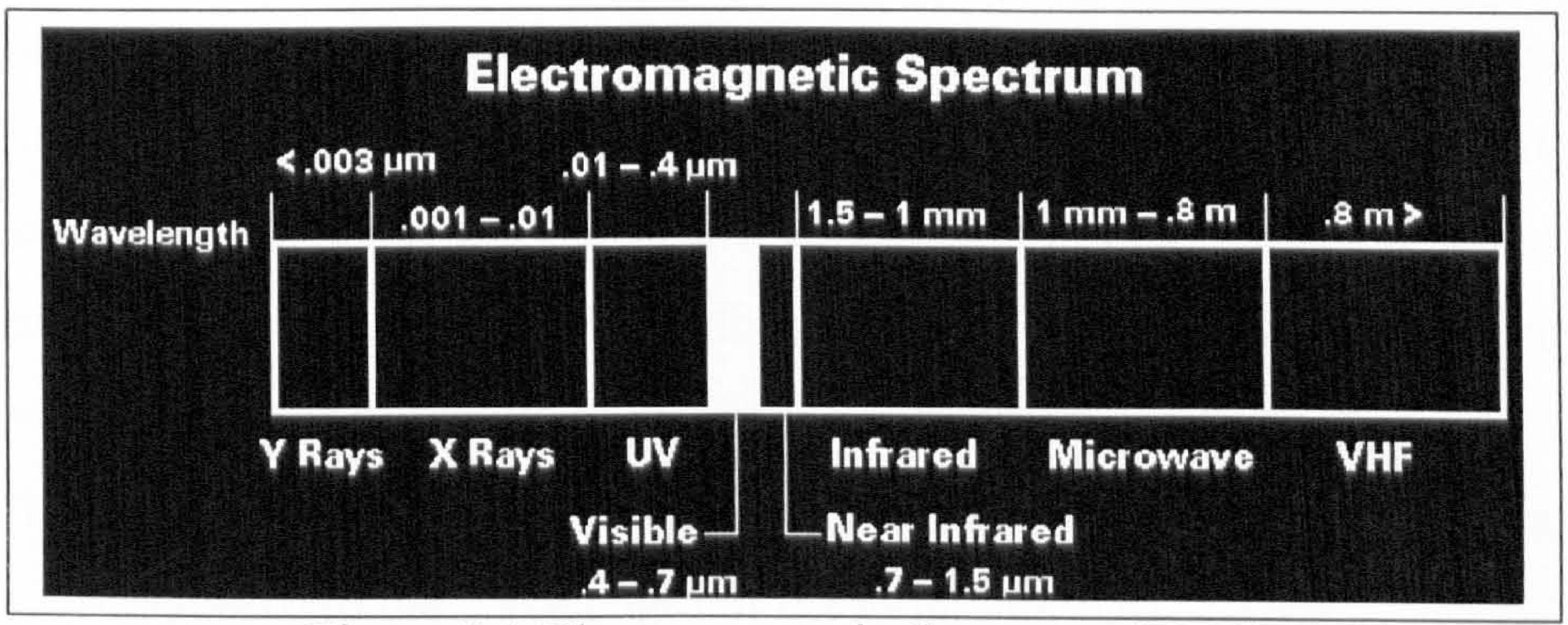


Figure 3.1 Electromagnetic Spectrum (EMS)

(http:**www.sci-ctr.edu.sq/ssc/publication/remotesence/em.htm#spectrum**)
Singapore science centre 2001

1) The visible region, wavelengths from 0.4μm to 0.7μm.

    a) Blue from 0.4µm to 0.5µm.
    b) Green from 0.5µm to 0.6µm.
    c) Red from 0.6µm to 0.7µm.
2) The infrared region, wavelength from 0.7µm to 15µm.
    a) Near-infrared from 0.7µm to 1.0µm.
    b) Mid-infrared from 1.0µm to 3.0µm.
    c) Thermal-infrared from 3.0µm to 15µm.
3) The microwave region, wavelength from 1 mm. to 1 meter.

These divisions of the electromagnetic spectrum are established for convenience and by tradition within the field of remote sensing. There is no clear-cut dividing line between one nominal spectral region and the next. Divisions of the spectrum have grown out of the various methods in sensing each type of radiation rather than from inherent differences in the energy characteristics of various wavelengths (Lillesand and Kiefer, 1994).

3.2.1.1 Energy interactions in the atmosphere

Radiation from the Sun is reflected by the Earth and then is detected by the satellite sensors, passing through the atmosphere twice, once on its way from the sun to Earth and then from Earth back to the sensor after being reflected. During these two journeys through the atmosphere, particles and gases can affect radiation by scattering and absorption. Scattering occurs when particles or large gas molecules present in the atmosphere interact with and cause the electromagnetic radiation to be redirected from its original path. There are three types of scattering:

1) Rayleigh scattering – This occurs when particles are very small compared to the wavelength of the radiation.
2) Mie scattering – This occurs when the particles are about the same size as the wavelength of the radiation.
3) Non-selective scattering – This occurs when particles are much larger than the wavelength of the radiation. The effect of this scattering is

important for remote sensing because all visible wavelengths are non-selectively scattered by the water droplets of which clouds are formed. It increases the haze level or reduces the contrast in an image. This reduction in contrast will result in a decrease in the detectability of features present in the image.

The second process by which the Earth's atmosphere interacts with incoming electromagnetic radiation is absorption. This is the process by which radiant energy intake is converted into other forms of energy. Gases such as Carbon Dioxide (CO_2), Oxygen (O_2), Ozone (O_3), Nitrous Oxide (N_2O) and water (H_2O) absorb radiation in particular regions of the Electromagnetic Spectrum called absorption bands. These regions are generally not suitable for remote sensing because to little energy is available to be sensed. But various portions of the spectrum (visible/near infrared 0.3μm-1.3μm, mid infrared 1.5μm-4.1μm and thermal infrared 7.0μm-15.0μm), called atmospheric windows, are useful for remote sensors because they transmit radiant energy effectively and are not severely influenced by atmospheric absorption (Jensen, 2000).

3.2.1.2 Energy interaction with the Earth surface

Solar radiation that is not absorbed or scattered in the atmosphere reaches and interacts with the Earth's surface. It may be reflected, transmitted or absorbed. Absorption occurs when the objects absorb radiation (energy) while transmission occurs when radiation passes through the objects. For example, in a forest, leaves absorb most of the visible wave band for photosynthesis, but some energy is also transmitted through the canopy.

Reflection occurs when radiation "bounces" off the object and is redirected. In both optical and radar remote sensing, the radiation reflected from objects is the source of information. There are two ideal types of reflection:

1) Specular reflectors are flat surfaces, where the angles of reflection equal the angle of incidence.

2) Diffuse or Lambertian reflectors are rough surfaces that reflect uniformly in all directions.

Most of the forest cover surfaces are diffuse reflectors (Figure 3.2). Diffuse reflections contain spectral information on the colour of the reflecting surface, so in remote sensing of vegetation we are most often interested in measuring the diffuse reflectance properties of vegetation cover features.

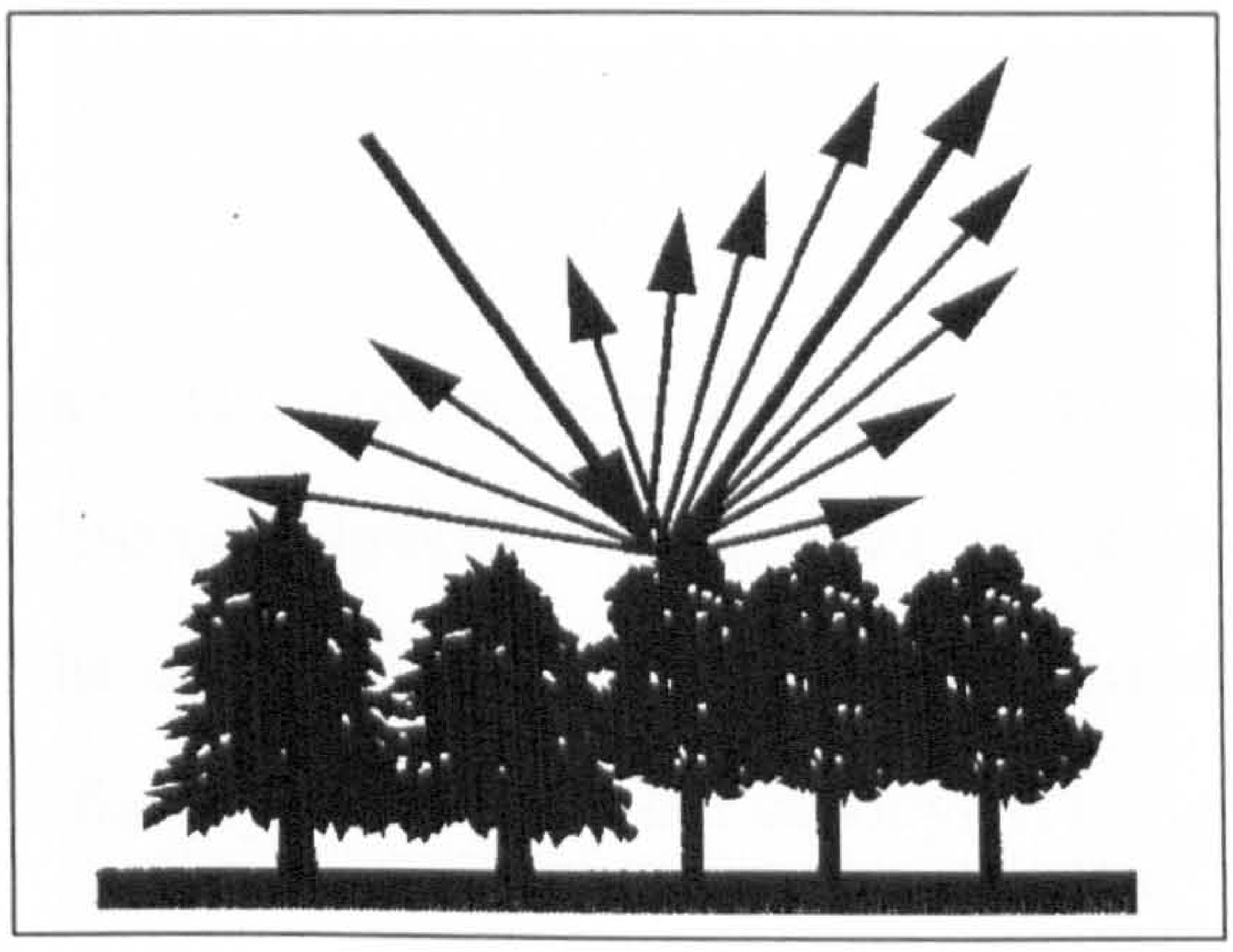


Figure 3.2: The nature of diffuse reflectance

from coniferous trees (Jensen, 2000)

In leaves, chlorophyll strongly absorbs radiation in the red and blue wavelengths but reflects green wavelengths. The internal structure of healthy leaves act as excellent diffuse reflectors of near-infrared wavelengths. The proportions of red and near-infrared radiation reflected provide an indication of vegetation health (Jensen, 2000).

3.2.2 Spectral Characteristics of Vegetation

The uppermost cover of a vegetation or forest canopy intercepts electromagnetic radiation transmitted through the atmosphere. The amount of incident radiant flux may be reflected, transmitted or absorbed. The amount of radiant energy reflected, transmitted or absorbed by a surface per unit time is called the radiant flux and is measured in Watts (Jensen, 2000). The characteristics of the radiant flux and what happens to it as it interacts with the Earth's surface is of critical importance in remote sensing. The spectral distribution of the reflected energy is used in remote sensing to infer the nature of the reflecting surface.

As many remote sensing systems operate in the wavelength regions in which reflected energy predominates, the reflectance properties of surface features are very important. So, it is useful to think of the energy reflected from the plant leaf surface as equation 3.1

$$r_\lambda = i_\lambda-(\alpha_\lambda+\tau_\lambda) \qquad (3.1)$$

Reflection (r_λ) of the plant leaf surface is equal to the incident energy (i_λ) minus the energy absorbed directly by the plant for photosynthetic or other purposes (α_λ) and the amount of energy transmitted directly through the leaf onto other leaves on the ground beneath the canopy (τ_λ).

The reflectance characteristics of the Earth's surface features may be quantified by measuring the proportion of incident energy that is reflected. This reflection is measured as a function of wavelength and is called spectral reflectance (ρ_λ). It is expressed as a percentage and a graph of it for an object as a function of wavelength is termed a spectral reflectance curve. The idealised spectral reflectance curves for two types of tree shown in Figure 3.3. It gives an insight into the spectral characteristics of the vegetation cover. The spectral reflectance curves for each tree type overlap in most of the visible portion of the spectrum, with relatively low values in the red and blue regions and a peak in the green region. These features are due to the absorption of blue and red light to provide energy for photosynthesis. There is a slight peak in reflectance at about 0.55 μm for both types of trees, which is the reason why growing vegetation appears green. In the "red edge" region (0.75 μm), reflectivity rises sharply and it remains high in the near-infrared region (0.75 and 1.35μm). The gap between the spectral reflectance of the deciduous and the coniferous trees is greater in the near-infrared region than the red region of the spectrum.

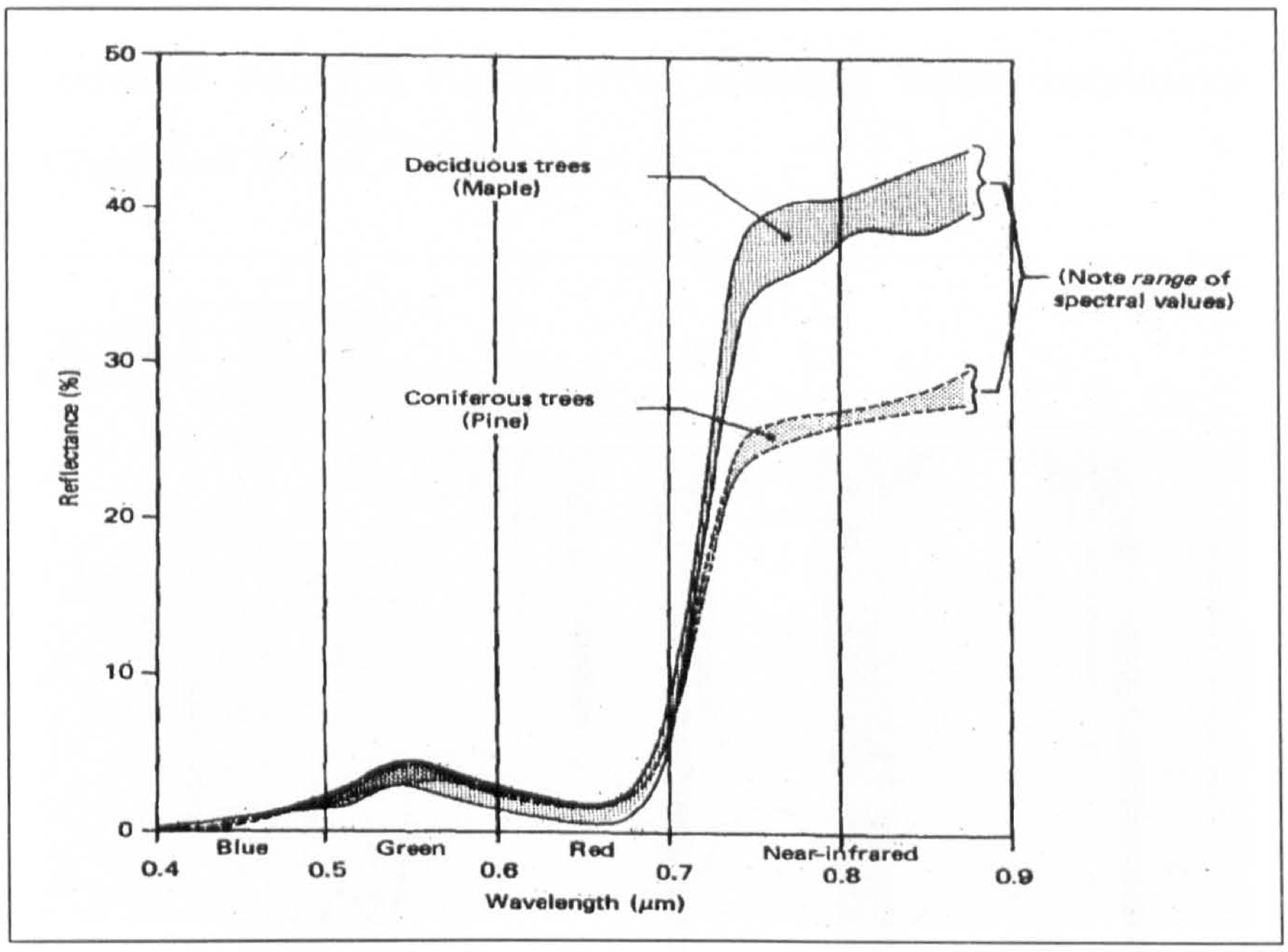


Figure 3.3: Idealised spectral reflectance curve for deciduous and coniferous trees (Lillesand and Kiefer, 1994)

Various factors control leaf reflectance and the transmittance of light in the different wavelengths of the spectrum. These are the shape and thickness of the leaf, pigments contained in the leaf and leaf water content. Peterson and Running (1989) pointed out that leaf pigments, internal scattering and leaf water all affect the reflectance and transmittance. The proportion of energy reflected, absorbed and transmitted varies for different vegetation structures, depending on vegetation type and size. These differences permit to distinguish different species of trees and different ages of the vegetation cover on an image.

The spectral reflectance of a living leaf is shown in Figure 3.4. At the edge of the visible region, as the absorption of red light by chlorophyll pigments begins to decline, reflectance rises sharply in the region from 0.70–1.20μm. The peak reflectance of a living plant is not in the green, but in the near infrared. The healthy green leaf reflects approximately 46% of the near infrared energy at 0.90μm (Jensen, 2000). The response of the near-infrared band is very useful for separating vegetation from non-vegetated surfaces. Furthermore differences of reflectance of plant species are more pronounced in the near infrared than the visible green allowing better discrimination of different vegetation types.

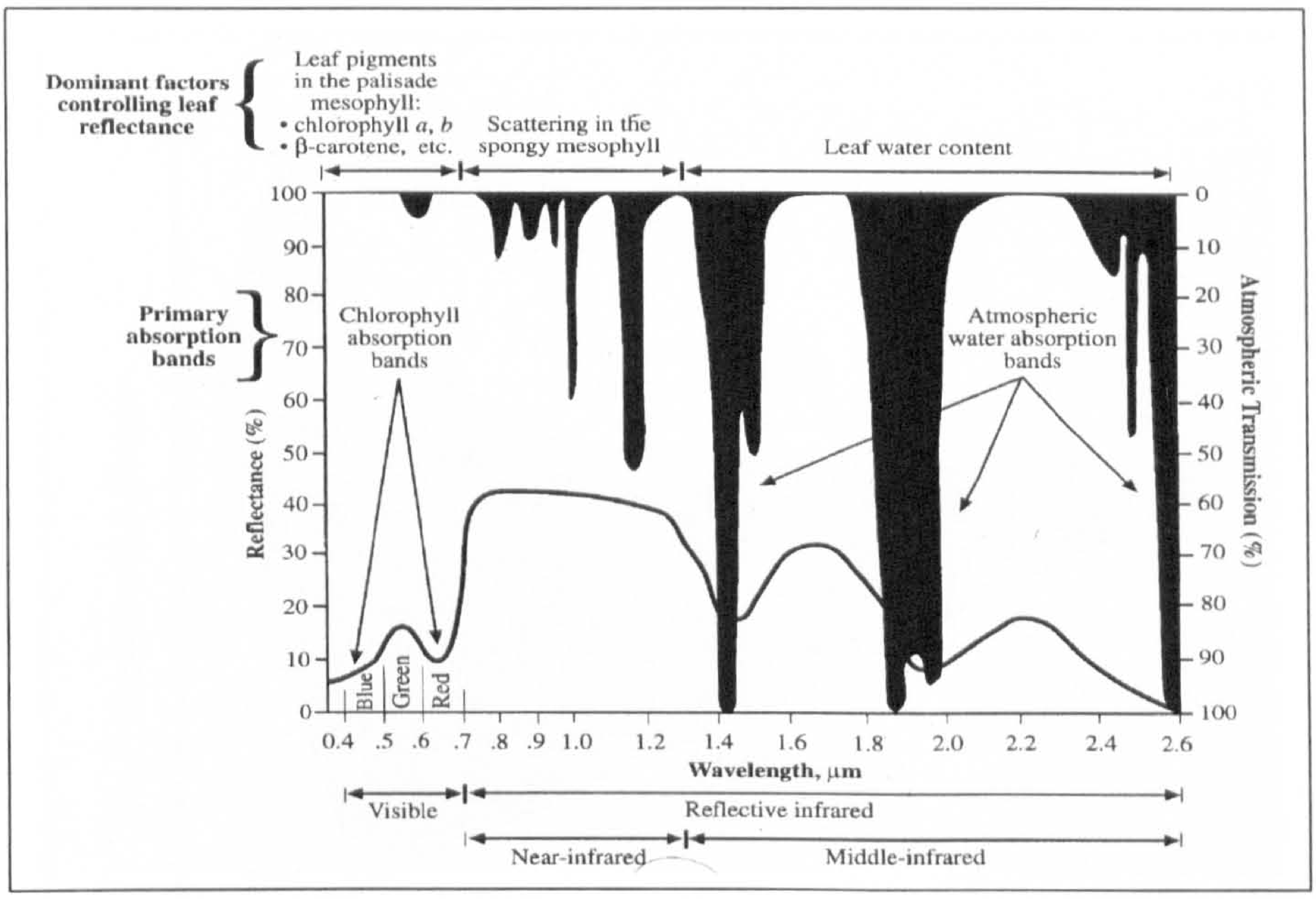


Figure 3.4: Spectral reflectance characteristics of green vegetation for the different wave lengths (Jensen, 2000)

3.2.2.1 Spectral reflectance characteristics of red and NIR regions

Reflectance characteristics in the red and near-infrared (NIR) regions are very important for vegetation studies. In the red region, absorption is very high, so that reflectance is low and leaf transmittance is also very weak. At the edge of the visible spectrum, absorption begins to decline; as a result reflectance rises sharply in the NIR region. In a typical healthy green leaf, the near-infrared reflectance increases dramatically in the region from 700 –1000 nm (Jensen, 2000): 40%-60% of the radiation is reflected; 40%-60% is transmitted through the leaf onto underlying leaves and 5%-10% is absorbed.

Canopy spectral characteristics in the red and near-infrared regions have resulted in the development of numerous remote sensing vegetation indices.

Biomass estimation techniques also use multiple measurements in the visible and near infrared region (Lyon *et. al.,* 1998). A direct positive relationship between near infrared and plant biomass has been found together with an inverse relationship between the visible region and plant biomass (Figure 3.5).

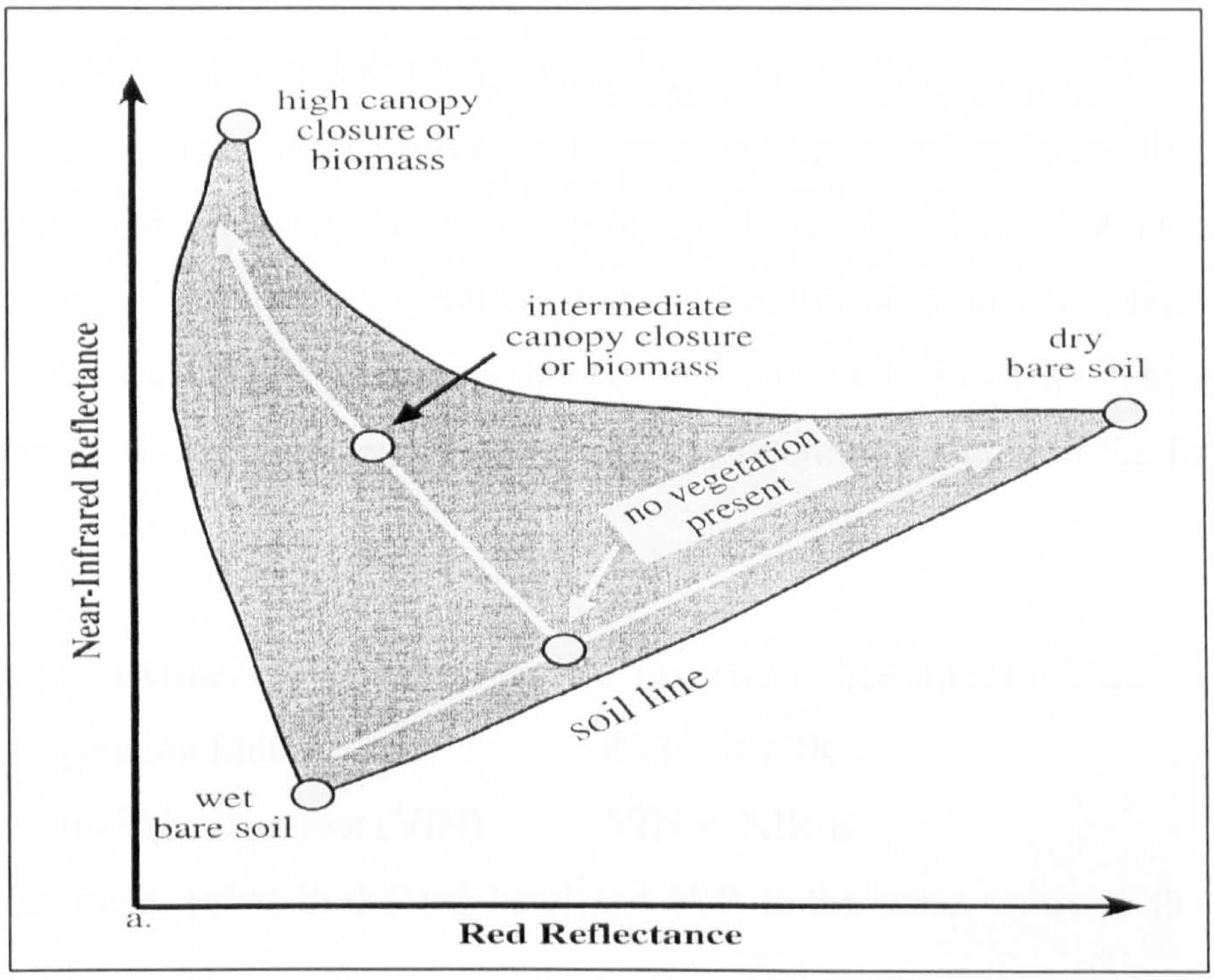


Figure 3.5: Response in red and near infrared region for different surfaces (Jensen, 2000)

This diagram shows reflectance changes with growing vegetation for different soil types. Wet soil reflects very low red and near-infrared energy. Conversely, a dry bare soil has higher red and near-infrared reflectance. In the graph, therefore, dry and wet bare soils are located at opposite ends of soil line. In this situation, a positive relationship appears between red and near-infrared reflectance. When vegetation canopy cover expands it reflects more near-infrared energy, while at the same time absorbing more red radiant flux for photosynthesis. As a result, the spectral reflectance of the pixel moves away from the soil line creating a negative relationship between red and near-infrared reflectance.

3.2.2.2 Vegetation indices

In the field of remote sensing application for vegetation studies, many authors have developed Vegetation Indices (VI) for quantitative and qualitative evaluation of vegetation covers using spectral reflectance measurements (Pearson and Miller, 1972; Rouse *et al.* 1974; Jackson, 1983; Huete, *et al.*, 1988; McNairn and Protz, 1993). They have shown that the use of red and near-infrared bands of the sensors on board satellites is particularly well suited for vegetation studies. The combination of these two spectral domains is helpful to discriminate vegetation from other surfaces and to determine photosynthetically active biomass through vegetation cover density. Therefore, this section reviews the vegetation indices most commonly used in the field of forestry studies.

Pearson and Miller (1972) developed the first two indices in ratio form:
Ratio vegetation Index (RVI) - RVI = R/NIR
Vegetation Index Number (VIN) - VIN = NIR/R
R is the mean value in the red band and NIR is the mean value in the near infrared band. These indices were developed using raw satellite DNs without transformation into reflectance. The validity of these two indices is low when the vegetation cover is less dense because they are sensitive to atmospheric effects and their discriminative power is weak

Numerous ratio-based vegetation indices have been used to estimate amount of vegetation present the most common being the Simple Ratio (SR) and the Normalised Difference Vegetation Index (Goward *et al.*, 1991; Baret *et al.*, 1991; Huete *and Lie,* 1994; Teillet *et al.*, 1997).The Normalised Difference Vegetation Index (equation 3.3) and the Simple Ratio (equation 3.4) are defined as follows:

$$NDVI = \frac{NIR - R}{NIR + R} \qquad (3.3)$$

$$SR = \frac{NIR}{R} \qquad (3.4)$$

Where R and NIR now represent surface reflectance averaged over ranges of wavelengths in the visible (λ~0.6 μm) and near-infrared (λ~0.8 μm) region of the spectrum, respectively. It is clear from its definition that the NDVI is not an intrinsic physical quantity, although it is correlated with certain physical properties of the vegetation canopy such as Leaf Area Index. (Curran *et al.*, 1992)

Various investigators have observed relations between NDVI and LAI. Carlson and Ripley (1997) stated that NDVI increases almost linearly with increasing LAI and then enters an asymptotic regime in which NDVI increases very slowly with increasing LAI. Curran (1983) pointed out that the latter asymptotic region pertains to a surface almost completely covered by leaves. The upper asymptote of NDVI versus vegetation density or LAI usually occurs near an NDVI value of 0.7-0.8 for sparse to dense vegetation. This upper limit however is rather variable and depends on vegetation type, age and leaf water content (Paltrige and Barber, 1988). For bare soil, NDVI tends to vary between -0.1 and 0.2 (Spanner *et al.*, 1990b). Nemani and Running (1989) showed that the change in LAI is nearly linear with NDVI until the former exceeds values of 3-4, above which NDVI rapidly loses sensitivity to increases of LAI.

3.2.2.3 The Bidirectional Reflectance Distribution Function (BRDF)

Most forest surfaces reveal a relationship between the amount of reflected radiance and the geometric characteristics of the Sun's irradiance and the sensor viewing geometry. It explains the bidirectional reflectance factor which is the ratio of the flux scattered into a given direction by a surface under given illumination conditions, to the flux scattered in the same direction by a perfect Lambertian more scatter under the same conditions. It is related to the BRDF or f_r, that is the ratio of reflected radiance in a given direction to the incident irradiance. It is formally defined as the ratio of radiance reflected in one direction to the Sun's incident irradiance from another direction (Sandmeier, 1999) as in equation 3.5

$$f_r(\theta_{i,}\varphi_i : \theta_{r,}\varphi_r : \lambda) = \frac{dL(\theta_{i,}\varphi_i : \theta_{r,}\varphi_r : \lambda)}{dE(\theta_{i,}\varphi_i)} \tag{3.5}$$

dL = the radiance reflected in one direction [W m^{-2} sr^{-r}]

dE = Sun's incident irradiance [W m^{-2}]

$\theta_i\varphi_i$ = Sun's zenith angle and azimuth angle

$\theta_r\varphi_r$ = Sensor zenith angle and azimuth angle

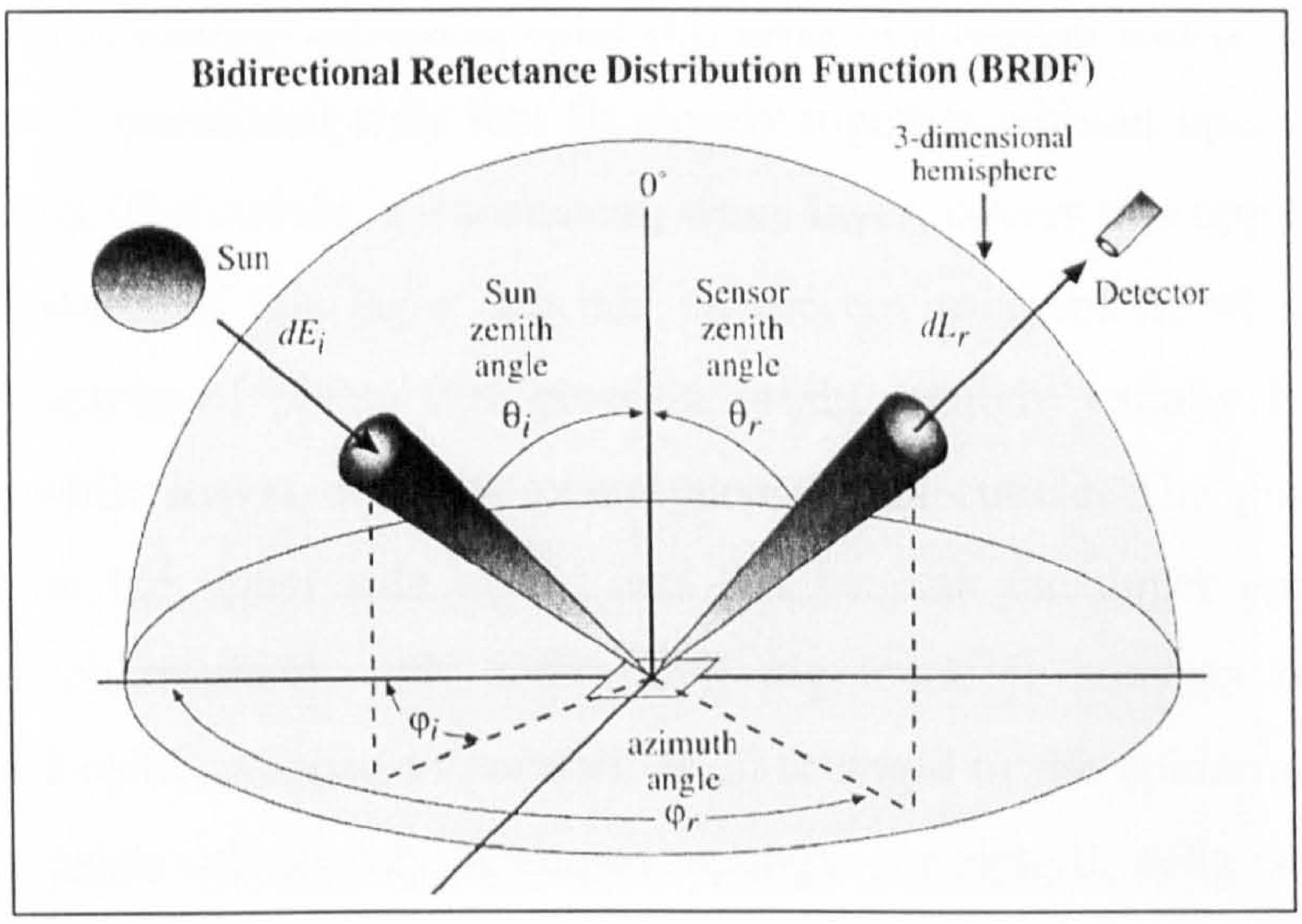


Figure 3.6: Bidirectional Reflectance Distribution Function (Jensen, 2000)

The bidirectional effect in remote sensing data is most obvious when the angle of illumination and sensor viewing angle are nearly identical in the same plane as shown in figure 3.6. That is where the BRDF effects are most pronounced. If the amount of radiant flux leaving the target is influenced by the sensor angle of view, may need to adjust for BRDF effects in order to compare remote sensing data obtained on multiple dates. If the reflectance is uniform then it is not necessary to account for BRDF effects.

3.2.3 Vegetation Response

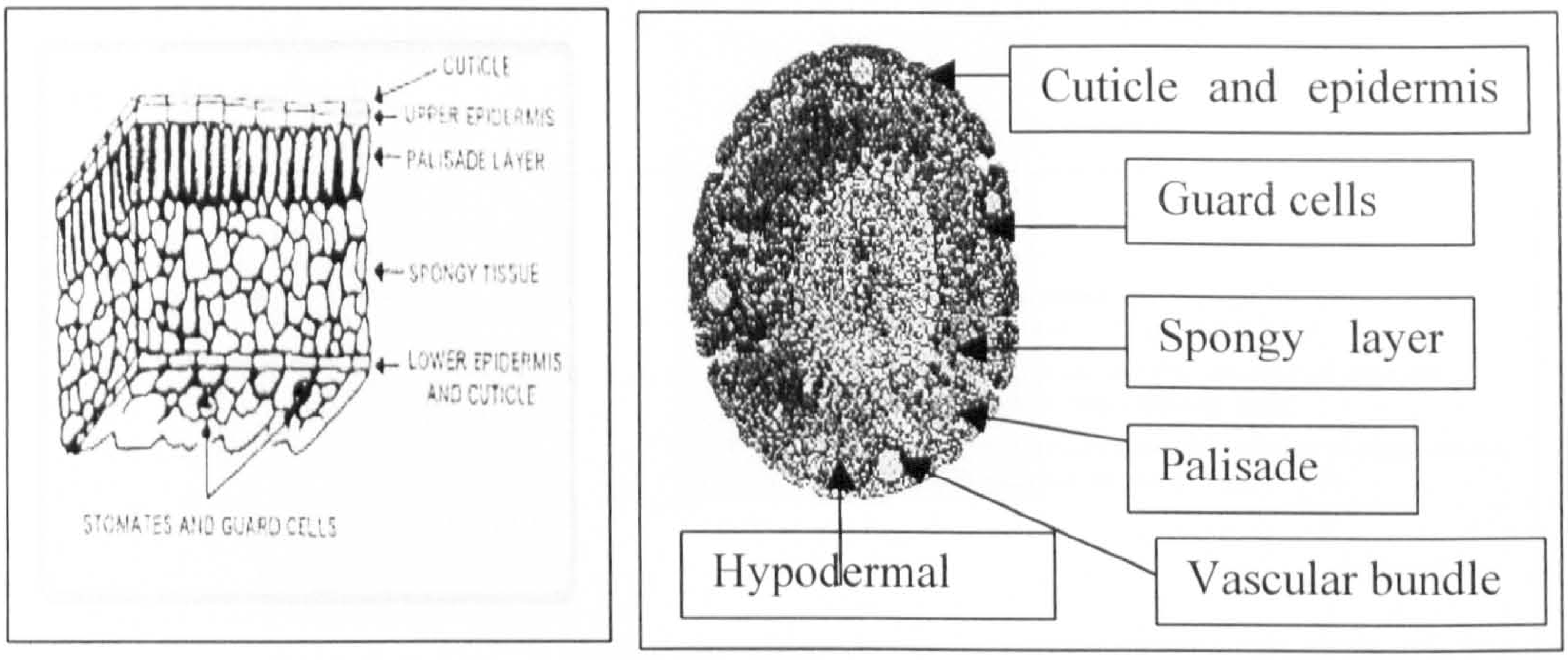
Plant structure and its interaction with electromagnetic energy has a direct impact on how leaves and canopies appear spectrally when recorded using remote sensing instruments (Jensen, 2000). These characteristics have been used for estimating important vegetation biophysical information. Therefore leaf structure and the spectral response of plant and the canopy is briefly explained in this section.

3.2.3.1 Leaf structure and spectral response

The upper epidermis forms the outer cell layer of a normal leaf (Figure 3.7a). It consists of specialised cells that fit closely together without openings or gaps in between. The cuticle, a translucent, waxy layer, covers this upper epidermis. The thickness of this layer depends on the environment in which the plant grows. Leaves of plants that grow in bright sunlight usually have a thick cuticle, while leaves of shady plants have a thin cuticle. The palisade tissue present on the upper side of the leaf lies beneath the upper epidermis and contains chloroplasts with chlorophyll pigments. It consists of vertically elongated cells arranged in parallel, at right angle to the epidermis. The next layer consists of loosely arranged spongy mesophyll cells separated by interconnected openings. Mesophyll cells are irregularly shaped with a large surface area. In this layer, there are other pigments present, for example yellow carotene and pale yellow xanthophyll, and relatively less chlorophyll. The underside of the leaf is protected by the lower epidermis, similar to the upper epidermis, except that it includes openings called stomata. Each stoma is protected by a pair of guard cells (Campbell, 1996).

Although this leaf structure is not identical for all plants, it provides a general outline of the major elements common to most. Figure 3.7b shows an almost identical structure in a pine needle. The epidermis of pine needles has a heavy cuticle. The deep sunken stomata are arranged in rows. Below the epidermis and surrounding the mesophyll is a thick-walled hypodermal layer.

Parenchyma cells of the mesophyll are deeply enfolded. One or two vascular bundles per needle are surrounded by transfusion tissue consisting of parenchyma cells (Campbell, 1996).



(a)Normal leaf (Campbell, 1996) (b) Pine needle

Figure 3.7: Leaf structure (US Forest product Lab., 1960)

These layers are composed of specialised translucent cells, which can be penetrated by electromagnetic radiation (Figure 3.8). The top layer of the leaf the upper epidermis cells have a cuticular surface that diffuses light but reflects very little. Most visible and near-infrared energy is transmitted through the cuticle and epidermis to the palisade cells. The palisade cells of the leaves contain green pigments that absorb the red and blue elements of white light and reflect the green elements. Therefore healthy plants appear green in the visible range.

A leaf reflects about 10-30% of the total light falling on it in the green part of the spectrum (Jensen, 2000). Chlorophyll *a* and *b* are the most important plant pigments absorbing blue and red light. Chlorophyll a absorbs at wavelengths of 0.46 and 0.66μm and chlorophyll *b* at wavelengths of 0.45μm and 0.65μm (Curran, 1983). There is a relative lack of absorption at approximately 0.55μm in the green portion of the electromagnetic spectrum. Carotene and xanthophyll pigments in the spongy mesophyll cells strongly absorb blue light at about 0.45μm and reflect about 60% of the near-infrared irradiation. Phycoerythrin pigments, which absorb predominately in the green region centred at about 0.55μm while reflecting red and blue light may also be present in this layer. Also Phycocyanin pigments absorb primarily in the green and red portion centred at about 0.62μm, allowing much of the blue in combination with green (cyan) to be reflected.

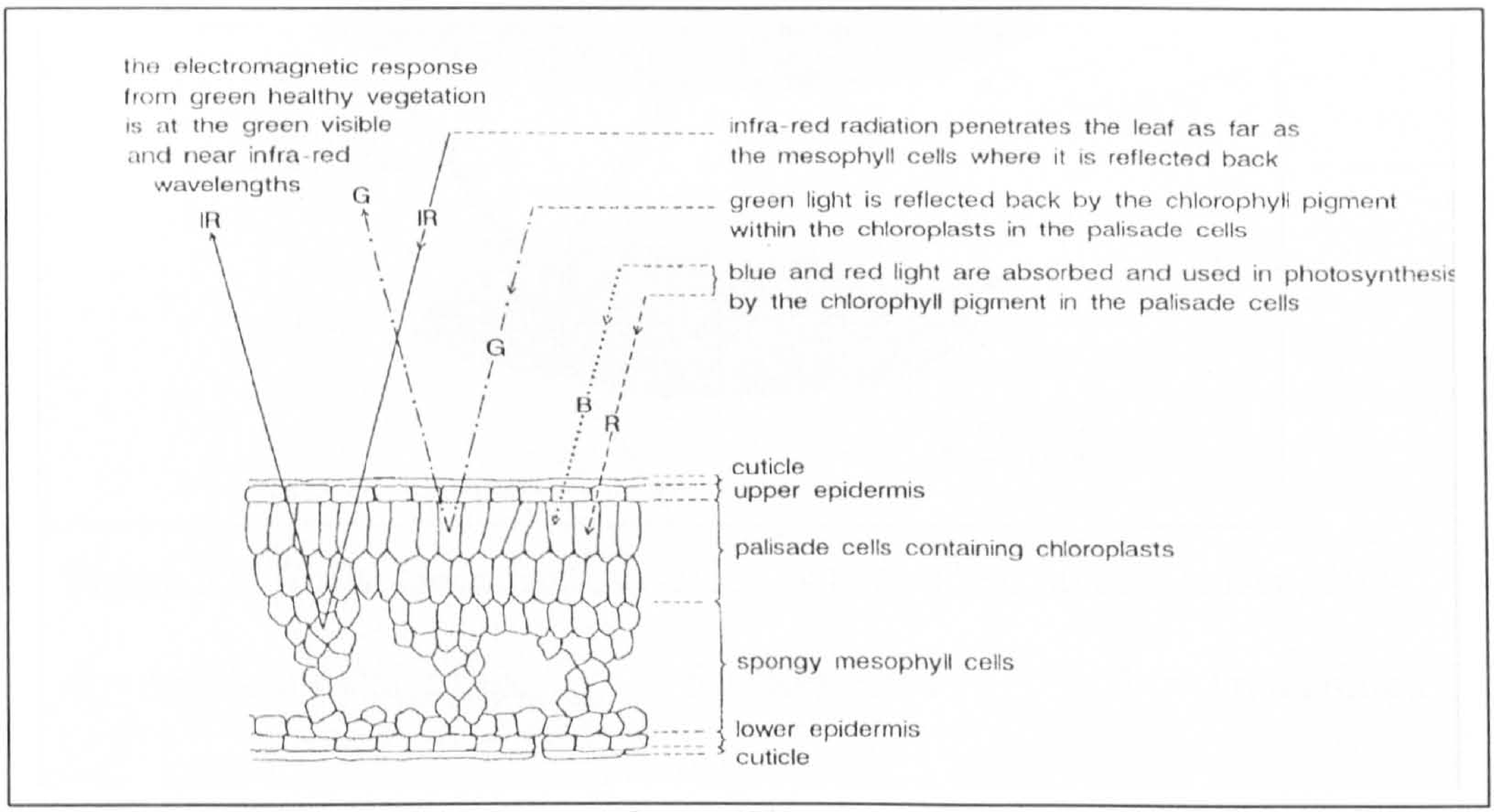


Figure 3.8: Spectral responses from different cell layers. (Campbell, 1996)

Each layer of the leaf structure plays an important role in the spectral response from vegetated surfaces but the spongy mesophyll layer is more important from this point of view because it scatters (upward -"reflected" or downward-"transmitted") especially in the near-infrared region. Very little of this near-infrared energy is absorbed internally. The internal structure of leaves plays a key role in the bright near-infrared response of living vegetation (Gibson, 2000).

3.2.3.2 Spectral response from tree canopies

Forest stands consist of a number of canopy layers, which scatter light between them. Therefore it is important to understand the spectral response of tree canopies, because canopies are composed of many layers of many leaves at different heights above the ground, and are of different sizes and orientations. Figure 3.9 illustrates the processes involved in a canopy of two layers.

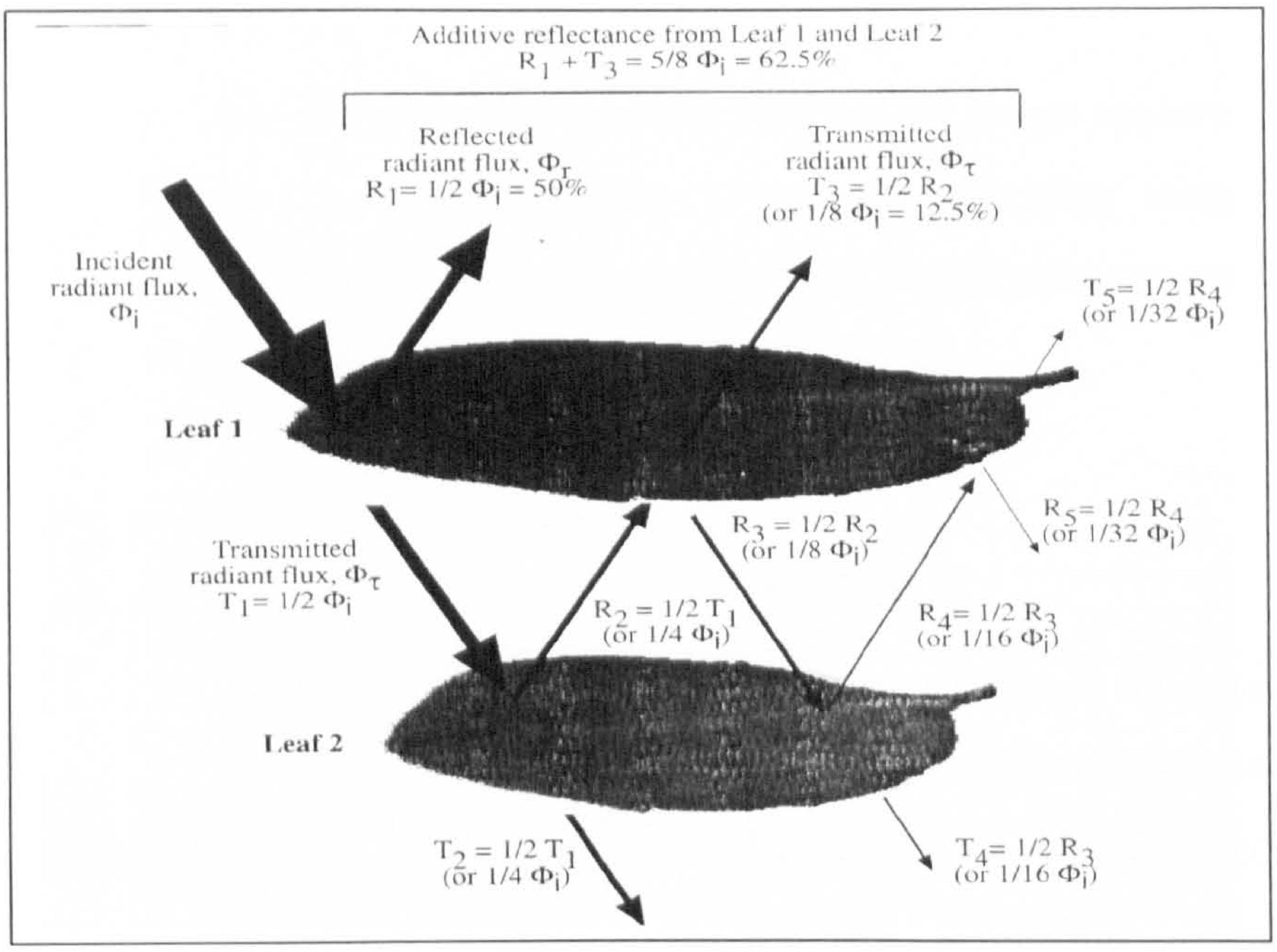


Figure 3.9: Reflectance from a canopy with two leaf layers (Jensen, 2000)

Φ = Incident radiant flux R = Reflected T = Transmitted

In general leaves higher in the forest canopy cast shadows on leaves below. The overall reflectance is a combination of direct leaf reflection and re-reflection of upper and lower layers. This reflection is more complex than the response from a single leaf. In healthy forest canopies, reflection in the near-infrared band is relatively higher than in the visible band. Reduction by shadows and reflection within the canopy of the returning radiation from lower layers is different in these two bands. Shadow effects are smaller in the near-infrared than in the visible, because near-infrared reflections are transmitted back through the canopy to the upper leaves so that they add to the returning electromagnetic reflection. Some of the reflection in the near-infrared may be from soil as well as leaves, but the visible wavelengths are unable to penetrate through the underside of the leaf (Jensen, 2000).

3.2.4 Forest biophysical parameters

Forest biophysical parameters provide data on the forest resources, structure and productivity. These parameters are also significantly related to forest canopy reflectance. Table 3.1 defines the forest biophysical parameters that are most commonly used in remote sensing applications.

Table. 3.1 Forest biophysical parameters

Parameters	Description
LAI	Leaf Area Index is the total one sided area of foliage per unit area of ground.
Biomass	Biomass is accumulated through primary production, which is the amount of organic matter fixed by plants in a given area over a given period of time.
NPP	Net Primary Productivity is the rate of biomass production per unit area, per unit time.

Leaf Area Index, biomass and primary production are key characteristics of forest ecosystems because they define the standing crop, and the flux of carbon and nutrients through transpiration and photosynthesis. Commonly used remote sensing techniques such as image classification may produce useful information on the location and spatial extent of forest, but they do not provide quantitative information about their biophysical properties. In fact, the spectral properties of vegetation canopies are functions of the biophysical properties, which should therefore be accessible from remote sensing measurements (Curran *et al.*, 1992).

3.2.4.1 Leaf Area Index

Knowledge of LAI is important for quantifying forest cover over large areas, but monitoring LAI in forest areas is difficult and expensive to do in the field. Leaf area index (LAI) quantifies the amount of foliage area per unit surface area; it varies from 0.0 (bare soil) to a maximum value of around 8 to 10 for annual crops and more than 15 for very dense perennial forests (Baret and Guyot, 1991). It is an extremely important structural characteristic, and also an important parameter controlling many biological and physical processes, associated with vegetation of the forest such as photosynthesis, respiration, transpiration, carbon and nutrient cycles and rainfall interception (Running and Gourer, 1991; Bonan, 1993, Qi, et al 2000). Satellite-derived LAI can be used in calculations with carbon, water and nitrogen cycles. Therefore, many ecological models use LAI as an input variable (Sellers *et al.*, 1988; Running and Coughlan, 1988; Dickinson *et al.*, 1993; Bonan, 1993) and it is considered as an important driver in the model. LAI is affected by tree density but will also vary with the seasons. Therefore monitoring of LAI is important for quantitative analysis of the spatial distribution of forest vegetation.

Optical remote sensing has mainly focused on the forest canopy layer and therefore it estimates forest LAI using canopy reflectance. Satellite remote sensing provides a unique way to obtain LAI over large areas. Green leaves are selective absorbers of solar radiation. Radiation in the near-infrared (NIR: 760-900 nm) and red (R: 630-690 nm) wave bands (Figure .3.1) has the potential for use in estimating forest LAI (Peterson and Running, 1989). At near-infrared wavelengths, within-leaf scattering is high, but at red wavelengths leaf pigments absorb more solar radiation for photosynthesis and therefore reflection is low (Jensen, 2000). The reflectance of the individual leaves or needles in coniferous trees varies, and it is important to identify the state of the forest ecosystem. The shape of the reflectance spectrum in visible wavelengths is controlled by the composition and concentration of the photosynthetic pigments in the leaves. On the other hand, leaf internal structure, in particular the number of air spaces and their arrangement dictates leaf reflectances at near-infrared wavelengths. Therefore, reflectance spectra of broadleaved species are different to those of conifer needles. It can also be seen that there are differences in spectral responses in single species. The spectral responses from younger conifer needles are different from older conifer needles (Gausman, 1985). Also reflectance in the near-infrared region varies from low levels of reflectance in sparse woods to a maximum level of reflectance in the evergreen forests. This reflectance is due to the spectral response of the needles changing with the orientation of the canopy. Reflection by the vegetation canopy is not a simple function of the reflectance of the component leaves. It changes with the number and the size of the foliage elements and the arrangement of the individual trees (Danson, 1995).

Remote sensing techniques, particularly the use of satellite imagery, may offer a practical means to measure LAI on a landscape scale or above (Running *et al.*, 1989). Relatively little research has been done on investigating the relationship between forest LAI and satellite data. The majority of such studies have been conducted in coniferous forests in Canada and the USA (Running *et al.*, 1986; Peterson *et al.*, 1987; Spanner *et al.*, 1990b, 1994). Research in UK coniferous forest is generally lacking (Curran, 1983, 1994). If wish to use satellite data to estimate the LAI of forests, it is vital to understand how LAI relates to the spectral properties of these forests.

3.2.4.2 Biomass

Biomass is a key characteristic of forest ecosystems as well as leaf area and primary production, because these characteristics define the standing crop and flux of carbon and nutrients. Estimation of forest biomass is as important in developing an accurate estimate of factors contributing to changes in atmospheric concentration of carbon dioxide and other greenhouse gasses as for forest management purposes. It may be particularly important for ecological studies. Biomass is accumulated through primary production, which is the amount of plant organic matter fixed in a given area over a given period of time (Odum, 1997). Direct measurements of biomass might be applicable to herbaceous plants and dwarf shrubs, because they have limited woody material and the leaf area extent is large, but collecting measurements of tall trees in the forest is very difficult.

Leaves are important as a percentage of total biomass. One way of measuring leaf biomass is a calculation of LAI. Leaf biomass differs substantially between life forms: from 7% for trees (Floret *et al.,* 1989) to 17% for shrubs and almost 100% for herbaceous plants (Tsiourlis, 1992). Therefore measuring leaf biomass is not applicable here as it does not provide an accurate measurement of total tree biomass, which includes both leaf and woody components. A few studies have assessed total biomass using optical remote sensing together with microwave data. However, microwave data have more often been used on their own for measuring above ground woody biomass (Ulaby *et al.*, 1990; Lang *et al.*, 1994).

3.2.4.3 Net Primary Productivity

Net Primary Productivity (NPP) provides highly synthesised information. It is useful for forest management mainly in production forecasting. It is defined as the difference between accumulative photosynthesis and accumulative autotrophic respiration by green plants per unit time and area (Leith and Whittaker, 1975). However, direct measurement of NPP for even one stand is very costly and time consuming. Therefore these estimates must be made indirectly. Most indirect methods involve correlation with some aspects of climate. There are three types of method used. The first method correlates NPP with climatic data, particularly precipitation and temperature, and was introduced by Leith and Whittaker (1975). A relationship of NPP with mean annual precipitation based on production data from the USA, Europe and Asia was used to estimate regional NPP over the entire biosphere. Gholz (1996), however, pointed out that relationships of NPP with growing season and annual precipitation were weak. In his own study, mean minimum January temperature was the best predictor of NPP.

In the second method, NPP is correlated with absorption and reflection of solar radiation from plant canopies. The amount of light intercepted by the vegetation is another major determinant of production. Photosynthetically Active Radiation (PAR) is absorbed strongly within green leaves by the plant pigments present. Therefore there is a high level of absorption of PAR in the visible (0.4-0.7μm) region and corresponding low values for reflectance and transmittance. On the other hand, in the 0.7-1.3μm region, because of very low absorption, there is high reflection. The ratios of the absorbed, reflected and transmission radiation to the incident solar irradiance at the same wavelength are referred to as the spectral absorption, spectral reflection and spectral transmission respectively. The incident spectral irradiance that interacts with green leaves results in absorbed, reflected and transmitted radiance as functions of wavelength. The spectral radiance from plant canopies in the 0.4-2.5μm region provides the basis for passive remote sensing of vegetated areas and can be measured from ground, air-borne and space-borne sensors. The direct results of red and near-infrared remote sensing observations are some indication of the chlorophyll density of the plant canopy. Since this quantity is related to the rate at which the plant cover can fix carbon dioxide and water into carbohydrates, these observations should provide production information about the photosynthetic capacity of the vegetated surface. In this case, the term 'photosynthetic capacity' means the gross production rate of the canopy (Law and Waring, 1994).

The third method estimates plant productivity by calculating the carbon, water and nitrogen cycles through a forest ecosystem. It requires several other variables that are not related to remote sensing, but are normally available from meteorological stations. NPP is then estimated through an ecological model (Running, *et al.,* 1989). The model calculates key processes involved in the carbon, water and nitrogen cycles for forests such as canopy interception and evaporation, transpiration, photosynthesis, growth and maintenance respiration, carbon allocation above and below the ground, litter fall, decomposition and nitrogen mineralisation. This model is related to remote sensing because the main variable is LAI derived from NDVI, which can be obtained from satellite data (Qi *et al.,* 2000).

3.3 BASIC CONCEPT OF FOREST MANAGEMENT

This section mainly concerns the nature of management and how it applies to plantation forests. Forest management is about making and implementing decisions carried out in the field of forestry. It means choosing courses of action that help to achieve the objectives of future plans. The most common objective of the plantation forest is to maximise the timber production. However, this objective may be supplemented by secondary objectives such as the landscape, recreation, and nature conservation. Forest management depends largely on a cycle of five steps (Hart, 1991).

1) The preparation through the definition of forest area, the identification of values and inventory of available data.
2) The selection of forecasting tools and the choice of management strategies.
3) The implementation of actions to achieve forest management objectives.
4) The measurement/assessment of forest conditions to compare performance with the objectives.
5) The review/improvement of actions to match desired outcome

Successful management is the result of careful planning, organisation and control over all forest operations.

3.3.1 Planning of plantation forests

Planning is the task of organising the forest operations to achieve policy objectives, and comprises three main phases:

1) Collection of data.
2) Analysis of the various possible courses of action.
3) Formulation of plans.

According to Hart (1991), the first step in planning is to describe the forest resource both quantitatively and qualitatively. It involves the collection and analysis of data. Without these it is impossible to evaluate the results of future actions. Data from earlier surveys, planting and felling records, compartment schedules and forest histories will provide a useful guide to data collection. The most useful item for collection of data is a forest stock map, because it can be used as a base map for collecting data. Forest stock maps show road lines, which form compartments and sub-compartment boundaries. The basic management unit of the forest is the stand or sub-compartment. Each sub-compartment contains a more or less homogeneous crop in terms of age, species composition and condition. Sub-compartments are not necessarily permanent units of management since they will probably change as the forest develops through felling, restocking etc. Compartments are permanent management units: their boundaries should be permanent and clearly defined on the ground. They are normally based on the forest road systems and other well-defined features such as streams, paths or other natural features. The sizes of the compartments are varied, depending upon a number of factors including the terrain, intensity of working and size of the forest.

The Forestry Commission uses aerial photographs for collecting and monitoring crop inventory with the help of ground surveys. Ground surveys are very expensive and time consuming, so that survey and inventory design has combined air photo interpretation with ground checks. Features detected by up-to-date aerial photographs are often transferred directly on to the base map. When scale differences between plots and the basic map are small, this task is done by means of a scale rule or proportional dividers. Identification of crops, the proportions of different species in mixtures, stocking densities, clear-cut areas and canopy cover are more accurately measured from aerial photographs than from ground surveys. Ages of the crops are generally obtained from records, but may be estimated by whorl or ring counts where records are not available. Where suitable photographs are not available, 35 mm photographs taken from a light aircraft by handheld camera can be inexpensive provided the pilot and photographer have had some experience. These photographs are probably unsuitable for basic mapping but can be used for sketching in sub-compartments and delimitation of areas. Additional information such as assessment of disease occurrence or damage, assessment of risk of wind-throw can be gathered from additional surveys to provide management information (Booth, 1977).

After collecting basic information on the area, age and species composition of crops, the Forestry Commission calculates standing volume and rate of growth of each stand and formulates management tables. Rates of growth are conventionally defined through yield classes. These are based on yield models, which have been produced on the computer at the Forestry Commission's research station. They are based on data collected since 1919 by the Forestry Commission in yield plots, and in thinning and spacing experiments. Models have been prepared for all the major forest species in Britain, and for a wide variety of treatments including a range of initial spacings, thinning at marginal intensity and no thinning (Forestry Commission, Booklet 48,1981). Yield class, which is usually used for management purposes, is obtained through top height and the age of the stand and it termed General Yield Class (GYC). It has become a vital tool in forest management in Britain. Yield classes do not always reflect the precise growth of individual stands, but they do accurately describe the differences between different treatments, so they are suitable for comparisons. They can be used to decide which initial plant spacing will be better in a particular situation, whether to thin, and if so when, how frequently, how heavily and what ways and when to fell the stand.

The rate of tree growth is conventionally defined through yield classes. Yield class is an estimate of the maximum Mean Annual Increment (MAI) of tree volume per hectare per year. The average volume increment from planting to any point in time shown by the MAI curve (Figure 3.10) reaches a maximum where it crosses the Current Annual Increment (CAI) curve, which represents an annual volume increment at any point in time. This point defines the maximum average rate of volume increment which a particular stand can achieve, and indicates yield class. Simply splitting the MAI range into steps of two cubic meters per hectare and numbering steps with even numbers accordingly creates yield classes. Therefore yield class has a unique number, in cubic meters per hectare. For example, a stand with a maximum MAI of 14m^3 /ha has a yield class of 14.

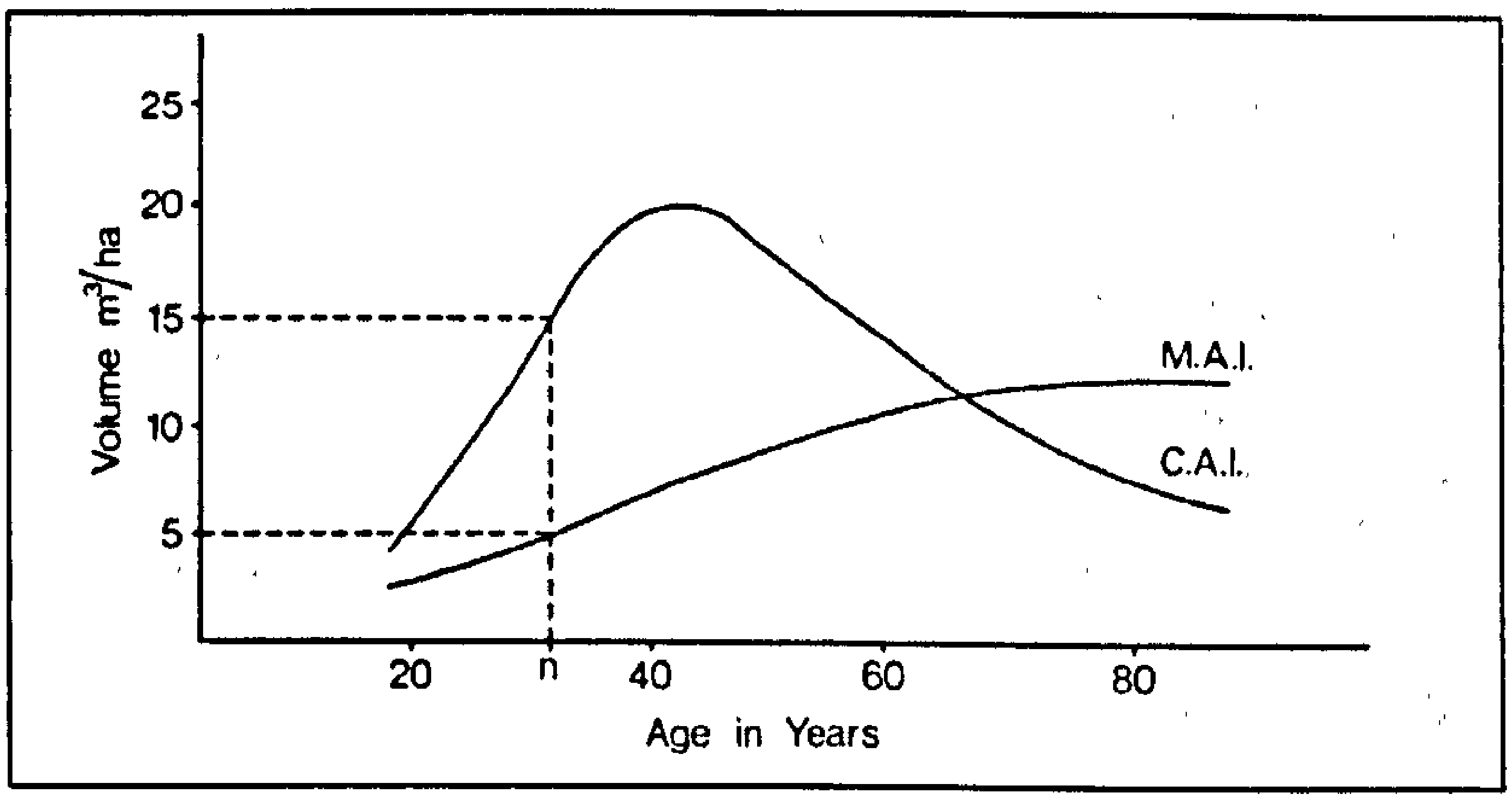


Figure 3.10 Patterns of volume increment in an even-aged stand

(Source: FC Booklet 48 (1981) p.1)

There are two types of yield class.

1) Yield classes obtained through top height and age of the stand alone is termed General Yield Class (GYC).
2) Yield classes obtained from some measures or predictions of the actual mean annual volume increment of the stand are termed Local Yield Class (LYC)

In order to assess yield class it is possible to avoid the measurement or prediction of cumulative volume production because there is a good relationship between top height and cumulative volume production of the stand. The relationship allows yield class to be read directly from top height/age curves. The GYC of Scots pine and Corsican pine with the top height/ age curves are shown in Figure 3.11. Spaces between top height/age curves indicate even numbered yield classes.

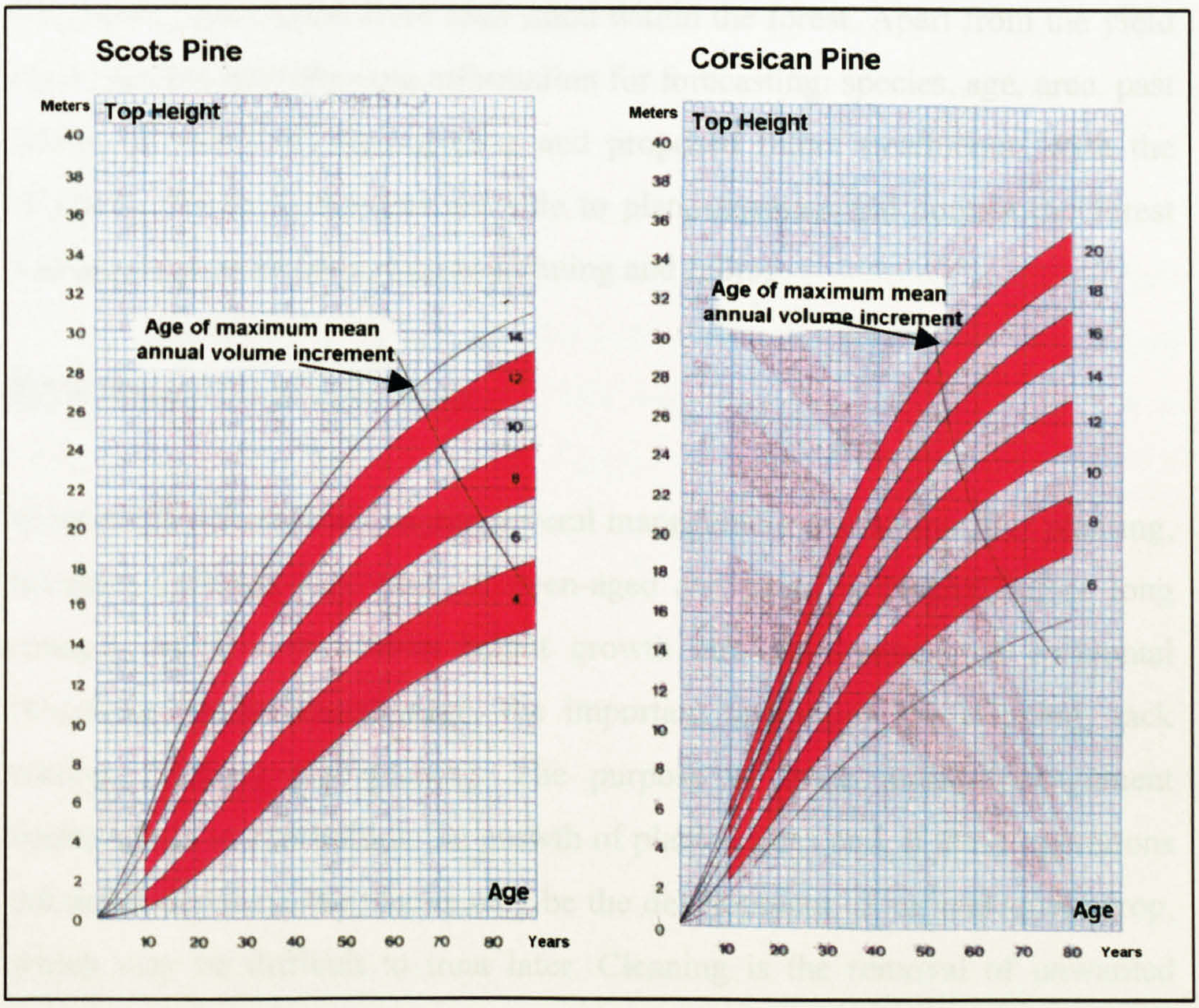


Figure 3.11 Scots pine and Corsican pine: Top height curves giving GYC (Source: FC Booklet 54, (1981) p.38 & 39)

GYC is usually adequate for most management purposes, but a better estimate of yield class can be obtained by assessing Production Class (PC). PC is assessed by measuring either cumulative volume production per hectare or cumulative basal area production per hectare. It is generally expensive and time consuming, so in East Anglian forests and most of the Britain forests the FC is normally restricted to the major species (informal discussion during fieldwork in 2000).

Yield classes are used for forecasting forest growth. According to the Forest Commission records (Forestry Commission, booklet 48, 1981) it is very important that the recorded yield classes give the best possible estimate of future growth. Forecasts of forest production are calculated by totalling the forecasts of production from each stand within the forest. Apart from the yield class they use the following information for forecasting: species, age, area, past treatment including plant spacing and proposed future treatments. With the forecasts, the forest officers are able to plan, organise and control the forest management treatments, such as thinning and felling.

3.3.2 Management operations

Most conifer plantations require several management operations after planting, because, although they start off even-aged and equal in height, before long changes occur with uneven height growth and development of horizontal branching. In the initial stage, the important operations are cleaning, rack cutting, brashing and pruning. The purpose of these initial management operations is to concentrate the growth of planted trees and, if these operations are not undertaken, the results may be the development of an inadequate crop, which may be difficult to treat later. Cleaning is the removal of unwanted bushes and woody growth usually before canopy closure. In coniferous stands, rack cutting is the removal of the lower branches of one or two adjacent rows of trees, usually in straight lines. Brashing comprises the removal of the dead and dying lower branches of trees up to a height of 2m. This last operation is very labour intensive and costly, so nowadays it is often omitted. It coincides with pruning or initial thinning. To improve the quality of timber, pruning is a valuable aid to the early production of clear timber in the outer zone of each stem, because pruning of conifers at an early stage is helpful to keep the knotty core of the tree small.

Thinning is the major operational treatment in the study site and starts at a tree age of 20-25 years. It continues every five years if necessary. It involves the removal of a proportion of trees in a stand with aims both economic and silvicultural. Thinning is usually practised in order to provide more growing space for the remaining trees, to increase the total yield of useable timber over the life of stand. It also helps to make the remaining trees more able to stand alone, and affects the growth and yield of stands, their size class distribution, quality and stability. Whereas, in conifers, the main aim of thinning is to maximise the total production per hectare, in broadleaves the primary purpose of thinning is to favour the growth of final crop trees (Hart, 1991). Therefore another objective in thinning practice is to obtain the largest financial return from the crop. First thinning may yield very little profit immediately, but it affects on the ultimate profitability of crop.

There are two types of thinning:

1) Selective thinning
2) Systematic thinning

These types refer to the dominance class of trees, which are removed in the thinning. Selective thinning involves removal of trees on their individual merits and practice follows two methods. For thinning purposes, trees in the stand are classified based on their canopy classes (Figure 3.12). Upper canopy trees are classified as dominant and co-dominant while lower canopy trees are classified as sub-dominant, suppressed, wolf trees or whips. Trees are planted relatively close together, normally 2000 to 3000 trees per hectares in establishing a plantation (Forestry Commission bulletin 14).

During the growing stage, the competition between individual trees will have begun. At this stage, trees, which are suppressed, will die because the dominators have overtopped them. If the stand is left without thinning operation, this process will continue and causes considerable loss in the final crop. This loss could be prevented by thinning before death occurs. In general, upper canopy trees such as dominants and the best co-dominants are left for the final crop because they are the main contributors of the total volume production. Under the method of selective thinning, most of the "wolf trees" with unnecessary branches and whip trees are removed in the first thinning to provide sufficient growing space for the rest of the trees in the stand. The sub-dominants and suppressed trees are removed from the lower canopy in the mid-thinning, which opens up the canopy by breaking up groups of competing dominant and co-dominant trees and encourages the development of the better trees to leave an open and fairly uniform stand. This operation is actually the first commercial thinning and for pine species usually occurs when the crop has reached the age of twelve to twenty years.

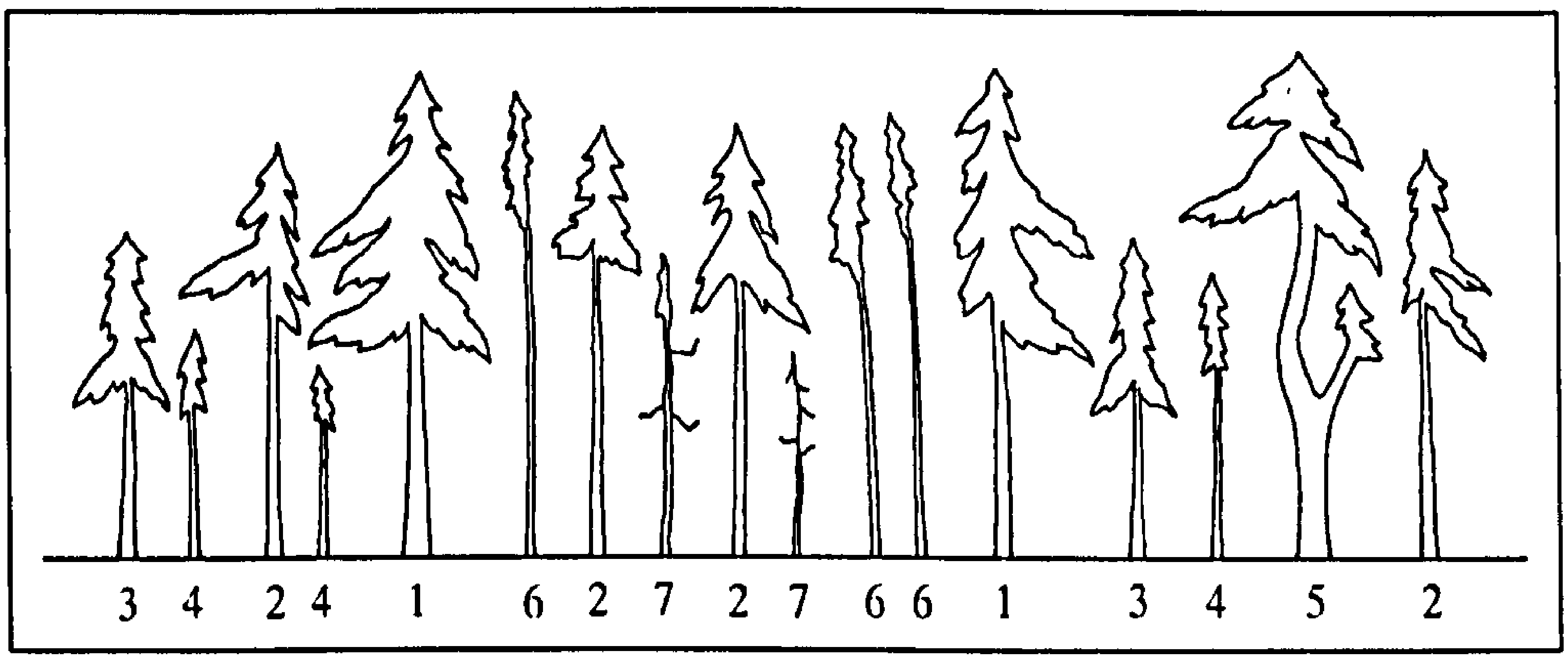


Figure 3.12 Classification of trees found in a crop on canopy classes

[Source: Hart (1991) p.293]

1 Dominant, 2 Co-dominant, 3 Sub-dominant, 4 Suppressed trees

5 Wolf trees, 6 Whips, 7 Leaning – dead or dying

The first systematic method is lower-thinning in which trees are removed predominantly from the lower canopy. The second method is crown thinning, which removes selected trees in the upper canopy. In general, upper canopy trees tend to be more efficient producers, so that lower thinning is usually considered more practicable. It encourages the development of better trees to leave an open and fairly uniform stand. The pattern of thinning mainly depends on the size of the sub-compartment and the growth status of the planted trees (Forestry Commission, Booklet 54,1985).

Thinning practice is governed by various factors. From an economic point of view, the price of small diameter round wood is considered in assessing the desirability of starting thinning at traditional ages. Foresters have adopted two main practices to try to make the first thinning profitable. The first is to adopt a low thinning or other forms of neutral thinning to raise the mean tree size at the conventional time of first thinning and to lower the harvesting cost. The second is to delay the time of first thinning usually by five or ten years. However, these actions are likely to increase the risk of wind damage. In areas where windthrow hazard is high, thinning is done very rarely. Where the hazard is moderate, thinning is done at the conventional first thinning age, and on stable sites thinning can be delayed five to ten years (Hamilton, 1980).

At the end of the rotation, trees in the plantation are harvested by clear felling. The age of felling and length of rotation are the most important factors for management purposes and depend on the growth rate, which is mainly determined by the species and site factors. According to Hart (1991), there are six main way of determining the length of rotation. They are:

1) Physical rotation: the trees continue growing until they die of old age.
2) Silvicultural rotation: the trees are grown until conditions are reached when restocking is most easily achieved.
3) Technical rotation: the crop is felled when it reaches a specific marketable size.
4) Rotation of highest net annual income: the stand is managed to yield ultimately the highest net annual income per ha. regardless of the time to achieve this.
5) Rotation of maximum mean annual volume increment: the stand is managed to yield the highest volume of timber per ha.
6) Financial rotation: the rotation which is the most profitable.

Table 3.2: Typical felling ages (years) for Scots pine (SP) and Corsican pine (CP)

Yield class	Thinned		Unthinned	
	SP	CP	SP	CP
4	75			71
6	74	64	65	58
8	69	63	61	53
10	63	60	57	51
12	58	56	55	48
14	53	53	53	47
16		49		46
18		46		45
20		45		44

Source: Constructed from the Forestry Commission Investment Appraisal handbook (1980)

The normal rotation for Scots pine may be 55-100 years and for Corsican pine 45-80 years, but the length differs according to yield class and thinned or unthinned states (Table 3.2). From an economic point of view, forest managers base their decisions on demand for either small diameter round wood or sawlogs.

3.4 SUMMARY

This chapter discusses the basic principles of remote sensing for biophysical studies and forest management. Remote sensing is demonstrated to be a potentially valuable tool to detect and monitor forest cover changes. The detection of properties of objects by remote sensing is based on the processing of electromagnetic energy reflected from the surface. Therefore, the first part of this chapter explains the main subdivisions of the electromagnetic spectrum. Solar radiation passes through the atmosphere twice, as incident and reflected. During these two journeys, scattering and absorption affect the radiation. The radiation that is not affected reaches and interacts with the surface and is redirected as reflection. Energy, which is reflected by the surface object, is detected by the sensor system on board an aircraft or satellite, recorded or transmitted to a ground receiving station and stored in digital format. The main focus of optical remote sensing is to study the reflected energy in the visible and near-infrared region of the electromagnetic spectrum.

For photosynthesis, leaves of the forest canopy absorb radiant energy. At the same time, some radiation passes through the canopy layers, or is reflected. The proportion of reflected energy varies with the spectral reflectance characteristics of the green vegetation, so that the magnitude of reflection from a vegetated surface depends on the physiological properties of the leaf cover. Green vegetation has a low reflectance in the visible region due to the high chlorophyll absorption. In the near-infrared, the reflectance rises dramatically. It is due to internal cell structure of the leaves, whereby about half of the incident energy is reflected and the remaining portion is transmitted. Very little of this energy is absorbed by the leaf canopy. Spectral response patterns of vegetation also vary with the plant species, especially in the near- infrared region of the spectrum. Canopy spectral reflectance relationships between red and near-infrared radiation are very useful for vegetation studies. These relationships are a good indicator of biophysical parameters such as LAI, biomass and NPP.

The second part of this chapter highlights the basic concepts of forest management and forest management operations. It explains the main phases of planning of plantation forest management. The initial stage of planning involves data collection and analysis and is useful for evaluating the results of future actions. The purpose of this information is to record what is there, to judge the effect of past treatments and to assess growth and yield for future treatments. To evaluate this basic information, the Forestry Commission has prepared yield models for all major forest species in Britain. These are used for production forecasting and the carrying out of management operations.

CHAPTER FOUR

DATA ACQUISITION AND METHODOLOGY

4.1 INTRODUCTION

The main aim of this study is to examine the applicability of the use of remotely sensed data to detect the amount of vegetation present in the forest canopy cover and monitor changes due to management operations. Satellite data are compared with detailed management data to verify their accuracy, and to assess how they can assist in forest management decisions. The study is mainly concerned with Corsican pine and Scots pine trees grown in coniferous plantations. These species were selected because

1) They are clearly identifiable on imagery.
2) Planting and management records are available.
3) They are less variable than other species.

The first part of the study uses SPOT satellite images to identify different types of forest canopy features. This study mainly uses vegetation indices based on satellite radiometric measurements to calculate the quantity of greenness in the forest canopy. These indices are integrated with field data such as planting areas, age from the compartment records and calculated forest structural data such as top tree height, mean diameter and basal area.

A number of vegetation indices (Chapter three) have been proposed for relating radiometric measurements in the visible and near infrared wavelength intervals to the amount of vegetation present. Over forty vegetation indices have been developed during the past decades. Here the attention has focused on a commonly used index, the Normalised Difference Vegetation Index

(NDVI). NDVI separates green vegetation from other surfaces. In addition, high NDVI values indicate high leaf biomass, canopy closer (Jasinski, 1990; Sader & Winne, 1992)

In this study NDVI values were extracted from SPOT images. The following three types of data set were used to analyse the NDVI and the variables affecting vegetation growth.

1) Satellite data - SPOT HRV multispectral data in June of 1994, 1995, 1996 and 1997, from which NDVI was calculated.
2) Secondary data:
    (a) Ordnance Survey maps
    (b) Forest Commission Census
    (c) Forestry Commission management survey records
    (d) Forest compartment records from the Forestry Commission.
    (e) Meteorological data.
3) Field investigations- June 1999, June 2000, June 2001, August 2002 and September 2002.

Figure 4.1 shows the approach used to assess forest cover patterns in the study area.

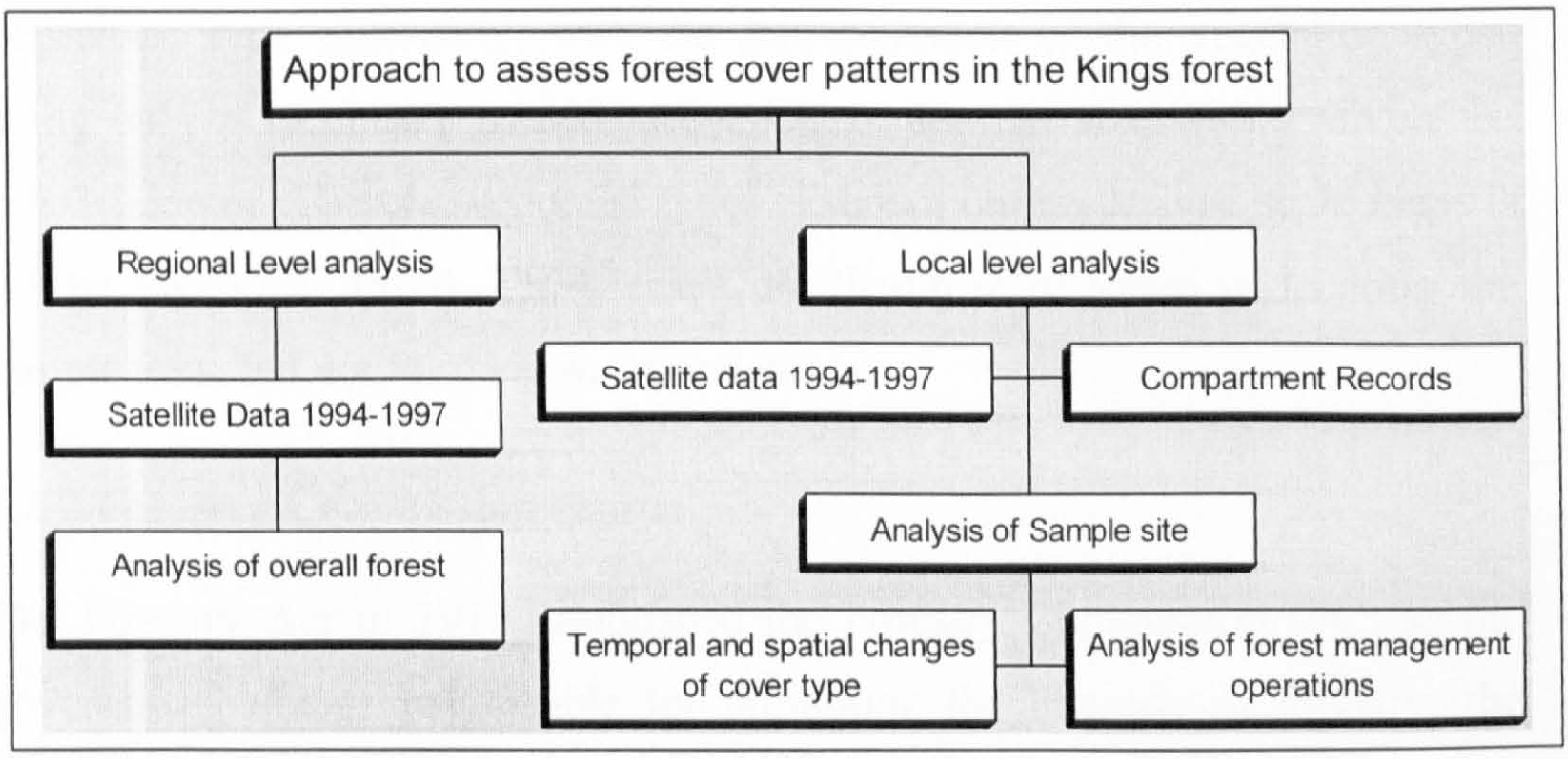


Figure 4.1: schematic diagram of the approach to assess forest cover

4.2 SOURCES OF DATA

This section considers the data sources used in this study. It presents the methodology of integrating these data sources to a common base or co-ordinate system and of using them to identify and classify forest compartment maps.

4.2.1 Ordnance Survey

The primary responsibility of the Ordnance Survey (OS) is to survey and provide maps of Great Britain. The modern authority for these activities dates back to the Ordnance Survey Act of 1814. The OS publishes maps at various scales from the basic scales of 1:1250 (Urban), 1:2500 (Agricultural and forest) and 1:10,000 (mountainous areas) to derived scales of 1:10,000, 1:25,000, and 1:50,000 and 1:100,000. The scales used in this study were 1: 25,000 and 1:50,000. The information recorded between scales needs to be known in order to understand the shortcomings of various maps and the appropriate areas to use in the study. In the context of this study, the mapping of forest areas, OS maps contain information relating to the distribution, area, shape, density and type of forests. However, like any other maps they omit certain details, generalise others, enlarge some features and use conventional signs to codify much of the surface details (Harley, 1975). In general terms, the main objective of OS mapping is to delineate the boundary of a particular vegetation type accurately, with the representation of the vegetation types being only a secondary consideration. The minimum size within which the subdivision of different woodland types is shown on the derived scale maps is 0.1 ha (Watkins, 1983). These maps are therefore of value in locating the sample area, but not for their woodland data.

4.2.2 Forestry Commission census

The Forestry Act of 1919 established the Forestry Commission (FC) as the government agency responsible for promoting the interests of forestry, the development of afforestation and the production and supply of timber. The FC has two roles. First, the FC is the National forest authority, in that it acts as the government agent in relation to policy, private forestry, research and education. Second, the FC is the National Forest Enterprise, responsible for developing and managing its own estate. The Commission, through these varying responsibilities, thus has an interest in all forms of woodland survey, from the detailed survey of commercial forest plantations to the collection of data on individual trees.

Statistics on the extent and composition of all woodland are acquired through a regular woodland census taken on a 15 to 20 year cycle. The first census was in 1924 and the second was conducted in 1938. Since then it has been taken in 1947, 1980 and 1990. In 1980, the census involved a woodland survey to provide an estimate of the total woodland area within each county on the basis of ownership, woodland types, species, age classes and timber volumes. The survey covered woodlands of 0.25 hectares and over, and was based on a three-stage sampling system using the 1:50,000 maps, aerial photographs and ground surveys. The FC census was not considered to be a major source for this study because it gives an estimate of the total woodland types, species, age, and timber volume per county, but does not give detailed statistics of plantation forests separately.

4.2.3 Forestry Commission - Forest Management Survey

One of the key roles of the Forestry Commission is forest management. It is especially concerned with timber management, maintenance, and the improvement of existing forest stands. Forest Management Surveys collect all the information on forest stands in the initial stage of the plantation. Regular resurveying is also carried out with local annual updating to provide the data needed for management, mapping, forecasting, valuation, budgets and work programmes. The data collected are stored in a digital database called the Forestry Commission Sub-compartment Database. The computer files hold data on all FC land by forest districts. The data are stored on magnetic tapes, located at the computer bureau and accessed via the Research Station at Alice Holt, Farnham, Surrey. The requirement for detailed survey extends to soil and site type information, used to provide guidance on choice of species, growth potential, the need for site treatment, crop stability and harvesting methods. In the sub-compartment database, the data are held in three groups:

1) The key field, which provides the location of forest districts, geographical blocks, compartments and components (elements of a mixed crop or land use within the sub compartment).
2) The required data field, containing crop data such as species, age, yield class and area, other land use data and nationally required information such as the local authority area.
3) The optional data field, containing details of site factors such as soil and windthrow hazards and of codes that group up land units into treatment blocks.

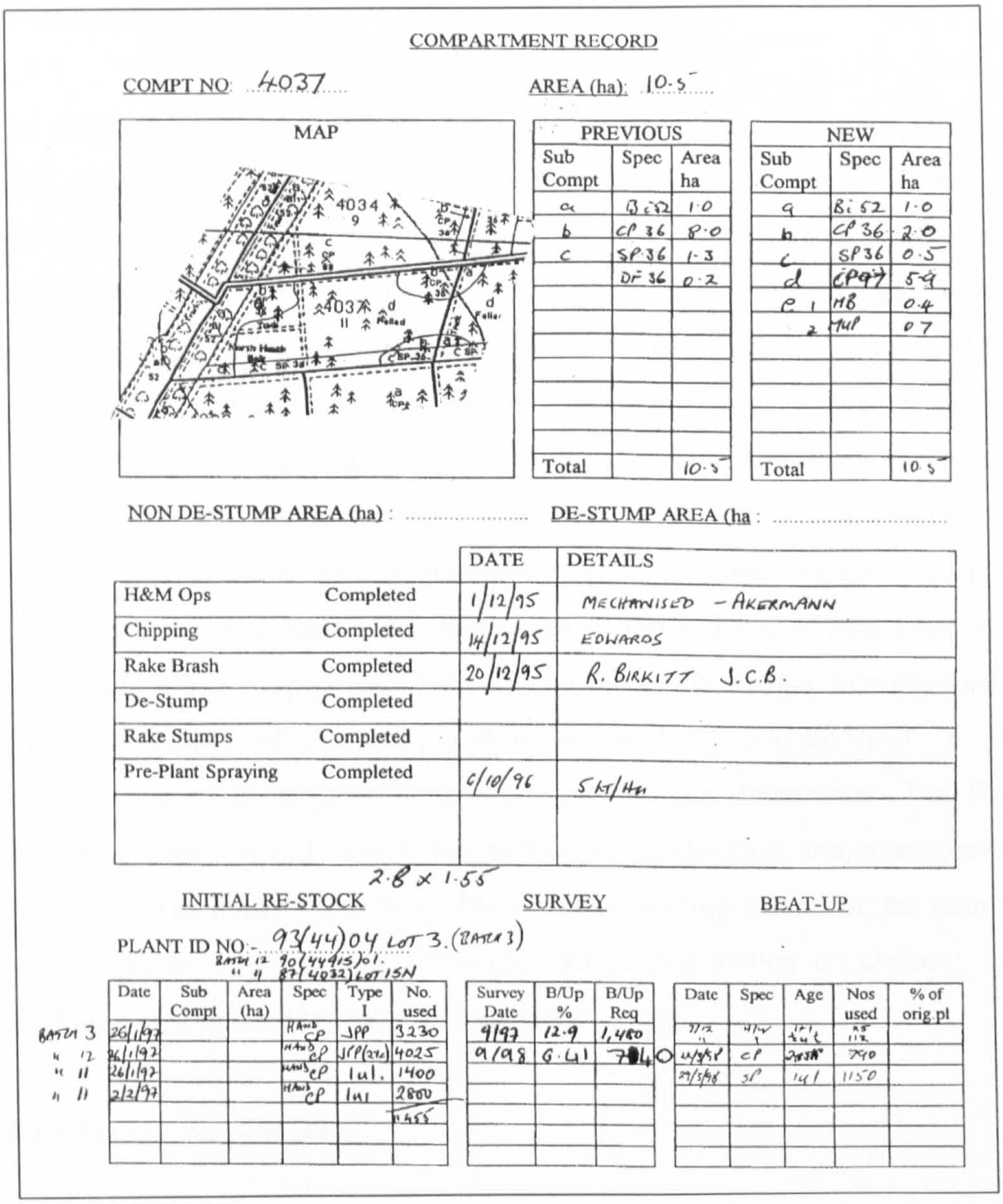
Each year on the 31st of March, the local managers are responsible for updating the data and rechecking the database (Forest enterprise district report, 1997). Field survey staff check that each forest district makes any necessary adjustment, giving advice if necessary. Forest Management surveys use 1:10,000 OS base maps and recognise forest stands down to 0.5 hectares in areas with boundary mapping to a maximum absolute error of 10 metres. Aerial photo interpretation is used as the standard way to plot forest trees and feature boundaries, while ground surveys supply tree species, age growth rate, and stocking and production areas (Forest enterprise district report, 1997).

The base map used by the Forestry Commission for management surveys was used in this study along with other Forestry Commission data to generate GIS maps for age, top tree height, mean diameter and basal area.

4.2.4 Compartment records

The most important field data used in this study were the compartment records collected by the Forest Commission district office in East Anglia (Table 1: Appendix B). Since 1990, the district office of the Forestry Commission at Brandon (East Anglian Region) has maintained these compartment records.

The 1:10,000 scale forest sub-compartment base maps were used as main source for this study. Figure 4.2 is a sample of compartment records of the study area.



COMPARTMENT RECORD

COMPT NO: 4037 AREA (ha): 10·5

MAP

PREVIOUS		
Sub Compt	Spec	Area ha
a	Bi 52	1·0
b	CP 36	8·0
c	SP 36	1·3
	DF 36	0·2
Total		10·5

NEW		
Sub Compt	Spec	Area ha
a	Bi 52	1·0
b	CP 36	2·0
c	SP 36	0·5
d	CP 97	5·9
e 1	MB	0·4
2	Mul	0 7
Total		10·5

NON DE-STUMP AREA (ha) : .... DE-STUMP AREA (ha : ....

		DATE	DETAILS
H&M Ops	Completed	1/12/95	MECHANISED – AKERMANN
Chipping	Completed	14/12/95	EDWARDS
Rake Brash	Completed	20/12/95	R. BIRKITT J.C.B.
De-Stump	Completed		
Rake Stumps	Completed		
Pre-Plant Spraying	Completed	6/10/96	5 kr/Ha

2·8 × 1·55

INITIAL RE-STOCK SURVEY BEAT-UP

PLANT ID NO:- 93(44)04 LOT 3. (BATCH 3)
BATCH 12 90(44915)01.
" 11 87(4032)LOT 15N

	Date	Sub Compt	Area (ha)	Spec	Type I	No. used
BATCH 3	26/1/97			HAND CP	JPP	3230
" 12	26/1/97			HAND CP	JPP(2½)	4025
" 11	26/1/97			HAND CP	1u1.	1400
" 11	2/2/97			HAND CP	1u1	2800
						11455

Survey Date	B/Up %	B/Up Req
9/97	12·9	1,480
9/98	6·41	7[illegible]40

Date	Spec	Age	Nos used	% of orig.pl
[illegible]	[illegible]	[illegible]	[illegible]	
4/3/98	CP	[illegible]	790	
29/3/98	SP	1u1	1150	

Figure 4.2 Sample of compartment records

Source: Forest Enterprise, East Anglian district office

These records hold several items of information (previous and present) on each component such as species, year of planting of each species and area of each species in hectares by sub-compartment. This information can be categorised as follows:

1) Details of crop information.
2) Different stages of ground preparation for planting.
3) Management treatments.

The compartment map shows sub-compartment boundaries, while the attached table gives information on the total area of each species and the year of planting. The aim of ground preparation is to make the land suitable for planting and to encourage rapid establishment and early growth of the crop to be planted (Hart, 1991), and takes place one year before planting. The need for ground preparation generally depends on whether the land has recently carried a tree crop. Recently felled areas probably do not need more treatment, because the slash has been removed as part of harvesting. But previously planted sites do require other preparations such as chipping and rake brushing. In the King's Forest study area, destruction of lop and top of pine trees by a heavy-duty brush chopper had been carried out partly to facilitate the use of planting machines, which make a shallow furrow. In the compartment records, this information is recorded with dates of chemical treatments. The final section of these records gives information of re-stocking and management treatments. The initial restocking table contains planting date, area, the number of trees planted and the type of species. More information on cleaning and brashing-pruning is added during subsequent surveys.

4.2.5 Meteorological Data

Meteorological data were collected from Institution of Arable Crops Research (IACR) Broom's Barn sugar beet research station (http//www.iacr.bbcsr.ac.uk/broom/weathermenu.html, 2001) from 1994 to 1997. This station is approximately 8 km from the study area. The data include daily temperature, humidity, short-wave radiation and precipitation.

4.2.6 Field investigations

Field investigations were carried out as follows:

1) 20th of June 1999 –A pilot fieldwork was carried out to investigate sites in the Kings forest.
2) 11th of June 2000. – A visit was made to the Forestry Commission district office in Brandon (with Mr. M. Johnson) to discuss the background of the study area and the management activities carried out by the forest managers. Compartment records and stock maps were collected.
3) 5th of June 2001 – Detailed investigations of different age stands and recently felled sub-compartments were made in the selected compartments.
4) 6th of August 2002 - A visit was made to the selected test site and canopy gaps were identified.
5) 12th of September 2002 – Information on typical thinning history, thinning cycles and related ground data were collected from the Forestry Commission district office.

These investigations were made in order to facilitate explanation and verification of observations in the remotely sensed data.

4.3 STUDY AREA

The Kings Forest has been selected as the study area. The requirements of the study site were a) a simple stand structure, with areas of even-aged single species plantations; b) a relatively flat area with no steep hillsides; c) the availability of good management data; d) the availability of a sequence of satellite data over several years. Various areas were considered as potential study sites. Two areas that fulfilled these criteria were parts of Thetford Forest in East Anglia, and Sherwood Forest in Nottinghamshire. The King's Forest, a northern outlier of the Forestry Commission's Thetford Forest, was selected as the study site. This fulfilled the four criteria above, and also adjoined agricultural land whose characteristics had been studied over the years by

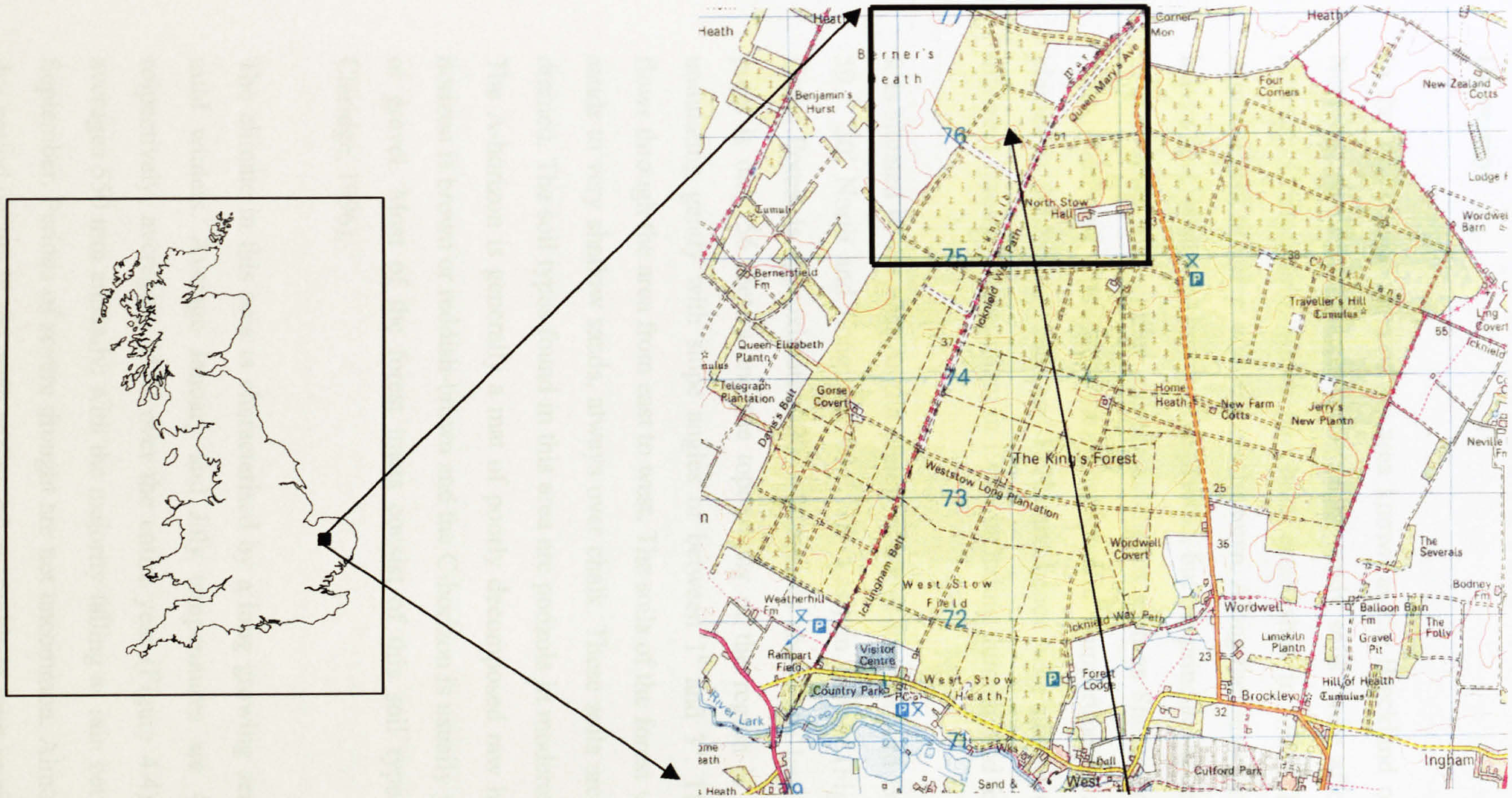


Figure 4.3 Location of Kings Forest

Source: Ordnance Surveys Map No: Landranger 144 (Thetford & Diss, Breckland & Wymondam) several other researchers from the School of Geography, Nottingham University.

In the 1920s large parts of the area known as the Breckland of Suffolk and Norfolk, which is characterised by poor sandy soils, were afforested by the Forestry Commission, which had been established in 1919. This area was named Thetford Forest after the nearby town. Along the ride sides some broad-leaved species such as beech were planted, but the principal species planted, as in other sites with similar soil characteristics such as Sherwood Forest, were Scots Pine and Corsican Pine. The specific compartments selected were planted in the 1950s, 1960s and 1970s and hence were subject to a variety of different types of management in 1990s including thinning and felling.

It is situated in the East Anglia region, south of the Thetford Forest (Latitude 50 ^{0}. 20' North and Longitude 00 ^{0}. 38' East) in Britain (Figure 4.3). The Kings Forest is approximately 20 – 50 metres above sea level. The highest point is only 56 meters and the topography of the region is generally flat, undulating gently with slope angles of between 1^0 and 3^0. The River Lark flows through the area from east to west. The soils of the forest vary from deep sands to very shallow sands, always over chalk. These soils are always freely drained. The soil types found in this area are podzols in moderately acid soils. The A-horizon is generally a mat of poorly decomposed raw humus. The B-horizon is brown or reddish-brown and the C-horizon is usually yellowish sand or gravel. Most of the forest tracts consist of this soil type (Ratcliff and Claridge, 1996).

The climate in this area is characterised by a long growing season and short mild winters. Average January and July temperatures are 4^0C and 26^0C respectively, averaging 15^0C over the entire year (Figure 4.4). Precipitation averages 550 mm annually, with the majority falling as rain between May and September. Periods of severe drought are not uncommon. Almost invariably a dry period occurs in the early spring, often combined with searing east winds.

The most serious factor is the regular occurrence of unseasonable frost in the spring and autumn, and ground frost can occur every month of the year (Meteorological data from IACR Broom's Barn, Bury St Edmunds).

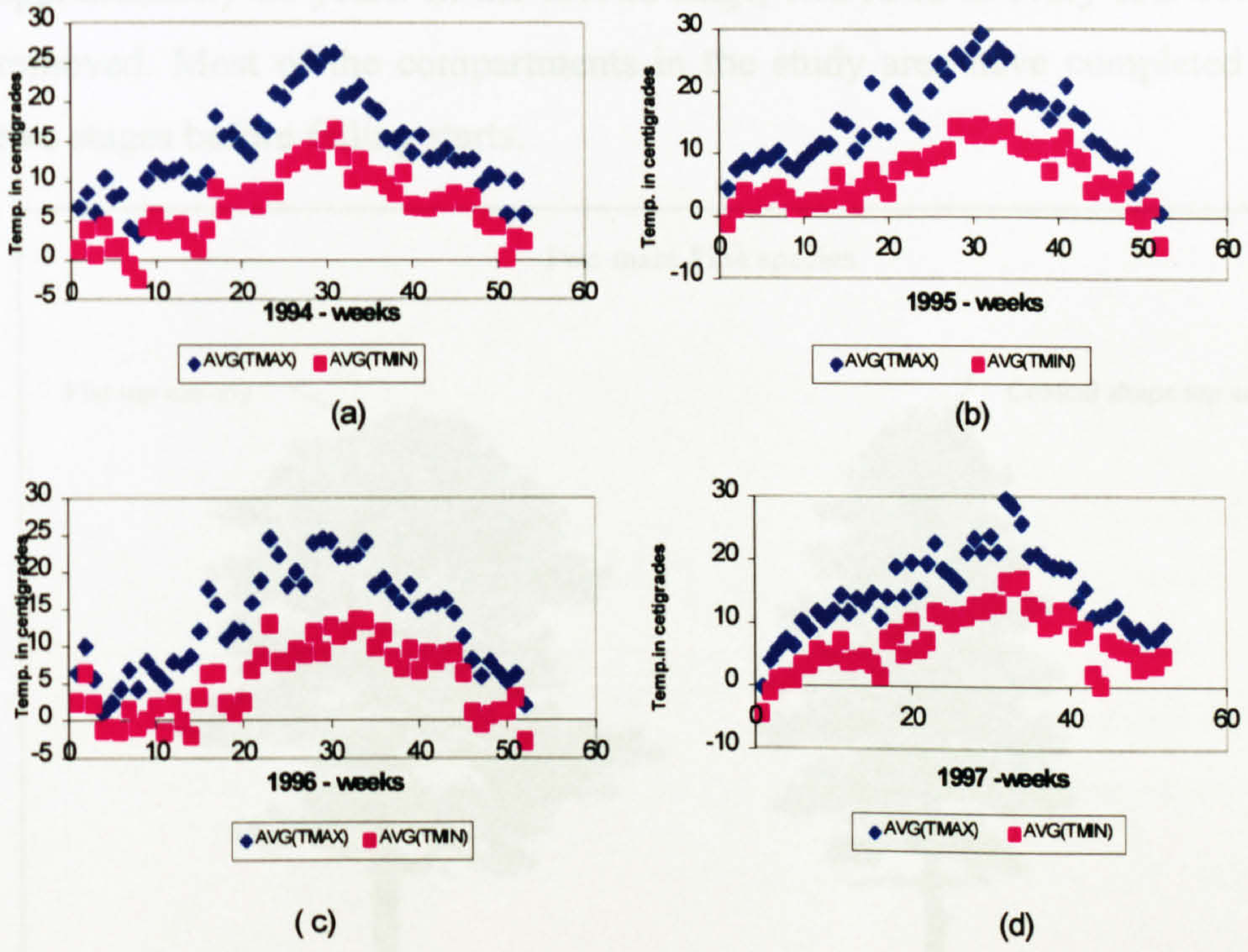


Figure 4.4: Annual temperature distribution (maximum and minimum) in the study area for the four years of study (*Source: Meteorological data -IACR Broom's Barn -Bury St Edmunds*)

AVG(MAX) = Average Maximum Temperature; AVG(MIN) = Average Minimum Temperate.

The forest was originally planted in 1930 through the afforestation of heath land and low-grade agricultural land. Further areas were planted in the 1950s and again in the 1960s (Forest records from Forestry Commission district office in Brandon – East Anglia). Thinning treatments have been carried out in the past ten years by systematic felling of intermediate-sized rows of trees. According to the Forestry Commission records, the first stage of management treatment was to brash the trees before the age of 15 or 16 years. This consists of cutting off all branches to a height of 2 metres to provide easy access for the next step, which is pre-thinning. First thinning begins at about the 20th year. A second thinning follows five years later and a third after a similar period if needed and so on. The first stage in the thinning is to completely remove two rows of trees in every six rows across the whole compartment to give the remaining trees more room to develop until economic maturity, which is approximately 60 years. In the second stage, two rows in every four rows are removed. Most of the compartments in the study area have completed these two stages before felling starts.

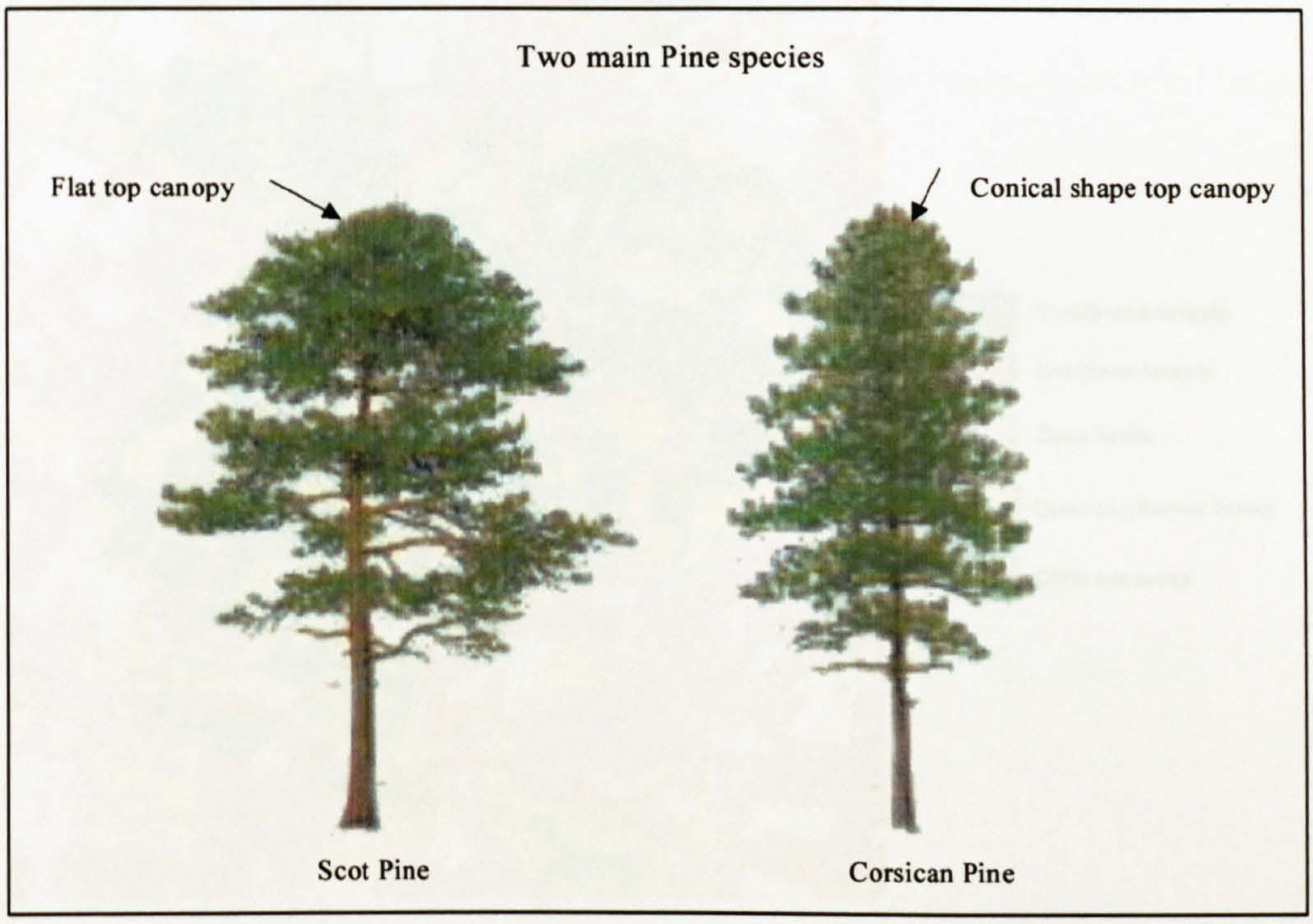


Figure 4.5 Two trees of main pine species Source: A photographic guide to trees of Britain and Europe – Paul Sterry & Bob Press (1983)

Today, the forest is dominated by single species, even-aged compartments of coniferous species, mainly Corsican pine (*Pinus nigra var. maritima*) and Scots pine (*Pinus sylvestris*) (Figure 4.5). The shape of the top canopy differs between these two types of stand. The top canopy of Scots pine is relatively flat compared to Corsican pine. A much smaller number of compartments of broadleaved species such as Beech (*Fagus Sylvatica*) belts grow along public roads and the compartment tracks. In less developed canopies, there is an understory of brambles, bracken, ferns and grasses.

Figure 4.6 shows a land use classification of the study area based on the analysis of SPOT data June 1997. The Kings Forest contains 213 compartments covering 2334 ha. It is intensively managed for timber plantation by the Forestry Commission. This study selected Northwest part of the Kings Forest as a study area for detail analysis.

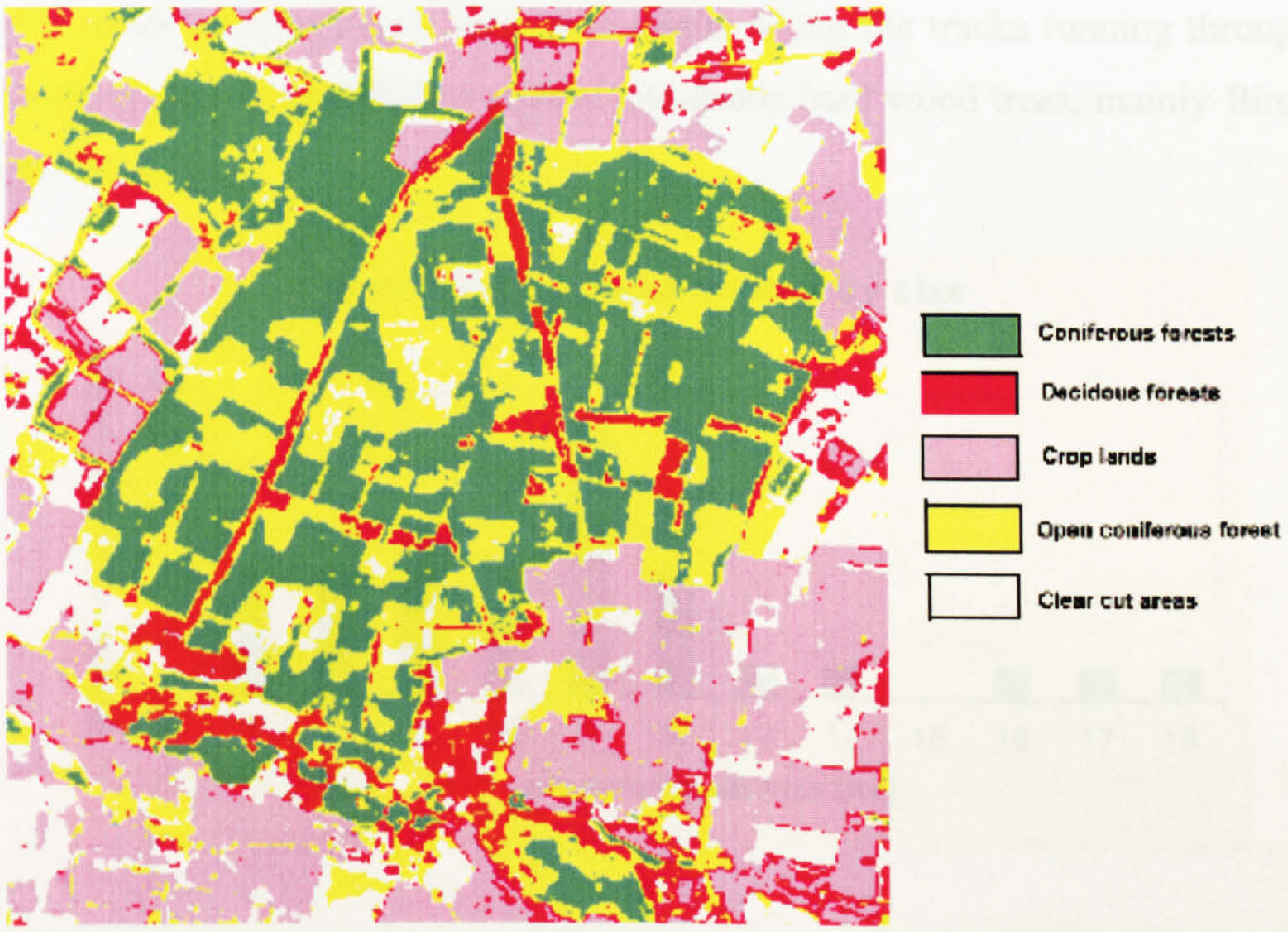


Figure 4.6 Land use classification of Kings Forest classification from 1997 SPOT image

4.3.1 Description of study area

Thirty-four compartments (73 sub-compartments) were chosen for analysis in this study on the basis of availability of inventory data. From the Forestry Commission stock map of the Kings Forest, a boundary map of study site compartments was built up, together with a table of attribute information derived from their records of planting date and species for each compartment. The total area of each sub-compartment (Figure 4.6) ranges from 7 to 18 ha. More than 50% of the compartments are less than 10 ha. in size, while very few (less than 15%) are more than 12 hectares

This study site is located in the north-west quadrant of the Kings Forest, covering 360 ha. (Figure 4.6). Corsican pine dominates all of the compartments, with smaller stands of Scots pine ranging from 0.05 to 1.75 ha in size in sub-compartments (Table 2 Appendix B). A total of 84% of the whole study site is coniferous (82% Corsican pine and 2% Scots pine). Among the coniferous dominated sub-compartments, 57 contain Corsican pine, while only 16 sub-compartments have Scots pine. Along the tracks running through the study site are established mature deciduous hard wood trees, mainly Birch and Beech.

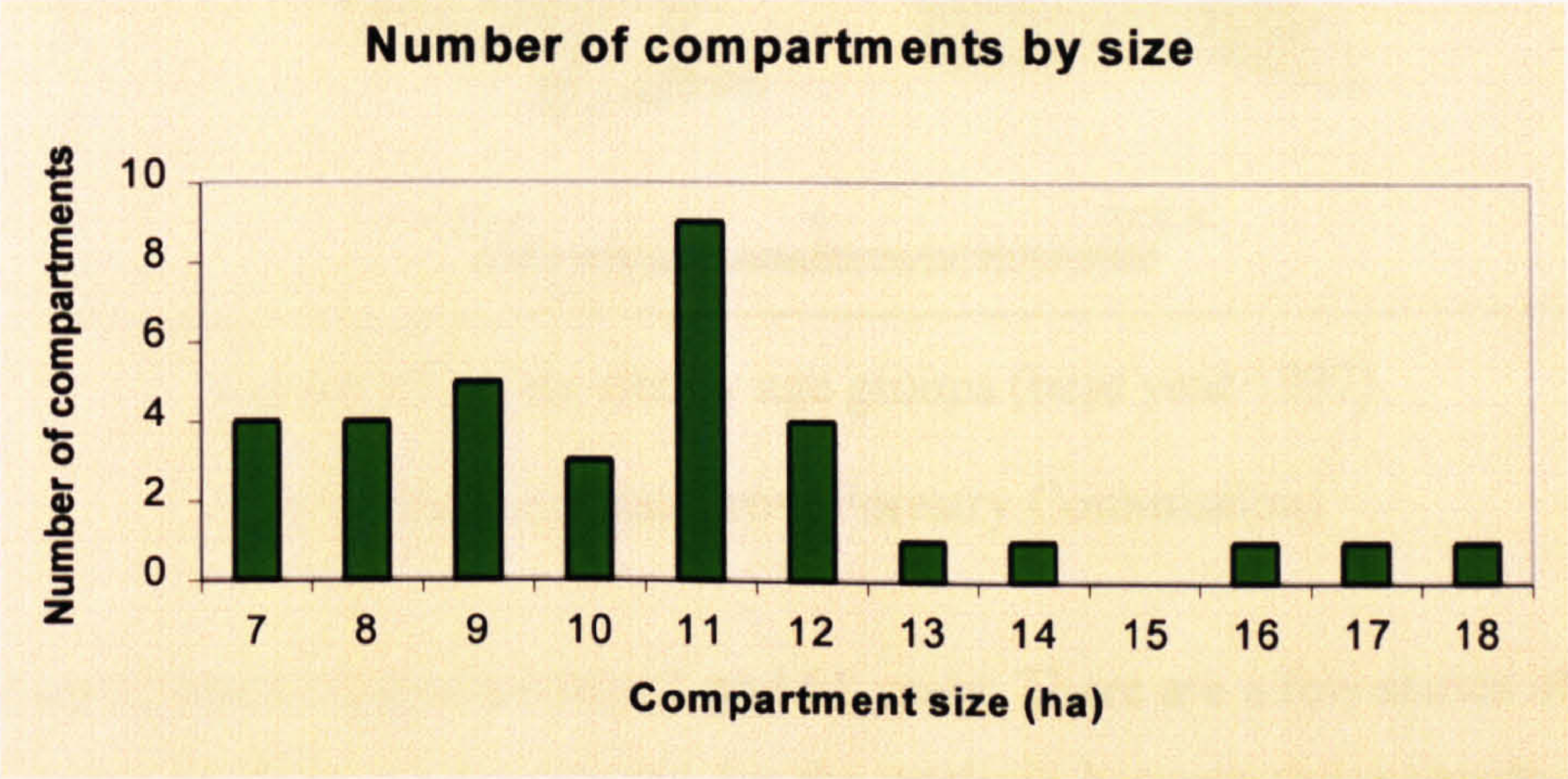


Figure 4.7 Size of compartments (data from Forestry Commission compartment records)

The coloured areas in Figure 4.8 show the age groups of the conifers, while the white areas either side of the tracks are mixed or deciduous trees. A small experimental plot located in the north-west corner of the study site consists of small samples with other species of pine. Because of the high correlation with tree age of other forest parameters, such as tree size (height and diameter), tree density, leaf area, and biomass, this study mainly treats the two dominant species of conifers according to age groups.

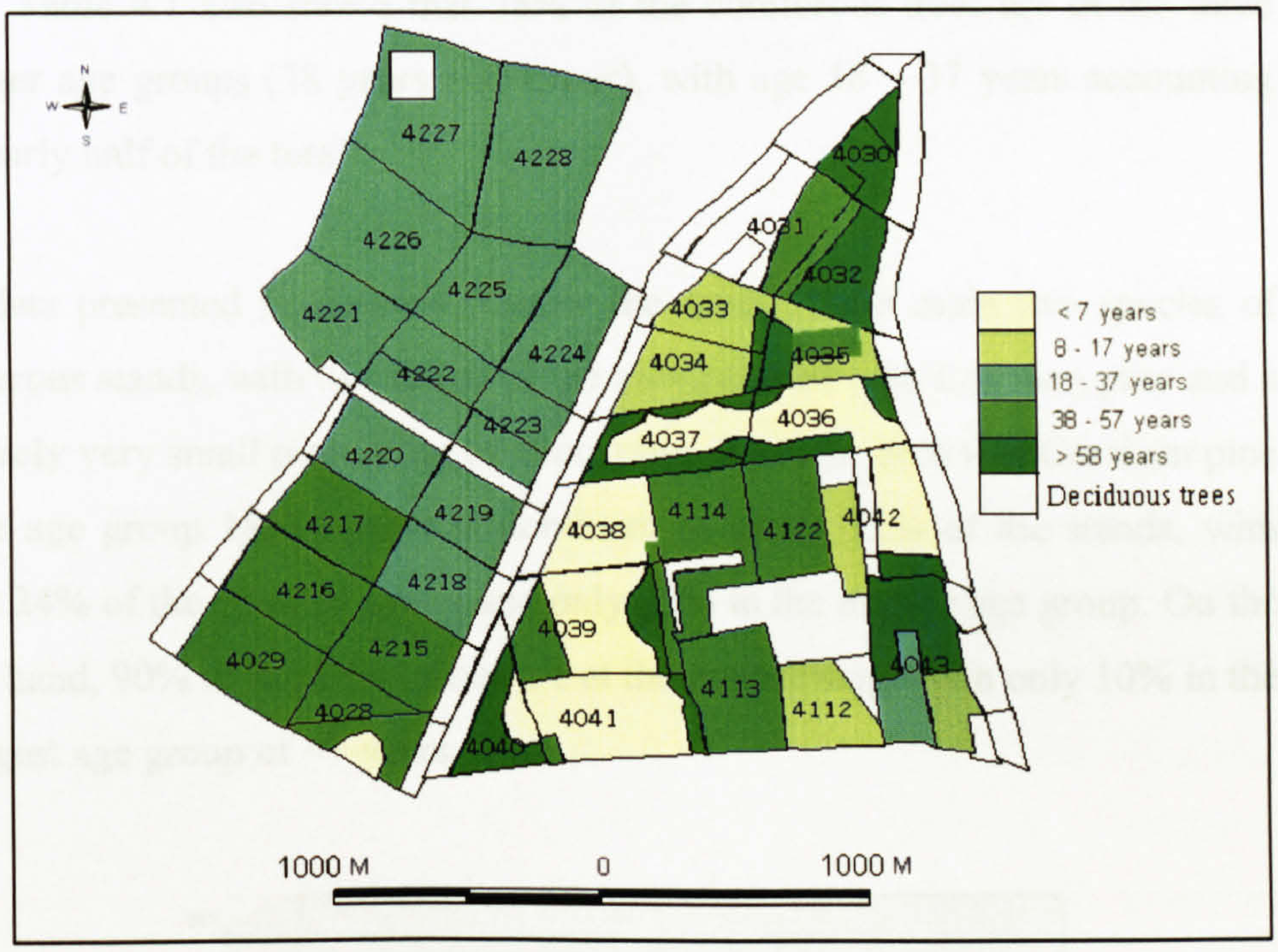


Figure 4.8 Study site by age groups (base year 1997)

(Compartment data from Forestry Commission)

The age of stand ranges between 1 and 61 years. There are a few stands of 100 year age, but these were excluded for the analysis because those stands were not under management. The remaining stands were separated into five age groups according to the growth stage and the different management practices.

Table 4.1 Corsican pine and Scots pine by age group in the study site

Age group	Area (ha) CP	Area (ha) SP	Area (ha) Total	Area %
<7 years	49	1	50	16
8-17 years	24.75	0	24.75	08
18-37 years	163	0	163	51
38-57 years	41.25	1.5	42.75	13
>58 years	29.75	7.5	37.25	12
Total	307.75	10	317.75	100

Table 4.1 shows the areas in five age groups as <7, 8 –17, 18 – 37, 38 – 57, and >58. Throughout this study, the reference year for these age groups is

1997. Table 4.1 also shows that 75% of the coniferous trees are in the three younger age groups (38 years and lower), with age 18 – 37 years accounting for nearly half of the total.

The data presented in figure 4.9 show the areas of the main two species of coniferous stands, with two thirds of the area covered with Corsican pine and a relatively very small proportion of Scots pine. It can be seen that Corsican pine in the age group 18–37 years is dominant in about 51% of the stands, with about 24% of the younger group and only 25% in the mature age group. On the other hand, 90% of the Scots pines are at the mature stage with only 10% in the youngest age group of <7 years.

Figure 4.9 Size of main two pine species in the study area by age groups

4.4 SATELLITE DATA

Four sets of SPOT images were used to collect remote sensing data and calculate the Normalised Difference Vegetation Index. Table 4.2 shows detailed information about these SPOT images. The visibility data were from Wattisham, as supplied by the meteorological office, and were used in the atmospheric correction procedure (section 4.4.1.2). All other data are from SPOT header file.

Table 4.2: SPOT images used for the study

Date of Year	*Sensor*	*Lat./ Long.*	*Path/ Row*	*Visibility*	*Sun.Ang.*		*View Ang.*	
					Ze.	*Az..*	*In.*	*Az*
21th June 1994	*SPOT 1 HRV 1*	*52.3/0.5*	*33/244*	*37.5KM*	31^0	$153^0.6^0$	16.6^0	133.4^0
28th June 1995	*SPOT 2 HRV 2*	*52.3/0.5*	*33/244*	*25 KM*	35^0	163.9^0	2.6^0	124.0^0
15th June 1996	*SPOT 2 HRV 2*	*52.3/0.5*	*33/244*	*40 KM*	31^0	161.0^0	13.3^0	130.2^0
5th June 1997	*SPOT 1 HRV 1*	*52.3/0.5*	*33/244*	*11 KM*	31^0	160.0^0	17.5^0	127.0^0

4.4.1 Data pre-processing

Pre-processing refers to those operations preliminary to the main analysis. In the acquisition of data by remote sensing systems, instruments are used to record the intensity of electromagnetic energy reflected from the Earth's surface. During the scanning, transmission and recording process, the electromagnetic energy passes through complex environmental conditions, which influence the quality of data being recorded. The recorded data are subjected to systematic errors, noise and geometric distortions, which need to be compensated for, so that the data resembles the original scene (Mather, 1999).

Before processing, the main analysis the following two main adjustments were carried out.

1) Geometric correction.
2) Atmospheric correction.

4.4.1.1 Geometric correction

The images were geometrically corrected to remove distortions caused by tilts of spacecraft and the Earth rotation at the time of imagery. Generally satellite data are acquired under different viewing geometry conditions. During data acquisition, the satellite also experiences orbital motion that causes variation in altitude and attitude within the orbit. At the same, time the Earth rotates about its axis, which produces a skewing effect on the image data. The combined effects produce geometric distortion during image formation. Despite the systematic error, which has been removed at the ground receiving station, considerable geometric distortions remain and are treated as unsystematic random error (Jensen, 2000). For this reason, there is a need to perform geometric correction for image rectification on the image data in order to remove or at least minimise such errors. This subject is particularly important for this study because it is dealing with multi-temporal data. In addition, each country has a different standard map projection system. In order for the image data to be integrated to the existing map or as an input to a GIS database, they need to be corrected so that the image data conform to the national co-ordinate system. Although SPOT imagery as supplied has already been corrected for earth curvature and rotation, variations in satellite altitude and attitude produce significant geometric distortions requiring detailed correction to register the image on a map.

Geometric correction involves repositioning a pixel in a two-dimensional image from its original position to a desired cartographic position. It is a process of transforming image co-ordinates (x,y) into geographical co-ordinates (E,N) using a map projection system, so that the position of each pixel can be related to the ground features. There are many different approaches to co-ordinate transformation. In this study, images were rectified using the first-order polynomial transformation method in ERDAS Imagine version 8.4. The mathematical expression of the first-order polynomial transformation can be written as equations 4.1 and 4.2: (Gibson & Power, 2000)

$$x' = a0 + a1.x + a2.y \qquad (4.1)$$

$$y' = b0 + b1.x + b2.y \qquad (4.2)$$

Where x' and y' are co-ordinates in the rectified image or map, and x and y represent corresponding co-ordinates in the original image. In practice, before applying the rectification to the entire image data, it is important to determine the goodness of fit of the polynomial function. The Root Mean Square error (RMS_{error}) for each ground control point is commonly used to measure the goodness of fit of the transformed co-ordinates against the reference points. The equation used to compute the RMS_{error} for each control point is expressed as equation 4.3:

$$RMS_{error}=\sqrt{((x'-x)^2+(y'-y)^2)} \tag{4.3}$$

The x', y' are transformed or predicted co-ordinates, whereas the x,y are the original or reference co-ordinates.

The difference between transformed values and original values is obtained from the transformation computation. In this study, the rectification was achieved by interactively displaying image data on one display window and map coverage on a second display window. Twenty Ground Control Points GCPs, which could be identified on both windows, were selected (Appendix F) and the total (RMS_{error}) after transformation was 0.1 pixel.

In principle, GCPs should be dispersed throughout the image, with good coverage near the edges (Mather, 1999). Therefore, the selection of GCPs was carried out accordingly. The transformation coefficients were then calculated using the first-order polynomial equations (4.1, 4.2). The images were then resampled using the nearest neighbour interpolation technique. This method was chosen because it does not alter pixel values during the resampling process, thus preserving the corrected data. All image data were resampled to 20 metre pixel size to match the new map base.

4.4.1.2 Atmospheric correction

Atmospheric correction is necessary in this study because the study compared multi-temporal data. Atmospheric correction is the process of converting values of radiance measured at the satellite to values of reflectance as if measured at the surface. This method is done by accounting for the contribution of atmospheric interference to the spectral values of an image. The radiation, which forms the spectral signal from a point on the Earth's surfaces through the atmosphere to a sensor, is altered in two ways. First, the atmosphere absorbs radiation, thus reducing the signal received by the sensor. Second, the atmosphere scatters radiation, deflecting it both from and into the signal received by the sensor. The cumulative effect of these two factors is to add an extraneous component known as path radiance to the signal and to reduce the signal overall (Mather, 1992; Jensen *et al.*, 1997).

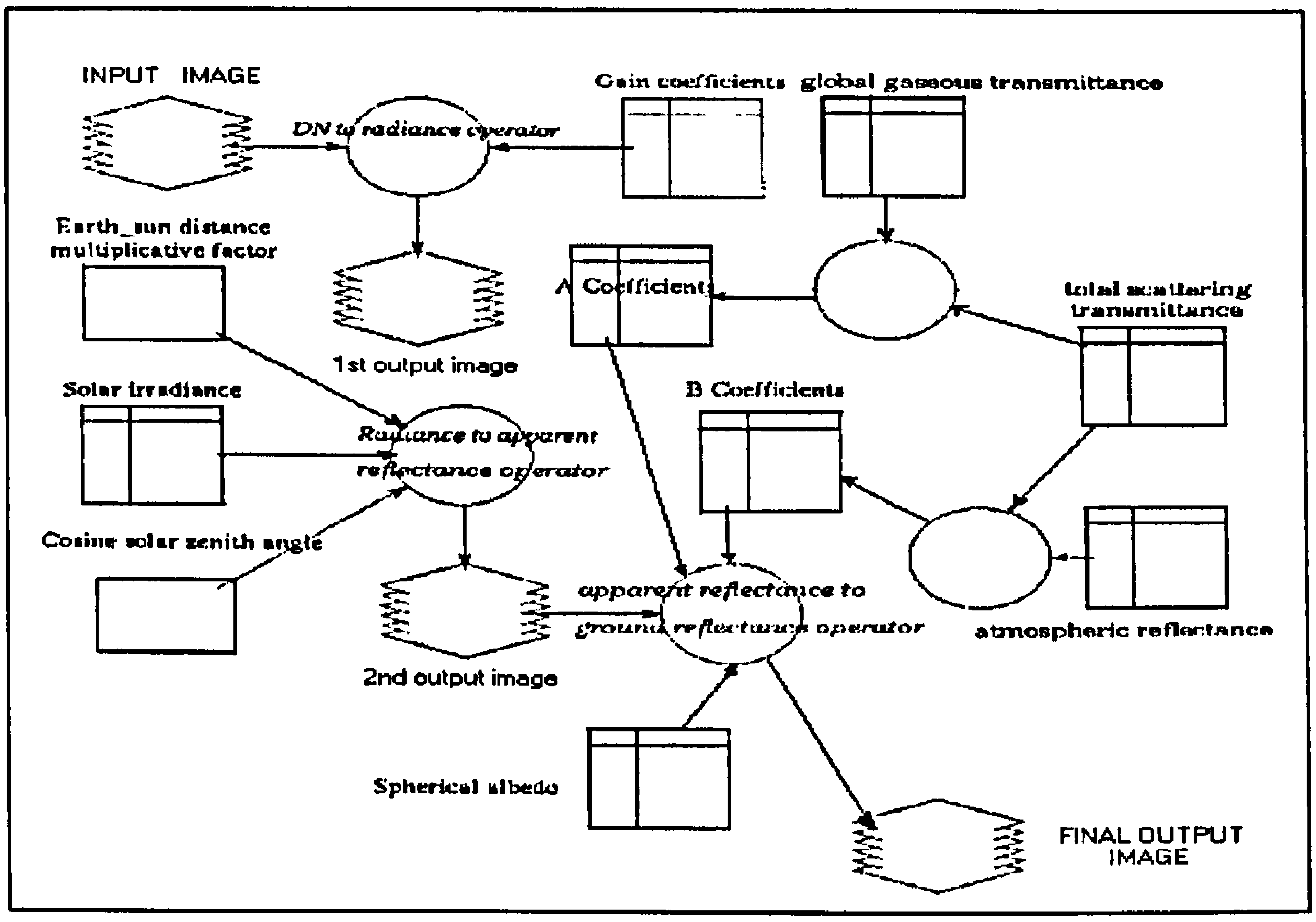


Figure 4.10 Schematic diagram for atmospheric correction

(see figure 4.12 for key to symbols)

Various methods have been devised to account for different components of atmospheric interference. In this study, a fairly simple technique was carried out using Simulation of the Satellite Signal in Solar Spectrum model (5S model) (Tanrē, 1990). The model converts apparent reflectance (ρ*) values as measured by the satellite to Surface reflectance (ρ_s) values (Appendix section A). In order to retrieve the surface reflectance from raw remote sensing data, this study carried out three stages of correction procedure (Figure 4.10).

1) DN values were converted to radiance.
2) Radiance was converted to apparent reflectance - Viewing and illumination angles, visibility and SPOT spectral band codes were used as input parameters to compute the apparent reflectance.

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4.4.2 Data processing

Most of the data manipulations and analysis in this study were developed in ERDAS Imagine Version 8.4, in particular using the Spatial-Modeller module. The Spatial-Modeller module has graphic editing capabilities that allow access to spatial analysis modelling for both image processing and GIS environments (ERDAS 8.4 User guide, 1999). The module has about 150 built-in library and analysis functions from which a graphical model of the desired process can be developed by defining input parameters, analysis operations and output format. Thus the user has more time to concentrate on the results of the analysis, instead of developing computer programs.

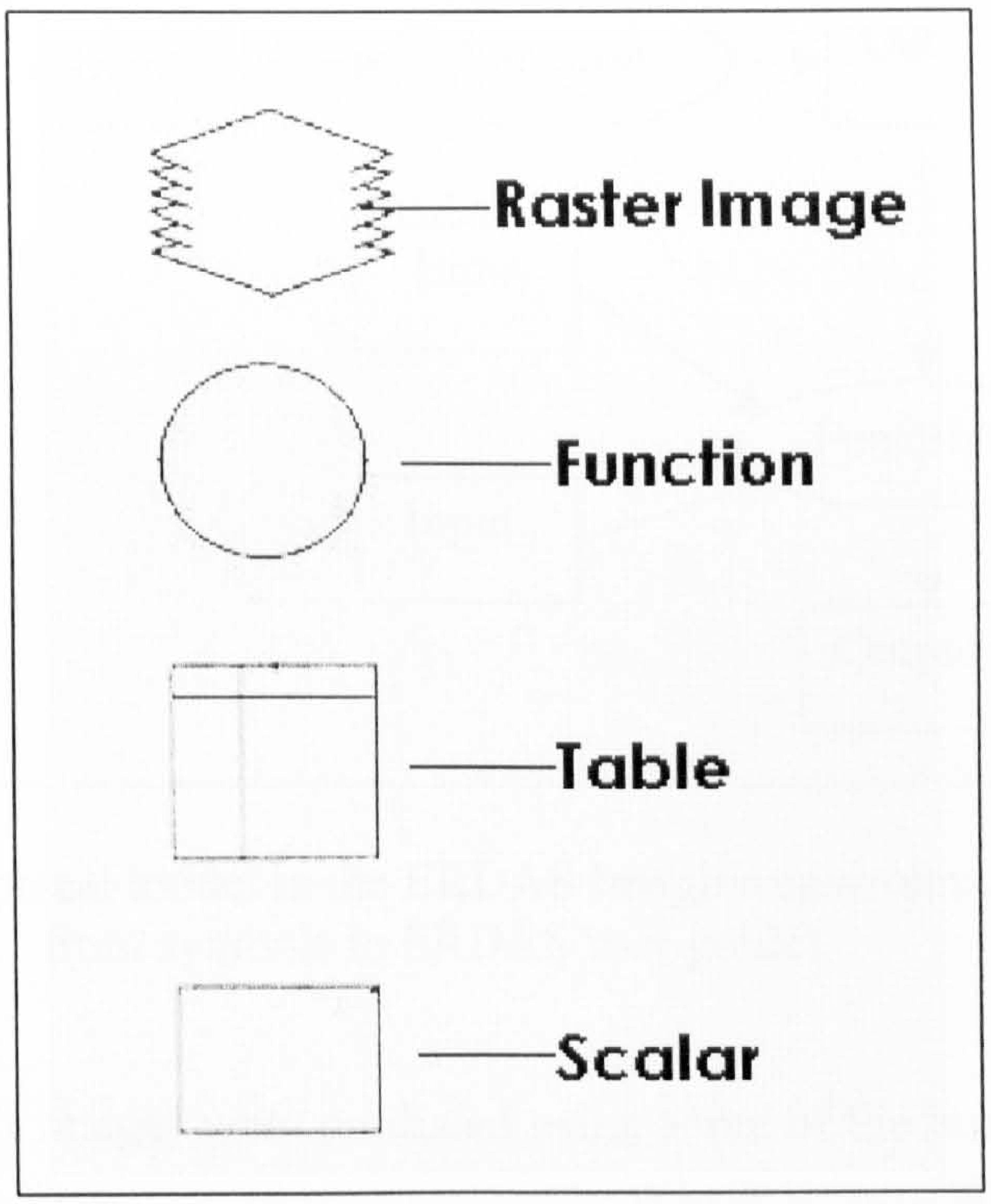


Figure 4.12 Modeller objects in ERDAS (created from symbols in ERDAS user guide, 1999)

Use of Spatial Modeller involves a number of steps i.e. graphical design, data input and output, and execution of the model. Upon invoking the 'model maker' icon, a blank sheet appears on the screen together with a window showing various objects including raster data sets, tables and scalars, criteria, mathematical functions, operators and connectors. Some of the most commonly used procedures are shown in Figure 4.12

To create a model, the user should choose and define the objects and place them on the sheet. For a basic model, at least three objects need to be selected; for example, an input object, an operator and an output object (Figure 4.13). The connector is used to draw connections from the input object to operators and from operators to the output object.

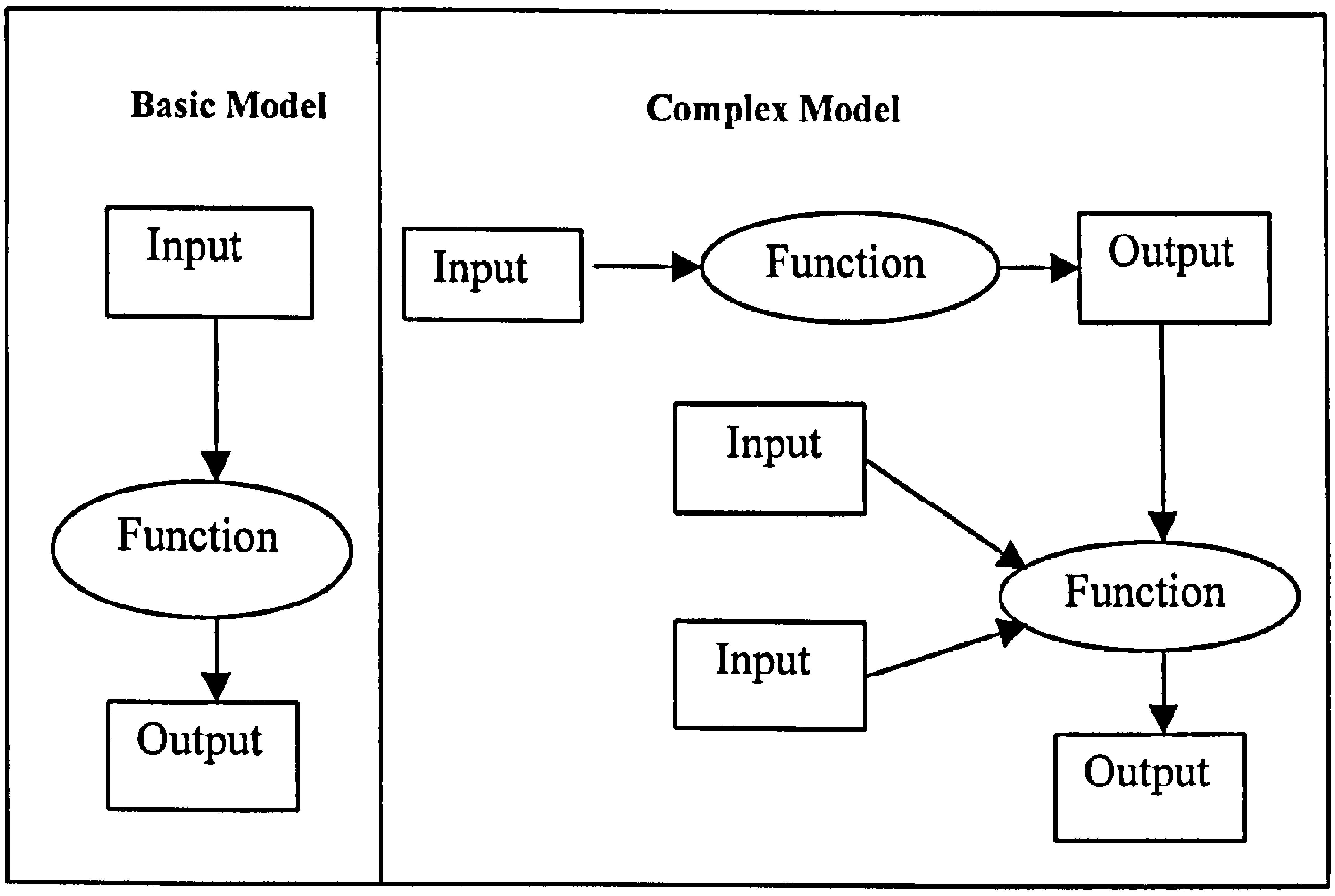


Figure 4.13: Graphical model in the ERDAS Imagine environment (created from symbols in ERDAS user guide)

In this study, NDVI images were produced using some of the built-in ERDAS functions with modification when necessary. The first step in creating an NDVI model is the choice and definition of the objects (Four raster layers) and placement on the blank sheet (Figure 4.14). Four sets of raster data (Multispectral SPOT images in 1994, 1995, 1996 and 1997) were placed as input layers. Figure 4.14 is the schematic diagram that illustrates the operation of the NDVI images. The basis for NDVI is described in Chapter 3.

The visible and near infrared reflectance may be obtained by remote measurements from satellites such as LANDSAT, SPOT, and the NOAA series, after correction for solar radiation input and atmospheric effects. In operation the values of NDVI were calculated for each of the images (1994-1997) using the atmospherically corrected reflectance values for SPOT bands 3 and 2 according to equation 4.4.

$$NDVI_{year} = (\rho_3 - \rho_2) / (\rho_3 + \rho_2) \qquad (4.4)$$

Where ρ_3 – reflectance value of band 3

ρ_2- reflectance value of band 2

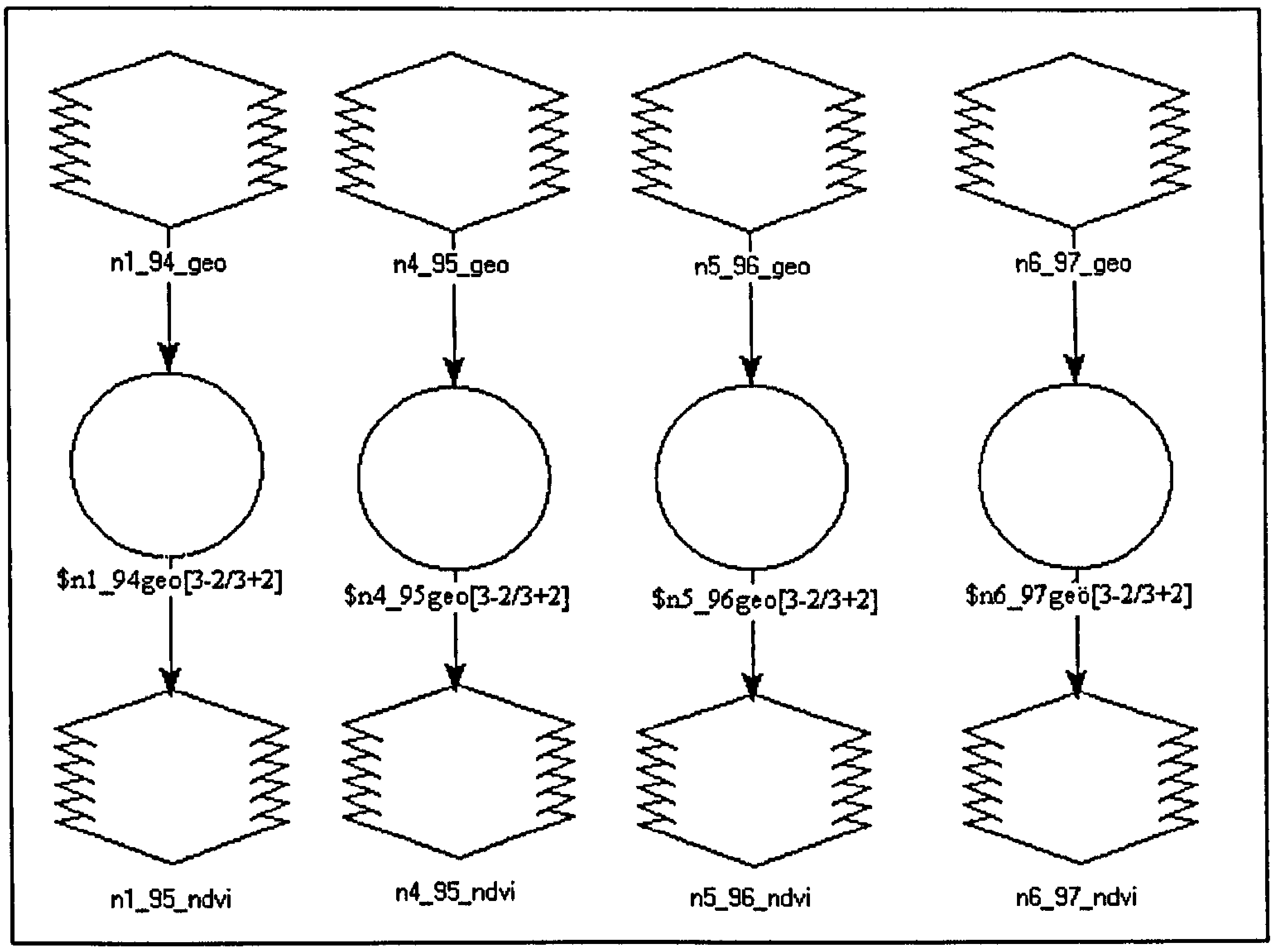


Figure 4.14: Schematic diagram for NDVI Model

This results in an NDVI image that is stored in an output file. The calculation in equation 4.4 uses the following expressions:

n1 ndvi = ($n1_94_geo 3-$n1 94_geo 2)/($n1_94_geo 3+ $n1_94_geo 2)
n4_ndvi =($n4_95_geo 3-$n4 95_geo 2)/ $n4_95_geo 3+ $n4_95_geo 2)
n5_ndvi =($n5_96_geo 3-$n5 96_geo 2)/ ($n5_96_geo 3+ $n5_96_geo 2)
n6_ndvi =($n6_97_geo 3-$n6 97 geo 2) / ($n6_97_geo 3+ $n6_97_geo 2)

Where n1 ndvi is the 1994 NDVI image, n4 ndvi is the 1995 NDVI image, n5 ndvi is the 1996 NDVI image and n6 ndvi is the 1997 NDVI image.

$n1 94 geo 3 = NIR band in the 1994 geo reference image.

$n1 94 geo 2 = RED band in the 1994 geo reference image

$n4 95 geo 3 = NIR band in the 1995 geo reference image.

$n 4 95 geo 2 = RED band in the 1995 geo reference image.

$n5 96 geo 3 = NIR band in the 1996 geo reference image.

$n5 96 geo 2 = RED band in the 1996 geo reference image.

$n6 97 geo 3 = NIR band in the 1997 geo reference image.

$n6 97 geo 2 = RED band in the 1997 geo reference image.

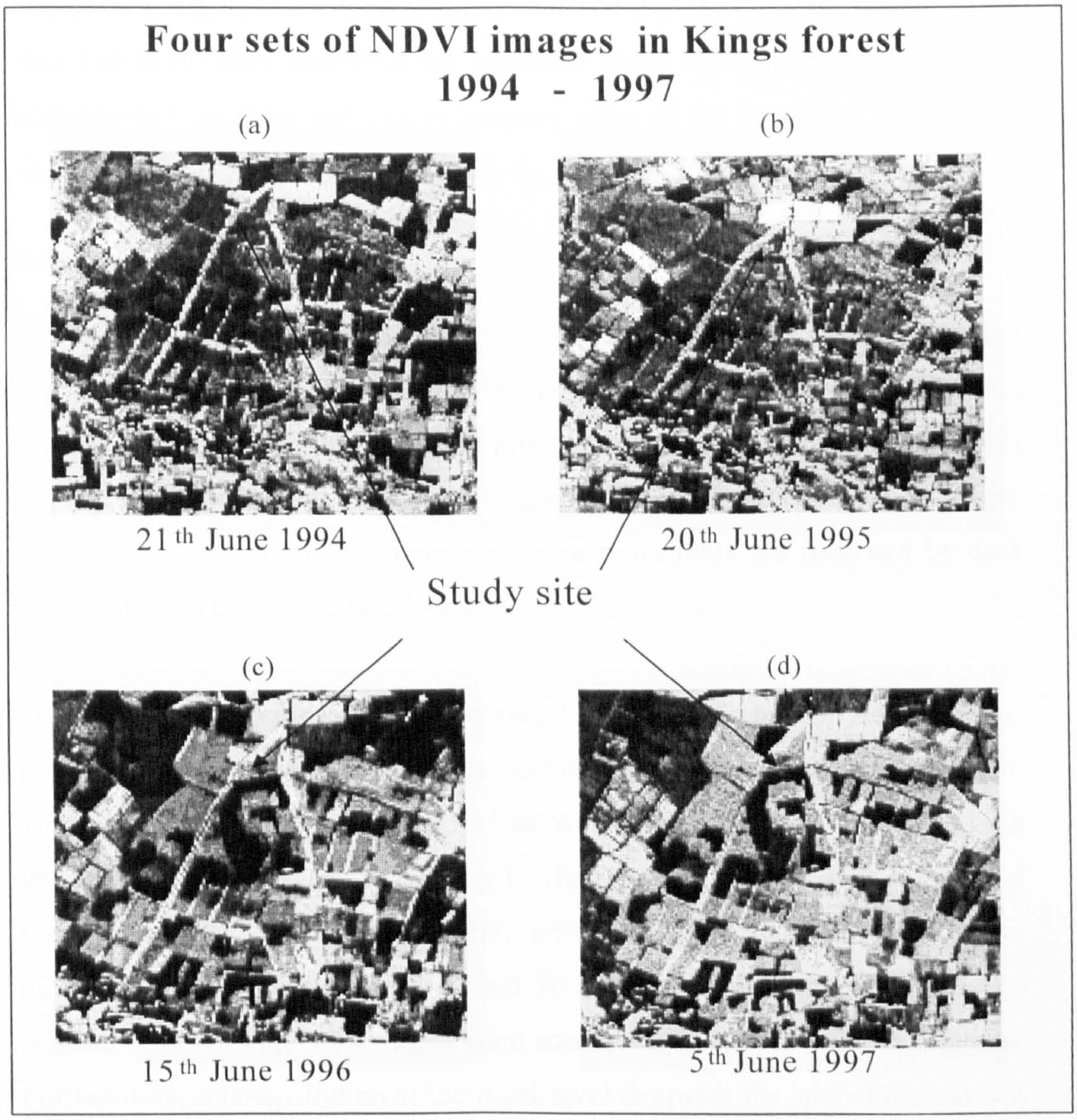


Figure 4.15: Four sets of NDVI images of the Kings Forest

Finally, all the components are connected to one another before the model is executed. Execution of the model only takes a few seconds; to create the NDVI images, as shown in figure 4.15.

4.5 DIGITAL CHANGE DETECTION TECHNIQUE

Change detection is the process of identifying differences in the state of an object by observing it at different times. Essentially, it involves the ability to quantify temporal effects using multitemporal data sets to analyse different types of land use change. Manual handling of data for change detection using sequential imagery is difficult to deal with. The digital nature of most satellite data makes it easily amenable for computer aided analysis, to automatically correlate and compare two sets of imagery taken of the same area at different times and display the changes and their locations.

4.5.1 Data pre-processing for change detection

Pre-processing and correction of satellite images prior to actual change detection is essential because it involves absolute comparisons between different dates in the same area. Pre-processing commonly comprises a series of sequential operations including image registration, geometric correction, atmospheric correction etc. Generally, these procedures are followed by data transformation to a vegetation index.

Of the various aspects of pre-processing for change detection, there are two main requirements: multidate image registration and radiometric calibration. Townshend *et al.* (1992) pointed out that for reliable change monitoring a high level of registration accuracy is need. Their results showed that for spatial resolutions of 250 and 500 meters, errors of more than 50% of actual difference in the NDVI were caused by misregistration of one pixel. To achieve errors of only 10%, registration accuracies of 0.2 pixels were required. Furthermore, misregistration at the pixel level degrades the spatial assessment of change or no-change boundaries. Therefore, prior to computing NDVI images in this study an accurate registration of the multidate imagery is required. The method used in this study (to 0.1 pixel error) is explained in this chapter section 4.4.1.1.

The second requirement for successful change detection is radiometric calibration. Duggin and Robinove (1990) strongly recommended that a reliable radiometric calibration should be carried out prior to multitemporal change analysis. This technique to correct images of common scenes is to use sets of targets on the land for which reflectance is nearly constant over time. Most of the studies (Hall *et al.,* 1991; Coppin and Bauer, 1994) make it clear that only when all sources of variation except surface cover can be adjusted or normalised to a common standard will it be possible to detect and identify changes in vegetation cover from multidate imagery. Therefore, this study also applied a reliable radiometric calibration to detect and identify forest cover changes during 1994-1997 in the study area as describe in section 4.4.1.2.

4.5.2 Vegetation Index Differencing (VID) algorithm

This study mainly focused on a transformation-based method called Vegetation Index Differencing (VID). Singh (1989) described NDVI image differencing as one of the more straightforward techniques, which gives accurate results for forest change detection. Coppin and Bauer (1996) reviewed more than 75 changed detection studies and concluded that image differencing and linear transformations appeared to perform better than other change detection methods. Hayes and Sader (2001) compared image differencing using NDVI analysis for tropical forest changes. They found NDVI change detection method to be the most accurate and efficient to analyse several dates of satellite imagery. For these reasons, VID method was selected as the change detection method suitable for analysing multidate of satellite imagery for this study. Four NDVI images (1994, 1995, 1996 and 1997) were used for the analysis. The period of four years is quite limited to monitor changes in the canopy cover. However, the study identified that within this period several management operations were carried out in the study site (thinning and felling dates and the compartment are shown in the chapter six Table 6.1). The main object of this study is to detect canopy cover changes by thinning and felling operations, Therefore selection of the period would be sufficient for the main purpose of the study.

The VID technique uses an arithmetic combination of reflectance measured in two spectral channels. It requires two co-registered data sets of the same format and size. In the first step, the value of each pixel (i,j) of $NDVI_{1995}$ was subtracted from corresponding pixel (i,j) of the $NDVI_{1994}$ .Then, in the second step, the value of the each pixel (i,j) of $NDVI_{1996}$ was subtracted from corresponding pixel (i,j) of the $NDVI_{1995}$. Finally, the value of the each pixel of $NDVI_{1997}$ was subtracted from the corresponding pixel (i,j) of the $NDVI_{1996}$ .The mathematical formula of this technique is in equation 4.5.

$$NDVI\ 3_{(i,j)} = \{ (NDVI\ 2_{(i,j)} - (NDVI\ 1_{(i,j)})\} \qquad (4.5)$$

Where 3,2 and 1 represent different years. The results of this operation is ($NDVI\ 3_{(,j)}$).

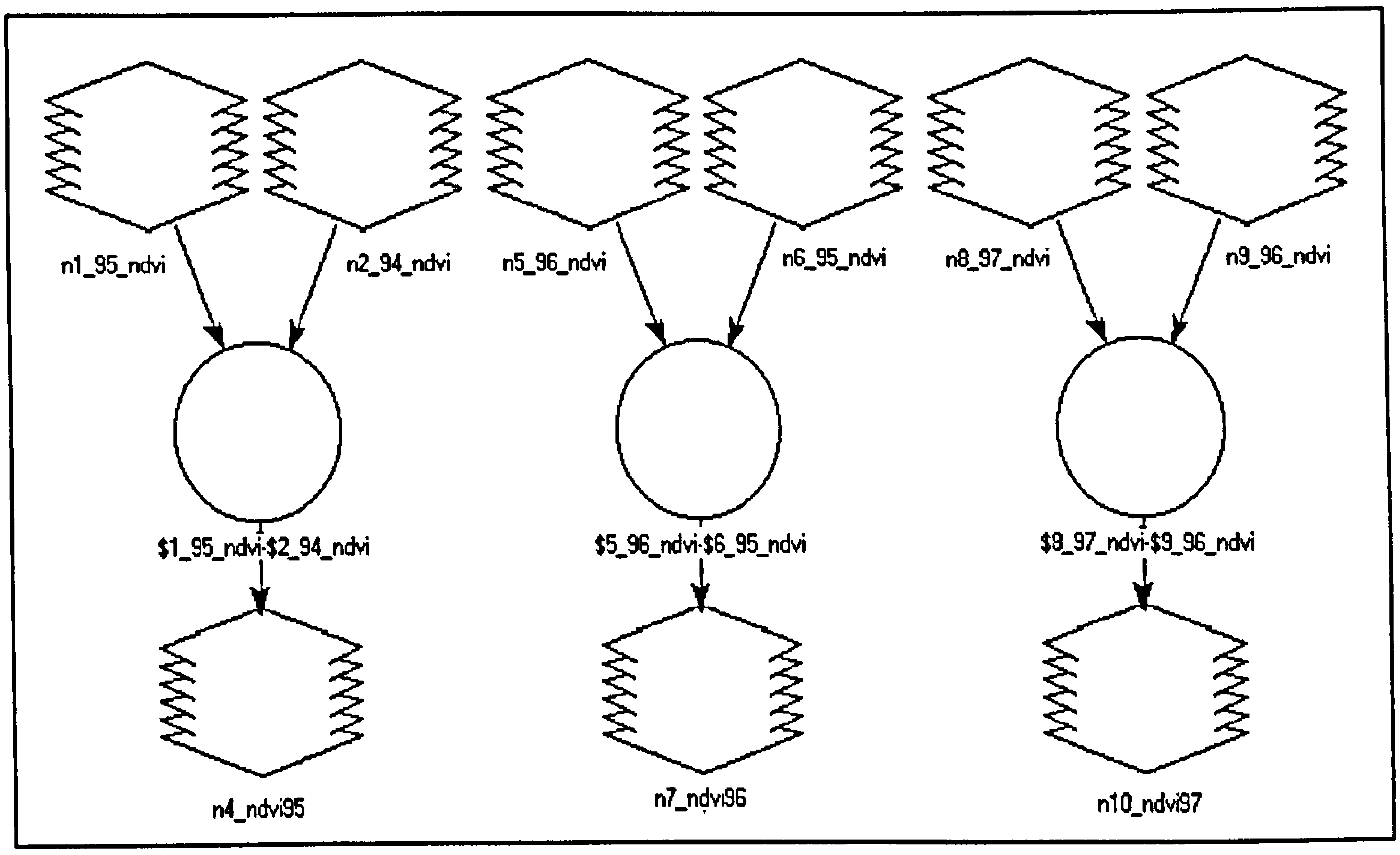


Figure 4.16: Schematic diagram of the change detection model

Figure 4.16 is schematic diagram that illustrates the operation of the change detection algorithm. It has two temporal input files in each output file as follows:

1) n95_ndvi and n94_ndvi
2) n96_ndvi and n95_ndvi
3) n97_ndvi and n96_ndvi

The operator performed arithmetic manipulation as follows:

1) $n1_95_ndvi - $n2_94_ndvi
2) $n5_96_ndvi - $n6_95_ndvi
3) $n8_97_ndvi - $n9_ 96_ndvi

At the final stage output files were created as follows:

1) n4_ndvi95
2) n7_ndvi96
3) n10_ndvi97

4.6 STATISTICAL METHODS

The most frequently used statistical methods in this study were correlation analysis and significance tests using MS Excel and SPSS. Forest stand parameters were used to establish a relationship between forest cover and the signatures derived from SPOT HRV images. In the first stage, the relationship between NDVI and forest cover data in different age groups was investigated using correlation analysis. Equation 4.6 was used for the correlation analysis.

$$\rho_{x,y} = \frac{\operatorname{cov}(x,y)}{\sigma x.\sigma y} \tag{4.6}$$

Where

$$\operatorname{Cov}(x, y) = \frac{1}{n}\Sigma(x_j - \mu_x)(y_j - \mu_x) \tag{4.7}$$

$$\sigma_x = \sqrt{\Sigma(x_j} - \mu_x)^2 \tag{4.8}$$

$$\sigma_y = \sqrt{\Sigma(y_j} - \mu_y)^2 \tag{4.9}$$

and μ represents the mean values and ρ is correlation coefficient. This calculates a correlation coefficient. It ranges in value from –1 (a perfect negative correlation) and +1 (a perfect positive correlation) a value of 0 indicates no linear relationship

Table 4.3: Data used for the multiple correlation analysis: structural variables were calculated from management tables provided by Forestry Commission. Comp = Compartments, the columns related 1994-1997 are NDVI values for the corresponding year, TH=Tree top height; MD= Mean diameter; BA=Basal area;

	COMP.	1994	1995	1996	1997	TH	MD	BA
1	4228	0.664	0.665	0.709	0.725	16.9	21.1	27.8
2	4227	0.683	0.688	0.711	0.736	17.9	22	28.8
3	4226	0.685	0.689	0.712	0.735	7.9	22	28.8
4	4225	0.671	0.676	0.721	0.745	19	26	30
5	4224	0.674	0.678	0.723	0.743	19	26	30
6	4223	0.651	0.657	0.702	0.742	19.9	26.5	30.3
7	4222	0.651	0.655	0.706	0.745	19.9	26.5	30.3
8	4221	0.655	0.661	0.747	0.763	19.9	26.5	30.3
9	4220	0.653	0.658	0.703	0.747	19.9	26.5	30.3
10	4219	0.653	0.657	0.705	0.741	19.9	26.5	30.3
11	4218	0.663	0.668	0.702	0.742	20	27	30.6
12	4217	0.645	0.658	0.701	0.715	19.5	26.5	31
13	4216	0.662	0.667	0.711	0.729	18	24.1	29.1
14	4215	0.643	0.652	0.701	0.714	19.5	26.8	31
15	4122	0.663	0.665	0.711	0.725	20.6	27.8	31
16	4114	0.658	0.665	0.73	0.736	9.9	12.6	26.6
17	4113	0.665	0.666	0.719	0.727	18.9	25.2	30
18	4112	0.658	0.666	0.733	0.741	9.8	12.6	26.6
19	4043	0.672	0.66	0.702	0.709	22.3	30.1	31.9
20	4042	0.345	0.661	0.661	0.683	26.9	38.1	36
21	4040	0.642	0.648	0.661	0.685	24.9	34.7	34.5
22	4041	0.641	0.645	0.667	0.689	24.9	34.7	34.5
23	4039	0.638	0.641	0.661	0.691	23.9	35.2	36
24	4038	0.641	0.645	0.665	0.681	24.9	38.9	34.5
25	4037	0.642	0.645	0.684	0.706	25.1	35.2	35
26	4036	0.643	0.645	0.681	0.706	27.1	38.9	36.7
27	4035	0.642	0.647	0.682	0.689	24.9	34.7	34.5
28	4034	0.641	0.649	0.686	0.708	24.9	34.7	34.5
29	4033	0.642	0.649	0.682	0.701	24.9	34.7	34.5
30	4032	0.641	0.649	0.682	0.701	26.9	38.1	36
31	4031	0.645	0.682	0.707	0.767	20.9	31.1	33.6
32	4030	0.628	0.641	0.683	0.706	24.9	34.1	34.5
33	4029	0.643	0.658	0.713	0.723	18.8	25.2	30
34	4028	0.636	0.645	0.727	0.727	22.5	30.8	32.8

This analysis assumes that a linear relationship exists between each of the independent variables (x1= top tree height, x2 = mean diameter, x3 = basal area,) and the independent variable (Y = NDVI where NDVI was from any of the years between 1994 and 1997). The study used data from 34 compartments (Table 4.4) to calculate r, and estimated the coefficient of the linear equation involving one or more independent variables that best predicted the value of the dependent variables.

4.7 METHODS USING GEOGRAPHICAL INFORMATION SYSTEM (GIS)

The sub-compartment forest base map of the study area, provided by the Forestry Commission district office in East Anglia, was one of the main sources for this study. Thirty four sub-compartments of Corsican pine of various ages were selected and the four stand parameters were calculated using yield tables provided by the FC district office.

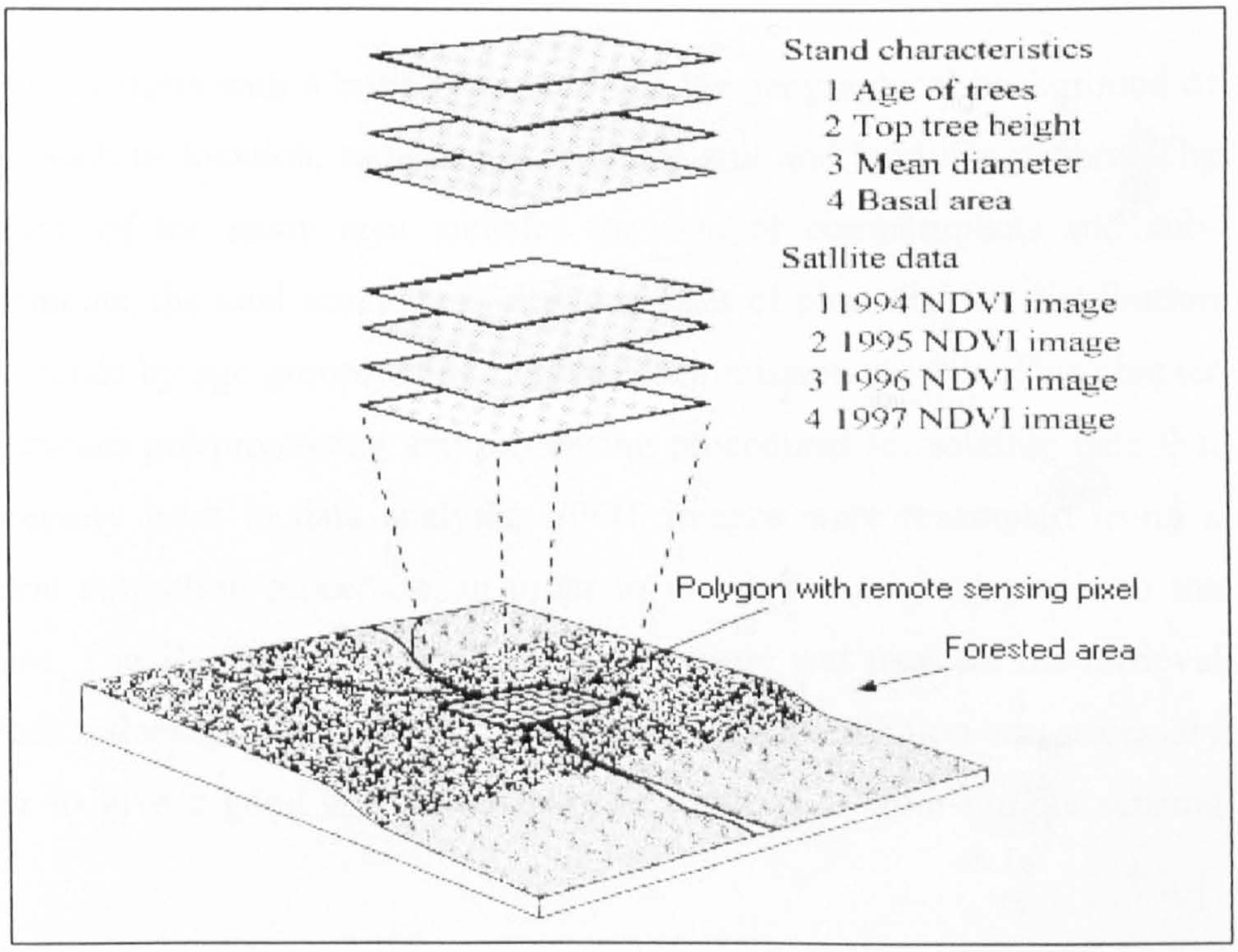


Figure 4.17 Overlaid data sets for GIS

Overlay operations performed within the GIS are shown in Figure 4.17. The compartment map of the study site was digitised and converted to raster format in MapInfo. The digital compartment map was registered to the remote sensed images using GCPs for which the co-ordinates had been accurately determined. The digital compartment map was imported into ArcView format. Data supplied by the FC district office were compiled for analysis.

4.8 SUMMARY

In this chapter, a review of the source materials used in this study is given together with a description of the study site. This chapter also includes a brief introduction to the main data sources. The maps and the data supplied by the Forestry Commission used for this study are discussed and the forest stand database is described. The pre-processing methods applied to the SPOT images used for the study were explained. The methodology used for the study is described.

This chapter starts with a brief explanation of the geographical background of the area such as location, topography, climate, soil and land use pattern. The description of the study area includes the size of compartments and sub-compartments, the total stand areas of two species of pine, and the distribution of pine stands by age groups using Forestry Commission records. This chapter also discusses pre-processing and processing procedures for satellite data that are necessary prior to data analysis. SPOT images were resampled using a geometric correction procedure, in order to match the original pixels to the map base. The 5S atmospheric correction procedure was used for the retrieval of surface reflectance from multi-temporal data. This correction was necessary in order to give a good estimate of surface reflectance from remote sensing data.

This chapter also highlights the procedures involved in graphical modelling in the ERDAS imagine environment. Algorithms for NDVI and change detection on a pixel by pixel basis have been developed. The advantages of graphical modelling algorithm development are that it is relatively easy to visualise and hence requires less time to understand.

The relationship between earth observation data and forest structural information is quantitatively analysed using multiple correlation algorithms. Therefore, the most frequently used statistical methods are also explained briefly in this chapter. Finally, overlay operations within the GIS are illustrated graphically and the formulations of digital compartment maps are explained.

CHAPTER FIVE

ANALYSIS OF SPATIAL VARIATIONS IN FOREST CANOPY COVER

5.1 INTRODUCTION

Forest cover is defined as all trees and other plants occupying the ground in a forest, i.e. including any ground cover (Society of American Foresters, 1983). It denotes the vegetation covering the forest surface. “Forest cover” is used in this thesis to refer to the overall density or greenness of the canopy. It should not necessarily be interpreted as the fraction of canopy cover, although it is usually closely related to this factor. When determining the spectral responses of forest canopies, forest cover plays a key role because it controls the amount of understorey vegetation, which is visible to the sensors (Nemani *et al.*, 1993). Therefore, detecting and monitoring vegetation cover, particularly in forest, has become a major application of satellite remote sensing (Hall *et. al.*, 1996; Sader and Winne, 1992). Remote sensing instruments measure the radiation flux for a unit area of the Earth surface and provide a spatially referenced representation of its surface. Measurements of radiation flux in the visible and near infrared portion of the electromagnetic spectrum have been used to calculate various vegetation indices, which have been used for both qualitative and quantitative assessments of vegetation cover. Vegetation indices are highly useful for detecting the amount of vegetation within the canopy cover because these indices enhance the contrast between the ground and vegetation. The most widely used vegetation index is the Normalised Difference Vegetation Index (NDVI), which is used this study.

The vegetation indices most commonly used in studies of forest ecosystems are simple algorithms based on the dissimilar interaction of red and near-infrared electromagnetic radiation with the vegetation canopy. Theoretically, the ideal vegetation index can be defined in the following way,

> "The index should be particularly sensitive to vegetation cover, insensitive to soil brightness and soil colour, little affected by atmospheric effects, environmental effects and solar illumination geometry and sensor viewing condition." (Jackson, 1983).

Vegetation Indices are robust spectral measures of the amount of vegetation present on the ground in a particular pixel. They typically involve transformations of two or more bands designed to enhance the vegetation signal and allow for precise inter-comparisons of spatial and temporal variations in terrestrial photosynthetic activity. Vegetation Indices are utilised both as a radiometric quantity for precise change detection studies and as intermediaries in the assessment of various plant biophysical parameters. Vegetation indices serve as precise measures of the amount, structure and condition of vegetation and have been used for:

1) Indicating seasonal and inter-annual variation in vegetation change detection studies, (Olsson, 1994; Coppin and Bauer, 1996)
2) Tools for monitoring and mapping vegetation cover, (Mas, 1999. Fung, 1990)
3) Estimating Leaf Area Index (LAI), % green cover, biomass, (Curran, 1983; Price and Bausch, 1995; Danson and Plummer, 1995))
4) Estimating the fraction of photosynthetically active radiation absorbed by the canopy, (Running *et al.*, 1989; 1991) and
5) Land cover changes and classification (Batista *et al.*, 1997)

This thesis is mainly concerned with the first two factors, which are very useful for management purposes.

To determine the density of plants in a patch of forestland must observe the distinct wavelength of radiation reflected off the plant cover. When radiation strikes an object, certain parts of the spectrum are absorbed and other parts are reflected or emitted. In plant leaves, chlorophyll absorbs red and other visible wavelengths for photosynthesis. The cell structure of the leaves, on the other hand, reflects near infrared light. The more foliage that a plant has, the more these types of light are affected. Remote sensing instruments have a number of detectors on board to measure specific wavelengths of radiation coming from the ground. A satellite image of the red and near-infrared radiation emanating from a plot of forestland can be used to compare the intensity of the two types of radiation at each pixel of the image to arrive at the vegetation density. In general, if the difference is large, then the vegetation at that pixel is likely to be dense and may contain thick green forest. If it is low, then the vegetation is probably sparse (Campbell, 1996).

There is an increasing need for accurate measurement of forest cover in terms of both its spatial and temporal variation for improvements in forest management. Therefore, this chapter initially analyses the spatial changes of forest cover using satellite-derived values of the Normalised Difference Vegetation Index (NDVI). The first part of the analysis concerns the statistical relationship of near-infrared reflectance to red reflectance for different age groups of pine trees in the study site. In addition, the analysis focuses on NDVI changes in different types of stands within the same site. Correlation analysis was also used to examine the relationship between NDVI and the age of trees in the different compartments of the forest stand. The final part of this chapter discusses the relationship between NDVI and selected forest stand parameters, such as tree height, mean diameter and basal area (calculated from management tables formulated by Forestry Commission). These types of relationship have been found in even-age intensively managed forests (Nilson and Peterson,. 1994) but they can be problematic in mixed-age natural forests due to the complex understory and a variety of natural and human disturbances.

5.2 RELATIONSHIP BETWEEN RED AND NIR REFLECTANCE

NDVI is determined by the difference between red and near-infrared reflectance, so this section explains how reflection in these two bands differs in each age group. Because the leaf becomes spongier with age, a mature leaf displays less reflection in the visible band and more in the infrared (Campbell, 1996). Younger leaves have a thinner layer of mesophyll tissue and fewer cavities so that relatively less reflection occurs in the NIR region, while red reflectance is relatively high.

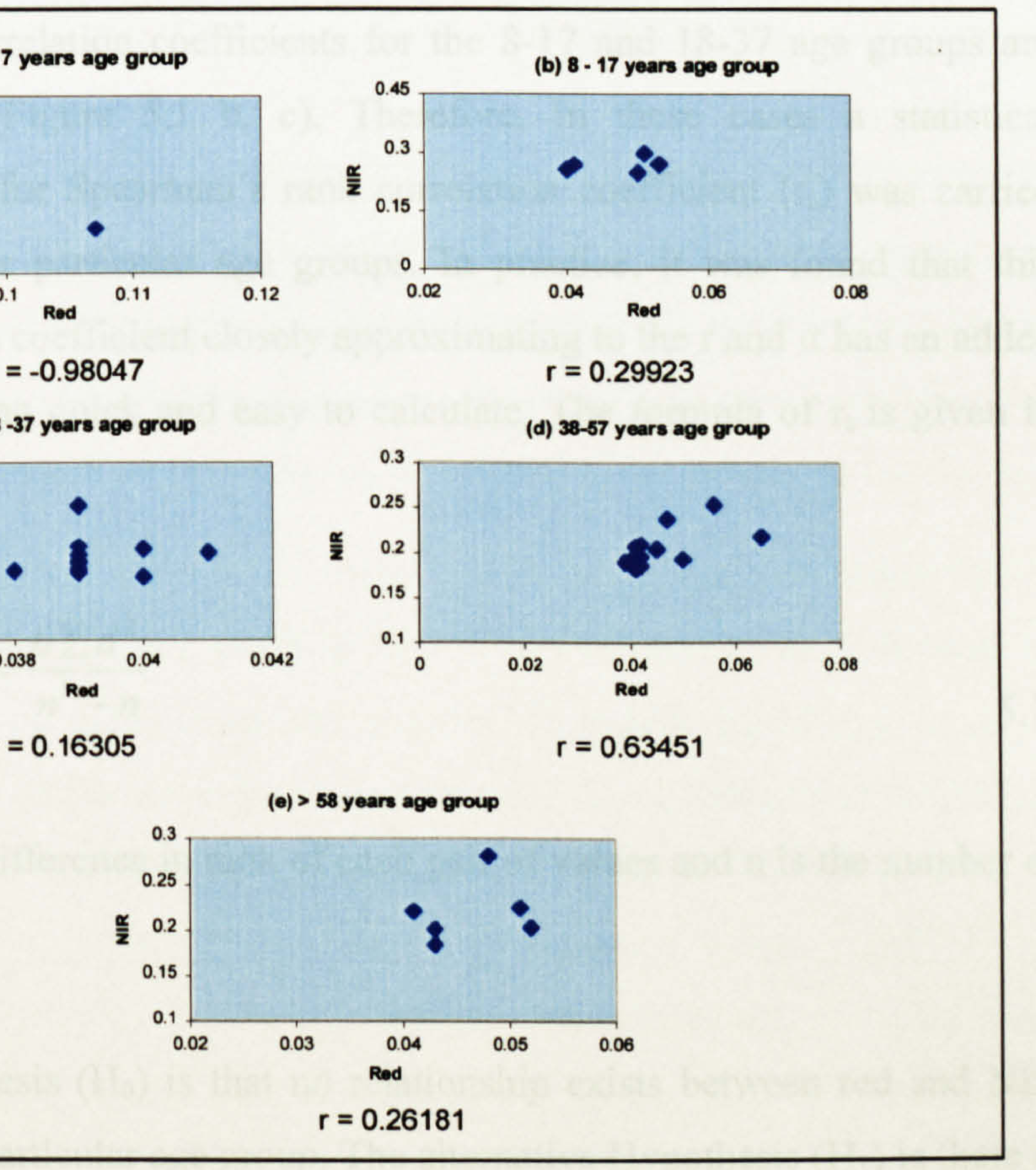


Figure 5.1: Relationship between mean NIR and red reflectance and age groups in 1997

Figure 5.1 summarises the relationship of mean NIR reflectance to the mean red reflectance for different compartments in the study area by age groups (<7. 8-17, 18-37, 38-57 and >58) for the 1997 SPOT data. These age groups were selected according to the growth stages of planted trees in the plantation. In addition, the separation of age groups closely relate to the different stages of management operations. For example, cleaning and brashing operations are carried out in the < 7 and 8-17 years age groups, thinning and partial felling at 18- 37 and 38-57 and clear felling in the > 58 age group.

In the lowest age group (< 7 years old), there is a strong negative correlation (r = -0.98), with a decrease of NIR reflectance as red reflectance increases (Figure 5.1a). On the other hand, the old age group (> 58 years old) shows a relatively low positive relationship (r = 0.26). In contrast, in the 8-17 and 18-37 age groups, the relationships were positively correlated, but not very strongly. The correlation coefficients for the 8-17 and 18-37 age groups are 0.30 and 0.16 (Figure 5.1 b, c). Therefore, in these cases a statistical significance test for Spearman's rank correlation coefficient (r_s) was carried out on these four particular age groups. In practice, it was found that this procedure gives a coefficient closely approximating to the r and it has an added advantage of being quick and easy to calculate. The formula of r_s is given in equation 5.1

$$r_s = 1 = \frac{6\sum d^2}{n^3 - n} \qquad 5.1$$

Where d^2 is the difference in rank of each pair of values and n is the number of pairs.

The null Hypothesis (H_0) is that no relationship exists between red and NIR reflectance in a particular age group. The alternative Hypothesis (H_1) is there is a correlation between these two variables. It was decided to reject H_0 with not less than 95% confidence; therefore $\propto = 0.05$.

Table 5.1 shows the calculation of r_s and tabulated critical values (Appendix E) with the degrees of freedom (df = n-1, where n is the number of fractions in the test) of five age groups (< 7, 8-17, 18-37, 38-57 and >58). In this case, the calculated r_s values of 8-17, 18-37 and >58 age groups are less than the tabulated r_s values. Therefore, according to the rules of significance testing, the null hypothesis can be accepted for the above two age groups and the alternative hypothesis is rejected. Therefore, it can be stated that there is no significant correlation between red and NIR reflectance in the 8-17, 18-37 and >58 age groups. However, the calculated r_s value of the < 7 and 38-57 age groups is greater than the tabulated r_s; therefore, in this case, it is possible to reject the null hypothesis and accept the alternative hypothesis, that there is a significant correlation of red and NIR reflectance in the < 7 and > 38 age groups.

Table 5.1 Statistics of significance test for correlation in the < 7, 8-17,18-37,38-57 and > 58 age group

Age group	<7	8-17	18-37	38-57	>58
Calculated r_s	0.830	0.400	0.191	0.631	0.300
Tabulated r_s	0.829	0.900	0.481	0.412	0.829
Degrees of freedom	6	5	13	15	6

Forest canopies are composed of many layers of leaves, the upper leaves shadowing the lower leaves, creating an overall reflectance that is formed by combination of leaf reflectance and shadow. Normally shadowing tends to decrease canopy reflectance below the value from an individual leaf (Knipling, 1970). He pointed out that the percentage reflectance in the visible band is typically 10% for a single leaf and 3%-5% for a canopy whereas reflection in the near-infrared is typically 50% and 35% respectively. At the youngest stage, < 7 years, (Figure 5.1a) the planted trees are small and do not dominate the site, and there are several thousand trees per hectare as well as other spontaneous vegetation, which dominates the canopy. As the crown covers increases with age, the proportion of background influence decreases and the proportion associated with the canopy and with shadows increases.

The thicket stage commences when the crowns merge to form a complete canopy, at about 15 years for most pine trees, and ends when thinning starts, usually at 20-25 years. Apart from occasional tree deaths, the thicket stage has a similar density of plants to the young tree stage. In this age group (8-17), the relationship between red and near-infrared reflectance is very weak (Figure 5.1b). Reflection of the near-infrared decreases with time, but the reflection from the red region shows an irregular pattern. According to the information gathered from forest officers, during the next stage (18-37 year age group), in the study site when the stand is regularly thinned, the number of trees decreases rapidly at first to around 1000/ha and then more slowly to about 100/ha. It has been stated that, when the thinning treatment affects 28% of the canopy, LAI tends to reduce permanently (Herwitz, 1990) and the pre-thinned LAI of the forest plantation does not become re-established. In the study area, ,there was little evidence of crown expansion of the remaining trees and broadleaved understory development was negligible (Figure 5.1c). However, pine trees have only a limited capacity to expand their crowns in response to changes in canopy structure. Some small bands of broadleaved trees become established along forest tracks on an area of less than 10% of the stand. Therefore, spectral reflectance differs in the 18-37 year age group from other age groups, especially from the mature age group.

During the mature stage (38-57 years old), when the thinning treatment stops, growth of the remaining trees in the canopy is very slow especially in pine plantations. But near-infrared reflectance increases, due to the influence of background effects and reflection from the red portion, also shows a slight increase. With increasing maturity, the roughness of the canopy increases (Olsson, 1994) producing shading and shadows that are expressed as an increase in the near-infrared reflectance accompanied by decreasing red reflectance. Therefore, a moderate positive correlation coefficient of r = 0.63 is shown in figure 5.1d at this stage.

Due to felling operations in the >58 year age group, very few mature trees are left in the plantation. The distance between crowns and inter-crown shadowing tend to increase. Increased shadowing would be expected to reduce reflectance, particularly in the visible band, and increase of near infrared reflectance (Figure 5.1e). A more likely explanation is that the woody twigs and branches supporting the pine foliage have become exposed to incoming radiation, which would be expected to increase red reflectance and decrease near-infrared reflectance (Campbell, 1996).

5.3 SPATIAL CHANGES OF NDVI IN STUDY SITE

The Normalised Difference Vegetation Index (NDVI) is a quantitative measure based on digital values, which attempts to measure vegetation vigour. It separates green vegetation from the other surfaces because the chlorophyll of green vegetation absorbs red light in photosynthesis and reflects the near-infrared wavelengths due to the scattering caused by internal leaf structure. Thus, high NDVI values indicate high leaf biomass, canopy closure or leaf area (Jansinski, 1990; Sader and Winne, 1992). There is potential for its use in quantification of forest canopy cover, because it gives a clear picture of the forest cover in terms of the proportion of green canopy.

Further the NDVI, the normalised difference of brightness values from the near-infrared and visible red bands, has been found to be highly correlated with crown closer, leaf area of the canopy cover and other vegetation parameters Sellers, 1985, Running *et al.*, 1886). Lyon *et al.*, (1998) compared seven vegetation indices to detect land cover in Mexico Chiapas study site and reported that the NDVI was least affected by topographic factors and was the only index that showed histograms with normal distributions. Therefore, changes in canopy cover can be detected by analysing NDVI values as applied in this thesis. High values of NDVI identify pixels covered by substantial proportions of green vegetation, while low values indicate bare land with very few green grass patches. These changes provide important information on vegetation growth of a plantation forest. The first part of this section is mainly concerned with differences of NDVI by age group. Changes of NDVI in parcels of different cover types within the survey site are explained. Finally, NDVI changes with different types of management treatments within the compartments are examined.

5.3.1 Comparison of NDVI by age groups

Figure 5.2 shows the NDVI image of the study site (part of Kings Forest pine plantation) in 1996. It is displayed in greyscale and emphasises the differences of NDVI values ranging from a minimum of 0.263 to a maximum of 0.831. The areas with high NDVI values appear in a lighter tone in the image, while low values are in darker tones.

According to the different tones in the main image, the following three cover types were identified:

1) Clear cut areas - low NDVI (0.263-0.366) with darker tone. (marked C in the image - Figure 5.2).
2) Coniferous plantation (mainly pine trees) - moderate NDVI (0.562-0.747) with medium tone. (marked * A1, A2, A3 and A4).
3) Broadleaf trees - high NDVI (0.778-0.835) with brighter tone B (Figure 5.2).

This study mainly concerns different ages of pine plantation. Because the canopy cover of a tree changes with its age, spatial changes of NDVI in the study site were identified on the basis of the following age groups (Figure 5.2).

1) <7 years - Very young pine plantation - marked *
2) 8 - 17 years - Young pine plantation - marked A 1,
3) 18 - 37 years - Pre mature pine plantation - marked A2,

4) 38 -57 years – Mature pine plantation –A3,
5) >58 years – Old age pine plantation -marked A4,

C and D refer to non-pine areas.

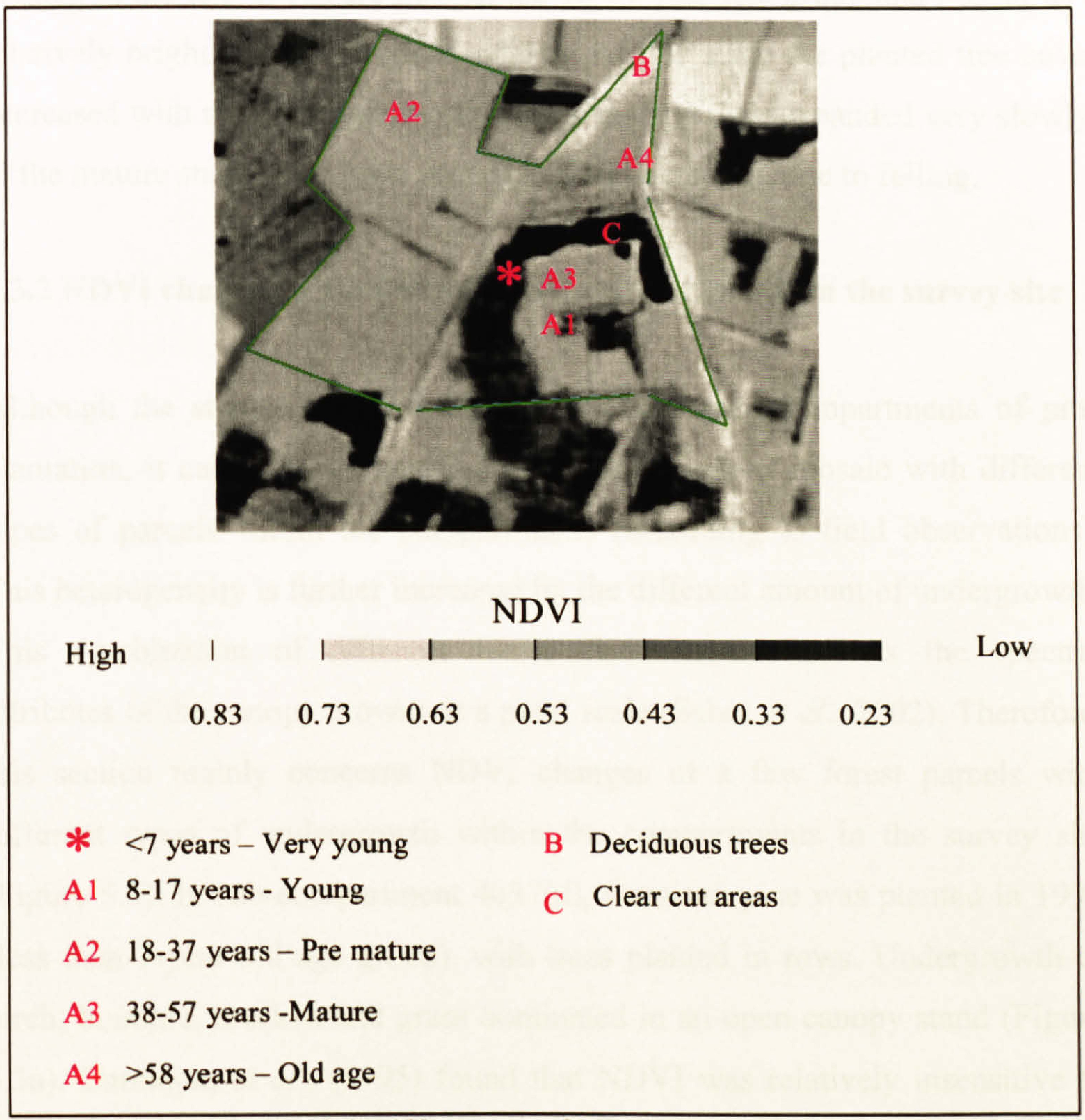


Figure 5.2: Spatial Differences of NDVI in the study site - 1996

In a one year-old plantation, the spaces between the trees consist of dry grass with rough vegetation and soil. Therefore, at this stage, very low values of NDVI (0.355-0.366) occurred. Until the increase of plant cover at the age of 8 years, NDVI changed very little. In contrast, in the 8-17 years age group (marked B in the images), NDVI changes with time are relatively greater. In the image this area appears in relatively brighter tones, due to the high value of NDVI. The evidence suggests the presence of a considerable amount of undergrowth, which remains until thinning treatment starts at 20 years, but is not exposed to the sensor because the canopy cover is fully developed at this stage. However, high near-infrared reflectance from the canopy is responsible for the high NDVI. In the area marked C on the image, pine trees that were planted in the late 1960s are now in the 18-37 year age group and appear as a relatively brighter area with dark patches. At this stage the planted tree cover decreased with thinning operations and the canopy then expanded very slowly. In the mature stage (38-57 age group), NDVI decreased, due to felling.

5.3.2 NDVI changes within selected sub-compartments in the survey site

Although the study site is a collection of even-aged compartments of pine plantation, it can also be identified as a heterogeneous mosaic with different types of parcels within the compartments (according to field observations). This heterogeneity is further increased by the different amount of undergrowth. This combination of different forest characteristics affects the spectral attributes of the canopy crowns at a pixel scale (Sabol *et al.*, 2002). Therefore, this section mainly concerns NDVI changes of a few forest parcels with different types of undergrowth within the compartments in the survey site (Figure 5.3). In sub-compartment 4037(d), Corsican pine was planted in 1997 (less than 7-year old age group), with trees planted in rows. Undergrowth of birch, bramble, bracken and grass dominated in an open canopy stand (Figure 5.3a). Gammon, *et al.*, (1995) found that NDVI was relatively insensitive to changes in canopy structure in stands that have high green canopy typical of dense shrubs and trees.

This study found that NDVI in sub-compartment 4037(d) was relatively low at 0.383 (Figure 5.4), but variations can be identified with differences of undergrowth. Figure 5.3b shows a parcel dominated by grass followed by shrubs and regenerated pine seedlings. Here NDVI ranged from 0.423 in areas that were not replanted and where natural regrowth had been slow, to 0.502 where there was continuous grass cover with deciduous shrubs.

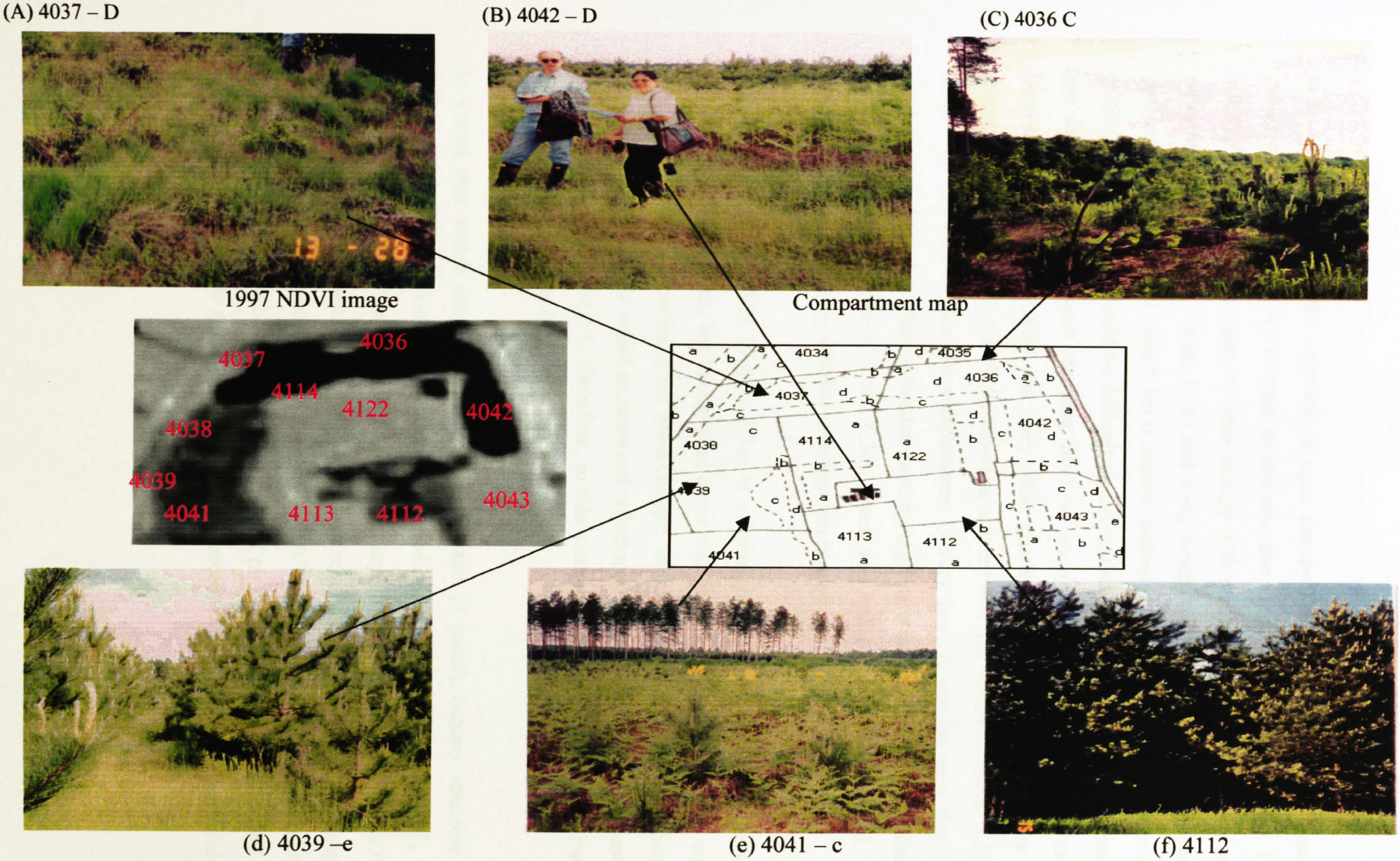


Figure 5.3 Different types of parcels within the samples in the survey site – June 2001

It is the general trend for regrowth in open canopy sites. However, as the canopy closes with tree growth, NDVI tends to increase, due to increases in green cover. The NDVI for the structural stages of open canopy with regenerated pine seedlings (sub-compartment 4042-d in Figure 5.3b) and open canopy with planted pine trees (sub-compartment 4041-a in Figure 5.3e) is similar, although the planted trees are at an age of four years and five would be difficult to distinguish. This probably occurs because the exposed area between standing trees in an open canopy stand is typically dominated by grass, shrubs and very little patchy bare soil. This similarity is illustrated in Figure 5.4. NDVI in sub-compartment 4041(c) varies between 0.511-0.602 and variation within the compartment is very low. It can be seen that the greatest contribution to stand reflection (mainly high near-infrared) occurred in these sub-compartments (Figure 5.3b and 5.3e), which was influenced by background. To discriminate these features, detailed investigation is needed.

Sub-compartment 4036(c) (Figure 5.3c) is of pine trees of the same age as the previously illustrated site, but background cover was variable. It has spatial gaps with a rough surface and variation in the stand canopy, which resulted in background being exposed to the sensor. It would increase red reflectance and decrease NIR reflectance, giving a reduction of NDVI. Therefore, in this case variation of NDVI is relatively high (0.208), from 0.308-0.516.

In young pine stands sub-compartment 4112(a) (age 17 years), canopy structure is relatively simple with continuous canopy layer trees of similar size (Figure 5.3f). In this stand, reflection is strongly related to the top layer of the tree canopy and NDVI shows very little variation (Figure 5.4). Because of relatively high NDVI in the image, it has a relatively light tone. Figure 5.4 shows NDVI variations within compartments in the survey site. These homogeneous canopies of pine plantations are very useful to estimate forest cover for management operations because the effect of background is very low.

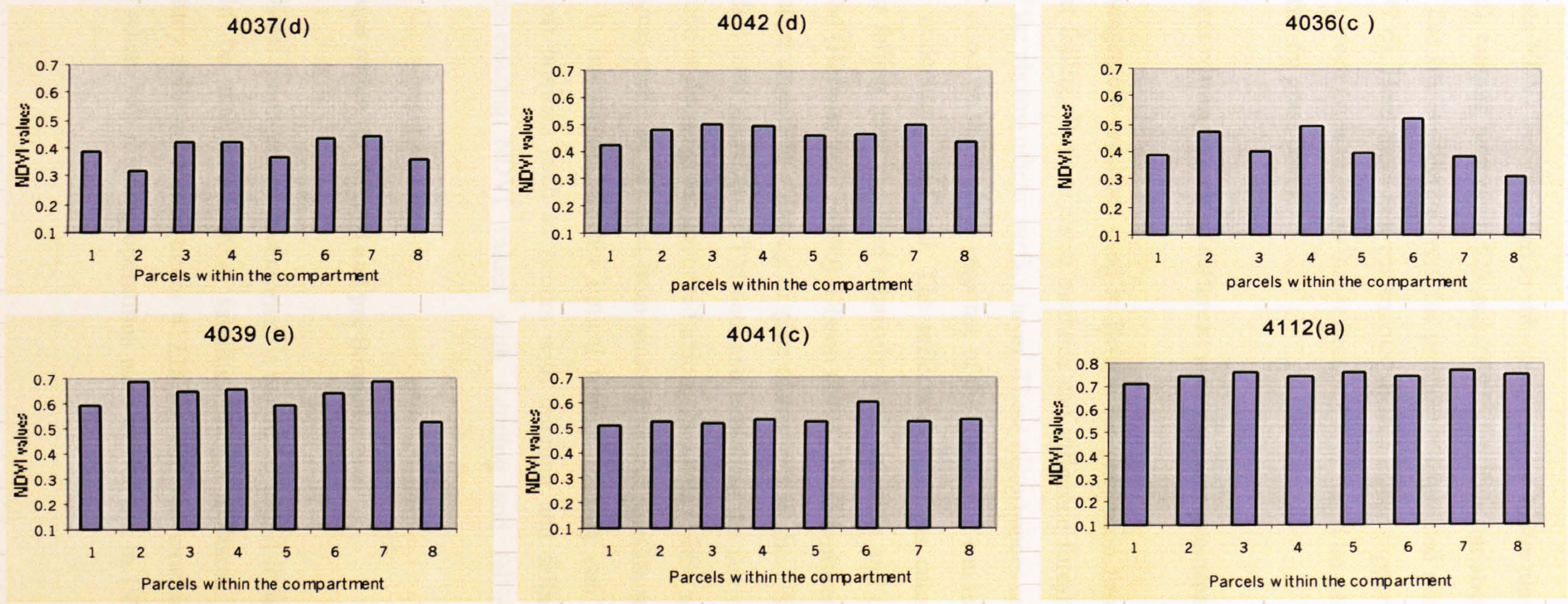


Figure 5.4 NDVI variations within compartments in the study site

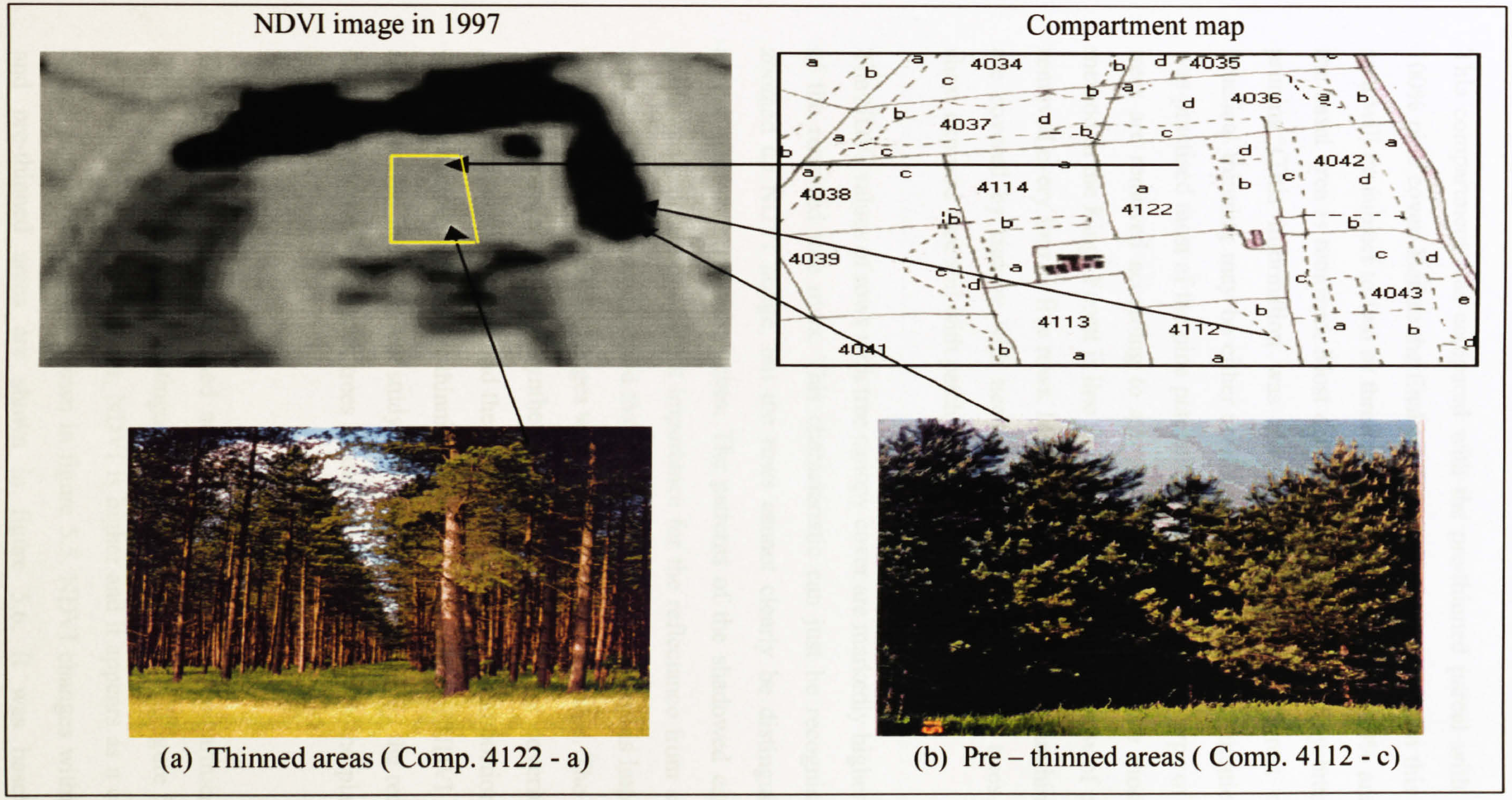
Relatively moderate NDVI was recorded in sub-compartment 4039a planted in 1988 (Figure 5.3d), ranging between 0.523 and 0.687 with little variation. The spatial pattern of this site is different from the previously explained site (sub-compartment 4037 d). Here there is a continuous surface cover supported by tree canopy with a green grass layer, so that reflectance was based on partly on tree cover and partly on grass cover.

5.3.3 NDVI changes within parcels of different management practices

The principal management practices used in Britain for plantation forest are thinning and clear felling. Both of these methods can influence forest cover due to removal of the photosynthetic surface layer. These disturbances can also have a significant effect on the spectral response of the forest as it can increase the effect of the understorey and soil. The reflectance changes caused by thinning and clear felling have received relatively little attention and are not yet well understood (Herwitz *et al.,* 1990). Olsson (1994) made multitemporal studies of the change caused by thinning of pine plantations in the USA and Sweden. The studies used LANDSAT TM data and explained the decrease of TM band 4 reflection as due to green cover reduction. Jaakkola (1989) showed that clear felled areas could be detected from multi-temporal satellite images. There is a need to investigate whether optical remote sensing can detect reductions of forest biomass such as occurs with thinning and felling. So changes from pre-existing NDVI values with thinning and felling are investigated here.

5.3.3.1 NDVI changes within the thinned and pre thinned areas

For updating of forest management inventories, it would be useful if thinning information could be interpreted from satellite images (Olsson, 1994) Therefore, this study selected compartment 4122a for detailed examination, with mature trees where two thinning operations were carried out in 1990 and 1995 (Figure 5.5).



(a) Thinned areas (Comp. 4122 - a)

(b) Pre – thinned areas (Comp. 4112 - c)

Figure 5.5 Thinned and pre-thinned areas in the pine plantation

This compartment was compared with the pre-thinned parcel with complete 100% pine cover. Before the final cutting, most forest stands in this surveyed area will be subject to two or three thinning where between 20% and 50% of the basal area is removed. Most of the thinning is followed by brashing and pruning (This information was obtained from the local forest manager). Practical thinning may be either selective or systematic. Systematic thinning was practised most of the pine plantations on this site. In this type of thinning, trees are removed according to a pre-determined system. The most popular method in the Kings Forest is line thinning in which a whole row of trees were removed every four or five rows. In thinned compartments, the unthinned rows are covered by canopy with needle leaves, while rows with trees removed show exposed bare soil with patchy dry grass.

The NDVI values of rows with tree canopy cover are markedly higher than that of the removed tree rows. This characteristic can just be recognised in the zoomed up NDVI image, but the rows cannot clearly be distinguished and appear only as scattered patches. The patterns of the shadowed canopy and shadowed ground are of great importance for the reflectance from coniferous forest. Thus, it can be assumed that change in shadow patterns is important for the appearance of NDVI changes with different tones of patches. The reduction in the proportion of photosynthetically active canopy, the covering of the ground with cutting debris and the changes in planted tree proportions explain the reduction of NDVI after thinning. However, reduction of NDVI in certain areas observed in the present study could also be explained by the reduction in the proportion of deciduous trees in the interspaces between the planted pine trees

The appearance of pre-thinned areas is shown in sub-compartment 4112-b (Figure 5.5b). It is easy to distinguish from the thinned area (Figure 5.5a). Due to 100% of planted tree cover, NDVI is higher and it appears as a continuous lighter tone in the images shown in figure 5.5. NDVI changes within thinned and pre-thinned areas are shown in figure 5.6. It was based on the measurement of thinned parcels (39 year-old pine trees) and pre-thinned parcels (17 year-old pine trees). In pre-thinned areas, high NDVI values were found with very little variation, while NDVI is lower and shows more variation in the thinned areas. To test this finding statistically a student t test was carried out. The formula of t is given in equation 5.2. To test this finding statistically a Student's t test was carried out. The formula for t is given in equation 5.2.

$$t = \frac{\mu_x - \mu_y}{\sqrt{\frac{s_1^{\,2}}{m} + \frac{s_1^{\,2}}{n}}} \qquad 5.2$$

Where μ_x and μ_y are the sample means s_l is their standard deviation and m and n is the sample sizes

The null hypothesis is that there is no difference between the means in the pre-thinned areas and the thinned areas. This hypothesis was tested at the 5% significance level, i.e.$\propto$ =0.05. Appendix G shows the statistics using an unpaired t test as well as the tabulated critical values. With the degree of freedom (df = 38) in this case, the computed t score of 3.081 is greater than the critical t table value, indicating that the null hypothesis can be rejected. Therefore the difference between the means in the pre-thinned areas and the thinned areas is significant.

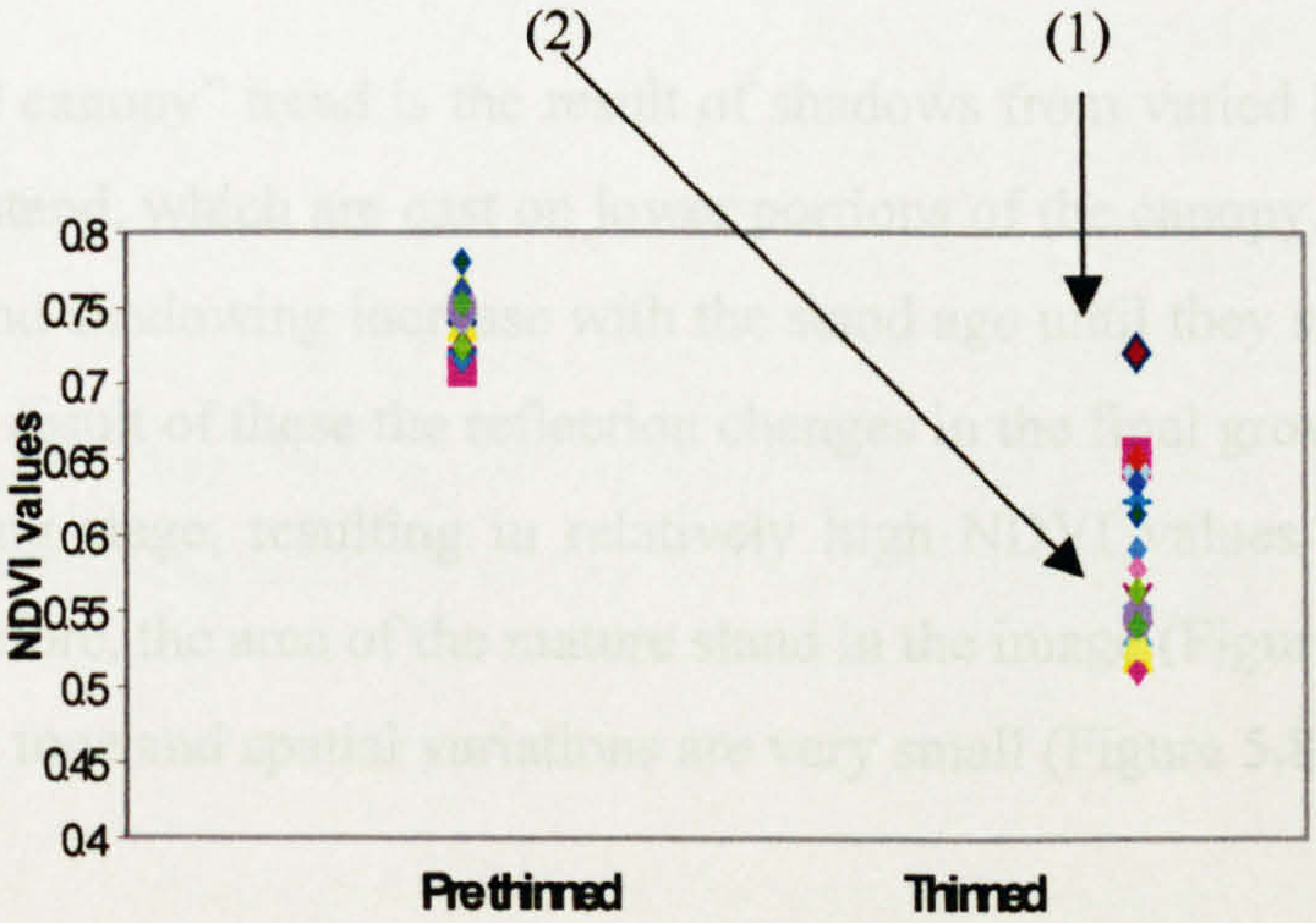


Figure 5.6 NDVI variations in thinned (Comp. 4122-a) and pre-thinned (Comp. 4112-b) stands

In Figure 5.6, arrow 1 indicates pixels showing trees with continuous canopy cover, resulting in photosynthetic green cover being exposed to the sensor. Therefore, NDVI is relatively higher than in the other selected pixels Arrow 2 points to a pixel where ground cover is becoming exposed to the sensor after thinning, resulting in low NDVI.

5.3.3.2 NDVI changes within the felled and pre - felled areas

At the end of the rotation, clear felling of all the trees is the most efficient and popular method of harvesting in plantation forests. The forest being a renewable resource, harvesting or final clear felling is a normal part of the events in forest management. Therefore this section investigates how NDVI changes in the pre-felling and felling stages. After the last stage of thinning at about 35 to 39 years, the natural canopy cover expands slowly. At the same time, the ground becomes increasingly covered with grass. Therefore, the tree canopy cover of the pine plantation may be as much as 65% to 75% in properly managed stands (Figure 5.7b), while the ground surface layer is covered with green grass. In addition, the amount of shadow in the canopy is also important at this stage. However, as the canopy closes, the shade fraction increases to roughly 55% in old growth stands (Sabol *et al.*, 2002).

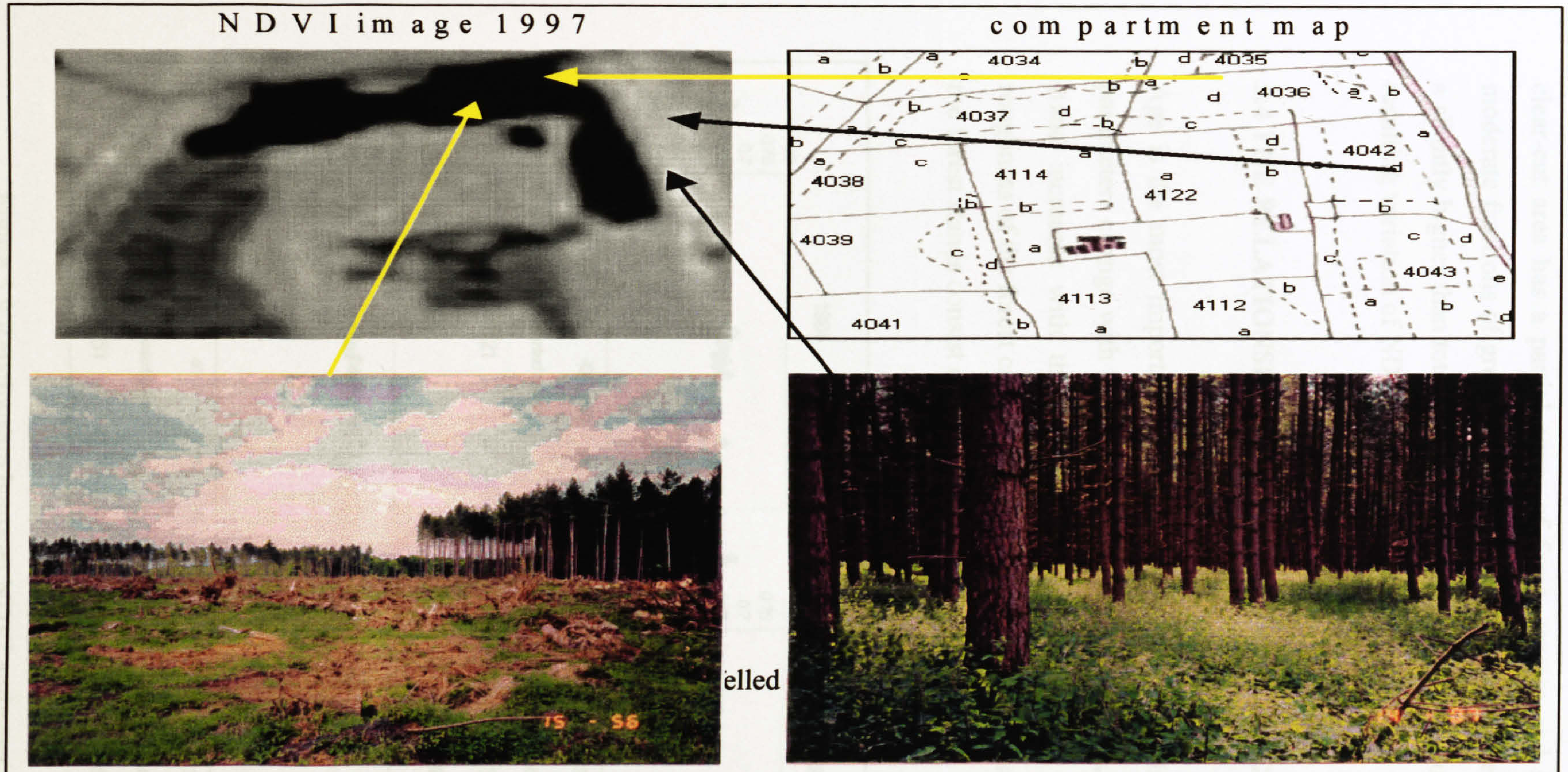
This "closed canopy" trend is the result of shadows from varied heights of the trees in the stand, which are cast on lower portions of the canopy. Both canopy roughness and shadowing increase with the stand age until they stabilise in old growth. The result of these the reflection changes in the final growth of trees in the pre-felling stage, resulting in relatively high NDVI values of 0.683 and 0.741. Therefore, the area of the mature stand in the image (Figure 5.7) appears as very light tone and spatial variations are very small (Figure 5.8).

After felling, the photosynthetic area of the canopy is reduced and the ground is covered with debris (Figure 5.7a). Reducing the numbers of planted trees explains the reflectance decrease in the near infrared band and the increase in the red band. The resulting NDVI is lower, ranging from 0.235 to 0.319. The clear-cut area has a partial cover of ferns, grasses and shrubs with low to moderate fractions of green vegetation. Therefore, in these areas, the NDVI is a slightly higher than totally exposed ground cover with cutting debris and the resulting variation of NDVI is a little higher (Figure 5.7).

Figure 5.7 NDVI variations in felled (Comp 4036-d) and pre-felled (Comp-4042 d) stands

The student's t test was applied to the felled and pre-felled areas using equation 5.2. The null hypothesis is that there is no difference between the means in the pre-felled areas and the thinned areas. This hypothesis was tested at the 5% significance level, i.e.$\propto$ =0.05. Appendix G shows the statistics using an unpaired t test and the tabulated critical values. With the degree of freedom (df = 38) in this case, the computed t score of 2.406 is greater than the critical t table value, indicating that the null hypothesis can be rejected. Therefore the difference between the mean in the pre -felled areas and the pre-felled areas is significant.

After felling, the photosynthetic area of the canopy is reduced and the ground is covered with debris (Figure 5.8a). Reducing the numbers of planted trees explains the reflectance decrease in the near infrared band and the increase in the red band. The resulting NDVI is lower, ranging from 0.235 to 0.319. The



(a) Felled areas (Comp.4036-d)   (b) Pre-felled areas (Comp. 4042-d)

Figure 5.8 Felled and pre-felled areas in the pine plantation clear-cut area has a partial cover of ferns, grasses and shrubs with low to moderate fractions of green vegetation. Therefore, in these areas, the NDVI is a slightly higher than totally exposed ground cover with cutting debris and the resulting variation of NDVI is a little higher (Figure 5.8).

5.4 THE RELATIONSHIP BETWEEN NDVI AND AGE

Age is the most important variable in forest growth. Many other structural parameters change with the growth of a tree. For example, the tree height of a stand increases with the growth stage. There is also an increase in the roughness of the forest canopy as a surface. However, the sub-compartments of the forest stands consist of even-aged trees.

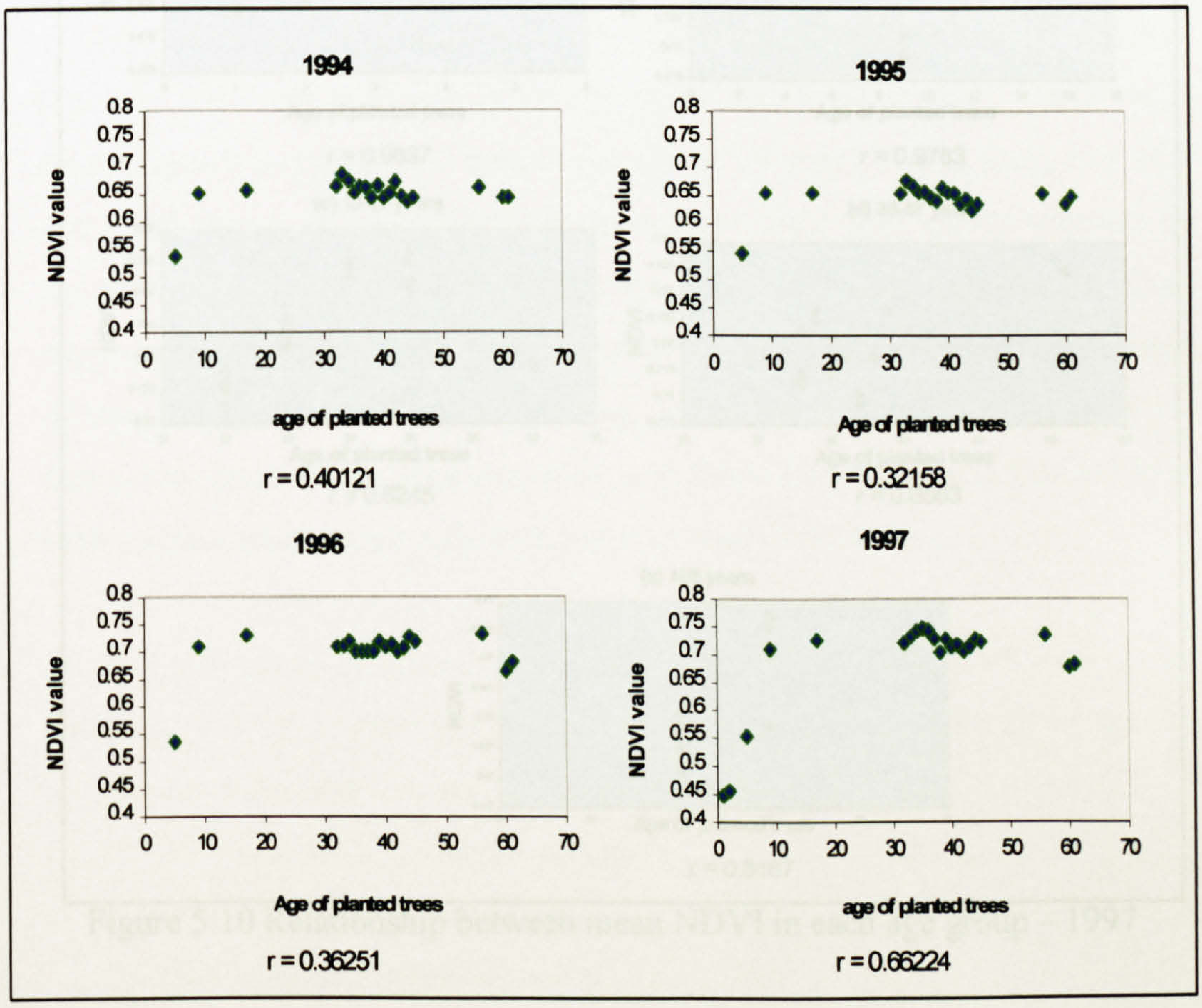


Figure 5.9 Relationship between NDVI and age (1994-1997)

This section of the analysis concerns how NDVI values vary with age in the 1994, 1995, 1996 and 1997 images. The results of the correlation analysis show moderate positive correlations between NDVI and age in all four years with r values of 0.40, 0.32, 0.36 and 0.66 for 1994, 1995, 1996 and 1997 respectively (Figure 5.9), but this relationship is not very strong. More detailed examination of these scatter diagrams shows that the rate of NDVI increase with age is greater in the younger (less than 18 year) age groups in all four images. Also the 18-37 year age group shows a more complex relationship between NDVI and age.

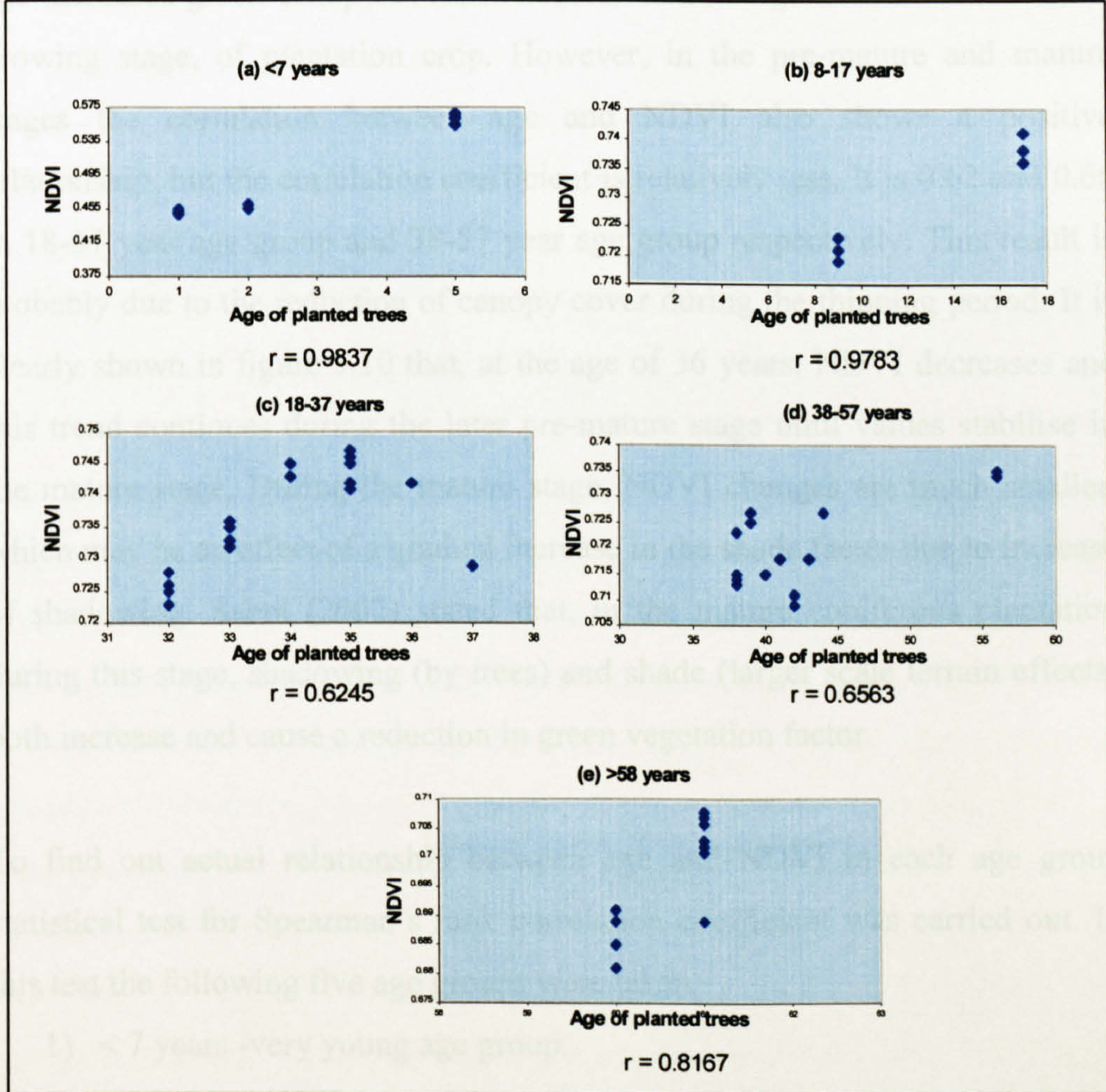


Figure 5.10 Relationship between mean NDVI in each age group – 1997

These values are very similar, and the scatter diagrams demonstrate similar patterns in each image year: as age increases NDVI also increases in < 20 years old trees. However, NDVI did not increase continuously with the age, and the pattern changes during the mature stage, probably due to the reduction in stand density when thinning operations start at the age of 20 years. To find out the influences of thinning operations during the mature stage and the NDVI changes, the study carefully considered the relationship between mean NDVI in selected year (1997) and the age of stands within each age group (Figure 5.10).

The results indicate that the very strong positive correlation coefficient of 0.98 0.97 in the <7 years and 8-17 years age groups respectively. It shows that when age increases green canopy cover increases,. It is the general trend for initial growing stage, of plantation crop. However, in the pre-mature and mature stages the correlation between age and NDVI also shows a positive relationship, but the correlation coefficient is relatively less. It is 0.62 and 0.66 in 18-37 year age group and 38-57 year age group respectively. This result is probably due to the reduction of canopy cover during the thinning period. It is clearly shown in figure 5.10 that, at the age of 36 years, NDVI decreases and this trend continues during the later pre-mature stage until values stabilise in the mature stage. During the mature stage, NDVI changes are much smaller, which may be an effect of a gradual increase in the shade factor due to increase of shadowing. Sabol (2002) stated that, in the mature coniferous plantation during this stage, shadowing (by trees) and shade (larger scale terrain effects) both increase and cause a reduction in green vegetation factor.

To find out actual relationship between age and NDVI in each age group statistical test for Spearman's rank correlation coefficient was carried out. In this test the following five age groups were taken

1) < 7 years -very young age group.
2) 8-17 years -Young age group.
3) 18-37 years - Pre mature age group.
4) 38-57 year - Mature age group.
5) >58 years – Old age

The null hypothesis (H_0) formulated for this significance test is that no relationship exits between age and forest canopy cover (NDVI) in a particular age group. The alternative hypothesis (H_1) is that there is a relationship between age and forest cover. It was decided to reject (H_0) with not less than 95% confidence level; therefore $\alpha = 0.05$.

Table 5.2 summarises the calculations of r_s and tabulated critical values (Appendix E) with the degrees of freedom (df = n-1, where n is the number of fractions in the test) of three age groups.

Table 5.2 Statistics of significance test for correlation between age and NDVI in the <7, 8-17, 18-37, 38-57 and >58 age groups

	<7 years	8-17 years	18-37 years	37-57 years	>58 years
Calculated r_s	0.860	0.843	0.672	0.386	0.717
Tabulated r_s	0.714	0.829	0.412	0.441	0.535
Degrees of freedom	7	6	17	15	11

The calculated r_s values for the <7, 8-17, 18-37 and >58 age groups are greater than the tabulated r_s. Therefore, according to the rules of significance tests the null hypothesis can be rejected and the alternative hypothesis is accepted at the 0.05 levels, which indicates that there is less than 5% probability that the correlation arose at random. In this case, it can be stated that there is a significant correlation between age and surface canopy cover, so that when age increases canopy cover also increases. However, the situation of the mature age group (38-57 year) is different. The calculated r_s value of this age group is less than the tabulated r_s value. Therefore, in this case, it is possible to accept the null hypothesis and reject the alternative hypothesis, that there is no significant correlation between age and canopy cover. The following subsection considers the real situation of each age group with respect to specific sub-compartments.

5.4.1 Age < 7 year

It was found that three sub-compartments (4036 d, 4037 d, 4042 b) in the 1997 image consisted of trees less than one year old and four sub-compartments (4038 c, 4039 c, 4040 c, 4041 c) had trees of five years old. The areas with tree age of one year or less after planting show a low NDVI (0.473), because of the high proportion of background reflection. Based on field observations, the interspaces of the planted trees (<1 years old) consist of soil or dry grass (Figure 5.12A a) and there is incomplete canopy cover. At this stage, the reflectance of newly planted trees does not seem to be a major factor affecting canopy reflectance. It is likely to become increasingly important after canopy closure, when background reflectance no longer dominates the remotely sensed signals.

From 1-7 years, several other types of deciduous tree dominate the plantation blocks as the leaf area expands (Figure 5.12A b). It has been stated that in forest studies, the leaf area is inversely related to red reflectance and positively related to near-infrared reflectance (Running *et al.,* 1986, and Peterson *et al.,* 1987). NDVI values increase rapidly (from 0.451 – 0.563) both with the increased age of the planted trees and the growth of the undergrowth vegetation cover. Therefore, in this age group, the correlation coefficient is relatively high (r = 0.98). However, there is clear evidence that at this stage NDVI is controlled more by the presence of understory vegetation visible to the sensor than by the early stages of tree growth. As observed by Nilson and Peterson (1994), there seems to be more than one factor dominating stand reflectance during the early stages of stand growth.

5.4.2 Ages 8-17 years

During the early stage of this age group (compartments 4034 c, 4035 a), canopies are still open or only partially closed and most of the stands still have understorey vegetation. At this stage, the understorey dominated the changes of NDVI, so that it is very difficult to predict the forest structural situation from remotely sensed data.

However, during the later stages (in compartments 4112 a, 4122 b - the trees of both sub-compartments are 17 years of age), the contribution of reflectance from the ground surface is negligible because of the closed condition of the canopy (Figure 5.12A c). It can be stated that this age group is the most relevant for remote sensing application for forest management. Because the ground is not visible to the sensors, the effect of surface cover is dominant. High values (0.736, 0.741 in 1997 image) of NDVI are influenced by the significant contribution of reflectance from the top layer of the pine canopy. The undergrowth consists of a thin layer of grass cover, but the effect of this layer no longer dominates the remote sensed signals. The high correlation coefficient (r = 0.97) in this age group indicates that NDVI can be used to predict forest cover reliably. Previous studies suggest that the strength of the relationship between NIR reflectance and forest structure varies according to the influence of the background (Spanner *et al.*, 1990b; Ardö, 1992; Danson and Curran, 1993; Gemmell, 1995). NDVI is strongly dependent on the NIR reflectance and is associated with tree growth and canopy closure.

5.4.3 Ages 18-37 years

In this age group only 32-37 year old pine stands were found in the study area and most of the compartments had been thinned twice. The normal age of first thinning is around 25-30 years of age, second thinning is around 30-35 years of age, but it varies depending on the species, yield class and the initial spacing of the stand. Initial canopy closure is disturbed by these operations, and canopy gaps are exposed to the sensors. Apart from thinning, sub-compartments 4221a and 4226b were significantly damaged by windthrow, so that second thinning was delayed (information collected from forest managers). Changes of NDVI with the increase of age therefore showed an irregular pattern (Figure 5.10 c). NDVI ranged from 0.725 in a 32 year stand to 0.732 in a 33 year stand, decreasing to around 0.729 in 37 year stand and 0.715 in a 38 year-old stand. No significant relationship was found between NDVI and age. This group gave the lowest correlation coefficient of 0.62, and the scatter diagram in this age group shows no pattern.

Figure 5.12B (a) shows a picture of a pine plantation of 36 years age. It looks different from the other age group stands because of the thinning operation in which the number of planted pine trees is reduced, and the undergrowth becomes very thin, with most of the area covered with soil. The first thinning removes two adjacent rows in every six rows where the original spacing is comparatively close. The second thinning then removes two other adjacent rows between two rows (Figure 5.11). Where the stand was regularly thinned, there was little evidence of crown expansion of the pine trees, and leaf area tended to reduce. Therefore NDVI changes vary with canopy structure.

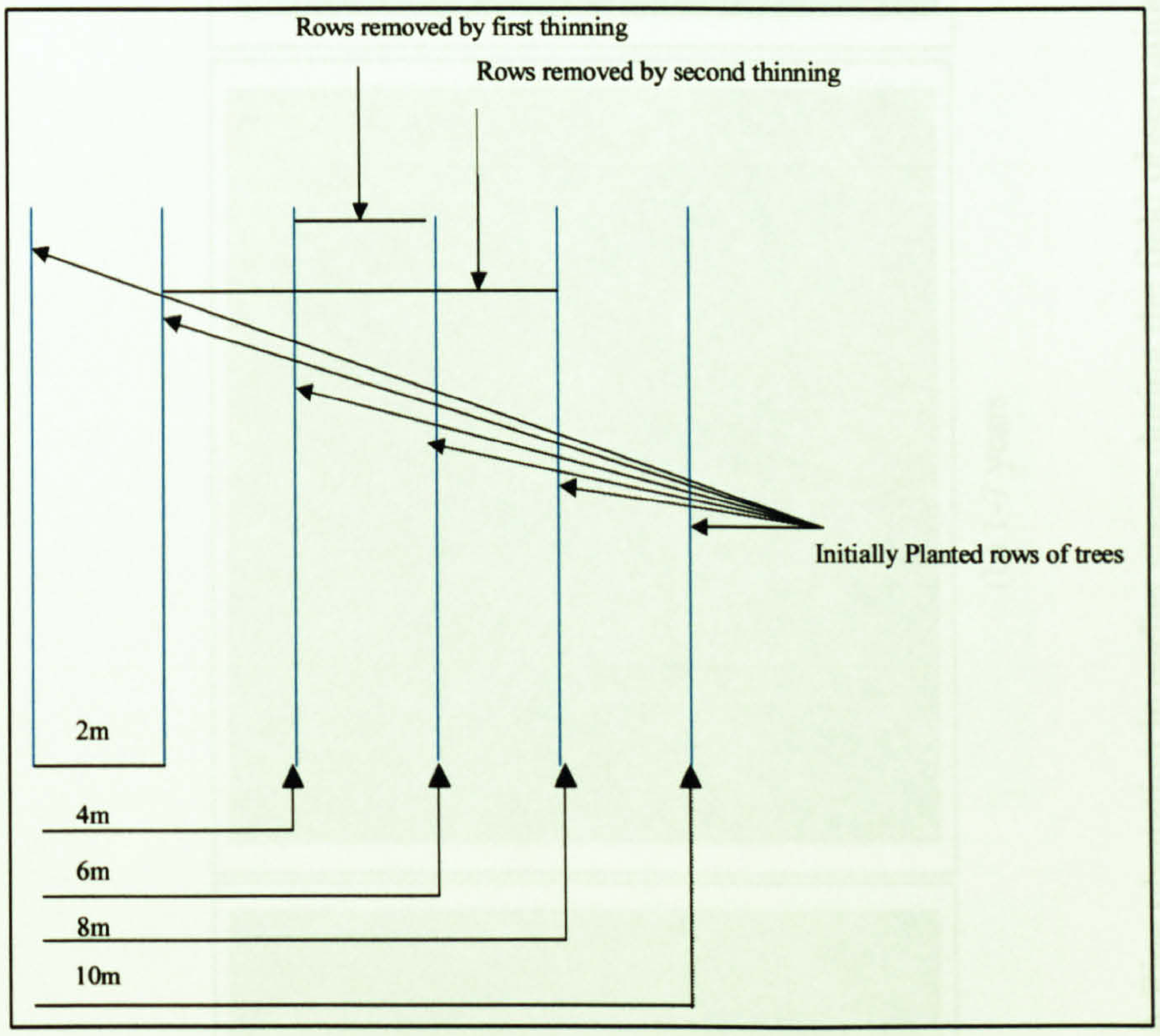


Figure 5.11 Systematic way of removal of rows of trees in thinning operations in the study site (created information gathered from forest manages)

5.4.4 Ages 38-57 years

In mature pine stands, canopy structure is relatively simple with a single canopy layer containing trees of similar size (Figure 5.12B b). It appears as a

(a) Less than 1 years

(b) 1-7 years

(c) 8-17 years

Figure 5.12A Pine plantation in earlier stages during the field observations in 5th of June 2001

(a) 18-37 years (b) 38-57 years (c) > 58 years

Figure 5.12B Pine plantation in later stage during the field observations in 5th of June 2001 significantly brighter tone and is similar to undisturbed forest. During the field visit, it was determined that these are fully-grown, and healthy plantations with few gaps between rows of planted trees.

NDVI is comparatively high (0.713 to 0.27) with a slight peak at the age of 56 due to the effect of continuous canopy cover and the understorey grass cover. A sudden decline of NDVI values recorded at the age of 42 (0.709) is most likely due to the disturbance of canopy cover following partial felling (Figure 5.10). However variations of NDVI in this group are very small. According to the significance test, the correlation of NDVI and age is relatively low (r_s = 0.386).

5.4.5 Ages > 58 years

There are few compartments in the old age group in the study area. According to the Forestry Commission records, these compartments were marked for clear or partial felling. Some compartments in the northeast corner of the study site were partially felled or wind damaged. Therefore, those areas appear as trees with open canopy (Figure 5.12B-c). With increasing maturity the roughness of the canopy increases, but this stage shows a greater frequency of scattered gaps between the trees. Based on field observations, the old growth stands typically have a higher proportion of dead wood, especially in the upper canopy and the ground cover has less green vegetation. Therefore, NDVI decreased to a relatively low NDVI ranging from 0.682-0.706.

Variations within this age group are comparatively large, which may be due to shadowing effects. Further investigations would be needed to confirm this. However, Danson (1995) has stated that pine stands of this age consist of trees whose crowns are less compact with relatively low needle density, so that as a consequence shadows are less pronounced. Results of the correlation analysis indicated a strong (r =0.81) relationship between NDVI and age. It can be stated that there is a gradual decline of NDVI until 60 years. However, after 60 years there is a considerable increase of NDVI most probably due to higher proportion of scattered regrowth in the partially felled areas.

5.5 RELATIONSHIP BETWEEN NDVI AND SELECTED STRUCTURAL VARIABLES

Optical satellites such as LANDSAT TM and SPOT multi-spectral data have been used to provide estimates of forest characteristics including stand density, height (De Wulf *et al.*, 1990), and Leaf Area Index (Spanner *et al.*, 1990a). From a management point of view, the growth of trees may be measured in terms of increase in height, diameter, volume or weight. This study selected the following three structural variables for analysis.

1) Tree top height
2) Mean diameter
3) Basal area

Correlation analysis was performed on each sub-compartment in the study site with forest stand variables and spectral variables. Selected stand variables tree Top Height (TH), Mean Diameter (MD) and Basal Area (BA) were calculated from forest management tables based on the age of trees (Forestry Commission, Booklet 39, 1975). These measurements of standing trees are necessary for several management purposes such as inventory, planning, and control of resources.

Tables 5.3 Correlation coefficient between forest stand parameters

		MD N=67	TH N=67	BA N=67
Correlation	MD	1.000		
	TH	.983	1.000	
	BA	.854	.786	1.000

Analyses of these data showed that all of these variables were inter-correlated (Table 5.3). Mean diameter and basal area both increase with tree height as they are related to tree growth.

5.6.1 Tree top height of the stand

Total height of standing trees is the vertical distance from the base of the tree to its uppermost point. The total height of young standing trees can be measured with graduated poles, while older trees can be measured with a hypsometer or clinometer (Forestry Commission Booklet 39, 1975 p.143).

For forest management purposes, two expressions of stand tree height are commonly used. The first is top height, which is the average height of a number of treetops in a stand. This is not necessarily the tallest tree.

Table 5.4: Stand mean height (metres) at specified top height
(Source: Forestry Commission Booklet 39, p.146)

Top height (metres)	Corsican pine	Scots pine
8	6.9	6.6
10	9.0	8.7
12	11.1	10.8
14	13.1	12.9
16	15.2	15.0
18	17.2	17.1
20	19.3	19.1
22	21.4	21.2
24	23.4	23.3
26	25.5	25.4
28	27.6	27.5
30	29.6	29.6

The second expression is mean height, which refers to the mean total height of the stand. It is closely related to top height and Table 5.4 summarises these relations for stands subject to conventional spacing and thinned according to principles outlined in Forestry Commission Booklet 39, p.146.

To obtain a reliable estimate of top height in a pure stand, a series of sample plots should be randomly located throughout the stand. The height of the tree of largest diameter of breast height (dbh) in each plot is measured. The arithmetic mean of the heights of the trees gives the top height of the stand. The number of top height trees to be measured will depend on the area of the stand and its uniformity. Table 5.5 gives the minimum number of trees required to give an adequate estimate of top height.

Table 5.5 Number of trees needed to measure top height
(Source: Forestry Commission Booklet 39, p. 144)

Area of the stand (ha)	Uniform crop	Variable crop
0.5 - 2.0	6	8
2.0 - 10.0	8	12
>10.0	10	16

The statistical table (Appendix section C) provides the results of classification with top height classes in the study site as shown in figure 5.13. A complete GIS digitised surface for the area coverage of each top height class based on calculated data from the Forestry Commission is included for the study site. According to the availability of data, the top heights of the stands range between 7.1 and 27.1 metres, which can be grouped into seven classes as 0-9.7, 9.8-17.9, 18.0- 19.9, 20.0-21.4, 21.5-22.6, 22.7-25.0, 25.1-28.0 metres based on available data set. Most of the compartments in the western part of the study site contain middle classes (9.8 m- 21.4 m) of top heights, for trees planted during 1958 - 1965. A few sub-compartments containing higher classes (>21.5m), which are scattered over the eastern part of the study area.

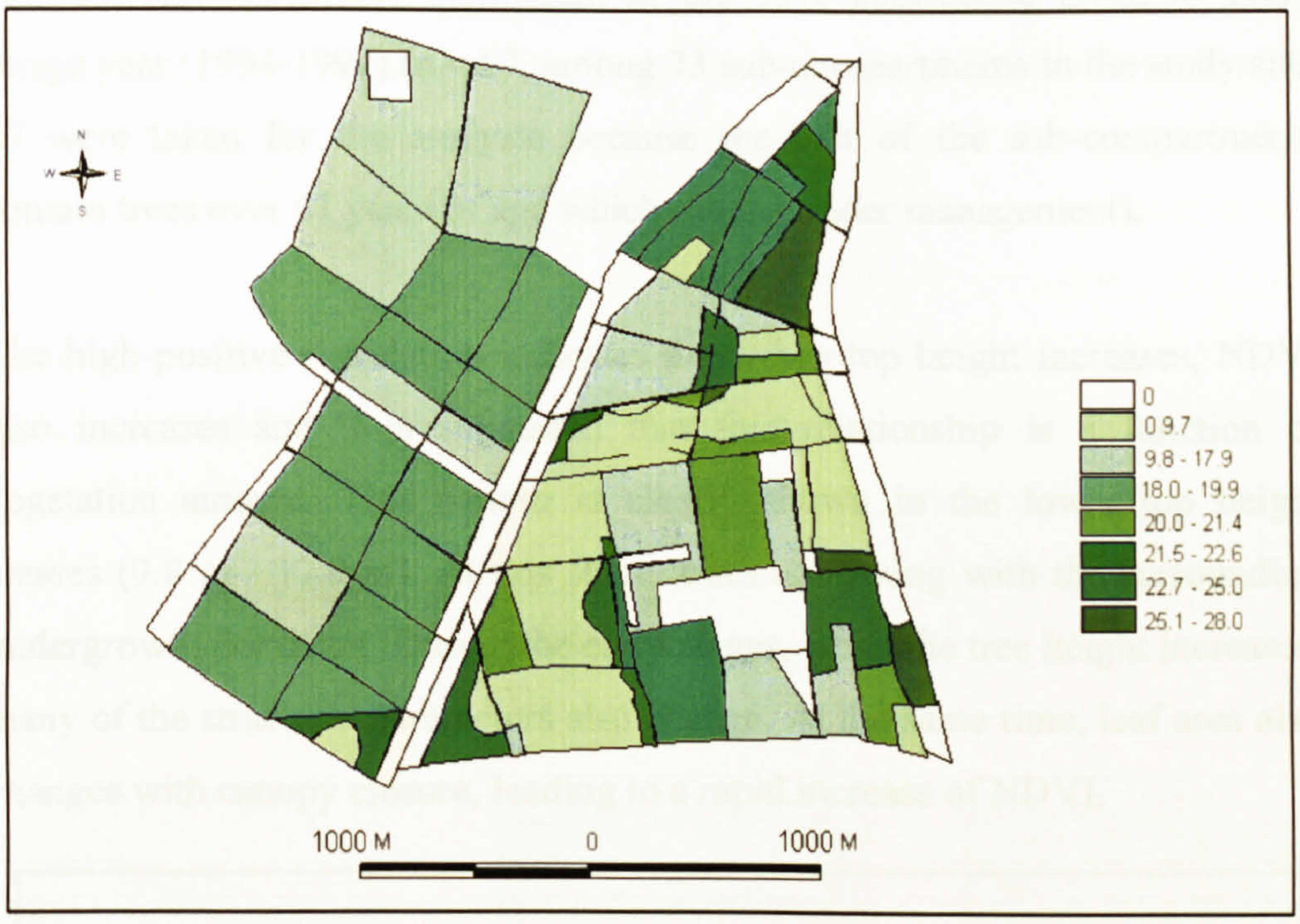


Figure 5.13 Distribution of top heights (meters)

The frequency histogram (Figure 5.14) indicates the distribution of top height classes in the study area. It shows that 55% of the trees in the area are attributed to three middle class top height groups (9.8 m-21.5 m.), with top height >21.5 m accounting for nearly 30%. Only 10% of the site is in the lowest class of <9.7 m.

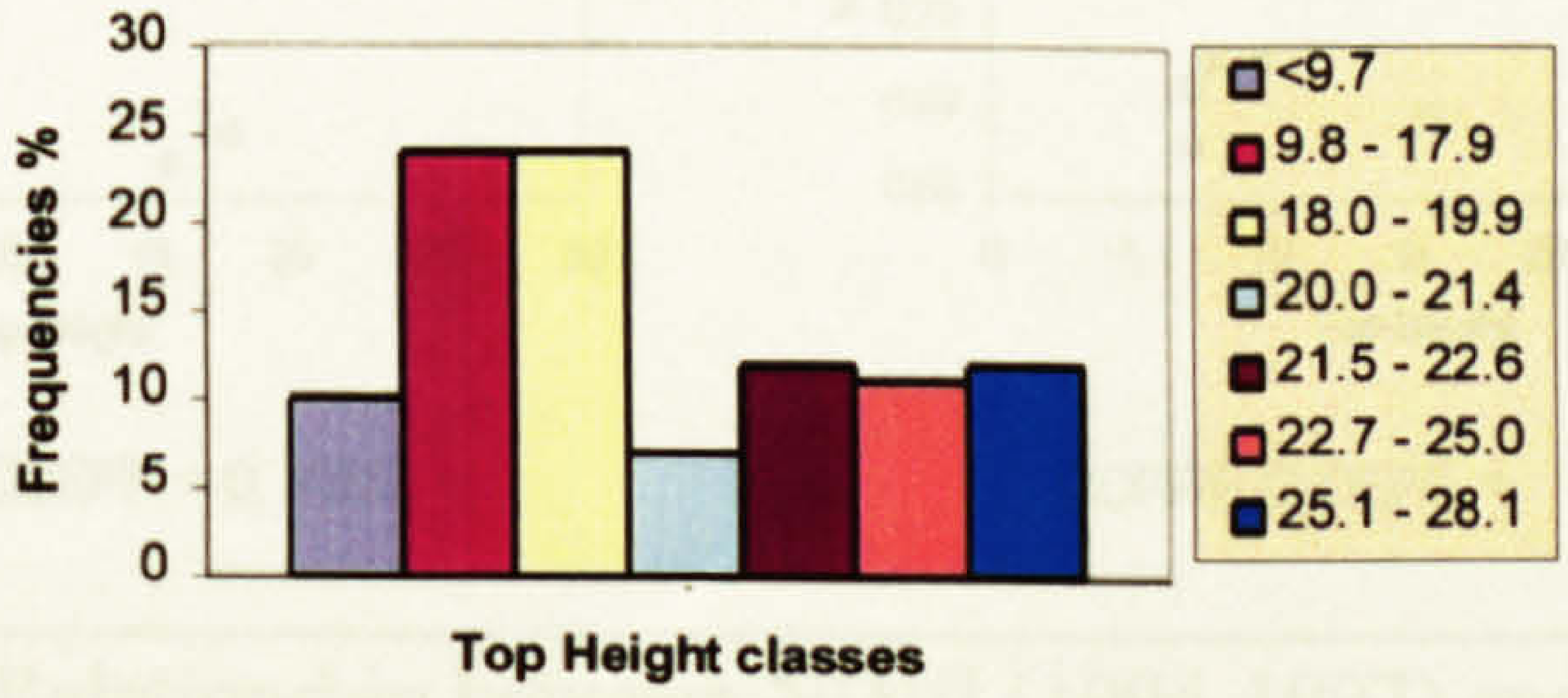


Figure 5.14 Variation of top heights in the study area

The results of the correlation analysis between NDVI data and the top height are given in figure 5.15. The correlation coefficient between these two variables was positively significant at the 95% confidence level, in every image year (1994-1997) (n = 67. among 73 sub-compartments in the study site, 67 were taken for the analysis because the rest of the sub-compartments contain trees over 61 years of age which are not under management).

The high positive correlation indicates that when top height increases, NDVI also increases and it is suggested that this relationship is a function of vegetation amount. This pattern is clearly shown in the lower top height classes (9.8 m - 17.9 m). At this stage, trees are young with the surrounding undergrowth dominant. During the early stages, when the tree height increases, many of the structural parameters also change. At the same time, leaf area also changes with canopy closure, leading to a rapid increase of NDVI.

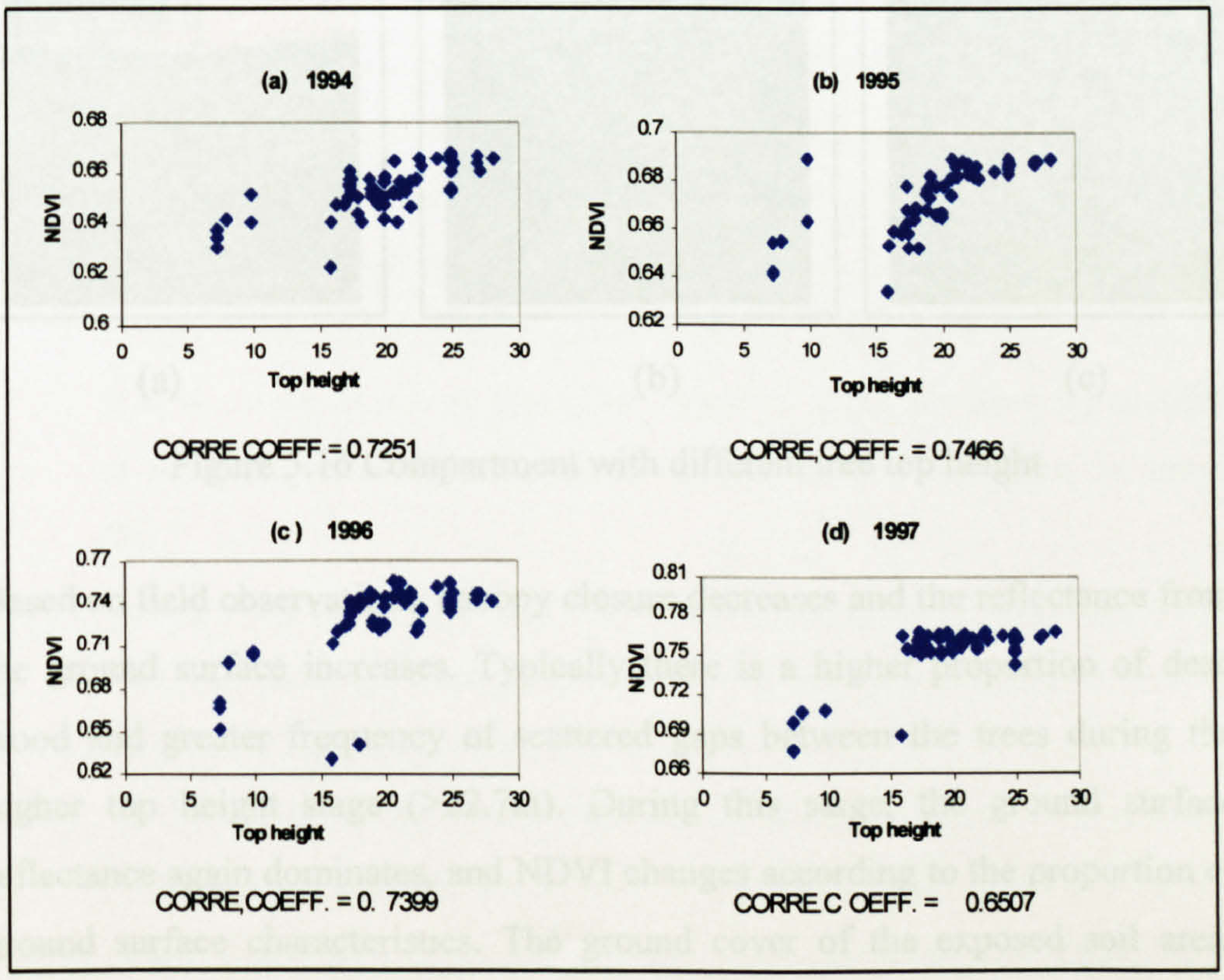


Figure 5.15 Relationship between NDVI (1994-1997) and Top height

Figure 5.16a shows forest cover of lower tree top height stage (<9.7m). Field investigation also shows that the green LAI of the ground layer vegetation causes the increase of reflectance in the compartments with low top tree heights. Therefore, NDVI also significantly increases. In this stage, planted pine trees are not dominant in the stand. Later during the next stage (9.8m - 19.0m), the pine canopy surface becomes thicker and the ground layer vegetation decreases (Figure 5.16b). Rapid increase of NIR reflectance causes high NDVI values. According to the Forestry Commission records, management treatments such as deciduous removals or thinning takes place at this stage (20.0m - 22.6m), so that canopy closure is reduced (Figure 5.16c). At the same time, reflectances change too, depending on the several factors. However, the main reason for the decrease in NIR reflectance during this period seems to be the reduction of surface canopy cover.

(a) (b) (c)

Figure 5.16 Compartment with different tree top height

Based on field observations, canopy closure decreases and the reflectance from the ground surface increases. Typically there is a higher proportion of dead wood and greater frequency of scattered gaps between the trees during the higher top height stage (>22.7m). During this stage, the ground surface reflectance again dominates, and NDVI changes according to the proportion of ground surface characteristics. The ground cover of the exposed soil areas shows relatively low near-infrared reflectance, and as a result NDVI decreases. As regrowth from saplings takes place, shadowing generally increases (Sabol *et. al.*, 2002). Therefore, again the situation is changed gradually. Analysis of correlation in 1996 and 1997 images clearly shows this decrease in NDVI (Figure 5.15). However, the analysis indicates that there is significant positive relationship between NDVI and tree top height. This strong positive correlation may be due to the effect of percentage of canopy cover, and it is suggested that these relationships are a function of vegetation amount.

5.6.2 Mean Diameter

For most measurement purposes, the mean diameter is also called quadratic mean dbh. Mean diameter is usually recorded to the nearest whole centimetre. Diameters are normally measured with a special tape marked in centimetres, known as a girthing tape, which is placed round the circumference of the tree at the point of breast height of 1.3 m above the ground level. Trees with a dbh of less than 7 cm are assumed to have no volume and so are conventionally classified as 'unmeasurable'. The mean diameter can be calculated by the following methods (Forestry Commission Booklet 54, 1985 p.31).

1) "Using the basal area table each dbh is converted into a basal area. Then all the basal areas are added together. Dividing this by the number of trees gives the mean basal area. Finally mean basal area is converted back into mean dbh using the same table."
2) "Using a calculator, with a square root key. First each dbh is squared then the squared values are added together. After dividing by number of trees, to give the mean squared dbh, the square root gives the mean dbh."
3) "Using local volume table or tariff number the mean volume associated with the tariff numbers are worked out and are multiplied by the number of trees in the stand."
4) "Estimate by Weise's rule. First all the dbhs are listed in ascending order of 1-cm classes. Then count up the list of dbhs starting with the largest dbh until 40% of the trees have been counted. The dbh class of the 40th percentile tree is approximately the mean dbh class. This should not be used for accurate work, but only for a quick check." (Forestry Commission Booklet 39, 1975 p.45)

In this study, the mean diameter was calculated according to the planted age using Forestry Commission management tables. The results of the analysis of the total area of coniferous trees in the study site by mean diameter classes are shown in Figure 5.17. The mean diameter of trees in the stands range between 9.6 and 38.9 cm, which can be categorised into five classes as 0-12.5 cm, 12.6-24.0 cm, 24.1-27.9 cm, 28.0-36.1 cm and 36.2-38.9 cm. Approximately 75% of the total area falls in the middle class categories (12.6 - 36.1 cm). There was a high correlation between NDVI and mean diameter with r values of 0.2, 0.76, 0.67 and 0.70 in 1994, 1995, 1996 and 1997 respectively (Figure 5.18). These values are significant at the 95% confident level. This relationship is shown graphically in the scatter diagram and has a similar pattern in every year. In the lowest mean diameter class (0-12.5m), it shows a high positive correlation, with increase in mean diameter, while NDVI increases in each scatter diagram.

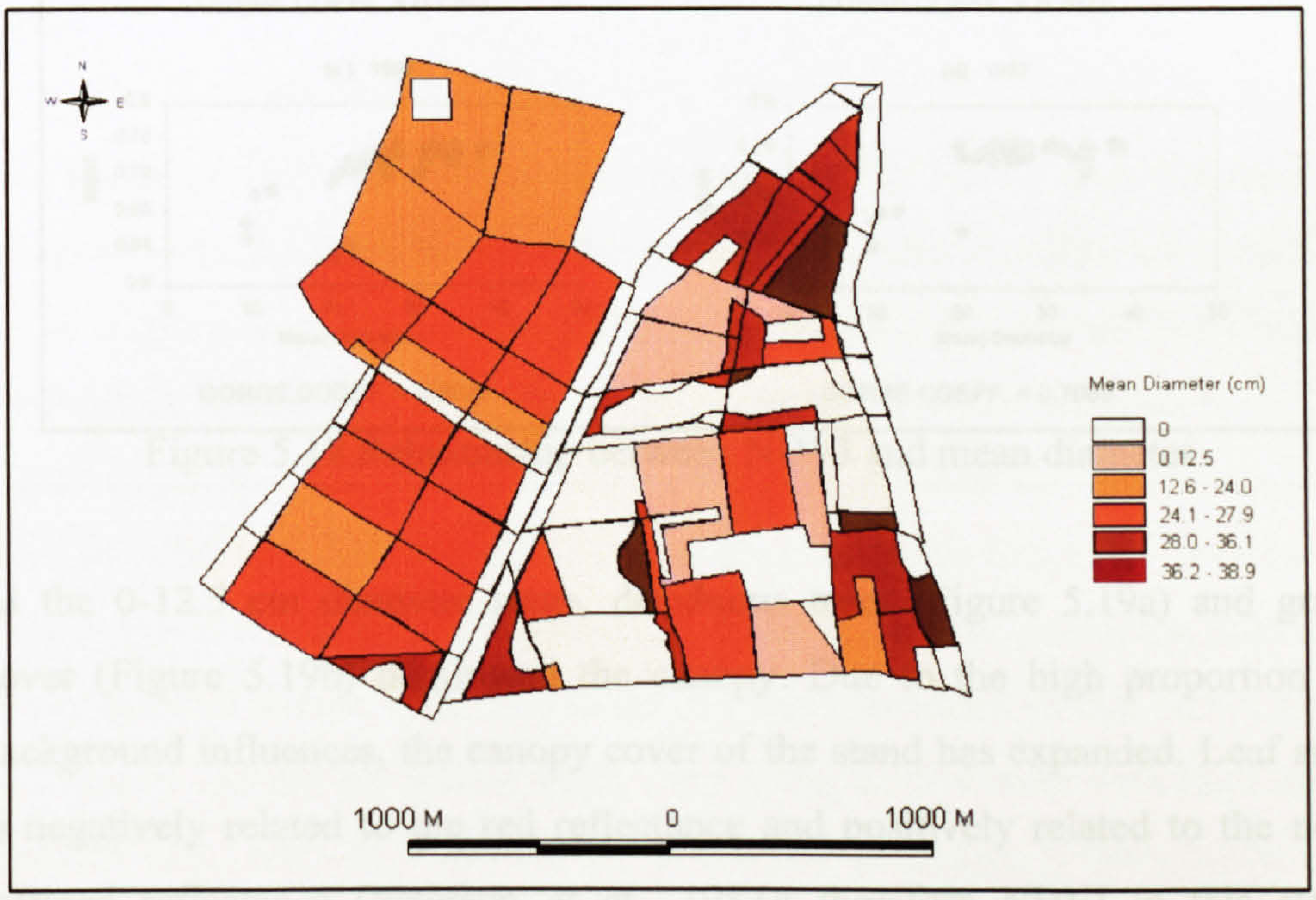


Figure 5.17 Distribution of mean diameter

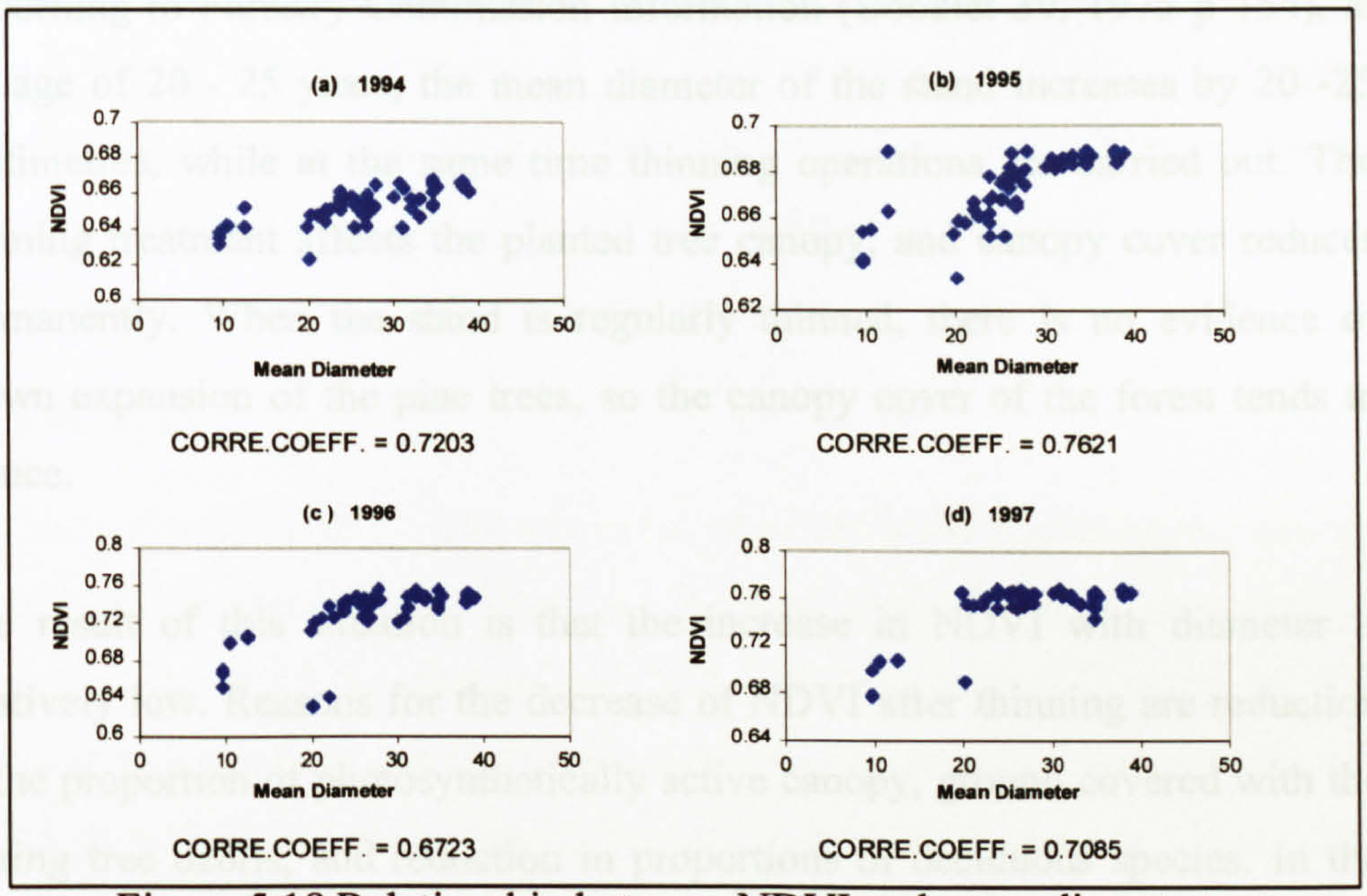


Figure 5.18 Relationship between NDVI and mean diameter

At the 0-12.5 cm diameter stage, deciduous trees (Figure 5.19a) and grass cover (Figure 5.19b) dominated the canopy. Due to the high proportion of background influences, the canopy cover of the stand has expanded. Leaf area is negatively related to the red reflectance and positively related to the near infrared reflectance (Peterson *et al.,* 1987); therefore NDVI in this stage increases rapidly. In the next stage (12.6- 20.0 cm mean diameter range), the increase of NDVI with mean diameter shows a different relationship.

(a) Pine trees with deciduous trees (b) Pine trees with grass

Figure 5.19 Pine plantation in the lowest diameter class

According to Forestry Commission information (Booklet 39, 1975 p 154), at the age of 20 - 25 years, the mean diameter of the stand increases by 20 -25 centimetres, while at the same time thinning operations are carried out. The thinning treatment affects the planted tree canopy, and canopy cover reduces permanently. When the stand is regularly thinned, there is no evidence of crown expansion of the pine trees, so the canopy cover of the forest tends to reduce.

The result of this situation is that the increase in NDVI with diameter is relatively low. Reasons for the decrease of NDVI after thinning are reduction in the proportion of photosynthetically active canopy, ground covered with the cutting tree debris, and reduction in proportions of deciduous species. In the higher mean diameter range (28.0 cm-36.1 cm), the thinning treatments have stopped or became very rare and the growth of the remaining trees replaces the empty gaps in the forest cover. However, at the same time, due to the influence of background effects, reflection in the red band decreases so that NDVI tends to increase. During the felling stage, only a few mature trees with high mean diameter (36.2 cm - 38.9 cm) are left in the pine plantation (Figure 5.20). The pattern of the shadowed canopy and shadowed ground is of great importance at this stage.

Figure: 5.20 Pine plantation with high mean diameter

Thus it can be assumed that change in shadow patterns is an important factor behind the reflectance increase in the mature stage (36.2 cm - 38.9 cm). Exposure of the woody surface of the pine plantation would be expected to increase red reflectance and decrease near infrared reflectance. At this stage NDVI changes with the mean diameter are very low.

5.6.3 Basal area

The basal area of an individual tree is the cross-sectional area in square metres of the tree at its breast height point. So the basal area of a stand is the sum of the basal area of all the trees in the stand. The basal area of a stand for any diameter at breast height is equivalent to the volume indicated for a length of 1 m, but expressed in square metres. For example a 20 cm tree has a basal area of 0.031 sq. m (Hamilton, 1975). The basal area of a stand can be obtained in several different ways (Forestry Commission booklet 39, 1975 pp. 202-241).

1) "For small areas it is possible to measure dbh of all trees to classify them and to convert this to basal area using the round wood table.
2) By laying down plots and assessing the dbh of all trees of 7m and above within the plots, and converting these values to basal area using the sample area method."

Another way of estimating basal area is by point sampling using an instrument called relascope.

The area coverage of basal area in the study site is shown in Figure 5.21. Basal area calculated using the management tables range between 27.9 -37.1 sq. metres. Approximately 75% of the compartments cover middle class category ranges from 27.9 - 33.1 sq. metres. Most of the trees planted between 1936 and 1988 come under this category. This type of relationship has been shown to be possible in even aged, intensively managed forests (Nilson and Peterson, 1994).

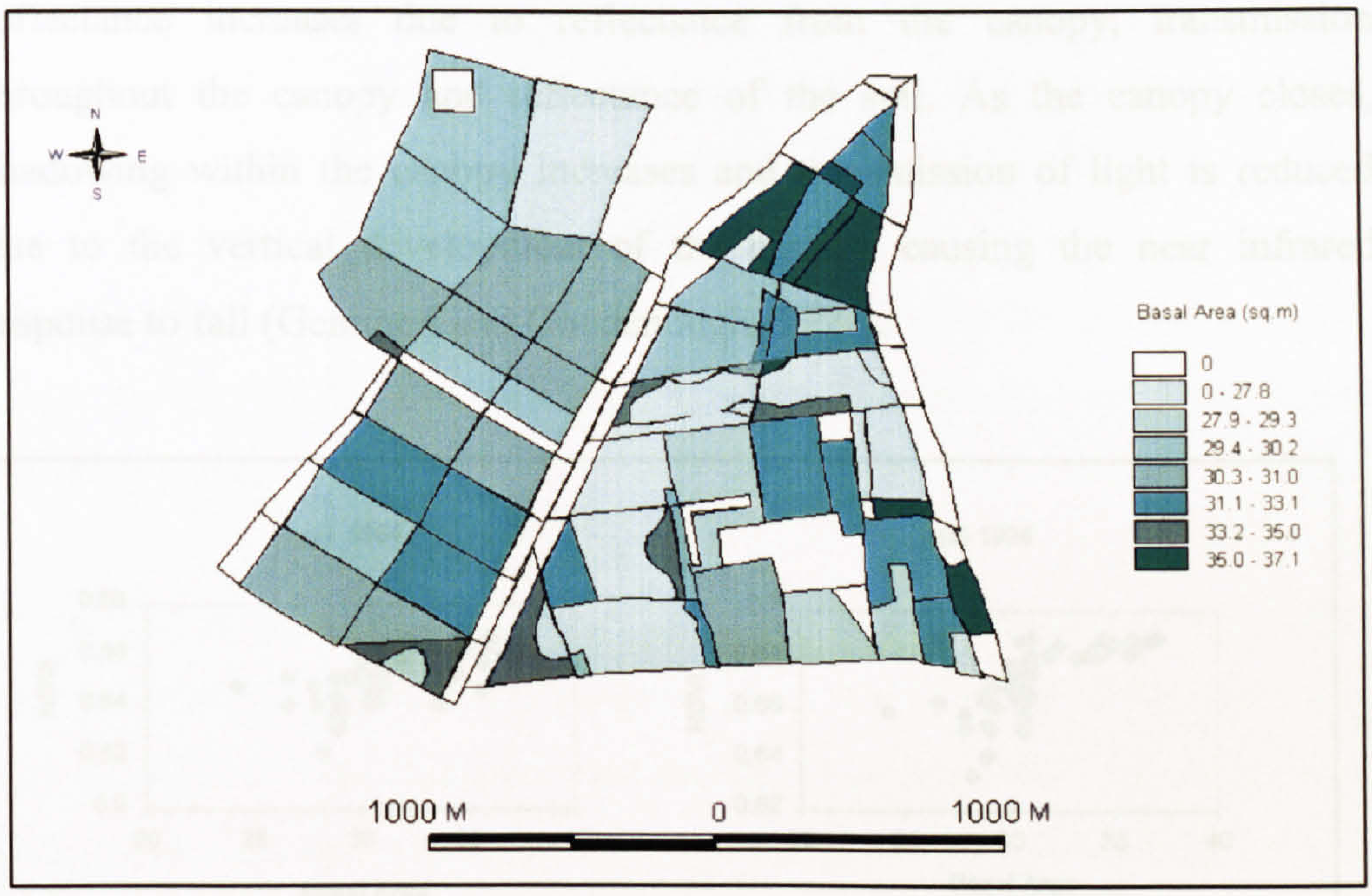


Figure: 5.21 Distribution of basal area

They can however, be problematic in mixed age forest due to complex overstorey and the variety of natural and human disturbance regimes, in particular fire and logging, leading to an array of structural and floristic patterns

The analysis indicates that there were statistically significant relationships between NDVI and stand basal area over the study site in each year from 1994-1997 (Figure 5.22). The correlation coefficient r was 0.61 in 1994, 0.70 in 1995, 0.50 in 1996 and 0.40 in 1997, all of which are significant at the 95% confident level. However, these relationships are statistically less significant than for tree top height and mean diameter. The difference of relationship clearly shows in the low basal area class (0.0-27.8 sq. metres).

At this stage NDVI is relatively high with a low basal area. It may be the effect of understorey vegetation dominating the signals or it may be due to the effect of canopy shadow. A more detailed investigation is required. As basal area increases, visible reflectance decreases in the red and blue region of the spectrum due to increased leaf area and absorption as well as shadowing both by and within the canopy. As density and leaf area increases, near-infrared reflectance increases due to reflectance from the canopy, transmission throughout the canopy and reflectance of the soil. As the canopy closes, shadowing within the canopy increases and transmission of light is reduced due to the vertical development of the canopy causing the near infrared response to fall (Gemmell and Goodenough, 1992).

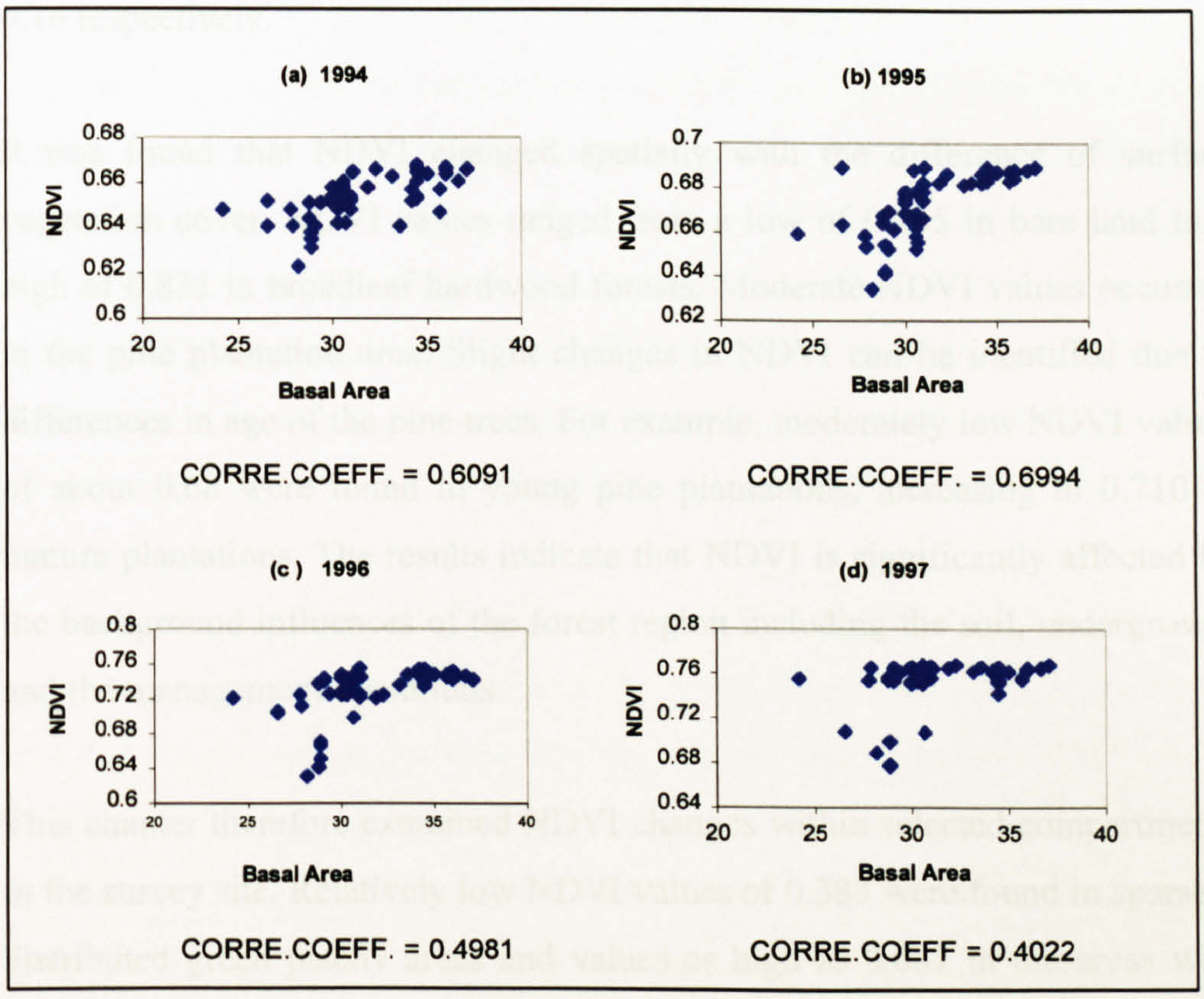


Figure 5.22 Relationship between NDVI and basal area

5.7 SUMMARY

This chapter consists of the following components.

1) Relationships between near-infrared and red reflectance were analysed.
2) Spatial changes of forest cover were identified.
3) Changes of NDVI with age were estimated.
4) Correlations between NDVI and selected forest structural stand parameters were assessed.

Correlation analysis shows that the relationship between the mean NIR reflectance and red reflectance varied with the different age groups. There is a very strong negative correlation (r = - 0.98) in the lowest age group, while there is a moderately low positive correlation (r = 0.46) in the mature age group. This relationship was not very strong, but positively correlated in two young age groups (8-17 and 18-37). The correlation coefficients are 0.30 and 0.16 respectively.

It was found that NDVI changed spatially with the difference of surface vegetation cover. NDVI values ranged from a low of 0.235 in bare land to a high of 0.831 in broadleaf hardwood forests. Moderate NDVI values occurred in the pine plantation area. Slight changes in NDVI can be identified due to differences in age of the pine trees. For example, moderately low NDVI values of about 0.68 were found in young pine plantations, increasing to 0.710 in mature plantations. The results indicate that NDVI is significantly affected by the background influences of the forest region including the soil, undergrowth and the management operations.

This chapter therefore examined NDVI changes within selected compartments in the survey site. Relatively low NDVI values of 0.383 were found in sparsely distributed green patchy areas and values as high as 0.681 in the areas with closed canopy pine plantation. Within this range, it varies with different types of canopy, such as undergrowth with birch, bramble, bracken and grass dominated open canopy stand, open canopy stand with regenerating pine seedlings, and open canopy stand with very young planted trees. In addition, spatial patterns were identified in areas where the principal management practices were carried out, mainly thinning and clear felling. In the pre-thinned areas, high NDVI values (0.758) were found with little variation, while relatively low NDVI values (0.55) with more variation were found in thinned areas. The influence of clear felling could also be identified compared with pre-felling sites. Pine plantations at the mature stage show relatively high

NDVI values of 0.763 and 0.781 due to the canopy roughness and shadowing. After clear felling, it decreased to a range of 0.235- 0.319.

This chapter also demonstrates changes of NDVI with different age groups in 1997. NDVI increased from 0.427 to 0.578 in the < 7 years and 0.706 to 0.738 in the 8 -17 years old pine stands in Figure 5.10. The results of the correlation analysis indicate a high positive correlation coefficient of 0.99 and 0.97 respectively. However, in the stands aged 18-37 and 38-57 years, the increase with age showed an irregular pattern with more variations than in the very young stands. No significant correlation was found between NDVI and age in this group, and it shows the lowest correlation coefficient of 0.62 and 0.65 respectively. The next stage the old age group indicates positive high correlation (r =0.81) due to considerable increase of NDVI at the age of 60 years suggesting that background features may have contributed to the reflected signals.

This chapter discussed the distribution of selected stand structural variables of tree top height, mean diameter and basal area. Approximately 75% of the compartments fell into middle class categories. For example, tree top height ranged from 18.0-22.7m, mean diameter surface ranged from 12.6-32.1m and basal area surface ranged from 27.9-37.1 sq. m.

The results of correlation analysis show there was a positive high correlation of NDVI with tree top height and with mean diameter, with r values of 0.73 and 0.76 respectively, both significant at the 95% confident level in 1997. The correlation between NDVI and basal area presented a different picture with a lower correlation coefficient of 0.70, although still significant at the 95% confident level. The correlation analysis for three stand parameters (tree top height, mean diameters and basal area) with NDVI showed a positive high correlation, indicating that NDVI data are useful for estimating forest stand parameters.

CHAPTER SIX

CHANGE DETECTION ANALYSIS

6.1 INTRODUCTION

Forest cover is a dynamic phenomenon. It changes at a variety of spatial and temporal scales and patterns. In remote sensing terms generally, change can be defined as an alteration in the components of the Earth's surface features in the spatio-temporal domain. In the specific case of vegetation studies, change can be defined as an alteration in the surface component of vegetation cover, the spectral/spatial movement of a vegetation entity over time (Coppin and Bauer, 1996). Two major changes appear in the forest: natural and man-made. Natural changes are consequences of seasonal variations, growth and motility. Man-made changes involve thinning, felling, drainage silvicultural treatments and man-made damage such as forest burning. Various detection techniques play important roles in the accurate identification of these changes in the vegetation cover.

Several studies have used remote sensing data to monitor changes in forest surface condition, mostly by applying comparative analysis of various detection techniques for specific applications (Collin and Woodcock, 1994; Coppin and Bauer, 1996; Cohen and Fierella, 1998). Change detection is a process of identifying differences in the state of an object or phenomenon by observing it at different times. Remote sensing techniques are used to monitor and map land cover change between two or more time periods and are now an essential tool in forest management activities (Dutt *et al.,* 1994). The ability to detect changes accurately in forested areas is central to the use of remotely sensed data for planning and forest resource management purposes. On the other hand, a major factor in achieving better management is the availability of up to date information about existing forest cover and changes over time.

The main aim of this chapter is to monitor forest cover changes using change detection methods. Monitoring is a process of detecting whether any change has occurred, establishing its direction and measuring its extent. This measuring should be accompanied by an assessment of the significance of changes detected (Hellawell, 1991). It should be a part of normal management, providing information to managers to assist in decision making. It is very useful for forest management to determine the relative effects of various treatments and causes of change. Monitoring should therefore be considered as a means of measuring the outcomes of management and a way of comparing effects of alternative treatments in research. This chapter mainly concerns monitoring of forest cover changes during 1994-1997. It focuses on two main methods. Firstly, changes are monitored visually and graphically using NDVI images, which are well known in forestry studies. The NDVI technique for monitoring vegetation greenness is a commonly used method in forest change detection (Wilson and Sader, 2002). Secondly, changes are detected using digital change detection techniques. Digital change detection approaches in the field of vegetation studies include comparison of vegetation cover classifications, multidate classification, image differencing or ratioing, vegetation index differencing, principal component analysis and change vector analysis (Coppin and Bauer, 1996). This study uses vegetation index differencing to detect forest cover changes temporally.

The first part of this chapter presents temporal changes of forest cover utilising multi-temporal NDVI data. The technique recognises only changes of NDVI but it does not separate the areas of change increase and decrease in the image and also is not able to distinguish the amount of change increase or decrease of canopy cover. Therefore, the second part deals with change detection analysis using the vegetation index differencing method. This method categorises the amount of change as an increase or decrease in NDVI. This chapter also discusses some methods of change detection, which can use multi temporal remote sensing data. Although these analyses identify major changes of forest cover, such as the effect of felling operations, it is difficult to detect minor changes due to the thinning operations. Therefore, chapter seven of this thesis will deal with a pixel-based classification to detect reduction of forest cover due to thinning operations.

6.2 TEMPORAL CHANGES OF NDVI DURING 1994 - 1997

The canopy cover of a plantation forest can be changed in different ways as follows:

1) The growth of planted trees and the undergrowth reduces canopy gaps. At this stage, NDVI increases with the growing vegetation.
2) Management operations, such as thinning and partial felling, break up the continuous canopy cover. The result of this process is that NDVI decreases slightly with the reduction of canopy. At a fine scale it ought to be able to see a more variable pattern or even more stripes developing. The 20m resolution of SPOT may not be quite fine enough to detect these stripes.
3) Clear felling destroys almost all the canopy cover. Therefore NDVI decreases dramatically due to the reduction of near-infrared reflection from the rough surface layer.

The objective of this chapter is to evaluate forest canopy changes over time due to felling and thinning operations using NDVI values from SPOT images of different dates. As NDVI changes with the surface cover, it separates green vegetation from other surfaces because the chlorophyll of green vegetation absorbs red light and reflects the near-infrared wavelengths. Therefore, high NDVI values indicate high biomass, and canopy closure (Sader and Winne, 1992; Jasinski, 1990).

Four SPOT NDVI images (1994-1997) were used to analyse forest cover changes (Figure 6.1). In the first stage, the study recognised major visual changes that occurred in the area. Although brighter tones (relatively high NDVI) appear in the 1996 and 1997 images of the study site, considerably darker tones (relatively low NDVI) appear in the 1994 and 1995 images. However, separation of areas with minor changes is very difficult, because during the period of four years (1994-1997), NDVI has changed little. But in each age group slight changes can be recognised (Figure 6.1). Areas with different age groups are indicated using coloured numbers in the four images. The 1997 image was used as the reference year to classify these age groups. The following five age groups were used for this analysis:

1) < 7 years
2) 8 – 17 years
3) 18 –37 years
4) 38-57 years
5) >58 years

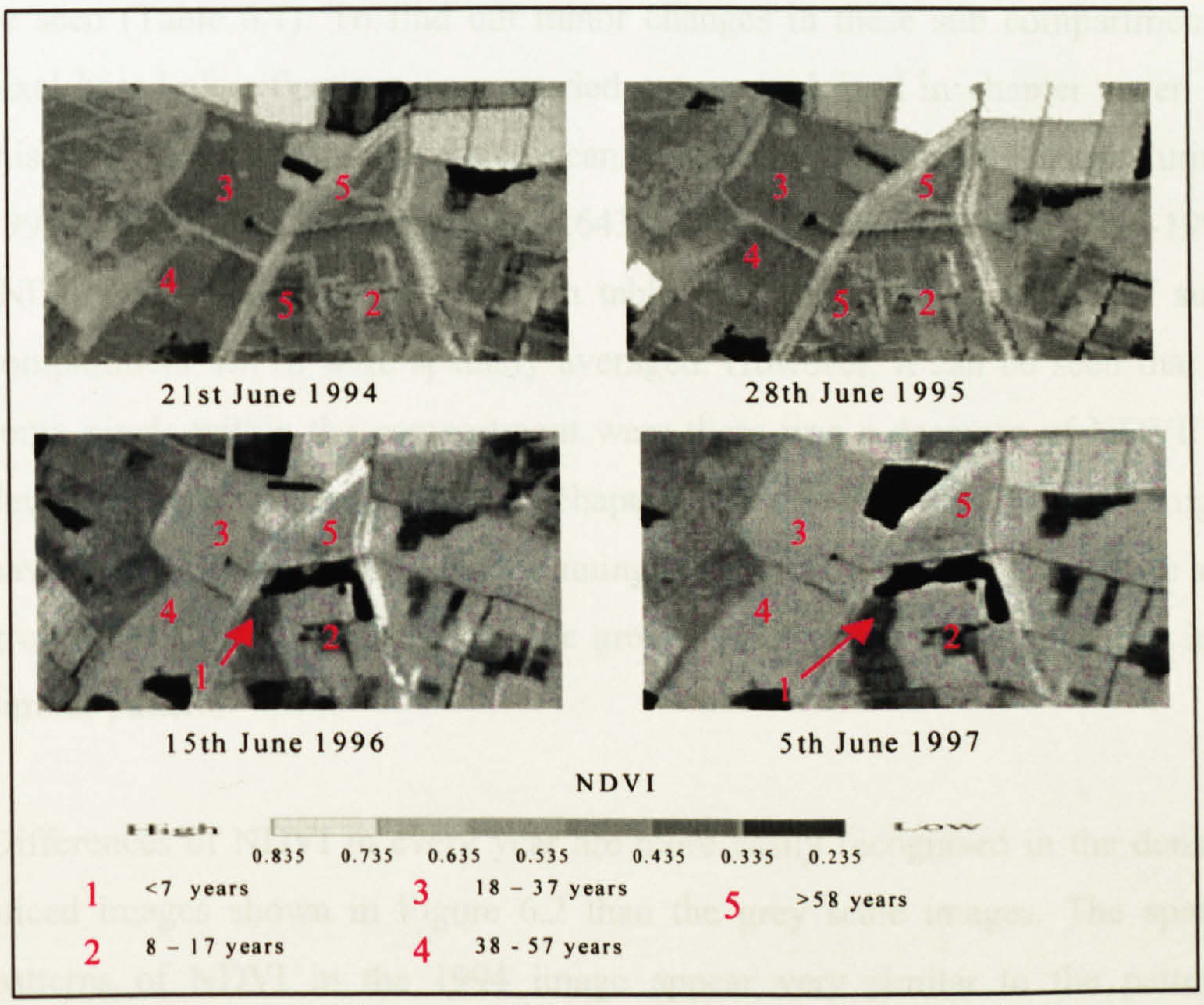


Figure 6.1 Temporal differences of NDVI in the study site

In the <7 years old plantation (marked 1 in 1996 & 1997 images), the spaces between the trees consist of grass patches and rough vegetation. Therefore in this stage, low values of NDVI have occurred. With the increase of planted tree cover, NDVI changed very little (10%). In contrast, in the 8-17 year age group (marked 2 in the images), changes over time are relatively greater (37%). In all images, this area appears in brighter tones due to the high value of NDVI. Field observation suggests the presence of a considerable amount of undergrowth, which remains until thinning treatment starts at the age of 20, and that the consequent high near-infrared reflectance from the interspaces in the canopy is responsible for this high NDVI.

The area marked 3 in the pine plantation was planted in the 1960s and is 1997 in the 18-37 year age group. It appears as a relatively darker tone in the 1994 image,but brighter in 1997 image with NDVI increasing from 0.654 to 0.726. At this stage, some sub-compartments (4226a, 4221a, 4224a and 4217b) were thinned in 1996, 1996,1995 and 1994 respectively, but no obvious change can be seen (Table 6.1). To find out minor changes in these sub compartments, pixel based classifications were carried out as explained in chapter seven of this thesis. However, at this stage, it can be seen that the increase is less during 1994-1995 (NDVI increases from 0.643 to 0.664) compared with 1995-1996 (NDVI increases 0.664 to 0.711) in table 6.1. These NDVI values of sub-compartment 4217b were spatially averaged. However, it can be seen that in some pixels within the compartment were there was a decrease of NDVI. A detailed interpretation is given in chapter seven in this thesis, which might have been effected by the second thinning at the end of 1994. In the mature age group (38-57 years) and the old age group (> 58 years), NDVI changes in a similar pattern.

Differences of NDVI in every year are more easily recognised in the density sliced images shown in Figure 6.2 than the grey scale images. The spatial patterns of NDVI in the 1994 image appear very similar to the patterns observed in the 1995 image. However, in the 8-17 age group (marked 2 in images) changes occurred from 0.50-0.60 to 0.60-0.70 NDVI class. Although year to year variations in conifers, such as natural growth, are generally assumed to be relatively minor (Spanner *et al.*, 1990), man-made changes such as clear cuts can be detected using SPOT imagery (Jaakkola, 1989). However, NDVI changed considerably from 1995 to 1996, as is shown in the images, especially in areas with 18-37 and 38-57 year-old pine plantation (marked 3 & 4 in each image in figure 6.2). In the 1996 image, 75% of the middle age group pine plantation falls in the 0.50-0.70 NDVI classes, but in the 1995 image these classes cover only 20-25%. The two images of 1996 and 1997 appear to have a similar pattern, because the forest cover variations are very minor, although areas marked 3 & 4 in the image (1997) do change relatively. In the 1997 image, 90% of the pine plantation area in the site fell in the 0.60-0.70 NDVI class.

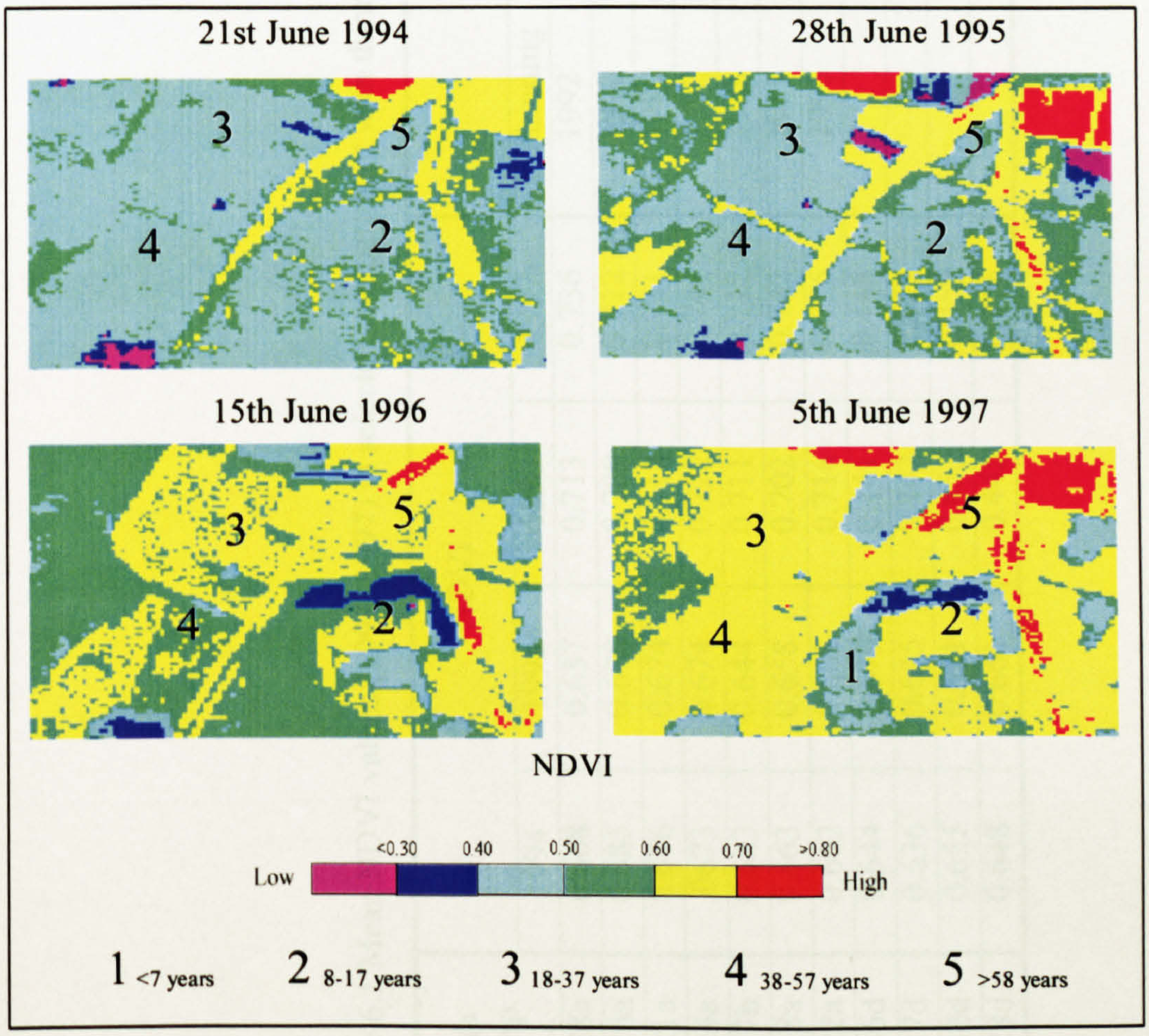


Figure 6.2 Density sliced NDVI images in the study site during 1994-1997

Table 6.1 Mean NDVI values (1994 -1997) in selected compartment with thinning and felling dates

Sub comp.	NDVI				Thinning years			Clear felling years	Age at 1997
	1994	1995	1996	1997	1st thinning	2nd thinning	3rd thinning		
4228a	0.668	0.657	0.713	0.736	1992	1998	-		32
4226a	0.685	0.678	0.709	0.712	1990	1996	2002		33
4221a	0.676	0.674	0.718	0.731	1990	1996	2002		34
4224a	.0673	0.674	0.722	0.741	1990	1995	2001		35
4217b	0.643	0.644	0.711	0.712	1988	1994	1999		36
4218a	0.663	0.658	0.702	0.742	1988	1994	1999		38
4122a	0.662	0.661	0.716	0.726	1990	1995	-		39
4036d	0.644	0.679	0.441	0.448				1995	1
4037d	0.636	0.645	0.442	0.458				1995	1
4042d	0.655	0.681	0.453	0.459				1995	1
4028d	0.648	0.661	0.445	0.458				1994	2

Table 6.2 Mean values of NDVI and annual changes by age groups during 1994-1997

Age groups	1994 NDVI	1995 NDVI	1996 NDVI	1997 NDVI	94-95	94-95 %	95-96	95-96 %	96-97	96-97 %	94-97	94-97 %
< 7	0.538	0.546	0.555	0.563	0.008	25	0.009	6	0.008	34	0.025	11
8-17	0.654	0.665	0.719	0.726	0.011	34	0.054	28	0.007	20	0.072	30
18-37	0.661	0.667	0.711	0.715	0.006	19	0.044	23	0.004	16	0.054	21
38-57	0.646	0.651	0.707	0.711	0.005	15	0.056	29	0.004	16	0.066	26
>58	0.643	0.645	0.645	0.673	0.002	7	0.027	14	0.001	4	0.03	12

6.2.1 Temporal change of NDVI in age groups

The changing pattern that occurred in the images can also be shown in Table 6.2. It shows NDVI changes during three periods (1994-95, 1995-96, and 1996-97) in each age group. These changes were calculated using mean NDVI in each age group. All the changes are positive. Therefore, in this analysis, NDVI tends to increase in most areas and decrease in fewer areas. During the 1995-96 period, the changes are considerably larger compared to the other two periods, which may be due some errors in the calibration procedure or correction method.

However, examining the changing pattern in each year during these periods, a relationship can be seen between NDVI changes and management operations especially felling. In addition, Figure 6.3 shows in more detail the extent to which each age group incurred these changes.

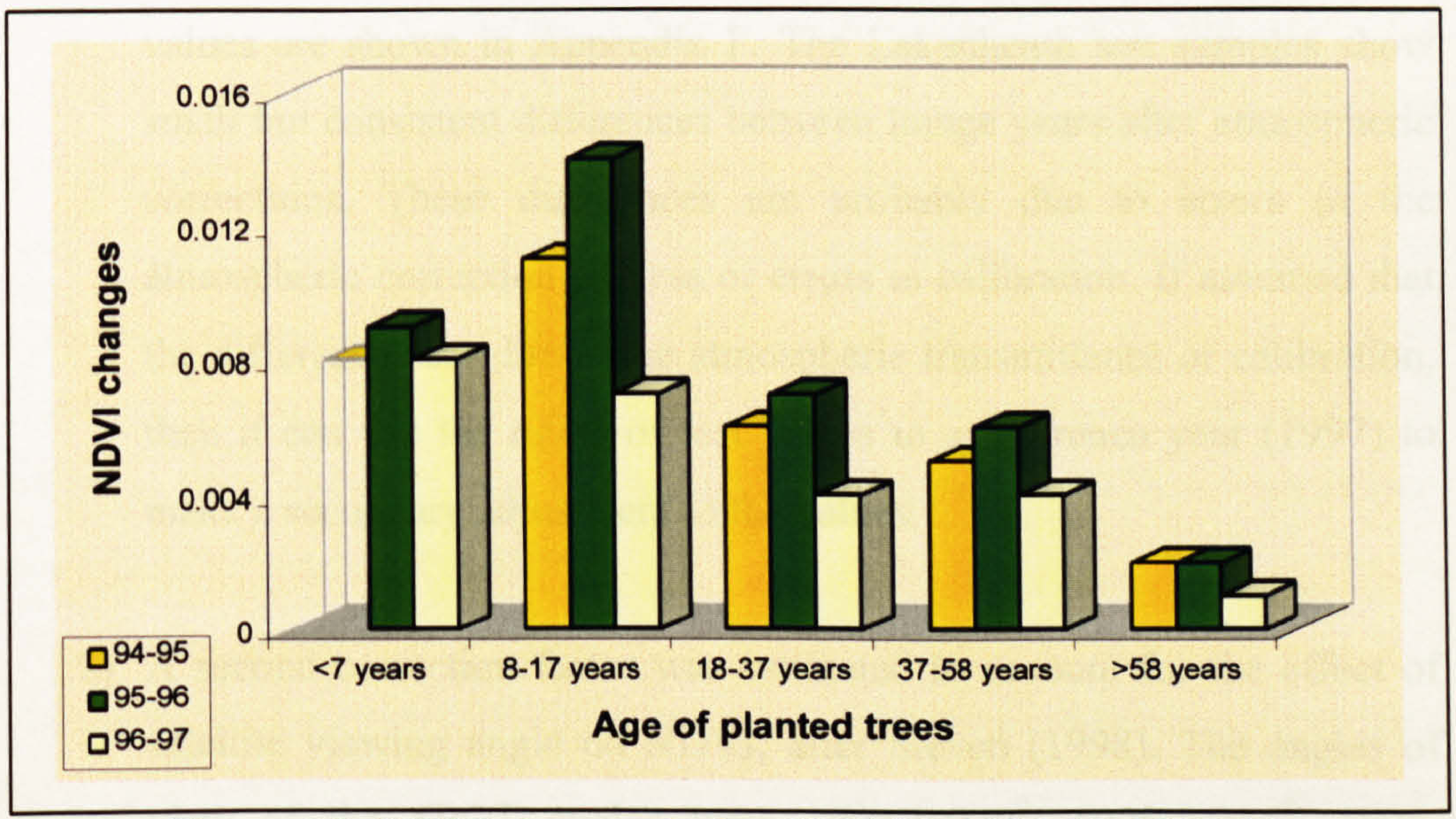


Figure 6.3: NDVI changes during 1995-96, 1996-95, 1997-96

The young group (8-17 year) has more changes (an over all change of 30%) of NDVI than the other age groups, indicating vegetation increase. This trend is due to the growth of planted trees and undergrowth. In the mature stage (18-37 and 38-57 years), NDVI changes are considerably smaller (21% and 26%). The effect of thinning operations on changes of canopy cover at this stage has not been closely analysed but there is some evidence that a number of sub-compartments were thinned in 1994, 1995 and 1996 (Table 6.1). Therefore, it can be stated that considerable influence may be seen in the mature stages. Examine the >58 year age group changes are much smaller especially in the 1996-97 image year (Figure 6.3) which corresponds to the surface green cover decrease. It because probably the effect of clear felling that took place in sub-compartments 4036d, 4037d and 4042d in 1995 and 4028d in 1994.

Figure 6.4 illustrates how NDVI changes during 1994 to 1997 in each age group. For this analysis, the original reflectance values derived after atmospheric corrections were further corrected with the two following methods

1) Lakenheath airfield was selected as a reference site. It is situated approximately 6 km away from the study site. It is assumed that certain targets on the airfield site do not change over time. The selected sites in the airfield and the samples with reflectance values and the correction values are shown in Appendix F. The Lakenheath test samples show small but consistent differences between image years after atmospheric corrections. These differences are probably due to errors in the atmospheric correction process or errors in calibration. If assumed that the differences are due to the atmospheric transmittance or calibration, then it can use the ratios of test values to a reference year (1997) to make a secondary adjustment to the values.

2) A second correction factor was estimated to account for the effect of satellite viewing angle on NDVI, after Steven (1998). The angles of view of the SPOT angles were 1994-left30^0, 1995-left15^0, 1996-right15^0 and 1997-right30^0. The original model calculations used by Steven (1998) were applied to NDVI. The estimated corrections to reduce values to nadir viewing are shown in Appendix F.

Figure 6.4 Temporal changes of NDVI during 1994-1997 by age

The changing pattern of NDVI in each image year (1994,1995,1996 and 1997) is shown in figure 6.4. Examine the changes over time in the graph 1994 is very similar to 1995 and 1996 is similar to 1997. Some of the NDVI values are overlapping. However, forest cover changes during 1995 and 1996 are relatively high especially before thinning and (9-17 years) and after thinning (42-56 years). During the thinning period, changes between each image year are visually more or less similar. In addition, change decreases due to the thinning cannot visually be discriminated in this graph. But reduction of forest cover after clear felling at the end of 1995 in a few sub-compartments has affected 1996 and 1997 NDVI values. It can be seen visually and it appears at the age of 56 years in the graph.

Comparison of corrected NDVI values of the four image years shows that there is similar trend in the <7, 8-17 and > 58 years age classes. The <7 years age trees can be found in 1996 and 1997 image and, at this stage, NDVI increases slightly, but in the 8-17 age period it has increased dramatically in every image year. However, variations between each year were very small until the age of 8. Thus, increase of NDVI gives an indication of change in vegetation condition. Because NDVI values are related to the status of the vegetation in terms of its biomass and Leaf Area Index, the main reason for increased NDVI is the growth of planted trees and the undergrowth at this stage. Based on field and aerial observation when the trees reach an age of 17 to 20 years, the canopy closes and undergrowth is no longer visible to the sensor. Therefore, reflection occurs mainly from the tree canopy and ,as a result, NDVI increases.

In contrast, in the > 58 years age stand, NDVI decreases considerably. NDVI reduction at this stage would be the effect of clear felling. Several sub-compartments (4028d in 1994 and 4036d, 4037d, 4042d in 1995) in this study site were felled and NDVI decreased dramatically (Table 6.1). In addition, based on field observations, the old growth stands have a higher proportion of dead wood, especially in the upper canopy and the greater frequency of scattered gaps between the trees that cause a decrease in the green vegetation. It caused a reduction of near-infrared reflectance accompanied by low NDVI. With increasing maturity in this stage, roughness of the canopy increases with shadows. When the shadows caused by variable heights of the trees are cast on lower portions of the canopy this results in a lower NDVI. Shadowing generally increases with the stand age until they stabilise in old growth, which decreases Green Vegetation (GV) fraction (Sabol *et al* 2002).

In the pre-mature (18-37 years) and the mature (38-57 years) age groups significant changes can be seen. However, NDVI remains moderately high probably due to fully-grown green canopy cover. Examine the 1994 and 1995 image years, the changing pattern is more similar than in 1996 and 1997. A slight reduction of NDVI can be seen in these two age groups in every image year, which may be due to thinning operations. The relationship between thinning and changes of NDVI is analysed in chapter seven.

6.2.2 Temporal change of NDVI in selected compartments

In order to analyse temporal changes in the study site within the compartments, two compartments (4037 and 4122) were selected. The reason for this selection was that significant management operations were carried out within compartment 4037 during 1994-1997. It consists of four sub-compartments (a, b, c, and d) of different age groups and three sites with different pine species (sub-compartments b, c and d) and one with deciduous trees (sub-compartment a). The compartment 4122 contains two sub-compartments with different age groups. The location of the selected sub-compartments is shown in figure 6.5.

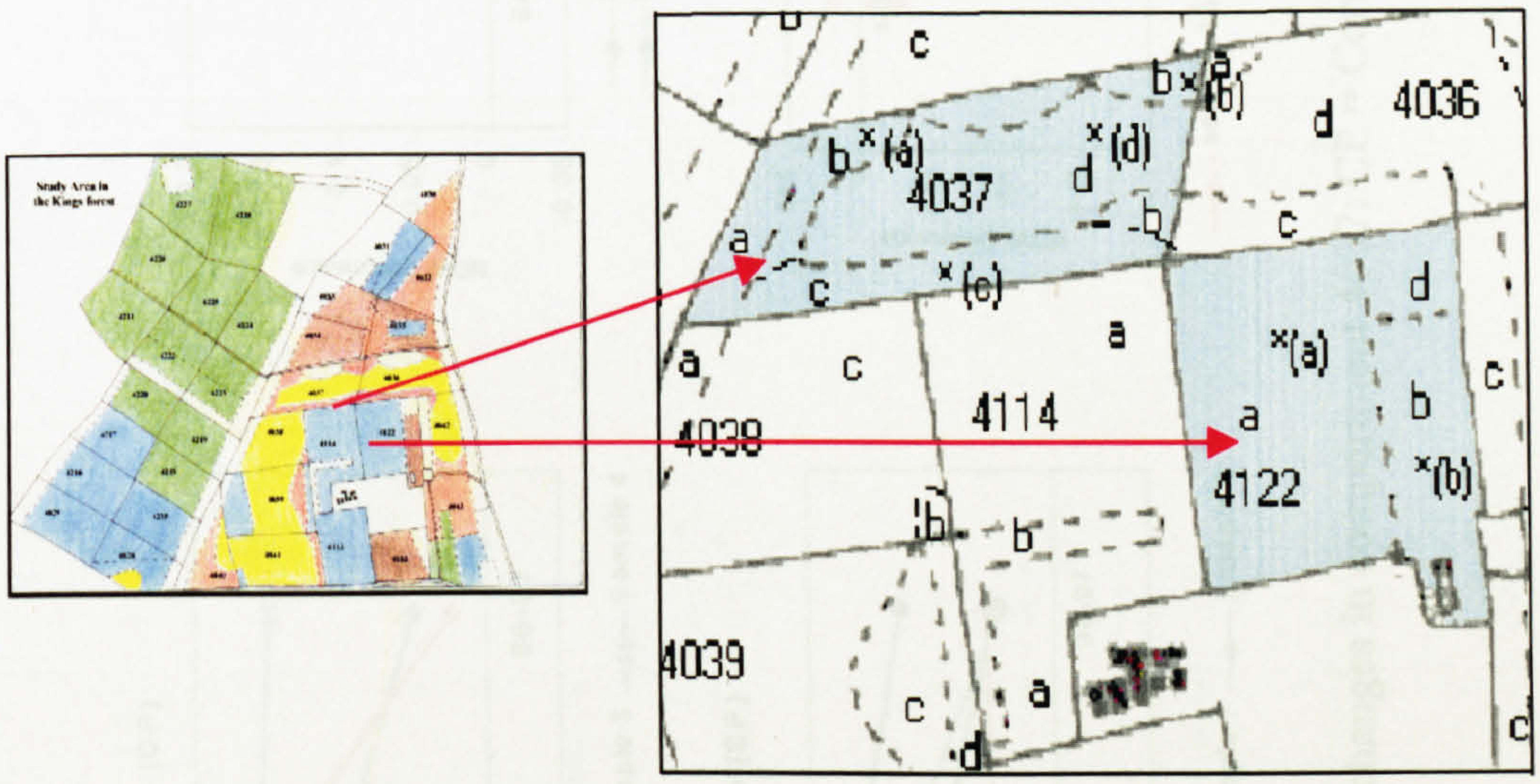


Figure 6.5 Selected compartments for temporal changes

Figure 6.6 illustrates the temporally changing pattern of each sub-compartment. These samples (comprising 10 pixels each) were selected randomly and temporal changes were calculated during 1994-95, 1995-96 and 1996-97. The changing patterns are very similar in sub-compartment (b) for both Corsican pine (Figure 6.6 a) and Scots pine (Figure 6.6 b) as well as for sub-compartment (c) with Scots pine (Figure 6.6 c). The pine trees in these sub-compartments were planted in 1936, and during the period of investigation, they were in the > 58 age group. Four samples (mean values of NDVI of the selected ten pixels in each sample) were selected from each site.

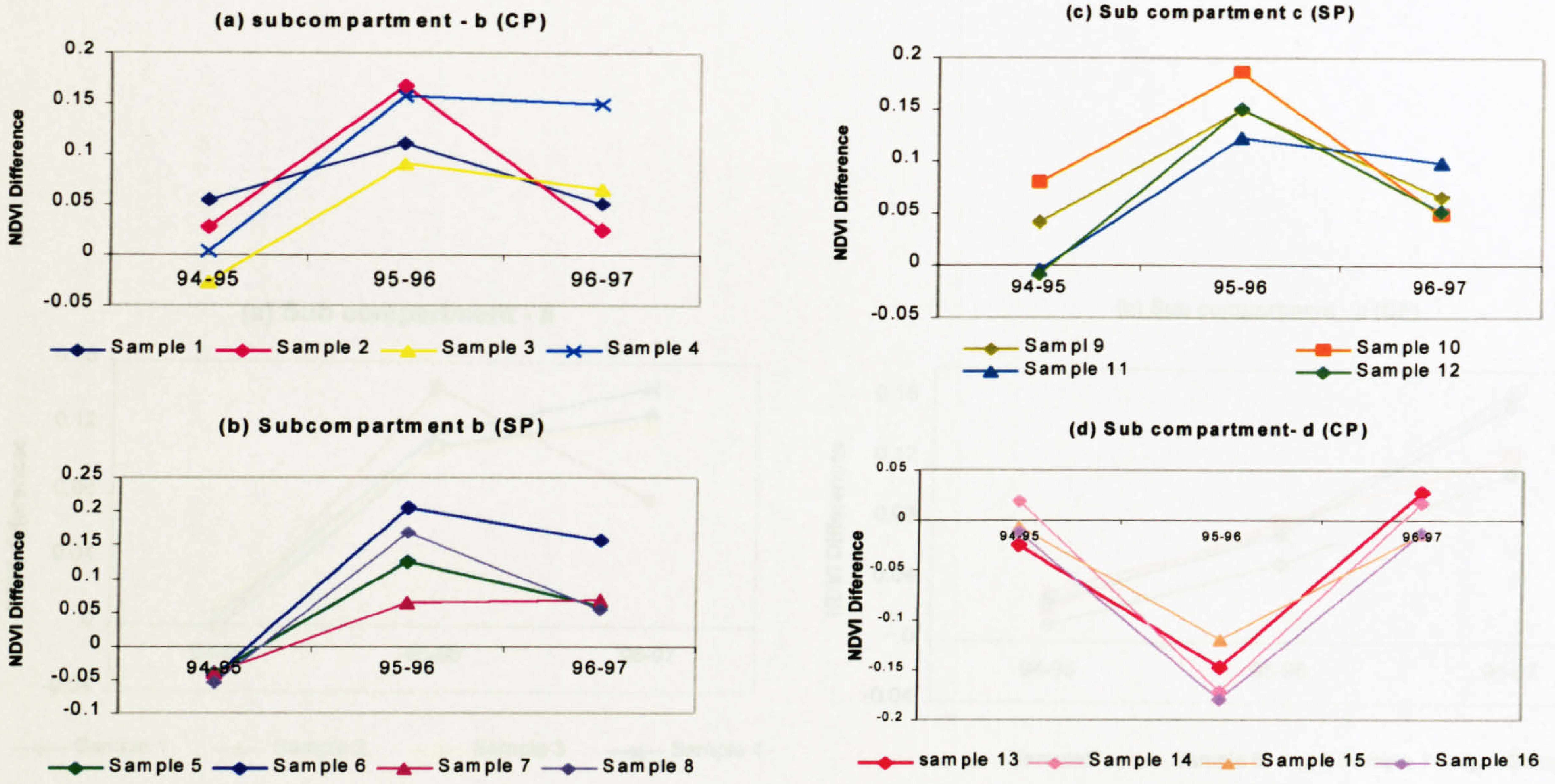


Figure 6.6 Temporal changes in compartment 4037: CP = Corsican pine; SP = Scots pine

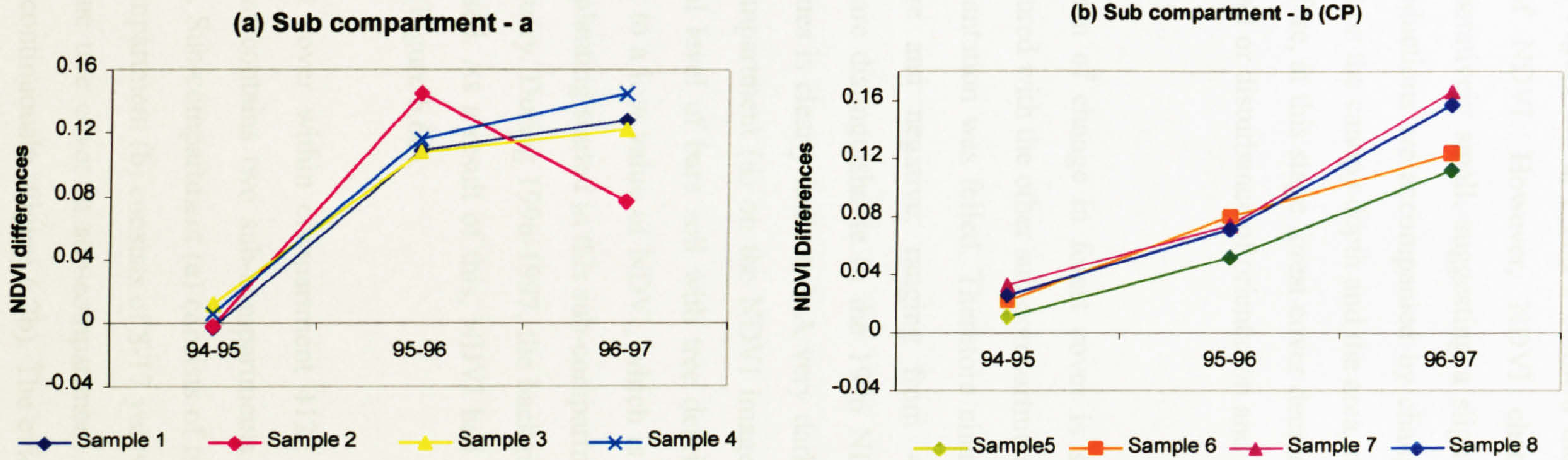


Figure 6.7 temporal changes in compartment 4122: CP = Corsican pine; SP =Scots pine

The findings suggest that NDVI changes during 1994-1995 were very small, ranging from –0.05 to 0.05. Figure 6.6 a, b and c confirm that most of the changes were increases of NDVI. However, NDVI changes in sub-compartment (b) were comparatively small, suggesting a slight reduction of forest cover. Forest cover reductions are accompanied by changes of canopy structure, which is dependent on the canopy depth and the area, orientation and distribution of leaves. Therefore, at this stage forest cover decreases may have occurred as a result of windfall or disturbance of orientation and distribution of branches and leaves.

A completely different pattern of change in forest cover is shown in sub-compartment (d) when compared with the other sub-compartments selected. At the end of 1995 the pine plantation was felled. Therefore changes of NDVI during 1995-1996 are large and negative, ranging from -0.01 to -0.2. Reductions of forest cover are distinguishable in the 1996 NDVI image. A sudden change of NDVI values is clearly indicated. A very dark tone appears in the whole area of sub-compartment (d) on the NDVI image (Figure 6.1). The reason is that the signal level of bare soil with tree debris in the near-infrared is very low, leading to a low value of NDVI, which is dominated by variation in NIR. In 1997, replanting started in this sub-compartment at the end of January, finishing in February. During 1996-1997, the background cover of grass and bushes has increased. As a result of this, NDVI had increased, but changes are relatively small (Figure 6.6d).

Temporal changes of forest cover within compartment 4122 are shown in figure 6.7. This compartment contains two sub-compartments with different age groups of Corsican pine. Sub-compartment (a) consists of trees in the >38 year age group while sub compartment (b) consists of 8-17 years old trees. It is apparent that changes of pine tree cover in sub-compartment (b) during the period of concern increased continuously (Figure 6.7b). The evidence suggests that generally young pine trees developed continuously and that the canopy is also continuous throughout the stand, remaining in an ideal condition until thinning is carried out. In contrast, changes of NDVI in sub-compartment (a) showed an increase during 1995-1996, but during 1996-1997 small increases were recorded except for the sample 2. NDVI in this sample decreased relative to the others. However, according to the Forestry Commission evidence, this sub-compartment was thinned in 1995 (Table 6.1). The decrease of NDVI was due to reduction of the canopy cover by thinning. When the pine plantation reaches this mature stage, growth becomes minimal until felling is carried out. Therefore, variations of NDVI are very little during this later stage.

6.3 CHANGE DETECTION ANALYSIS

The first part of this chapter analysed forest cover changes using a visual analysis of NDVI changes occurring over four years. This approach allows for easier data analysis and extraction of information, and it may also be appropriate at a very general level for forest management decision making. In this section, a digital change detection method is used to analyse the changes of forest cover. This method allows the investigator to stratify the area and identify locations for more detailed analysis. The study mainly concerned the detection of the nature and type of forest cover change in the study site during 1994-1997 using the Vegetation Index Differencing method (VID). This selection of method plays an important role in the identification of change and was made here on the basis of the type of change being addressed and the availability of data. However, it is difficult to say which method is most appropriate for a particular application. Nelson (1983) pointed out that forest canopy change due to Gypsy Moth defoliation in Pennsylvania was delineated more accurately with Vegetation Index Differencing than with any other single band difference or with band ratioing. The operational procedure of Vegetation Index Differencing is similar to image differencing. The only additional step that needs to be taken as compared to image differencing is the production of NDVI images prior to change detection analysis. The VID method involves subtracting the NDVI images of one date from that of another. The advantage of this method is that the output image can be related empirically to the physical condition of the vegetation cover. Thus, differences of vegetation index derived from VID give an indication of change in the vegetation condition. The NDVI values can also be used to relate the status of the vegetation in terms of its biomass and Leaf Area Index. However, examination of such relationships requires detailed field observations and proper modelling function and is beyond the scope of this study.

6.3.1 The nature of change detection

The NDVI difference technique, which is described in the first part of this chapter, is useful for identifying the main changes of forest cover, but it cannot stratify the change categories and cannot effectively separate zone of increase or decrease in forest cover. The change detection technique allows quantitative separation of the areas of forest growth from clear-cut areas. This section mainly analyses three detected change categories. They are:

1) No change
2) Forest cover increase
3) Forest cover decrease

The areas indicated as 0.0 values in the change detection images are defined as the no-change class while < 0.0 and > 0.0 values are defined as change classes. No change, increase and decrease in forest cover were categorised into five classes according to the magnitude of NDVI change as follows:

1) Large increase + 0.5 and above
2) Small increase 0.1 to + 0.4
3) No change 0.0
4) Small decrease 0.1 to - 0.4
5) Large decrease - 0.5 and below

6.3.2 Change detection images

This section explains how changes appear in change detection images. Figure 6.8 shows forest cover change detection during the periods 1994-95, 1995-96 and 1996-97 on the study site. The study site is enclosed with a green line. The areas of forest canopy with smaller changes appear in darker tones in the change detection images, whereas areas with larger changes appear in lighter tones. It is difficult to recognise changes visually in the 1994-1995 image, because tone differences are slight (Figure 6.8 (i)). Most of the compartments appear in relatively dark tones and consist of late mature or old age pine trees. Normally, at this stage, no thinning operations are carried out. After the final thinning, the remaining crop will reach maturity and the forest stand will remain stable. There was little evidence of crown expansion in the remaining trees at this stage and understory development was also negligible. However, old age pine trees have a limited capacity to expand their crowns or alter the branching patterns of their crowns in response to changes in the canopy structure.

In contrast, it is very easy to differentiate areas with changes in Figure 6.8 (ii). Substantial areas of old age pine trees that appear in the June 1995 image were felled at the end of 1995, in particular compartment 4037 (d). Therefore, due to the change in surface cover, the change detection image appears in a relatively lighter tone compared to the other areas. During the period 1996-1997, forest cover changes were not as large as in the previous year. Therefore, changes were considerably decreased and compartment 4037 (d) appears in a medium tone.

6.3.3 Analyses of change and no change categories

Change detection of forest canopy cover over time was also evaluated statistically in terms of change and no change classes (Table 6.2). The results indicate that only 35% of the area changed during 1994 – 1995, while 78% changed in 1995-1996 and 71% in 1996-1997. Some differences are apparent according to age class. The three age classes considered here are young (<17 years) mature (18-37 years) and old age (>38 years). Earlier analysis observed that in the < 7 years age group the changes are very small. Most of the changes tend to occur at the mature and old stages. However, considerable changes occurred in young age stands because of growth of the planted trees and the undergrowth (Table 6.3).

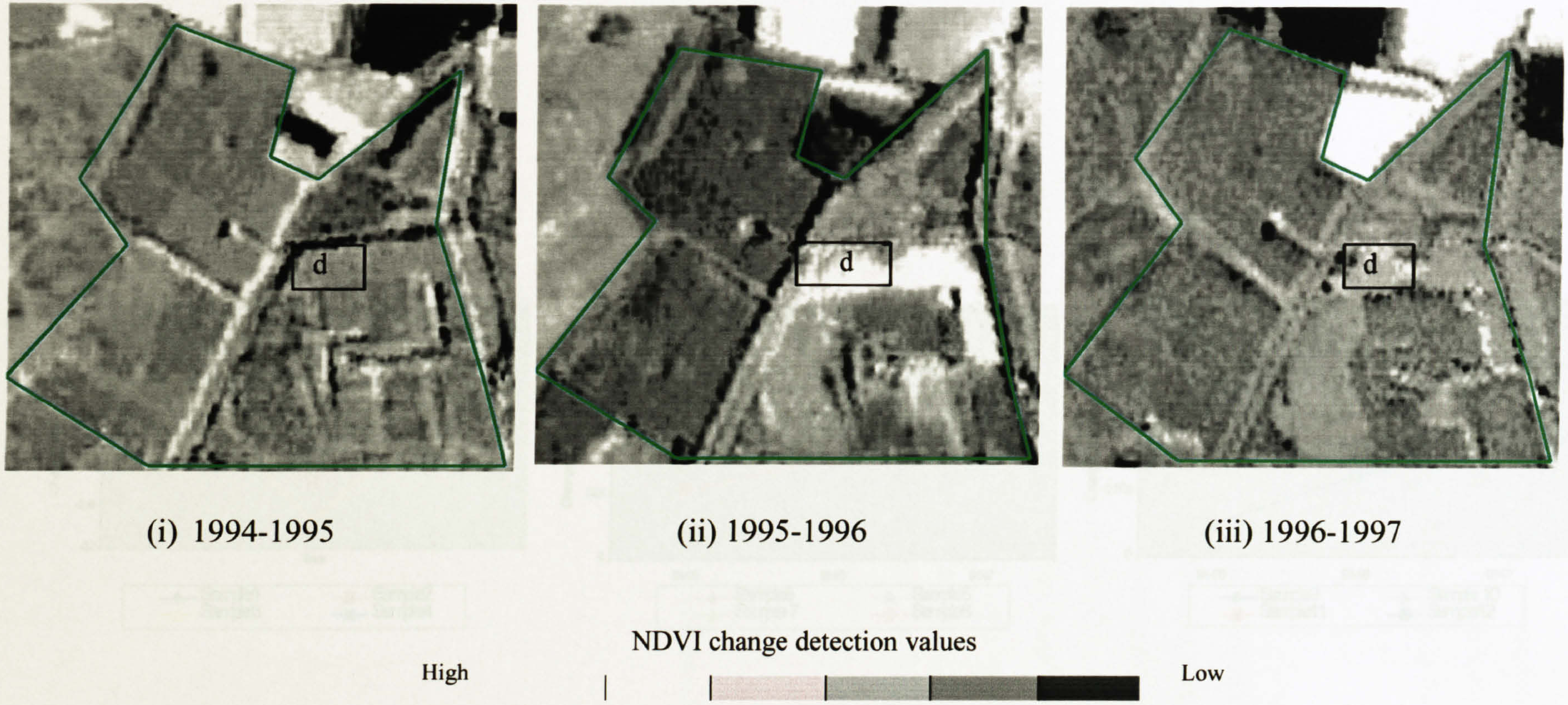
Although changes were small in the mature and old age groups (15%) during 1994-95, it was larger during 1995-96 (48%) and 1996-97 (40%). This analysed confirmed that forest cover changes mainly take place in areas where management operations (according to the forest management planning mainly thinning in mature stage and felling in old age) are carried out.

Table 6.3: Change detection classes by age group

Detection classes	1994-1995			1995-1996			1996-1997		
	<17	18-37 (%)	>38	<17	18-37 (%)	>38	<17	18-37 (%)	>38
No Change	10	28	27	6	3	11	10	8	17
Change	20	7	8	30	28	20	25	24	16
Totals	30	35	35	36	31	33	35	32	33

According to the Forestry Commission compartment records, most of the changes occurred in the compartment 4037 during this four year period. It was found that until the end of 1995 sub-compartment (d) was dominated by old age pine canopy cover. Then, in 1996, it changed after felling into bare land with a rough surface. In 1997, patches of undercover vegetation with a mixture of broadleaves and grass cover started to grow among the newly planted pine trees. Therefore, this compartment was selected for detailed analysis. In 1994, sub-compartments (b), (c) and (d) in the compartment 4037 consisted of mature or old age pine plantation, so, because of the high NDVI, these compartments appear relatively lighter in tone on the June 1994 image (Figure 6.1). In December 1995, sub-compartment (d) was completely felled and consisted of a rough surface until replanting was carried out in February 1997. Therefore, because of the low NDVI, this area appears in a very dark tone in the 1996 and relatively dark in the 1997 images. These changes are large and are easily recognised in change detection images (Figure 6.8).

Due to smaller changes that occurred in sub-compartment (d) during 1994-1995 it appears relatively dark. In June, 1994, it was a mature pine plantation, so that forest cover would have changed very little unless natural or human disturbances had occurred. The same area after felling at the end of 1995 is completely changed in appearance, because the forest cover had changed into a rough surface with tree debris and soil litter. In contrast, during the period 1996-1997, it consists of less than one-year-old pine trees with some patches of dry and green grass cover. Therefore, the changes are not as high as the previous image, and it appears in a lighter tone.



(i) 1994-1995

(ii) 1995-1996

(iii) 1996-1997

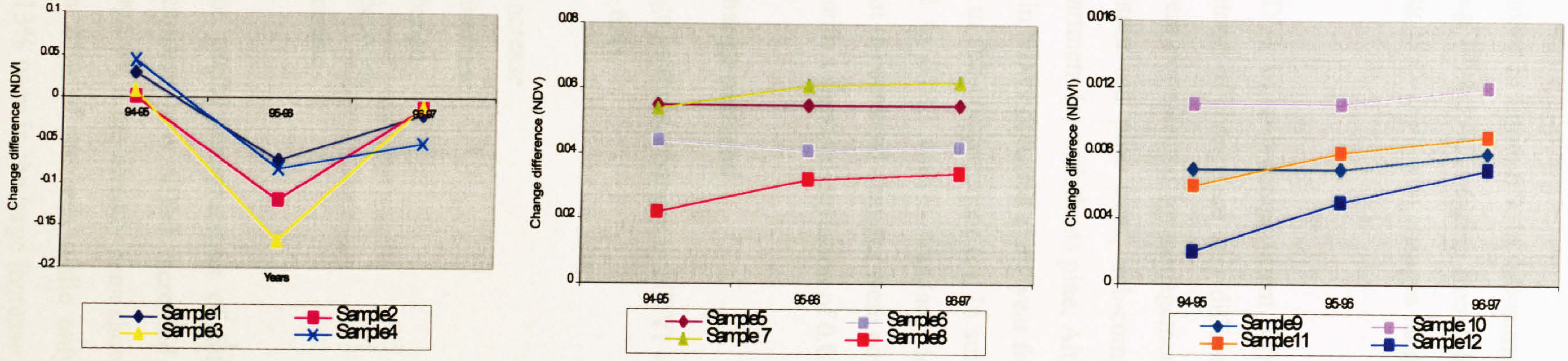
NDVI change detection values

Change (34%) No change (66%)

Change (79%) No change (21%)

Change (64%) No Change (36%)

Figure 6.8 Change detection images



(1) sub compartment d

(II) sub compartment c

b

(III) sub compartment

Figure 6.9: Change detection in compartment

These changes can be recognised in figure 6.9. In sub-compartment (d), NDVI increases only occurred during 1994-1995, ranging from 0 to 0.05. Then NDVI decreased dramatically during 1995-1996 with changes ranging from -0.05 to – 0.15.

During 1996-1997, the NDVI of sub-compartment (d) showed a small decrease. In contrast, the patterns of change are very different in the other two sub-compartments, which were not affected by management operations. Both of these compartments contain old pine trees, sub-compartment (b) with Corsican pine and sub-compartment (c) with Scots pine. Although in these two sub-compartments increases in NDVI occurred every year from 1994-1997, the changes were much smaller in sub-compartment (c). In sub-compartment (c), changes ranged from 0.002 to 0.012 with a standard deviation of 0.016. However, in sub-compartment (b) detected changes were comparatively higher ranging from 0.020 to 0.062 with a standard deviation of 0.035.

6.3.4 Analysis of detected change patterns

To analyse the detected change patterns, changes in NDVI were classified into five classes as follows (Table 6.4).

1) + 0.5 and above - large increase
2) + 0.1 to + 0.4 - small increase
3) 0.0 - no change
4) – 0.1 to – 0.4 - small decrease
5) 0.5 and below - large decrease

This classification allows for useful interpretation of forest cover among change classes. Initially, it explains how NDVI increased and decreased in each year (Figure 6.10). In 1994-95, it has already been shown in table 6.3 that positive changes occurred in 25% of the area while only 10% decreased. Among the NDVI increases, 13% were in the large increase class of + 0.5 and above and 12% were in the small increase class, 0.1 to + 0.4.

Table 6.4: Detected change classes (%change in NDVI) in each year and each age group

(a) Each year

Change classes	1994-1995	1995-1996	1996-1997
Large increase < + 0.5	13	15	18
Small increase 0.1 to + 0.4	12	12	15
No change 0.0	65	20	35
Small decrease 0.1 to – 0.4	3	26	11
Large decrease > - 0.5	7	25	21

Small increase 0.1 to + 0.4	8	2	2	4	2	6	10	4	1
No change 0.0	10	28	27	6	3	11	10	8	17
Small decrease 0.1 to – 0.4	4	1	2	9	14	3	2	5	4
Large decrease > - 0.5	1	1	3	12	9	4	3	11	7
Total	30	35	35	36	31	31	35	32	33

(b) Each age group

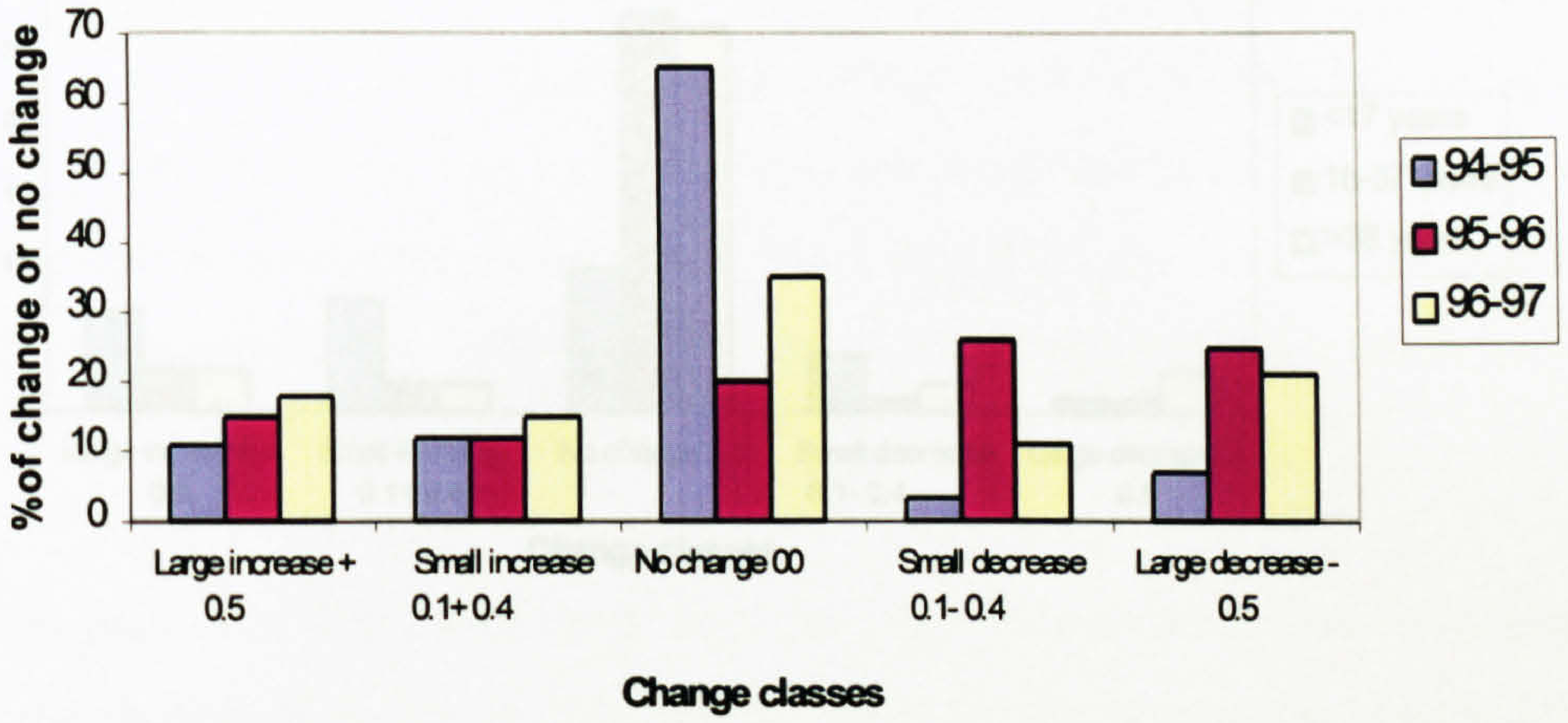
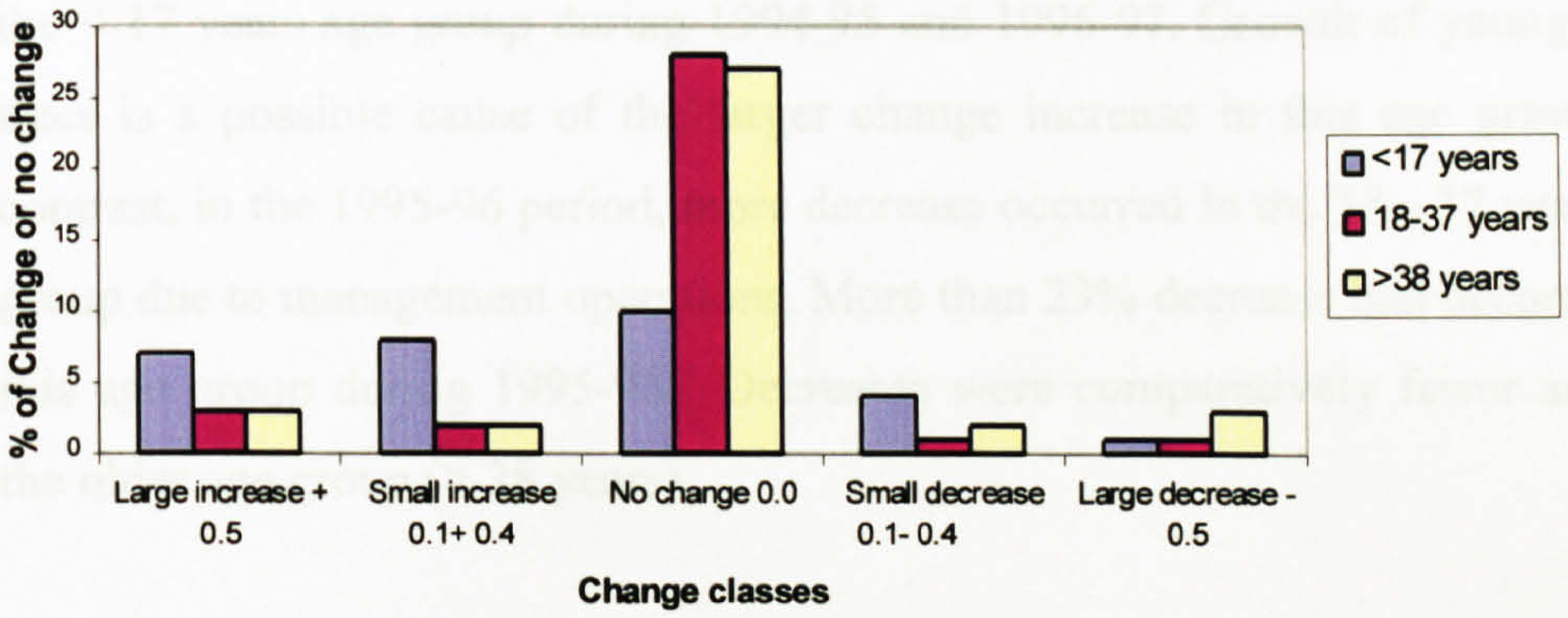


Figure 6.10: Percentages of change classes

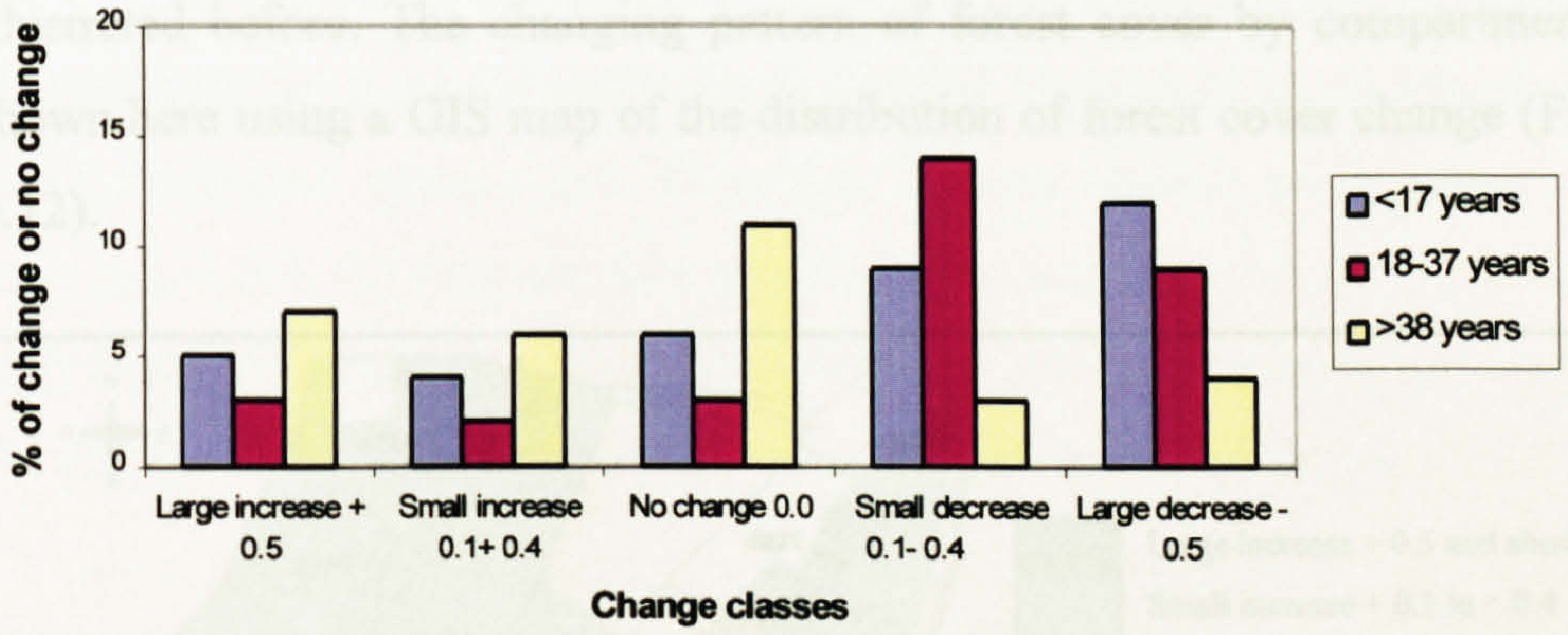
A completely different pattern can be identified during 1995-96, although it showed more changes than the previous year. In this period, most of the changes occurred as a decrease (52%), while only 27% of the area showed an increase of NDVI. However, increases greater than + 0.5 or in the range 0.1 to +0.5 are more or less similar in this period to the previous year. In the period 1996-97, a different change pattern can be seen. Forest cover increases and decreases were almost equal with few exceptions.

For management purposes, it is very useful to identify changing patterns of forest cover in different age groups, because it helps to determine which sub-compartments should be prepared for management operations. Therefore, the study analysed how NDVI change classes occurred in different age groups. In order to determine the pattern of change classification, three age groups (< 17 years, 18-37 years and > 38 years) were used. Figure 6.11 illustrates changes that occurred in these age groups in each year.

(a) 1994 - 1995



(b) 1995 - 1996



(c) 1996 - 1997

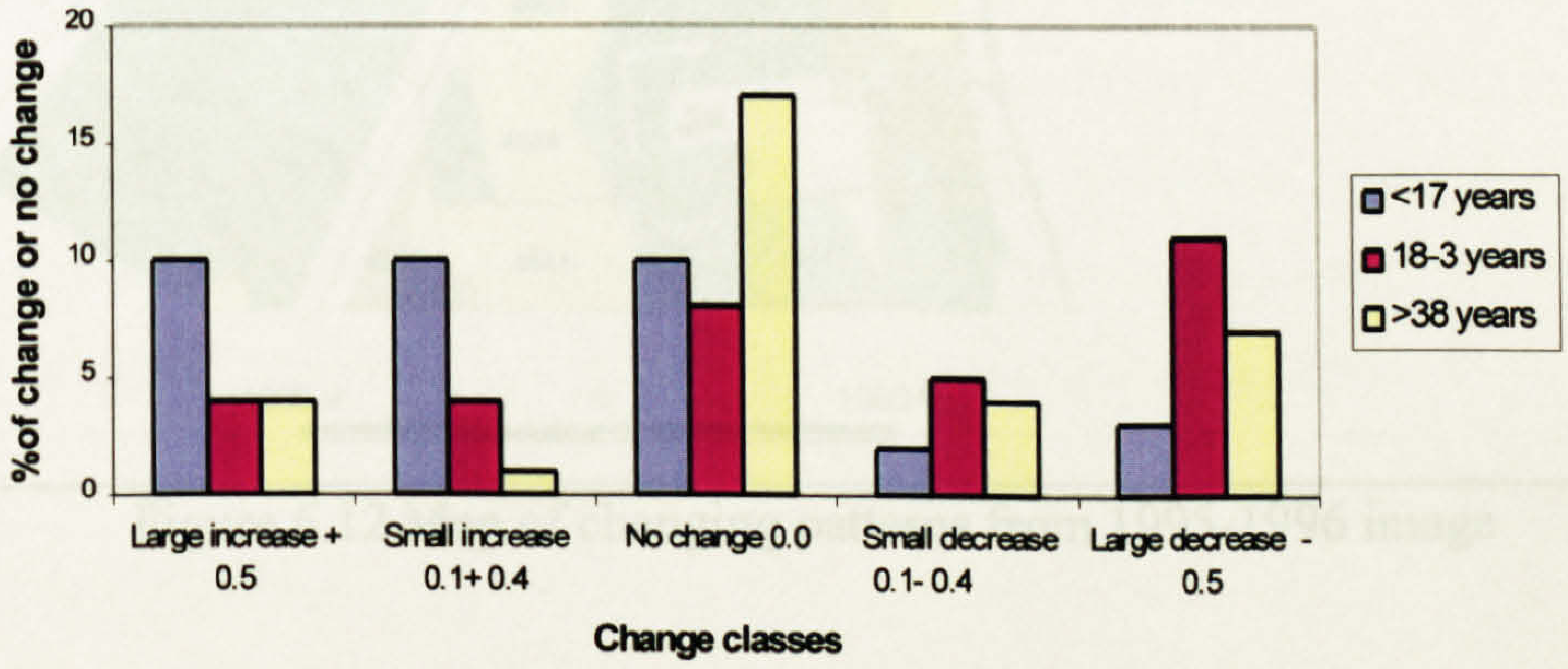


Figure 6.11 Change classes by age group

Although statistically, these changes are very small the changes are clearly identified in the increase and decrease classes. Increases are relatively high in the < 17 years age group during 1994-95 and 1996-97. Growth of young pine trees is a possible cause of the larger change increase in this age group. In contrast, in the 1995-96 period, more decrease occurred in the 18 - 37 year age group due to management operations. More than 23% decrease had occurred in this age group during 1995-96. Decreases were comparatively fewer among the older age group (> 38 years).

It has been seen that forest cover changes were considerably more widespread in the period 1995-96. In this period, 79% of the area showed significant change of forest cover; with 52% showing a decrease of forest cover as illustrated before. The changing pattern of forest cover by compartments is shown here using a GIS map of the distribution of forest cover change (Figure 6.12).

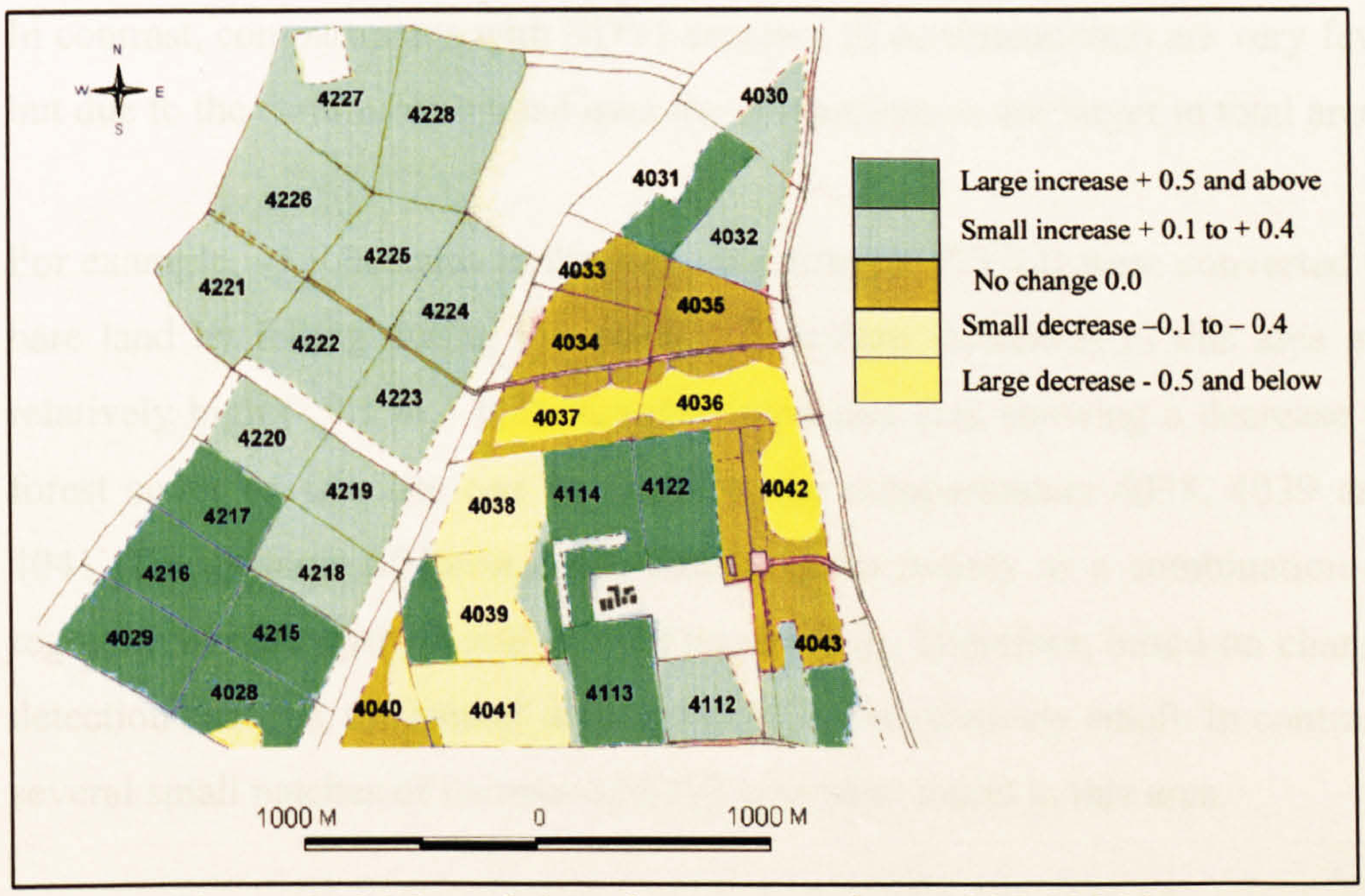


Figure 6.12 Map of changing patterns from 1995-1996 image

This map was produced by generalising the remote sensing-based forest change, and shows the changing pattern of the forest cover by compartments.

Only five compartments in the old stage of growth indicate the no-change category (Table 6.5).

Table 6.5: Number of compartments by change classes in 1995-1996

Change class	Number of compartments
Large increase + 0.5 and above	9
Small increase 0.1 to + 0.4	14
No change 0.0	5
Small decrease 0.1 to – 0.4	3
Large decrease – 0.5 and below	3

It is apparent that NDVI has increased in 29 compartments during this period. But changes that indicate increases are not continuously distributed. They are characterised by a patchy appearance, forming clusters of small change spots in an unchanged background. Therefore, if these clusters are ignored, it has been found that the increase change category is less than the area of decrease. In contrast, compartments with NDVI decrease (6 compartments) are very few, but due to the continuous spread over the compartments are larger in total area.

For example, 43.9 hectares in the sub-compartment 4037(d) were converted to bare land by felling during this period. Therefore, decreases in this area are relatively high (- 0.1 to – 0.5). Another important area showing a decrease in forest cover on this site can be found in the compartments 4038, 4039 and 4041. The patterns of forest cover change occur mainly as a combination of regrowth of undergrowth and planted tree growth. Therefore, based on change detection analysis, the area of decrease of NDVI is relatively small. In contrast, several small patches of increased NDVI were also found in this area.

6.5 SUMMARY

In this chapter, the temporal pattern of forest cover changes over four years were analysed. The analysis was carried out using the following two methods:

1) Temporal variations in vegetation cover were analysed using calculated NDVI.
2) Digital change detection was performed using a Vegetation Index Differencing method.

A number of points that are potentially important to remote sensing of forest cover for plantation forest management emerged from this investigation.

1) During the observed period, the overall changes were fairly small (mean NDVI ranged from 0.612-0.763). However, major local changes were visually recognised in each NDVI image. The changes of forest canopy cover were relatively greater in the 1995-96 period, and the largest area of forest cover changes was found in compartment 4037 (sub-compartment d), due to management operations (felling) at the end of 1995. These changes were indicated by a large decrease in vegetation index. The areas are regularly shaped and form closed areas. In contrast, changes with increase in vegetation cover are characterised by small patchy areas.
2) Temporal changes were relatively large in areas with certain tree age groups. It is apparent that changes in the old age group (> 38 years) were generally greater, whereas smaller changes occurred in mature age pine stands. Considerable changes had occurred in the <7 and 8-17 year plantations due to increase of canopy cover or plant growth, while less growth was found in the > 38 year old stand. On the other hand, larger negative changes were found in > 38 age group because of reduction of canopy cover by management operations, mainly partial felling in the earlier stage and clear felling in the later stage. The reduction of forest canopy cover at the mature stage is difficult to identify using these methods. Therefore, the next chapter analyses the changes in selected sub-compartments using a pixel-based classification method to detect fine changes causing by thinning.

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CHAPTER SEVEN

TESTING THE ABILITY TO DETECT FOREST COVER CHANGES FOR FOREST MANAGEMENT OPERATIONS

7.1 INTRODUCTION

The purpose of this chapter is to detect very fine variations of forest cover (mainly decreases) on the basis of the previous analysis and compare these changes with recorded thinning information. For this analysis, compartments within the 18-37 year age group were selected. The overall change detection analysis (chapter 6) confirmed that this area is in the class with an increase of NDVI > +.04. However, detailed analysis of the NDVI image showed small areas of decrease within some compartments. Change detection analysis also shows that within the 18-37 year age group, 16% of the area is categorised as having decreased during 1996-97. The availability of relevant ground-based thinning information in the site assisted the interpretation of minor changes of cover density.

The Vegetation Index differencing technique (VID), which this study used for change detection, identifies change and no-change areas, but it is difficult to determine where to select boundaries of change and no-change and difficult to interpret the spatial distribution of minor forest cover changes. Therefore, this chapter is intended to analyse classification of pixel by pixel forest cover changes within the 18-37 year plantation site between 1996 and 1997 to evaluate the potential use of earth observation data in management operations.

The purpose of this interpretation is to classify NDVI classes and create a spatial distribution map to identify minor forest cover changes attributed to thinning or partial harvesting. The effect of these physical changes is difficult to identify because typically reflectance in all bands would increase with reduction in basal area. However, in some areas, a reduction in basal area has been followed closely by an increase in leaf area as the understorey responds to the opening of the canopy (Franklin *et al.,* 2000b). This increase in leaf area can decrease reflectance in visible bands and increase near-infrared reflectance.

The test area is situated in the western part of the study site. Six compartments were selected in each age group on the basis of previous analyses. The first part of this chapter uses a simple and relatively accurate technique to classify spatial changes within the compartments in the 1996 and 1997 images. Then individual and overall changes are calculated pixel by pixel from two separate images using NDVI values. Secondly, temporal changes are calculated using change matrices with pixel by pixel representation of changes in different NDVI classes > 0.725, 0.705-0.724, 0.695-0.704, <0.694. Finally, using these data, forest cover changes are compared with Forestry Commission records on management operations to evaluate the quality of information derived from remote sensing data (Congalton and Green, 1999). It was regarded as an essential part of the study to determine how actual changes of the forest cover relate to thinning operations, as this information can be very useful for management purposes.

7.2 DESCRIPTION OF THE TEST SITE

The test site is situated in the western part of the study area. This site consists of 166 hectares of 32 - 38 years old pine plantation divided into sixteen compartments with an average size of approximately 10 ha. Figure 7.1 shows the compartment polygons in the test area with the age of plantation and the six sample polygons (numbered in red) selected for this analysis. The dominant species of the test site is Corsican pine, except in compartment 4221, which consists of Scots pine. Structurally, the site is extremely simple, being composed of 9.8 – 20.0m top height trees. The tree stands have single storey homogeneous canopies with few or no gaps. The forest understorey is relatively uniform, consisting mainly of a thin layer of grass.

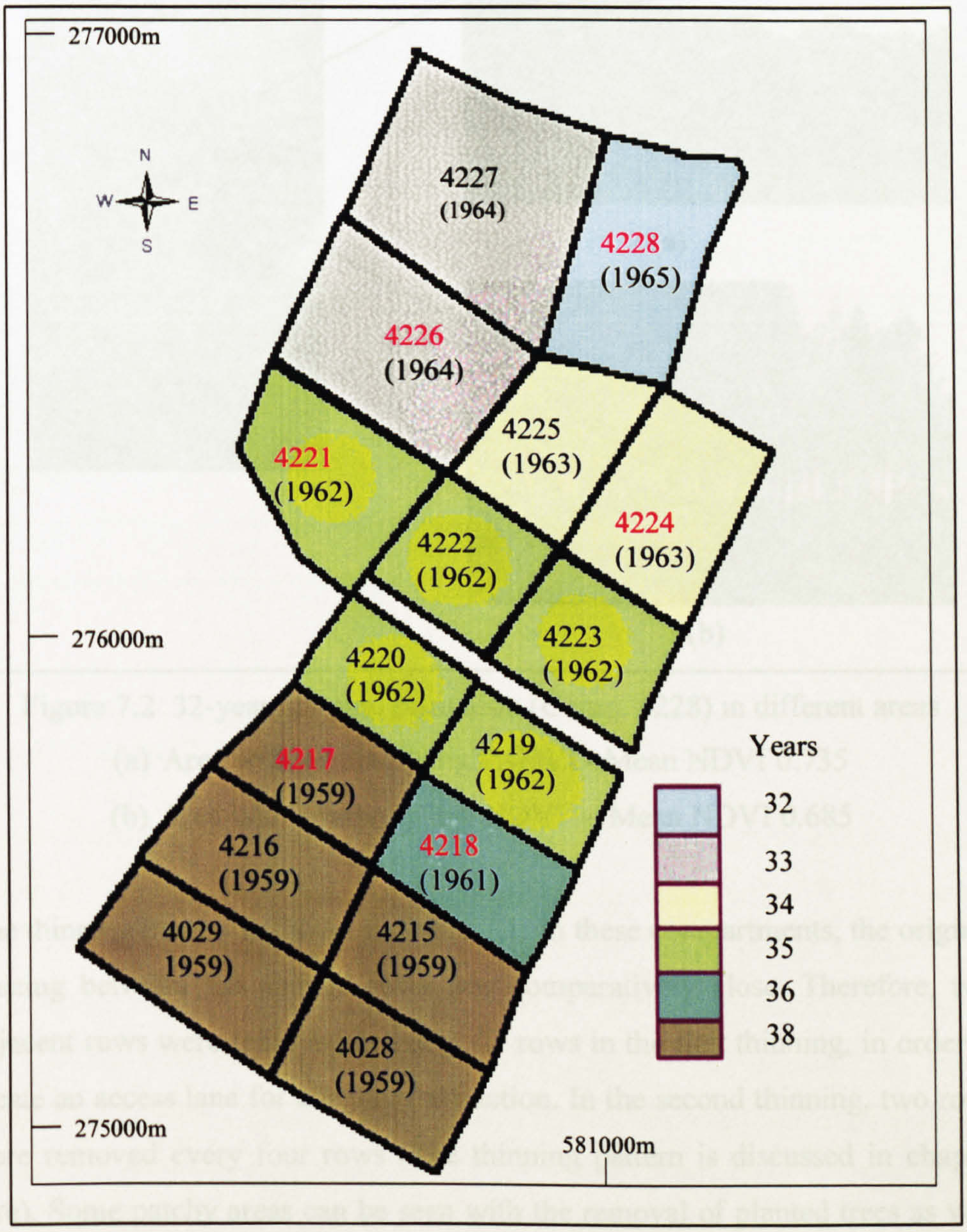
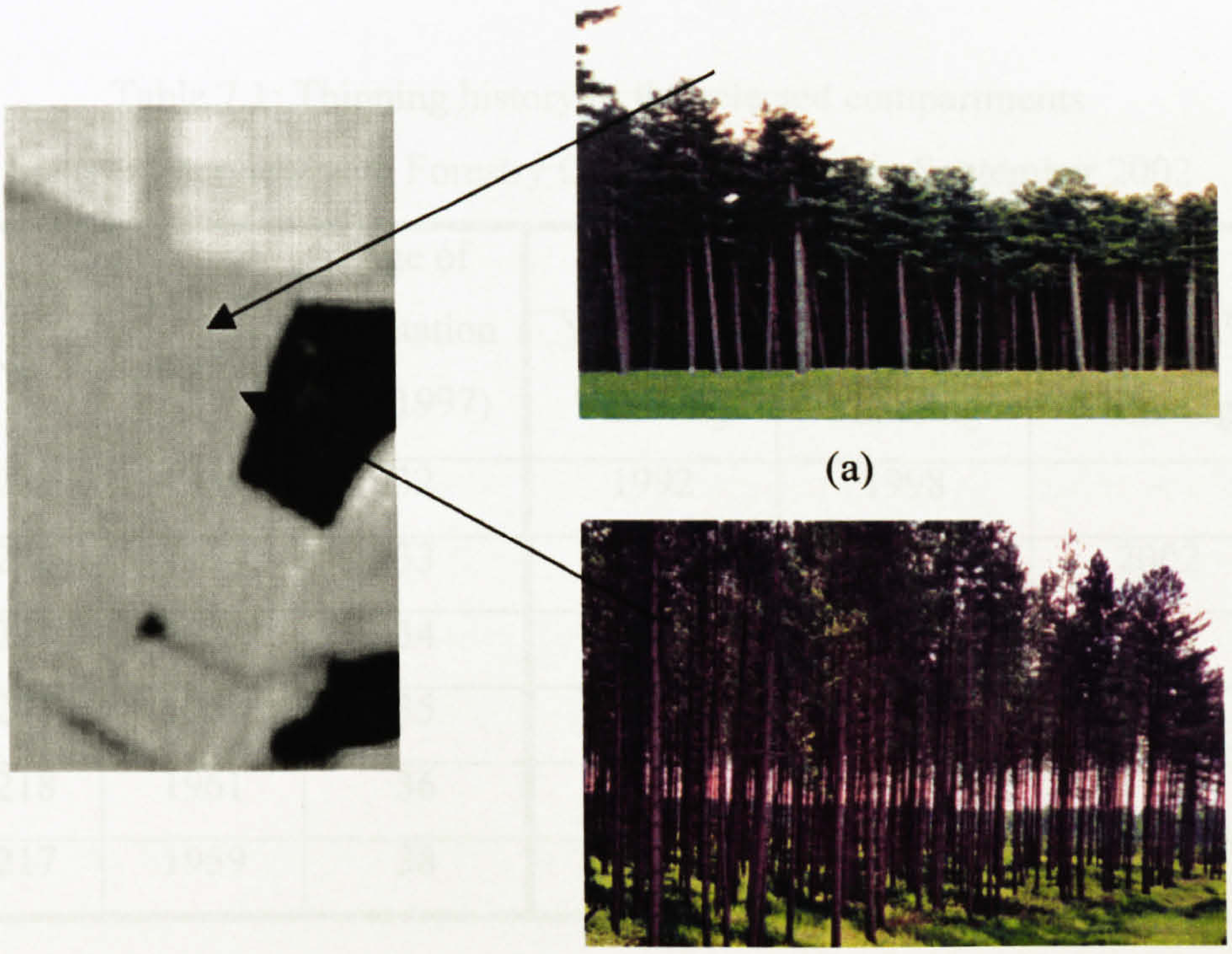


Figure 7.1 Map of selected compartments with the age of plantation (1997)

Figure 7.2 shows two photographs in different areas of compartment 4228, showing examples of pine plantations and their appearance in the NDVI image. This particular compartment was thinned only twice, but some other selected compartments were thinned three times.


(a)

(b)

Figure 7.2 32-year old pine plantation (Comp. 4228) in different areas

(a) Area with relatively high NDVI - Mean NDVI 0.735

(b) Area with relatively low NDVI - Mean NDVI 0.685

The thinning history is shown in Table 7.1. In these compartments, the original spacing between the planted rows was comparatively close. Therefore, two adjacent rows were removed in every six rows in the first thinning, in order to create an access lane for adequate extraction. In the second thinning, two rows were removed every four rows (The thinning pattern is discussed in chapter five). Some patchy areas can be seen with the removal of planted trees as well as gap replacement by regeneration processes on this test site. According to one of the forest managers in the East Anglian region (information collected from informal discussion in 2002), it was suggested that this area may have been affected by wind damage in 1987. Therefore during the first thinning these wind throw areas were also thinned selectively. Thinning was designed to remove about one third of the basal area. It often resulted in opening the stand canopy and reducing crown closure by approximately 30% in one thinning (Hart, 1991).

Table 7.1: Thinning history of the selected compartments

Source: Interview with Forestry Commission staff in September 2002

Comp. No	Year of planting	Age of plantation (in 1997)	Thinning history		
			Year of 1st Thinning	Year of 2nd Thinning	Year of 3rd Thinning
4228	1965	32	1992	1998	-
4226	1964	33	1990	1996	2002
4224	1963	34	1990	1995	2001
4221	1962	35	1990	1996	2002
4218	1961	36	1988	1994	1999
4217	1959	38	1988	1994	1999

7.3 NDVI VARIATIONS IN THE 18-38 AGE CLASS COMPARTMENTS

A visual analysis of the NDVI image was carried out to determine the spatial extent of changes in selected GIS polygons and to examine the NDVI patterns. The 1996 NDVI image was used for detailed analysis of spatial variations on the test site, with attention focused on six selected compartments. Examination of zoomed imagery with a standardised linear stretch permitted an initial inspection of NDVI changes and the differences that might be predictable in different types of stands. Mean NDVI values were calculated by averaging a few randomly selected sample pixels in order to examine the variation between the compartment polygons. Then to analyse the variation within the compartments, a simple classification procedure was carried out.

7.3.1 NDVI variations between the compartments

The test site was relatively homogeneous and NDVI is comparatively high. Most of the areas were from 0.689 to 0.749 in the 1997 NDVI image. Therefore, most of the areas appear in significantly bright tones (Figure 7.3). It is quite apparent that in certain areas, for example the western edge of the compartments 4226 and 4221, NDVI values are somewhat higher than in the other areas and appear much brighter on the image because these areas consist of deciduous trees. The pine plantation extending eastward appears in a less bright tone. These compartments were thinned in 1990, 1996 and in 2002 (Table 7.1). Removal of part of the canopy tends to change the structural pattern of the forest canopy and is likely to decrease NIR reflectance. In general, one reasonably consistent finding in several mortality studies (Collins and Woodcock, 1994; Franklin *et al.,* 1995) and in clear-cut mapping (Cohen *et al.,* 1996) is that visible reflectance tends to increase, while NIR reflectance tends to decrease with decreasing amounts of vegetation.

During the field visit to the site, it was observed that the western edges of compartments 4221 and 4226 consist of deciduous trees (mainly birch). The understorey was quite dense and consisted of at least two layers of grass and shrubs. The eastward pine plantation in these compartments was a patchy stand which appeared to be older cutovers that now contained significant regeneration; during the field visit it was determined that these pine plantation areas were vigorous and healthy, very dense and growing extremely well. In the 1997 image, the areas appear spectrally very similar, but when zoomed up it shows strips of disturbance, which are related to the removal of vegetation from the canopy, resulting in decreased red absorption and decreased green reflectance. NDVI values are relatively low in these areas.

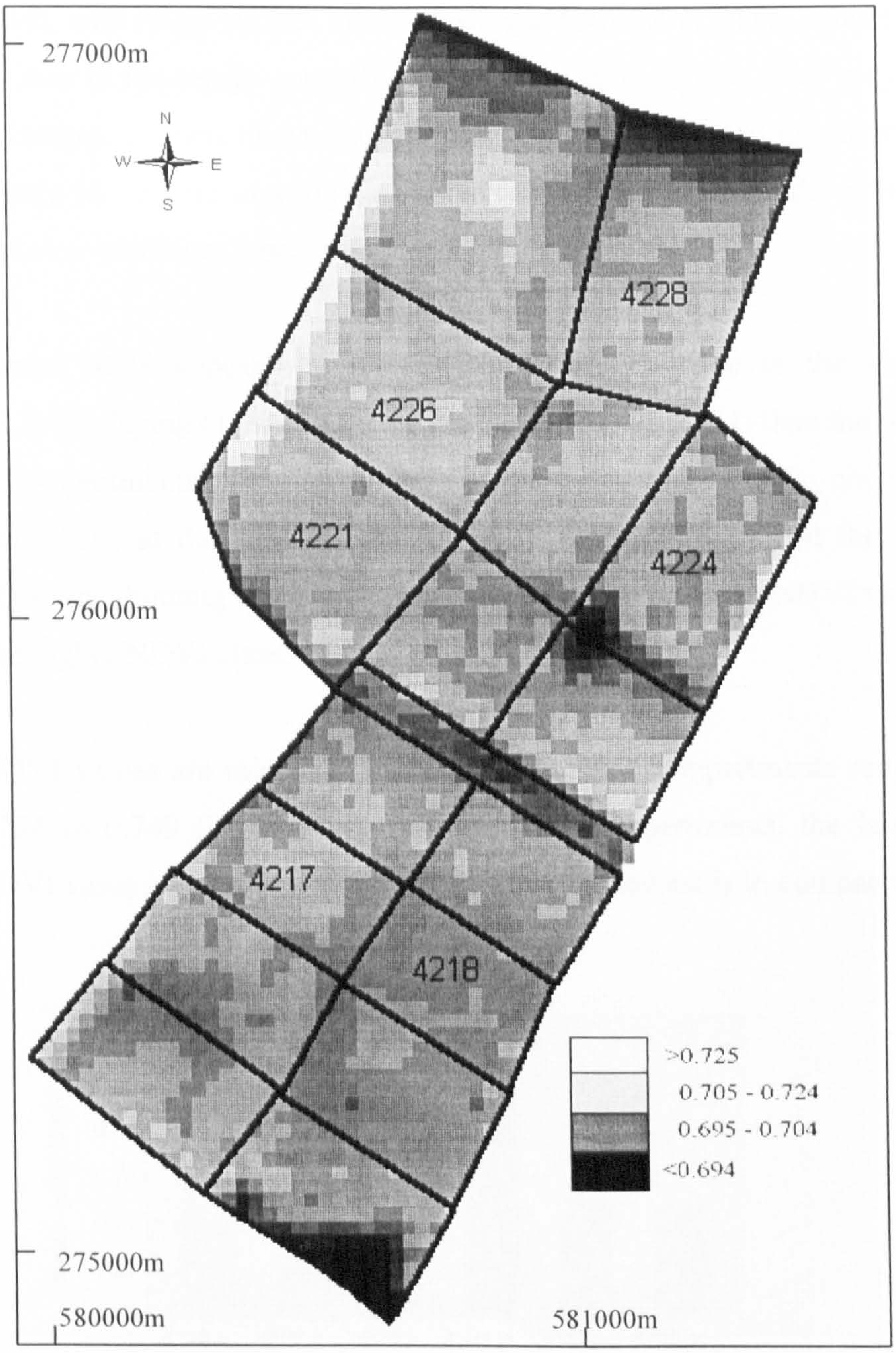


Figure 7.3 1996 NDVI image in the test site

Compartment 4218 (36 years old) and 4217 (38 years old) contain relatively old pine trees that will be ready for clear felling during 2007-2010 (Forestry Commission records). These compartments had been thinned twice, at the end of 1988 and 1994, at the time the satellite data were collected (Table 7.1). In 1999, they were thinned again. Green cover will typically decrease following disturbance. It is probably related to the emergence of a thin layer of undergrowth, with rough surface layer, creating a decrease in NDVI. There are a few patches in the image appearing in a darker tone. These areas may be selective cuttings or areas blown down by the wind and consist of regenerating plant growth. More field investigations are required to determine the reasons for forest cover variation, especially within these patchy areas.

Compartment 4228 appears in a significantly brighter tone in the image (Figure 7.3) displaying higher NDVI values (mean NDVI 0.744) than the other selected compartments. This compartment had been thinned only once (in 1992 Table 7.1), at the time the satellite data were collected and the area removed by line thinning can just be recognised as strip of lower NDVI values within the higher NDVI class.

Mean NDVI values are relatively high in the selected compartments ranging from 0.724 to 0.749 (Figure 7.4). Among these compartments, the highest mean NDVI value is in compartment 4228, while the lowest is in compartment 4218.

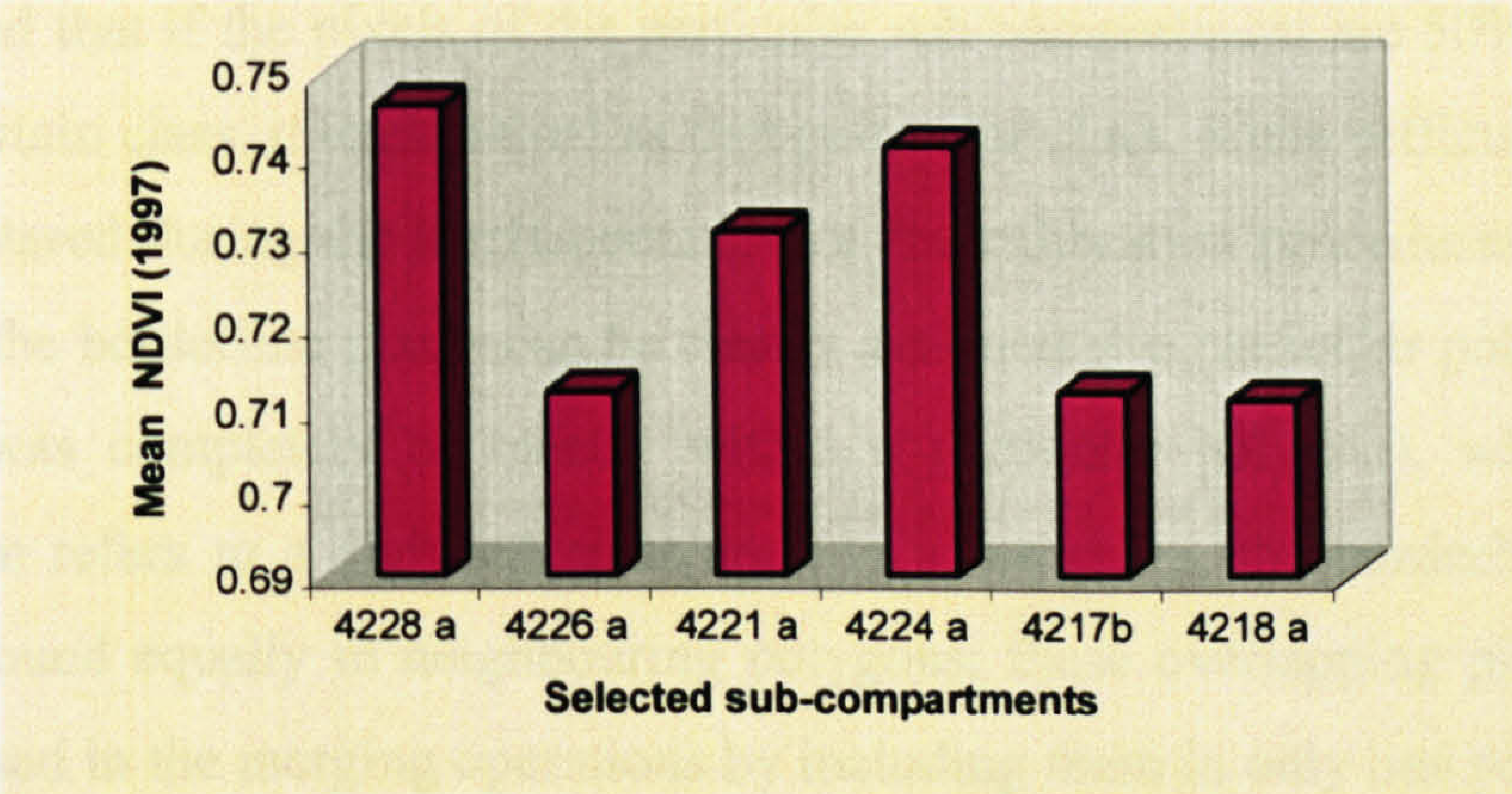


Figure 7.4 Mean NDVI in the selected compartments

The pattern of mean NDVI of this test site is also correlated with the thinning operations that have taken place. Compartment 4228, which was thinned only once, has a higher mean NDVI (> 0.749) than the others. However, compartments 4221 and 4226 that were recently thinned for a second time, showed relatively low mean NDVI values. The other two compartments (4217 and 4218) were also thinned twice, but less recently and also showed comparatively low mean NDVI values due to the decrease of canopy cover. It was possibly due to wind damage. Damage by diseases or insects is another possible cause of reduction of forest cover. These mortality changes were not considered in this research, but more detailed information is needed to correctly identify the small changes.

7.3.2 NDVI variations within the compartments

Pixel by pixel variations of NDVI within the compartment are shown in the distribution map based on digitised polygons (Figure 7.5). These polygons were separated into four NDVI classes as follows:

1) >0.725
2) 0.705 - 0.724
3) 0.695 - 0.704
4) <0 .694

The number of pixels in each individual class is shown in Table 7.2. In this pixel-based procedure, the traditional classification approach is applied: it is assumed that if the pixels of the particular sub-compartment are 50% or more of a certain class, it is classified as that particular class. Some difficulties were encountered during the implementation of the calibration procedures. In most cases, the borderline pixels can be clearly assigned to a particular polygon (the pixel was completely or mostly within a particular polygon), where each polygon refers to a digitised class area. In some cases, the borderline pixels were found equally in neighbouring polygons; these overlapping pixels were processed in the merging operations by including them in only one polygon. In another set of cases, the borderline pixels did not fall within any polygon; these missing pixels were replaced with values from the original compartment map. Finally, changes in each of the NDVI classes were calculated in every selected compartment.

Table 7.2 Pixel statistics by NDVI class in each selected compartment

		1996				1997				Changes in each NDVI class			
Comp. No	Total pixels	>0. 725 (1)	0.705 - 0.724 (2)	0.695 - 0.704 (3)	< 0.694 (4)	>0. 725 (1)	0.705- 0.724 (2)	0.695 - 0.704 (3)	< 0.694 (4)	>0 725 (1)	0.705 – 0.724 (2)	0.695 – 0.704 (3)	<0.694 (4)
4228	212	84	53	44	31	120	51	41	0	36	-2	-3	-31
4226	204	138	25	41	0	96	63	45	0	-42	38	4	0
4221	208	140	68	0	0	104	86	18	0	-36	18	18	0
4224	187	71	66	50	0	64	59	64	0	-7	-7	-14	0
4217	142	92	11	39	0	111	13	18	0	19	2	-21	0
4218	132	82	14	36	0	90	17	25	0	8	3	-11	0

On examination of the distribution map (Figure 7.5), it can be seen that the pattern of NDVI values (1996) varies in every selected compartment and it is possible to identify NDVI changes within the compartments. The overall statistics show that in the selected compartments, the proportion of the area covered by the highest NDVI class (> 0.725) is greater than all the other NDVI classes (Table 7.2). In compartment 4228, NDVI varies from < 0.694 to > 0 .725: which is the only compartment with values in the lowest range in 1996.

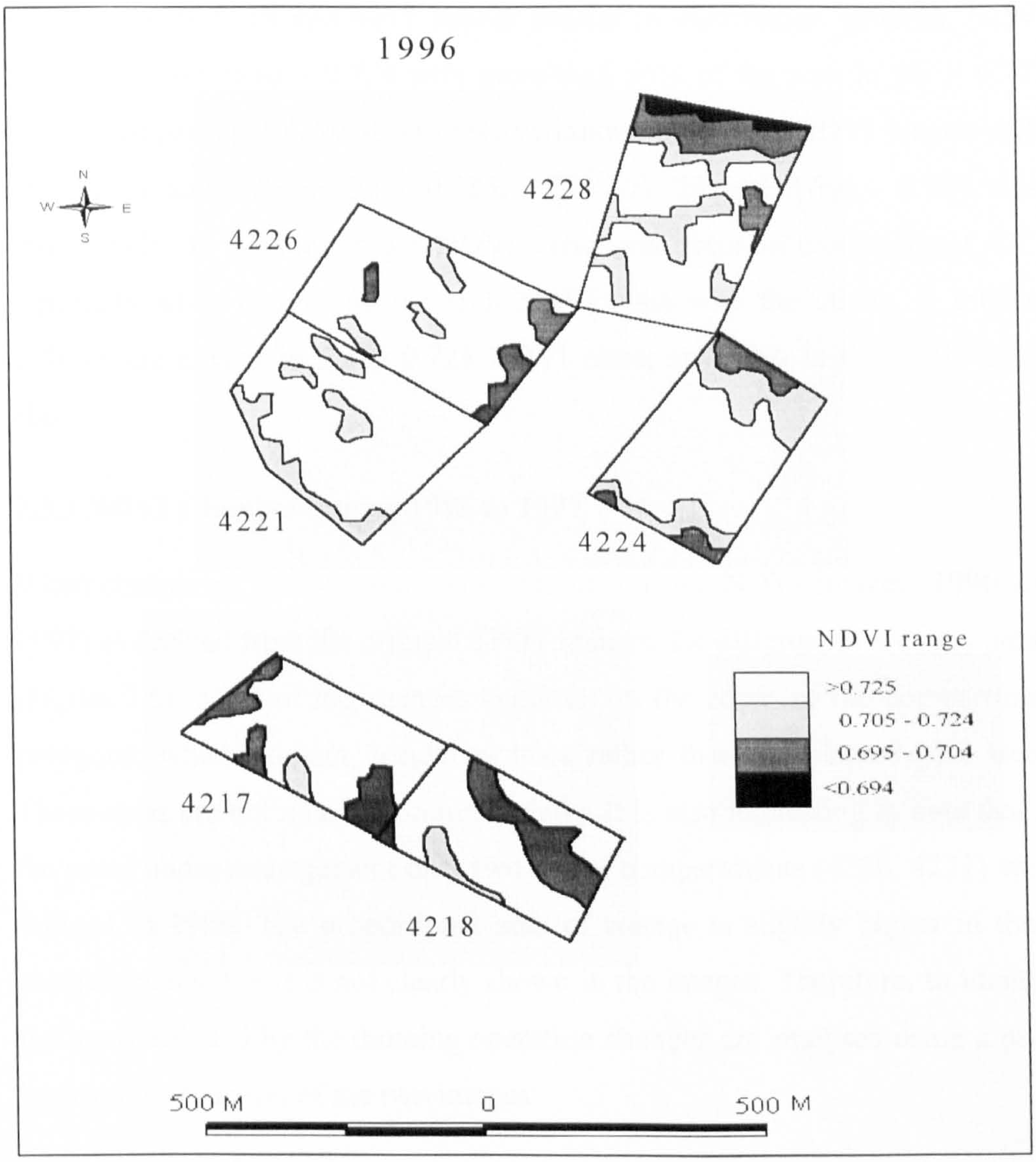


Figure 7.5 Distribution of NDVI in selec./ted compartments of the test site in 1996

These low values are spread over a very small part (15%) at the top of the compartment close to the neighbouring agricultural site. However, this region was in a state of regrowth in 1997 image and appears with relatively high brightness corresponding to next higher NDVI class. In addition, nearly half of the total area (40%) in this compartment is covered by high NDVI values (> 0.725). In compartment 4224, although the higher NDVI class is greater than the other classes, there is less variation between the other NDVI classes

Compartments 4218 and 4217 appear similar in distribution patterns. NDVI varies from 0.695 to > 0.724 with more than 55% of the area in the > 0.775 class. Compartment 4226 shows less variation among the NDVI classes with 68%, 12% and 20% in the > 0.725, 0.705 - 0.724 and 0.695 - 0.704 class respectively. In contrast larger NDVI variations occur in compartment 4221 especially when comparing the high NDVI class with the others. A total of 67% of the area is in the > 0.725 NDVI class, and 38% in the 0.705-0.724 class.

7.3.3 NDVI Changes during 1996 to 1997

When comparing the selected compartments on two NDVI images (1996 and 1997) as derived from the original SPOT images, the differences are very small (Figure 7.6). Most of the changes occurred on the edges of the compartment polygons, which contain deciduous trees rather than the planted pine trees. These areas are not managed commercially. It is also interesting to note that in the areas under management only two of the compartments (4226, 4221) were thinned in 1996. The proportional area of change is slightly higher in these compartments, but it is not clearly shown in the images. Therefore, to identify the areas affected by the thinning operation changes are analysed using a pixel by pixel comparison of the two images.

The results of the calculation of pixels in each compartment by NDVI classes in two different years (1996 and 1997) can be seen in the Table 7.2.

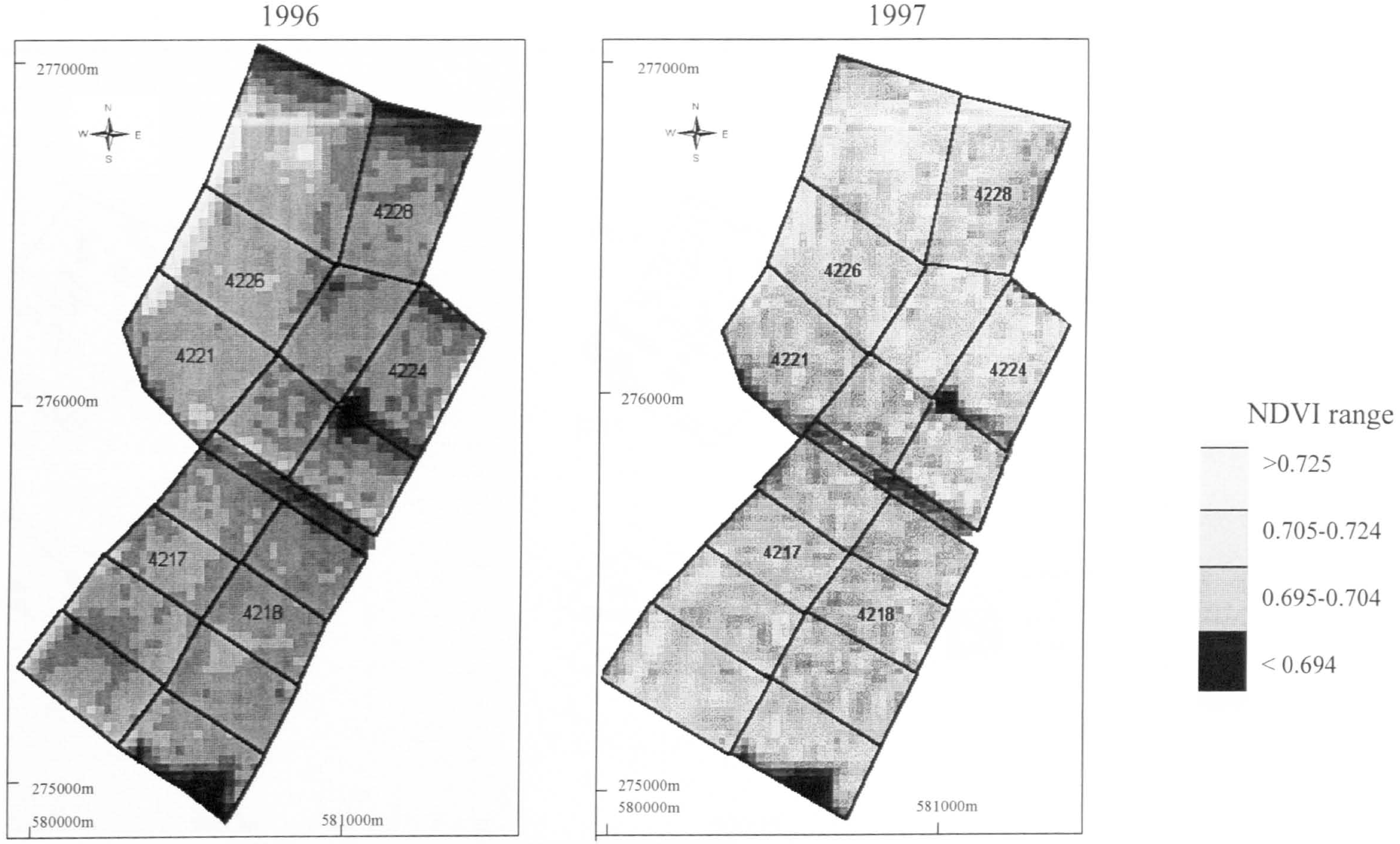


Figure 7.6 NDVI images with compartment polygons in 1996 and 1997

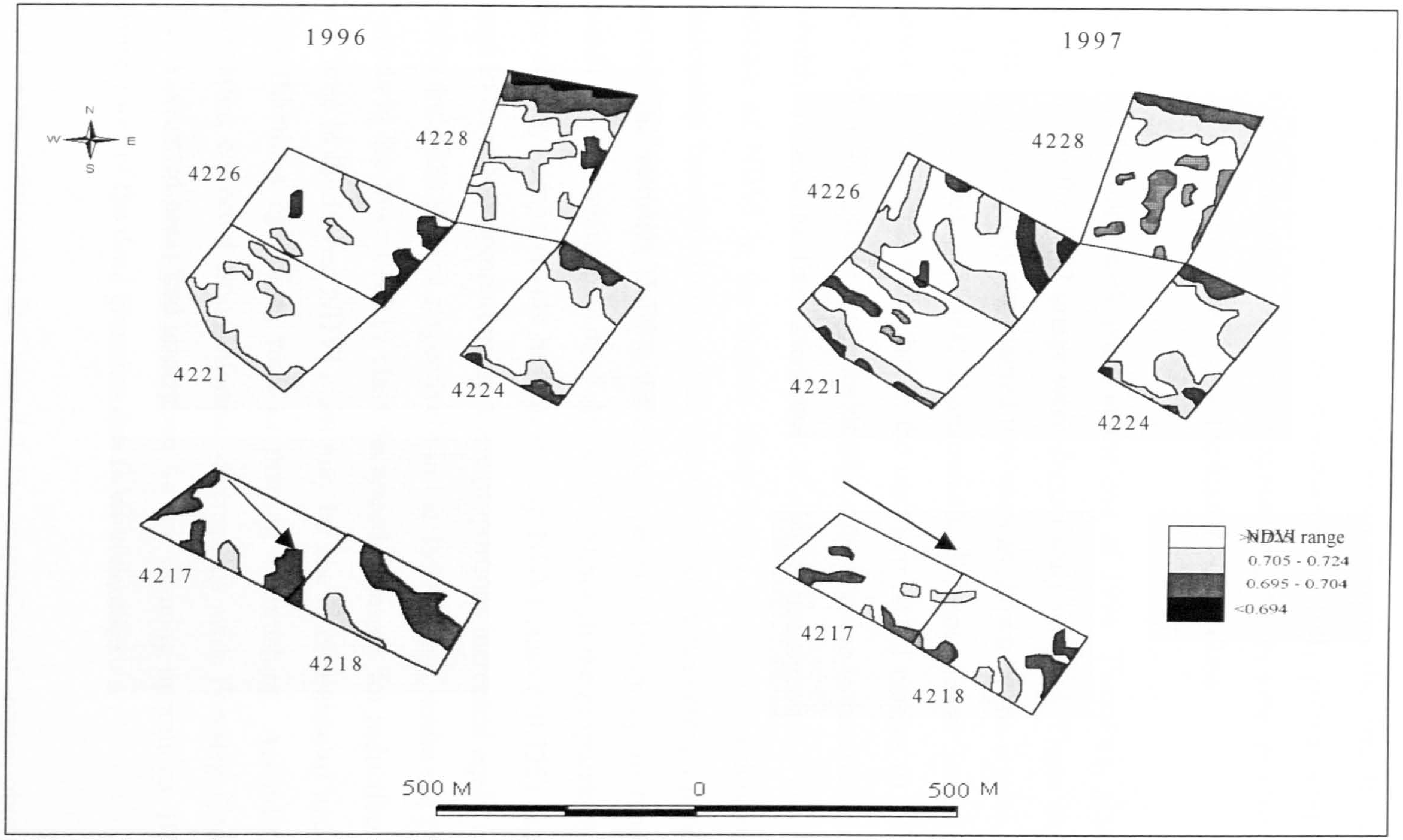


Figure 7.7 NDVI distribution maps derived from 1996 and 1997 NDVI images (The direction of tree rows shown by arrows)

In the 1996 image, more than 50% of the pixels are in the higher NDVI class (>0.725) in compartments 4226 and 4221. It is notable that those compartments had been thinned only once (1990) by the time the data were collected in 1996. Therefore, the plantations was fully grown compared with the other selected compartments and appear brighter in tone, resulting in 68% and 67% of the area respectively in the higher NDVI class.

The second thinning took place at the end of 1996. Therefore, pixels in the higher class in the 1997 image were dramatically reduced. These changes are especially shown along the planted tree rows as shown by the arrows in Figure 7.7. However, this particular characteristic did not appear in other NDVI classes. The statistics show that in the next two NDVI classes (0.695 – 0.704 and 0.705- 0.724), there was considerable increase due to natural growth. It is probably related to the emergence of dense undergrowth. The dramatic decrease of NDVI in the highest class during this short period suggests a relationship between forest cover changes and management operations. In contrast, the statistics show a different type of relationship to management operations in compartments 4217 and 4218. Although the proportions of pixels were already comparatively high in the top NDVI class (>0.725) in the 1996 image in these two compartments, these proportions increased again from 64% to 78% and 62% to 68% respectively in the 1997 image, while the proportion of pixels in the lowest NDVI class decreased. Reasons for reduction of forest cover area in the lowest NDVI class may be due to clearance of undergrowth or pre-thinnings operation, such as pruning or brushing. According to the information collected from informal discussions with Forestry Commission officers, selected areas had undergone for pre-thinning operations. Because to cleanup most of the dead branches due to wind damage.

Based on the information in Table 7.2, the proportion of change pixels in each NDVI class and the total proportions of change pixels in every selected compartment, are shown in Table 7.3. Compared with other selected compartments very few changes (mainly change decrease) had occurred in compartment 4228 except in the lowest NDVI class. The highest changes occurred in compartment 4217 and 4218 where the proportion of change increase is very high.

Table 7.3 Proportions of change pixels during 1996-1997 by NDVI classes

	>0.725	0.705 - 0.724	0.695 - 0.704	< 0.694	Total
4228	CI (17%)	CD (0.9%)	CD (1%)	CD (15%)	34%
4226	CD (20%)	CI (19%)	CI (2%)	-	41%
4221	CD (17%)	CI (9%)	CI (9%)	-	35%
4224	CD (4%)	CD (4%)	CI (7%)	-	15%
4217	CI (13%)	CI (1%)	CD (15%)	-	29%
4218	CI (6%)	CD (2%)	CD (8%)	-	16%

CI = Change Increase CD = Change Decrease

Both of these compartments were thinned for a second time in 1994. The high NDVI class is due to a fully grown Corsican pine plantation. In compartments 4226 and 4221, changes were relatively larger, especially in the higher NDVI class, and exceptionally low changes occurred in compartment 4224 compared to compartment 4226 and 4221. More information is needed to explain the relative lack of change in this particular compartment. The changes are shown in Figure 7.8 with increase and decrease pixels.

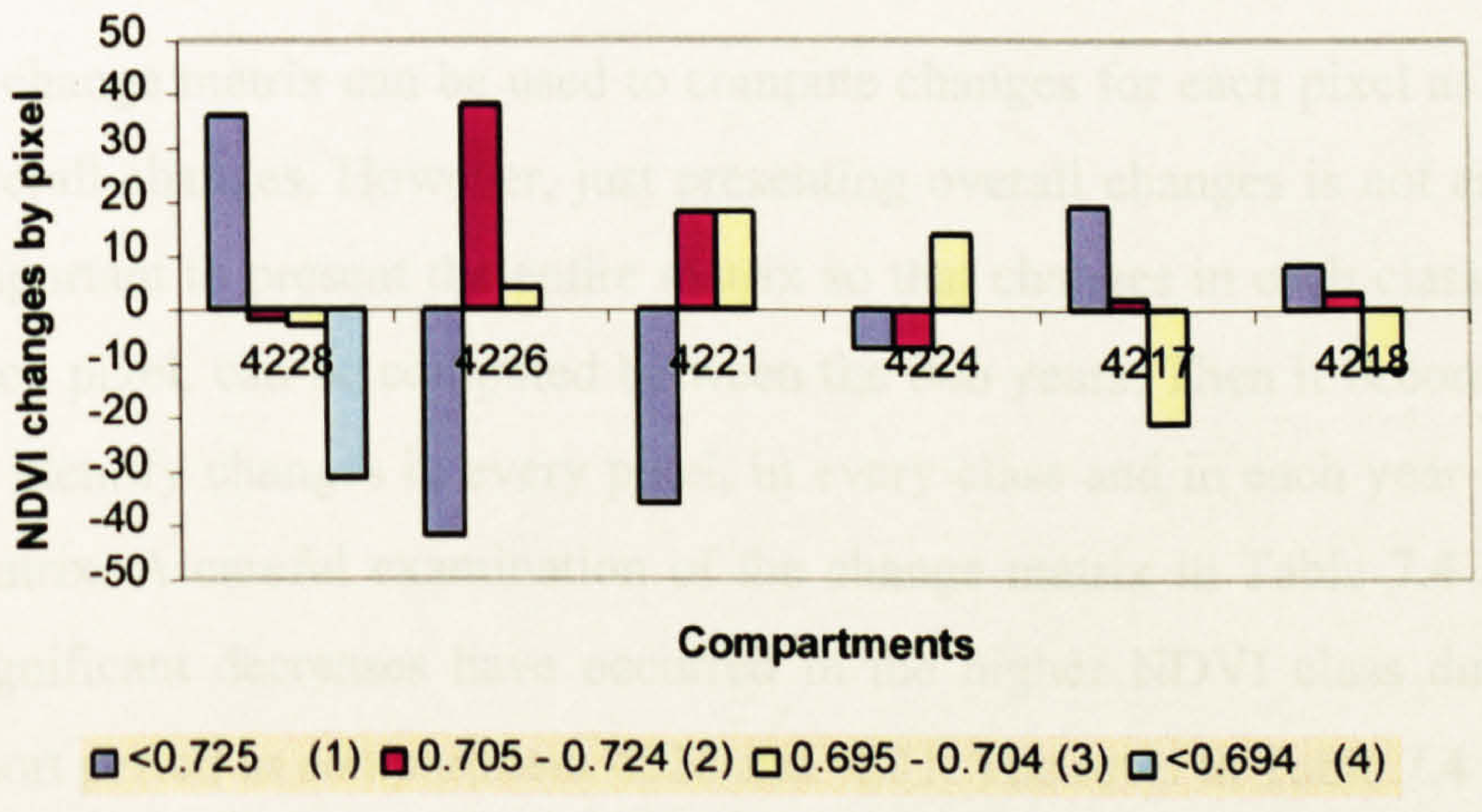


Figure 7.8 NDVI changes by pixels in each selected compartment

Finally, this chapter discusses changes that occurred during 1996 and 1997 using change matrices. Computation of matrixes was performed by comparing pixels on the image in 1996 with the same locations on the 1997 image and keeping track of the changes between particular NDVI classes. A change matrix is a square array of numbers set out in rows and columns that express the number of sample units (pixels) assigned to a particular category in one classification relative to the number of sample units assigned to a particular category in another classification (Table 7.4 and 7.5).

According to the Forestry Commission (Hamilton, 1980), thinning operations were mainly carried out in areas with closed canopies of pine trees. These are areas that can be identified in the higher NDVI class. Table 7.3 shows the compartments (4226 and 4221) that were thinned for a second time during 1996-1997 where the proportions of change decrease are mostly in the higher NDVI class. It can also be clearly seen in compartments 4217 and 4218, which were thinned two years before in 1994, that the proportion in the highest NDVI class has increased. On the other hand, compartment 4228 was thinned only once in 1992 and was fully grown with a dense understorey. As it was undisturbed during 1996-1997, a change increase was found in the highest NDVI class and the change decreases were very small. These results suggest that identification of canopy cover changes at pixel level would be very useful for management operations.

A change matrix can be used to compute changes for each pixel as well as the overall changes. However, just presenting overall changes is not enough. It is important to present the entire matrix so that changes in each class, as well as each pixel, can be computed between the two years. Then it becomes possible to identify changes in every pixel, in every class and in each year in the same matrix. A careful examination of the change matrix in Table 7.4 reveals that significant decreases have occurred in the higher NDVI class during a very short period in compartment 4226 and 4221. The rows in Table 7.4 show the

Table 7.4 Change matrices of compartments 4228, 4226 and 4221 classes (1= >0.725, 2 = 0.705-0.724, 3 = 0.695 - 0.704, 4 = < 0.694)

Compartment 4228

1996

1997

	1	2	3	4	Row Total
1	36	67	76	89	+268
2	-33	-2	7	20	-35 +27
3	-43	-12	-3	10	-58 +10
4	-84	-53	-44	-31	-212
olumn Total	-160 +36	-67 +67	-47 +83	-31 +119	-301 +301

Compartment 4226

1996

1997

	1	2	3	4	Row Total
1	-42	71	55	96	-42 +222
2	-75	38	22	63	-75 +123
3	-93	20	4	45	-93 +69
4	-138	-25	-41	0	-204
olumn Total	-348	-25 +129	-41 +81	+204	-414 +414

Compartment 4221

1996

1997

	1	2	3	4	Row Total
1	-36	36	104	104	-36 +244
2	-54	18	86	86	-54 +190
3	-122	-50	18	18	-122 +36
4	-140	-68	0	0	-208
Column Total	-352	-118 +54	+208	+208	-470 +470

Table 7.5 Change matrices of compartments 4224, 4217 and 4218 classes (1= >0.725, 2 = 0.705-0.724, 3 = 0.695- 0.704, 4 = < 0.694

Compartment 4224

1996

		1	2	3	4	Row Total
1997	1	-7	-2	14	64	-9 +78
	2	-12	-7	9	59	-19 +68
	3	-7	-2	14	64	-9 +78
	4	-71	-66	-50	0	-187
	Column Total	-97	-77	-50 +37	+187	-224 +224

Compartment 4217

1996

		1	2	3	4	Row Total
1997	1	19	100	72	111	302
	2	-79	2	-26	13	-105 +15
	3	-74	7	-21	18	-95 +25
	4	-92	-11	-39	0	-142
	Column Total	-245 +19	-11 +109	-86 +72	+142	-342 +342

Compartment 4218

1996

		1	2	3	4	Row Total
1997	1	8	76	54	90	+228
	2	-65	3	-19	17	-84 +20
	3	-57	11	-11	25	-68 +36
	4	-82	-14	-36	0	-132
	Column Total	-204 +8	-14 +90	-66 +54	+132	-284 +284

classes in 1997 with each box showing the number in that class and the four different classes in 1996. Thus, in compartment 4228, row 2 column 4, the value 20 represents the difference between the numbers in class 2 (0.705 - 0.724) in 1997 (51) and the number in class 4 (< 0.694) in 1996 (31).

In addition, a change matrix is a very effective way to represent changes of a map in that the individual changes of each category are plainly described along with both the changes of inclusion and changes of exclusion present in the classification. A change of inclusion is defined here as including an area, in this case a pixel, into a category in 1997 when it did not belong to that category in 1996. Change of exclusion is excluding that area from the 1997 category, which it belonged to in 1996. Every change is an omission from the 1996 category and a commission to the 1997 category. For example, in the change matrix of compartment 4226 in Table 7.4, there are 38 pixels that were defined in the 1997 data as class 2 (NDVI 0.705 - 0.724) when the 1996 data show that they were originally class 1 (NDVI < 0.725). Therefore, 38 pixels were omitted from class 1 and committed to class 2.

Studying the change matrix in the compartment 4228 reveals an overall change in 72 pixels (36+2+3+31) taking the absolute values of both positive and negative changes. At this stage mostly interested in changes in the higher NDVI class (>0.725) because most of the thinning operations were carried out in those areas. The matrix shows that 36 pixels have increased in this class. However it also shows that in the other three classes (< 0.694, 0.695 - 0.704 and 0.705 - 0.724) 2, 3 and 31 pixels respectively have decreased due to other natural reasons. At the time data were collected in 1996 and 1997, this particular compartment had been thinned only once, in 1992. Therefore, most of the areas were in a relatively undisturbed condition. But a more examination of the matrixes of the other two compartments in the same table shows different patterns. It is probably due to thinning operations carried out in late 1996. Compartments 4226 and 4221 reveal an overall change of 84 (42+38+4) and 72 (36+18+18) pixels respectively. In this case, changes in the higher

NDVI class (class 1) indicate that 42 pixels in compartment 4226 and 36 pixels in compartment 4221 have decreased. It can be suggested that it is mainly due to the reduction in forest cover, and should be related to the thinning operations that took place in end of 1996 place between the dates of the two images.

7.4 SUMMARY

This chapter discussed the ability of earth observation data to identify forest cover change over short periods of time as a result of management operations. The beginning of the chapter described the present situation of the selected compartments in the test site. Then variations within the compartment were examined over a selected period of time (1996-1997). To evaluate the potential use of satellite data for management purposes, this chapter was mainly concerned with forest canopy changes caused by thinning operations. The main conclusions of this chapter are:

1) Observations made by visual comparisons of enlarged imagery found strips of Vegetation Index decrease within the compartments. This finding is supported by experience from an earlier visual interpretation of temporal change images (explained in the Chapter Six). However, it is recognised that in these areas the expected pattern of increase in NDVI has been altered to a decrease of NDVI due to thinning operations.
2) The results of the calculation of pixel numbers within the compartment polygons also confirm that significant changes had taken place in the recently thinned areas. During the period of concern, a dramatic reduction of pixel numbers in the higher NDVI class was observed. Although it may be difficult to discriminate between thinning and changes caused by damage (Olsson, 1994), comparison with thinning records and consideration of the shapes and the orientations of change classes suggest that earth observation data may be a valuable data

source for reporting and monitoring forest management operations. Further investigation is required with experimental forest thinning sites for better understanding of this relationship, which could then be used for management purposes.

This discussion shows that earth observation data could be made useful for management of plantation forests. The use of multi-temporal data does improve the discrimination of forest cover changes under different type of management operation, such as thinning. Although multi-temporal SPOT imagery has not been able to detect changes within the tree rows, it was found relevant for the extraction of changes within the compartment for the needs of forest managers. A combination of the new generation of high-resolution satellite sensors like IKONOS with SPOT should allow fine mapping, which could improve the provision of management information.

CHAPTER EIGHT

SUMMARY AND CONCLUSIONS

8.1 INTRODUCTION

Forest management depends on reliable sources of information on forest conditions and changes. There is a need to have as much relevant information as possible on the conditions of the forest to prescribe treatments, to help formulate policy and to provide predictions about future forest conditions. Remote sensing has been a valuable source of information in inventory, mapping and monitoring forest condition over the past decades (Lillesand & Kiefer, 1994). As far as forest management research in Britain is concerned, it is useful to estimate changes of plantation forest cover. Through the investigation of forest cover condition and changes using optical remotely sensed data and other ancillary data (Forestry Commission stock maps and database), this study is able to contribute useful information to plantation forest management. The main task of this study was to detect plantation forest cover change information, mainly for thinned and clear-cut areas. This area of research is popular in Canada, the USA and Scandinavian countries such as Sweden and Finland (Drieman, 1994; Olsson, 1994; Banner and Ahern, 1995; Yatabe and Leckie, 1995; Murtha and Pollock, 1996; Fransson *et al.*, 1999), but there are fewer papers on UK plantation forest and remote sensing (Danson and Curran, 1993).

Many forests are slow growing and have a relatively long life, so changes of such forests may be apparent only after many years. But plantation forests change frequently following management activities; therefore changes in plantation forest can be detected in a relatively short period of time. The detection and monitoring of large areas of plantation are two of the most important tasks that remote sensing can accomplish in support of forest management (Franklin, 2001). Forest managers traditionally use the idea of the forest stand as the unit for collecting information about resource management. The stand is an area of forest defined as having a homogeneous condition with respect to specific management objectives. Information for each stand is collected from detailed field reports. The cost of such surveys is high and continues to rise. The use of remotely sensed data could reduce the cost of collecting stand data significantly.

This chapter summarises the results presented in previous chapters and provides conclusions. Finally, recommendations for further research are outlined.

8.2 SUMMARY AND CONCLUSIONS

This study is mainly concerned with thinning and felling, two of the main operational activities of forest management. To detect areas that have been thinned or felled, the study considered three fundamental aspects. First, the condition of forest stands was identified using Forestry Commission (FC) records and field surveys. This information was then linked to digital remote sensing data. Second, changes over time in the remote sensing data were examined, particularly the effect of felling and thinning. Third, FC thinning records were related and compared to the digital remote sensing data to validate the interpretations.

This study collected information on the present and past status of the Kings Forest (study area) from compartment records and sub-compartment base maps provided by the Forestry Commission district office in East Anglia. Results were obtained from the Kings Forest, which is relatively flat terrain typical of plantation forest on sandstone soils in lowland Britain. The question arises how transportable these results are to other environments. The NDVI techniques used do compensate to a large extent for variations in surface slope and aspect (Chi-Chung Lau, 1997). Therefore, it is expected that the results can be applied quite widely and are not limited to the study area.

Details of crop information such as species, area of each species and planting years, different stages of ground preparation for planting and management treatments were collected from these records. In addition, more information on management operations was collected from informal discussions with forest officers and forest managers during the field visits. The selected study site (north-west quadrant of the Kings Forest) covers 360 ha. This plantation contains thirty-four compartments (73 sub-compartments). Structurally, this site is extremely simple. It is composed almost exclusively of Corsican pine (*Pinus nigra var. maritima*) and Scots pine (*Pinus sylvestris*). This sample structure allowed the analysis to examine the extent to which remote sensing can detect management operations.

Four sets of multispectral SPOT images in 1994, 1995, 1996 and 1997 were used to collect remote sensing data and calculate the Normalised Difference Vegetation Index (NDVI) for the main analysis. A number of key findings, which are relevant to remote sensing of forest canopy cover from SPOT HRV data in forest plantation conditions, emerged from this investigation.

8.2.1 Spatial changes of forest cover

This study used a Normalised Difference Vegetation Index (NDVI) based on radiometric measurements integrated with field data to detect forest canopy cover changes. Age is an important variable in forest tree growth, and it is relatively easy to identify even-aged compartments in a plantation forest. Therefore, this study investigated changes of NDVI in different age groups to identify spatial changes of forest cover. Different aspects of spatial change of forest cover were investigated as follows:

1) Relationships between near-infrared and red reflectance.
2) Spatial variations of forest cover.
3) Changes in NDVI with age of trees.
4) Correlation of NDVI and selected forest structural stand parameters.

8.2.1.1 Relationship between near infrared and red reflectance

The relationship between mean NIR reflectance and red reflectance was examined because NDVI is determined by the difference between these two bands. Correlation analysis showed that the relationship between mean NIR reflectance and the red reflectance varied with different age groups. In the lowest age group, there was a very strong negative correlation, (r =-0.98) with an increase of NIR reflectance, while red reflectance decreased. On the other hand, there was low positive correlation(r=+ 0.26) in the old age group. It was found that a high proportion of background influences dominated these two age groups.

The relationship between NIR and red reflectance in very young (8-17), and young (18-37) age groups was not very strong (r values of 0.30 and 0.16 respectively), but positively correlated. Statistical significance tests showed that there was no significant correlation between NIR and red reflectance in these age groups. However, there was a significant, moderately strong, positive correlation of 0.63 in the mature age group (38-57), due to the increase of NIR signals from the undergrowth grass cover and with a slight increase of red reflectance. These findings are not related directly to the forest management, but analysis of the relationship between red and NIR reflectance in different age groups supported the spatial variation analysis and can be considered as an initial step for the main findings.

8.2.1.2 Spatial variations of forest cover

The main aim of this part of the analysis was to identify relationships between different types of forest cover and the areas of principal management operations. The study found that NDVI changed spatially with differences in surface vegetation cover. NDVI values ranged from lows of 0.263-0.366 in clear cut areas with bare land to highs of 0.778-0.835 in broadleaf areas. In the pine plantation, with which this study was mainly concerned, moderate NDVI values (0.562-0.747) were found. Slight changes in NDVI can be identified due to the differences in age of the pine trees. For example, moderately low NDVI values of 0.594 were found in very young pine compartments and moderately high NDVI values of 0.710 in mature pine compartments. The results indicated that NDVI was significantly affected by the background influences of the forest, including the soil, the undergrowth and management operations. Results from previous research concluded that the shadowing effect within the canopy was a dominant influence on spectral response (Danson 1987; Franklin and McDermid, 1993). It was also found that TM spectral response was dominated by soil reflectance after a fire in Lodgepole pine stands in Yellowstone National Park in the USA (Jakubauskas, 1990). These studies showed that further investigations are needed to identify clearly the changes of NDVI with these variations and their influences.

This study therefore examined NDVI changes within selected compartments in the survey site. Relatively low NDVI values of 0.446 were found in sparsely distributed, green, patchy areas and values as high as 0.743 in the areas with closed-canopy pine plantation. Within this range, NDVI varied with different types of canopy, such as undergrowth with birch, bramble, bracken and grass-dominated open canopy stands, open canopy stand with regenerated pine seedlings, or open canopy stand with very young planted trees. In addition ,spatial patterns were identified in areas where the principal management practices were carried out, mainly thinning and clear felling. In the pre-thinned areas, high NDVI values (0.743) were found with little variations, while relatively low NDVI (0.511) with more variations were found in thinned areas.

The influences of clear felling could also be identified compared with pre-felling sites. Pine plantations at the mature stage showed relatively high NDVI values of 0.683 and 0.741 due to canopy roughness and shadowing. After clear felling, it decreased to a range of 0.235- 0.319, because of reduction of green cover. Clear felling would be easily identified visually and the areas affected measured quantitatively in the images. So it can be stated that these findings are helpful to forest managers and planning officers,

8.2.1.3 Changes of NDVI with age of trees

It would be difficult to argue that the age of individual forest trees can be remotely sensed directly, but remote sensing data can be used to help identify different age classes. Because of the differences in tree size and density, understory, canopy development, nutrient status and species among young and old forest stands. Needle reflectance changes with both age and canopy position, the largest spectral differences occurring between needles of different ages sampled from the same level in the canopy (Danson, 1995). In this thesis, changes of NDVI between different age groups were demonstrated. NDVI increased from 0.451 to 0.741 in the < 18 year old pine stands with the growth of the planted trees. Although in the initial stage the influences of under-growth vegetation dominated, at the later stages of this age group the pine canopy was the main factor in the increase of NDVI. Towards 18 years, the tree density was high and there were very few gaps within the canopy. The Leave Area Index (LAI) and biomass of this young stage reached a high level. In this forest stand, there was little radiation penetrating the canopy and, as a result, the level of reflected radiation of the canopy as a whole was relatively high. The results of the correlation analysis indicate a high positive correlation coefficient of 0.94 between NDVI and age.

In the stands aged 18-37 years, NDVI showed an irregular pattern with the increasing age of the stands, with more variations than in the very young stands. At this stage, tree density was relatively low because of the removal of trees by thinning and there were many gaps within the canopy. However, LAI, biomass and canopy cover were maintained at a high level. In these stands, the initial penetration and subsequent absorption of red radiation would have been great, giving rise to a large amount of canopy shadow and lower levels of reflected radiation. Similarly, the penetration of near infrared radiation would also have been high with multiple scattering and absorption taking place deep within the canopy. A smaller percentage of the incident near infrared radiation therefore emerged from the top of the canopy producing lower recorded radiance. Significantly, not a very strong correlation was found between NDVI and age in this age group, and it showed the lowest correlation coefficient of 0.62. It was found that the initial continuous canopy was disrupted and canopy gaps were exposed to the sensors due to thinning and natural damage, especially windthrow.

The next age group (38-57 years) again showed an increase of NDVI because of continuous tree cover with few grass covered gaps due to the termination of thinning operations. Therefore, a comparatively strong relationship ($r = 0.66$) was shown between NDVI and age. However, NDVI decreases at the age of 42 were probably due to partial felling. Very few trees were left in the stand in the old age group (>58 years), so that many open gaps were exposed to the sensor. As a result NDVI values decreased (0.686). However, after 60 years there was a considerable increase of NDVI due to the higher proportion of regrowth in the partially felled areas. Therefore, the relationship between NDVI and age is relatively strong in this age group. This piece of work indicates how forest management operations are related to the different age groups of planted trees. These findings could be useful for the selection of areas or sub-compartment to be removed or replanted.

8.2.1.4 Correlation of NDVI with selected forest structural stand parameters

In large extensively managed areas, such as timber plantations with a simple canopy structure and few species, empirical relations between space and ground data may serve to provide general, but useful information as an input to forest management (De Wulf *et al.*, 1990). These authors suggested that stand density, mean diameter, basal area, mean canopy height and stand volume could be estimated with reasonable accuracy using satellite data. These measurements are necessary for forest management and planning purposes. This study discussed the distribution of selected stand structural variables of top tree height, mean diameter and basal area. Three quarters of the compartments fell into the middle class categories. For example, top tree height ranged from 18.0-22.7m, mean diameter ranged from 12.6-32.1cm and basal area ranged from 27.9-32.1m^2.

The results of correlation analysis showed there was a high positive correlation between NDVI and top tree height as well as with mean diameter with r values of 0.73 and 0.76 respectively, both significant at the 95% confidence level. The correlation between NDVI and basal area had a lower correlation coefficient of 0.70, although still significant at the 95% confidence level. The three stand parameters (top tree height, mean diameter and basal area) were inter-correlated and all had a strong positive correlation with NDVI because these parameters have a strong relationship with forest leaf area. Therefore, investigation of stand parameters could be done by remote sensing to provide up date forest management tables.

8.2.2 Temporal pattern of forest cover changes

The major objective of this section was to examine temporal trends and identify different types of forest management operations. The most important finding for the temporal pattern of forest cover changes during the four year (1994-1997) period was that changes mainly occurred due to management operations. The study found that forest cover had changed drastically because of clear cutting. Partial cutting by thinning operations is more difficult to detect on satellite imagery than clearcuts. However, thinned areas on satellite imagery appear distinctly different from the homogeneous appearance of undisturbed forest or clear harvested areas. Partially harvested areas appear textured with distinct boundaries, and the textured appearance is probably due to the heterogeneous canopy with tall trees and canopy gaps causing mixed pixels with varying NDVI values. With the help of detailed ground information, it would be possible to decide whether those areas were thinned or damaged by natural disturbances, such as windthrow.

In this study, the following two methods were applied to analyse the temporal pattern of forest cover changes related to forest management operations.

1) Temporal variations in vegetation vigour were analysed using Normalised Difference Vegetation Index (NDVI).
2) Digital change detection was performed using Vegetation Index Differencing (VID) method

8.2.2.1 Temporal variations in vegetation vigour

Temporal variations of forest cover during 1994-1997 were obtained from NDVI images. Age is an important variable in forest growth. Therefore, this study investigated changes of NDVI in different age groups <7, 8-17, 18-37, 38-57 and >58 years. The study found that during the period 1994-1997, NDVI changed little, with values in the range 0.4-0.7. However in each age group slight changes can be easily recognised. There was a significantly positive moderate correlation between NDVI and age in all four years with r values of 0.40, 0.32, 0.36 and 0.66 for 1994 to 1997 respectively. The results show that changes in NDVI provide important information on vegetation growth in a plantation forest. The results from comparing NDVI and age were also encouraging, but further work is needed to determine the potential use of earth observation data in forest growth and management.

The results indicate that temporal variations were very small within the period of concern because it is very short. An analysis was made of a particular sub-compartment, 4037d, where clear felling operations were carried out at the end of 1995. The 1996 image clearly indicated the sudden reduction of NDVI values due to reflection by bare soil and tree debris. On the other hand, following replanting, which was carried out at the end of January 1997, the entire sub-compartment presented a different picture in the 1997 image, with a relatively high NDVI value. A background cover of ground vegetation was dominant by this stage. These results indicate that NDVI is significantly affected by background factors including the soil, the undergrowth and the effect of management operations.

Identification of clear felled areas using multi-temporal analysis of LANDSAT TM was also done by Nilson and Olsson (1995), who stated that the reflectance changes caused by light or moderate thinning are small compared to the changes caused by intense thinning or clear felling. The analysis in this thesis also confirmed very small variations within the compartments that can hardly be identified in the NDVI image. The separation of thinned areas and planted tree areas was very difficult. Therefore, the study also applied a pixel-based classification for identifying thinned areas within the test site.

8.2.2.2 Digital change detection

Change detection analysis was performed using the Vegetation Index Differencing method and the results confirmed its strong ability to monitor forest canopy changes. Change detection was carried out on three periods (1994-1995, 1995-1996 and 1996-1997). Changes were evaluated in terms of change and no-change classes as follows.

1) Change and no change was calculated in three age groups.(<17, 18-37,>38 years).
2) Change patterns were classified as large increase, small increase, no change, small decrease and large decrease.
3) Overall changes were evaluated in each period by age group.

A number of points that are important in remote sensing of forest cover for plantation forest management emerged from this analysis. Changes were larger in the second period (1995-1996) and third period (1996-1997) than in the first period (1994-1995). Identification of change type in terms of increase or decrease of NDVI was then performed. The change pattern showed that during 1995-1996, change increases were more numerous than change decreases. The overall statistical evaluation emphasised that change decreases occurred in the 18-38 young age group, which is normally the age group in which thinning operations are carried out. Therefore, this finding suggested that there is a significant relationship between forest cover reduction and forest management activities.

The changing patterns of forest cover by compartment showed that there is a strong relationship between change decreases and clear felling. According to the Forestry Commission records, 43.9 ha. were felled in sub-compartment 4037d in 1995. It is interesting that this area is clearly identified in the GIS distribution map (Chapter six p.189) as a large decrease class (-0.5). Although recently clear felled areas could easily be identified within forested areas using satellite image change detection techniques (Fransson and Olsson, 1999), it was difficult to detect very fine variations in thinning operations. It was found that a relatively large area of the 18-37 age group was classified as a change increase in this generalised change detection map. Therefore, this study also generated pixel based change information to detect decreases in forest area connected to thinning activity. These findings are important is that decision makers have access to updated information on current forest operational activity, timing of harvest and its effect on the stands in order to design and implement science-based policy. Time series satellite images will likely become an important data source to address these information needs. Also it could be helpful for operational forest inventory and monitoring programmes to become more cost effective.

8.2.3 Testing the ability to detect forest cover changes for forest management operation

The purpose of this section is to test the ability to detect very fine variations of forest cover (mainly decreases) on the basis of the previous analysis and compare these changes with recorded thinning information. To determine the effect of thinning on forest cover changes in the test site (compartments of the 18-37 age group) the study used pixel-based classification. For this analysis, two images were compared for changes before and after thinning operations. Changes were visually identified and different strips of change decrease were determined (by tone changes - dark coloured areas within the light coloured areas) within some compartments. After the examination of the shapes of these changes, the study suggested that reduction of NDVI was due to thinning operations.

The pixel-based classification also examined the proportions of pixel change between 1996 and 1997 in each compartment. It was found that the proportions of change decrease were greater in the higher NDVI class in recently thinned (end of 1996) compartments (4226 and 4221). Compartments that were thinned two years before (4217 and 4218) can also be identified by a comparatively high percentage of change decrease in the middle NDVI class. Therefore, the study confirmed that there is a significant relationship between forest cover decrease and thinning operations.

Finally change matrices presented changes in each class as well as each pixel in two different years at the same time as the overall change. So the study managed to identify real changes in every pixel, in every class and in each year of the same matrix. These data are very useful in determining to what extent earth observation data can be considered as valuable for forest management applications. The pixel-based change information has the potential to contribute effectively to forest management when pre-change information is already available, because it allows remote sensing data to cross reference with management operations.

This classification-based analysis has evaluated the potential use of satellite data for management purposes, mainly thinning operations. Although multi-temporal SPOT imagery has not been able to detect changes within the tree rows, it was found relevant for the extraction of changes within the compartment for the needs of forest managers.

8.3 ROLE OF REMOTE SENSING AND GIS IN FOREST MANAGEMENT

The aim of this section is to discuss how remote sensing and GIS can be useful as a tool for forest management. Forest management needs to be based on an inventory and mapping of the whole forest environment. In addition to both natural changes (regrowth of plantation, development of undergrowth, forest damage by wind or disease) and man-made changes (thinning, felling, clearing, reforestation and deforestation) need to be monitored for proper management. Remote sensing and GIS provide for the continuous monitoring of forest developments by detecting changes and for the integration of the results into an existing database.

Traditionally, forest managers obtain information about forests for their management purposes by sending a team into the field to select samples. The data are then analysed and extrapolated throughout the entire forest. Satellite remote sensing has been widely used for gathering land surface information since 1970, and during this period, forestry applications of remote sensing have increased. Remote sensing can help to provide a timely and cost effective source of forest cover information as well as monitoring forest cover changes in large areas. Satellite remote sensing provides repetitive coverage of the land surface at short intervals with consistent image quality. The repetitive coverage capability is vital for monitoring and quantifying changes in land surface features at both global and regional scales. The temporal resolution of SPOT (26 days) imagery, which this study used, is nominally high enough for most of the forestry information requirements. With its off-nadir capability, SPOT can, nominally again, acquire data at 3-4 days intervals. An image once a year would be enough for many forest management purposes. Higher resolution data have recently become available from IKONOS and Quick Bird. These imagery will be very useful for special purposes such as monitoring regeneration, various types of forest damage and thinning. SPOT can detect large-scale changes such as clear felling areas, but it is difficult to differentiate thinning rows. The spectral bands of SPOT data are rather conventional, comparable to LANDSAT MSS. Although forest classification and discrimination of timber stand characteristics are difficult using SPOT, these bands are sufficient for applications where vegetation index approaches to forest cover inventory and monitoring changes can be applied.

Considerable attention has been focused world wide, especially in Canada, USA and Scandinavian countries, on the use of satellite imagery and GIS techniques for forest management strategies and operations (Ardo, 1992, Nel *et al.,* 1994, Olsson, 1994, Cohen *et al.*, 1995, Gemmell *et al.*, 1995, Kimes *et al.*, 1996, Nilson *et al.,* 2001). However, little specific work has undertaken using satellite data in combination with GIS techniques in British coniferous plantation and these have mainly concerned forest classification and mapping (Wallington *et al.*, 2003). Some have attempted to develop computer models to predict the interaction of remote sensing data with forest biophysical variables, such as leaf area index (Danson & Curran, 1993, Danson and Plummer, 1995). If satellite remote sensing is to be used in forest management, it reasonable to assume that the information obtained should contribute to the planning processes in some way. The applicability for forest management planning may, however, be of less value. An example can be found in the frequent studies of Leaf Area Index, which has been well estimated using satellite remote sensing. (Spanner, 1990; Curran, 1994). However, as the dependent variable LAI is not

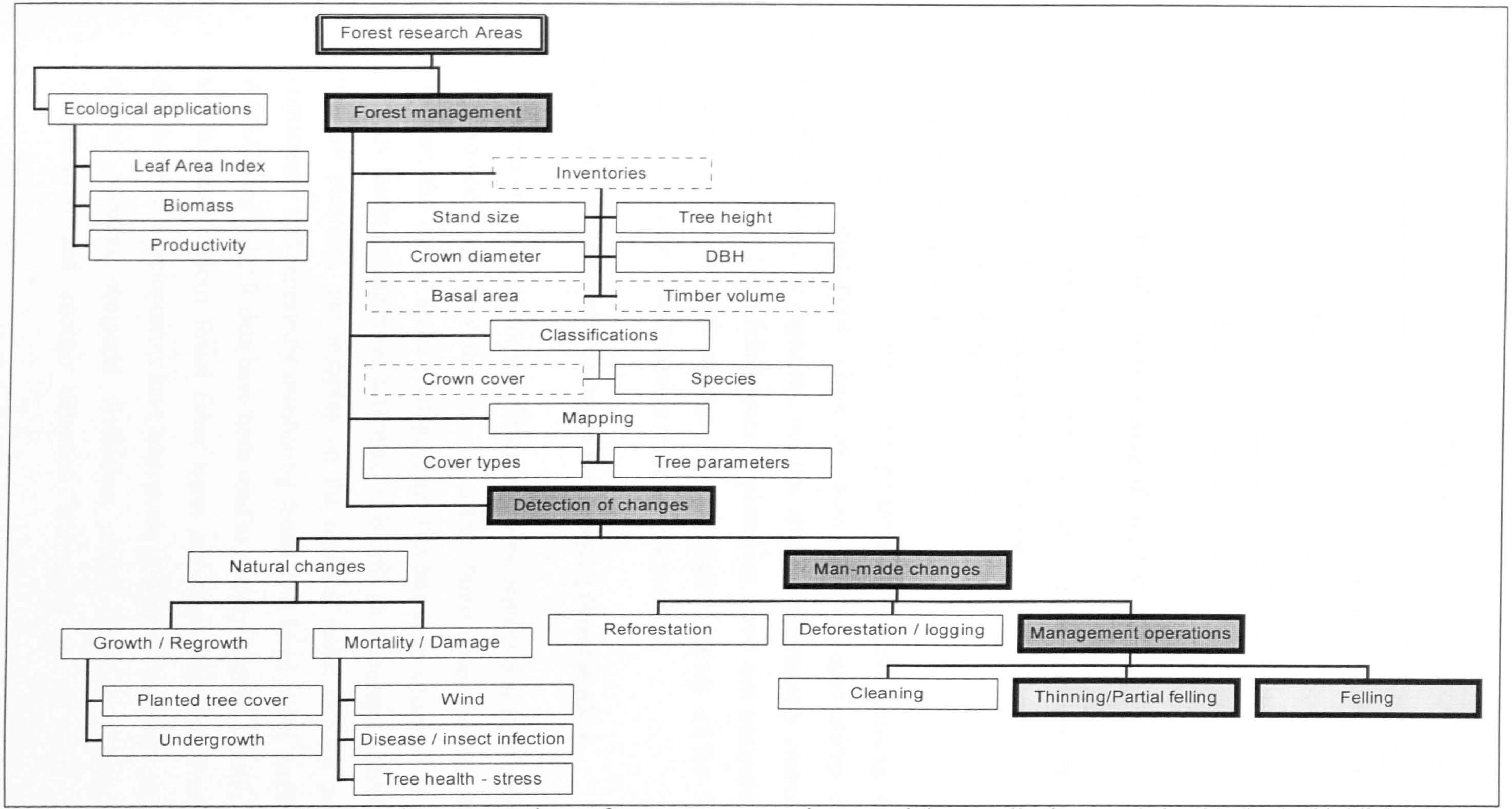


Figure 8.1 Potential application of remote sensing to forest management issues and the contributions made by this thesis (highlighted)

very useful for management decisions and only weakly correlated with more significant variables, such as wood volume and quality, it will not be of major assistance to forest management decision-makers. However, LAI can be interesting for other uses, such as ecological research. Spatial and temporal changes of forest cover using a vegetation index provide useful information for management operations.

8.3.1 Application of remote sensing of forestry

There are two different types of forestry application to which remote sensing and GIS can be applied (Figure 8.1). They are:

1) Ecological applications
2) Forest management

The present study examined the potential of remote sensing for forest management operations. There are many potential applications of remote sensing to forest management, but this study used remotely sensed data for detecting thinned and felled areas in plantation forest and analysed different patterns of forest cover change. The highlighted boxes of the figure 8.1 indicate the areas of contribution made by this thesis.

8.3.2 New sensors and techniques for applying forest studies

This section discusses the development of new sensors and their improvement in resolution and how these might affect forest management. For many decades, the use of aerial photographic data has been accepted as a tool in various forest management activities. It is still an important remote sensing tool for planning, and mapping on the regional scale. For the purpose of consistently and repeatedly monitoring forest over large areas, multi-spectral, RADAR and LIDAR data have been used to detect, identify, classify, evaluate and measure various forest cover types and their changes. Over the past decades, new developments have been made in sensor technology especially in spatial, spectral, temporal resolution, which improve forest mapping, classification and change detection techniques in the field of forest management applications. On the other hand, image analysis techniques, such as image transformations and, interferometry, also enhance specific areas of forestry applications.

The application of RADAR remote sensing for UK forestry has been recently developed. Recent progress can be seen in the development of classification of biomass density. Wallington, *et. al.*, (2003), carried out a study, which explains the use of dual-baseline coherence to classify a forest in Glen Affric, Northern Scotland to improve a basic backscatter intensity approach, and to give an indication of vegetation density. Synthetic Aperture Radar (SAR) data were used for supervised maximum classification, which differentiates vegetation density as plantation and semi-natural. The areas of water were also classified more accurately. When this classification of water bodies was compared to a forest structural map, there was a good deal of similarity. A classification algorithm was developed for a retrieval of growing stock volume over four different regions (Tansey, *et al.*, 2003). The main test site in this study was boreal forest in southern central Siberia. The classification algorithm has been applied to a managed temperate forest site (Thetford Forest, UK), semi-natural forest (Siggefora, Sweden) and tropical forest (Rondonia, Brazil). The algorithm was developed and calibrated using European Remote Sensing Satellite (ERS) tandem coherence and Japanese Earth Resource Satellite (JERS) classes in 1997 with each box showing the number in that class and the four different classes backscatter data. The results show that the classification gives accurate and representative picture of the growing volume and can be used for the global forest stock volume mapped. Balzter *et. al.,* (2003) estimated tree growth in a conifer plantation over 19 years from multi- satellite L-band SAR data. A SEASAT SAR image from 1978 and JER-1 SAR image from 1997 over Thetford Forest, UK were used to retrieve tree growth of Corsican pine stands. They examined incremental growth from the changes of backscatter coefficient and compared to the expected tree growth from general yield class models used by UK Forestry Commission. They stated that for managed forest plantation, multi-temporal L-band SAR data has some potential for detecting incremental biomass to support sustainable forest management.

RADAR imagery using multi-temporal and interferometric processing techniques advances certain mapping possibilities, which could be useful for forest management operation planning. A major recent improvement of mapping in the field of forestry is "Tree mapping" introduced in the Indonesian Radar Experiment (INDREX) campaign (Nugroho, *et al.*, 2002). It was prepared using high-resolution (1.5-meter) Dornier Synthetic Aperture Radar (DO-SAR) interferometric images with application of models of vertical variation backscatter intensity. The SAR data were integrated with a tree crown parameter retrieval algorithm by segmentation using IKONOS data. These maps were able to extract accurate tree positions, which would be very useful for forest managers because they would like to know the location of particular pockets of trees to remove or replace in order to improve the rest of the stand. In addition, the authors were able to estimate tree crown parameters. This information would be very useful to monitor forested areas with several canopy layers or agro-forestry systems in tropical mixed forest.

LIDAR systems operate similar to RADAR, but at optical wavelengths. An imaging LIDAR is the only instrument that can see both vertical and horizontal fine scale structures of a forest. A LIDAR beam penetrates diffuse targets, so that one main use is to assess tree canopy conditions (Lefsky, *et al.*, 1999). It can be interpreted these data to indicate the amount of biomass associated mainly with the leaves. Although these are of prime importance for ecological research, the ability to differentiate density of canopy cover and classify canopy type would also be useful for management. It also permits measurement of tree height, which is not possible with data available from optical satellite imagery or RADAR (Wulder and Seemann 2003). Estimation of stand height is an integral component of forest inventory so that LIDAR could be used to update the data. In addition, it may be able to identify specific ages of forest stands such as young, mature and old, these aiding in management decisions about future uses of these forests. Wulder and Seemann (2003) updated a stand tree height inventory through integration of LIDAR data with segmented LANDSAT imagery. In this study, they estimated tree heights using LIDAR data along sample flight lines and extended the analysis to a greater area by segmenting LANDSAT-5 TM data so that heights were estimated over an entire landscape. Finally, they developed a regression model for segment/ height empirical relationship to extend the height estimates. This information was used to update tree height inventories and it could identify areas where selected trees had been felled and other forestry management issues.

One of the highest spatial resolution systems in present civilian operation is IKONOS, which has 1 metre panchromatic, and 4 metre multi-spectral data. These data permit the discrimination of smaller units such as age classes of forested area (Franklin, *et al.*, 2001). Instead of using aerial photos, highly detailed forest compartment maps can be frequently and easily updated using IKONOS data. Forest managers can monitor changes along the tree rows and are able to plan thinning operations or replanting programmes in greater accuracy over a short period. A study was undertaken using IKONOS-2 data on Saint-Michel and Freyr forest in Belgium (Kayitakire, *et al.*, 2002). They investigated two classification procedures (per-pixel and per-parcel methods), which were found relevant for the extraction of a forest stand maps for the needs of forest managers. The procedures supplied detailed information on age classes and species composition. Although the per-pixel method distinguished five coniferous stand classes, the per-parcel method improved computation of eight classes within each parcel polygon with a clustering procedure. Therefore, the per-parcel method helped to make a fine and reliable age-class discrimination that would be interest for forest management at the stand level.

Recent developments of high spectral-resolution data can be also used to identify tree health for the purposes of update of stand inventories. A study was carried out with the Compact Airborne Spectrographic Imager (CASI) at

60 cm resolution to detect tree root disease in a Douglas fir dominated site in Canada (Leckie, *et al.,* 2003). Trees with varying levels of damage were assessed in the field and manually defined and outlined. There was a considerable overlap of the spectral signatures of the different damage levels. These damage levels such as healthy, light-healthy, light, moderate and severe damage were classified using ratios of near-infrared and red bands to the blue band with an automated tree isolation method.

8.4 RECOMMENDATIONS FOR FURTHER STUDIES

The critical issues for efficient forest management and assessment are better characterisation of plantation forest cover at various spatial and temporal scales. It requires an efficient decision support technology with provisions for easy updating, and integrating data from various sources at different levels. Towards this end, remote sensing and GIS have been used for decision making and to derive meaningful outputs for forest management. The state of remote sensing and GIS and their application to forest management cannot be considered separately, as the technologies are interrelated. The collection of data from several remote sensing sources is an initial stage of this application. Before integrating these data into forest management they require the following procedures:

1) Pre-processing and processing stage.
2) Analysis and interpretation.

Then the results of image interpretation and various analyses must be efficiently integrated into the forest management decision making process with the help of computer aided decision support systems.

Most of the reference data used in this study were compartment-wise inventories supplied by the Forestry Commission. To carry out the compartment level accuracy estimation needed, more pre-existing field data using intensive plot sampling. The study found that changes of clear cutting could be easily recognised using an NDVI image, because it is a simple and reliable measure of greenness in remotely sensed data and it generally shows the proper sense of change. Some changes of forest cover because of thinning could be detected using pixel-based classification

Due to the limitation of time and the cost of remote sensing materials and field data, this study was quite limited. Therefore, further research is necessary to test different approaches with a longer period of remotely sensed data and more specific field data. The spatial resolution (10 to 20 metres) of SPOT imagery, which this study has used, is high enough for most of the forestry information requirements. But for special requirements of forest management such as operative planning of plantation forest, information on where, when, and how much to cut is necessary. Therefore, it would be very useful to detect within-canopy variation and to obtain volume estimates of forest stands over a long period. The use of SAR imagery may therefore be considered as better from a management point of view, because it is extremely difficult to obtain up-to-date cloud-free SPOT or LANDSAT imagery of many parts of Britain. The most important potential forest management application of SAR imagery will be detection and delineation of forest clear-cuts. The capability to produce good imagery under cloudy conditions gives the forest managers a guaranteed source of imagery when it is necessary. However, detection of small-scale areas and minor changes will still be difficult using radar images. The integration of various high-resolution optical data, such as IKONOS, Quick Bird, could help solve this problem.

The work reported in this thesis explores how optical remote sensing could potentially contribute to the forest management operations. The information extracted from a managed plantation in the UK using SPOT data reveals what could be used for future management planning. Although the study included a limited sample from a single study area, some generalised conclusions can be made. This study applied the following three methods for detecting and monitoring forest cover changes on compartment level.

1) Visual interpretation and NDVI change analysis

2) Change detection analysis using Vegetation Index differencing
3) Pixel-based classification

The main finding of this study is to detect forest canopy changes by thinning and felling. It also identified spatial and temporal changes between and within the compartments. Although the overall temporal changes are very small over the four years (1994-1997), the sub-compartments felled during the period of concern can be seen visually as well as quantitatively as a change decrease. An advanced pixel-based classification could help to discriminate particularly change decrease areas due to thinning operations. This approach will be of interest for forest management on a compartment level and could be used to update management operation records. These findings of this thesis could also be relevant for extraction of stand maps and help to create a new database for the future management of plantation forest in UK. The knowledge produced in this thesis could also be used to develop methods towards monitoring changes in the populations of conifers in plantations on semi-natural sites within Britain. As policies are developed to reduce the number of conifers, whether in plantations on moorland on heathland, or on ancient semi-natural woodland sites, there is an increasing need for reliable and cheap means to measure the effectiveness of these conservation policies. This thesis had highlighted methods and approaches, which are appropriate to be applied for this purpose.

The techniques, applied in this study, to detect and identify forest cover features and variations could be also used for further studies in the developing world. In SriLanka, for example, the Forest Department maintains a well established database only on a national and district level. But there is a lack of information for small-scale forest plantations, although this information is essential for management operations. These plantations have to be managed intensively to obtain high yields and be profitable. Considerable areas of pine and eucalyptus plantations in the high lands that were planted during the 1980s are overstocked and neglected and there are also significant backlogs in thinning (Sri Lanka Ministry of Agriculture, Lands and Forestry, 1995). To upgrade the quality and to manage these crops for the market requires a compartment or stand level database. The pixel-based classification technique could be used to create small-scale compartment stock maps and also the inventory of stand variables such as the area and species of each sub-compartment, could be updated. In addition, decision makers need more information on different ages of the stands. These age classes could be discriminated using a NDVI variation technique.

Almost 28% of forest plantation in the dry zone of the country (mainly teak *T. grandis*) is regarded as unproductive (Sri Lanka Ministry of Agriculture, Lands and Forestry, 1995) because of poor quality and low stocking density. The detailed information on unproductive areas such as irregular growth, or poor forms of trees could be discriminated at a compartment level and these areas could then be either clear-felled, replanted or rehabilitated. This can be done by monitoring small-scale plantation blocks using change detection. Although this study used SPOT data for the Vegetation Index Differencing method, other types of data such as RADAR, or LIDAR could also be used to differentiate different stages of tree growth.

In addition to the plantation forest, the techniques of this study could be applied for management issues related to the natural forests in SriLanka. Natural forests are protected for water and soil conservation, and for biodiversity. The main issue in these protected forests is continuing loss by fire, illegal logging, encroachment, grazing and browsing, including elephant damage. To identify these factors, affected areas could be analysed using a change detection method. From the experience with change detection methods and the existing literature, could expect that it will be possible to carry out research on hill-country forested areas in SriLanka which are difficult to access, to create an accurate, spatially detailed dataset. For example a study on Adam's Peak wilderness conservation forest concluded that the forested land has been diminishing because of encroachment, extraction of timber and non-timber products and gemstone mining (Wickramasinghe, 1995). This forest is situated approximately 1800 metres above the base level in very rough terrain.

Due to the difficulty of access to the area, the study by Wickramasinghe was carried out with limited samples. Therefore satellite images could be the main data source for these types of area to detect clear boundaries of encroachments and other activities. The change detection technique with high-resolution optical data together with other sources of data such as RADAR would be one of the best methods to detect and monitor decrease of forested areas and create small-scale dataset for decision makers. A combination of data sources and techniques may also provide better results than the individual data sources. Detecting disturbed forested areas, classification and mapping using this type of combined data could be explored in future studies.

As summarised in section 8.2 this study mainly investigated forest cover condition in different aged stands. Temporal scale changes were found with felling and very fine variation of forest cover due to thinning operation at compartment level were sorted. Table 8.1 shows the expected detectability of various management operations by satellite and highlights the specific achievements of this thesis. The multidate study of the Kings Forest from SPOT and additional data (FC compartment records and field surveyor) provided forest managers with:

1) The characterisation of Kings Forest through detailed analysis by multi-spectral images, outlining the contributions and limitations of remote sensing as regards the forestry environment such as the effects of stand type and age.
2) Cartographic presentations of forest canopy variations at different spatial and temporal scales and statistical inventory in terms of felling and thinning during the four years. These information help track management progress and spotlights different types of felling, thinning and partial felling.
3) The development and of a database from the mapped changes and the available conventional data, in the form of a GIS to facilitate the regular monitoring and continuous management of the forest.

Table 8.1: Different types of sensors and methods that useful for the forest management operations

Remote sensing sensors Management operation	Planting	Cleaning	Rack cutting	Brashing	Pruning	Thinning	Partial felling	Clear felling
LANDSAT						*	*	*
SPOT					*	*	*	*
RADAR			*	*	*	*	*	*
LIDAR	*	*	*	*	*	*	*	*
IKONOS	*	*	*	*	*	*	*	*
Methods use in this study								
NDVI analysis – Visual interpretation							*	*
Change detection – temporal analysis							*	*
Pixel based classification						*	*	*

* indicated expected detectability of satellite systems. The shaded areas represent those aspects studied in this thesis

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Appendices

Appendix A

Atmospheric correction procedure

The first step is to convert Digital Number (DN) to radiance, which corrects the data for gain (A) and offset (B) effects of the imaging system. The absolute calibration gain A is provided by SPOT Image for each scene on a parameter sheet accompanying the image. It can vary from scene to scene depending on the gain setting used. The calibration is achieved using:

$$L = A/DN\ (Wm^{-2}\ sr^{-1}\ \mu m^{-1}) \qquad \text{(A.1)}$$

The offset (B) is zero for the SPOT system.

The second step is conversion of radiance to apparent reflectance (ρ^*) which relates the measured radiance, L in a sensor channel to the solar irradiance incident at the top of the atmosphere and is expressed as:

$$\rho^* = \frac{\pi L}{E_s d \cos(\theta_s)} \qquad \text{(A.2)}$$

Where L (Wm^{-2} sr^{-1} μm^{-1}) is the radiance recorded in the sensor spectral band; E_s (Wm^{-2} μm^{-1}) is the band average equivalent solar irradiance in the sensor spectral band at the mean earth-sun distance; The values of E_s for SPOT HRV – 1 is band 1- 586.0, band 2- 504.0, band 3- 331.0. The parameter d is a multiplicative factor to account for the variation in the solar irradiance as a function of changing earth-sun distance; θ_s is the solar zenith angle. The value of d can be obtained for a given Julian Day (JD = day number of the year) using following equation:

$$d=1/[1-(0.01674*\cos(0.9856(JD-4))]^2 \qquad \text{(A.3)}$$

The final step of determining surface reflectance ρ_s is obtained by using the 5S (Simulation of the Satellite Signal in the Solar Spectrum) radiative transfer model. The 5S model can be used to describe the different interactions of solar radiation with atmospheric constituents during its traverse through the atmosphere. (Tanre *et al.*, 1990).

5S Model:

The apparent reflectance ρ^* for the combine surface-atmosphere system is the product of the scattering and absorbing atmosphere which can be expressed as:

$$\rho^* = T_s(\theta_s, \theta_v)[\rho_a(\theta_s, \theta_v, \Delta\phi) + [\frac{\rho_s}{(1-\rho_2 S)}] \bullet T(\theta_s) \bullet T(\theta_v)] \qquad (A.4)$$

ρ^* = apparent reflectance

ρ_s = surface reflectance

ρ_a = atmospheric reflectance

θ_s = solar zenith angle

θ_v = view angle

$\Delta\phi$ = relative azimuth between sun and satellite direction

S = atmospheric spherical albedo

$T(\theta)$ = total scattering transmittance at zenith angle θ

$T_g(\theta_s, \theta_v)$ = total gaseous transmittance;

it obtain by: $\Pi^4{}_{i=1}\ T_{gi}(\theta_s, \theta_v, U_{gi})$ (A.5)

U_{gi} = gaseous content

Therefore ρ_s is obtained using the following equation based on the above equation.

$$\rho_s = \frac{Y}{1+SY}$$

Where $Y = A_1\rho^* - B_1$

$$A_1 = \frac{1}{T(\theta_s\theta_v) \bullet T(\theta_s) \bullet T(\theta_v)} \qquad B_1 = \frac{\rho_a(\theta_s, \theta_v, \Delta\phi)}{T(\theta_s)T(\theta_v)} \qquad (A.6)$$

The inversion coefficients A_I and B_I and the S (spherical albedo) were derived to compute the surface reflectance from the apparent reflectance. In order to correct SPOT HRV 1 data the same sun-target sensor geometry can be assumed to exist across the image due to the small field of view of these systems. Therefore A_I, B_I and S are appropriate for the entire scene and need only be computed once for that scene.

Input parameters for the 5S model are:

1) The viewing and illumination geometry - solar zenith, solar azimuth, view zenith, view azimuth angles.
2) Atmospheric profile (atmospheric condition)
3) An aerosol model - indicating the fractions of basic aerosol components example dust like, oceanic, water-soluble and soot component. In addition three troposphere aerosol type models are provided in the 5S code - continental, maritime and urban.
4) Aerosol concentration estimate-visibility (km).
5) Spectral band codes for SPOT HRV, - band 1 = 9, band 2 = 10 and band 3 = 11.
6) Ground reflectance.

Table AI: Input parameters

Date of Year	Visibility	Sun Angels		View Angels	
		Zenith	Azimuth	Incidence	Azimuth
1994	37.5KM	31^0	$153^0.6^0$	16.6^0	133.4^0
1995	25 KM	35^0	163.9^0	2.6^0	124.0^0
1996	40 KM	31^0	161.0^0	13.3^0	130.2^0
1997	11 KM	31^0	160.0^0	17.5^0	127.0^0

Table AII: Output values (1994, 1995, 1996 and 1997 SPOT images) in each band

Output values	1994			1995			1996			1997		
	Band 1	Band 2	Band 3	Band 1	Band 2	Band 3	Band 1	Band 2	Band 3	Band 1	Band 2	Band 3
Global Gas Trans.	0.936	0.932	0.934	0.927	0.921	0.925	0.938	0.912	0.932	0.912	0.886	0.903
Total Sca. Trans.	0.838	0.887	0.924	0.831	0.881	0.911	0.841	0.885	0.921	0.801	0.828	0.876
Spherical Albedo	0.121	0.053	0.047	0.118	0.033	0.051	0.132	0.068	0.048	0.111	0.024	0.031
Atmos. Reflectance	0.46	0.027	0.013	0.042	0.021	0.015	0.051	0.032	0.016	0.033	0.013	0.011

Table AIII: Inversion coefficients (1994, 1995, 1996 and 1997 SPOT images) in each band

Inversion coefficients	1994			1995			1996			1997		
	Band 1	Band 2	Band 3	Band 1	Band 2	Band 3	Band 1	Band 2	Band 3	Band 1	Band 2	Band 3
A_I	1.274912	1.209652	1.158727	1.298133	1.232436	1.186697	1.267655	1.199515	1.664996	1.368903	1.363126	1.264178
B_I	-0.5489	-0.03044	-0.01407	-0.05054	-0.02383	0.01646	0.06064	-0.3616	-0.01737	0.04119	-0.01570	-0.01256
S	0.121	0.053	0.047	0.118	0.043	0.051	0.132	0.068	0.048	0.111	0.024	0.031

Appendix B

Table 1 Compartments details

Compartment No.	Total Area (ha)	Sub Compartments	Species	Date planted
4030	13	a	Agr.land	-
		b	OK	1936
		c	BE	1936
		d	CP	1936
		c	SP	1941
4031	12	a	BI/BE/OK	1936
		b	SP	1941
		c	CP	1955
		d	OK/SP	1941
		e	SP	1941
4032	8	a	SP	1941
		b	BI/OK/LI/BE	1936
		c	CP	1952
4033	7	a	BI	1952
		b	CP	1936
		c	CP	1988
4034	9	a	BI	1952
		b	CP	1936
		c	CP	1988
4035	7	a	CP	1988
		b	CP	1952
		c	BI/MB	1936
		d	CP	1936
4036	11	a	CP	1936
		b	BI/BE	1952
		c	SP	1936
		d	CP	1997
4037	11	a	BI	1952
		b	SP	1936
		c	CP	1936
		d	CP	1997
4038	9	a	BI	1936
		b	CP	1937
		c	CP	1992
4039	14	a	BI	1936
		b	CP	1952
		c	CP	1937
		d	CP	1954
		e	CP	
4040	8	a	BI	1936/1952
		b	CP	1937
		c	CP	1992
4041	11	a	CP	1957
		b	CP	1932
		c	CP	1992
4042	11	a	BE/BI	1936/1960
		b	CP	1937
		c	OK	1860
		d	CP	1997

Appendix B

Table 1 Compartment details Cont.

4043	18	a	CP	1965
		b	CP	1955
		c	CP	1937
		d	BI/BE	1936/1937
		e	CP/EL	1900
4112	7	a	CP	1980
		b	Bare	-
4113	9	a	CP	1958
4114	11	a	CP	1958
		b	Bare	-
4122	12	a	CP	1958
		b	CP	1980
4227	16	a	CP	
	Experimental Site	b	CP/SP/WEP/XP	1964
4228	17	a	CP	1965
4226	12	a	CP	1964
4225	10	a	CP	1963
4224	12	a	CP	1963
		b	BI	1952
4221	10	a	CP	1962
		b	SP	1960
4223	11	a	CP	1962
		b	BI	1952
		c	Bare	-
4220	7	a	CP	1962
		b	SP	1960
4222	10	a	CP	1962
		b	Bare	-
4219	8	a	CP	1962
		b	BI	1936
4217	8	a	SP	1960
		b	CP	1959
4218	9	a	CP	1961
		b	BI	1936
4216	11	a	SP/EL	1960
		b	CP	1959
4215	9	a	CP	1959
		b	BI	1952
4029	11	a	SP/EL	1960
		b	CP	1959
4028	11	a	CP	1953
		b	BI	1952
		c	CP	1959
		d	SP	1997

SP = Scots pine, CP = Corsican pine, BI Birch, BE = Beach
EL = Elm, MB = Maple, OK = Oak

Appendix B

Table 2 Areas in ha. by age groups

COMP.	Species			Age groups			
No		7 <years	8-17 years	18-37 years	38-57 years	58> years	Total
4038	CP	7			4	2.75	13.75
4039	CP	7				1.25	8.25
4040	CP	1.5				3.5	5
4041	CP	10			0.25	0.75	11
4042	CP	7				1	8
4037	CP	8.5					8.5
	SP					2	2
4036	CP	8				1	9
	SP					1	1
4028	CP				8.75		8.75
	SP	1					1
4112	CP		6				6
4122	CP		3.25		8		11.25
4033	CP		5.25			0.75	6
4034	CP		7.25			0.75	8
4035	CP		3		1.25	1.75	6
4218	CP			8			8
4219	CP			7.75			7.75
4220	CP			6.25			6.25
	SP					0.75	0.75
4221	CP			9.75			9.75
	SP					0.25	0.25
4222	CP			9.25			9.25
4223	CP			9.25			9.25
4224	CP			11			11
4225	CP			10			10
4226	CP			10			10
4227	CP			15.75			15.75
4228	CP			17			17
4043	CP			3.75	3.75	4.25	11.75
4029	CP				10.25		10.25
	SP					0.5	0.5
4215	CP			8.25			8.25
4216	CP			10			10
	SP				0.5		0.5
4217	CP			7			7
	SP				1		1
4113	CP			9			9
4114	CP			11			11
4030	CP					6	6
	SP					1	1
4031	CP				5		5
	SP					1	1
4032	CP					6	6
	SP					1	1
		50	24.75	163	42.75	37.25	317.75

Appendix C

NDVI values with structural variables in the study site

COMP.	SUB.	AREA ha.	SPECIES	1994	1995	1996	1997	AGE	TOP HEIGHT (M)	MEAN DIAMETER. (CM)	BASAL AREA (SQ.M)
				NDVI	NDVI	NDVI	NDVI	at 1997			
4028	a	3.8	CP	0.636	0.645	0.727	0.727	44	22.5	30.8	32.3
	c	4.5	CP	0.643	0.652	0.711	0.713	38	18.8	25.2	30
	d	0.7	SP	0.648	0.661	0.445	0.458	2	_	_	_
4029	a	1	SP	0.621	0.655	0.685	0.706	100	_	_	_
	b	9	CP	0.643	0.653	0.713	0.723	38	18.8	25.2	30
4030	d	2.5	CP	0.628	0.641	0.683	0.706	61	24.9	34.1	34.5
	e	0.5	SP	0.662	0.666	0.734	0.735	56	21.9	33.1	35.7
	f	0.2	CP	0.641	0.646	0.682	0.706	61	22.7	31.2	33.2
4031	a	0.6	SP	0.645	0.648	0.682	0.707	61	20.9	31.1	33.6
	b	0.5	SP	0.661	0.664	0.733	0.734	56	21.9	33.1	35.7
	c	0.6	SP	0.652	0.655	0.715	0.718	41	17.3	23.8	30.6
4032	a	1.5	SP	0.651	0.663	0.732	0.736	56	21.9	33.1	35.7
	b	4.7	CP	0.641	0.648	0.682	0.703	61	26.9	38.1	36
4033	b	0.4	CP	0.642	0.649	0682	0.701	61	24.9	34.7	34.5
	c	4.1	CP	0.653	0.655	0.709	0.721	9	7.2	9.6	28.9
4034	b	0.3	CP	0.641	0.649	0.686	0.708	61	24.9	34.7	34.5
	c	6.7	CP	0.652	0.656	0.708	0.719	9	7.2	9.6	28.9

4035	a	2.9	CP	0.651	0.655	0.709	0.721	9	7.2	9.6	28.9
	b	1	CP	0.643	0.645	0.734	0.736	45	20.7	28	31.1
	d	2.1	CP	0.642	0.647	0.682	0.689	61	24.9	34.7	34.5
4036	a	1	CP	0.643	0.645	0.681	0.706	61	27.1	38.9	36.7
	c	1	SP	0.641	0.642	0.683	0.706	61	21.1	32.1	34.2
	d	5.4	CP	0.644	0.678	0.441	0.448	1	_	_	_
4037	b	2	CP	0.642	0.645	0.684	0.706	61	25.1	35.2	35
	c	1.3	SP	0.643	0.644	0.685	0.702	61	21	32.1	34.2
	d	5.9	CP	0.636	0.645	0.442	0.458	1	_	_	_
	e	0.4	CP/MB	0.641	0.663	0.441	0.451	1	_	_	_
4038	b	0.5	CP	0.641	0.645	0.665	0.681	60	24.9	34.7	34.5
	c	6.5	CP	0.483	0.542	0.553	0.568	5	_	_	_
4039	b	0.5	CP	0.642	0.656	0.702	0.715	40	20.6	27.8	31
	c	2	CP	0.638	0.641	0.661	0.691	60	23.9	38.1	36
	d	1	CP	0.646	0.655	0.709	0.713	43	21.5	26.3	30.5
	e	9.5	CP	0.491	0.543	0.552	0.556	5	_	_	_
4040	b	4	CP	0.642	0.648	0.661	0.685	60	24.9	34.7	34.5
	c	1.5	CP	0.488	0.541	0.551	0.563	5	_	_	_
4041	a	0.5	CP	0.641	0.653	0.701	0.711	40	17.2	22.6	29.4
	b	1	CP	0.641	0.645	0.667	0.689	60	24.9	34.7	34.5
	c	9.1	CP	0.489	0.542	0.558	0.561	5	_	_	-

4042	b	0.6	CP	0.641	0.645	0.651	0.683	60	26.9	38.1	36
	d	5.9	CP	0.655	0.681	0.453	0.459	1	–	–	–
4043	a	0.5	CP	0.664	0.665	0.706	0.725	32	15.8	20.1	28.2
	b1	4.7	SP	0.672	0.678	0.701	0.709	42	19.1	26.2	31
	b2	0.4	CP	0.672	0.676	0.702	0.709	42	22.3	30.1	31.9
	c	7.5	CP	0.642	0.646	0.663	0.691	60	24.9	33.7	34.5
	e	1.3	CP	0.635	0.647	0.689	0.703	100	28.1	37.9	37.1
4112	a	5.5	CP	0.658	0.666	0.733	0.741	17	9.8	12.6	26.6
4113	a	8.8	CP	0.665	0.666	0.719	0.727	39	18.9	25.2	30
4114	a	9.5	CP	0.658	0.665	0.730	0.736	17	9.8	12.6	26.6
4122	a	7.5	CP	0.663	0.665	0.711	0.725	39	20.6	27.8	31
	b	3	CP	0.658	0.667	0.731	0.738	17	7.9	10.5	30.7
4215	a	8	CP	0.643	0.652	0.701	0.714	38	19.5	26.8	31
4216	a1	0.4	SP	0.633	0.648	0.691	0.703	100	17.3	23.8	30.6
	a2	0.9	SP	0.662	0.667	0.711	0.729	37	15.9	19.8	27.9
	b	8	CP	0.643	0.652	0.701	0.723	38	18	24.1	29.1
4217	a	1	SP	0.628	0.645	0.689	0.707	100	17.3	23.8	30.6
	b	7	CP	0.645	0.655	0.701	0.715	38	19.5	26.8	31
4218	a	7	CP	0.663	0.668	0.702	0.742	36	20	27	30.6
4219	a	6.5	CP	0.653	0.657	0.705	0.741	35	19.9	26.5	30.3
4220	a	6	CP	0.653	0.758	0.703	0.747	35	19.9	26.5	30.3

	b	1	SP	0.632	0.646	0.688	0.705	100	17.3	23.8	30.6
4221	a	9.5	CP	0.655	0.661	0.704	0.747	35	19.9	26.5	30.3
	b	0.5	SP	0.633	0.643	0.685	0.709	100	17.3	23.8	30.6
4222	a	4.5	CP	0.651	0.655	0.706	0.745	35	19.9	26.5	30.3
	c	3.5	CP	0.665	0.667	0.707	0.728	32	17.4	23.8	29.4
4223	a	4	CP	0.651	0.657	0.702	0.742	35	19.9	26.5	30.3
	d	3	CP	0.664	0.665	0.706	0.725	32	17.4	23.8	29.4
4224	a	9	CP	0.674	0.678	0.723	0.743	34	19	26	30
4225	a	9.5	CP	0.671	0.676	0.721	0.745	34	19	26	30
4226	a	12	CP	0.685	0.689	0.712	0.735	33	17.9	22	28.8
4227	a	13.5	CP	0.683	0.688	0.711	0.736	33	17.9	22	28.8
	b1	0.5	CP	0.681	0.685	0.709	0.732	33	18.2	25.5	29.1
	b2	0.5	SP	0.685	0.688	0.710	0.733	33	16.3	20.3	24.2
4228	a	15.5	CP	0.664	0.665	0.709	0.725	32	16.9	21.1	27.8

APPENDIX D

Ground control points and RMS $_{error}$, X and Y Residuals for geometric corrections. Values as in the UTM coordinate system where x and y are distance in meters east and north of grid reference respectively

			1994			1995			1996			1997		
GCP	X	Y	X Res	Y Res	RMS$_{error}$ (pixel)	X Res	Y Res	RMS$_{error}$ (pixel)	X Res	Y Res	RMS$_{error}$ (pixel)	X Res	Y Res	RMS$_{error}$ (pixel)
1	581376	275781	0.013	0.078	0.079	-0.098	0.132	0.164	-0.076	0.081	0.111	0.152	-0.084	0.174
2	580368	276093	0.052	-0.121	0.121	0.101	-0.086	0.132	0.056	-0.155	0.165	0.157	-0.111	0.163
3	581904	274629	0.114	-0.065	0.131	-0.081	1.053	0.096	0.108	-0.008	0.109	-0.073	0.045	0.086
4	581376	273957	-0.085	0.135	0.159	-0.064	0.111	0.128	0.020	0.029	0.035	-0.117	0.113	0.164
5	585336	274749	0.111	-0.038	0.117	-0.104	0.048	0.115	-0.077	-0.087	0.116	0.109	-0.025	0.110
6	581328	276189	-0.067	-0.054	0.086	0.121	0.091	0.151	0.054	-0.027	0.060	-0.137	-0.110	0.174
7	580344	272496	0.085	0.121	0.085	0.098	0.113	0.149	0.071	0.155	0.170	0.135	0.052	0.144
8	579744	274053	-0.151	0.086	0.173	0.036	-0.083	0.090	0.029	0.069	0.074	-0.159	0.016	0.160
9	581520	275853	-0.113	-0.092	0.145	0.131	-0.041	0.137	-0.126	0.075	0.146	-0.114	-0.132	0.154
10	583755	274800	-0.006	-0.061	0.061	0.011	0.069	0.069	-0.003	-0.079	0.079	-0.025	0.030	0.039
11	582144	276141	-0.105	0.012	0.105	0.105	-0.009	0.105	-0.115	0.002	0.115	-0.114	0.064	0.131
12	579792	272637	0.083	-0.071	0.109	0.075	0.056	0.093	0.084	0.057	0.102	-0.021	-0.073	0.076
13	583584	273957	-0.121	0.096	0.154	-0.109	0.093	0.143	-0.126	0.111	0.168	0.105	0.106	0.150
14	584568	275733	-0.101	0.113	0.151	0.098	0.101	0.140	-0.114	0.080	0.140	-0.076	0.177	0.143
15	578904	272949	0.048	0.107	0.117	0.103	-0.086	0.094	0.095	-0.107	0.143	0.039	0.036	0.053
16	580752	277029	-0.018	0.128	0.129	0.039	0.128	0.133	0.009	-0.157	0.157	0.052	0.161	0.167
17	585267	273582	0.047	-0.141	0.148	0.063	-0.118	0.134	0.038	-0.161	0.165	-0.124	0.063	0.138
18	582744	276581	0.081	0.023	0.084	-0.009	0.031	0.032	-0.004	0.025	0.025	0.092	-0.018	0.094
19	578616	274517	-0.112	0.067	0.131	-0.021	0.011	0.011	-0.023	0.000	0.023	0.068	0.079	0.104
20	583179	272988	0.096	-0.051	0.108	0.083	-0.071	0.109	0.099	0.098	0.140	0.103	-0.023	0.105
Control points errors			(X) 0.0804, (Y) 0.0791 Total 0.1196			(X) 0.0775, (Y) 0.0766 Total 0.1082			(X) 0.0781, (Y) 0.0985 Total 0.1218			(X) 0.1171, (Y) 0.1216, Total 0.14878		

Appendix E

(1) Significance tests for correlation between Red and NIR reflectance in < 7, 8-17, 18-37 & > 38 age groups.

< 7 age group

Red (X)	Rank (X)	NIR (Y)	Rank (Y)	d	d^2
.107	6	.265	1	5	25
.093	1	.300	6	5	25
.098	5	.288	3	2	4
.096	4	.289	4	0	0
.094	2	.291	5	3	9
.095	3	.275	2	1	1
					64

$$r_s = 1- \frac{6*\sum d^2}{n^3-n} \qquad = 1 - \frac{384}{210} \qquad = 1\text{-}1.82 \quad r_s = - .840$$

8-17 age group

Red (X)	Rank (X)	NIR (Y)	Rank (Y)	d	d^2
.050	3	.247	5	2	4
.053	1	.209	2	1	1
.051	2	.297	1	1	1
.041	4	.267	3	1	1
.040	5	3256	4	1	1

$$r_s = 1- \frac{6*\sum d^2}{n^3-n} \qquad = 1 - \frac{48}{120} \qquad =1\text{-}0.4 \quad r_s = 0.600$$

18- 37 age group

Red (X)	Rank (X)	NIR (Y)	Rank (Y)	d	d^2
.039	4.5	.193	5.5	1	1
.040	2.5	.196	3	2.5	6.25
.041	1	.194	4	3	9
.039	4.5	.197	2	2.5	6.25
.037	13.5	.193	5.5	8	64
.039	4.5	.218	1	3.5	12.25
.039	4.5	.189	8	3.5	12.25
.040	2.5	.182	13	10.5	110.25
.039	4.5	.186	9	4.5	20.25
.038	11.5	.185	10	1.5	2.25
.037	13.5	.183	12	1.5	2.25
.039	4.5	.184	11	6.5	42.25
.039	4.5	.190	7	2.5	6.25

$$r_s = 1- \frac{6*\sum d^2}{n^3-n} = 1- \frac{1767}{2197.13} = 1\text{-}0.8090 \quad r_s = 0.191$$

38-57 age group

Red (X)	Rank (X)	NIR (Y)	Rank (Y)	d	d^2
.041	4.5	.184	2	2.5	6.25
.041	4.5	.182	1	3.5	12.25
.042	8.5	.186	3	5.5	30.25
.042	8.5	.209	11.5	3	9
.045	11	.204	10	1	1
.040	2.5	.194	8	5.5	30.25
.041	4.5	.193	6.5	2	4
.040	2.5	.191	5	2.5	6.25
.042	8.5	.196	9	0.5	0.25
.050	13	.193	6.5	6.5	42.25
.056	14	.253	15	1	1
.039	1.5	.190	4	2.5	6.25
.041	4.5	.209	11.5	7	49
.047	12	.238	14	2	4
.065	15	.218	13	2	4

$$r_s = 1- \frac{6*\sum d^2}{n^3-n} = 1 - \frac{6*206}{3360} = 1-0.369 \quad r_s = 0.631$$

Red (X)	Rank (X)	NIR (Y)	Rank (Y)	d	d^2
.043	2.5	0.201	2	0.5	0.25
0.41	1	0.221	4	3	9
0.51	5	0.225	5	0	0
0.43	2.5	0.185	1	1.5	2.25
0.52	6	0.203	3	3	9
0.48	4	0.281	6	2	4

$$r_s = 1- \frac{6*\sum d^2}{n^3-n} = 1 - \frac{6*24.5}{210} = 1-0.7 \quad r_s = 0.3$$

(2) Significance test for correlation between age and NDVI (1997) in < 7, 8-17, 18-37, 38-58 and >58 age groups.

< 7 age group

Age (X)	Rank (X)	NDVI (Y)	Rank (Y)	d	d^2
1	1.5	0.459	4	2.5	6.25
1	1.5	0.448	1	0.5	0.25
1	1.5	0.455	2	0.5	0.25
2	4.5	0.458	3	1.5	2.25
2	4.5	0.485	5	0.5	0.25
5	6.5	0.585	6	0.5	0.25
5	6.5	0.591	7	0.5	0.25
5	6.5	0.596	8	1.5	2.25

$$r_s = 1 - \frac{6 * \sum d^2}{n^3 - n} \quad = 1 - \frac{6*12}{8^3 - 8} \quad = 1 - \frac{72}{504} \quad = 1 - .143 \quad r_2 = 0.86$$

8-17 age group

Age (X)	Rank (X)	NDVI (Y)	Rank (Y)	d	d^2
9	1.5	0.709	1	0.5	0.25
9	1.5	0.712	2	0.5	0.25
9	1.5	0.717	3	1.5	2.25
17	4.5	0.736	4	0.5	0.25
17	4.5	0.733	5	0.5	0.25
17	4.5	0.738	6	1.5	2.25

$$r_s = 1 - \frac{6 * \sum d^2}{n^3 - n} \quad = 1 - \frac{6*5.5}{6^3 - 6} \quad = 1 - \frac{33}{210} \quad = 1 - .157 \quad r_2 = 0.843$$

18-37 age group

Age (X)	Rank (X)	NDVI (Y)	Rank (Y)	d	d^2
32	1.5	0.721	1	0.5	0.25
32	1.5	0.723	2.5	1.0	1
32	1.5	0.723	2.5	1.0	1
32	1.5	0.755	13	11.5	132.25
33	5.5	0.733	5	0.5	0.25
33	5.5	0.734	6	0.5	0.25
33	5.5	0.737	7	1.5	2.25
33	5.5	0.732	4	0.5	0.25

34	9.5	0.741	8	0.5	0.25
34	9.5	0.753	12	2.5	6.25
35	11.5	0.765	16	4.5	20.25
35	11.5	0.775	17	5.5	30.25
35	11.5	0.773	15	3.5	12.25
35	11.5	0.751	11	0.5	0.25
35	11.5	0.746	10	1.5	2.25
36	16	0.742	9	7	49
37	17	0.757	14	3	9

$$r_s = 1- \frac{6*\sum d^2}{n^3-n} = 1- \frac{6*267.5}{17^3-17} =1- \frac{1605}{4896} = 1- .3278 \quad r_2 = 0.672$$

38-57 age group

Age (X)	Rank (X)	NDVI (Y)	Rank (Y)	d	d^2
38	1.5	0.713	3.5	2	4
38	1.5	0.714	5	3.5	12.5
38	1.5	0.723	9	7.5	56.25
38	1.5	0.715	6.5	5	25
39	5.5	0.725	10	4.5	20.25
39	5.5	0.727	11.5	6	36
40	7	0.715	6.5	0.5	0.25
41	8	0.718	8	0	0
42	9.5	0.707	1	8.5	72.25
42	9.5	0.711	2	7.5	56.25
43	11	0.713	3.5	7.5	56.25
44	12	0.727	11.5	0.5	0.25
45	13	0.736	14.5	1.5	2.25
56	14.5	0.734	13	1.5	2.25
56	14.5	0.736	14.5	0	0

$$r_s = 1- \frac{6*\sum d^2}{n^3-n} = 1 - \frac{6*344}{15^3-15} = 1 - \frac{2064}{3360} = 1-0.614 \quad r_s=0.386$$

>58 years group

Age (X)	Rank (X)	NDVI (Y)	Rank (Y)	d	d^2
60	1.5	0.681	1	0.5	0.25
60	1.5	0.691	6	4.5	20.25
60	1.5	0.689	4.5	3	9
60	1.5	0.683	2	0.5	0.25
60	1.5	0.685	3	1.5	2.25
61	7.5	0.706	9	1.5	2.25
61	7.5	0.707	10	2.5	6.25
61	7.5	0.703	8	0.5	0.25
61	7.5	0.701	7	0.5	0.25
61	7.5	0.708	11	3.5	12.25
61	7.5	0.689	4.5	3	9

$$r_s = 1 - \frac{6 * \sum d^2}{n^3 - n} = 1 - \frac{6 * 62.25}{11^3 - 11} = 1 - \frac{373.5}{1320} = 1 - 0.283 \quad r_s = 0.717$$

The critical values of Spearman's Rank Correlation Coefficient (r_s) at the 0.05 level of significance.

N	Significance level (One tailed test) 0.05
4	1.000
5	0.900
6	0.829
7	0.714
8	0.643
9	0.600
10	0.564
11	0.535
12	0.506
13	0.481
14	0.456
15	0.441
16	0.425
17	0.412
18	0.399
19	0.388
20	0.377
22	0.359
24	0.343

Source: Quantitative techniques in Geography
(from Siegel 1956) *Hammond & McCullagh ,1978*

APPENDIX F

Correction procedures of NDVI values after atmospheric correction

(1) Correction with Lakenheath test site

Figure FI shows five selected sample blocks along the runways on the Lakenheath airfield site. These areas were selected because it is assumed that these targets do not change over time. Both bright and dark targets areas were chosen. Reflectance values (Red and near-infrared) were extracted from each block and are shown in table FI. Reflectance values in the image are adjusted using the average ratios of the test values to a reference year (1997) are shown in table FII. The formula for corrected NDVI ($NDVI^I$) is shown.

Figure F1 Lakenheath test site

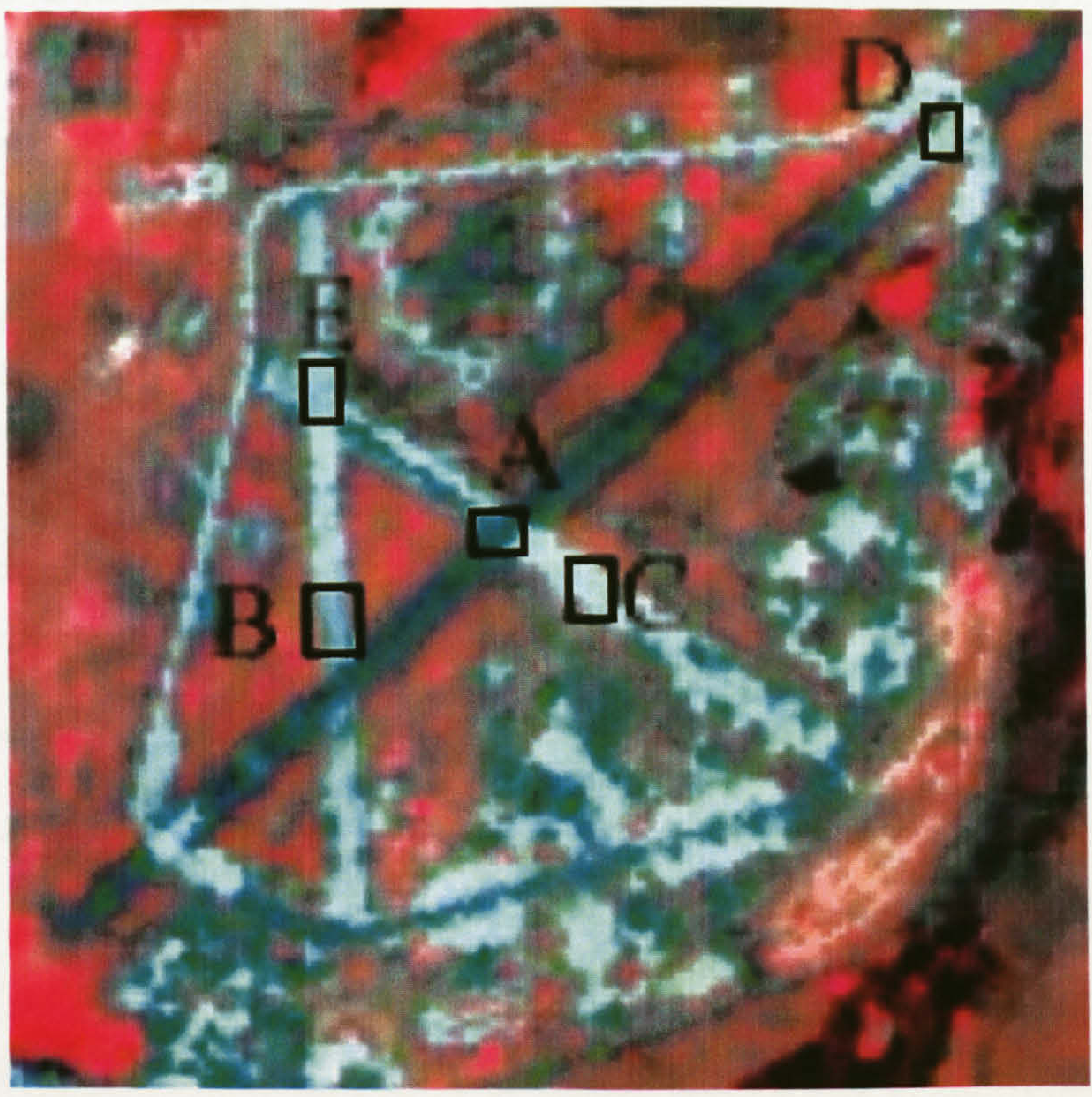


Table FI: Red and IR reflectance

Target	Red band reflectance				IR band reflectance			
	1997	1994	1995	1996	1997	1994	1995	1996
A	0.081	0.08	0.081	0.081	0.152	0.148	0.15	0.152
B	0.143	0.141	0.141	0.141	0.235	0.224	0.229	0.232
C	0.283	0.281	0.281	0.283	0.375	0.364	0.365	0.375
D	0.209	0.207	0.207	0.209	0.264	0.256	0.257	0.263
E	0.215	0.208	0.209	0.215	0.306	0.295	0.296	0.306

Table FII: Red ($r_{corr.}$) and IR ($IR_{corr.}$) correction

Target	Ratios/1997	Red correction ($r_{corr.}$)			Infrared reflectance ($IR_{corr.}$)		
		1994	1995	1996	1994	1995	1996
A		0.988	1.000	1.000	0.974	0.987	1.000
B		0.986	0.986	0.986	0.953	0.974	0.987
C		0.993	0.993	1.000	0.971	0.973	1.000
D		0.990	0.990	1.000	0.970	0.93	0.996
E		0.967	0.972	1.000	0.964	0.967	1.000
	Average	0.967	0.988	0.997	0.966	0.975	0.997

The corrected NDVI formulae as follows: Corrected NDVI[1] = $$\frac{(\rho IR / IR_{corr.}) - (\rho red / red_{corr.})}{(\rho IR / IR_{corr}) + (\rho red / red_{corr})}$$

(2) Correction with viewing angles model used by Steven (1998)

This correction was estimated to reduce the NDVI values to nadir viewing. The correction factor was estimated to account for the effect of satellite viewing angle on NDVI after Steven (1998). The correction values by angle of view of the SPOT are shown in table FIII.

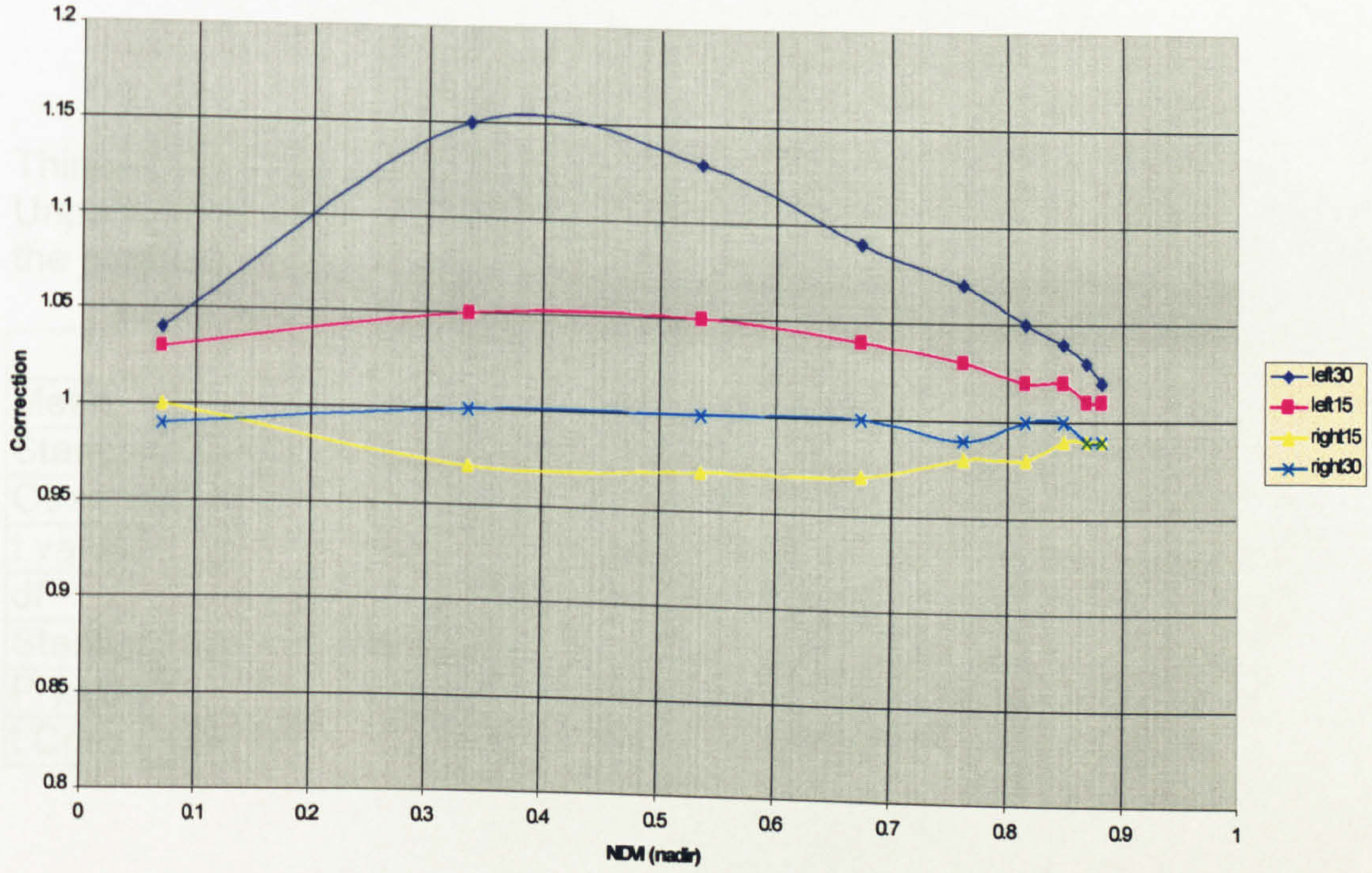
Table FIII: Correction values by angle of view of the SPOT

	Solar Z		31	31	31	31	31
	View Z		-30	-15	0	15	30
	View AZ		117	117	0	48	48
cover		NDVI	Left30	Left15	vertical	Right15	Right30
0	0	0.07	1.04	1.03	1	1	0.99
0.225	0.5	0.336	1.15	1.05	1	0.97	1
0.339	1	0.536	1.13	1.05	1	0.97	1
0.534	1.5	0.673	1.09	1.04	1	0.97	1
0.639	2	0.761	1.07	1.03	1	0.98	0.99
0.72	2.5	0.815	1.05	1.02	1	0.98	1
0.783	3	0.848	1.04	1.02	1	0.99	1
0.832	3.5	0.869	1.03	1.01	1	0.99	0.99
0.869	4	0.882	1.02	1.01	1	0.99	0.99

The study site is situated at about Latitude of $52\text{-}53^0$ and SPOT imageries during the month of June were used for the present study. Therefore Solar Zenith, View Zenith and View Azimuth angles were selected for this correction as in the original model used by Steven (1998).

NDVI values in Appendix C were corrected according to the correction values shown in Figure II. The 1997 image was taken as the reference year.

Figure FII: Correction values of NDVI



Appendix G

Thinned and Pre-Thinned areas
Unpaired two tailed t test for the difference between the means.

	Pre-Thinned	*Thinned*
Mean	0.740	0.598
Standard deviation	0.056	0.199
Observations	20	20
t values	3.081	
df	38	
Standard error of difference	0.046	
P value	0.0038	
t Critical one-tail	1.729	

Felled and Pre-felled areas
Unpaired two tailed t test for the difference between the means.

	Felled	*Pre-felled*
Mean	0.323	0.736
Standard deviation	0.766	0.058
Observations	20	20
t values	2.405	
df	38	
Standard error of difference	0.172	
P value	0.0211	
t Critical one-tail	1.729	

Student's t Table

Student's t distribution: As indicated by the chart below, the areas given at the top of this table are the right tail areas for the t-value inside the table. To determine the 0.05 critical value from the t-distribution with 6 degrees of freedom, look in the 0.05 column at the 6 row: $t_{(.05,6)} = 1.943180$.

t table with right tail probabilities

df\p	0.40	0.25	0.10	0.05	0.025	0.01	0.005	0.0005
1	0.324920	1.000000	3.077684	6.313752	12.70620	31.82052	63.65674	636.6192
2	0.288675	0.816497	1.885618	2.919986	4.30265	6.96456	9.92484	31.5991
3	0.276671	0.764892	1.637744	2.353363	3.18245	4.54070	5.84091	12.9240
4	0.270722	0.740697	1.533206	2.131847	2.77645	3.74695	4.60409	8.6103
5	0.267181	0.726687	1.475884	2.015048	2.57058	3.36493	4.03214	6.8688
6	0.264835	0.717558	1.439756	1.943180	2.44691	3.14267	3.70743	5.9588
7	0.263167	0.711142	1.414924	1.894579	2.36462	2.99795	3.49948	5.4079
8	0.261921	0.706387	1.396815	1.859548	2.30600	2.89646	3.35539	5.0413
9	0.260955	0.702722	1.383029	1.833113	2.26216	2.82144	3.24984	4.7809
10	0.260185	0.699812	1.372184	1.812461	2.22814	2.76377	3.16927	4.5869
11	0.259556	0.697445	1.363430	1.795885	2.20099	2.71808	3.10581	4.4370
12	0.259033	0.695483	1.356217	1.782288	2.17881	2.68100	3.05454	4.3178
13	0.258591	0.693829	1.350171	1.770933	2.16037	2.65031	3.01228	4.2208
14	0.258213	0.692417	1.345030	1.761310	2.14479	2.62449	2.97684	4.1405
15	0.257885	0.691197	1.340606	1.753050	2.13145	2.60248	2.94671	4.0728
16	0.257599	0.690132	1.336757	1.745884	2.11991	2.58349	2.92078	4.0150
17	0.257347	0.689195	1.333379	1.739607	2.10982	2.56693	2.89823	3.9651
18	0.257123	0.688364	1.330391	1.734064	2.10092	2.55238	2.87844	3.9216
19	0.256923	0.687621	1.327728	1.729133	2.09302	2.53948	2.86093	3.8834
20	0.256743	0.686954	1.325341	1.724718	2.08596	2.52798	2.84534	3.8495

Source: Quantitative techniques in Geography, Hammond & McCullagh, 1978