A COMPARISON OF SELECTED SATELLITE REMOTE SENSING TECHNIQUES FOR MAPPING FIRE SCARS IN LIMESTONE FYNBOS

by

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DECLARATION

I, the undersigned, hereby declare that the work contained in this thesis is my original work and has not previously in its entirety or in part been submitted at any university for a degree.

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SUMMARY

There are many reasons to conserve fynbos. Not only does fynbos form part of the Cape floral kingdom, one of the richest floral kingdoms in the world, but the contribution that it makes to the regional economy through utilisation, education, recreation and tourist opportunities is immeasurable.

Fire plays an integral role in fynbos ecosystems. According to Van Wilgen, Richardson & Seydack (1994: 322) "...managing fynbos equates to managing fire". Therefore managers need accurate fire information about a fynbos area to manage it properly. This is where satellite remote sensing can provide the manager with useful information about the fire regime. In other words, satellite remote sensing can help a manager establish where and when an area has burnt.

Using readily available satellite data, this study attempts to establish (through comparison) what techniques would be most suitable and affordable to compile a fire information database. Landsat Thematic Mapper data from 1990 - 1996 of the south-western Cape was used and compared with existing fire records of the area.

The results show that techniques such as supervised and unsupervised classification are reliable in identifying burnt areas, but a major drawback of these techniques is that they require a large amount of user input and knowledge. They are thus not regarded as simple or easily repeatable.

The more simple techniques like image differencing and image ratioing were also found to be reliable in identifying burnt areas. These techniques require less user input and in some instances less data (image bands) to produce similar (or better) results than supervised and unsupervised classification techniques.

The results show that differencing temporally different images, obtained from applying principle components analysis, produces reliable results with very little confusion and little user input. Using such a technique could enable users to procure only two bands of Landsat data and still produce reliable fire information for managing a fynbos ecosystem.

OPSOMMING

Daar is verskeie redes waarom fynbos bewaar moet word. Nie net vorm dit deel van een van die rykste blommeryke in die wêreld nie, maar die bydrae wat dit tot die streeksekonomie maak, deur die benutting van veldblomme en die geleenthede wat dit bied vir toerisme en ontspanning, is enorm.

Vuur speel 'n belangrike rol in die bestuur van fynbos ekosisteme. Soos beklemtoon deur Van Wilgen, Richardson & Seydack (1994: 322) se stelling: "...managing fynbos equates to managing fire". Om hierdie rede is dit belangrik dat 'n bestuurder akkurate inligting oor die verspreiding van veldbrande moet hê. Satelliet-afstandwaarneming kan hier 'n belangrike rol speel deur sulke inligting te verskaf.

Deur gebruik te maak van maklik bekombare satellietdata, poog hierdie studie om te bepaal (d.m.v. vergelyking) watter tegnieke die mees geskikte is in terme van bekostigbaarheid en gebruikersvriendelikheid. Landsat Thematic Mapper data van 1990 tot 1996 van die suidwes-Kaap is gebruik en vergelyk met bestaande branddata van die studiegebied.

Daar is gevind dat tegnieke soos gerigte en nie-gerigte klassifikasie in staat is om gebrande dele betroubaar uit te ken. Hierdie tegnieke verg egter baie insette en kennis van die gebruiker en is ook nie maklik om jaar na jaar te herhaal nie. Daarom word hierdie tegnieke nie aanbeveel nie.

Daar is gevind dat die eenvoudiger tegnieke soos veranderingsanalise ook gebrande dele betroubaar kon uitken. Hierdie tegnieke het die voordeel dat die gebruiker nie baie kennis van die gebied hoef te hê nie en ook nie so baie insette hoef te lewer nie. Hierdie tegnieke word bo gerigte en nie-gerigte klassifikasie aanbeveel.

Die resultate dui daarop dat betroubare resultate verkry kan word deur temporeel verskillende beelde, verkry deur hoofkomponentanalise, van mekaar af te trek. Hierdie tegniek vereis relatief min gebruikersinsette en daar kan selfs met slegs twee Landsat bande gewerk word. So 'n tegniek kan beslis 'n bekostigbare en effektiewe manier wees om nodige inligting vir die bestuur van 'n fynbos ekosisteem te bekom.

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CHAPTER ONE: FIRE AND FYNBOS – STUDY BACKGROUND

1.1 INTRODUCTION

Fynbos forms part of the Cape floral kingdom, the richest per unit area floral kingdom in the world (Cowling 1992). Apart from the obvious importance of preserving biodiversity, the continued conservation of the unique fynbos ecosystems is essential to preserve the contribution that it makes to the regional economy through utilisation, education, recreation and tourist opportunities.

According to Van Wilgen, Richardson & Seydack (1994: 322) "Fire is the principal driving force in fynbos dynamics. To a very large extent, resilience at the level of species, communities and ecosystems is determined by the fire regime, and managing fynbos equates to managing fire". Therefore managers need accurate information about the fire history of a fynbos area to manage it properly. However, fire records are only kept for provincial conservation areas and proclaimed Mountain Catchments Areas. Fires in privately owned land, such as in the lowland areas and next to conservation areas, are not systematically mapped. Many areas are also not accurately mapped because of a lack of funds, manpower and difficult terrain. It is these areas that are most at risk of biodiversity loss due to unnatural fire regimes (Burgers 1998).

Satellite remote sensing offers an opportunity to gather historic information about fires that would be helpful to managers. This has been proved in other ecosystems (e.g. Ekstrand 1994; Jakubauskas, Lulla & Mausel 1990; Kasischke & French 1995; Thompson 1993; Thompson & Vink 1997; Viedma, Melià & Garcia-Haro 1997). Only Thompson (1990) has used Landsat (MSS) imagery to map fire scars in a fynbos ecosystem. The finer resolution of Thematic Mapper (TM) imagery has not been utilised for this purpose until now.

The author hopes to ascertain whether satellite remote sensing is indeed a viable means of mapping burnt areas in fynbos communities. In reaching this goal the study will compare different image processing techniques and assess the benefits and limitations of each.

1.2 DEFINING FYNBOS

The Western Cape province is well known for its indigenous vegetation, called fynbos. Dutch settlers referred to the predominant vegetation of the south-western Cape as "fijnbos". Whether this term referred to the ubiquitous small- or fine-leaved component of the vegetation or to the fact that it was too slender for harvesting as a forestry resource is debatable. Nevertheless the term fynbos has become imbedded in biological literature and enthusiastically assimilated by scientists and laypeople alike (Cowling 1992).

According to Cowling *et al* (1989) some confusion around the definition of fynbos is understandable due to the great diversity of biomes, communities and plant species in the subcontinent. Pierce (1984: 3) describes fynbos as: "sclerophyllous shrublands and heathlands". Fynbos is regarded as a mediterranean ecosystem and forms part of what is known as the Cape Floral Kingdom, the smallest, but richest, of the six floral kingdoms of the world (Cowling 1992). Perhaps more remarkable than species diversity of the Cape flora is the degree of endemism: in the order of 68,2% for species and 19,5% for genera. As a result of this, combined with the naturally limited range of many species, and the spread of agriculture and urbanisation, numerous Cape plants are now seriously endangered or extinct (Bond & Goldblatt 1984).

The continued conservation of the unique fynbos ecosystems is essential to preserve the contribution that it makes to the regional economy through utilisation, education, recreation and tourist opportunities (Van Wilgen *et al.* 1992). Pierce (1984) also highlights the considerable scientific and aesthetic interest that the various fynbos ecosystems, their plants and animals, hold. Furthermore, the mountain catchment areas of the fynbos biome are of particular economic importance both as sources of water and as recreational areas.

1.3 THE ROLE OF FIRE IN FYNBOS ECOSYSTEMS

These sclerophyllous shrublands have evolved in response to the interacting factors of a harsh climate, nutrient-poor soils, varied topography and to the disturbance of fire (MacDonald 1995). At the present time, according to Cowling (1992), the incidence of frequent fire rather than a mediterranean-type climate is the key environmental factor which is coupled with nutrient paucity. "The fires do not merely initiate phases of regeneration, as in so many vegetation types, but are vital for the persistence of fynbos flora and vegetation in the landscape" (Cowling 1992: X). This is confirmed by Van Wilgen, Richardson & Seydack (1994: 322) "...to a very large extent, resilience at the level of species, communities and ecosystems is determined by the fire regime, and managing fynbos equates to managing fire".

Our understanding of the importance and role of fire in these ecosystems has grown rapidly over the last few decades and has been well documented (Van Wilgen *et al.* 1992; Bond & Van Wilgen 1996). Understanding of fire's use in the management of these ecosystems has consequently also improved.

1.4 THE USE OF FIRE IN FYNBOS ECOSYSTEM MANAGEMENT

Fire is a management tool that can be used to manipulate habitat patterns and reduce the risk of property damage, but fire is also a naturally occurring agent of disturbance (Meffe & Carroll 1997). Before fire can be used as a management tool, certain information about the fire regime of the relevant ecosystem must be obtained.

The most basic information that a manager would need is the frequency of previous fires. According to Cowling (1992) the season of fire is also a major concern, as has been shown in other studies. Today policy statements call for regular burning (12-15-year cycles) in late summer or early autumn. These cycles are mainly based on the response of serotinous fynbos and other *Proteaceae* to fire and will therefore favour *Proteaceae*, but it is currently believed that this is the best option generally for most species (Van Wilgen, Richardson & Seydack 1994). It has been pointed out that any fixed regime would lead to a decrease in biodiversity.

The intensity of the fires is also a concern for the ecosystem manager. In other words, did they leave cleared, mineralised land and volatilise large amounts of soil nitrogen, or were patches of vegetation left untouched (Meffe & Carroll 1997)? Related to this would be the extent of the fires and whether they occurred over a simple or complex topography. This would mean that post-fire vegetation and animal population responses would vary.

Lastly, according to Meffe & Carroll (1997), one needs to ask the question of whether the present ecosystem will respond in the same way as it did in the past. This is where the presence of alien invasive trees and shrubs further complicates the management of fynbos. These invaders alter the fire regime, reduce species diversity, reduce water yield and change nutrient cycling and biomass accumulation processes (Van Wilgen, Richardson & Seydack 1994).

An additional problem for managers is the fact that fynbos ecosystems are becoming more fragmented, mainly because of human development. Fires that would have spread over extensive areas are now cut off from isolated patches or "islands". Species that need fire to reproduce can disappear from these patches if they are not burned regularly (Van Wilgen 1981).

1.5 CURRENT FIRE MANAGEMENT POLICIES

The policies controlling the use of fire in fynbos management have changed from complete protection in the mid-20th century to more integrated policies used today.

Management involves varying the fire season, fire intensity and size, fire frequency, as well as reconciling ecological and practical requirements (Van Wilgen, Richardson & Seydack 1994). There are four basic models by which an area can be managed according to Seydack (1992) and they all differ in the amount of interference or control that is applied to the fire regime.

The system that enforces the most control over the fire regime is **scheduled block burning**, also called prescribed compartment burning (Van Wilgen, Richardson & Seydack 1994). Under this system the area is divided into blocks and burned at predefined times so that a mosaic of different vegetation ages is formed. This system can be customised for the achievement of many goals. These goals could include: maintenance of a sustained water flow, creating a mosaic of different vegetation ages for fire prevention and for tourism, synchronisation with alien vegetation control measures and to benefit the aims (e.g. harvesting of wild flowers) of the landowner.

The second management system is **two phase block burning**. This system was devised to overcome some of the drawbacks of scheduled block burning, namely: high operating costs and a high risk of runaway fires from prescribed burns. Two phase block burning is based upon the identification of large areas that require burning. These large areas or macro-compartments are then isolated by using a combination of natural fire barriers and regular block burning. The macro-compartments can then be burnt under conditions that would otherwise have been unsafe, by allowing more fynbos to be burnt under optimum fire conditions (Van Wilgen, Richardson & Seydack 1994).

The third system is called **adaptive-interference** fire management. This method is more flexible than either of the previously mentioned systems. It works on the principle that natural fires are only supplemented when deemed necessary. If the vegetation age patterns and threat to private property are acceptable, natural fires are also left to burn. Adaptive interference fire management requires an annual assessment of age class configuration. Four types of areas should be identified: areas where fires should not occur; areas where fire can be left to burn; areas where fire is becoming a priority; and areas where pre-emptive prescribed fires are essential for wildfire control (Seydack 1992).

The most flexible of the four management options is called **natural fire zone** (NFZ) management. This system is based on the belief that ecosystem function is best maintained with a fire regime that varies naturally with respect to frequency, size, intensity and season. Thus natural fires are left to burn without interference and man-made fires are kept from entering such areas where possible (Van Wilgen, Richardson & Seydack 1994). Such areas should consequently be large enough to allow natural fire patterns to develop. Seydack (1992) mentions that it is also necessary to protect surrounding areas from such natural fires, to suppress man-made fires and accurately map all fires in the natural fire zones.

Van Wilgen, Richardson & Seydack (1994: 326) concludes that "the decision to burn is based on records of previous fires in the area, the status of alien invasive plants and the actions taken to treat them, the occurrence of rare or other noteworthy species, and the risk of damage to private property". From the above it is quite clear that accurate maps of previous fires are essential for managers to make informed and correct decisions. As these decisions can directly influence the state of fynbos ecosystems, managers should have access to the best possible data.

1.6 THE STUDY AREA

The area defined in this study as the Southern Overberg streches from 20 to 21 degrees east, with the Langeberg mountains in the north and the De Hoop Nature Reserve in the south. As can be seen in Figure 1.1 this area lies near the southern-most tip of the African continent. The study area is also quite diverse as it stretches from the coast in the south to the Langeberg mountains in the north.

The main focus is the natural vegetation occurring in the south of the study area, this being the Limestone fynbos which occurs mainly in the De Hoop nature reserve (Jarman 1986). The natural and human environment of the area will be discussed in more detail in the following sections.

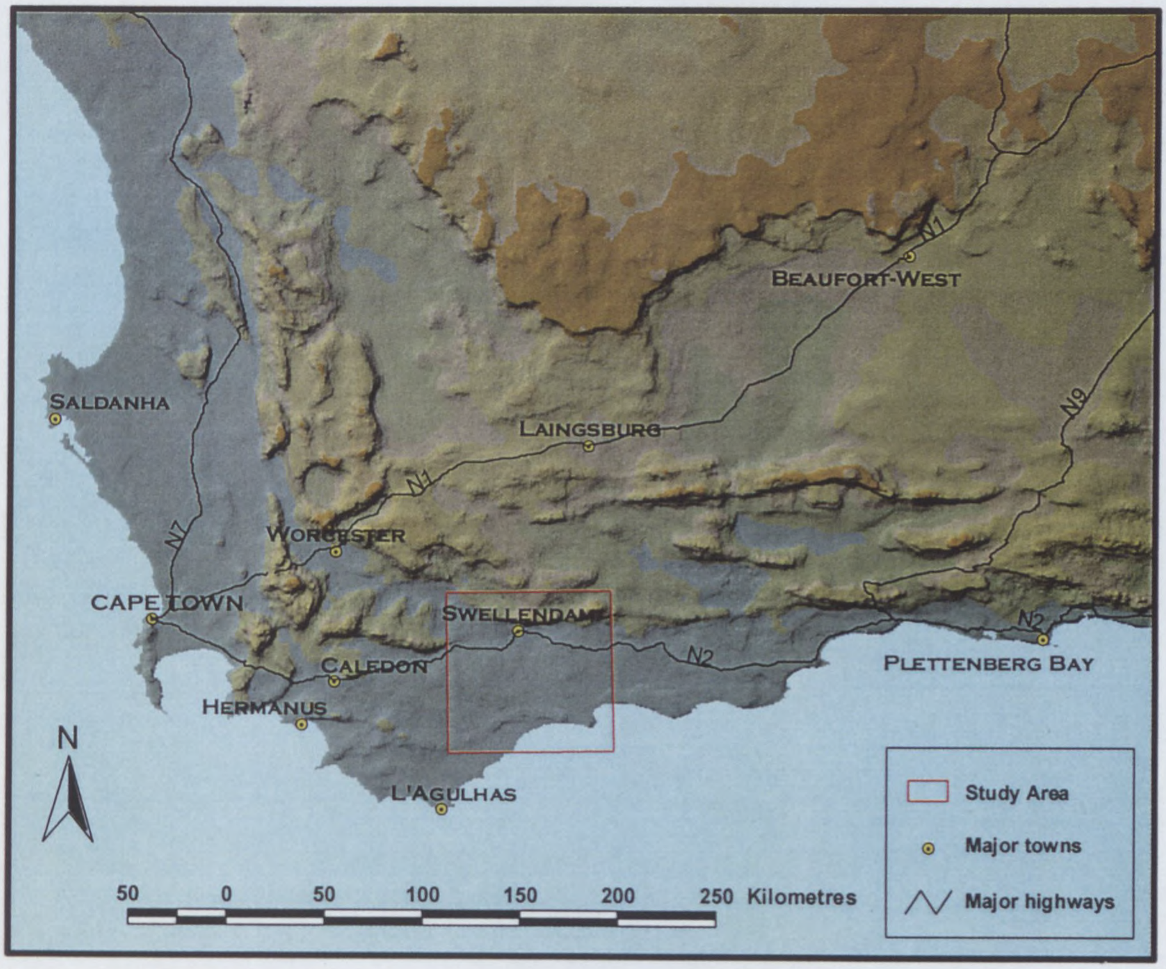


Figure 1.1: The study area

1.6.1 Physiography of study area

The geological formations in the south of the study area are mainly coastal limestone and sand, deposited on underlying shales of the Bokkeveld Group during the Tertiary period. Sandstones and quartzites of the Table Mountain group are also found (Cape Nature Conservation 1999). There are also the extensive sand and calcrete flats, the Potberg hills and the De Hoop vlei.

One of the largest remaining areas of coastal fynbos in the Western Cape province is found in the study area. About 85 per cent of this habitat has already disappeared under the plough and the De Hoop nature reserve thus plays an important part in the protection of what remains. It is estimated that more than 1500 plant species occur in the area, 71 of which are rare or endangered (WildnetAfrica 2000). The De Hoop coastal lake (vlei) has been a Ramsar site since 1975 (Ramsar 2000).

Rainfall varies from 300mm in some of the southern parts to more than 1200mm per year in the mountainous northern parts of the study area. About 65% of this rainfall occurs between April and September (although in some of the northern parts rainfall occurs all year round).

Mean daily temperatures are moderate with temperatures rarely dropping below 3° or exceeding 35° Celsius. The warmest months are usually December through February, with the coldest temperatures usually recorded in June and July.

1.6.2 Human activity

The main human activity in the study area is farming as there are no large or industrial towns in the area. Most of the central parts of the study area fall in the farming region called the "Rûens". This region is well known for the production of small grain (wheat and barley) rotated with cultivated grazing (lucern) in the summer months. Livestock farming is comprised mainly of sheep (wool) and cattle (dairy and meat) farming (Suidkussubstreekontwikkelingsprogram 1985).

The southern parts of the study area (where most of the natural veld exists and where most of the fires occur) are not extensively cultivated, because of the low suitability of the natural veld and soils (Suidkussubstreekontwikkelingsprogram 1985).

1.6.3 Limestone fynbos

As can be seen from Figure 1.2 Limestone fynbos covers most of the southern parts of the study area and the De Hoop nature reserve. Limestone fynbos is restricted to calcareous, neutral to alkaline, shallow sands overlying limestone and associated calcretes of the Bredasdorp Formation. The dominant species on limestone are: Limestone Sugarbush (*Protea obtusifolia*), Limestone Conebush (*Leucadendrom meridianum*), Limestone Pincushion (*Leucospermum truncatum*), Limestone Heath (*Erica propinqua*), Bietou (*Chrysanthemoides monilifera*) a dominant non-proteoid shrub, and *Thamnochortus paniculatus, Thamnochortus guthrieae,* Dwarf Reed (*Chondropetalum microcarpum*) and Whisk Reed (*Ischyrolepisleptocladus*) amongst the restios (Low & Rebelo 1996).

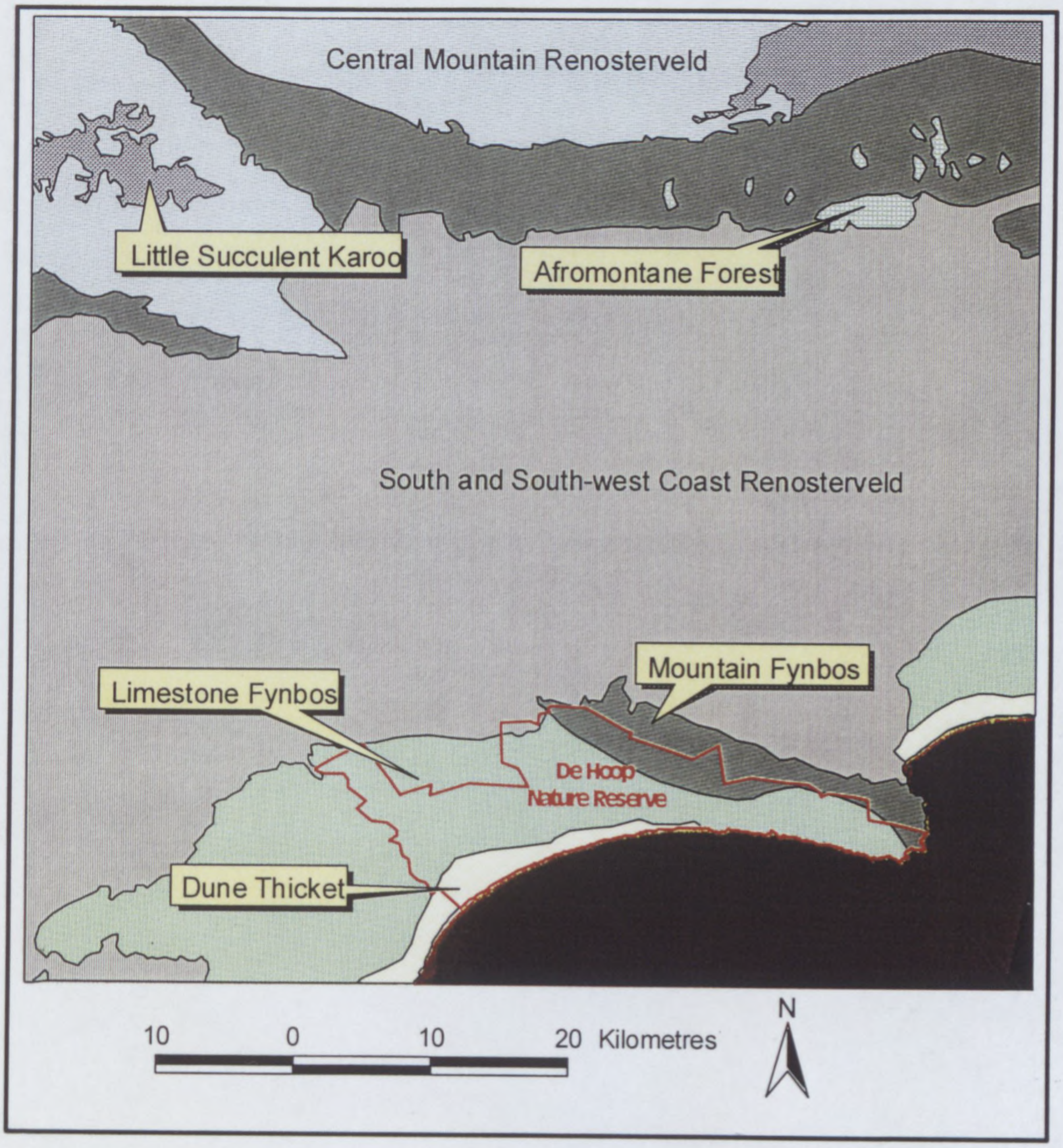


Figure 1.2: Vegetation types within the study area
Source: Low & Rebelo 1996

Figure 1.3: Limestone fynbos vegetation from study area

A typical example of a Limestone fynbos landscape can be seen in Figure 1.3. Limestone fynbos is restricted to the winter, autumn and spring rainfall areas, where rainfall varies from 350 to 600mm per year.

1.7 SPECIFIC OBJECTIVES OF THIS STUDY

To determine how the best possible fire scar data can be extracted optimally, the specific goals of this study is to:

i) find the most effective (in terms of accuracy, costs, repeatability and simplicity) remote sensing procedure (for Landsat Thematic Mapper data) to map fire scars in fynbos communities within the study area and;
ii) test the accuracy of the Landsat-derived fire scar maps; and
iii) propose a suitable strategy for fire scar mapping.

In reaching these goals the author hopes to prove that satellite remote sensing is a viable means of building and updating a historic fire database for the management and monitoring of the fynbos biome.

To achieve these goals the author will briefly discuss the basic principles of remote sensing in Chapter two. Some other applications of remote sensing and different satellite platforms will also be discussed. In Chapter three the different image processing techniques, as used in this study, are explained and the results compared to existing records. In the last chapter, Chapter four, the author will summarize the results obtained in Chapter three. Possible improvements on the techniques used in this study are also discussed.

CHAPTER TWO: THE BASIC PRINCIPLES OF REMOTE SENSING

Many authors have pointed out that satellite remote sensing has enormous potential in the field of environmental science (e.g. Mackay 1994; Newby 1989; Thompson & Whitehead 1992; Van Wilgen, Richardson & Seydack 1994; Wessman 1990). These authors routinely point out the great value of remote sensing data for the conservation manager. To objectively judge this potential one must have a basic knowledge of the processes involved in satellite remote sensing. This is explained in the following sections.

2.1 A DEFINITION OF REMOTE SENSING

Mather (1987: 1) describes remote sensing as "…the measurement and recording of electromagnetic energy reflected from or emitted by the Earth's surface and atmosphere from a vantage-point above the Earth's surface and the relating of such measurements to the nature and distribution of Earth surface materials and atmospheric conditions". To fully appreciate this definition one needs a basic understanding of the electromagnetic spectrum and how it interacts with the earth's surface and atmosphere. An understanding of the instruments used in remote sensing is also useful.

2.1.1 Electromagnetic radiation and the electromagnetic spectrum

All objects, except those at absolute zero (0^{o} Kelvin or -273^{o} Celcius), emit electromagnetic radiation and some also reflect radiation from other objects. Basic wave theory describes how this energy is transmitted. Curran (1985: 9) writes: "...an electromagnetic wave is equally and repetitively spaced in time, moves with the velocity of light and has two force fields that are orthogonal to each other, one of which is electric and the other is magnetic". Three measurements can be used to describe this:

Wavelength is the distance between successive wave peaks and it is usually measured in micrometers (μm). **Frequency**, which is measured in hertz (Hz), is the number of wave peaks that passes a fixed point in space per unit time. Thirdly one can measure **velocity** which, in a given medium, is the speed of light. For reasons of custom, wavelength (usually in μm) is generally used to characterise an electromagnetic wave in remote sensing.

A full range of electromagnetic energy is radiated towards the Earth from the Sun. This range of energy is called the **electromagnetic spectrum**. It can be arbitrarily divided into different regions according to wavelength. Starting with the shortest (<0.03nm) waves called Gamma rays, it continues through X rays (0.03-300nm), ultraviolet (0.30-0.38μm), visible (0.38-0.72μm), infrared (including near, mid and far infrared from 0.72μm to 1mm), microwave (1-300mm) and radio waves (≥30cm). But not all this radiation is useful for remote sensing. According to Curran (1985) the most usable wavelengths are: visible and near infrared (0.4 - 3μm), infrared radiation in the waveband 3 - 14μm and microwave radiation in the waveband 5 – 500mm. This distinction is mainly based on the interaction that certain wavelengths have with the earth's surface and atmosphere.

2.1.2 Interaction with the atmosphere and earth surfaces

All radiation used for remote sensing must pass through a part of the atmosphere, and in satellite remote sensing the radiation must pass through the entire atmosphere. Naturally there has to be some interaction between the radiation and the earth's atmosphere. One can distinguish three types of interaction that have an effect on remote sensing:

Scattering is the redirection of electromagnetic energy by particles suspended in the atmosphere or redirected by large molecules of atmospheric gases. Scattering can be wavelength dependent, which means that radiation in the shorter wavelengths is reflected more than radiation with longer wavelengths. A common example would be Raleigh scattering - the reason the sky is blue. When an observer on the earth's surface watches the sky at midday (when the sun is high in the sky) he will mainly see the blue light (short wavelenght) preferentially redirected by Raleigh scattering. But at sunset (when the solar beam has to travel along a longer path through atmosphere) only the longer wavelengths (red) which are not attenuated by this scattering will be seen.

Another form of wavelength dependant scattering is **Mie scattering**, which is caused by larger particles such as dust, smoke, pollen and water droplets. This type of scattering can influence a broad range of wavelengths in and near the visible spectrum. Because of this wavelength dependence the blue and ultraviolet regions of the spectrum are usually considered less useful for remote sensing. For the same reason radiation in the infrared region of the electromagnetic spectrum is widely used in remote sensing. Campbell (1996) also writes that scattering tends to make bright objects seem darker and dark objects seem brighter. In other words scattering decreases the contrast of an image.

Scattering can also be wavelength independent, also called **nonselective scattering**. With this type of scattering the particles that scatter the radiation have a larger diameter than the wavelength (commomly large water droplets and dust). As all visible wavelengths are scattered equally, one observes this type of scattering as a white or greyish haze.

Refraction is defined by Campbell (1996: 33) as: "...the bending of light rays at the contact of two media that transmit light". This occurs as electromagnetic radiation passes through a stratified atmosphere. It becomes a problem in a turbulent atmosphere when the bending of the waves has an effect on the geometric accuracy of remotely sensed images (Curran 1985).

"**Absorption** occurs when an atmospheric atom or molecule becomes excited by the absorption of electromagnetic radiation; instead of re-emitting radiation at the wavelength at which it was absorbed it uses the energy in heat motion and eventually releases it at much lower wavelengths" (Curran 1985: 54). Water vapour, ozone and carbon dioxide are the primary absorbers of electromagnetic energy. Absorption can both decrease and increase radiation at the sensor and this usually necessitates atmospheric correction of remotely sensed data.

After travelling through the earth's atmosphere the energy reaches the earth's surface. Here it interacts with different surfaces like water, soils and vegetation. Of the energy that reaches vegetation for instance, the tree canopy and the leaves will reflect much of those in the infrared region. Blue and red radiation will, however, be absorbed for use in photosynthesis.

2.1.3 Some concepts used in remote sensing

As described in Mackay (1994) there are four types of resolution that should be considered when using remotely sensed data. Firstly there is **spectral resolution** which refers to the range of wavelength that the specific sensor can measure and record. The number of unique spectral bands and their spectral bandwidth defines the spectral resolution of the satellite system. The more and narrower the spectral bands that a system can record, the more detailed an image of the earth surface will be.

Secondly there is **spatial resolution** which refers to the smallest size of object that can be resolved by the sensor. This so-called Immediate Field of View (IFOV) is the physical dimension of an area on the earth's surface for which one spectral measurement, represented by a single data value, can be made. The **pixel** (or picture element) size of a remotely sensed image is usually chosen to be similar to its spatial resolution. For the Landsat Thematic Mapper sensor this is 30 by 30 meters. Thus a remotely sensed image consists of a matrix of pixels where the intensity of reflectance for each pixel is a digital value. Spatial resolution is also dependent on the swath width of the sensor. This is the total area that is viewed by the sensor at one instance in time. One should keep in mind that spatial resolution is related to scale and if spatial resolution is low, interpretation of large-scale (detailed) products may be difficult or inappropriate.

The third type of resolution is **radiometric resolution** which refers to the range of possible data values (for each band) that are available to describe each individual pixel. For example: In 8-bit data a range of 256 brightness values (2^8 =256) can be obtained, whilst in 7-bit data only 128 brightness values (2^7 = 128) can be recorded. This has implications for the contrast in an image.

The last type of resolution to consider is **temporal resolution**. It refers to how often an image of the same area can be obtained. Some satellite sensors can obtain imagery on demand, but many have a fixed interval at which they pass over the same area on the earth's surface. This is restricted by the orbit and design of the satellite.

2.2 DIFFERENT SATELLITE PLATFORMS

Several different satellite platforms currently orbit the earth, but only a few were specifically designed for terrestrial observation. Some of the satellites that would be potentially useful for this study are discussed here. One that was designed specifically for terrestrial observation, and the one used in this study, is the Landsat series of satellites.

2.2.1 Landsat

The Landsat series of satellites probably had the biggest impact on satellite remote sensing over the last 19 years. First launched in 1972, this satellite platform provided a wide variety of researchers with easily accessible and useful remotely sensed data. The platform is currently in its seventh generation as Landsat-7 was successfully launched on April 15th 1999 (Sheffner 1999). The data for this study came from Landsat-5, which was activated in March of 1984, as Landsat-6 was destroyed at launch.

According to Mackay (1994) Landsat-5 has an altitude of 705 kilometres, an orbital cycle of 98.9 minutes and an equatorial crossing time of 09h30. It crosses the same area every 16 days. On board it has two sensors, the Multispectral Scanner (MSS) and the Thematic Mapper (TM). The Multispectral Scanner is a multi-spectral scanning system recording four bands of reflected/emitted electromagnetic radiation from the visible and near-infrared regions of the spectrum. The swath width is approximately 185 kilometres, thus giving a coverage area per image of approximately 34000 square kilometres. The pixel size is only 79 by 79m. Radiometric resolution is 7-bit (2^7), thus giving data values ranging from 0 to 127. One should, however, keep in mind that this sensor has been in use since 1972.

The more modern Thematic Mapper sensor has been in use since 1982 with the launch of Landsat-4 and can be seen as an improvement on the MSS. It has the same swath width of approximately 185km, but improvements include: 7 bands for better spectral resolution and 8-bit radiometric resolution, giving a possible range of pixel values from 0 to 255. Furthermore the spatial resolution has been reduced to 30 by 30 metres (except for the new thermal band which has a resolution of 120 by 120 metres on Landsat-5). The characteristics of the different bands and some of their potential uses are summarised in Table 2.1.

Table 2.1: Characteristics of Landsat TM bands (adapted from Mackay 1994)

Band	Resolution	Spectral definition	Some applications
1	30m	Blue-green 0.45 - 0.52μm	Penetration of clear water; bathymetry; chlorophyll absorption; mapping of coastal waters
2	30m	Green 0.52 - 0.60μm	Records green radiation reflected from healthy vegetation; assesses plant vigour
3	30m	Red 0.63 – 0.69μm	Chlorophyll absorption important for plant-type discrimination
4	30m	Near infrared 0.76 – 0.90μm	Indicator of plant cell structure; biomass; plant vigour; complete absorption by water
5	30m	Mid infrared 1.55 – 1.75μm	Indicative of vegetation moisture content; soil moisture mapping; penetration of thin clouds
6	120m	Far infrared 10.4 – 12.5μm	Vegetation stress analysis; soil moisture discrimination; plant heat stress
7	30m	Mid infrared 2.08 – 2.35μm	Discrimination of rock types; alteration zones for hydrothermal mapping

2.2.2 Other platforms related to remote sensing of fire

There are many other satellite platforms that have the potential to map fire related features. The following are examples of such systems:

Systeme Pour L'Observation de la Terre (Centre National D'Etudes Spatiales) (**SPOT**) is relatively similar to Landsat but managed by France. The fourth member in the SPOT family, SPOT 4, was successfully launched in 1998 with enhancements that include a new spectral band and improved image acquisition capabilities. The spatial resolution of the multispectral bands are 20m while the panchromatic band has a spatial resolution of 10m (CNES 2000). This system monitors worldwide vegetation cover and has been used for mapping and monitoring crops (Justice & Kaufman 1999). Since SPOT is capable of imaging virtually all exposed landmasses once a day, it is particularly useful for fire scar detection and identifying changes in vegetation over time. The images are however considerably more expensive than Landsat data.

The Advanced Very High Resolution Radiometer (**AVHRR**) is operated by the National Oceanic and Atmospheric Administration (**NOAA**). This system has a low spatial resolution of 1.1 km, but high temporal (twice daily) resolution (Curran 1985). It has been used to detect active fires, smoke plumes, fire scars and vegetation indices. It also forms the basis of proposed global fire monitoring initiatives (Dwyer, Gregoire & Malingreau 1998). Another advantage according to Desbois *et al* (1999) is its good spectral information (visible, near, medium and thermal infrared).

Earth Remote Sensing Along Track Scanning Radiometer (**ERS ATSR-2**) of the European Space Agency produces global 1km spatial resolution images of fires or burned areas. The addition of a new 1.6 μm band makes it particularly useful for measuring high surface temperatures and scars since it can penetrate smoke plumes (Justice & Kaufman 1999).

Defence Meteorological Satellite Program Operational Linescan System (**DMSP OLA**) is made up of two telescopes, one visible and one infrared. The OLS records visible and infrared emissions from the sun or the moon reflected off clouds and other features. This system's ability to monitor fire is limited to night-time, but information is obtained 1-2 times per night (Justice & Kaufman 1999). The spatial resolution of the OLS is 2.7 km for global scale and 0.56 km for specific areas (ECRSME 2000).

Japanese Earth Remote Sensing Synthetic Aperture Radar (**JERS SAR**) is operated by the European Space Agency and the National Space Agency of Japan. This satellite system is equipped with an active microwave sensor and OPS, an optical sensor that measures light reflected off the surface of the Earth. This technology enables JERS to detect burn scars (Justice & Kaufman 1999). For the Global Boreal Forest Mapping project this satellite was used to produce 100m spatial resolution images of the entire tropical and boreal forest belts of the earth (Jonsson 2000).

FIRESAT is still in the design stage, but is significant in that it is the only instrument to be designed specifically for the monitoring of global fire events and biomass burning. It is envisaged to have spatial resolution of no worse than 250m. It might be launched in a sun-synchronous orbit of 830 km so that it will cover virtually the whole globe twice daily. This project is under development at the National Aeronautics and Space Administration (NASA) in the USA (Levine *et al* 1999).

2.3 REMOTE SENSING AND FIRES

Satellite remote sensing of fire has become a very active field of study in recent years. It has prompted interagency and even international cooperation as in the Megafires project (Chuvieco, Salas & Vega 1999). There are also efforts to establish a global satellite fire monitoring system. The internet has become littered with various websites related to remote sensing of fire features. A few examples of such sites are given in Appendix A.

Remote sensing of fire-related features can be divided into three fields. Firstly there is estimation of fire potential, which is usually based on some kind of fuel/biomass and environmental information. Secondly there is active fire mapping, which is of most interest to those in a disaster management environment. Thirdly there are studies (like this one) that focus on burned areas. These results are often used in an environmental management milieu.

2.3.1 Estimation of fire potential

In recent years estimation of fire potential and prediction of fire risk has become an accepted part of fire management. Maps of high fire risk areas are often posted along with daily weather forecasts and currently there are many agencies that focus mainly on fire prediction. There are several fuel indices and fuel moisture models (short-term, mid-term and long-term) of which examples are given by Bovio & Camia (1999).

A good example of a national fire risk prediction system is run by the United States Department of Agriculture's Forestry Service. Fire predictions have been standardised with the National Fire Danger Rating System (NFDRS). "NFDRS computations are based on once-daily, mid-afternoon observations ...from the Fire Weather Network which is comprised of some 1500 weather stations throughout the Conterminous United States and Alaska" (Bradshaw 1998). It takes into account current and antecedent weather, fuel types, and the state of both live and dead fuel moisture.

Dead fuel moisture is critical in determining fire potential. In the case of NFDRS dead fuel moisture can be defined as the time it takes a fuel particle to reach 2/3's of its way to equilibrium with its local environment. Four vegetation greenness maps are derived weekly from Normalized Difference Vegetation Index (NDVI) data observed by satellites" (Bradshaw 1998).

The main data source for this fire danger rating system is the NOAA AVHRR satellite system. It is the most widely used satellite system for fire prediction worldwide. It is also used in a similar application for fire risk prediction in Australia (Freeman & Bullen 1997).

Landsat TM images have also been used to evaluate forest fire risk in Mediterranean areas. Maselli *et al* (1996) compared three indices that could be correlated with fire frequency on the Italian island of Elba. He found that a common spectral vegetation index (NDVI) was slightly inferior to a locally standardised index based on known environmental factors such as slope, aspect and vegetation. A supervised spectral index trained on the specific ecological situation was found to be the most effective in discriminating between different levels of fire risk.

2.3.2 Fire identification in real-time

Efficient response to wildland fires is of critical concern to various agencies. Examples of the type of data they would require include: maps of existing regional fires, fuel type or vegetative greenness, and maps of populated areas that might be threatened. "For effective response to the fire, these data must be up to date and easily accessible for prediction, planning, and resource allocation..." (Knapp, Andrews & Turek 1996).

Currently the AVHRR is the most commonly used satellite system for detecting active fires, albeit at low spatial resolution. The reason for this is its high temporal resolution, which means that it can deliver data twice daily. Still, "the challenge in the area of emergency response is to provide the technology to extract crucial information from images quickly enough to influence the decision-making process" (Knapp, Andrews & Turek 1996). According to Pereira & Setzer (1996) such a real-time operational system to detect and fight fires using AVHRR was developed in Brazil and has been used since 1987.

In the United States the National Geographic Data Center (NGDC) within the National Oceanographic and Atmospheric Administration (NOAA) has developed classification algorithms for fires using the Defense Mapping Satellite Program (DMSP) operational linescan (OLS) sensor. "These algorithms are used on the visible band of the night orbit and are adjusted for clouds, city lights, and lightning.... Using a wildland fire classification algorithm an analyst could search a sequence of images for current fire locations, examine the temporal extent of a fire, or compare different years/seasons. Including additional classification algorithms, the analyst could pose additional queries to determine wildland fires near urban areas or to find other spatial areas exhibiting similar characteristics to those currently burning, e.g. very dry with heavy fuel load" (Knapp, Andrews & Turek 1996).

For a review of global satellite fire monitoring see the IGBP-DIS Working Paper # 21: Report of the 4th IGBP-DIS fire working group meeting, available online at http://apex.ngdc.noaa.gov/paleo/igbp-dis/frame/publications/wp_21/sc_wp_21.html .

2.3.3 The detection of fire scars

There are numerous and diverse fire scar studies to be found in the literature, using many of the above-mentioned satellite systems. A summary of the use of Landsat imagery for this purpose is provided in this section.

In 1990 Jakubauskas, Lulla & Mausel studied fires in a Michigan pine forest. Working on the principal that the effect of fire reduces the infrared in direct relation to the intensity of the fire, they created a burn severity map to assess change in the forest landscape. The burn severity was calculated using a ratio of infrared and red bands from Landsat MSS images. They successfully used this ratio image to identify burnt areas by "exploiting the near reversal of the standard vegetation reflectance spectral curve caused by the destruction of forest vegetation by the fire" (Jakubauskas, Lulla & Mausel 1990:373).

López García & Caselles (1991) used Landsat TM images to map forest fire scars in the province of Valencia in Spain. This study area had a sub-tropical climate where the vegetation had adapted to semi-arid conditions and was frequently ravaged by fire. They found that radiance in the thermal band could be used to delineate burnt areas. They also found that normalised difference images of near- and middle infrared bands were well suited to identify burnt areas and monitor vegetation recovery after a fire.

In 1993 Pereira & Setzer studied the spectral characteristics of fire scars in Landsat Thematic Mapper images of Amazonia. They found that TM images could be used to detect and assess biomass burning in tropical forests. Thematic Mapper channel 4 was found to be the most effective for identifying fire scars, with band 5 also detecting fire scars. The techniques used were based on supervised classification using single-cell and maximum likelihood classifications. The same authors undertook a fire scar detection study in the savannahs of central Brazil in 1996. By applying the parallelepiped algorithm to NDVI images (created from bands 3 and 4) and bands 4 and 5, they successfully mapped fire scars at a 1:100 000 scale (Pereira & Setzer 1996).

Crawford & Pianka (1996) used Landsat MSS imagery to map fire scars in the Great Victoria Desert in Australia. They exploited the high absorptive characteristics of ash and high reflective characteristics of vegetation in the near-infrared band. They detected change by subtracting the one year's brightness values from another. From this resultant layer, a pyramid segmentation method was used to accurately delineate the fire boundaries (Crawford & Pianka 1996).

Salvador, Diaz-Delgado, Valeriano & Pons (1998) set out to establish a fire history for the period 1975-1993 of Catalonia in the Northeast of Spain. They calculated NDVI values from bands 2 and 4 of the Landsat MSS sensor. Subtraction of NDVI values between consecutive images was chosen as method for its "simplicity and robustness". The level of accuracy increased when the burnt areas were equal or greater than 30 hectares. Factors, such as the different fire intensities, soil response in sparse shrub-covered zones and clearing activities did pose some difficulty.

In 1998 Yool used Landsat TM imagery to calculate the severity of fires in the Coronado National Forest in Arizona, USA. Yool employed the Kauth-Thomas transform (KT) to estimate three classes of burn severity (Yool 1998).

Kitchin & Reid (1999) undertook a study in Guy Fawkes River National Park in New South Wales, Australia. They evaluated AVHRR and Landsat imagery to establish a comprehensive fire history of the national park. For Landsat TM they found "an increase in band 7 due to the burn, a moderate increase in band 5 and little change in bands 4 – 1". Band 7 and band 5 were the most accurate in separating the spectral response of burnt and non-burnt vegetation and hence for mapping the fire boundary. They also found that the best discrimination of the fire boundary was the ratio of band 7 over band 5. After using the ratio and difference to highlight change, they determined the actual fire boundary through visual interpretation.

2.4 SOUTH AFRICAN REMOTE SENSING STUDIES OF FIRE

The potential of satellite remote sensing for ecosystem management has long been recognised in South Africa (e.g. Newby 1989; Thompson 1990, 1993; Thompson & Whitehead 1992). The following studies are of particular interest with regard to the application of remote sensing to fire management.

In 1990 Thompson used Landsat MSS data to map fires of the 1988 – 1989 season in the south-western Cape region. The results showed that Landsat MSS data provided a viable technique for synoptic, repetitive, regional monitoring of burn extents and for the development of fire history datasets (Thompson 1990). Principal components analyses (PCA) was used to delineate total burn extent. According to Thompson (1990:3) this technique has a "proven ability in identifying and extracting localised regions of change (such as burns) from within multitemporal datasets". Thompson also calculated qualitative classes of fire severity from the post-fire imagery using NDVI.

In 1993 Thompson used Landsat Thematic Mapper imagery to monitor biomass and fire severity in a savannah environment. The NDVI was used to estimate pre- and post burn quantitative biomass in the Hluhluwe-Umfolozi Game Reserve. PCA and unsupervised classification was also used to calculate burn extent. Although the NDVI was found to be effective for general estimates of quantitative herbaceous biomass, it was not sufficiently sensitive to extremely low biomass levels. This meant that biomass remaining within a fire scar could not be calculated, but unburned vegetation "islands" were however identifiable. From this study he found that both quantitative NDVI biomass maps and accurate fire-scar extent could be derived from Landsat TM at scales suitable for wildlife and natural resource management. The data produced could also be used in the development of fire prediction models and the monitoring of actual burn extent (Thompson 1993).

In 1997 Thompson also studied fire scars in the Pilanesberg National Park with the use of TM data. The aim of the study was to find the most appropriate technique for mapping fire-scars in the complex topography of the park. It was found that the most significant problems were those of relief shadowing and the variable shadow lengths between the images used. For this reason procedures like PCA did not perform well, since the statistical measures within them were not able to clearly discriminate between changes due to fire-related activities and other temporal factors. In the end an unsupervised classification of a combined dataset (NDVI and composites of bands 3,4 and 5 of the different dates) was found to be the most suitable (Thompson & Vink 1997).

CHAPTER THREE: IMAGE PROCESSING OF LANDSAT TM IMAGERY

To do digital image processing one needs certain hardware and software. The bulk of image processing for this study was carried out on personal computers with the Idrisi for Windows version 2 software package. This particular package was chosen because it is relatively inexpensive and user-friendly. The main beneficiary of this study, the Western Cape Nature Conservation Board (WCNCB), also had a license for this software and could thus easily incorporate the proposed techniques. This chapter will cover the process of data correction and the extraction of fire scars through the proposed techniques.

3.1 PRE-PROCESSING OF DATA

The Scientific Services branch of WCNCB supplied most of the data used for this study. This included six Landsat Thematic Mapper quarter scenes for the years 1990 to 1996, excluding 1992. All images were in band interleaved by line (BIL) format and then imported to Idrisi for Windows.

Unfortunately very little ancillary data about these images was available. These images were originally captured and processed by the CSIR Satellite Applications Centre (SAC) at Hartebeeshoek and cover the area south of 33°45' South and between 20° and 21° East. The images were recorded on the following dates: **27.02.1990**, **13.01.1991**, **02.01.1993**, **22.02.1994**, **09.02.1995** and **15.03.1996**.

The images were all geometrically corrected to the Transverse Mercator projection with 21° east as central meridian. It was deemed unnecessary to georeference the images further as the registration error of approximately 1-2 pixel was considered acceptable for the purposes of this study.

Hill & Sturm (1991) note that multi-temporal comparisons assume that changes are related to landcover change, not to atmospheric or other differences. As multi-temporal comparisons would make up a large part of the study, some radiometric or atmospheric correction was considered essential to ensure that changes due to external factors are minimised.

Absolute atmospheric correction techniques, which require information other than the digital image data, were not considered, as such data was not available. Instead the author considered a technique that would only use information contained in the image data itself. A dark object subtraction technique as described by Chavez (1988) was decided upon. This type of correction involves subtracting a constant value from the entire image. The constant is derived from a clear water body in the image. The spectral response in each band is then adjusted to expected values for such a clear water body. Thus a different constant is used for each spectral band, with a different set of constants used from image to image. A noted drawback of such a correction is the assumption that atmospheric effects are constant over the whole image, which is often not the case (Hill & Sturm 1991). As the images in this study were firstly selected to be cloudless, it was found that only small (<6) corrections had to be made for all of the images.

For this study a large dam near Swellendam was used as the clear waterbody, while the 1993 image was used a reference image. The Buffeljags dam was chosen because it is deep and relatively free of sediment. The 1993 image was chosen because it had values closest to the expected norm.

The possibility of topographic normalisation was also considered. Although much research has gone into this subject (e.g. Civco 1989; Colby 1991; Conese *et al* 1993; Proy, Tanré & Deschamps 1989) the author felt it was inappropriate for this study. Firstly such normalisation seems to decrease contrast within the image, which decreases the effectiveness of change detection techniques. Secondly the software and auxiliary data (e.g. DEM) needed for such corrections was not readily available. Thirdly it is only in a small part of the study area that topography would have a noticeable impact on reflectance. The images were also taken in the same season (summer), which would make the effects of topography and shadow more or less equal over all images.

Ideally results (from the proposed techniques) should be tested against field observations to ascertain their accuracy. Unfortunately the most recent satellite data available for this study was from early 1996, which is more than two years before this study was initiated. Therefore field observations were not considered. Using aerial photographs as reference was also found to be less than ideal, as the only photographic coverage of the study area between 1990 and 1996 was in 1:150 000 scale and covered the area only once in those 6 years. Trying to accurately digitise fire scars from such a source would have been futile. Fortunately the Western Cape Nature Conservation Board provided digitised fire data that corresponded with the years in which the satellite images were gathered.

The existing fire data was gleaned from several sources that had interests in the study area. It ranged from inaccurate sketch maps of fire events to meticulously digitised polygons from Landsat imagery and aerial photographs. In other words, the mapping was done by means of visual interpretation or as some would call it - "traditional" mapping techniques. It is to the latter that the techniques proposed in this study were compared.

When comparing these digitised fire scars to the fire scars extracted by the techniques suggested in this study, one must consider the following: it has been shown by Thompson (1990, 1993) that fire scars extracted by computerised techniques (as in this study) identify less burnt area than "traditional" techniques; and this is mainly due to small unburnt areas (islands) inside a large fire scar that are usually not digitised manually.

From the existing fire records five fire scars were selected to which the extracted fire scars could be compared. These are shown in Figure 3.1. Note that only the southern four fire scars (1990, 1991, 1992 and 1996) fall in the Limestone fynbos region, whereas the northern-most fire scar (1993) falls in a Mountain fynbos region. This fire scar was included only to give the reader an idea of how suitable the proposed techniques could be in another vegetation type. This one fire should not be considered as representative of the whole Mountain fynbos region.

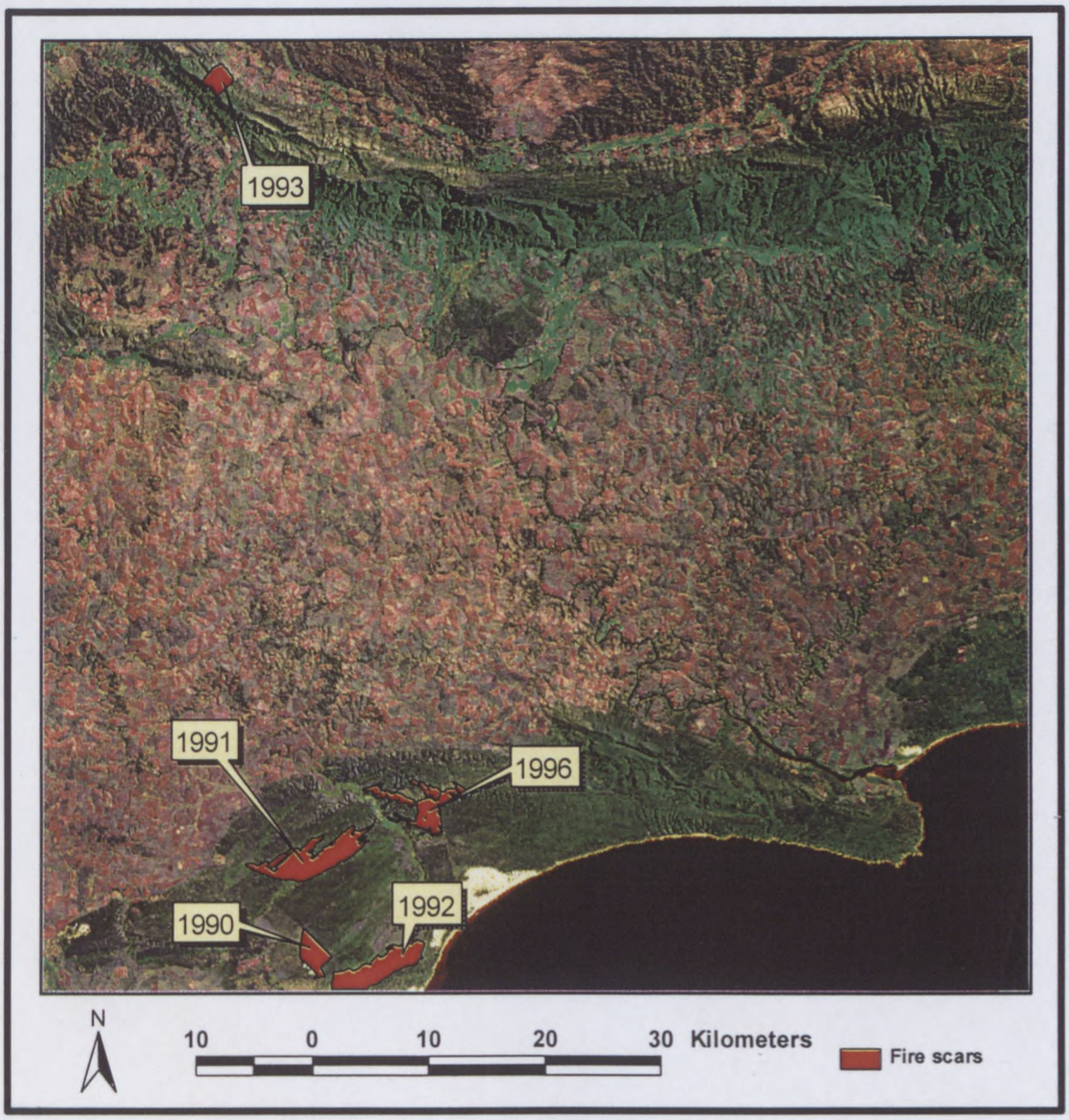


Figure 3.1: Selected existing fire records in study area

The comparative ages of the fire scars depicted in Figure 3.1 are of some importance. The fire scars were first recorded by Landsat when they were: less than 25 days (1990 fire scar), less than 30 days (1992 fire scar), less than 2 months (1996), less than 3 months (1993) and 22 months (1991) old. These five fire scars should give a reliable indication of how the proposed techniques perform when mapping fire scars at varying ages and in different (1993 fire scar) vegetation types.

3.2 PRELIMINARY INSPECTION OF SATELLITE DATA

The basic premise of image classification (and remote sensing in general) is that different objects on the ground have different spectral responses, which can be detected by remote sensors. Unfortunately, many objects do not have a stable, easily discernible or distinct spectral signature. From the literature one can ascertain how the spectral response of different landcover classes *should* look, but one must keep in mind that these are particular to a study area and/or season.

3.2.1 Comparison of spectral signatures

With this in mind the author decided to inspect the spectral signature of fynbos in the study area and compare it to signatures of other landcover types. In Figure 3.2, the signatures of irrigated annual crops (grnveg) and limestone fynbos are compared.

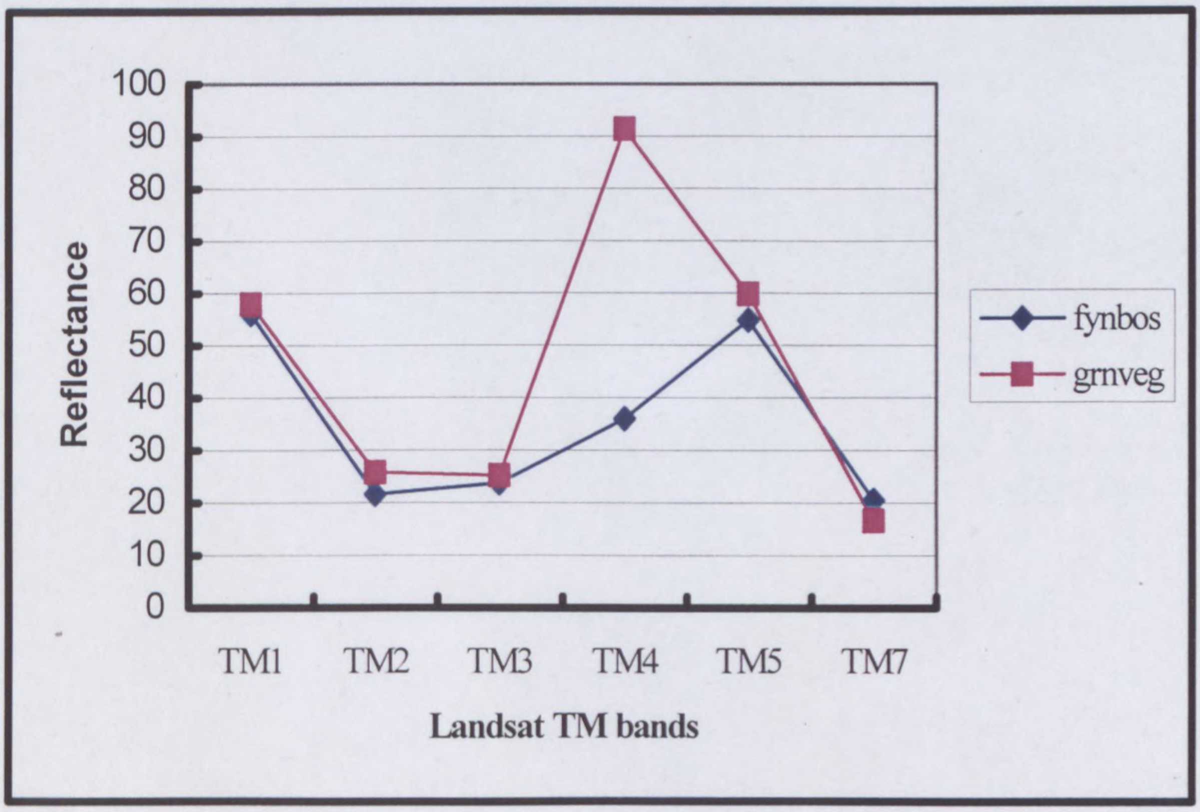


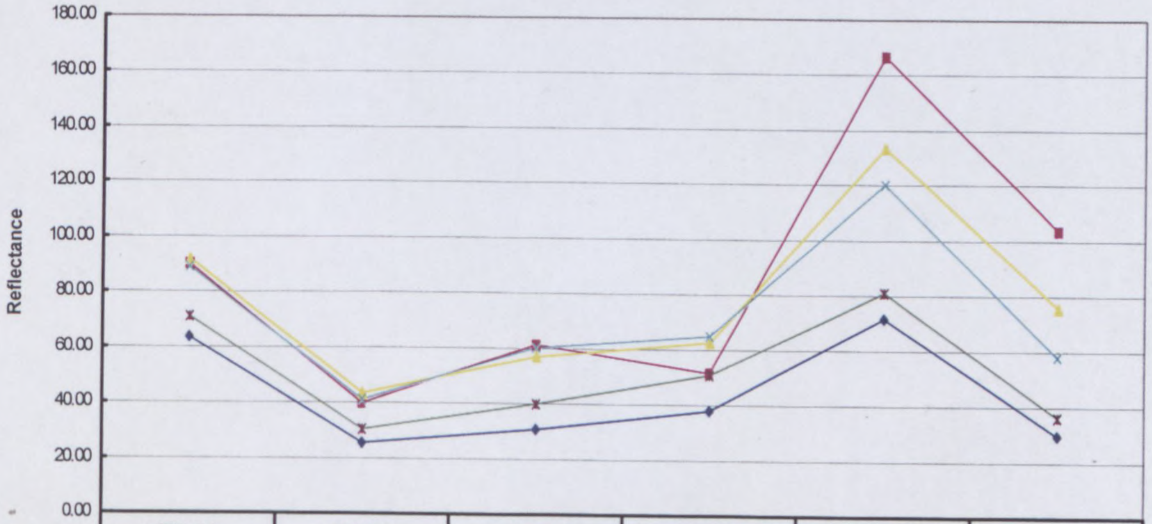
Figure 3.2: Comparison of fynbos and green vegetation signatures

From Figure 3.2 it is evident that fynbos does not show the high reflectance in the near infrared region (TM band 4) as compared to healthy green vegetation. Other authors such as Morris (in Thompson 1990) have also noted this phenomenon: "...fynbos has unusually low reflectance levels (prior to burning) even for mediterranean vegetation types". This characteristic makes it very different from vegetation types studied by authors such as Baret *et al* (1988); Ekstrand (1994); Jakubauskas, Lulla & Mausel (1990) and Maselli *et al* (1996).

This also has an impact on identifying burnt areas as many authors indicate that burnt vegetation is characterised by a drop in reflectance in the near infrared region (TM band 4). From Figure 3.2 it is clear that a drop in near infrared reflectance would not be as noticeable in this fynbos region. Thompson (1990:12) writes: "...in fynbos the burn mapping is sometimes easier to accomplish in the following growth season, as new vegetation 'flushes' can be easier to identify than low burn reflectance levels within regions of already depressed vegetation reflectance". This has led the author to investigate whether other TM bands would be better able to identify burnt areas in this study area.

3.2.2 Influence of fire response on spectral signatures

To find which bands would be potentially more suitable for fire scar identification one has to know how fynbos spectrally responds to fire. From fire records supplied by the WCNCB a known fire scar was selected and its spectral signature extracted. In Figure 3.3 the spectral signature of this fire is displayed along with the spectral responses of the same area before the fire and the following post-fire years.



	TM1	TM2	TM3	TM4	TM5	TM7
Prefire	63.80	25.65	30.83	38.02	71.77	29.81
2 months	90.26	40.09	61.64	51.73	166.93	103.74
15 months	91.9	43.52	56.95	62.74	133.4	75.89
27 months	89.08	41.16	60.36	65.09	120.11	58.2
40 months	71.35	30.56	39.94	50.72	81.05	36.41

Figure 3.3: Temporally different fire scar signatures

This particular fire occurred in December of 1992 and the satellite image was taken in February of 1993. The fire scar (at the time of the image) is thus roughly two months old, which would give the burnt vegetation some time to die off and enough time for the ashes to be dispersed by the elements.

The results displayed in Figure 3.3 were somewhat unexpected, because from the literature one expects "...overall lowering of reflectance levels as vegetation has been burnt away" (Thompson 1992:121). The author suspects that Thompson was referring to the spectral response directly (days) after a fire, which would be dominated by ash (which has a low spectral response for all Landsat reflective bands). The chart shows how the burnt area has generally higher reflectance in all bands and much higher reflectance in the middle infrared bands (TM5 and TM7) at two months after the fire.

3.2.3 Influence of soil on spectral signatures

The only comparable results that could be found came from Spain where López García & Caselles (1991) studied a mediterranean forest growing on a limestone substratum. They found "...higher response in the middle infrared (bands 5 and 7) is a consequence of vegetation disappearance" (López García & Caselles 1991: 34). The major commonality between their study and this one is the limestone substratum. They found that the limestone substratum had high reflectance in the middle infrared bands. This would explain the high reflectance in those bands for this study, as illustrated in Figure 3.3.

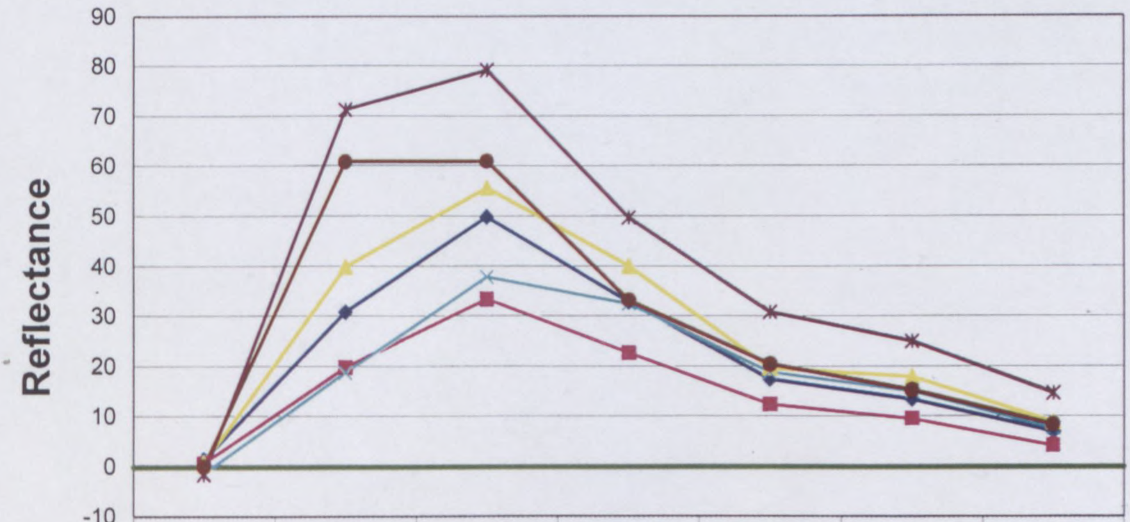
On consequent field visits to the study area the influence of the bright white limestone soils became apparent. In Figure 3.4 one can clearly see the bright soils, which are prevalent in Limestone fynbos and the De Hoop nature reserve, where this photograph was taken.

Figure 3.4: Exposed bright limestone soil of the study area

3.2.4 Resolving the puzzle

Looking at Figure 3.3 again, the only anomaly is that the near infrared band (TM4) shows lower reflectance at two months than at 15 and 27 months. As pointed out in Section 3.2.1, near infrared reflectance can be linked to vegetation vigour and biomass. One can thus hypothesise that the fire reduced vegetation vigour for a few months and then more vigorous regrowth followed in the two years after the fire. After that reflectance in the near infrared band returned steadily towards pre-fire levels. This pattern could indicate that the vegetation cover was almost completely removed by the fire and that recovery was especially strong between 15 and 27 months. This is comparable with results from other studies such as Seydack (1992), Van Wilgen *et al* (1992) and Viedma, Melià & Garcia-Haro (1997).

In Figure 3.5 the spectral response of the same area (a burnt area) is plotted against an adjacent control area (which did not burn) to show how the burnt area spectrally responds over time. One can see how middle infrared reflectance (TM bands 5 and 7) rises steeply after a fire and then decreases steadily over time until 73 months after the fire. At that time the spectral response closely resembles that of pre-fire conditions. As noted in Thompson (1990) it is expected that the (fynbos) canopy should be at 80% of pre-fire levels at an age of four to five years after a fire. This would also seem to be the case here, although it must be remembered that the age of the fynbos in the pre-fire signature is not known. It is noticeable that after 73 months (± 6 years) this fynbos canopy has almost completely recovered to pre-fire levels (compare the first and last columns in Figure 3.5).



	Prefire	<26 days	11 months	35 months	48 months	60 months	73 months
TM band 1	1	31	50	33	18	14	7
TM band 2	1	20	34	23	13	10	4
TM band 3	1	40	56	40	20	18	9
TM band 4	-1	19	38	33	19	15	8
TM band 5	-1	71	79	50	31	25	15
TM band 7	0	61	61	33	21	15	9

Figure 3.5: Difference between control area and burnt area over time

From the above it would seem that the middle infrared band (TM5) would be most effective for identifying fire scars. The results displayed above were all extracted from fire scars in the Limestone fynbos region, but the results for Mountain fynbos are virtually identical. The only minor difference is that the response of band 3 is more similar to that of the MIR bands (as displayed in Figure 3.5) in the Mountain fynbos region.

It has been shown by Baret *et al* (1988) that band 5 of Landsat TM was most suitable for monitoring wheat canopies. He found this band contained more information than visible or near-infrared bands. Dadhwal *et al* (1996) also found this band to be very beneficial in crop discrimination. The Canada Centre for Remote Sensing (1998) notes that TM band 5 can be used to discriminate fire scars. This is somewhat contrary to much of the literature on fire scars (e.g. Jakubauskas, Lulla & Mausel 1990; Pereira & Setzer 1993, 1996; Thompson 1990, 1993).

In a review of fire scar studies, Pereira *et al* (1999) note that: "...MIR has, in general, higher capability to identify burns than the visible range. At least in boreal and temperate biomes, burns appear brighter and this spectral region is also much less sensitive to atmospheric disturbances". As shown by Figure 3.5, TM band 5 is the slowest to recover to normal pre-fire levels. This characteristic would make it the most suitable band to map "old" fire scars.

3.3 SUPERVISED CLASSIFICATION TECHNIQUES

The success of any supervised classification routine is dependent on the quality of the signatures used. Fortunately Landsat imagery is of such quality that one can visually discriminate between many landcover types. With the added knowledge gained from visiting the study area and the data provided by the Western Cape Nature Conservation Board, delineating training areas for landuse types in this study area was not overly difficult.

Delineating training areas for fire scars did pose some challenges however. It must be remembered that a fire does not always burn with the same intensity and some unburned areas may exist within a fire boundary. More importantly a fire scar is also dynamic over time, as shown in the previous section. Therefore it was decided to focus on fire scars that were known to be less than three months old (i.e. satellite imagery was taken less than three months after the fire).

The signatures that were created for this study were:

- sand – mostly sand dunes along the coast;
- water – sea water and a clear lake;
- agricultural land – land that has been stripped of natural vegetation, consisting mainly of grain and fallow fields;
- green vegetation – irrigated fields and afromontane forest;
- fynbos – Limestone fynbos, natural veld; and
- fire scar – burnt areas.

The author evaluated these signatures by running an unsupervised classification to see if discernible classes could be detected. The signatures were also checked to ensure that they had normal distributions in all bands. These signatures were then used in all further classifications.

Idrisi for Windows has three supervised classification routines. The first is called **Piped**. It undertakes a parallelepiped classification based on the information contained in a set of signature files. A set of lower and upper threshold reflectances is determined for a signature on each band. A pixel must exhibit reflectances within this reflectance range to be assigned to a particular class. The parallelepiped procedure is also the fastest of the classification routines available in this software package (Idrisi 1997). Because some landcover classes in this study area have some degree of overlap in some spectral bands, this technique proved to be unreliable. Overlap between signatures of fire scars and agricultural land was particularly noticeable, which made this technique too unreliable for identifying fire scars.

The second supervised classification routine is called **Mindist**. It undertakes a Minimum Distance to Means classification based on the information contained in a set of signature files. The Minimum Distance to Means classification is based on the mean reflectance on each band for a signature. Pixels are assigned to the class with the mean closest to the value of that pixel. To account for differences in the variability of signatures, Mindist allows band-space distances to be normalized. Mindist is slightly slower than the parallelepiped classification procedure, Piped (Idrisi 1997). Mindist did not improve on the results obtained with Piped. Again its inability to discriminate between fire scars and agricultural areas was the main cause of the poor results.

The third technique offered in Idrisi for Windows is called **Maxlike**. This procedure undertakes a Maximum Likelihood classification based on information contained in a set of signature files. Maxlike is also known as a Bayesian classifier since it has the ability to incorporate prior knowledge using Bayes' Theorum. Prior knowledge is expressed as a prior probability that each class exists. The Maximum Likelihood classification is based on the probability density function associated with a particular training site signature. Pixels are assigned to the most likely class based on a comparison of the posterior probability that it belongs to each of the signatures being considered (Idrisi 1997). For this study the author used equal prior probability for all classes.

As in the previous supervised classification routines, six signatures were used. When using all six of the reflective Landsat bands the results were outstanding, as can be seen in Figure 3.6. It is clear that very little confusion occurred between fire scars and fynbos. There was still some confusion between agricultural land and fire scars in the cultivated areas (as can be seen in the north of Figure 3.6) but this falls outside the main focus of this study (natural veld). The pale green area on the map depicts the fynbos region.

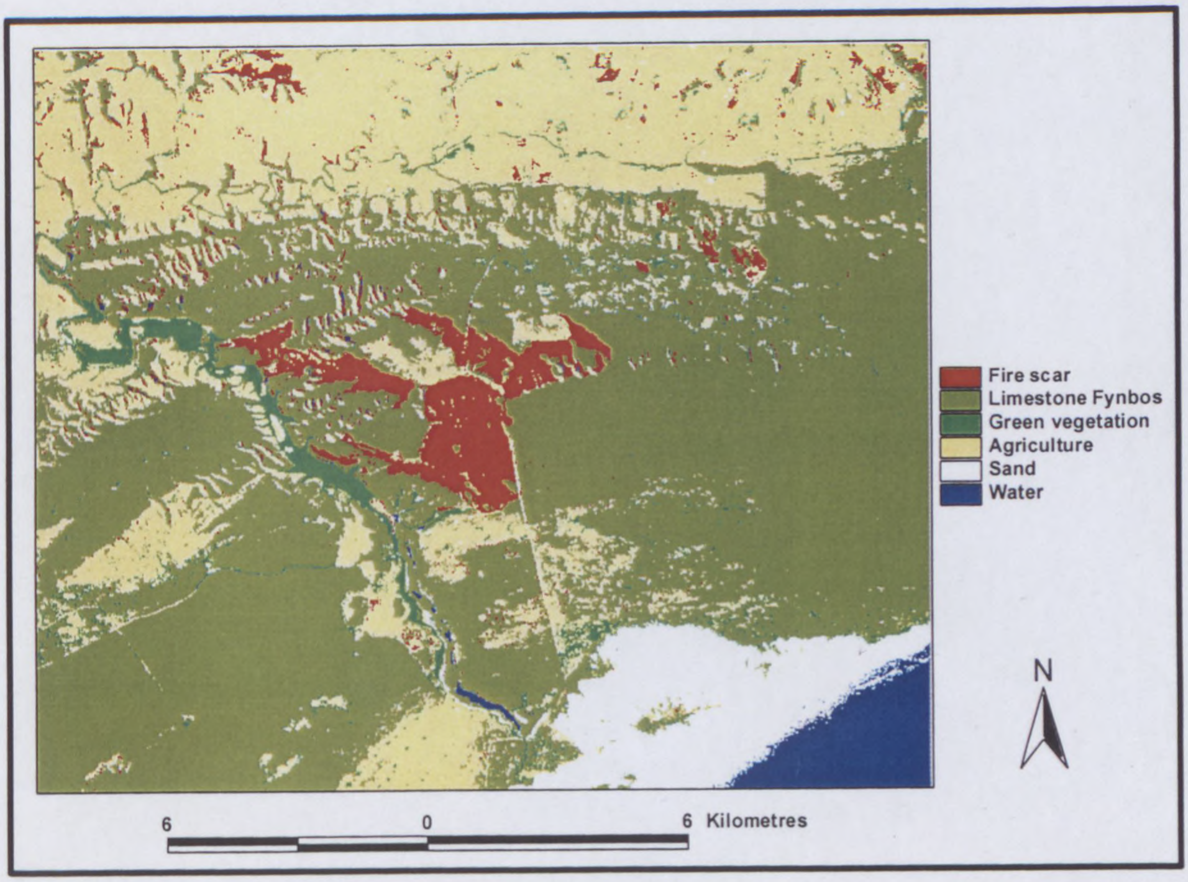


Figure 3.6: Example of Maxlike output image (1996 fire scar)

Although maximum likelihood supervised classification proved to be a reliable technique, it is limited by the chosen training sites. One must remember that only fire scars that have the same spectral response as the training sites can be extracted. This limits its use to fires that occurred within the same vegetation type, soil background, season and, to a lesser extent, fires that burned with the same intensity. So although this type of classification can be very accurate there will always be a need for considerable user input and interpretation.

In Figure 3.7 the extracted 1996 fire scar is displayed along with the existing fire record of that fire (the background is a false colour composit of bands 4, 5 and 7). As can be seen from Figure 3.7, the extracted and existing fire scars are very similar.

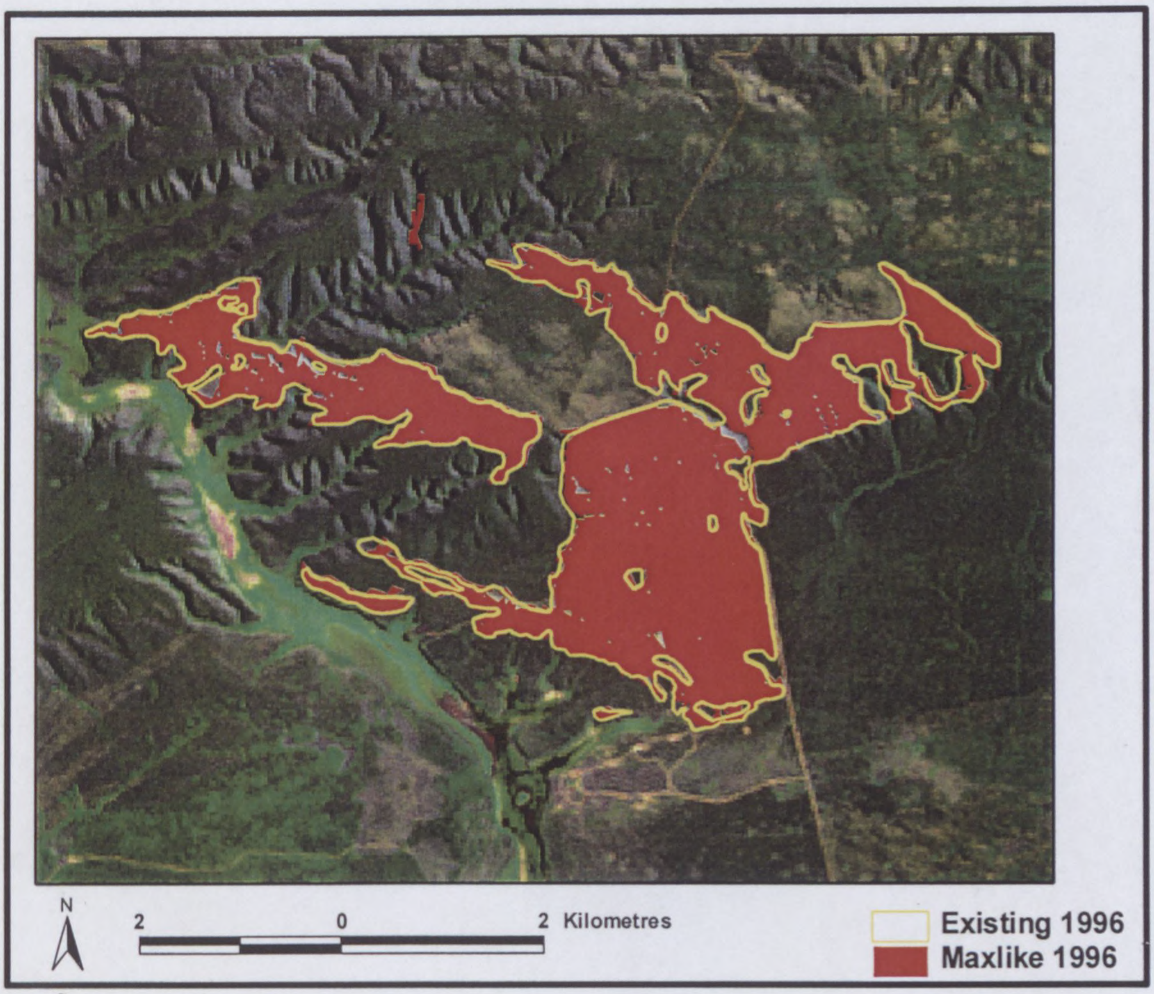
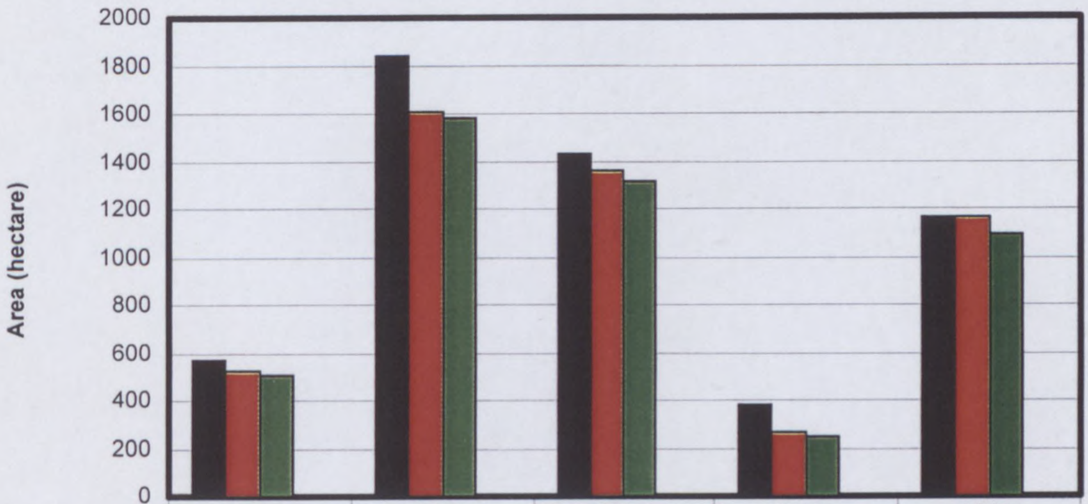


Figure 3.7: Extracted 1996 fire scar from Maxlike vs existing data

In Figure 3.8 the relationship between the extracted fire scar areas (in hectares) and the existing data is compared graphically. The percentage overlap is an indication of similarity between the existing data and extracted fire scars.



	1990	1991	1992	1993	1996
■ Existing data	570	1836	1428	384	1164
■ Extracted data	521	1613	1361	270	1163
■ Overlap area	508	1585	1313	246	1094
Percentage overlap	89.1	86.3	91.9	64	94

Figure 3.8: Calculated areas from Maxlike routine

The results in Figure 3.8 can be clarified by noting that the extraction of the 1990 fire scar was hampered (confused) by an adjoining fire that occurred only a year earlier. The 1991 fire scar was only captured in 1993, which made it relatively "old" and this also influenced the accuracy of its extraction. The reason for this is that the old fire scar had many spectral similarities to areas with little vegetation cover (fallow agricultural fields for example). The 1992 and 1996 fire scars gave sound results, probably because they are relatively "young" . Poor results for the 1993 fire scar can be attributed to the finding that the existing record of the fire scar in the Mountain fynbos region (1993) was not well digitised. Still, the Maxlike routine did not perform as well (as later techniques) in that fynbos region as in the Limestone fynbos region.

3.4 UNSUPERVISED CLASSIFICATION TECHNIQUES

Unsupervised classification is a technique where a computer routine interprets a remotely sensed image by identifying typical patterns in the reflectance data. The user must then assign these computer created clusters to land-use classes. Idrisi for Windows has two unsupervised classification modules named Cluster and Isoclust.

Cluster "provides an unsupervised classification of an image based on the information in a color composite image..." (Idrisi 1997). It is up to the user to establish what bands to use in creating this composite image. For Landsat it is suggested that one uses bands 3, 4 and 5. These cover the basic image dimensions of greenness, brightness and moisture content, and thus carry most of the information in the satellite image (Idrisi 1997). From Section 3.2.1 one can derive what other combinations of spectral bands might also be useful. In Figure 3.9 for example, the author used the three Kauth-Thomas (KT) components (see Section 3.5.3) to create a composite image, which was then used in Cluster.

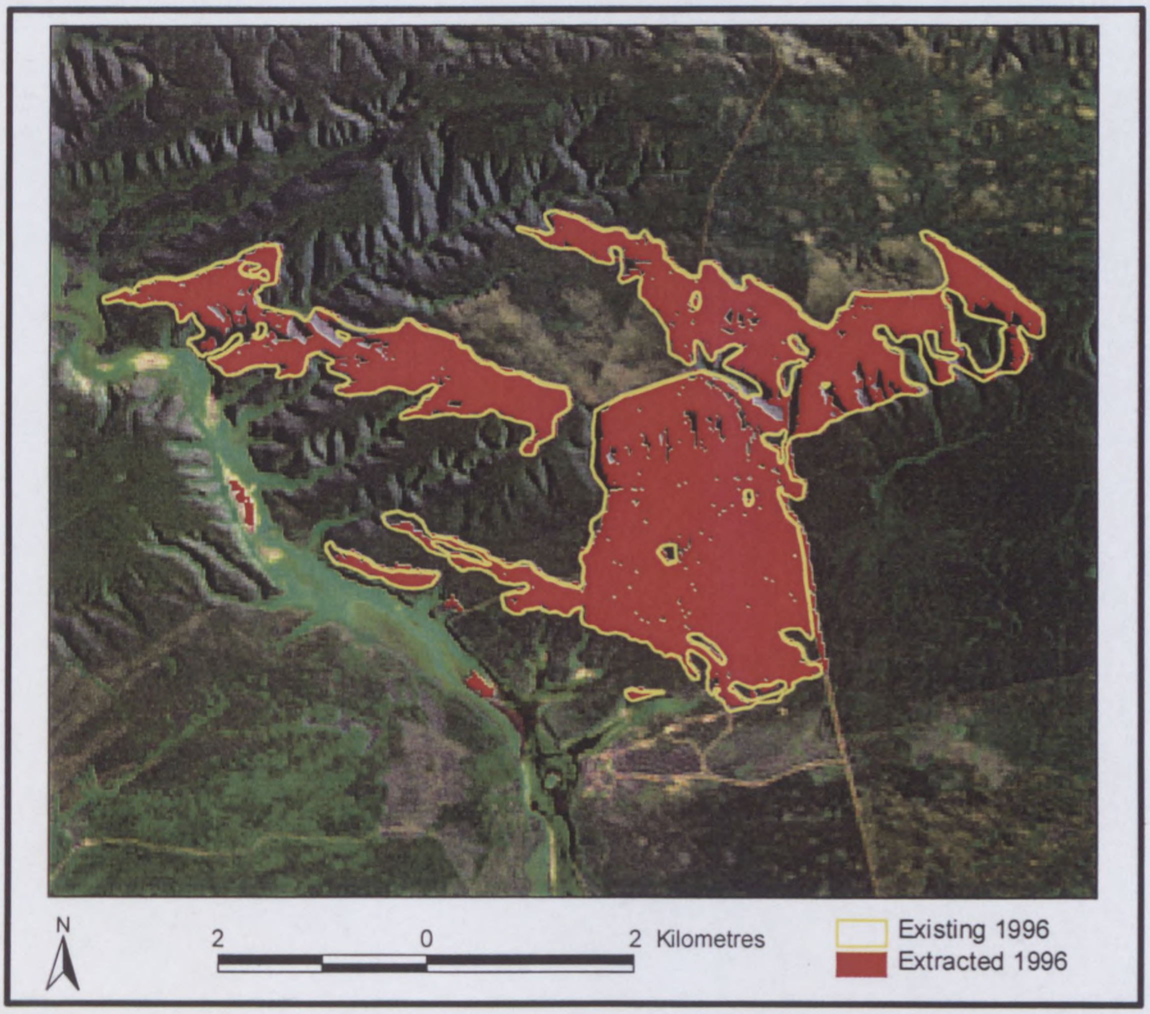


Figure 3.9: Extracted 1996 fire scar from Cluster (KT-bands)

As can be seen from Figure 3.9 this composite gave satisfactory results, although a small degree of confusion did occur (note the small burnt area in the west – which is actually in the middle of the De Hoop vlei).

Overall the results from this technique were quite accurate and the calculation very fast. In contrast Isoclust, the other unsupervised classification technique, is relatively slow.

Isoclust "…is an iterative self-organizing unsupervised classifier based on a concept similar to the well-known ISODATA routine of Ball and Hall (1965) and cluster routines such as the H-means and K-means procedures" (Idrisi 1997). The typical logic of this family of cluster algorithms is as follows:

a) The user decides on the number of clusters to be uncovered. One is clearly "blind" in determining this. As a consequence, a common approach is to ask for a large number and then aggregate clusters after interpretation;

b) A set of N clusters is then arbitrarily located in band space. In most systems, these locations are randomly placed or systematically placed within the region of high frequency reflectances;
c) Pixels are then assigned to their nearest cluster location;
d) After all pixels have been assigned, a new mean location is computed.
Steps c) and d) are iteratively repeated until no significant change in output is produced.

The implementation of this general logic in IDRISI for Windows is different in the following respects:

- In addition to the raw image bands, IDRISI for Windows requires a colour composite image for use in the cluster seeding process.
- The cluster seeding process is actually done with the CLUSTER module in IDRISI for Windows. This leads to a far more efficient and accurate placement of clusters than either random or systematic placement.
- The iterative process makes use of a full Maximum Likelihood procedure that provides a very strong cluster assignment procedure (Idrisi 1997).

Building on the results obtained from using the Cluster routine, the author found that using a composite image of Kauth-Thomas components or bands 3, 4 and 5, gave reliable results. The author discovered that using the KT composite image was the most suitable for all fires. Using a composite image of bands 3, 4 and 5 did perform very well for some fires, but was not reliable for all fires. Not surprisingly the results were superior when using all six of the Landsat reflective bands. An example of a Maxlike extracted fire scar (using a KT-composite image and six Landsat bands) is shown in Figure 3.10.

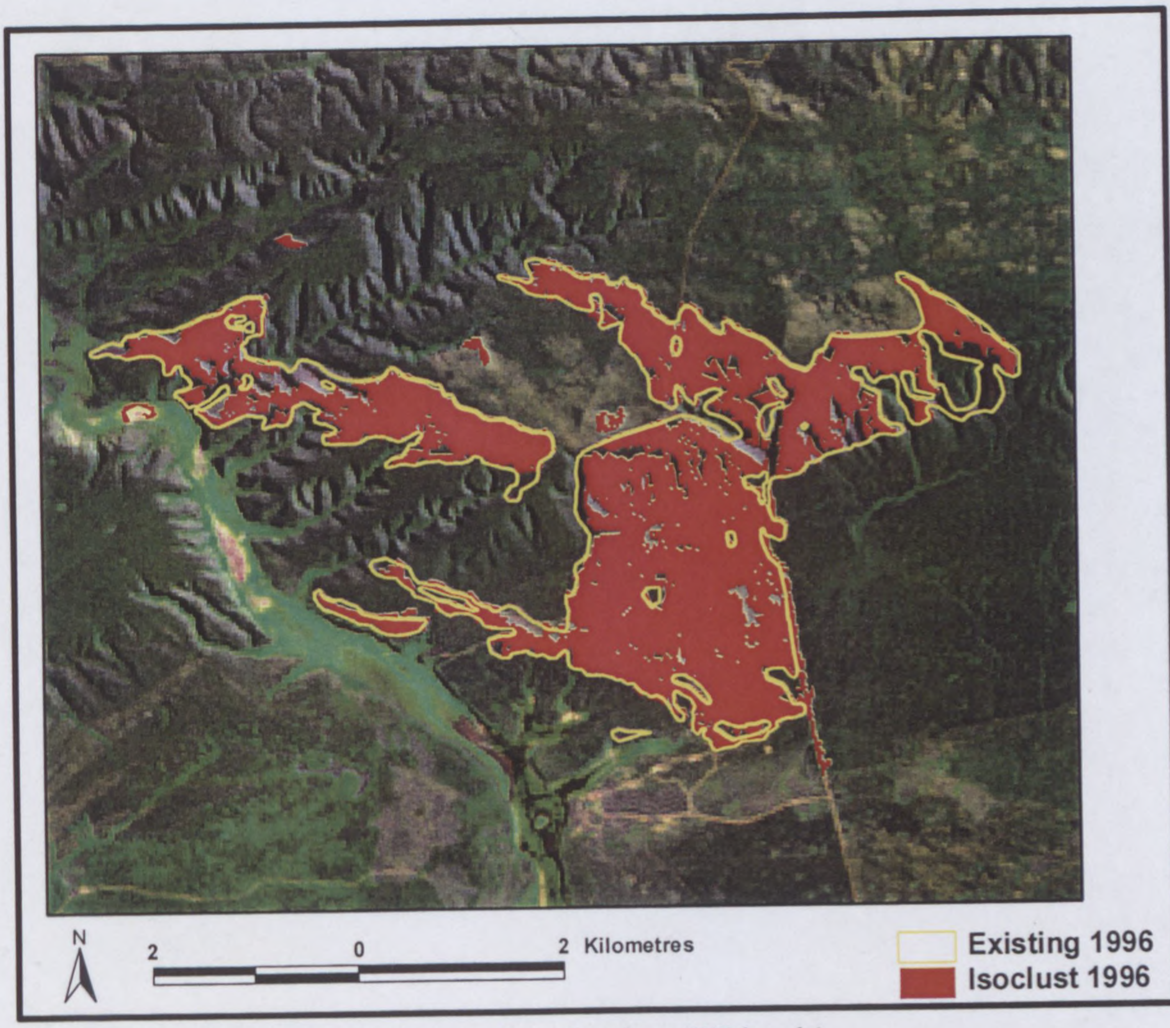
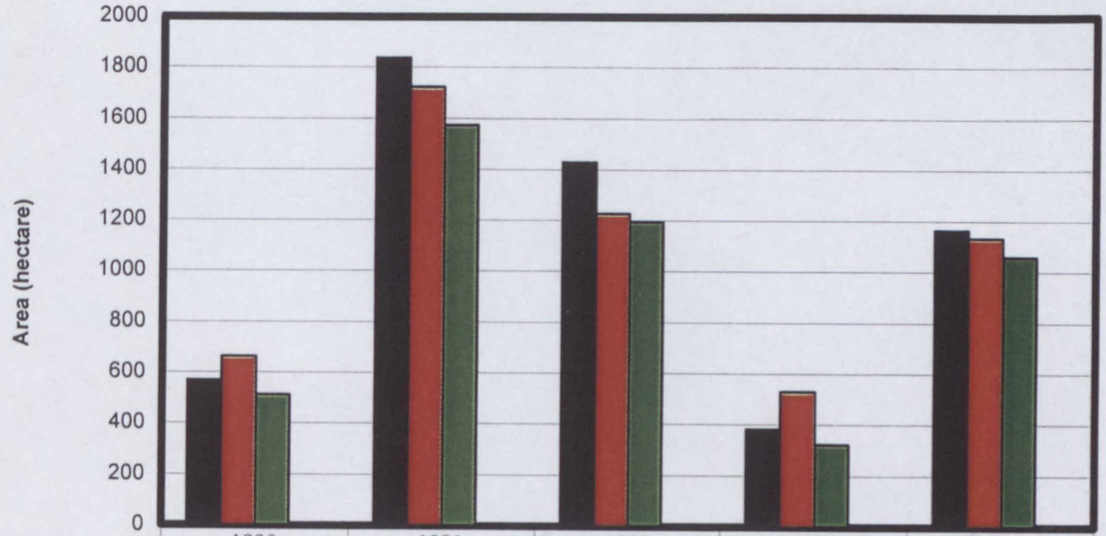


Figure 3.10: Extracted 1996 fire scar from Isoclust (KT-bands)

It should be remembered that one of the aims of this study was to find a feasible operational system for detecting fire scars. The results of a simple unsupervised classification have to be interpreted by the user to establish what the different classes represent. One would therefore need ancillary data to accomplish this successfully. Moreover, one would also have to interpret the results of each year separately, which would disqualify such a technique for simple, repeatable operational use.

The author found that there was considerable confusion between agricultural land (possibly fallow fields) and older fire scars. As can be seen in Figure 3.11, unsupervised classification performed moderately well for all fire scars. Again one should note that extraction of the 1990 fire scar was hampered by an adjoining fire scar (which explains the larger extracted area). It is also evident that unsupervised classification did not perform well in the Mountain fynbos region (1993 fire scar).



	1990	1991	1992	1993	1996
Existing data	570	1836	1428	384	1164
Extracted data	663	1723	1226	530	1133
Overlap area	511	1572	1196	323	1061
Percentage overlap	89.6	85.6	83.7	84.1	91.2

Figure 3.11: Calculated areas from Isoclust routine

The most accurate of these techniques require considerable computer processing time. The author also discovered that these techniques are only suitably accurate when all (reflective) spectral bands were used.

3.5 CHANGE ANALYSES

Singh (1989) describes change detection as "...the process of identifying differences in the state of an object or phenomenon by observing it at different times". The basic premise is that changes in land cover should result in changes in radiance values. Furthermore these changes would be larger than radiance changes caused by other factors such as differences in atmospheric conditions, differences in sun angle and differences in soil moisture (Jenson , in Singh 1989).

3.5.1 Simple univariate image differencing

Univariate image differencing is the most widely used change detection technique (Singh 1989). In this technique two temporally different images of the same area are subtracted, pixel by pixel, to form a new image that shows the changes between the two images.

The analyst must then decide at what threshold change should be assumed. In other words, one must decide at which point can differences between the images be contributed to actual land-use change or to other seasonal or radiometric changes. It is a major drawback of this technique, especially if the images are not extensively corrected for such influences.

When studying fire scars one must also remember that more recent fire events will show greater difference than older fire scars. While this can be used to roughly estimate the date of a fire event, older fire scars become increasingly difficult to distinguish from other land-use changes. Fire scars of different ages occuring on the same image will also have to be thresholded separately, as the degree of change could be significantly different.

When deciding which bands to use for single band univariate differencing, the author relied on the results described in Section 3.2.1. Some examples of how the different Landsat bands react to fire activity are given in Table 3.1.

Table 3.1: Average difference between pre-fire and post-fire spectral response

Fire ID	***Average Difference from pre-fire***					
	Band1	**Band2**	**Band3**	**Band4**	**Band5**	**Band7**
90	29	19	39	20	73	61
91	54	38	71	54	109	67
92	26	14	31	14	95	74
93	22	16	23	17	53	45
96	3	0	3	-9	19	25

In Table 3.1 one can see how the five fire scar sites changed from pre-fire to just after (first satellite image) the fire event. The bands that show the largest degree of change should be the most appropriate bands to use for differencing. In Table 3.1 bands 5 and 7 show the greatest differences. These bands did prove to be the most reliable for image differencing.

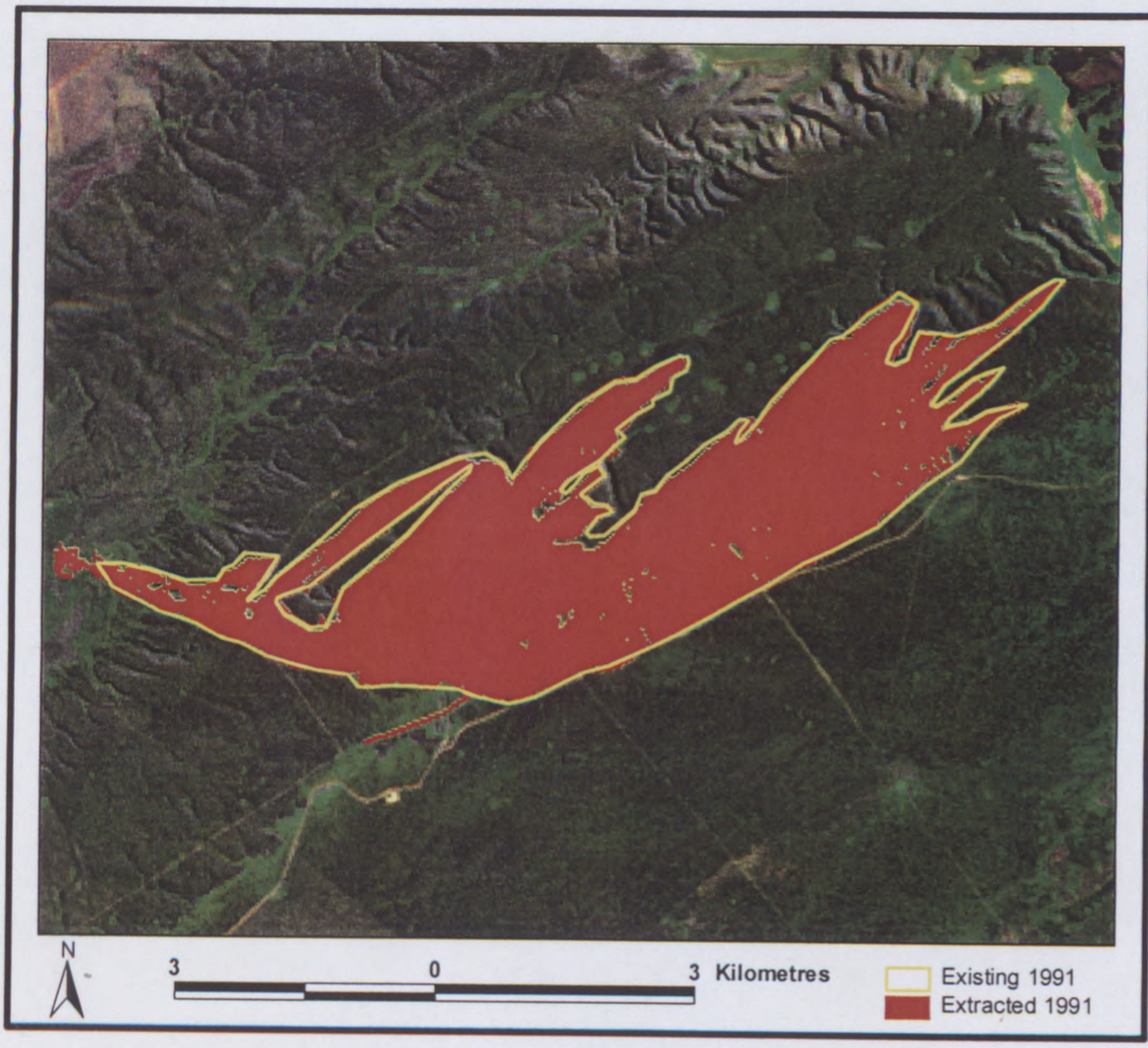
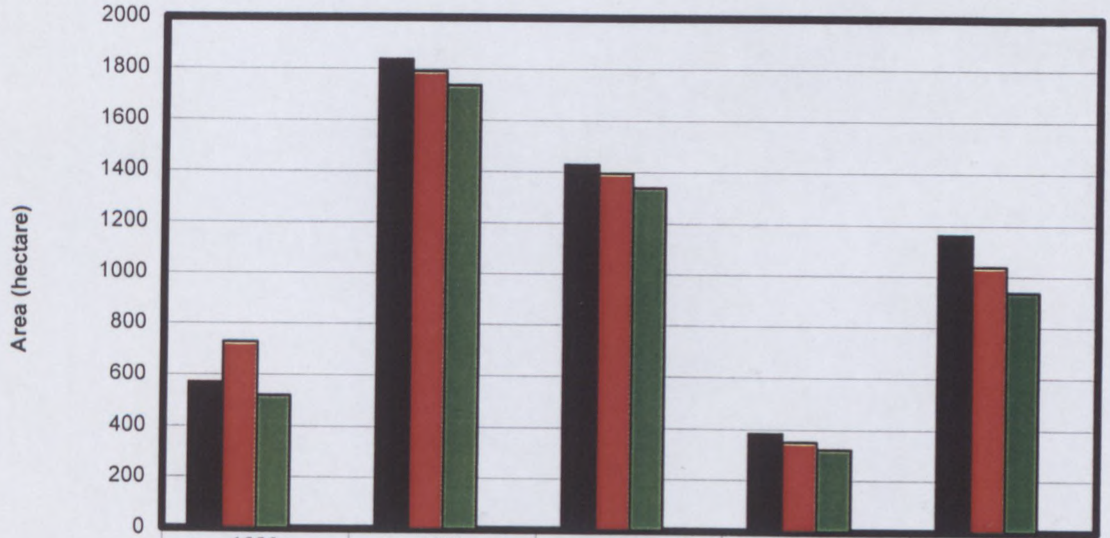


Figure 3.12: Extracted 1991 fire scar from image differencing (band 7)

The author found that areas that were most likely burned areas (for example some of the holes within a fire boundary) were difficult to include in the desired threshold. As the threshold was moved to include these areas (presumed to be lightly burned areas) other areas that clearly were not fire scars (gravel roads for example) were also included. In Figure 3.12 one can see how a part of a gravel road, near the southern tip of the fire scar, was mistakenly extracted. Kitchin & Reid (1999) noted that all change detection techniques included changes not associated with fire and required user interpretation to distinguish between other causes of change such as forestry or agriculture.

Simple univariate differencing (using bands 5 or 7) proved to be a relatively simple and quick way to extract fire scars. The author was able to delineate fire scars that were relatively old (more than 22 months). The author found that TM band 5 was the slowest to recover to pre-fire spectral response levels and thus the best band to use when mapping older fire scars. The author also found that band 7 might be slightly better for extracting more recent fire scars (less than 3 months).



	1990	1991	1992	1993	1996
Existing data	570	1836	1428	384	1164
Extracted data	730	1790	1395	351	1037
Overlap area	518	1736	1337	323	936
Percentage overlap	90.9	94.6	93.6	84.1	80.4

Figure 3.13: Calculated areas from simple image differencing

The results shown in Figure 3.13 for the 1990 fire scar seem unusual, but this fire scar was (as noted previously) influenced by a directly adjacent fire that occurred a few months earlier. That would explain why such a large area was extracted but the overlap area was smaller and more accurate.

Why simple differencing did not work well for the 1996 fire is not as clear. The author can only hypothesise that there is an error in the existing fire records and that this fire scar was in fact much "younger". Examination of the spectral signature of this fire scar supports this hypothesis (see Table 3.1). If the fire only occurred very recently, burnt vegetation would not have had time to die off and drop its leaves, thus not showing a great deal of difference from the previous year (note the small differences shown over all bands in Table 3.1).

Another contributing factor to the poor performance of this technique for the 1996 fire scar is the large seasonal difference between the 1996 image (captured in middle March) and the other images used for calculating change (1993, for example, was captured in early January). Seasonal vegetation spectral differences could "hide" the spectral differences caused by the fire event.

3.5.2 Image ratioing

In this technique two temporally different images are ratioed to create a new image. Mathematically one computes:

$$R = \frac{x(t1)}{x(t2)} \qquad [1]$$

where x is a pixel value at a certain row and column, with $t1$ and $t2$ denoting the different dates. In areas of no or little change the values should approach 1. In areas of change the values should be significantly greater or less than 1, depending on the nature of change.

Table 3.2: Ratio of average pre-fire and post-fire response

Fire ID	***Ratio with pre-fire***					
	Band1	**Band2**	**Band3**	**Band4**	**Band5**	**Band7**
90	0.68	0.56	0.42	0.62	0.48	0.32
91	0.91	0.90	0.86	0.81	0.71	0.67
92	0.77	0.68	0.55	0.85	0.57	0.40
93	0.72	0.59	0.57	0.74	0.70	0.50
96	0.95	0.99	0.89	1.33	0.79	0.54

From Table 3.2 it is difficult to ascertain which spectral band would be ideal to map fire scars. Bands 7 and 5 are, however, the most consistent for all fire scars.

According to Singh (1989) the critical element of the methodology is selecting appropriate threshold values in the lower and upper tails of the distribution representing change. The author found that it is relatively easy to establish a threshold from image ratioing. Compared to image differencing, there seems to be less confusion between the burned area and unchanged areas. As with image differencing, older fires are more difficult to distinguish from radiometric and seasonal changes. In most respects there was little difference between image differencing and image ratioing. For this reason the author did not employ this technique for later calculations, but rather focused on image differencing.

3.5.3 Vegetation index differencing

Vegetation indices (VI's) are one of the most commonly used band combination techniques used in vegetation studies (Curran 1981; Tucker, in Singh 1989). Vegetation indices are also very popular tools for burned area mapping, both in unitemporal and in multitemporal frameworks (Pereira *et al* 1999). Vegetation indices were developed to exploit and enhance the spectral characteristics of green vegetation - the strong vegetation absorbance in the red and strong reflectance in the near-infrared part of the electromagnetic spectrum. Jakubauskas, Lulla & Mausel (1990: 373) are of the opinion that one can exploit "...the near reversal of standard vegetation spectral response curve caused by the removal of green vegetation and lowering of NIR reflectance, the degree of which is directly related to the severity of the fire".

Vegetation index differencing is mathematically similar to univariate image differencing, but with the input images being vegetation indices from different dates. There are several vegetation indices that one could use for this application, but to evaluate all of them would be beyond the scope of this study. Others (e.g. Asrar, Mynemi & Choudbury 1992; Elvidge & Lyon 1985; Guyot & Gu 1994; Rodriguez y Silva *et al* 1999) have investigated vegetation indices and from this it was decided to evaluate only some of the most commonly used vegetation indices. This includes the Normalised Difference Vegetation Index (NDVI), the Soil Adjusted Vegetation Index (SAVI) and the Tasselled Cap Transformation (also called the Kauth-Thomas Transform).

A complicating factor in this particular study, as shown in Section 3.2.1, is the low spectral reflectance (VI response) of fynbos. This means that a removal of above ground vegetation will not alter the VI response (of the fynbos vegetation) as much as in other vegetation types. This low reflectance is particularly noticeable in the near infrared band (TM4). This band is unfortunately also one that is often used in vegetation indices.

The **Normalised Difference Vegetation Index** (NDVI) is probably the most widely used vegetation index in satellite remote sensing studies today. Like most other vegetation indices it makes use of a combination of two spectral bands. In this case the characteristic difference between near-infrared and red reflectance of green vegetation is exploited. For Thematic Mapper one computes:

$$NDVI = \frac{TM3 - TM4}{TM3 + TM4} \qquad [2]$$

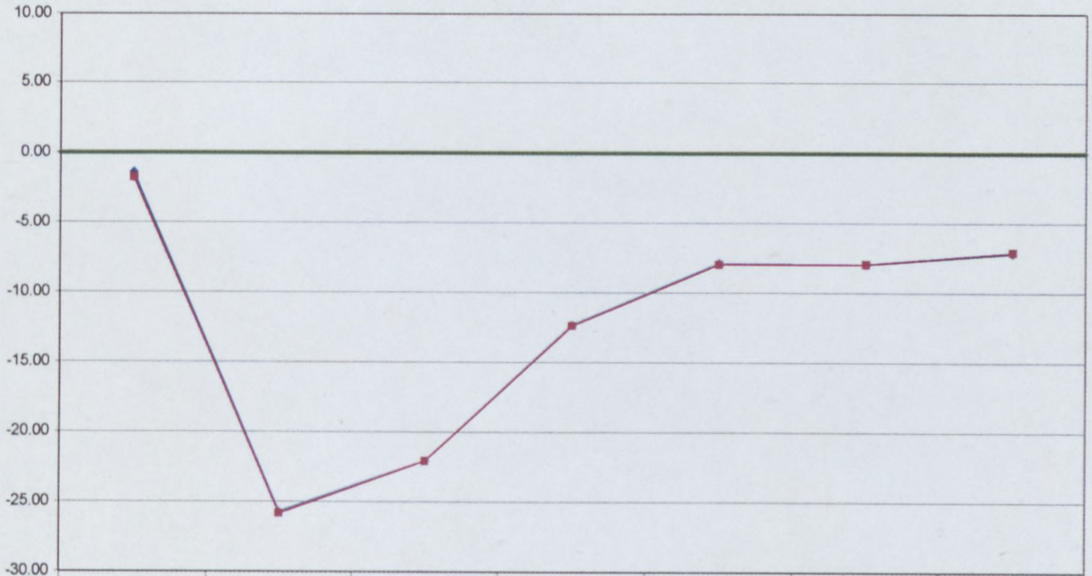
where TM3 is the red band and TM4 is the near-infrared band on Landsat 5. It has been shown by other authors (Myneni, Ganapol & Asrar 1992; Myneni & Williams 1994; Thompson 1993; Viedma, Melià & Garcia-Haro 1997) that NDVI is closely related to above ground biomass levels, leaf area index and photosynthetic activity. Kasischke & French (1995) and Viedma, Melià & Garcia-Haro (1997) showed that NDVI can successfully be used to identify fire scars. As noted above, because of the particular spectral response of fynbos vegetation, one would expect somewhat different results for this study.

Another well known vegetation index is SAVI. Heute (1988) developed the **Soil Adjusted Vegetation Index** to reduce the sensitivity of vegetation indices to soil background influences. It has been shown that vegetation indices like the NDVI are sensitive to external factors such as background reflectance (Elvidge & Chen 1995; Elvidge & Lyon 1985; Qi *et al* 1994). SAVI is particularly useful when the background soils are varied. In this study the focus is on fires that occurred on the same soil background, thus minimising such effects. One would thus expect the results of NDVI and SAVI to be very similar in this study.

Table 3.3: Average difference between pre- and post-fire VI-response

Fire ID (age)	*Average difference between pre-fire and post-fire*	
	NDVI	**SAVI**
90 (<25 days)	-24.31	-24.39
91 (<22 months)	-29.68	-29.18
92 (<30 days)	-35.89	-35.39
93 (<3 months)	-17.86	-19.23
96 (<2 months)	-23.59	-24.10

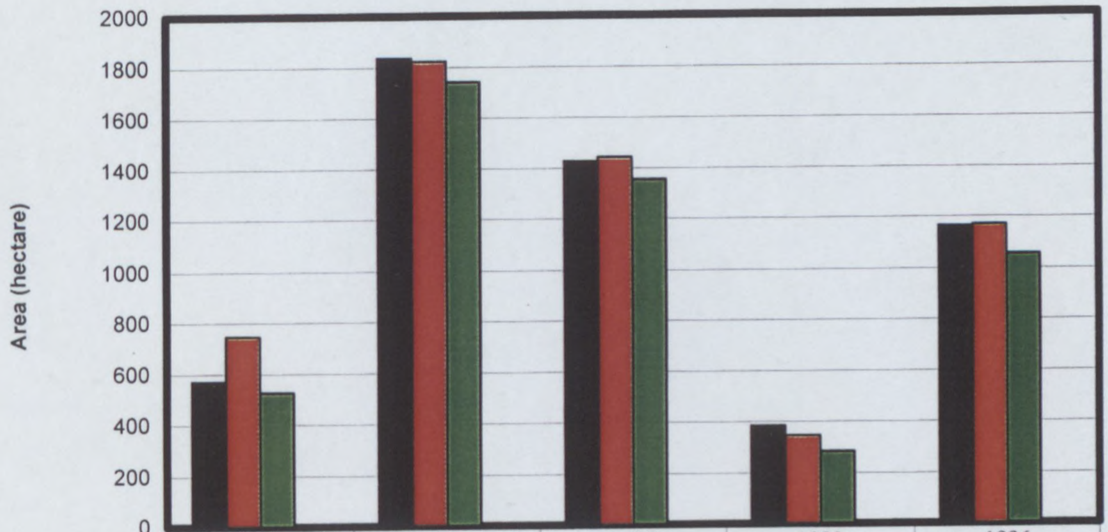
In Table 3.3 the difference between pre-fire and post-fire vegetation index response is shown. The difference between VI-response before and directly after a fire is dependent on the severity of the fire. One would expect a larger difference in VI-response after a severe fire. The age of the fire scar would also influence the difference between pre- and post-fire response. Depending on the age of the fire scar, burned vegetation could not have died off yet or vegetation regrowth could have started. These considerations could explain the differences shown in Table 3.3. It is also noticeable that differences in the Mountain fynbos region (1993 fire scar) are significantly smaller than in the Limestone fynbos region.



	Prefire	<26 days	11 months	35 months	48 months	60 months	73 months
NDVI	-1.41	-25.72	-22.03	-12.31	-7.85	-7.93	-7.12
SAVI	-1.77	-25.80	-22.04	-12.37	-7.92	-7.88	-7.03

Figure 3.14: NDVI and SAVI response over time

From Figure 3.14 it can be seen that NDVI does drop sufficiently to map fire scars, a condition being that the image was taken shortly after (less than 2 months) the fire event. The author found it relatively difficult to establish a threshold for NDVI differencing, as there seems to be much overlap between lightly burned areas and (relatively) unchanged areas. This is probably because of seasonal changes in the vegetation spectral response. It is noticeable that at 11 months after the fire event NDVI has already started recovering towards pre-fire levels.



	1990	1991	1992	1993	1996
Existing data	570	1836	1428	384	1164
Extracted area	746	1821	1442	347	1169
Overlap area	527	1742	1356	283	1056
Percentage overlap	92.5	94.9	95	73.7	90.7

Figure 3.15: Calculated areas from NDVI differencing

From Figure 3.15 one can gather that this technique did not perform successfully for the fire scar in the Mountain fynbos region. It has to be noted that this index was most effective when mapping recent fire scars.

Vegetation index differencing does not have any significant advantages over simple image differencing, except that one can measure the extent of vegetation cover. These techniques require more than one spectral band and are thus potentially more expensive than simple image differencing.

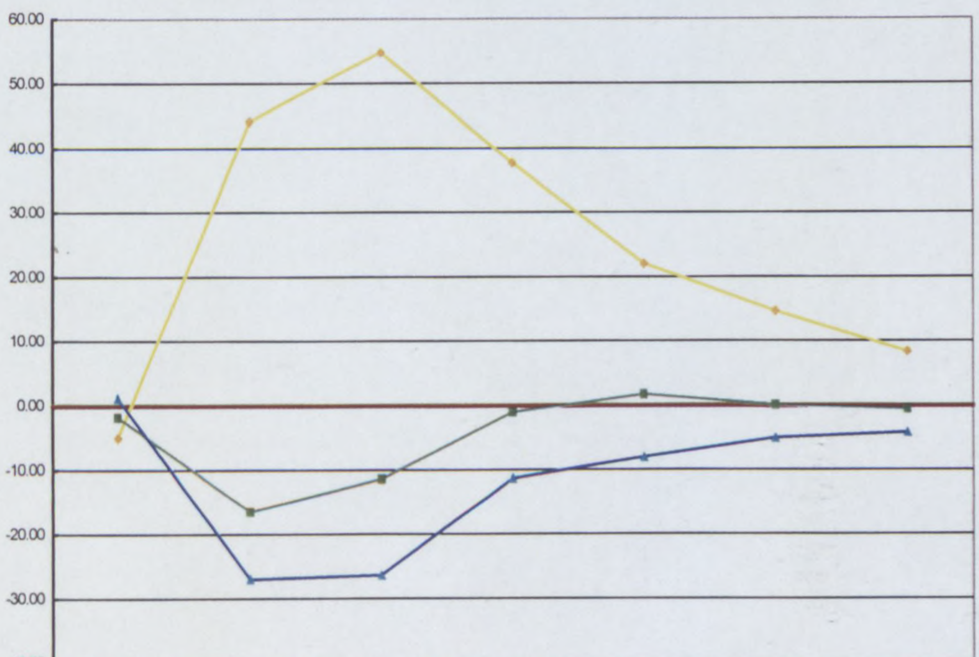
3.5.4 Tasselled Cap Transformation differencing

The Tasselled Cap Transformation or **Kauth-Thomas** (KT) index is not a ratio based vegetation index like NDVI or SAVI. The KT index involves the application of a technique of sequential orthogonalisation following the Gram-Schmidt process (Collins & Woodcock 1994). In the case of the Thematic Mapper sensor, the data of the six reflective bands is dispersed into a three-dimensional space, defining more precisely two perpendicular planes (plane of vegetation and plane of soils) that are called greenness and brightness. There is also a third component related to moisture status. The transformation results in a set of linear combinations directly correlating physical vegetation cover characteristics to the transformed features (Coppen & Bauer 1994).

Table 3.4: Average difference between pre- and post-fire KT-response

Fire ID (age)	*Average difference between pre-fire and post-fire*		
	KT-green	**KT-bright**	**KT-moist**
90 (<25 days)	-15	49	-28
91 (<22 months)	-15	66	-16
92 (<30 days)	-22	40	-40
93 (<3 months)	9	38	17

In Figure 3.16 the response of the three Kauth-Thomas components to a fire is plotted over time. A few weeks after the fire, one can see that moisture and greenness have dropped and brightness has increased. This result is also shown for four other fires in Table 3.4. The change can be expected, as removal of vegetation would decrease greenness and moisture content, while increasing the exposure to the bright soils. At 11 months after the fire, moisture has not started to recover, while greenness has started to recover toward normal. Brightness however, has increased further from normal. This suggests that the burnt vegetation and ash has been washed away by the elements and that the bright soils are now even more exposed.

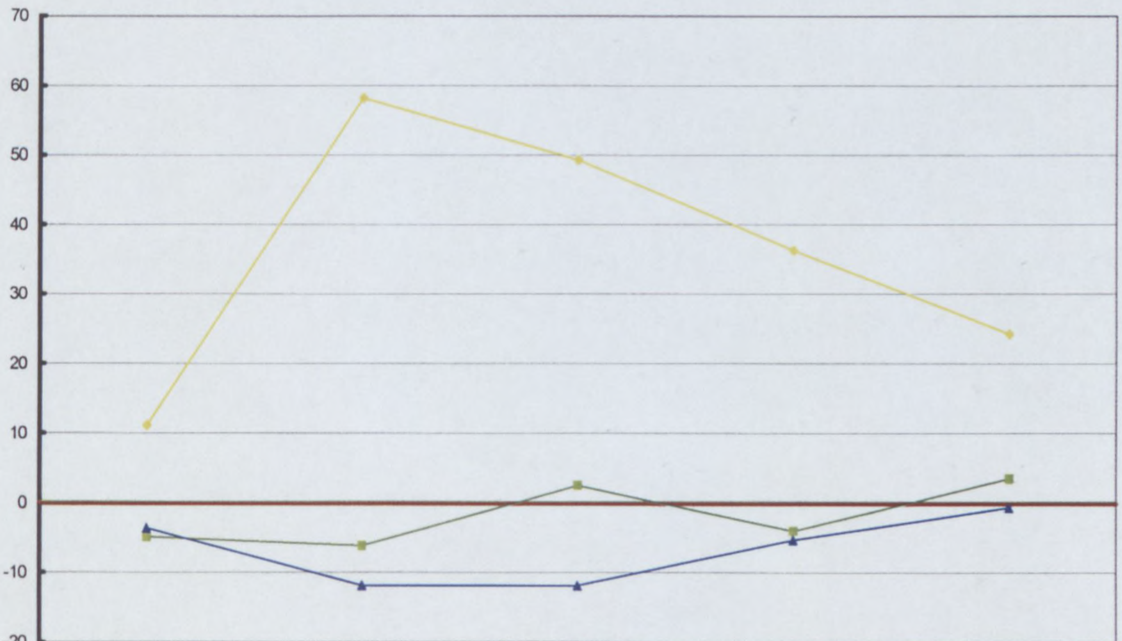


	Prefire	<26 days	11 months	35 months	48 months	60 months	73 months
brt	-4.93	44.19	54.9	37.61	22.05	14.72	8.39
grn	-1.80	-16.44	-11.32	-1.06	1.72	0.09	-0.51
mst	1.22	-26.94	-26.38	-11.3	-8.05	-5.09	-4.21

Figure 3.16: KT-response over time compared to control area (Limestone fynbos)

At 35 months greenness has virtually recovered to pre-fire levels, while moisture has only begun to recover towards normal levels. Brightness has also just started to decrease towards normal unburnt reflectance. Brightness is still the furthest from normal and could probably still be accurately used to map changed areas.

At 48 months after the fire one can say that greenness has recovered fully and that the other components are steadily recovering towards normal. At 60 and 73 months after the fire this trend is continuing, with brightness being the component with the slowest recovery. This recovery process is as expected, as it duplicates the responses of the standard Landsat TM bands documented in Section 3.2.1. As noted earlier, this rate of recovery is normal for fynbos vegetation.



	Prefire	18 months	31 months	43 months	56 months
brt	11.2	58.27	49.44	36.42	24.36
grn	-4.83	-6.08	2.57	-3.93	3.59
mst	-3.49	-11.83	-11.79	-5.23	-0.55

Figure 3.17: KT-response over time compared to control area (Mountain fynbos)

As shown in Figure 3.17 the KT-response of Mountain fynbos differed from the response of Limestone fynbos. In Figure 3.17 one can see that neither KT-greenness or KT-moisture changed significantly after a fire event. KT- brightness again proved to be the most suitable component to use for fire scar detection. KT-moisture only showed a slight drop in reflectance, while KT-greenness exhibited strange responses (note the drop at 43 months) after the fire event. The author can only hypothesize that the relatively low KT-moisture response is related to the relatively high (and year round) rainfall in this Mountain fynbos region.

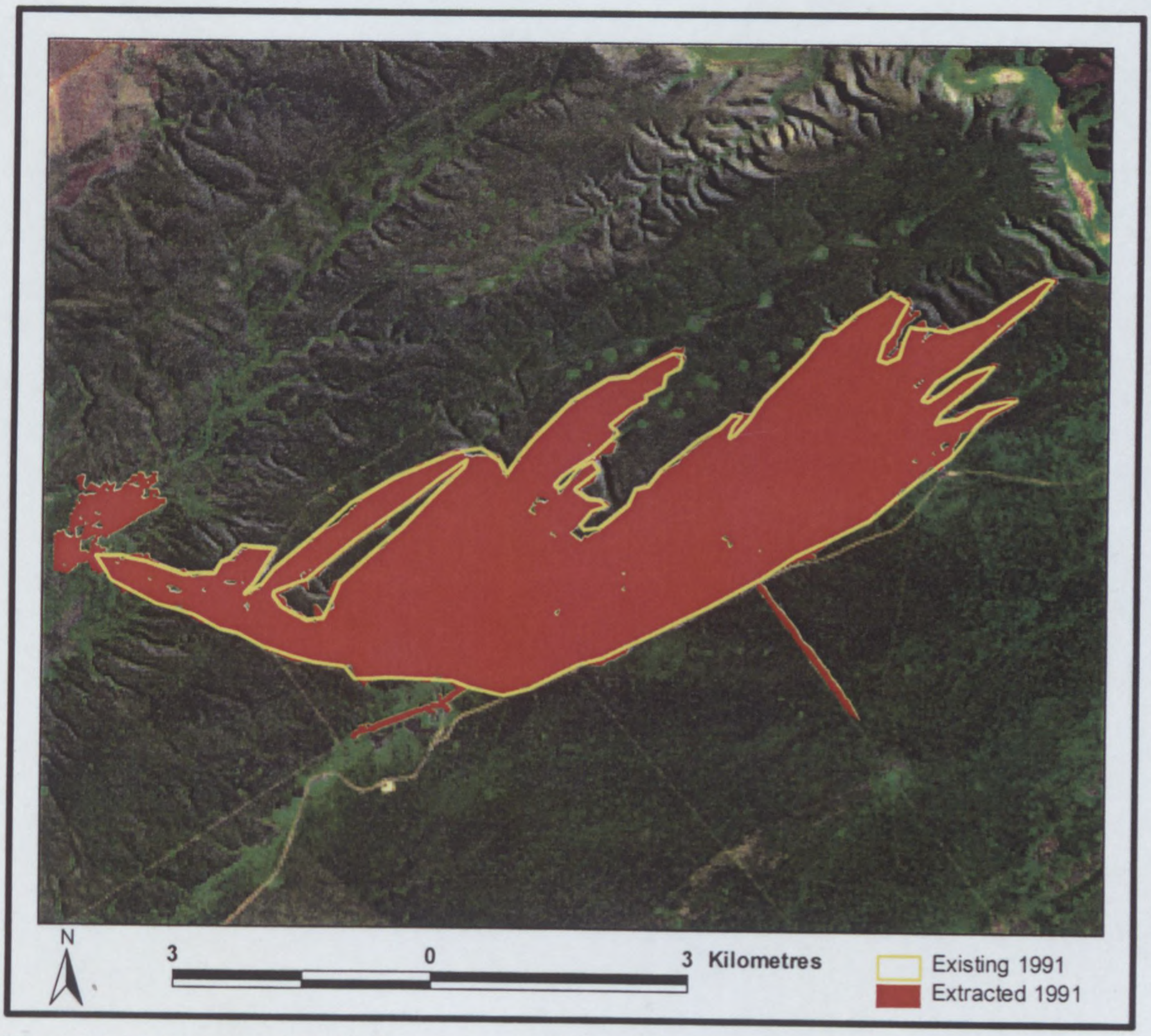
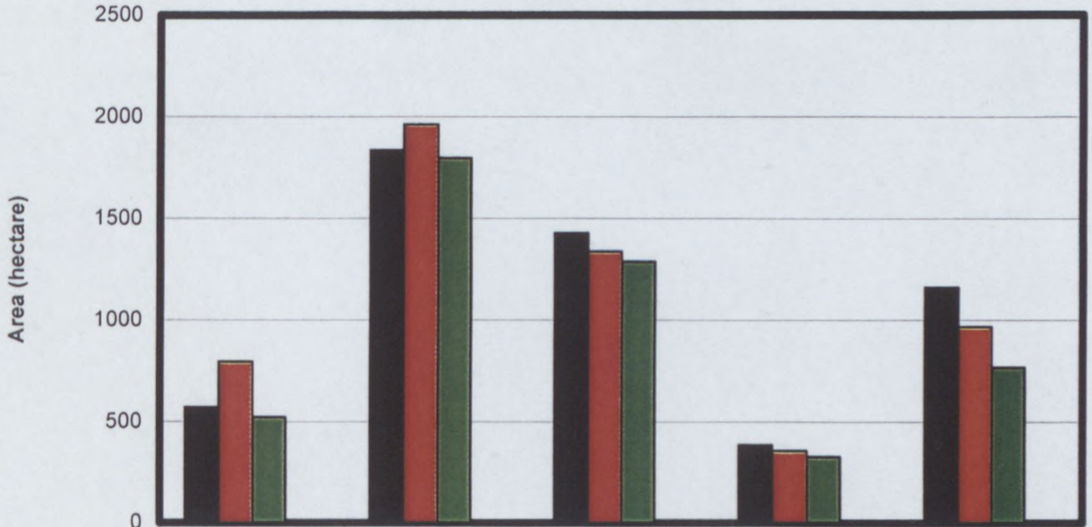


Figure 3.18: Extracted 1991 fire scar from KT-brightness differencing

Kauth-Thomas components proved to be very effective for mapping fire scars. KT greenness was however found to be unsuitable as it did not drop significantly below normal levels after a fire and recovered quickly to pre-fire levels (this is probably due to the previously mentioned low VI response of fynbos). KT brightness and moisture consistently showed noticeable change from pre-fire to post-fire. KT brightness also proved to be effective for mapping older fires (like the 1991 fire scar displayed in Figure 3.18), as it was the slowest to return to pre-fire response levels.



	1990	1991	1992	1993	1996
Existing data	570	1836	1428	384	1164
Extracted data	794	1961	1336	356	967
Overlap area	521	1798	1289	328	768
Percentage overlap	91.4	97.9	90.3	85.4	66

Figure 3.19: Calculated areas from KT-brightness differencing

From Figure 3.19 it is clear that this technique is very effective for fire scars in Limestone and Mountain fynbos regions. The results for the 1996 fire were disappointing. As noted in Section 3.5.1, this fire seems to be very young (approximately two weeks old) and therefore shows little difference from the previous year's spectral response. The technique did prove to be reliable for all the other fire scars, but it was noted that results for older fires (between 2 and 3 months) were slightly superior.

3.5.5 Ratio differencing

A variation of vegetation index differencing was used by López García & Caselles (1991). The NDVI algorithm was used but the red and infrared bands normally used, were substituted with bands that were more suitable to map burnt areas. To find the bands most suitable for mapping burnt areas, statistical analysis (correlation) of the spectral reflectances was employed. A correlation matrix of unburnt reference areas and burnt areas showed the most uncorrelated pair of bands to be TM bands 4 and 7. The same technique was used for this study, except that band 7 could have been substituted with band 5. The author calculated:

$$X = \frac{TM4 - TM7}{TM4 + TM7} \qquad [3]$$

A similar technique was named the Normalized Burn Ratio by Key (1999). This ratio proved to be quite reliable. It must be noted, however, that this technique is at its most accurate when the satellite image is taken shortly after the fire event. TM bands 4 and 7 are most uncorrelated just after burnt vegetation has been cleared away and just before vigorous vegetation regrowth starts. In this study area, that translated into 1 to 2 months after the fire.

One can extend the idea of most uncorrelated band pairs to include bands created by other techniques. For example, the author calculated the normalised difference between two highly uncorrelated Kauth-Thomas components:

$$X = \frac{Brightness - Moisture}{Brightness + Moisture} \qquad [4]$$

The reasoning for this combination was that brightness would increase sharply as the bright soils were exposed after the vegetation removal. At the same time vegetation moisture would drop sharply because of vegetation loss. When this "vegetation index" is calculated for all images, one can use them separately to extract fire scars. One can also (as the author did) difference these temporally different "vegetation indexes" to establish change. It is then relatively easy to establish a threshold for burned/changed areas.

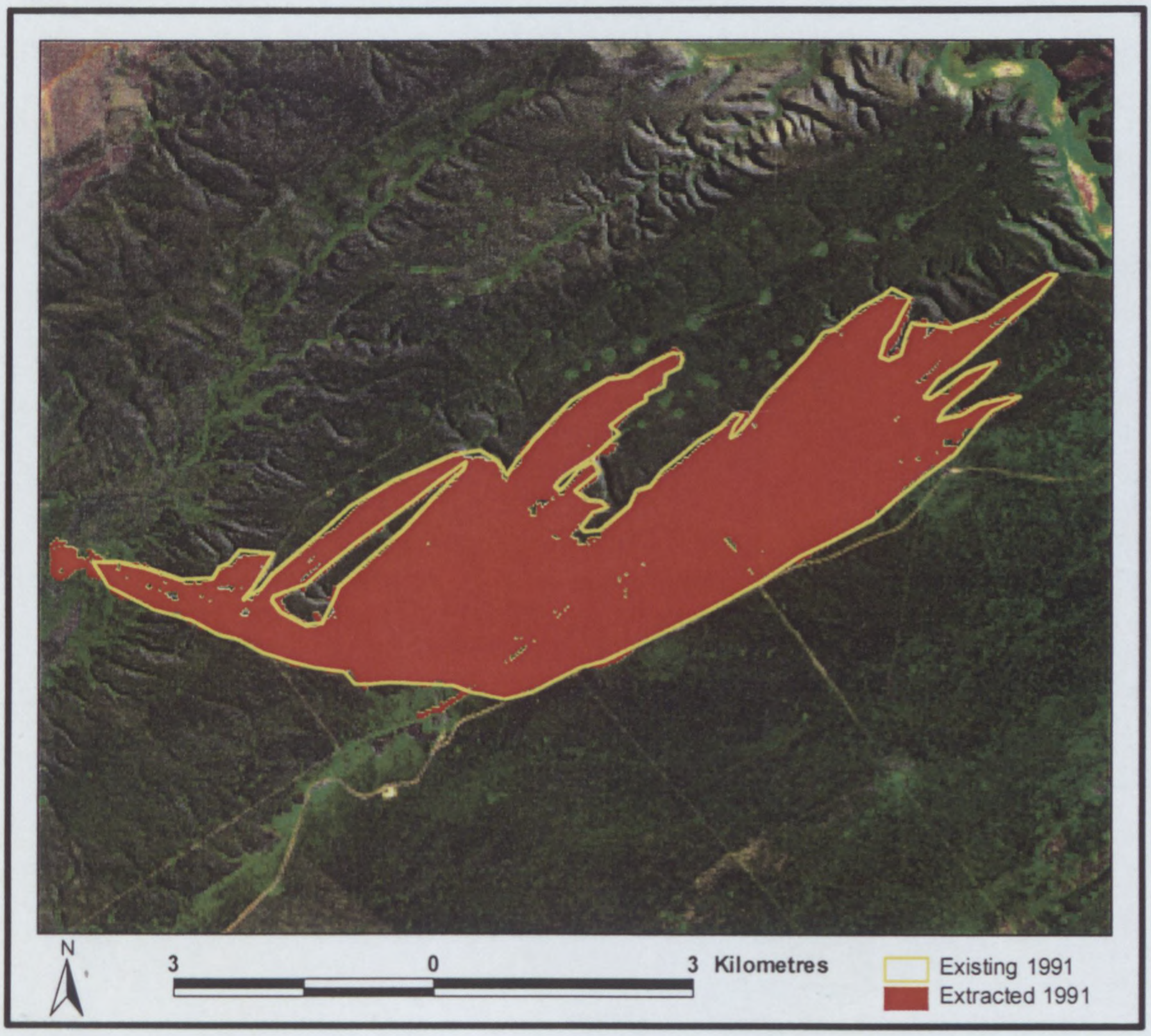
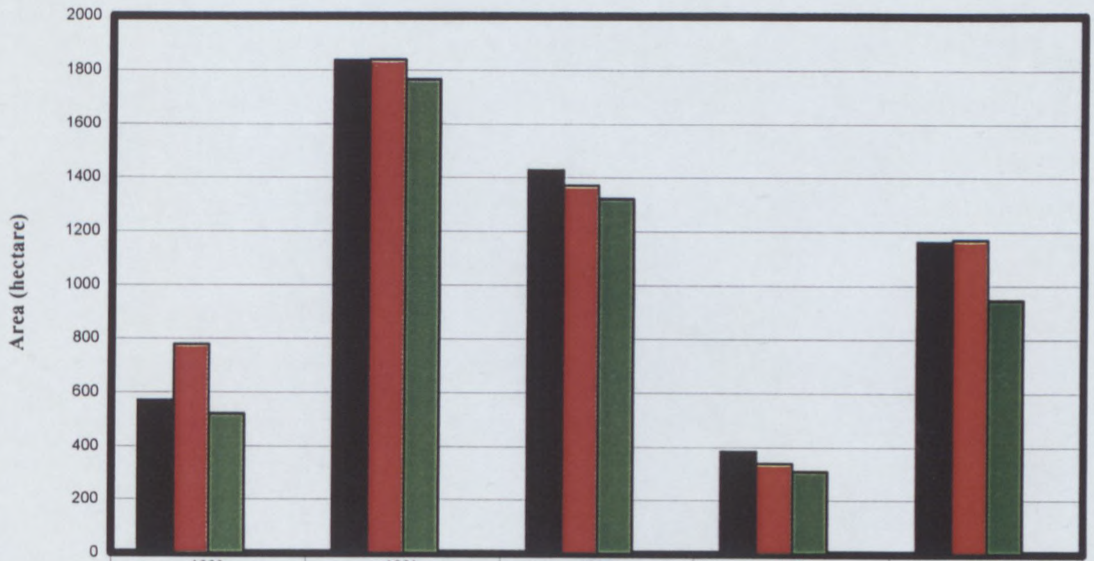


Figure 3.20: Extracted 1991 fire scar from differencing brightness and moisture ratio

From Figure 3.20 it is clear that differencing this ratio eliminates most of the confusion associated with other techniques.



	1990	1991	1992	1993	1996
Existing data	570	1836	1428	384	1164
Extracted area	777	1839	1370	341	1171
Overlap area	521	1768	1320	310	947
Percentage overlap	91.4	96.3	92.4	80.7	81.4

Figure 3.21: Calculated areas from ratio differencing (KT-components)

From Figure 3.21 one can gather that this technique worked well for most fire scars, except for very young (read 1996) fire scars. The same influences as explained in Section 3.5.1 can probably be blamed for the poor results for the 1996 fire scar. This technique does seem to work particularly well for older fire scars, as can be seen from the results for the 1991 fire scar (22 months after fire event). The results for the 1993 fire scar (Mountain fynbos) is also quite serviceable as one must keep in mind that it was badly digitised in the existing records.

3.6 PRINCIPAL COMPONENTS ANALYSES

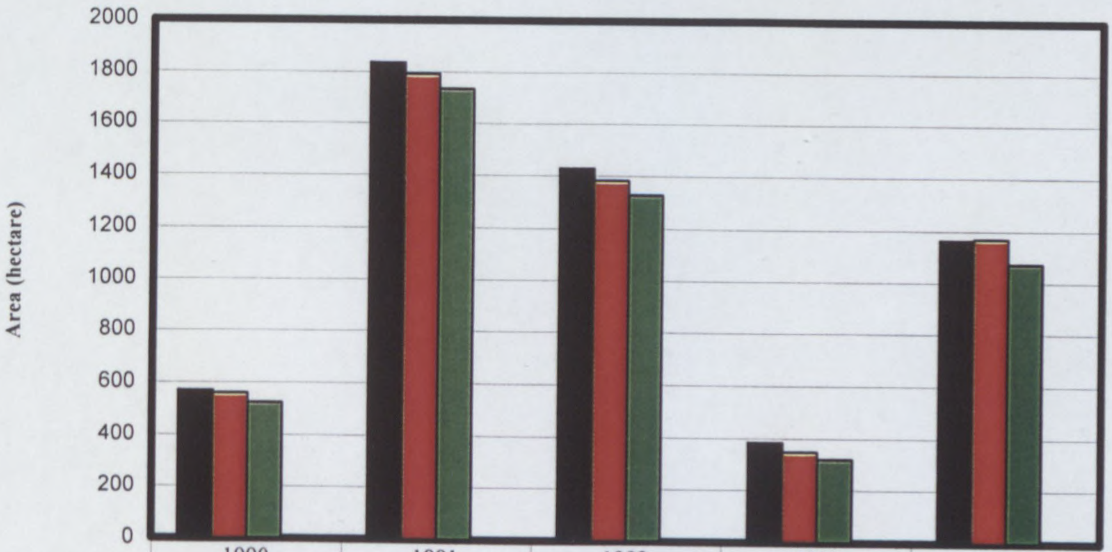
Principal components analyses (PCA) is a data reduction technique often used in multitemporal change detection. Singh (1989: 995) describes it as a "multivariate analyses technique used to reduce the number of spectral components to fewer principal components accounting for the most variance in the original multispectral images".

The basic assumption when using PCA for mapping fire scars is that the gross differences associated with overall radiation and atmospheric changes should appear in the major components. The statistically minor changes associated with local land cover changes (like fire scars) should then appear in the minor component images (Byrne *et al* and Richards & Milne, in Singh 1989). An added advantage of this technique is that seasonal and radiometric differences are accounted for in the major components, which means that pre-processing or corrections for such differences are less important than with other techniques.

The effectiveness of PCA to map burnt areas in different South African environments has already been proved by Thompson (1990, 1993). The technique does have some limitations, as reported by Thompson & Vink (1997: 1) "...the statistical measures used within them were not able to clearly discriminate between changes due to fire-related activities and other temporal factors". Furthermore, for the statistical measures to work well the changed area in the image must be relatively small (Collins & Woodcock 1994). In this study it was found that the fire events were usually located in the minor components (from component 3 and lower). Establishing a threshold for change was also found to be easier than with most of the other techniques tested.

A variation on standard principal components analyses as proposed by Singh (1989) also proved to be effective. This variation (which the author will call **PCA differencing**) involves calculating the principal components of two temporally different images. The basic premise of this technique is that the major differences between the two dates will be displayed in the major components and that the minor landcover changes (like fire scars) will be shown in the minor components. For this reason this technique seems to be less influenced by seasonal differences in vegetation spectral response.

PCA differencing proved to be potentially much faster than standard principal components analysis, because one can use fewer spectral bands (or even only one spectral band) from each date. Establishing a threshold from this procedure is relatively easy.



	1990	1991	1992	1993	1996
Existing data	570	1836	1428	384	1164
Extracted area	559	1791	1383	348	1169
Overlap area	523	1736	1329	320	1072
Percentage overlap	91.8	94.6	93	83.3	92.1

Figure 3.22: Calculated areas from PCA differencing

From Figure 3.22 it is noticeable that this technique performed well for all fire scars. Even the results for the Mountain fynbos fire scar (1993) were encouraging.

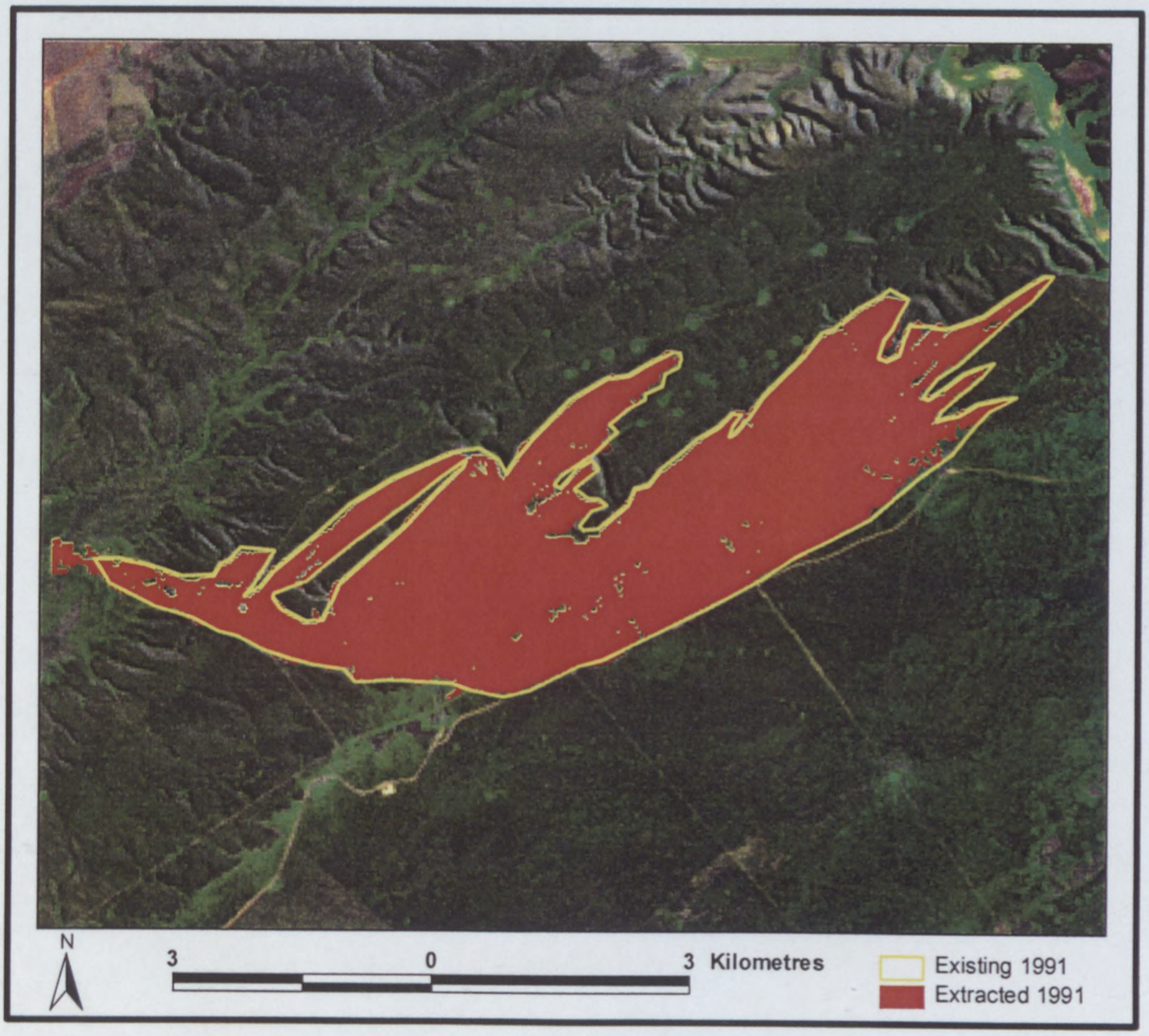


Figure 3.23: Extracted 1991 fire scar from PCA-differencing (band 7)

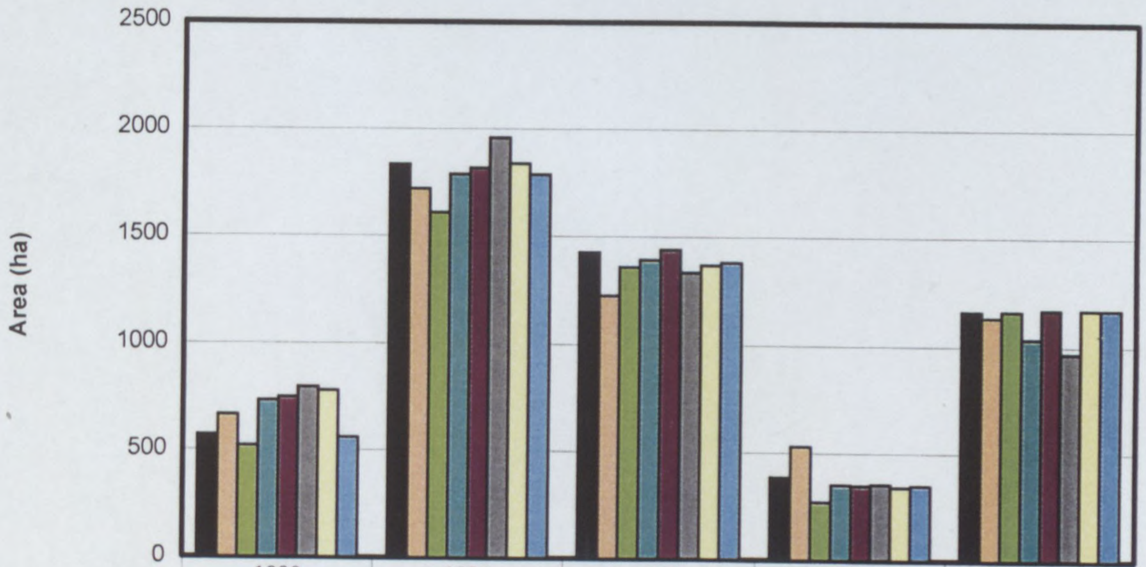
In Figure 3.23 the "old" fire scar from 1991 is displayed along with the existing fire record. It is clear that the boundary of the extracted fire scar is more than accurate enough for using in a regional fire-history database.

CHAPTER FOUR: AFTER THE FIRE

Comparing the selected techniques to existing fire records shows that all have some potential to map fire scars in Limestone fynbos. When comparing the techniques among each other it becomes noticeable that most techniques do not consistently give good results. A summary of all the results for every fire scar tested shows this clearly.

4.1 SUMMARY OF RESULTS

In Figure 4.1 the manually digitised fire scars (existing fire data) are represented in black, with the different techniques plotted in various colours.

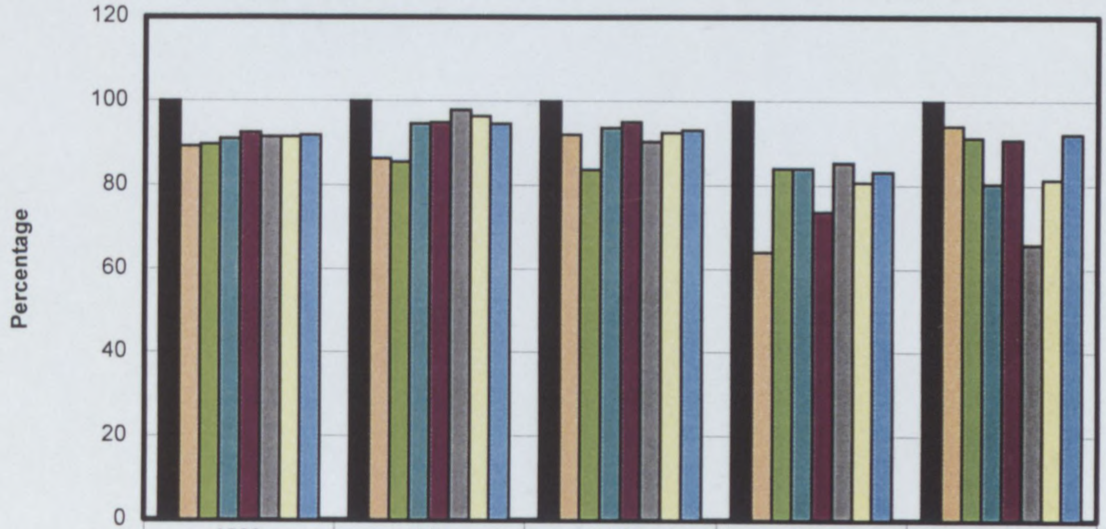


	1990	1991	1992	1993	1996
Existing	570	1836	1428	384	1164
Unsupervised	663	1723	1226	530	1133
Supervised	521	1613	1361	270	1163
Simple differencing	730	1790	1395	351	1037
NDVI differencing	746	1821	1442	347	1169
KT-bright. differencing	794	1961	1336	356	967
Ratio differencing	777	1839	1370	341	1171
PCA differencing	559	1791	1383	348	1169

Figure 4.1: Extracted area by technique for each fire

Ideally the different techniques should have extracted the same area (in hectares) as the existing area of the fire scars. In reality one would expect the extracted areas to be less than the existing area because of the usual generalization that occurs when digitising (unburnt islands are usually included in a fire scar when digitising). If the area extracted exceeds the existing area, one can assume that some form of confusion (thus leading to over estimation) has occurred during the mapping process.

In conjunction to the total area extracted as a fire scar, one should also consider the percentage overlap between the extracted area and the existing fire data. This figure should indicate that the technique did not include unburnt areas falling outside the actual fire scar. Results are displayed in Figure 4.2.

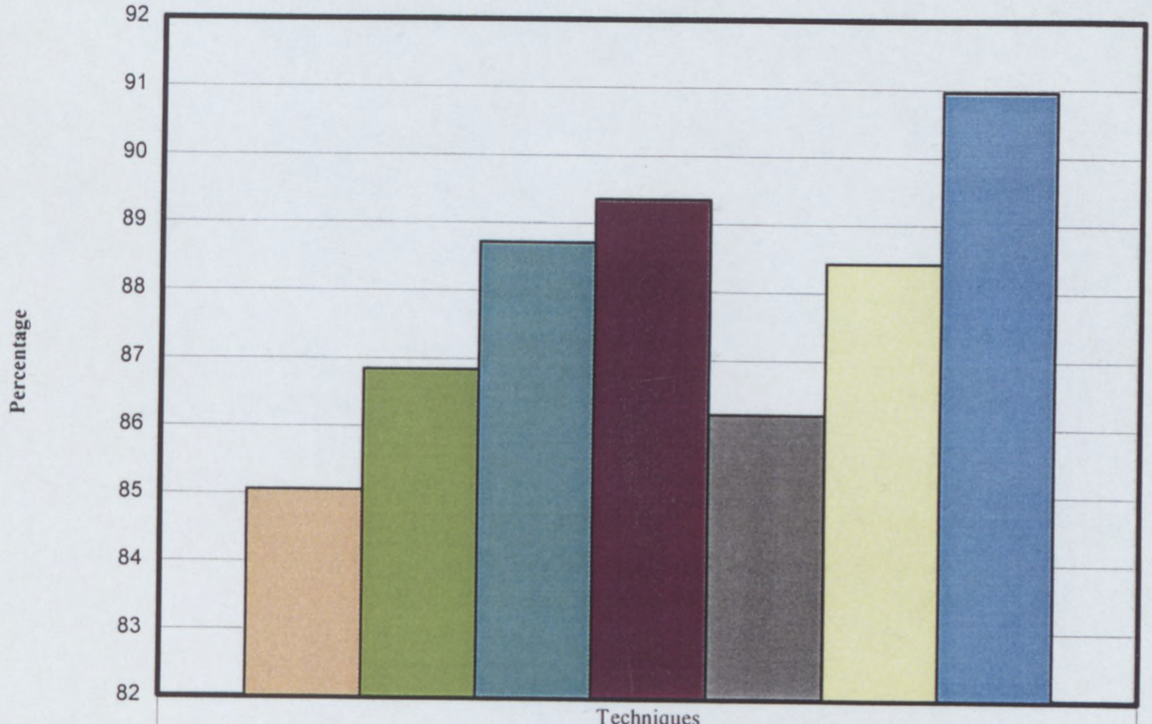


	1990	1991	1992	1993	1996
Existing	100	100	100	100	100
Supervised	89.1	86.3	91.9	64	94
Unsupervised	89.6	85.6	83.7	84.1	91.2
Image differencing	90.9	94.6	93.6	84.1	80.4
NDVI differencing	92.5	94.9	95	73.7	90.7
KT-bright. differencing	91.4	97.9	90.3	85.4	66
Ratio differencing	91.4	96.3	92.4	80.7	81.4
PCA differencing	91.8	94.6	93	83.3	92.1

Figure 4.2: Percentage overlap between existing and extracted areas

As mentioned earlier, one would expect the extracted area to be less than what existing records show. If the fire scar areas extracted by a technique exceeds the area calculated from the existing fire records, one can assume that there is "confusion" in the result. In other words, the technique has classified unburnt areas as burnt areas. This is usually the case with the techniques where burn thresholds are difficult to determine.

It is notable that for nearly every fire a different technique was found to be the most accurate (have the highest percentage overlap). However, PCA differencing is the most consistent technique, with an average area overlap of more than 90 percent when considering all fires (see Figure 4.3). Interestingly, this technique did not prove to be the best technique for any one fire, but performed well on all fires. It is also evident that supervised classification was the best technique for mapping the 1996 fire scar (a very young fire scar), but performed relatively poor on the other fire scars and seems to be the worst performer on average.



Supervised	85.06
Unsupervised	86.84
Image differencing	88.72
NDVI differencing	89.36
KT-bright. differencing	86.2
Ratio differencing	88.44
PCA differencing	90.96

Figure 4.3: Average percentage overlap for all fires

4.2 RECOMMENDATIONS TOWARDS USING THE TECHNIQUES

Considering the criteria listed under specific objectives of this study, one could make the following recommendations when comparing the techniques evaluated:

4.2.1 Supervised classification

The very nature of this technique makes it unsuitable for the proposed application. It is time consuming to compile suitable training sites, which would have to be done for every series of satellite images. The user/analyst should also have a thorough knowledge of the area being studied, which is not always the case.

This technique is not easily repeatable and would require all Landsat bands to be used for optimum results. The financial cost of buying all Landsat bands could be prohibitive. The results also show this technique to be a relatively unreliable performer.

Supervised classification does have one notable advantage though. It identifies only fire scars (based on selected training sites) and not all areas of change. This means that the analyst does not have to determine if changed areas were caused by fire or another activity or event.

4.2.2 Unsupervised classification

This technique shares all of the drawbacks of supervised classification mentioned above, which make both techniques prohibitively expensive and time consuming. It was also shown, in Figure 4.3, that unsupervised classification was one of the poorer performers on average.

One must, however, mention that this technique (as with supervised classification) is not influenced by small rectification errors or radiometric and seasonal changes, since no comparison is made between different images.

4.2.3 Image differencing

With any change analyses technique the major challenge is to establish of a change threshold. Fire scars of different ages/intensities in the same image will not have the same change threshold. This could lead to over- or underestimation of the real fire scar extent. Another drawback of change analyses techniques is that only *changes* are extracted. Whether these *changes* represent a fire or some other event or action, is for the analyst to decide. However, in nature conservation areas (as in this study area) fire would be the most probable cause of significant changes.

With this particular technique it was found that a single Landsat band (band 5 or 7) would be adequate to map fire scars. The technique is also relatively simple and requires little user input. Visual verification is however recommended.

4.2.4 Normalized Difference Vegetation Index differencing

As this technique is also a change detection technique it shares the drawbacks mentioned in the previous section. A major advantage of this technique is that it can be used to estimate vegetation cover (and possibly fire severity).

In comparison with image differencing, NDVI differencing is only slightly more complicated, but needs two Landsat bands (usually bands 3 and 4). From Figure 4.3 one can see that this technique was one of the better techniques tested.

4.2.5 Kauth-Thomas (brightness) differencing

Again the drawbacks mentioned in Section 4.2.3 apply. An additional shortcoming is that all six reflective Landsat bands are required, which could make it prohibitively expensive. This technique is also more complicated than any of the above differencing techniques. Finally, the added complexity of this technique did not complement its performance, with NDVI differencing being more accurate on average (see Figure 4.3).

KT differencing however produced excellent results for the 1991 fire scar (97,9%), possibly because it was easier to establish a change threshold with this technique than when using NDVI differencing.

4.2.6 Ratio differencing

The main drawback of this technique (as used in this study) is that all six Landsat bands are needed. This technique is probably the most complicated of all the differencing techniques, which also makes it relatively time consuming (see Section 3.5.5).

The main advantage is that there is little "confusion" when using this technique and thus it is relatively easy to establish a change threshold. The results of this technique offer little reward for the increased effort.

4.2.7 PCA differencing

The author found PCA-differencing to be the most suitable technique (in terms of cost, simplicity and repeatability) of those tested. The main reasons being that it requires little user input, few Landsat spectral bands and relatively short computer processing time. Another advantage is that atmospheric, radiometric and seasonal changes are (mostly) accounted for in the major components. This makes establishment of change thresholds much easier than in other change detection techniques. This would also compensate for less than perfect radiometric and atmospheric correction.

When interpreting the results, one should remember the potential pitfalls of any change analyses technique. A thorough knowledge of the studied area is always a benefit and coupled with visual interpretation of the Landsat images (see next section), one should be able to validate the results of the remote sensing technique. In so doing one would be able to exclude areas that might have been changed by other causes or actions (like new development or excavations etc.).

In a Limestone fynbos region the author would thus recommend that one uses PCA differencing with a single Landsat band (band 5 or 7) from each year (or shorter intervals if data is available). If possible the images should be taken shortly after the main fire season, which is February (late summer) in this study region. If possible each image should be acquired in the same season, so that seasonal differences (and thus the need for corrections) can be minimized. Using a combination of PCA differencing and traditional fire mapping, an accurate fire history database could be produced. From the results obtained in this study it is clear that a more than acceptable level of accuracy can be obtained to aid persons/institutions involved in the management of a fire regime in their fynbos region.

4.2.8 Visual interpretation

As mentioned in the previous section, even if the techniques used prove to be reliable, one should also consider the use of visual interpretation to verify the results. This is not a extraction technique, but merely a way to verify results already obtained. Clearly the analyst must have a thorough knowledge of the study area when trying to visually verify the results obtained through other techniques.

Visual interpretation requires the user to be able to visually discriminate between burnt areas and areas not affected by fire. This is usually done by displaying the satellite image bands (or combinations thereof) on screen. From Landsat TM imagery the user can choose to display individual raw spectral bands or a combination of raw bands in a so-called false colour composite image. For simple visual interpretation of raw image bands the author recommends a RGB combination of TM bands 4, 5 and 7.

The user can also employ a range of "improved" images. This could include change detection images (as described in Section 3.5), component images from PCA, various vegetation indices, ratios of raw and/or other "improved" bands, or any combination of these options. The possibilities are too numerous to mention here, but some examples that could be considered include:

- Difference NDVI images using KT-brightness and KT-moisture as input bands (Figure 4.4)
- a false colour composite of TM band 5, Kauth-Thomas greenness and NDVI
- PCA differencing images using band 7 or band 5
- a false colour composite of TM band 5, NDVI and principal component 2
- a false colour composite of Kauth-Thomas components
- a false colour composite of Kauth-Thomas brightness, NDVI from TM 4 and 7 and principal component 2

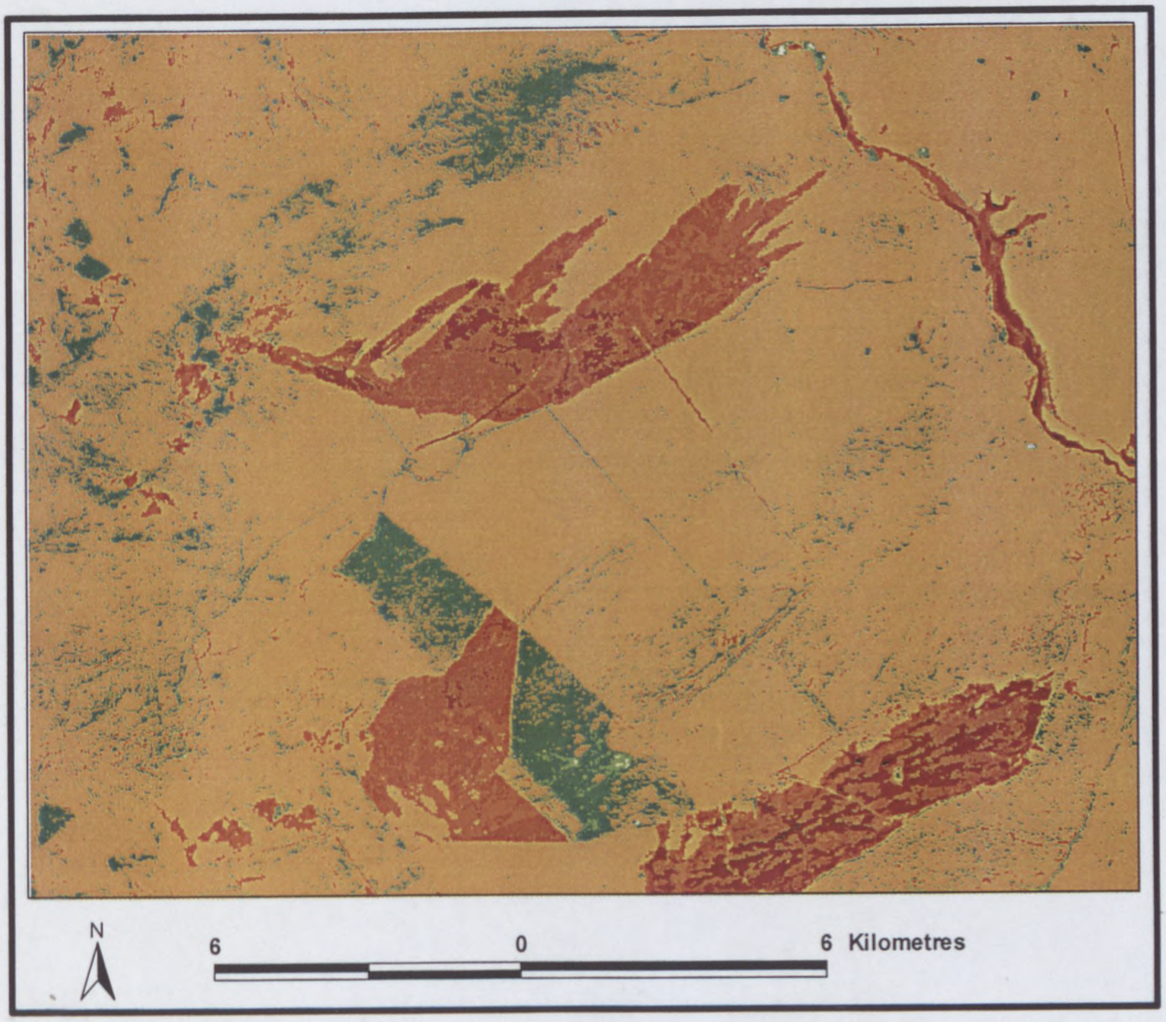


Figure 4.4: Practical image for visual interpretion

In Figure 4.4 the difference between KT-brightness images from 1991 and 1993 was calculated and displayed in 256 colours. From Figure 4.4 one is able to distinguish the 1992 fire scar (southern most dark orange area), the 1991 fire scar (northern most dark orange area) and another fire scar from 1991 (dark orange area flanked by green areas). The green areas are fire scars from 1990 which show vegetation recovery from 1991 to 1993. The other noticeable linear area in Figure 4.4 shows the De Hoop vlei.

4.3 POSSIBLE REFINEMENTS

The first objective of this study was to determine the most effective (in terms of accuracy, cost, repeatability and simplicity) remote sensing technique (using Landsat TM) to map fire scars in the study area. Thus only techniques that potentially meet these requirements were considered. In this section areas where one could improve or modify the techniques selected (and other techniques not selected) are discussed.

4.3.1 Pre-processing and data extraction

As suggested before, images should be taken in the same season to minimise the need for data calibration. For the same reason images taken in summer are preferable to ones taken in winter months (when shadow effects are most severe). If images are collected over different seasons, one should also correct for sun-angle and the like.

One should concentrate on image registration accuracy, as any image differencing (change analyses) is adversely affected by poor registration (Singh 1989). One should attempt to standardise multitemporal images as much as possible. In this regard corrections for relief, illumination, radiometric errors, atmospheric interference and sensor degradation should be considered.

4.3.2 Additional data sources

The benefits of linking remotely sensed data with additional GIS information have been well documented: "Fire location mapping on a broad area will be especially useful when it is combined with GIS ancillary data such as political boundaries ..., land ownership ..., cities and roads, lakes and rivers, lat/long grid, and vegetation and fuel type.... A fire manager might want to identify and display fires ...in wilderness areas, fires within a specified distance of major cities, or fires that are on forested land" (Knapp, Andrews & Turek 1996).

Ancillary data could also include data from other satellites like SPOT, AVHRR or others, which have better spatial or temporal resolution than Landsat. One could identify the fire scars with annual Landsat images and then use the additional satellite images to determine the age of the fire scars more precisely. This would be a cost saving strategy, as one can get lower resolution satellite images from the Centre for Scientific and Industrial Research (Satellite Application Centre) through the internet at no cost. Although this data is not useful in demarcating fire scars, it is reliable enough to determine more precisely the date of a fire occurrence.

It should also be noted that since the launch of Landsat 7, the cost of Landsat imagery has dropped significantly. It is now possible to buy all the Landsat bands for a price comparable to that of one band from Landsat 5. Organisations with limited budgets should now be able to benefit from the use of more spectral bands and hence higher accuracy.

4.3.3 Neural networks

The relatively new field of artificial neural networks (ANNs) has shown the potential to surpass "traditional" image analyses. Several studies have shown artificial neural networks to be more effective than other methods in image classification (e.g. Benediktsson, Swain & Ersoy 1990; Bischoff, Schneider & Pinz 1992; Carpenter *et al* 1997; Dai & Khorram 1999 and Kanellopoulos *et al* 1992). Pereira *et al* (1999) point out, in a recent review of fire scar studies, that: "there is ...no experience with more modern approaches, such as fuzzy and neural classifiers". The technology and expertise is still hard to come by, but artificial neural networks would probably be well suited to the study of fire scars as well.

The reasons for this are explained by Gopal & Woodcock (1996:398): "They represent a fundamentally different approach to problems like pattern recognition, as they do not rely on statistical relationships. Instead, neural networks adaptively estimate continuous functions from data without specifying mathematically how outputs depend on inputs (i.e. adaptive model-free function estimation using a nonalgorithmic strategy)". Gopal & Woodcock (1996) further demonstrated that artificial neural networks were superior to other techniques in a change detection application.

Carpenter *et al* (1997: 308) lists the following advantages of artificial neural networks: "...a) neural network classifiers, which make no *a priori* assumptions about data distributions, are able to learn nonlinear and discontinuous data samples; b) neural networks can readily accommodate ancillary data such as textural information, slope, aspect and elevation; c) neural networks are typically more accurate than conventional classifiers; and d) neural network architectures are quite flexible and can be adapted to improve performance on particular problems".

4.3.4 Other techniques not considered for this study

Numerous other ways to extract fire scars exist. One such technique is **spectral mixture analyses**. Pereira *et al* (1999) note a study where the data was analysed with image endmembers, and burned areas extracted using a charcoal endmember. They are of the opinion that: "...this approach appears to work effectively, and seems to minimise the effects of some of the more common sources of confusion" (Pereira *et al* 1999). Roberts *et al* (1999) also believe that such a technique "may prove invaluable for fire hazard prediction". However, research into its application for fire scar mapping is limited.

Several other change detection techniques could also be considered. One such a technique uses the **Gramm-Schmidt transformation**. Collins & Woodcock (1994) successfully used it to map forest mortality in the Lake Tahoe Basin using Landsat TM images. It was shown that such a technique achieved an accuracy of about 70 percent. This technique was not considered for this study because it is similar to the Kauth-Thomas technique investigated.

After change detection one may want to use a classification technique to extract the fire scars automatically. Here a technique proposed by Acton (in Crawford & Pianka

1996) called **pyramid segmentation** could be an option. With such an algorithm the fire scars can be extracted more efficiently and with little input from the user.

4.4 CONCLUSION

In an advertisement for GIS software the advertiser had this to say of remote sensing and fire management:

"Effective Fire Management within your parks, on your pastoral property, in forests and bushland requires timely and accurate information. Without timely and accurate fire history information your fire management and planning effectiveness will suffer….Fire history maps will show you exactly where the fires have occurred during your burning season. Fire area measurements will enable you to build a year by year profile so that you can monitor your fire management and planning effectiveness. This information can be derived from satellite imagery. Some satellites have been collecting data over your area for the last 15 or more years. Using this historical data you can extract fire information that will enable you to see the trends and patterns over a long period of time. You will also see the changes that your fire management practices are having" (Southern Remote Sensing 1998).

The author wishes that this study has added to the belief that satellite remote sensing is indeed a viable, cost effective and beneficial way of mapping fire scars. That satellite remote sensing can also be used in a South African environment has been proven beyond doubt. Hopefully this study will contribute to the conservation and prosperity of the unique floral kingdom of the Cape.

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APPENDIX A

Bushfire Mapping in Northern Australia using AVHRR data.
http://www.erin.gov.au/land/vegetation/plant_cov/fire_paper.html

Fire Management in Sequoia and Kings Canyon National Parks
http://www.nps.gov/seki/fire/index.htm

Fire Monitoring by Satellite - Related Links
http://modarch.gsfc.nasa.gov/fire_atlas/links.html

Fire Monitoring by Satellite - Satellite Fire Monitoring Systems
http://modarch.gsfc.nasa.gov/fire_atlas/systems.html

Southern Remote Sensing http://www.ozemail.com.au/~srs/Fires_int.htm

Satellite sensing of fires and estimation of resultant emissions in Brazil.
http://geo.arc.nasa.gov/sge/brass/Brass.Fire.html

Great Victoria Desert, Australia Topic: Wildfire Behavior.
http://www.csr.utexas.edu/projects/rs/aussie.html

Image Navigation for Wildland Fire Location Mapping.
http://ncgia.ucsb.edu/conf/SANTA_FE_CD-ROM/main.html

A spatial decision support system for urban/wildland interface fire hazards.
http://www.esri.com/library/userconf/proc95/to200/p175.html

Canada centre for remote sensing
http://www.ccrs.nrcan.gc.ca/ccrs/imgserv/tour/images/01/01burne.html

Megafire project http://www.infocarto.es/id/eur/position-papers.html

Optimum Strategies for Mapping Vegetation using Multiple Endmember Spectral Mixture Models http://vache.ucdavis.edu/papers/sustin/optstrat/paper.html

Texas Forest Service Fire Control Mapping Project http://www-msl.tamu.edu/projects/proj.html

A Spatial Decision Support System for Urban/Wildland Interface Fire Hazards
http://www.esri.com/library/userconf/proc95/to200/p175.html

Bushfire council of the northern territory research projects
http://savanna.ntu.edu.au/research/projects/firsav.html

US forest service Fire + Aviation page http://www.fs.fed.us/fire/links2.shtml

USFS Wildland Fire Assessment System http://www.fs.fed.us/land/wfas/

A GIS system for the western Cape
http://dwst02.edvz.sbg.ac.at/geo/idrisi/GIS_Environmental_Modeling/sf_papers/fairbanks_dean/my_poster1.html

Australian Environment online http://www.erin.gov.au/index.html

Firenet http://www.anu.edu.au/forestry/fire/firenet.html

Monitoring of fire regimes at the wet screlorphyll forest and rainforest ecotone: application of ecological remote sensing techniques
http://www.jcu.edu.au/~sci-mjn/default.html

Tropical savanna CRC – research projects.
http://savanna.ntu.edu.au/research/projects/firsav.html

USDA Forest service Home Page
http://www.fs.fes.us/

Riverside Fire Lab
http://www.rfl.psw.fs.fed.us/

The Fire Science Centre at the University of New Brunswick
http://www.gov.nb.ca/cnb/update/fire.htm

Fire and Environmental Research Applications Team (FERA)
http://sol.cfr.washington.edu/fera.html

FFASR Directory http://www.fs.fed.us/research/ffasdir.html

FireNet Information Network http://www.csu.edu.au/firenet/firenet.html

Forest Fire Research http://www.denendeh.com/flycolor/wildfire

Canadian Wildland Fire Information System http://www.nofc.forestry.ca/

Forest fire http://www.gov.nb.ca/cnb/update/forstfir.htm

Remote Sensing http://www.ccrs.nrcan.gc.ca/ccrs/homepg.pl?e

Pyr.sos http://wwwrtd.algo.com.gr/algoeu/pyrsos1.htm

FireWeb Fire Service Related Links http://www.fireweb.com/nav/support.html

The Boreal Forest Watch Homepage
http://www.bfw.sr.unh.edu/html/files/activity.html

Wildfire Magazine Home Page http://www.neotecinc.com/wildfire

Firebreak http://msowww.anu.ed.au/~barling/firebreak/firebreak.html

East Bay Hills/Contents http://www.ced.berkeley.edu/aegis/eastbay/scon.htm

Fire and Forest Meteorology Education
http://earthlab.meteor.wisc.edu/firewx/index.html

Flashpoint http://www.ee.ualberta.ca/%7Ecbecker/shawn.htm

BIBEX Home Page http://www.mpch-mainz.mpg.de/bibex.html

Fire Growth Modeling in an Integrated GIS Environment
http://www.esri.com/base/common/userconf/proc97/PROC97/abstract/A696.htm

Environmental Training Centre Fire Management Course Schedule
http://www.gov.ab.ca/~env/cms/hrd/etc/fsched96.html

World Forestry Congress
http://www.fao.org/waicent/faoinfo/forestry/wforcong./PUBLI/default.htm

FERA Products and Publications http://sol.cfr.washington.edu/pub.html

Prescribed Fire RWU Home Page http://www.rfl.pswfs.gov/prefire/

FARSITE: Home page (1-Sep-97)
http://www.montana.com/sem/public_html/farsite/farsite.html

CELLAN code: Forest Fire (14-Aug-97)
http://rucs2.sunlab.cs.runet.edu/%7Edana/ca/examples/ffire/ffire.html

Wallace's Web Page (4-Jan-1997) http://longwood.cs.ucf.edu/~wallace/

EMBYR : Simulating Fire Patterns in Heterogeneous Landscapes (Jan- 1996)
http://www.esd.ornl.gov/ern/embyr/embyr.html

Forest Fire (26-Feb-1996) http://cuiwww.unige.ch/spc/Cosmase/forestfire.html

BURN: A Simulation of Forest Fire Propagation (Jan 1994)
http://www.npac.syr.edu/REU/reu94/mveach/burn.html

Forest Fires
http://www.earthbase.org/home/stock/PollDesNat/ForestFire/.ForestFire.html

Forest Fire Fighting Hotshot Crew http://www.sover.net/~kenandeb/fire/hotshot.html

Photo gallery http://www.odf.state.or.us/photo.htm

Resource Listing http://earthlab.meteor.wisc.edu/firewx/firewxrl.htm