Assessing Intra-seasonal land surface change and long term trends in the Succulent Karoo biome using coarse resolution satellite data and interpolated rainfall surfaces

Jonathan **Wesley** Roberts

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Abstract

The Succulent Karoo is a biodiversity hot spot situated along the west coast of southern Africa. While it is predominantly recognized as a west coast vegetation type its borders stretch as far east as Steytlerville in the Little Karoo. The area contains the largest number of endemic succulent species in the world and harbors nearly 10 percent of the total number of succulent species worldwide. Furthermore, spring mass-flowering events draw thousands of tourists to the region, providing welcome input to the local economies. The floral diversity is however under threat from various environmental forces. These forces include inappropriate land use practices resulting in Land Degradation and the ever-present threat of Climate Change.

With the pressures that are presently being placed on the biome and the threat of future changes to the climatic regime, it is necessary to develop methodologies to monitor vegetation changes within the biome. These methodologies should be able to discern between climate driven and land use driven changes that may denude the rich biological diversity of the biome. Monitoring regional changes in vegetation necessitates the use of coarse resolution satellite data in conjunction with statistically derived rainfall surfaces.

For the purposes of this study intraseasonal land surface change is monitored using the Normalized Difference Vegetation Index derived from the National Oceanic and Atmospheric Administration (NOAA), Advanced Very High Resolution Radiometer (AVHRR). Rainfall surfaces are taken from Hewitson and Crane (2005). Ancillary temperature data taken from NCEP reanalysis is also used. Three analysis methodologies are used to answer questions relating to the relationship between rainfall and vegetation growth. Firstly, a Spatio Temporal Correlation filter (STCf) is used to investigate the spatial and temporal nature of seasonal vegetation changes (*Where is seasonal vegetation change homogenous?*). Secondly Principal Component Analysis is used to monitor seasonal vegetation change (*What is the seasonal nature of NDVI in the Succulent Karoo?*) and finally the relationship between precipitation and vegetation growth is classified using a Self Organising Map (*When and where is the relationship between rainfall and vegetation growth strongest?*).

Results from the three analysis methodologies are combined to determine *zones of potential critical change*. Within each of these zones drivers of vegetation change are identified and discussed. Most notably, regression analysis conducted on the output of the Self Organising Map indicates that temperature plays a more important role in vegetation growth than precipitation. This result indicates that the biome may be more vulnerable to the impacts of Global Warming than previously anticipated. Results also indicate that future studies of vegetation change using satellite imagery should be cognisant of the potential effects of soil background reflectance.

In conclusion this thesis shows that much of the Succulent Karoo biome is under threat from both inappropriate land use and Climate Change, which may potentially lead to degradation of the biodiversity and rangelands that support the local population.

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Chapter 1

Introduction

1.1 Problem Statement

Arid and semi-arid rangelands comprise 50 percent of the world's total land surface area (Meadows and Hoffman, 2002). Many of these are threatened by degradation and potential desertification from anthropogenic activities and climate change. In southern Africa the arid and semi-arid regions are characterised by extremely high levels of plant diversity. These areas support a large number of commercial and communal stock farmers utilizing the ground cover as feed for cattle, sheep and ostriches. The Northern and Western Cape provinces are home to some of the largest arid rangelands in southern Africa, which are poorly understood, and at the limits of their carrying capacities. Overgrazing on communal and commercial rangelands has negatively influenced nearly two-thirds of the Succulent Karoo (SKEP, 2002).

In South Africa, the Succulent Karoo is a semi-arid biome with a unique plant community. It has the largest number of endemic succulent species in the world (Esler *et al.,* 1999) and contains almost 10 percent of the total number of succulent species worldwide (Cowling *et al.,* 1998). While this diversity is sometimes overshadowed by the far more popularised Fynbos biome, the Succulent Karoo is well known for its endemic succulent species and annual spring mass-flowering events. The biome is, however, under threat from several environmental factors, such as agricultural expansion, overgrazing and climatic changes. These combined pressures pose significant threats to the future survival of the regions endemic flora.

The Climate Research Group at the National Botanical Institute recently published a report on the possible effects of climate change on plant biodiversity in southern Africa. The report was entitled "South African Country Study on Climate Change: Plant Biodiversity: Vulnerability and Adaption Assessment." The Succulent Karoo was modelled using a Bioclimatic Modelling approach that derived environmental limits from key climatic parameters. In the study, two General Circulation Models (GCMs), namely the Hadley Centre's Coupled Ocean-Atmosphere Model, (HadCM2) and the National

Centre for Atmospheric Research's Climate System Model (CSM) were used. Results indicate that the areal extent of the Succulent Karoo will decrease by the year 2050, due to a warming climate as well as extended aridification (Rutherford *et al.,* 1999). This is of concern as the area contains over 5000 plant species with more than 50 percent endemic, (Milton *et al.,* 1997) making it one of the most biodiverse "hot" spots on the planet.

Climate change is not the only impact likely to alter the plant biogeography of the Succulent Karoo. The biome has undergone sustained transformations since the arrival of pastoral colonists. Sheep, goats and cattle first entered the Karoo from the north; it is believed that herders brought these animals to the Succulent Karoo more than 2000 years before present (Webley, 1986). When the first colonial settlers arrived in the Western Cape, the arid zone supported a limited pastoral economy. A group of Khoi herders known as the "Little Namaqua" were present in the Kamiesberg region for at least 2000 years before the arrival of colonial settlers in the 1750's. Farming was initially transhumance, where cattle grazed along geographical and climatological gradients, making use of ecological niches supporting grazing at different times of the year (Hoffman *et al.*, 1997). By the end of the 19th century, the large herds of indigenous grazers present in the biome had been shot out by colonial settlers giving way to large-scale farming. Later, an increasing number of farmers and grazing animals made it impossible to continue traditional pastoral agriculture. A more sedentary agricultural practice developed with farmers restricted to surveyed parcels of land. No fences existed at this time and animals were kept in *"Kraals"* to protect them from predators. The introduction of boreholes and windmills meant that agriculture expanded into marginal areas where grazing could take place throughout the year (Hoffman and Ashwell, 2001). Stocking rates and management practices have not always incorporated the lower resilience of arid areas to grazing pressures, resulting in areas undergoing transformation. This transformation is highlighted in the fenceline contrasts observed in the arid regions of South Africa (Hoffman and Ashwell, 2001).

Land degradation, and potential vegetation change as a result of climate change are vitally important issues that need to be addressed within the Succulent Karoo biome. Land degradation is defined as follows:

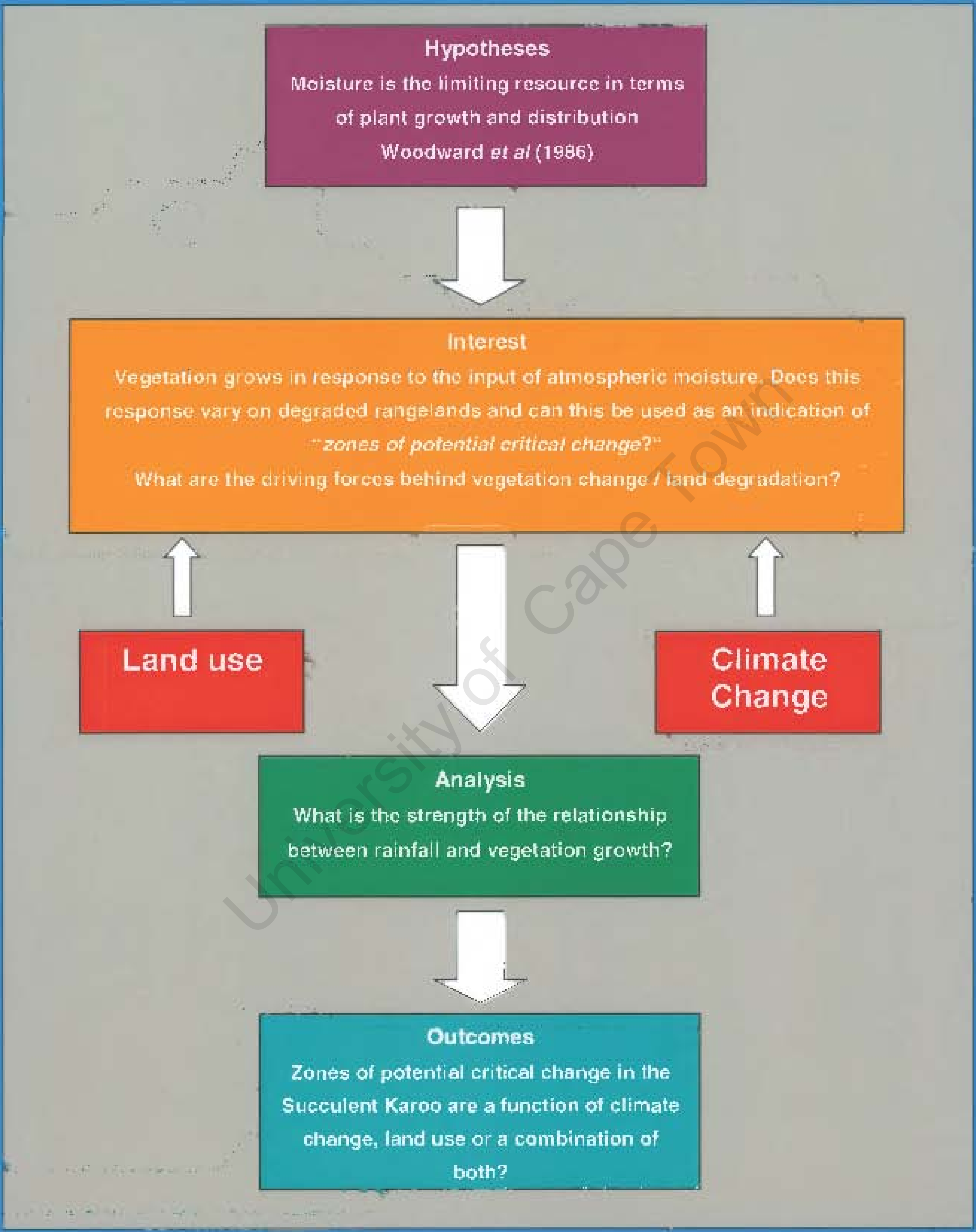
> *"Reduction or loss, in arid, semi-arid and dry sub-humid areas, of the biological or economic productivity and complexity of rainfed cropland, irrigated cropland, or range, pasture, forest and woodlands resulting from land uses or from process or combination of processes arising from human activities and habitation patterns"* UNCCD (1995)

Rangeland science in the past has failed to produce a generally accepted framework for assessing the sustainability of a rangeland in terms of the changes, and / or pressures imposed on the rangeland (Stafford Smith and Pickup, 1993). A long-standing challenge is the differentiation between naturally occurring vegetation changes and anthropogenic or human-induced change. While it may be possible to identify areas where vegetation change is taking place, identifying the driving forces behind the transformation is complex. One could presume climate change is occurring and directly impacting on vegetation health and that land use is a secondary factor or *vice versa*.

1.2 Research question

In the problem statement above, several questions relating to vegetation change in the Succulent Karoo were introduced. The complexity of the plant biogeography and high levels of endemism in the biome make it difficult to pinpoint drivers of vegetation change. The working thesis as outlined in Figure 1.1 states that: *"Moisture is the limiting resource in terms on plant growth and distribution"*. This relationship has been established elsewhere (Woodward *et al.*, 1986). This thesis seeks to test this hypothesis by analysing the relationship between plant growth and precipitation within the context of Climate Change and Land Degradation research. It is certainly argued that Climate Change and Land Degradation have their own part to play; the key becomes identifying areas that may be vulnerable to impacts associated with Climate Change and Land Degradation. To do this it is necessary to identify the climate change signal within the highly variable climate of the Succulent Karoo. To achieve this, scientists need to develop sound methodologies that incorporate the history of the vegetation as well as the complexities of human vegetation interactions. This research will test various methods that aim to enhance our understanding of the Succulent Karoo and the pressures being placed on it.

The rest of this chapter will be devoted to introducing the questions and relationships being explored. Section 1.3 introduces some of the key questions and paradigms that underpin the research methodology. An outline of the research structure is given with a brief summation of outcomes. Section 1.4 and 1.5 discuss two potential drivers of vegetation change / land degradation namely Climate change and Land use. Finally the research outline is touched upon outlining the structure of this thesis and the various analytical techniques employed.



Hypotheses

Moisture is the limiting resource in terms of plant growth and distribution Woodward *et al* (1986)

Interest

Vegetation grows in response to the input of atmospheric moisture. Does this response vary on degraded rangelands and can this be used as an indication of "*zones of potential critical change*?"

What are the driving forces behind vegetation change / land degradation?

Analysis

What is the strength of the relationship between rainfall and vegetation growth?

Outcomes

Zones of potential critical change in the Succulent Karoo are a function of climate change, land use or a combination of both?

Figure 1.1: Conceptual Flow chart of key questions and potential outcomes of present research

1.3 Research objectives and potential outcomes

Figure 1.1 outlines the research questions and relationships explored in this thesis. The major theory is that moisture is the major limiting factor in plant growth and distribution (Woodward *et al.*, 1986). This is especially important when the study area is an arid to semi-arid desert. The Succulent Karoo receives most of its rainfall in the winter months, but does make use of overflow water from summer rainfall falling elsewhere (see chapter 2).

The interest and basis for the research project is to analyse the varying response of vegetation to the input of precipitation. It is well known that vegetation will grow in response to precipitation, but does this response vary according to the state of the vegetation? Do degraded rangelands respond differently to a healthy / well managed rangeland and can this response be used to identify "*zones of potential critical change*"? Two potential drivers have been identified; Climate Change and Land use. Present research analyzes concurrent NDVI and Precipitation data to identify trends and or changes that may be attributed to either Climate Change of Land Degradation.

Statistical methods are used to explore the relationship between rainfall and vegetation growth. Three separate methodologies will be used to explore various questions regarding vegetation growth, temporal behaviour of vegetation and the relationship between rainfall and vegetation growth. The final question uses a similar methodology to Nicholson *et al* (1990) whereby time lags between rainfall and vegetation growth are used to determine the best-correlated parameter. Temperature, derived from NCEP reanalysis data are also used (Kalnay *et al.*, 1996). Results from the three analyses (see chapter 5, section 5.6) are collated and used to comment on their applicability for identifying "*zones of potential critical change*".

Finally, given that we have applied the above methodology to determine potential areas of *"zones of potential critical change",* implicit relationships used, could then be employed to determine the nature of critical change within the biome. The following two sections 1.4 and 1.5 give a brief introduction to Climate Change and its potential impact on the biome as well as land use, its history and recorded impacts in the Karoo and Succulent Karoo regions of South Africa.

1.4 Climate Change and its impact on the Succulent Karoo

Human activities continue to cause a loss of biodiversity through land-use and land cover change, soil and water pollution, degradation and desertification and air pollution (Climate Change and Biodiversity IPCC Technical paper V, 1999). Since the Industrial Revolution man has begun to contribute to climate change. Climate change, however, is not a new phenomenon. Vegetation patterns found in the Succulent Karoo are the result of climatic changes that occurred some 14 million years ago. These changes came about as a result of the establishment of the Benguela current, which developed during the late Miocene (23.5 – 5.3 million years BP). The cool current now found along the west coast contributes to the arid climate of the area (Tyson and Preston-Whyte, 2000). The difference between vegetation changes in the past and potential changes presently being observed is that changes in the past occurred over longer time spans and were principally driven by natural climatic change. Today more pressures are being imposed on the fauna and flora not only through climate change but also land use (see below). Climate change is especially critical in areas where plants have established themselves in environmentally sensitive areas, where a small change in environmental conditions such as the amount and timing of winter rainfall, may render the area unsuitable for specific species. The Succulent Karoo is one such area with a large number of endemic species that are found nowhere else on earth. These endemic species have evolved within the biome as a result of a unique climate and environmental conditions.

The IPCC technical paper V, "Climate Change and Biodiversity" reports that the composition of the atmosphere is changing and that this is having an effect on global climate patterns. These observed changes are summarised into the following observations

- Atmospheric concentrations of Greenhouse gases and aerosols have increased since pre-industrial times
- Both surface temperature and precipitation patterns have changed, with temperature increasing and precipitation patterns changing especially over the northern hemisphere.
- Snow cover and ice extent have decreased due to increased surface temperatures; sea level has risen due to the melting of large ice masses in Polar Regions.

- The occurrence of El Nino Southern Oscillation (ENSO) on more frequent basis points towards changes in climatic variability.
- Observed changes in extreme climatic events: higher maximum temperatures, higher minimum temperatures, fewer cold days as well as fewer frost days.

Projected changes using results from the Special Report on Emissions Scenarios (SRES) are as follows (Nakicenovic, 2000)

- Emission scenarios report an increase in atmospheric concentrations of CO_2.
- The global average surface temperature is predicted to increase between 1.4°C and 5.8°C.
- Precipitation is likely to increase globally but regional changes are set to increase or decrease depending on the area.
- Global warming is likely to lead to greater extremes of drying and precipitation, thereby increasing the risk of flooding and droughts.
- Global ice caps are likely to continue their retreat and sea level rise is projected to be around 0.09 to 0.88m.

Projected changes in global weather patterns will have a marked effect on the global / regional spatial distribution of vegetation. A general effect of climate change on the vegetation distribution is a poleward movement of vegetation. Migration of plant and animal species will be towards the poles, in areas where long-lived plants such as forests occur; this will have a devastating effect on the ecological systems present. Given the nature of selective regime present in the Succulent Karoo it remains to be seen how this will impact the biome. Studies suggest that the Succulent Karoo is in grave danger (Rutherford *et al.,* 1999). As mentioned earlier, results from analysis performed by the Climate Research Group at the National Botanical Institute indicate a decrease in the spatial distribution of the Succulent Karoo (Rutherford *et al.*, 1999). Given the botanical importance of this biome it is important to undertake studies concerned with vegetation change as well as the driving forces behind change. Anthropogenic impacts are not confined to emission scenarios but also manifest in the form of land use.

1.5 Stock Farming in the Succulent Karoo

Land-use in the Succulent Karoo has shifted form hunter-gatherer economies to localised sedentary pastoralism finally settling into widespread stock farming (Hoffman, 1997). There are two main agricultural production systems at work in the Karoo. Firstly the communal system which predominates in the western Succulent Karoo biome (e.g. Leliefontein, Komaggas, and Richtersveld), and secondly the commercial sector which is the dominant agricultural production system in the rest of the Karoo (Hoffman *et al.,* 1997).

Initially, company owned farmers and trade with the Khoikhoi sustained the needs of the cape colony. By the 1700s, however, the supply of agricultural products and cattle from trade with the Khoikhoi proved insufficient. A rapid expansion ensued and most of the local Khoikhoi were either exterminated or remained in regions such as the Khamiesberg and Richtersveld (Hoffman *et al.,* 1997). These regions became focal points for communal farming and trade; still today communal farming dominates some areas. During the eighteenth century many "trekboers" settled in the Karoo and practiced transhumance herding where ecological niches in the Karoo provided resources for grazing. This, however, changed as competition from other colonialists led to a diminished resource. Land tenure also played an important part in shaping the grazing strategies. When the Karoo was largely unpopulated, farmers could move around exploiting resources as they wished. With more colonists leaving the colony, a formal land tenure system was instituted (Hoffman *et al.,* 1997).

Before 1708, land tenure was granted as a short-term grazing license with a largely undefined spatial area. In 1708, however, this was replaced by a loan farm system, which provided a more secure tenure but still allowed the farmer the freedom of transhumance herding cycles using common grazing lands. By 1878, however, changes to the relevant acts gave farmers the right to purchase their own property and secure sole right to the land (Hoffman *et al.,* 1997). Changes in the tenure type have had a pronounced effect on grazing strategies. Before 1813, initial tenure allowed the farmers full access to large areas that could be used at different times of the year, thereby exploiting each ecological niche without placing too much pressure on the vegetation. After 1813, farmers were confined to a surveyed area of land thereby limiting them to a specific area and placing more pressures on the vegetation. By 1877, tenure changed again and while farmers were able to own their own land, they were once again limited by their choice of grazing sites. Even before 1877 rangeland management practices left much to be desired. The so called "kraaling system" of the eighteenth and nineteenth centuries were blamed for degradation of karoo rangelands. Later on in the nineteenth century, fences and windmills were introduced, bringing about another change in management systems: camps or paddocks within the farm unit were set up and grazed for a given amount of time, then rested. Rotational grazing systems proved popular in the Karoo with non-selective grazing (NSG) and short duration grazing (SDG) making up the utilization philosophies (Hoffman *et al.,* 1997).

When large-scale commercial farming began, the Khoikhoi were forced to practise a form of semi-nomadic pastoralism confined to areas around the missionary stations. These confinements lead to many of the Khoikhoi leaving the area to work as wage labourers on mines and settler farms (Hoffman *et al.,* 1997). Migrant labour is a well-documented (During, 1990) characteristic of the apartheid regime and has had a marked effect on all aspects of households. The migrant labour system aided in the development of communal land-use. Many locals left and worked as wage labourers either on mines, farms or in the fishing industry. In these areas there are strong kinship ties and migrant labourers invest capital into stock that is left in home districts to be looked after by friends or family members. The herd is a form of investment and management objectives of the communal farmers are different from their commercial neighbours. In 1995 between 2 and 10 percent of the herd were sold of for cash and only 5 percent were slaughtered for local consumption. Currently communal areas of the Succulent Karoo and Karoo make up only 1.1 percent of total land area in South Africa. In the Karoo region this value is elevated to 2.3 percent. In the Namaqualand district this value again increases to 26.3 percent and total population living on the land is around 45 percent (Hoffman *et al.,* 1997).

Farming on natural rangelands remains the major agricultural practice in the Karoo. Large-scale stock farming currently uses over 90 percent of the land within the biome (CEPF, 2003). Production systems in the Karoo revolve around wool and mutton production. This production is dependant on climatic variability and the ability of the farmer to keep costs to a minimum (Hoffman *et al.,* 1997).

Stocking rates in the Karoo and Succulent Karoo have varied through the last 200 years. Dean and Macdonald (1994) gave a detailed account of stocking rates and their relation to degradation. The authors reported a reduction in the mean stocking rate in almost all the districts of what was the old Western Province (44.4 percent decrease). The reduction of stocking rates was found to be far greater in the more arid districts and greatest in the Succulent Karoo where seven of the eight districts experienced stock reductions of greater than 50 percent. What drove this reduction in stock density? Dean and MacDonald (1994) gave five possible reasons for the reduction in stocking rates

1. The number of livestock units may be regulated by economics (the economics hypothesis).
2. Early settlers saw the semi-arid rangelands as being more productive than they really were (the insight hypothesis).
3. With irreversible losses to topsoil and changes in infiltration rates, the Western Cape had experienced a reduction in the amount of forage available to the livestock population (the desertification hypothesis).
4. Carrying capacity of rangelands is directly related to primary productivity, which in turn is related to rainfall; if primary productivity is below average, then rainfall must be decreasing (the climate change hypothesis).
5. Stocking rates may have decreased due to a reduction in the number of boreholes and wells producing water (the desiccation hypothesis).

The authors choose no single reason as the main cause of the reduction in stocking rates; they do conclude that primary production had decreased throughout the Karoo and that irreversible changes had occurred in the diversity and abundance of Karoo vegetation. It is thought that when the settlers / "trekboers" arrived; the Karoo was grazed by a rather limited population of indigenous herbivores. In a short period of time, these indigenous herbivores were wiped out. Vegetation thus thrived under these conditions. Farmers of the time perceived this to be the normal vegetation cover, and that the Karoo would in fact support large numbers of livestock (Hoffman, 1997). This was not the case, and in the late 1800's degradation and reduced above ground biomass began to impact on the industry as well as the health of the vegetation. It would seem that reducing the stock numbers was the only solution.

Ostrich farming and more recently game farming have emerged in the last 120 years as new land-use practices each with their own environmental impacts. Most of the Ostrich farming occurs in the Little Karoo around Oudtshoorn and began in 1895 when the feathers of the land-bound birds were extremely fashionable. Recently, however, the market has moved to the sale of skins and meat. Generally ostriches earmarked for the abattoir are raised in small camps while breeding pairs are allowed to roam free on natural rangeland. The camps are generally small and the impact of the ostriches is immediately seen, due to their mass and large footprint; long term denudation and transformation of the paddocks is inevitable. Game farming is a relatively new land-use, comprising of around three million hectares in the Karoo and Succulent Karoo. Hunting and venison are the main income for the game farms. The change from stock farming to game farming is largely due to stock theft and the promise of higher returns from eco-tourism and hunting (SKEP, 2002).

With the Karoo and Succulent Karoo undergoing such varied and intense pressures over the last 200-300 years, it is of utmost importance that we develop methods to monitor the vegetation on the ground on a timely basis. Using GIS and remote sensing it may be possible to monitor vegetation health.

1.6 Research Outline

The aim of this research is to determine the relationship between rainfall and vegetation growth at the biome level. The thesis will seek to characterize this relationship using three separate methodologies with a view to determining whether the established hypothesis concerning moisture (section 1.3) and plant growth is suitable to determine drivers of *"zones of potential critical change"* in the Succulent Karoo (Figure 1.1). *"Zones of potential critical change*" could be defined as an area where the vegetation growth could not be fully explained by the input of atmospheric moisture. To identify these areas it is essential to use data that is both spatially explicit and temporally adequate. A detailed description of the data used is given in chapter 5. The research methodology is described loosely as a statistical analysis of the relationship between rainfall and vegetation growth on an intra-seasonal time scale using coarse resolution satellite data and interpolated rainfall statistics. The statistical methods used include time series analysis using a Spatio Temporal Correlation filter (STCf), Principal Component Analysis (PCA) and Self Organising Maps (SOMs).

Spatial homogeneity of vegetation response to atmospheric moisture is analysed using the STCf. Long term trends in seasonal vegetation growth are identified using PCA analysis (Eastman and Faulk, 1992). Self Organising Maps (Kohonen, 1995) are then used to classify the relationship between vegetation growth and precipitation. Finally, a Linear Regression analysis is used to determine the strength of the relationship between precipitation and vegetation growth within each SOM node. Temperature, derived from NCEP reanalysis data (Kalnay *et al.*, 1996) are also used in the regression analysis.

The time period of the study is 14 years, from 1985 through to 1999. Unfortunately, data for 1994 are not available necessitating the exclusion of this year. An outline of the study area is given in chapter 2. Chapter 3 takes the form of a general literature review while chapter 4 introduces the various tools used to analyze vegetation using Remote Sensing and Geographical Information Systems. Case studies drawn from published literature are used to explain the methods. Chapter 5 outlines vegetation indices and their respective derivation while also introducing the reader to various examples of published research performed using the aforementioned vegetation indices.

Chapter 5 describes data and methodologies used in this study. The National Oceanic and Atmospheric Administration (NOAA) series of satellites are discussed with special reference to vegetation indices. Interpolation methods used in the creation of the interpolated rainfall data are discussed as well as ancillary spatial GIS data. The methodology will be followed by a full description of the statistical techniques used. Chapter 6 reports the results of the various analyses performed. Chapter 7 includes a discussion of the results obtained and attempts to answer several questions posed at the beginning of chapter 1. Chapter 8 concludes the research and summarizes relevant findings, making recommendations for future research activities.

Chapter 2

Outline of Study Area

2.1 Introduction

Chapter 2 introduces the study area for this research project. It begins with a brief introduction to the biomes of South Africa, defined by Low and Rebelo (1996). Abiotic factors contributing to the unique plant geography are discussed. The abiotic elements of the region are outlined to give the reader a better understanding of the "broader picture." Once climate, soils and geology have been introduced, vegetation types are discussed using Acocks (1988), Rutherford and Westfall (1986) and Low and Rebelo (1996). The chapter serves to introduce the reader to the study area in the context of southern Africa. It does not attempt any detailed explanation of the levels of species diversity or endemism found in the biome.

2.2 Biomes of South Africa

South Africa has 7 biomes (Low and Rebelo, 1996, see figure 2.1 below), namely Grassland, Savanna, Forest, Nama Karoo, Fynbos, Thicket biome and finally the Succulent Karoo, each placed into a broad geographical unit. Rutherford and Westfall (1986) define a biome as *"a broad ecological unit representing a major life zone extending over a large natural area"* or *"a biome forms the highest type of ecological unit and is followed by the community and other levels of detail"* (Rutherford 1997, 91). Furthermore a biome is characterized by life forms that have similar physiognomic features. Biotic components of the biome include fauna and flora, which are closely tied to environmental conditions such as climate (Rutherford and Westfall, 1986). Rutherford and Westfall (1986) used a moisture matrix of Summer Aridity Index and winter concentration of precipitation to include the influence of climatic factors in their map of vegetation types of South Africa. A full explanation of the moisture matrix is given in the cited text (sections 2.3 and 2.4). The biome boundaries used in this study are taken from Low and Rebelo (1996).

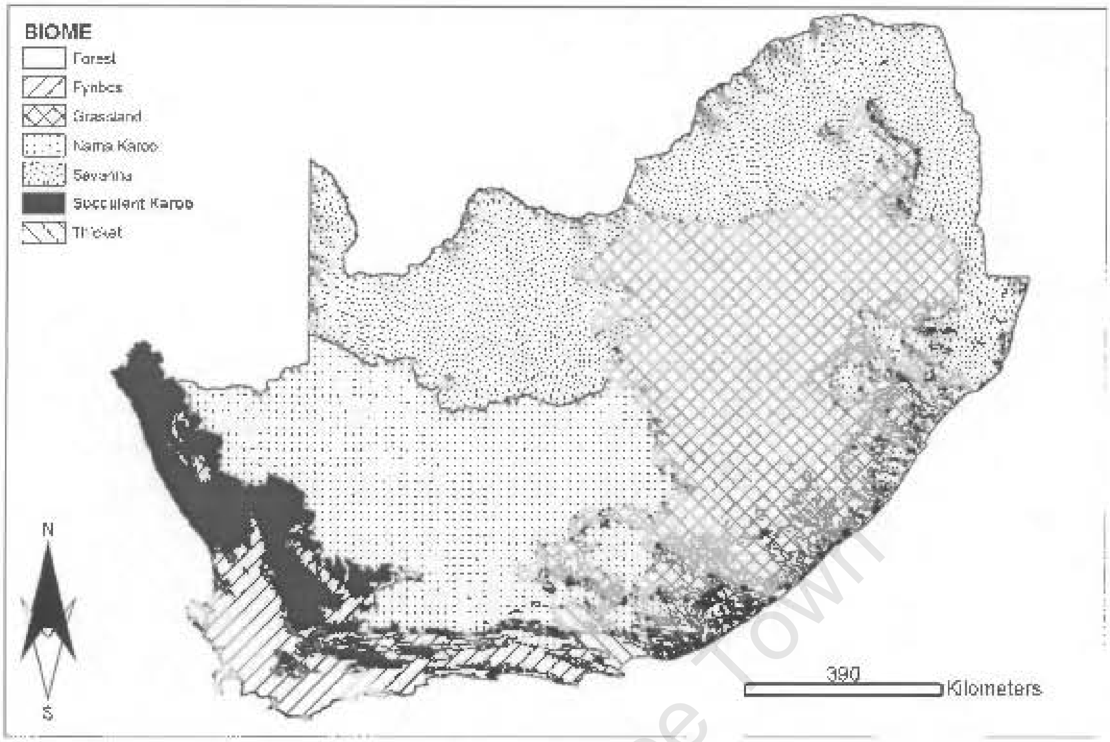


Figure 2.1: Major Biomes of South Africa, study area highlighted in black (Low and Rebelo, 1996)

The largest of all the biomes is the Savanna biome. It occupies over one third of the area of South Africa. A grassy ground layer and an upper layer of woody plants characterize the biome. Altitude ranges from sea level to 2000 m and rainfall varies from 235 to 1000 mm per year. The biome is well conserved thanks to the Kalahari Gemsbok National Park and the Kruger National Park. One of the major factors delimiting the biome is a lack of sufficient rainfall, preventing the upper woody layer dominating. Fire and grazing contribute to the prevalence of grasses as the dominant vegetation type (Low and Rebelo, 1996).

The Grassland biome is found on the central plateau of South Africa. Topography is limited, and altitude varies from near sea level to 2850m above mean sea level. A single layer of grass made up of C_3 and C_4 types dominates. Agriculture has had a marked influence on the biome; maize, sorghum, wheat and sunflowers are farmed. The biodiversity of the biome is considered to be very high with many rare and endangered species (Low and Rebelo, 1996).

The Nama Karoo biome occurs on a central plateau of the western half of the country. Altitude varies from 500 m to 2000 m above mean sea level. Rainfall is summer orientated and varies between 100 and 520 mm depending on location. The dominant vegetation type is grassy dwarf shrubland (Low and Rebelo, 1996).

The Thicket biome is rather ambiguous, as it is not recognized in scientific literature as a biome. Low and Rebelo (1996) included it as they felt it did not fit into the forest biome. Subtropical thicket is a closed shrubland to low forest, dominated by evergreen species, Succulents and shrubs (Low and Rebelo, 1996).

The Forest biome is restricted to areas with mean annual rainfall of more than 525 mm in winter rainfall areas and 725 mm in summer rainfall areas. Altitude ranges from sea level to around 2100 m above mean sea level. Forests tend to occur in patches with an area of less then 1 km^2. Those areas that are larger tend to occur along the Garden route and Lowveld escarpment. The canopy of the Forest biome is completely closed; ground cover is absent due to the nature of the canopy (Low and Rebelo, 1996).

The Fynbos biome or "Cape Floral Kingdom" is the smallest of the six floral kingdoms worldwide. Fynbos vegetation is characterized by the occurrence of three elements or components, a restioid component, an ericoid or heath component and a proteoid component. Endemicity is very high with over 80 percent of plant species found nowhere else on earth. Rainfall sufficient for Fynbos growth varies from 600 to 800 mm. Areas receiving less than 200 mm are usually replaced by Succulent Karoo vegetation (Low and Rebelo, 1996).

Finally the Succulent Karoo (the study area) is situated on the western half of the country. The altitude of the biome ranges from sea level to around 800 m above mean sea level with some areas in the Kamiesburg reaching 1500 m above mean sea level. The biome is primarily determined by the presence of low winter rainfall and extreme summer aridity. Rainfall varies from 20 mm in the extreme north to 290 mm in the south. Summer temperatures regularly top 40 °C. Fog is common along the coastline and berg winds occur throughout the year. Dwarf Succulent shrubs dominate the vegetation and spring mass flowering events are also common in the area (Low and Rebelo, 1996).

In each of the biomes described above, one recurring theme is always present, the influence of rainfall. In the Savanna biome large woody species are restricted due to the lack of rainfall to support them. The Forest biome is restricted to areas of mean annual rainfall of 525 mm or more. The Fynbos biome is restricted to rainfall between 600 and 800 mm per year. The Succulent Karoo is primarily determined by low winter rainfall. While many factors contribute to vegetation distribution, rainfall is by far the most important.

2.3 Climate

The climate of South Africa has several gradients along which temperature and precipitation vary. Mean annual precipitation (MAP) decreases as one moves westwards from the escarpment across the plateau (Schulze, 1997). While the MAP is a good indication of water availability it says nothing of the variation of inter-annual or intra-annual rainfall. Woodward (1986) suggests a close link between a plant's life cycle and the temporal variation controlling climatic processes. Examples of the life cycles affected include rate of germination, rate in amount of die-off / survival and biomass production. The coefficient of variance of inter-annual precipitation as computed by Schulze (1997) reveals an inverse of the east-west gradient seen in MAP. The MAP gradient is inversely related to the coefficient of variance (COV); in areas with high rainfall the COV is small, in areas where rainfall is low the COV is high. The Succulent Karoo falls into an area where MAP is low and COV is high (greater than 40 percent) (Schulze, 1997). This high COV has serious implications for the region as a whole. Increased likelihood of abnormal rainfall and frequent occurrences of drought have a major impact on the distribution of vegetation and indeed the type of vegetation present (Esler *et al.*, 1999).

Temperature regimes in South Africa reflect the influence of topography and altitude. Schulze (1997) computed mean annual temperature (MAT) over South Africa. The isotherms reflect the topography of South Africa. The Succulent Karoo falls within the greater than 20°C region. The coastal weather stations also experience the anomaly of recording their highest maximum temperatures in mid winter due to the heating effect of warm berg winds blowing off the plateau (Schulze, 1997, Cowling *et al.*, 1999).

The Succulent Karoo receives most of its moisture from weather systems associated with disturbances in the westerly stream. The three vegetation types of the Succulent Karoo, which benefit most from this system, are the Strandveld, Lowland and Upland Succulent Karoo (Low and Rebelo, 1996). They receive the majority of their moisture from the cold fronts during the winter months (Desmet and Cowling, 1999). These cold fronts occur together with westerly waves, depressions and cut-off lows. The cold fronts occur mostly in the winter months when the amplitude of westerly disturbances is greatest (Tyson and Preston-Whyte, 2000). Cold fronts influence not only the Succulent Karoo but also parts of the Western Cape. Reliability of the rainfall is attributed to the equator-wards penetration of the westerly air stream, which is strongest in southern Africa (Tyson and Preston-Whyte, 2000). Annual rainfall in the biome varies from 300 mm in the southern regions of the little Succulent Karoo to less than 60 mm around Port Nolloth (Cowling and Desmet, 1999). Rainfall gradients exist in both a south-north orientation and an east-west direction. This makes the analysis of vegetation growth in the biome inextricably linked to rainfall regimes. Moisture is however not limited to rainfall.

Advective sea fog is characteristic of the entire west coast of southern Africa. Advective fog occurs when warm air with high relative humidity is advected over a cool surface. Fog events occur mostly during the summer months due to the cool coastal sea temperature brought about by the intensification of the mid-Atlantic Ocean high. Warm moist air from the mid-Atlantic high moves in over the cooler water and fog is formed near the coast (Desmet and Cowling, 1999). The temperature difference between the air and the surface must be sufficiently large to enable the air to reach saturation (Cowling and Desmet, 1999). Olivier (1995) used Meteosat images to analyse fog frequency along the west coast. Results indicate that frequency was highest between Sandwich Bay and Cape Cross in central Namibia (>100 days per year). This frequency decreases to less than 75 days per year south of the Orange River. It was also noted that fog penetrated along major river courses. The fog forms an alternative source of moisture for the vegetation of the area. Although no precipitation actually occurs, moisture is intercepted by vegetation and filters down into the soil making it available to plants (Cowling and Desmet, 1999). Interception loss in the biome is not reported as being a major problem (Schulze, 1997).

Vegetation and primary production in the Succulent Karoo are driven by climatic conditions that are influenced by large-scale weather systems. Cold fronts and west coast troughs bring winter rainfall to the area with the southern regions of the biome receiving its rainfall in late autumn and early spring. Coastal advective fog is a potentially significant source of water in the Succulent Karoo. The amount of moisture contributed by the fog is not known and is difficult to calculate, as conventional rain gauges cannot be used. Cowling and Desmet (1999) suggest that plants could derive moisture from the fog by means of absorbing condensation on their surface and as a result of stem flow.

In conclusion, most of the moisture in southern Africa originates from the advection of air across the warm Indian Ocean. This provides much of the moisture associated with rainfall across the eastern parts of the country. The arid lands of the western half of the country are geographically marginal to this rainfall and thus rely on cold fronts and disturbances in the westerly streams (Cowling and Desmet, 1999). Rainfall in the Succulent Karoo is low but fairly reliable with annual rainfall ranging from approximately 290 mm in the south to less than 60 mm in the north.

2.4 Soils and Geology

2.4.1 Geology

Geology plays an indirect role in the distribution of Karoo and Succulent Karoo vegetation (Visser, 1986). In certain areas bedrock makes it impossible for Karoo plants to exist. Areas where thick Cenozoic sediments influence underground water, in turn influence the karoo plant types present. The stratigraphy and lithology of the Karoo is complex and what follows serves only as a brief introduction. Detailed discussion may be found in (Meadows and Watkeys, 1999)

Quaternary and Tertiary coverings are found along the west coast. The northwestern parts of the biome are made up of Nama Sequence and Namaqualand complex, the latter occurring eastwards into the Nama Karoo. Nama Sequence is also found in the central southern regions of the Succulent Karoo. Moving down into the Tanqwa and Hantam region of the biome, the geology becomes more complicated. Northwest of Sutherland; Dwyka formations, Bokkeveld group and Table Mountain Group are all found in close proximity to each other. Further south the formations become even more complex with no one geological unit dominating. The region stretching from Worcester to Oudtshoorn comprises Chalk layers, Bokkeveld Group, Nama sequence and Dwyka formations (Visser, 1986).

The Quaternary and Tertiary coverings of the west coast are mainly windblown sands, river, beach gravels and local claystone. The Nama Sequence is found along the west coast from the Richtersveld to Piketberg and north of Oudtshoorn. Beds vary from slightly deformed Nama Group to highly deformed Malmesbury Group. Rock types include sandstone, mudstone and limestone of the Nama Group and phyllite, greywacke and limestone of the Malmesbury Group, as well as quartzite, limestone and tillite of the Gariep Complex. The Namaqualand complex consists of metamorphic sedimentary rocks that are a product of intense folding and shearing. The area consists of Metasedimentary and Metavolcanic formations that are associated with batholithic intrusion. The intrusions are mainly granites and gneisses and cover 60 to 70 percent of the area. The Dwyka formation is found in the south and the north. The irregular distributions of the outcrops in the south are attributed to folding associated with the Cape Fold Mountains. The result of the folding means that Dwyka formations are found in narrow synclines. In the north however the Dwyka deposits are horizontal and undisturbed. The Bokkeveld group underlies strips between mountains in the west, southwest and southeast. This is due to processes associated with folding. Softer Bokkeveld beds have also been preserved in the synclines. The table mountain group is covered with Karoo vegetation in the Vanrhynsdorp area as well as the Ladysmith area and north of Port Elizabeth. It forms part of the Cape Fold Belt and has a maximum thickness of 4 000m. Chalk layers around the Oudtshoorn region are the result of local erosion, deposition and sedimentation (Visser, 1986).

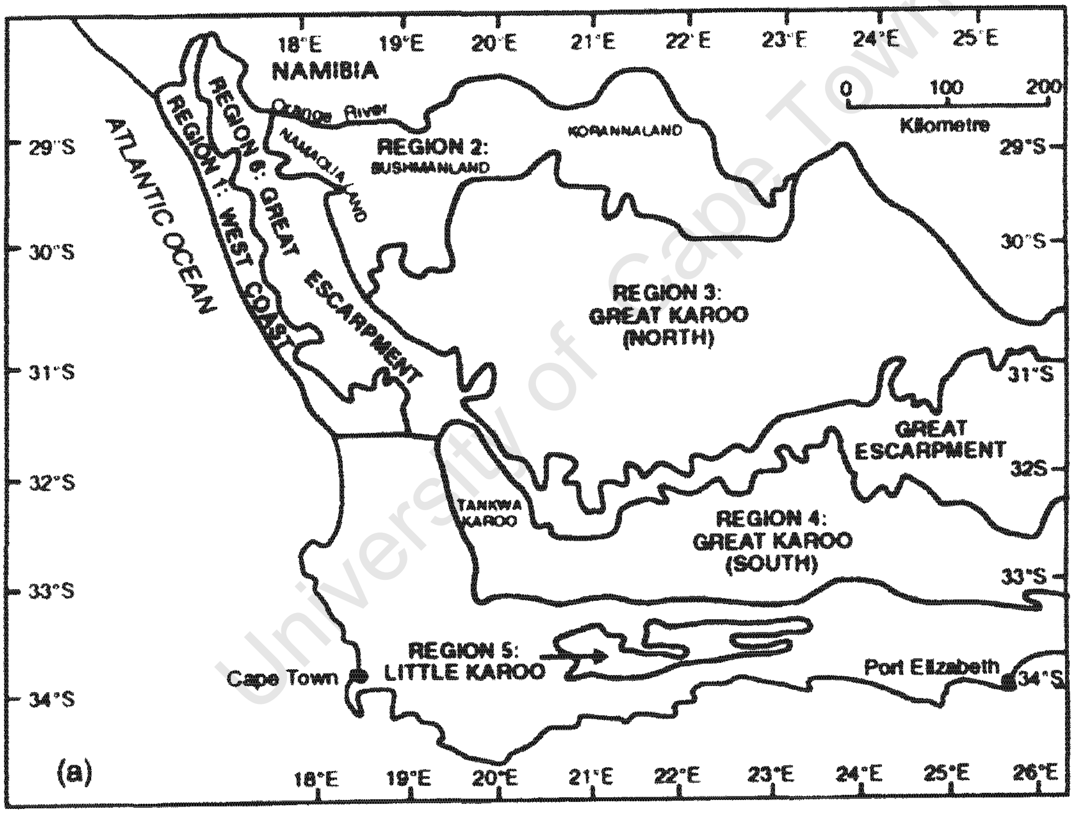


Figure 2.2 Soil classification of the Arid Zone of South Africa (After Watkeys, 1999)

2.4.2 Soils

Soil is a mixture of inorganic and organic particles that have various amounts of water and air. The two most important controls in soil formation are the climate of the area and the parent material. The breakdown of rock to form regolith that may in turn form soil is the combination of several physical processes (Watkeys, 1999). Mechanical, chemical and biological processes all contribute to weathering.

Weathering in the Succulent Karoo is limited to mechanical processes where thermal expansion breaks down parent material. Soil formation is thus very slow leading to coarse shallow soils that have sharp boundaries between soil types. The nature of arid-zone soils makes them very sensitive to soil degradation (Watkeys, 1999).

Watkeys (1999) subdivided the Karoo into 6 regions based on geological, geomorphological and pedological factors. The Succulent Karoo biome falls into four of these regions namely region 1, 4, 5 and 6.

Region one: West Coast.

The region is approximately 50 km wide and 350 km long. The Namaqualand Metamorphic Complex underlies the area with Pan-African belts occurring in the northern and southern regions. Grey regic sands bordering the oceans are recent Aeolian deposits. Yellow high-base soils occur nearest the coast with a transition zone of yellow-red soils separating the most common form of soil, a red high-base status soil that is apedal to weakly structured, freely drained, coarse in texture and of variable thickness (Watkeys, 1999).

Region four: Great Karoo.

The region lies between the Great Escarpment and the Cape fold mountains; it is 60-100 km wide and over 600 km long. Underlying rocks are made up of the Beaufort Group sediments of the Karoo Supergroup that became deformed as a result of the cape fold belt. Soils of the region are developed on a pedologically young landscape. They lack structure due to *in situ* weathering while their composition reflects underlying parent material (Watkeys, 1999).

Region five: Little Karoo.

The region consists of valleys, which may be up to 50 km wide and 200 km long. The mountains consist of the Karoo and Cape Supergroups that were folded during the Permo-Triassic. Shallow soils of pedologically young landscapes dominate the region. Red high-base status apedal to weakly structured soils with medium texture overly the Jurassic sediments. Soils of the region are well correlated with the geology. The geology partly determines the distribution of fynbos in this area (Watkeys, 1999).

Region six: The Great Escarpment.

The Great Escarpment is the dominant feature separating the interior plateau of the arid southwest from the seaward areas of the west and south. It varies in width from a single cliff face in some parts to a wide area in others. Elevation ranges from 300m to over 1700m above mean sea level in the Kamiesberg, in the east elevation ranges from 900m to around 2000m above mean sea level in the Sneeuberge. Snow regularly covers the region and contributes to mechanical weathering. Soils of the region are difficult to classify as data is lacking and most of the region has exposed rocks. Initial stages of soil development occur where water can concentrate and contribute to chemical weathering processes. Examples of this can be seen in Namaqualand along the western part of the escarpment. Soils developed here are low in plant nutrients. Palaeosols found on the western sections of the Escarpment suggest that these soils developed under wetter climatic conditions reflecting a different climatic regime (Watkeys, 1999).

Soils of the Succulent Karoo and surrounding areas are typical of arid to semi-arid regions. Development varies across geographical gradients with climate and parent material playing a dominant role. The region has little organic matter to provide organic topsoil or to assist with biological and chemical weathering. In the northwest regions of the Karoo the simplified geology is Basement Complex. Soils are generally freely drained due to the absence of chemical and biological weathering. The southeastern region is underlain by the Karoo Supergroup where soils are shallow and developed on a pedologically young landscape. The northwestern region falls within a low winter rainfall climate where soil forming processes are a lot slower than in the east where higher rainfall facilitates faster soil forming processes (Watkeys, 1999).

2.5 Vegetation types

Vegetation types of South Africa have been identified and mapped by various authors. Acocks (1953) produced one of the earliest maps of vegetation in South Africa and continued his work till the late 1970's. *Veld types of South Africa, Memoirs of the Botanical Survey of South Africa* became a definitive text on veld types in South Africa. In 1986 Rutherford and Westfall produced a new classification of South Africa's vegetation entitled *Biomes of Southern Africa, an objective categorization*. Ten years later in 1996 Low and Rebelo published *Vegetation of South Africa, Lesotho and Swaziland*, accompanied by a wall map representing the seven biomes of South Africa. The map included 68 vegetation types all defined within one of the seven biomes. Section 2.2 outlined the seven biomes identified and mapped by Low and Rebelo (1996). Section 2.5 introduces and discusses the various vegetation types found within the Succulent Karoo. It makes use of Acocks (1953), Rutherford and Westfall (1986) and Low and Rebelo (1996). At present the National Botanical Institute is completing a new vegetation classification of South Africa, which should be available in early 2006.

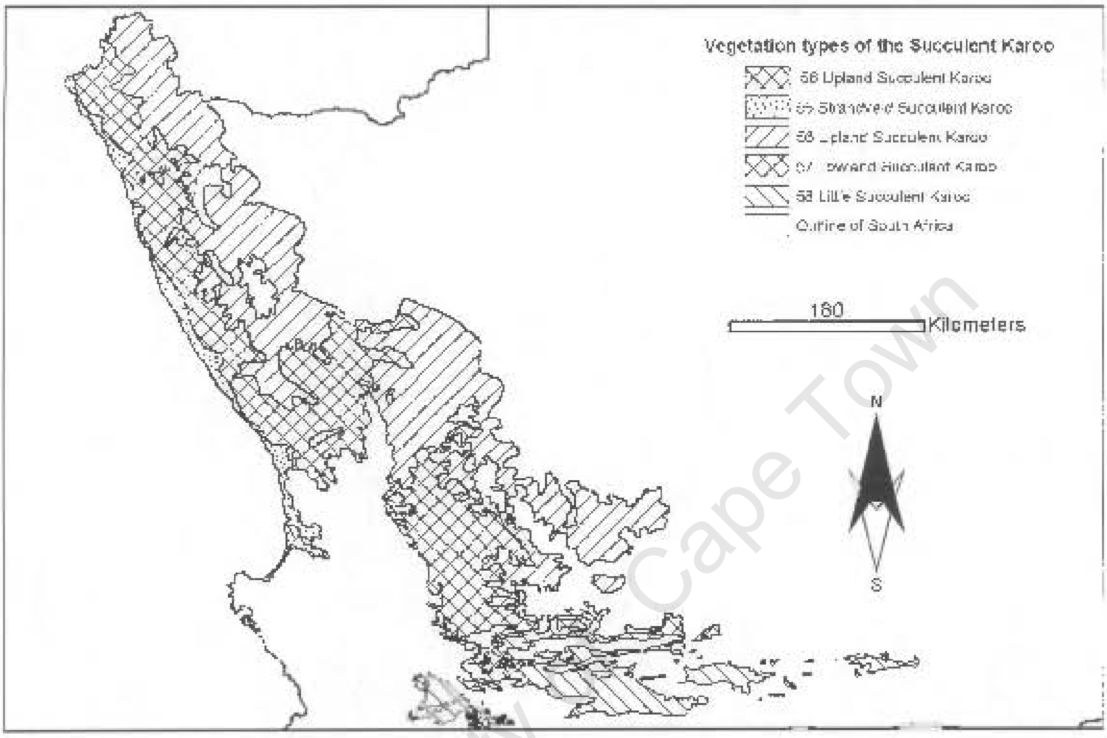


Figure 2.3 Vegetation types of the Succulent Karoo (Low & Rebelo, 1996)

Strandveld Succulent Karoo occurs on the coastal plains of the west coast. It extends over a distance of 500 km from north to south. Scattered low shrubs, small trees and Succulent shrubs dominate the area (Low and Rebelo, 1996). The vegetation type is confined to the coastal sands of the west coast as defined by Watkeys (1999) (see section 2.4.2). In the same area Acocks (1988) identified Strandveld of the West Coast (34) with two variants, dense scrub (34a) and strandveld proper (34b). Two classes of Fynbos were also defined, Coastal Fynbos (47) occurring on the limestone sands, and False Fynbos (70).

Upland Succulent Karoo forms the boundary between Nama and Succulent karoo. The vegetation type occurs on the higher lying areas with elevations ranging from 300 to 1700 m above mean sea level. The quiver tree characterizes vegetation of the region with mesembryanthemaceae or vygie families dominating the dwarf shrubs. Annuals are also present. The winter rainfall regime favours shrubs and annuals while the major difference between the Strandveld and Upland Succulent

Karoo is elevation, higher rainfall and cooler temperatures (Low and Rebelo, 1996). In roughly the same area, Acocks (1988) identified the following veld types, Arid Karoo and Desert False Grassveld (29) with three variants, Blomkoolganna Veld (29a), Driedoring Veld (29b) and Semi-Succulent form (29c). Acocks described this area as being one of the driest parts of the country. Central Upper Karoo (27) occurs on the central part of the upper plateau south of the Orange River with small patches occurring in the Succulent Karoo. The plains on which the veld type occurs are stony with a covering of shallow red sandy loam with wide, silty flats or flood plains along the rivers. Acocks believed that the whole area was invaded by elements of the Arid Karoo (Acocks, 1988).

Lowland Succulent Karoo vegetation types occur below the escarpment with elevations ranging from 0 to 600m above mean sea level. While the area is extremely arid one finds a wide range of growth forms including annuals, geophytes and of course the vygie or mesembryanthemaceae family. Old or disturbed lands may contain *Galenia africana* (Kraalbos). The low but predictable rainfall encourages shrubs with very little grass present. Acocks (1988) identified several veld types within the Lowland Succulent Karoo. False Succulent Karoo (39) was seen as being hardly suited to the region. Acocks believed that this veld type was a relic of the Arid Karoo. Karroid Broken Veld (26) found in the same area was described as Karoo veld dotted with dwarf trees and shrubs while also including varying amounts of grass and Succulent species. Three variants were identified namely, The Great Karoo (26a), The Little Karoo (26b) and The Grassy Mountain Scrub (26c).

Little Succulent Karoo occurs in the hot dry valleys of the Cape Fold Belt between the Riviersonderend-Langeberg-Outeniqua in the south and the Hex-River Witteberg-Swartberg in the north. Again, wide ranges of growth forms are present including both succulent and non-succulent species as well as low trees. Dwarf shrubs dominate while grasses are scarce. Once again the rainfall is low but fairly predictable; where rainfall increases the vegetation gives way to Renosterveld (Low and Rebelo, 1996). According to Acocks (1988) this region contained various veld types. Due to the varying topography and highly variable soils of the area, vegetation types are diverse in terms of growth form and phenology. Valley Bushveld (23) is confined to the valleys found along rivers, mostly in the southern parts of the Succulent Karoo where the rivers drain into the Indian Ocean. Western Mountain Karoo (28) occupies stony areas that are mostly made up of fine-grained sandstones and granite. Topography varies from gently undulating hills to steep mountain slopes. Two variants are present, the Upper form (28a) and Lower form. Acocks noted that much of this area had been heavily grazed and as such he found it difficult to classify the vegetation purely on a distinctive habitat of growth (Acocks, 1988).

Other veld types found in the region as defined by Acocks (1988) include, Mountain Renosterveld (43) found in parts of the Upland Lowland and Succulent Karoo. Acocks believed that this veld type had been invaded by False Karroid vegetation. Namaqualand Broken veld (33) is described by Acocks as having three variations, Typical Namaqualand Broken Veld (33a), Rhigozum trichotomum Veld (33b) and False Desert Grassveld (33c). This veld type is found in Upland and Lowland Succulent Karoo types. Succulent Karoo (31) is present in all vegetation types described by Low and Rebelo (1996). The veld type is found on low altitude areas where temperatures are hot with high aridity and low winter rainfall. Succulents with few trees and large shrubs dominate the veld type. Three variants occur, namely Namaqualand coastal belt (31a), Tanqua karoo (31b) and Steyterville Karoo (31c).

The boundaries of the biome are determined by various factors that separate it from the Nama Karoo, Fynbos and Desert biomes. Duration and temperature of the growing season separates the biome from the Fynbos, Nama Karoo and Desert. The Succulent Karoo experiences a short cool growing season whereas the fynbos biome has a long cool growing season. The Nama Karoo on the other hand is short and warm while the desert biome has a long dry growing season (Milton *et al.*, 1997). The growing season also differs from other deserts, which share similar climatic conditions. Esler *et al* (1999) developed an empirical model, which attempted to explain the divergent patterns in growth form and phenology. The model was based on comparisons between the Namaqualand Namib domain of the Succulent Karoo and the Mojave and Sonora Deserts in the USA.

Moisture as a limiting factor in plant growth is a central theme in this research and the observational model developed by Esler *et al* (1999) built on this premise. Due to the low but reliable rainfall (Cowling and Desmet, 1999) of the Namaqualand Namib domain, the selective regime present is biased towards shallow root structures (Cowling and Hilton-Taylor, 1999) and low, leaf-succulent shrubs (Esler *et al.,* 1999). The growing season extends through the winter months when moisture is present. Plants harvest the moisture and no significant soil storage pools accumulate. On the other hand, species of the Sonora and Mojave Desert have their growing season during the summer months. Rain falls during the winter months but growth cannot take place due to the mean minimum and mean maximum temperatures being so low (Esler *et al* 1999). Rainfall and moisture enters soil storage during the winter months and is only taken up and used when the maximum temperature rises above 15 °C and minimum rises above 0 °C.

Selection in the Sonora and Mojave deserts are towards a variety of rooting strategies (Esler *et al.,* 1999). This leads to the presence of a range of growth forms. The various growth forms are able to exploit moisture resources at different times of the year, minimizing competition for resources. This is in sharp contrast to the Namaqualand Namib domain where growth forms are limited to low, leaf-succulent shrubs reaching a maximum of 20-40 cm in height (Esler *et al.,* 1999). Selection is towards shallow rooted species that successfully compete for water resources (Esler *et al.,* 1999). Growth forms and phenology of the Namaqualand Namib domain are thus determined by the climatic regime. Mild winters with low but predictable rainfall facilitate growth during this time. A prediction from the model was that species within the Namaqualand Namib domain should and indeed do exhibit a variety of adaptations that maximise the absorption of solar irradiance thereby increasing rates of photosynthesis and facilitating the development of plant tissues (Esler *et al.,* 1999).

With over 7000 species of which 50 percent are endemic, levels of diversity and endemism in the Succulent Karoo are unparalleled. Leaf Succulents are widespread within the biome. Two families dominate the flora, Mesembryanthemaceae and Crassulaceae (Milton *et al.,* 1997). Cowling and Hilton-Taylor (1999) compared levels of diversity in the Succulent Karoo with the Nama Karoo. Local, differentiation and regional diversity were analysed. Results indicate that there are vast differences between the Succulent Karoo and the Nama-Karoo. The Succulent Karoo has higher levels of local endemism as well as higher local and differential diversity. The higher diversity found in the Succulent Karoo can be explained by the climatic regime present. Mild coastal conditions and low but predictable rainfall have selected for short-lived shrubs. The majority of the species are leaf succulents that have limited water storage capacity and shallow root systems (Esler *et al.,* 1999). The relatively benign environment of the Succulent Karoo enables regular germination. When drought does occur mortality is high. This ensures that there is sufficient space for seedling recruitment. Thus high species turnover may be responsible for the elevated levels of diversity (Cowling Hilton-Taylor, 1999).

2.6 Conclusion

Chapter two has outlined the general environmental features of the Succulent Karoo. Climate, geology, soils and vegetation types were discussed. Each of these environmental variables contributes to the overall plant geography of the biome. Climate is by far the primary component as it controls the development of soils and has a marked impact on the distribution of vegetation. Within each of the seven biomes, climate and moisture availability are a limiting factor with regards to type of vegetation present, or the limits to what type of vegetation may persist. For example, in the Savanna biome grass dominates, as the rainfall in the region is not high enough to support large woody trees, similarly the Forest biome only occurs where mean annual rainfall is 525 mm or more in winter and 725 mm in summer (Low and Rebelo, 1996).

The Southern Subtropical High pressure belt determines the climatic regime present in South Africa. Rainfall in the eastern half of the country is derived from advection of moist air over the warm Indian Ocean. The western half of the country including the arid lands derives moisture from cold fronts, cut off lows and west coast troughs. Mean annual rainfall displays an east west gradient across the country with mean annual rainfall decreasing as one-moves westwards. The Coefficient of variance of mean annual rainfall displays an inverse gradient to mean annual rainfall with high COV in the western half and low COV in the eastern half. The Succulent Karoo falls within the high COV for South Africa.

The climatic regime not only impacts vegetation at the biome level but also plays a direct role in the development of soils (Watkeys, 1999). Soils of the western portion of the country are weakly developed due to the nature of the weathering processes and the climate regime. Soil forming processes need moisture and organic material to aid in the process of weathering. Due to the lack of moisture and organic material in the west, soils are not as well developed as in the eastern portions of the Karoo (Watkeys, 1999)

Vegetation types found in the Succulent Karoo are partly a function of the climate. Winter rainfall coupled with mild winters allows for winter growth to take place. As mentioned earlier this is rather unique for a winter rainfall desert. The timing and length of the growing season have selected for limited growth forms with shallow root structures that take advantage of the low but predictable inputs of moisture

(Esler *et al.,* 1999). Shrubs found in the biome are short lived and susceptible to drought. High species turnover associated with drought and mortality may contribute to elevated levels of diversity. Furthermore the warm summer conditions are ameliorated by fog and relatively high nighttime humidity (Esler *et al.,* 1999).

In conclusion, this chapter has outlined the major physical characteristics of the Succulent Karoo. The biome's uniqueness as a centre of biodiversity and endemism is well known. This uniqueness is, however, built upon a fragile system driven by the unusual climatic conditions. Low but reliable winter rainfall and relatively mild temperatures facilitate growth during a time when most winter rainfall deserts are dormant (Esler *et al.,* 1999). The fragility of the system is characterised by the weakly structured communities of short-lived shrubs that are susceptible to droughts (Cowling and Hilton-Taylor, 1999). These communities are highly susceptible to any disturbance be it climatic or anthropogenic. It is therefore extremely important to monitor vegetation patterns and health on a timely basis at the appropriate spatial and temporal resolution. Land degradation and monitoring techniques are the subjects of the following chapter. The chapter will also serve as a literature review of land degradation assessments and monitoring procedures.

Chapter 3

Literature review: Land Degradation

3.1 Introduction

This chapter serves as a literature review of land degradation, focussing on International developments in the field and how these developments have impacted on issues surrounding land degradation in South Africa. The chapter begins with an introduction to land degradation giving an overview of the international developments since 1992. Thereafter land degradation is placed into its social / ecological context focusing on the world, Africa and finally South Africa. Conceptual issues surrounding Land Degradation are discussed, as well as issues of climatic variability and vegetation change. The chapter continues with Acocksian ideas and hypotheses. Following Acocks, the National review of Land Degradation and National Action Plan are discussed.

3.2 Introduction to Land Degradation / Desertification: A brief History

The term desertification was first used by a French scientist named Aubreville (1949) (cited in Mainguet 1991), who, observed that deserts where developing in areas of Africa that receive between 700mm and 1500mm per year. Environmental degradation and processes of desertification were also noted by among others, Lowdermilk (1935) and Jacks (1939), (cited in Mainguet 1991) who wrote of the denudation associated with human habitation. After devastating droughts in the 1960's and 1970's the problems associated with degradation and desertification were finally recognised and the 1977 United Nations Conference on Desertification (UNCOD) took place. Here, worldwide statistics on degradation and desertification were presented for the first time. In 1984 a review of the action taken against desertification took place. The conference was preceded by a study based on a questionnaire designed to assess the successes and failures of the UNCOD held in 1977. The outcomes were largely useless as; in most cases the questionnaires requested data that simply didn't exist (Mainguet, 1991).

In 1992 representatives from 179 countries met at what is now known as the Rio Earth Summit (United Nations Conference on Environment and Development, UNCED). Here they sought ways to mitigate and reverse the effects of environmental degradation. They agreed upon and recognized three environmental issues that would each later become the subject of their own international conventions. The key issues were the loss of biological diversity, global climate change, and desertification (Hoffman and Ashwell, 2001).

In 1995, South Africa signed the United Nations Convention to Combat Desertification (UNCCD) and became a full member of the convention. All countries that signed and ratified the UNCCD are bound by a legal agreement that obligates them to develop a National Action Program (NAP). The NAP's are responsible for allocating funding to research focused on desertification and land degradation, as well as to specify the roles of government, land users and the local communities. The UNCCD is unique in its approach as it is guided by the principles of public participation at all levels, within the framework of Agenda 21 (Hoffman and Ashwell, 2001).

The NAP began with a national review of land degradation conducted by the National Botanical Institute (NBI) and the Program for Land and Agrarian Studies (PLAAS) at the University of the Western Cape. The aim of the report was to provide a scientific basis for decision-making regarding land degradation. The final research report can be obtained from the National Botanical Institute's website (www.nbi.ac.za/landdeg). In 2000 the NAP process was initiated by the Department of Environmental affairs and Tourism, the goal being to develop a national strategy to combat desertification (Hoffman and Ashwell, 2001).

3.3 Land Degradation in Context

Approximately 1.9 billion hectares of land are affected by land degradation; worldwide about the size of Canada and the USA (United Nations, 1997). Each year approximately 21 million additional hectares of land is lost to degradation, of which six million hectares are so badly degraded that they may never again support any kind of agricultural production (UNEP, 1986). Factors contributing to land degradation include unsuitable land-use practices, deforestation, removal of natural vegetation and overgrazing. Natural disasters such as drought, landslides and floods also contribute to transformation and or degradation. Furthermore, an estimated 23 percent of all usable lands have been degraded to a point where agricultural production is no longer economically viable (Global environmental Outlook 3, 2002). Soil erosion is a major factor in land degradation with many of the soil's functions impaired by degradation. Causes of soil degradation include overgrazing (35 percent), deforestation (30 percent), agricultural activities (27 percent), over exploitation of vegetation (7 percent), and industrial activities (1 percent) (GACGC, 1994).

3.3.1 Agriculture and Land Degradation in Africa

Land degradation and desertification are important issues in Africa as more than 60 percent of the population are reliant on the land for their income as well as basic nutritional needs (Moyo, 2000). The contribution to the Gross National Product (GNP) is an indication of Africa's reliance on agriculture. During the 1990s, agriculture contributed nearly 17 percent to the GNP of Africa, and during the 1980s more than 70 percent of the population were employed in agriculture. The 1990s have seen a drop in this figure to around 60 percent. Approximately 1108 million hectares are currently under either cultivation (202 million hectares) or being used as permanent pasture (906 million hectares) (FAOSTAT, 2001). The percentage of land either under cultivation or permanent pasture varies according to the geographical region. Southern Africa has the largest area under cultivation with 57 percent of the region being utilized for agricultural purposes - 5.8 percent is cultivated and 48.9 percent is used for pasture (ADB, 2001).

In the past agriculture production was centred on subsistence agriculture. In today's world of globalisation and international trade, subsistence agriculture is being replaced by more market-driven agricultural systems. Agricultural cash crops are fast becoming a popular means for stimulating economic growth. This type of resource-based growth becomes problematic when the agricultural practices are not developed in line with a move towards cash crops and not subsistence agriculture. The so-called low-input agricultural (Reich *et al.,* 2000) systems cannot keep up with the demands placed on them and the eventual outcome is degradation leading to desertification.

By definition land degradation and desertification are confined to arid, semi arid, and dry sub-humid areas (Reich *et al.,* 2001). Reich *et al* (2001) estimate that processes of land degradation and desertification affect about 46 percent of Africa. Results from the study indicate that there are 2.5 million km^2 of land under low risk, 3.6 million km^2 under moderate risk, 4.6 million km^2 under high risk and 2.9 million km^2 under very high risk. The region with the highest propensity for degradation and desertification is located along desert margins and occupies 5 percent of the total African land surface (Reich *et al.,* 2001).

A compounding factor contributing to Africa's long standing fight with degradation is the fact that many of the land tenure systems have been inappropriate and inequitable, leaving large portions of the population attempting to live off very small tracts of land. Southern Africa is a case in point; the legacy left by colonial powers and that of the apartheid regime is one of inequitable land tenure and a failure to recognise that previous land tenure systems were biased towards one portion of the population. "Inequitable access to land in Southern Africa is a critical constraint on poverty eradication because, for rural households, land is a natural resource for the reproduction of future generations." (Moyo 2001, 57) This quote from Chapter four of the book *Environmental Security in Southern Africa* highlights just one of the problems associated with poverty and land degradation in South Africa.

3.3.2 Apartheid and its contribution to Land Degradation

The Bantustans or homelands of the apartheid regime left millions of black South Africans living off small tracts of land scattered around the country. Land tenure systems were vastly different. *Freehold land tenure* (mostly white commercial farmers) gives the owner property rights to the land; he or she can sell the land for personal profit. On the other hand *Communal land tenure* is usually quite insecure. People living on the land have little or no rights. The areas managed under a communal tenure are somewhat equivalent to the former homelands. The relative size of these lands is vastly different. Moyo (2001) reported that some 70 000 white farmers owned 72 percent of all arable land, while black farmers, who were approximately 300 times more numerous, owned less than 14 percent of the arable lands. The blatant bias towards white farmers was not only prevalent in the sheer size of the land allocated to farmers, but also in the way issues of drought and land degradation were dealt with. While white South African commercial farmers were included in all conservation acts and drought relief programmes, e.g. the 1969 Soil conservation Act, No 76, later replaced by the Conservation of Agricultural Resources Act (CARA), No 43 of 1983, and the Disaster Drought Assistance Scheme of the 1990s, black farmers received little or no assistance from the government. In the period 1992-1993, R500 million was spent on drought relief in the former homelands; at the same time over R3 billion was given to white farmers (Hoffman and Ashwell, 2001).

3.4 Land Degradation, Conceptual Issues

To understand the dynamic relationship between vegetation and the pressures being imposed on it, it is helpful to present a brief outline of the paradigms, theories and models that have shaped our own management practices and our understanding of vegetation change. The implications for degradation assessment are inextricably linked to our understanding of how vegetation responds to environmental pressures. Milton and Hoffman (1994) identify three types of models that could be used to describe vegetation change; directional, cyclic and stochastic. The two more prominent models (directional and stochastic) will be discussed in detail, while a brief explanation of the cyclic model is included.

For a large part of the 20th century much of the research performed on assessing rangeland / vegetation status was performed under the premise of Clementsian succession (Behnke and Scoones, 1994), succession theory or range succession models. Succession theory originated at the turn of the 20th century and was used to explain the variation in vegetation types in North America (Behnke and Scoones, 1994). The theory assumes that a single or persistent vegetation type would dominate a given area; known as the climax state. The climax state would be determined by the soil and climate of a particular area. If, however, this climax community were disturbed, the vegetation would return to its climax state through successional plant communities, finally attaining the previous climax state (Benkhe and Schoones, 1984). Range management uses succession theory to describe the influence of grazing as maintaining the vegetation in a form of sub-climax. Range managers would try and maintain a balance between vegetation regrowth and stocking rates, later known as carrying capacity (i.e. the maximum number of live stock units that can be maintained by a given rangeland without causing any permanent damage to the rangeland's ability to regenerate). Carrying capacity then set the standard for stocking density leading to a natural balance, provided the range manager did not overstock. This would facilitate a sustainable yield of livestock products (Behnke and Scoones, 1994).

The range succession model accounts for varying rainfall in the same way it deals with grazing. In times of plentiful rain, management would respond by increasing stock density, while in times of drought, a reduction in stock density would occur (Westoby *et al.,* 1989). The reduction in stock numbers during times of drought would allow for the natural "balance" to be maintained and a continuation of successional tendencies.

While range succession may have been the preferred paradigm in range management, there has been a recent shift from this paradigm. Westoby *et al* (1989) suggest the following reasons for this change, changes in response to grazing have not always followed the successional theory; alternatively range succession has been found to be non-continuous, not reversible and not consistent. In particular, Milton and Hoffman (1994) found that vegetation did not return to its original composition when livestock were withdrawn. Furthermore, Westoby *et al* (1989) also argue that in areas with strongly seasonal rainfall, grazing actually induces a change from perennial to annual grasslands. Succession theory therefore does not account for changes in vegetation types in rangelands, nor does it attempt to explain why these changes have occurred.

The cyclic models on the other hand, are driven more by the influence of climate and it's inherent variability. These models propose that plant and animal populations change in response to the natural oscillations of abiotic factors such as rainfall seasonality, intensity and quantity. The models focus on the competition between plant species and maintain that herbivory plays less of a role in plant composition (Milton and Hoffman, 1994). An example of where a cyclic model may in fact work is Lake Turkana, Kenya. Ellis and Swift (1988) found that due to the variability of the rainfall and the frequent occurrence of drought, livestock numbers varied in accordance with the amount of rainfall received in any one season. Furthermore, due to the nature of the rainfall, stock numbers could never reach the desired density. They concluded that the condition of a grazing system was not determined by the number of livestock units present, it was more a function of climate controlling the amount of vegetation available for forage (Benkhe and Schoones, 1994). It should be noted that a model of this nature is site specific and cannot be generalized across bio-geographical borders.

Stochastic models have become more prominent in research as well as in range management; in particular, the state-and-transition model first proposed by Westoby *et al* (1989). Range succession models fail to account for evidence of species change after a rangeland has been rested. Westoby *et al* (1989) argues that the mechanisms operating on a rangeland are far to complex to be defined by a simple succession or cyclic model. It is therefore necessary to describe the vegetation in a different manner. This is where the state-and-transition models become far more powerful than the cyclic or succession alternatives.

Westoby *et al* (1989) proposed that rangeland dynamics could be fully described by a set of discrete "states" of vegetation and a set of equally discrete "transitions" between these states. The transition between each state is triggered by a natural event (flood, drought, climate change) or by a change in management practice (land use, stocking densities). Transition phases may often be single events such as fire, but may also be long-term events that occur over many years (Westoby *et al.,* 1989). The point is that the system does not come to rest halfway through a transition; generally the vegetation community is dynamic and variable both in space and time.

The models relate to how researchers and rangeland managers define a given vegetation state and the processes that drive transitions. How then do these models affect our own perceptions of land degradation? If we choose to follow a specific model / paradigm, what implications does this have on our definition of degradation? If we choose the range succession theory to model vegetation change then grazing will have a marked impact on our results. If an area were deemed to be degrading, then grazing pressure would be assumed to be the cause and climate would not be a driving factor. If on the other hand, we chose a cyclic model, then any degradation found would be driven by climate variability, such as drought or extended periods of above average rainfall. State and transition models therefore provide the perfect model through which to assess potential vegetation change in the Succulent Karoo.

3.5 Land Degradation, Vegetation change and Climatic variability?

In arid and semi-arid areas, the influence of climate variability is far more pronounced than in areas of higher rainfall. These areas are also more prone to land degradation (Reich *et al.,* 2001). Arid and semi-arid areas are characterized by variable spatial and temporal rainfall patterns. These patterns can lead to drought and diminished vegetation cover. Woodward (1987) states that the availability of rainfall and moisture is one of the greatest limiting factors in terms of plant growth and distribution. Discriminating between land-use and climate, as causes of land degradation are central themes in this research, as well as determining the relative role each plays. Reich *et al* (2001) suggest that due to the large number of people affected by land degradation it is clear that degradation is driven by humans. The following review outlines various methodological approaches to monitoring land degradation and distinguishing land degradation from climate variability.

Mapping, monitoring and explaining the causes of land degradation using remotely sensed imagery have utilised several different analysis methodologies. These methods are based on the premise that vegetation growth occurs as a result of rainfall. In general the relationship between rainfall and vegetation growth is analysed using measures of statistical correlation and regression. Yang *et al* (1998) assessed the relationship between vegetation growth and various climatic parameters using multiple regression analysis. Time integrated Normalised Difference Vegetation Index (NDVI) maps were used as a surrogate for primary production. They found that the dominant control of grassland growth in the central United States was summer and spring precipitation rather than total annual precipitation. Furthermore inter-annual variability in temperature and precipitation also impacted grassland productivity. Elsewhere in the United States, Wang *et al* (2001) analysed the spatial responses of NDVI to precipitation and temperature. They too found that the spatial patterns of NDVI were primarily related to patterns of precipitation with temperature playing a secondary role. Jury and Weeks (1997) took the idea one step further when they analysed the impact of year to year climatic fluctuations on NDVI. They found that NDVI patterns were a function of the regional climate system dynamics with the eastern half of the country susceptible to the negative effects of ENSO related environmental perturbations. In Namibia, Du Plessis (1999) used 10-day interval precipitation, NDVI and measured biomass to assess the relationship between rainfall and vegetation growth. The author recognized that NDVI and vegetation growth have stronger relationships with annual and cumulative rainfall than with 10-day interval data. He also suggested that outliers should be identified and removed, and that the standard error of these relationships should be used to give an indication of the fundamental strength of these relationships. The above mentioned studies indicate quite clearly that seasonal NDVI accurately reflects the spatial and temporal precipitation patterns of a given area. While these results quantify the relationship between rainfall and vegetation growth they do not comment on the applicability of these two parameters with regards to identifying and mapping patterns of Degradation or Desertification.

A pertinent question to ask is how strong are these relationships and can we use them to identify long term changes brought about by unusual climate activity or inappropriate management practices? Prince *et al* (1998) analysed trends derived from the ratio between net primary productivity and rainfall, known as rain-use efficiency (RUE) to assess regional degradation in the Sahel for a nine year period. They found that NDVI (proxy measure for net-primary production) was fairly resilient throughout the study period and that the relationships indicated a recovery in vegetation growth post the 1984 drought. Furthermore it was reported that RUE showed a small but systematic increase between 1982 and 1991. The authors note that RUE may be used as an indicator of degradation at the local scale but that up-scaling this parameter for use on regional studies warrants further research. Holm *et al* (2003) also used RUE in a study of vegetation trends in Australia. Modelled estimates of total phytomass and RUE were compared with remotely sensed estimates of phytomass and RUE to determine if integrated NDVI was a suitable indicator of degradation at the landscape-scale. They also sought to determine if the interpretation of trends in landscape degradation were improved if community type were included in the analysis. Results indicated strong relationships between plot level biomass measurements and satellite derived measurements (r = 0.82) but weaker relationships between RUE ground and satellite measures (r = -0.4). However, temporal changes associated with RUE could be used as a broad scale indicator of landscape degradation. The inclusion of community type did not improve the relationships. Diouf and Lambin (2001) also use RUE, but recognise the need for appropriate indicators of degradation. They hypothesised that degradation could be measured in three ways, firstly through a decrease in the resilience of vegetation, secondly through a decrease in rain-use efficiency and finally through a change in floristic composition. They found that the most suitable parameter for assessing land cover change was using rain-use efficiency; they also found that after a drought the given increase in vegetation growth per unit rainfall was less than times of normal rainfall. The results mirror those of Holm *et al* (2003), Prince *et al* (1998) and Wessels *et al* (2004) in that, relationships that exist between rainfall and vegetation growth can be used to identify areas that may be undergoing degradation.

It is however not always necessary to use both climate and satellite derived variables to identify land degradation. Milich and Weiss (2000) used ground based measurements and satellite derived measures of biomass to assess the interannual variation seen in satellite data. The authors utilized a series of six transects running from north to south in the West African Sahel. They reported that annual images of Coefficient of Variation (CoV) identified localised areas of high CoV values. Through field work these areas were identified and labelled as seriously degraded with some being described as irreversibly degraded (on human timescales). These results should however be interpreted within a drought context as the study ends in 1994 at which time the area was recovering from a severe drought. Anyamba and Tucker (2005) highlight this in their study of annual growing season NDVI anomalies where two distinct time periods were identified pre 1994 and post 1994, with the post 1994 period showing significant recovery from the sustained drought. Climate variability in arid zones contributes to the complexity of identifying and monitoring the impacts of climate change. The literature reviewed thus far has firstly introduced the use of satellite data in the form of vegetation indices and how they reflect known climatic conditions; it then presented several studies that use the relationships identified to map and monitor land degradation and desertification. Finally the review will now present three studies that seek to identify the driving forces behind degradation using remotely sensed data.

Discriminating between climate and human-induced degradation is of vital importance if we are to develop effective methodologies for the assessment of the state of a rangeland. Furthermore the combination of the two factors has the potential to be catastrophic agents contributing to vegetation change. Hutchinson *et al* (2000) investigated the causes of vegetation change in southeast Arizona. Both land-use and climate were explored as possible causes of vegetation change. Using repeat aerial photography covering a period of 50 years as well as historical records, two primary hypotheses were examined; either climate or land-use is the dominant factor in vegetation change. Results from this study indicated that land-use and not climate change was the primary driver of historical vegetation change.

In Syria, Evans and Gerken (2004) use vegetation indices (see chapter 4 section 4.5) derived from NOAA's Advanced Very High Resolution Radiometer sensors and rainfall data, to discriminate between human and climate-induced dryland degradation. They argue that due to the high inter-annual rainfall variations observed in drylands, minor trends in biomass change imposed by human activities are difficult to verify. Utilising different periods of accumulated rainfall and annual NDVI, they identified the rainfall period that is best related to maximum NDVI. Using positive and negative deviations of the residuals from regression analysis, they were able to identify areas where change was accounted for by human activities. Results from the study could then be used in identifying potential areas of human-induced change. These areas could then be examined in more detail with a focus on their vegetation cover, the driving forces triggering a reduction in biomass, and the most suitable rehabilitation program.

More locally, in the Grassy Karoo Archer (2003) investigated the effects of grazing strategies and their effect on the vegetation of the area. The research used a 14-year NDVI data set that had been corrected for the effects of precipitation. The study focused specifically on the impact of different grazing strategies using the Normalized Difference Vegetation Index as a measure of vegetation health. The detrending methodology applied to the data allowed for any changes in biomass to be attributed to the grazing strategies. Results indicated that vegetation change in the study area (Grassy Karoo) was not solely a response to variable rainfall, but more a function of stocking strategies.

The studies conducted by Archer (2003), Evans and Gerken (2004) and Hutchinson *et al* (2000) highlight the need and potential outcomes scientific studies have. The established relationships between rainfall and vegetation growth (Yang *et al* 1998; Wang *et al* 2001) provide researchers with a robust tool that has the potential for region wide mapping and monitoring of vegetation status and the driving forces behind unexplained changes. Several researchers have used a parameter known as rain-use efficiency to assess and explain temporal changes in vegetation growth (Holm *et al.*, 2003; Diouf and Lambin, 2001; Prince *et al.*, 1998). Given the rainfall gradients in the biome RUE may not be applicable at the regional scale, literature reviewed above confirms this, but should a researcher wish to perform an analysis at the local scale then RUE should be considered. Other methods using statistical measures of variance (Milich and Weiss, 2000), spatial patterns of integrated NDVI (Wessels *et* al., 2004) and degradation indicators (Symeonakis and Drake, 2004) have also returned results promising results. The Succulent Karoo however is unique in both its plant community and the climate. It is therefore necessary to test and develop new methods that take into account the rainfall regime, low plant cover and variable land tenure systems when attempting to understand the biome dynamics.

3.6 Acocks Expanding Karoo Hypothesis

3.6.1 Pre Acocks

The issue of desertification and land degradation in South Africa has a somewhat punctuated history. Chapter one discussed the expansion of sedentary agriculture into the Karoo. The effect of this expansion into the Karoo meant that the vegetation was placed under increasing pressure. With more "trekboers" settling in the region, less of the natural rangeland was available for grazing, various laws pertaining to land tenure were passed and movements of farmers were restricted to surveyed plots of land. The impact of heavy grazing in the Karoo was noted as early as 1873, when Shaw commented on the greedy nature of the Merino sheep farming industry and the impact it was having on the veld. Furthermore the Kraaling system employed at the time was criticised as being the cause of much of the degradation seen in the area (Hoffman *et al.,* 1999).

Drought and below average rainfall seem to accompany interest in land degradation, as mentioned by Hoffman in chapter one of the technical report prepared for South Africa's NAP. During the early twentieth century drought caused massive losses in South Africa and ways were sought to mitigate the effect of drought and prevent agricultural losses. The Drought Investigation Committee was set up in September 1920. The commission held over 100 public meetings around South Africa where they collected information on the state of the veld. They also attempted to raise awareness and educate the farmers on effective land use practices (Hoffman *et al.,* 1999). The report declared that there was no proof of change in mean annual rainfall while the rest of the report focused on land use practices and their affect on rainfall efficiency. A period of indifference and inactivity followed the publishing of the report. Stock numbers began to increase and by 1930 had risen to around 48 million animals (Hoffman *et al.,* 1999).

Authors and academics of *"The Age of Awareness"* (Mainguet, 1991) continued to criticise the stocking levels and wrote of the desiccation of the Karoo and the rest of South Africa (Kanthack 1930, Phillips 1931). It was around this time that the *"Karoo Desertification Hypothesis"* began to take hold. Both de Klerk (1947) and Tidmarsh (1948) wrote of vegetation changes taking place in the Karoo, but it took another five years before John Acocks published his ideas on vegetation change, and the driving forces behind degradation and desertification of the grasslands of South Africa (Acocks, 1953). The idea of the expanding Karoo has become so entrenched in the debate around vegetation change and desertification that it necessitates a closer look at Acocks' work and how it has driven the debate over the last 50 years.

3.6.2 Acocks' Expanding Karoo Hypothesis

In 1953, J. P. H Acocks published the first of three volumes of *Veld Types of Southern Africa*. In the first publication in 1953 he presented two theories or hypotheses surrounding the degradation debate. The two hypotheses were presented in four colour maps. Firstly, he drew a map of South Africa before colonial occupation (AD 1450), depicting a pristine environment where the eastern Karoo was dominated by perennial grasses. His second more influential hypotheses stated that the eastern Karoo grasses were becoming invaded by Karroid shrubland. This invasion was seen to be a direct result of overgrazing in the area. Acocks argued that continued grazing by domestic stock was depleting the root reserves of the grasses resulting in the extinction / replacement of the grasses with Karoo bushes (Hoffman and Cowling, 1990). Acocks believed that the Karoo-type shrubland was invading the more productive grasslands of the southern Free State. Further, Acocks postulated that if left unchecked the Karoo shrubs would extend over much of the subcontinent by the year 2050 (Hoffman *et al.*, 1995).

The maps published by John Acocks in 1953 proved to be powerful tools in convincing the authorities that degradation was a reality. It did however take some time before government took active steps to conserve soil and veld resources. While various acts encouraged farmers to develop sustainable farming practices (Soil Conservation Act 1946), by 1961 few had developed farm plans as recommended by the Soil Conservation Board (Meadows, 2003). The Soil Conservation Act of 1969 and the Conservation of Agricultural Resources Act of 1983 brought the issue of soil conservation and sustainable farming practices into active policy implementation (Meadows, 2003). Mainguet (1994) described the period as *"the age of awareness"* with regards to land degradation. The views held by Acocks were consistent with an awareness campaign initiated by the Department of Agriculture, which developed into the Stock Reduction Scheme implemented between 1969 and 1978 (Meadows, 2003). During this time little original research took place with regards to land degradation, save for one study by Jarman and Bosch (1973) on the feasibility of using Landsat imagery to understand patterns of vegetation change in the semi-arid Karoo (Dean *et al.,* 1995). Their research confirmed Acocks' ideas about the expanding karoo. Results suggested that the Karoo was expanding northwards between 45 and 70 km in the 20-year period since Acocks first published his maps (Dean *et al.*, 1995). Both Hoffman and Cowling (1990) and Dean *et al* (1995) question the validity of the research as only one drought season image was used and various techniques were employed to identify vegetation boundaries. It should however be noted that the work done by Jarman and Bosch (1973) was the first study using Remotely Sensed Imagery in a time when access to data must have been impossibly difficult, not to mention the computer resources needed to process the data. Acocksian philosophies influenced agricultural policies right up to the 1985 National Grazing Strategy. This strategy accepted the view of a pristine grassland environment and endeavoured to return the Karoo to its former glory by implementing more conservative stocking numbers and more effective management strategies (Meadows, 2003; Hoffman *et al.,* 1995).

The debate seemed once again to stagnate after Acocks first published *Veld Types of Southern Africa* in 1953. Renewed interest in the matter arose in the late 1980s when as part of the International Geosphere Biosphere Programme (IGBP); South Africa had to synthesize the local desertification literature. The resulting synthesis by Hoffman and Cowling (1990) found little support for the expanding Karoo hypothesis. They suggested that perennial grasses did not dominate the pre-colonial Karoo and that perceived vegetation changes may have been the result of seasonal rainfall effects. A second review five years later by Dean *et al* (1995) confirmed that archaeological and paleoecological evidence provided conflicting reports regarding the nature of pre-colonial karoo environments. Dean *et al* (1995) commented “Despite more than 100 years of research effort, the most basic question surrounding the problem remains, ‘Are desert-like conditions in the Karoo more prevalent today than they were in earlier times?’ Conflicting, even unreliable evidence means that we cannot yet be sure of our answer.”

Studies supporting the expanding Karoo hypothesis include an analysis of stocking rates in the then Western Cape by Dean and Macdonald (1994). They found that there had been a decline in stock numbers between 1920 and 1980. The reduction was attributed to a lowering of the carrying capacity brought about by overgrazing, thus confirming a decline in the abundance of palatable species and supporting the expanding Karoo hypothesis. Hoffman, Bond and Stock (1995) performed a similar analysis for the eastern Karoo, while they confirmed that stock numbers had decreased for the 18 districts studied, the reasons for the decline were not entirely explained by a decrease in carrying capacity. An analysis of rainfall records for the area showed that the region experienced relatively high summer rainfall and that biomass in the area had not decreased (Palmer *et al.,* 1990; Connor and Roux, 1995). Hoffman Bond and Stock (1995) commented that the decrease in stocking numbers might not be attributed to a decrease in carrying capacity, rather a response to state interventions such as the Stock Reduction Scheme initiated in 1971. Analysis of carbon isotopes from various sites in the Nama Karoo supported Acocks’ hypothesis for an increase in shrub cover (Bond, Stock and Hoffman, 1994). The analysis, however, did not support Acocks’ view of pristine Karoo grassland prior to colonial settlement.

The Acocksian hypothesis has been the central debate in desertification literature over the past 20 years and has indeed been the preferred paradigm since its first publication in 1953. Much research has been published in scientific journals either rejecting or accepting it; these have been briefly introduced in the above section. The research formed the backbone of scientific understanding of degradation in the late twentieth century and set the stage for South Africa's entry into the degradation debate. In 1994 South Africa became a democracy, and in 1995 signed the United Nations Convention to Combat Desertification (UNCCD). The UNCCD was ratified in 1997, and became a legally binding document committing South Africa to producing a National Action Programme. The Department of Environmental Affairs and Tourism (DEA&T) commissioned a review / audit of the land degradation debate in South Africa and institutions were invited to tender for the review (Hoffman and Ashwell, 2001). The National Botanical Institute and Programme for Land and Agrarian Studies were successful in their joint submission. The review formed the basis of the National Action Plan needed in accordance with the UNCCD. The resulting study is by far the most comprehensive assessment of land degradation in South Africa (Hoffman and Todd, 2000).

3.7 Conclusion

The topic of land degradation and vegetation change is not a new phenomenon in Southern Africa. As early as the 19th century, travellers were noting the desolation of the central interior of South Africa as a result of the Sheep Farming industry (Shaw, 1873, cited in Hoffman, 1999). In the early part of the 20th century a series of debilitating droughts once again highlighted the issue of land degradation. In 1920 the Drought Investigation Commission was set up to determine the present state of the veld in South Africa; the commission found that there was no noticeable change in rainfall while the rest of the report focused on rain use efficiency and improving management strategies (Hoffman *et al.,* 1999). At the time, degradation or desertification was not an issue. Improved management strategies and farm plans were few and far between, stock numbers continued to rise and by the late 1940's stocking rates were at their highest with over 40 million animals in South Africa alone (Hoffman *et al.,* 1999). Debate around the issue of degradation or desertification began to surface in the 1930s and 1940s (Kanthack, 1930; Phillips, 1931; de Klerk, 1947; Tidmarsh, 1948). Acocks' publication of his Expanding Karoo Hypothesis in 1953 proved to be a turning point in the debate. His ideas and theories were presented in four maps, which were impressive for that time and have influenced the desertification debate for the last 50 years. While the publication of *Veld Types of Southern Africa* may have renewed interest in degradation or desertification, little original research followed until the late 1980s. Internationally, the land degradation debate was in full swing with several conferences (UNCOD, 1977) and conventions (UNCCD, 1994) advocating aid and intervention programs. The UNCOD failed, but lessons were learnt and the United Nations Convention to Combat Desertification (UNCCD) was far better prepared to tackle the problem of land degradation. South Africa signed the UNCCD in 1995 and ratified it in 1997 (Hoffman and Ashwell, 2001). The resulting review of land degradation in the country is by far the most comprehensive. Once again a public participation approach was used and the results of the review were presented to the Department of Environmental Affairs and Tourism.

The review also included the previous homelands in its assessment of land degradation. This was the first time that the homelands had been included and the final combined degradation index developed highlighted the impact that apartheid's homeland policy had on these areas (Hoffman and Ashwell, 2001; During, 1990). At this time researchers were also questioning the entrenched Acocks Expanding Karoo Hypothesis. For many years it was believed that degradation was only affecting the Karoo Biome, purely because of the influence of Acocks. The review conducted by the National Botanical Institute and the Programme for Land and Agrarian studies at the University of the Western Cape, highlighted the fact that degradation is found all over the country. Various authors have conducted research into the issue and results have been published either authenticating or refuting the Acocksian hypothesis (Hoffman and Cowling, 1990; Dean and MacDonald, 1994; Bond, Stock and Hoffman, 1994; Dean *et al.,* 1995; Hoffman, Bond and Stock, 1995). The problem here is not to resolve the issue but merely state that scientific results from research are unable to fully support or oppose Acocks Expanding Karoo Hypothesis and that the issue needs more attention.

One way of better understanding the dynamic nature of vegetation seasonality is to monitor vegetation growth at the regional or continental scale. By fully characterizing the relationships that exist between vegetation and precipitation, for instance, we can better understand how vegetation responds to changes in climate and or anthropogenic forcing such as stock farming. This is particularly true for the Succulent Karoo as stock farming forms the basis of economic activity in the Biome. Remotely Sensed images used in combination with ancillary GIS data and fieldwork provides an excellent tool for the monitoring of vegetation health at various spatial scales and periods. Chapter 4 outlines various vegetation indices as well as their use in studies of vegetation change and degradation.

Chapter 4

GIS & Remote Sensing: Applications in Land Degradation

4.1 Introduction: Remote Sensing and Geographical Information Systems as tools for degradation assessment

Remote Sensing (RS) and Geographical Information Systems (GIS) are highly evolved tools in degradation assessment. Jarman and Bosch (1973) were the first to use remotely sensed images as tools for the assessment of the Acocksian Karoo desertification hypothesis. The methods and tools used by researchers today have evolved into a complex set of methodologies and applications utilizing a wide variety of data sources. When using remotely sensed imagery for ecological studies of vegetation change / land degradation, methodologies are based on some form of vegetation index (VI). These VI's are derived from remotely sensed satellite imagery. Commonly the red and near infrared bands are used. VI's are simple algorithms that make use of the differing absorption and reflective properties of red and near infrared light. While the Normalised Difference Vegetation Index is a widely used index, there are a plethora of indices available to the researcher. The following sections serve to introduce some of these indices and their application to studies of land degradation and vegetation change.

4.2 Introduction to Vegetation Indices

Spectral radiance from plant canopies in the 0.4 – 2.5 *um* region of the electromagnetic spectrum provide the basis for remote sensing of vegetation (Tucker and Sellers, 1986). Leaf structure and function facilitates distinctive variation in absorption and reflection of solar radiation from plant canopies. Structure and function are also directly linked to photosynthesis. Thus the potential for measuring photosynthesis exists in terms of measuring reflected solar energy (Tucker and Sellers, 1986). Photosynthetically Active Radiation (PAR) is strongly absorbed in green leaves with low levels of reflectance and transmittance. Conversely, in the 0.71 – 1.3 *um* region (near-IR), very low absorption occurs in green plants (Tucker and Sellers, 1986). Thus this relationship can be used to determine the rate of photosynthetic activity. Healthy vegetation reflects between 40 percent and 50 percent of near infrared (0.7 – 1.1 *um*) light with chlorophyll in plants absorbing approximately 80 to 90 percent of light in the visible (0.4 – 0.7 *um*) portion of the electromagnetic spectrum. Dead or dying vegetation reflects a greater amount of visible energy than healthy vegetation and conversely reflects less energy in the near infrared than healthy vegetation (Jensen, 1996). The differing absorption properties of red and near-IR light are the corner stone of vegetation studies using remotely sensed imagery. Figure 4.1 outlines the above-mentioned relationship.

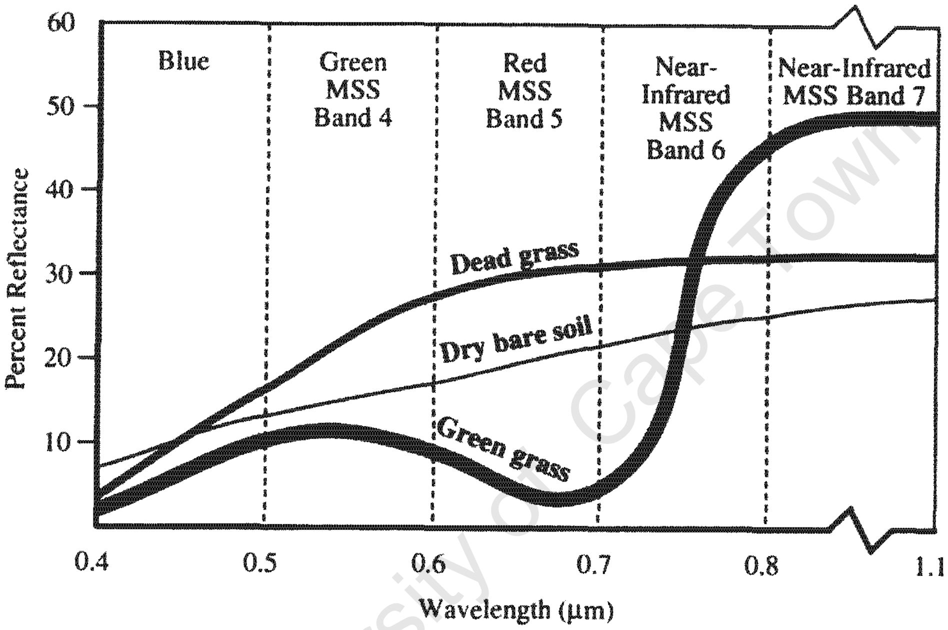


Figure 4.1: Spectral Characteristics of Dead grass, Dry bare soil and Green grass (After Jensen, 1996)

The use of satellite derived vegetation indices, as a measure of vegetation growth is widespread. Pioneering work began, using hand-held spectrometers. Tucker *et al* (1981) analysed the temporal characteristics of winter wheat by measuring red and near-IR spectra at various times of the year. Results indicated that the red and near-IR spectral data were strongly correlated to the canopy vigour of winter wheat. Authors have used vegetation indices to assess vegetation parameters such as, total dry matter accumulation (Tucker *et al.,* 1983), global vegetation phenology (Justice *et al.,* 1985), land cover classification in Africa (Tucker *et al.,* 1985) primary production (Tucker and Sellers, 1986), rangeland health (Prince and Astle, 1986a, Prince and Tucker, 1986b) the expansion and contraction of the Sahara desert (Tucker *et al.,* 1991a) as well as the inter-annual variation of growing seasons in the Sahel (Tucker *et al.,* 1991b) and desert spatial extent (Tucker *et al.,* 1994).

There are three broad categories of vegetation indices. Slope based, distance based and orthogonal indices. Only slope and distance based are discussed, as they are the most widely used, for a detailed explanation of orthogonal indices see Jensen (1996)

4.2.1 Slope Based Vegetation Indices

Slope based vegetation indices are by far the most widely used. The indices are based on the slope of the line between the origin and a pixels location in a 2-D scatter plot (Using the red and near-IR bands on the X and Y axis). The steeper the slopes the higher the vegetation cover. Tucker *et al* (1981) used variations on the Ratio Vegetation index (RVI) and Normalised Difference Vegetation index (NDVI) to study winter wheat phenology. The RVI (Rouse *et al.*, 1974) and NDVI were some of the first indices to be used. Tucker *et al* (1985) used the RVI for land-cover classification over Africa. Prince and Astle (1986) used the RVI in an analysis of vegetation cover in Botswana. The index is calculated as a ratio (equation 4.1) between the red and near-IR bands / channels available on several satellite platforms.

$$\text{RVI} = \text{near-IR} / \text{Red} \qquad (4.1)$$

This method is also known as band rationing where the two bands are combined and used to estimate and monitor green biomass. When using the above-mentioned index the higher the pixel value the greater the amount of vegetation cover. The index is known as a slope-based index because the result of the division is geometrically equivalent to the slope of the line connecting the origin to any particular point within the scatterplot.

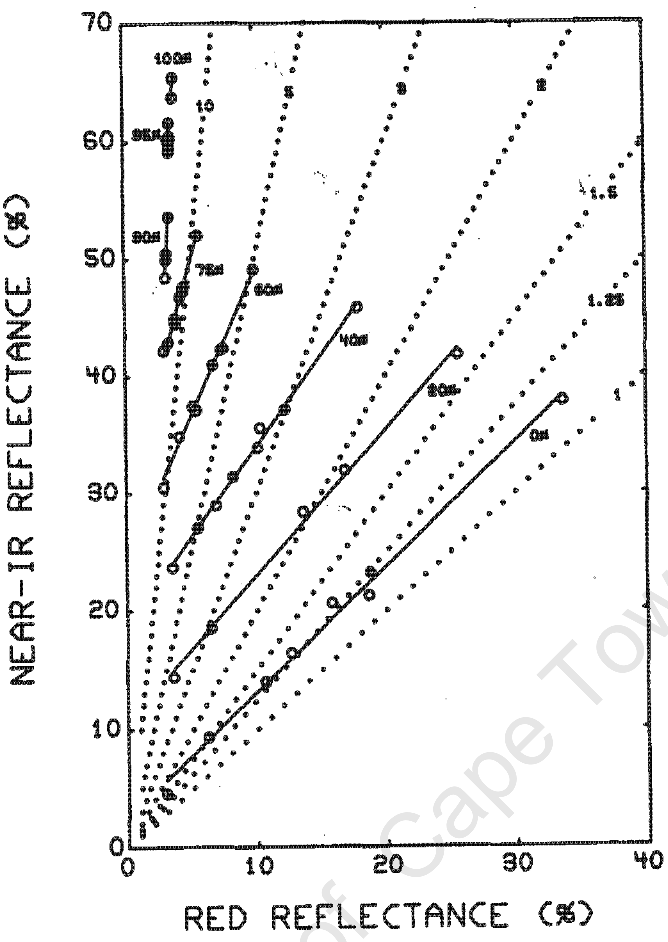


Figure 4.2: Scatterplot of red and near-IR channels.

The index being used in the present research is another slope-based index also introduced by Rouse *et al* (1974) is known as the Normalized Difference Vegetation Index. This index takes the difference of the near-IR and Red bands and divides this by its sum; equation 4.2 shows the general form the index

$$\text{NDVI} = (\text{NIR}-\text{RED}) / (\text{NIR}+\text{RED}) \qquad (4.2)$$

NDVI returns values ranging from –1 to 1. Very low values (below 0.1) correspond to barren, rocky non-vegetated areas including snow and ice. Shrub and grasslands usually return NDVI values of between 0.2 and 0.4 while values above 0.6 indicate temperate or tropical rainforests. The Normalized Difference Vegetation Index has emerged as the most popular index. Original work by the above mentioned authors utilized early versions of the Ratio Vegetation Index and the Normalized Difference Vegetation Index. The primary focus was on refining indices and developing methods for the analysis of vegetation health and phenology. Later work began to incorporate ancillary geographical data. Nicholson, Davenport and Malo (1990) assessed vegetation response to rainfall in the Sahel. More recently Millich and Weiss (2000a, 2000b) used rainfall combined with potential evaporation in the grazing lands of the Gourma (Sahel) and Niger.

4.2.1.1 Case Studies using Slope Based Indices

4.2.1.1.1 Medium Resolution Satellite Platforms (Landsat Multi Spectral Scanner and Thematic Mapper)

Medium resolution satellite sensors are widely used platforms for the collection of earth observation data. The fine spatial resolution (30m pixel size) of the sensor makes them perfect for discerning local scale patterns such as degradation around watering points and fenceline contrasts. The following section outlines some of the methodologies developed during the last 20 years.

Ringrose *et al* (1990, 1996, 1999) used medium resolution Landsat data to determine the development and extent of changes and or causes of degradation in southern Botswana. In all three papers referenced, the authors used either Landsat MSS or TM data. Various techniques were used; these included classification of mutli-temporal Landsat MSS data (Ringrose *et al.,* 1990), GIS buffer analysis of homesteads and boreholes using a single Landsat TM image (Ringrose *et al.*, 1996) and finally analysis of spectral reflectance curves for seasonal Landsat TM images (Ringrose *et al.,* 1999). Results indicate that the medium resolution data proved effective at identifying anthropogenic vegetation change.

4.2.1.1.2 Coarse Resolution Satellite Platforms (NOAA AVHRR)

Coarse resolution data in the form of NOAA AVHRR has been widely used for vegetation studies. The fine temporal resolution of the sensor makes it perfect for vegetation studies. The NOAA series of satellites orbit the earth several times a day. Chapter 5 (section 5.2) provides a detailed description of the sensor characteristics. The rest of this section outlines the use of coarse resolution data for monitoring trends and patterns that may or may not indicate denudation or degradation.

The office of Arid Land Studies, Arizona Remote Sensing Centre at the University of

Arizona used coarse resolution data in various studies. In the late eighties and early nineties Hutchinson *et al* (1991, 1992) used both coarse and fine resolution data for vegetation studies in Africa. In 1991 a paper was published by Hutchinson entitled "Uses of satellite data for famine early warning in sub-Saharan Africa." The paper outlined the present use of Remote Sensing as a tool for famine early warning systems, and made several suggestions regarding the use of extremely coarse Global Area Coverage GAC (8km) data as a means of determining crop yields and comparisons between regions (Hutchinson *et al*., 1991).

Weiss *et al* (2001) used AVHRR NDVI time series data to assess changes in Saudi Arabia's rangelands. The authors take advantage of the temporal resolution of the AVHRR data but only use monthly Maximum Value Composites (Holben, 1986). The primary objective was to assess the condition of a portion of Saudi Arabia's rangelands and evaluate the effects of grazing by animals over the last 10 years (Weiss *et al*., 2001). The analysis used coefficient of variation (COV) as a measure of vegetation biomass change, higher COV values represent larger change and lower values represent less change. Linear regression was then used to determine the trends present in the COV over a 14-year period. Results were combined with land cover information to provide an assessment of the desertification status of rangelands in Saudi Arabia (Weiss *et al*., 2001).

Tabor and Hutchinson (1994) also combined geo-information in the form of Remotely Sensed images and GIS with indigenous knowledge for sustainable development of an arid zone. The paper outlined the potential use of GIS and RS combined with indigenous knowledge as tools for effective management. The paper highlights the varied use of RS and GIS as well as the potential links that remote sensing can have with various fields of research.

Nicholson, Davenport and Malo (1990) compared vegetation response to rainfall in the Sahel and East Africa using the coarse resolution AVHRR NDVI data. The study attempted to characterize the relationships between rainfall and vegetation growth. Nicholson *et al* (1990) used a best-correlated parameter to identify a time lag defining the relationship between rainfall and vegetation growth. The analysis was performed in east Africa and the Sahel. Results contributed to a better understanding of the dynamic relationship between precipitation and vegetation growth as well as the variability between the two areas (Nicholson *et al.,* 1990); furthermore the study substantiated the use of coarse resolution satellite data. Further research by

Nicholson *et al* (1994) and Farrar *et al* (1994) used similar methods of analysis in the Kalahari. NDVI derived from AVHRR data were used in an analysis of the influence of soil type on the relationship between rainfall vegetation growth and the role played by soil moisture.

Weiss and Milich (1997), used coefficient of variation images to characterize the Sahel, and examine the implications of using the digital number (DN) to calculate the COV images as opposed to using NDVI values. Methods used by Milich and Weiss (1997; 2000) differ somewhat from those employed by Nicholson *et al* (1990; 1994) in that the aforementioned authors only examine the NDVI variance as an indication of change, they do not include precipitation data. Milich and Weiss (2000a, 2000b) do however remedy this in later publications where they use rainfall and potential evaporation in the grazing lands of the Gourma (northern Sahel) and the Niger. NDVI derived from AVHRR GAC were used in conjunction with rainfall surfaces to explore the unpredictability of the rainfall for the Gourma and Niger areas. The results confirmed a widely accepted idea that rainfall and vegetation growth are for the most part linearly related. This relationship is the focus of the present research. Research reported on above use remotely sensed imagery and rainfall in some form of statistical analysis with the result being a value that indicates the existence of either a strong or weak relationship. This is a standard method of analysis. Present research uses similar statistical methods.

Finally Thiam (2003) used various methods and techniques to assess the causes and spatial patterns of land degradation in Mauritania. The author also used NOAA AVHRR NDVI data at the 1 km resolution. Rainfall data, soil types and field survey data were combined with the RS imagery to identify and characterize the spatial patterns of land degradation and possible drivers of degradation. Thiam (2003) found that all soils in Mauritania were at risk and that uncontrolled resource-base exploitation by the local population was denuding large parts of the West African country. The author also noted that degradation was compounded by below average rainfall.

4.2.2 Distance Based Vegetation Indices

Distance based indices, like slope-based indices, rely on the differing absorption and reflective properties of the red and near-IR portions of the electromagnetic spectrum.

The difference lies in the way that vegetation cover is measured. Instead of using the slope between the red / near-IR point and the origin, distance based indices define a soil line in data space. Figure 4.3 shows the basic workings of a distance based vegetation index. The line F-B-A (figure 4.3) is used as a reference point from which to measure vegetation cover. The Euclidean distance from this line (in data space) is used a means of measuring vegetation cover. Distance based indices were originally developed to mitigate the effects of background soil reflectance in partial canopies.

Huete (1988) noted the background influence of soils in vegetation indices following studies conducted by Colwell (1974), Elvidge and Lyon (1985) and Huete *et al.,* (1985). Elvidge and Lyon (1985) found that a variation in rock and soil spectral characteristics adversely affected measurements of green biomass using ratio or slope based vegetation indices. Heute *et al* (1985) reported that ratio and orthogonal vegetation indices are strongly dependant on soil background characteristics. They concluded that soil and plant spectra interactively mix in a no-additive manner to produce a composite canopy spectrum.

The background influence of soil on incomplete canopies is due to the dependency of the soil background on the properties of the overlying canopy. The physical nature of soil background reflectance is as follows. Considerable amounts of near-IR flux are scattered and transmitted towards the soil surface. The soil below the canopy reflects part of this flux back to the sensor. The reflectance back to the sensor is dependant on the optical properties of the soil beneath the canopy as well as the canopy itself. Conversely the canopy absorbs red light while irradiance at the soil surface is dependant on the sun itself. This characteristic makes any vegetation index "soil-dependant" (Heute, 1988). Authors have noted the impacts of various soil types and colours on vegetation indices (Elvidge and Chen, 1995; Qi *et al.*, 1993; Bausch, 1993; Heute *et al.*, 1985). Most notably Rondeaux *et al* (1996) analysed the sensitivity of various vegetation indices to different soil background conditions. They found that among the SAVI (soil adjusted vegetation index; see equation 4.4) family of indices a value of 0.16 (*L*) optimised the performance of the chosen index. The general effect of soil background reflectance on NDVI can be generally defined as follows; dark soils increase the NDVI and bright soils decrease NDVI measurements.

Huete (1988) presented a technique that minimized the effect of soil brightness influences whereby the origin of the spectra plotted in near-IR (NIR) – red (R) wavelength space was shifted to account for first-order soil-vegetation interactions.

The resulting index known as the Soil Adjusted Vegetation Index mitigated the effect of differing soil background conditions on NDVI using the algorithm given in equation 4.3.

$$\text{SAVI} = [(\text{NIR} - \text{red}) / (\text{NIR} + \text{red})] \times (1 + L) \qquad (4.3)$$

The constant L represents the shift in the origin of near-IR – red wavelength space. The value of L is determined by vegetation densities determined through fieldwork and expert knowledge (Huerte, 1988). Similarly the Perpendicular Vegetation Index (PVI) first proposed by Richardson and Weigand (1977) attempted to mitigate the effects of soil on partial canopy reflectance. The PVI is also based on the near-IR – red combination only this time it is not the slope that determines the index but the distance from a predefined soil line (see fig 4.3).

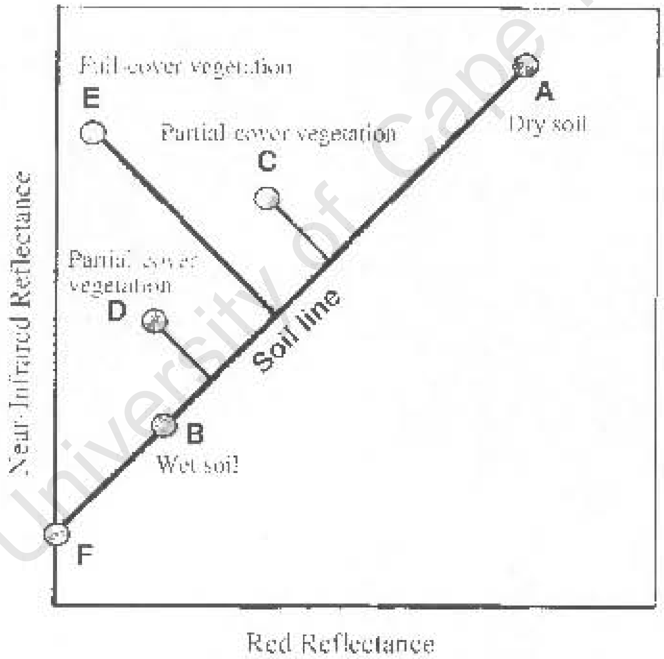


Figure 4.3: Graphic depicting the distance based vegetation index (After Jensen, 1996)

The distance (E, C, D) of any given pixel from the predefined soil line determines the amount of vegetation cover present (Jensen, 1996). The index is calculated using the following algorithm

$$\text{PVI} = (\text{NIR} - \text{RED}) / (1 + a^2) \qquad (4.4)$$

Where a represents the slope of the soil line (A, B, F) (Rees, 1999). Rangeland research in Australia has seen the development of another distance based index known as the PD54. The index was first known as a vegetation cover index in band 4 and band 5 data space (Pickup *et al.*, 1993). Previous indices discussed have been based on the red and near-IR bands / channels. The PD54 is based on the PVI (Richardson and Weigand, 1977) but used band 4 and band 5 of Landsat MSS data. The index uses the soil line as a reference point rather than a vegetation line, the reason for this is that in arid areas you are more likely to have pixels representing pure soil as opposed to vegetation and therefore a more stable feature (see fig 4.4). The index has been widely used with positive results.

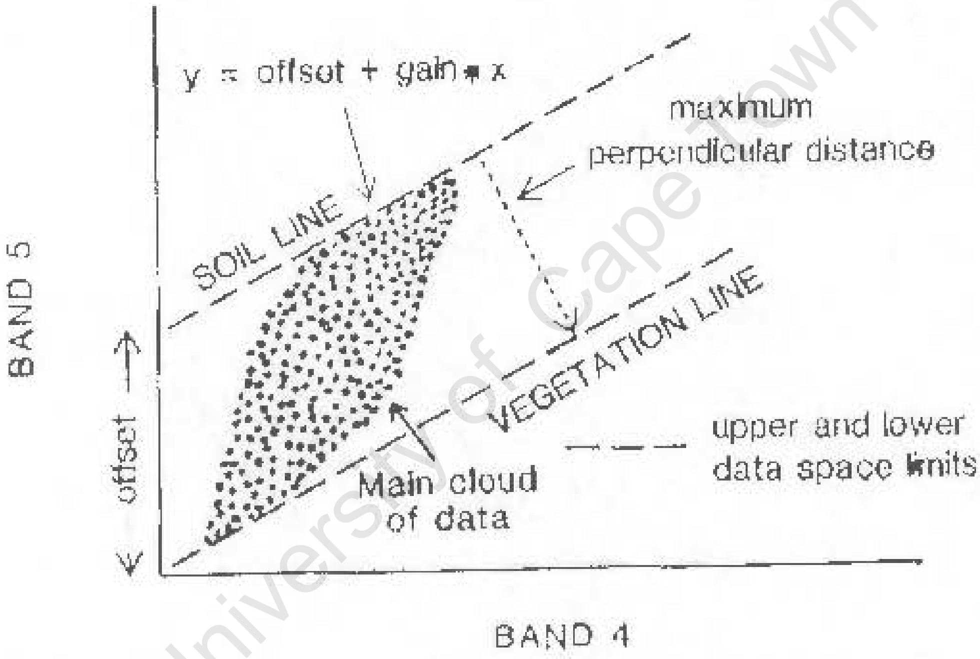


Figure 4.4: Graphic depiction of the PD54 index (After Pickup *et al.*, 1993).

The indices mentioned above are related to the use of the near-IR and red bands of any given satellite platform, only a few indices are mentioned as expanding on the rest would be beyond the scope of this project, Jensen (1996) gives a full description of the range of vegetation indices.

4.2.2.1 Case Studies using Distance Based Indices

4.2.2.2 Medium Resolution Satellite Platforms (Landsat Multi Spectral Scanner and Thematic Mapper)

The PD54 index mentioned above has been used in various studies of rangeland assessment in Australia. These include a condition assessment for non-equilibrium rangelands where the PD54 was used to assess the impacts of large scale commercial grazing. Landsat MSS data was used to derive a set of range condition indicators that are measured and monitored from space (Pickup *et al.*, 1994). It has also been used to estimate the effects of land degradation and rainfall variability on productivity in rangelands (Pickup, 1996). Furthermore, the Commonwealth Scientific and Industrial Research Organisation (CSIRO) used Landsat MSS to identify trends of land degradation in non-equilibrium rangelands (Pickup *et al.*, 1998). In this paper they assessed the impact of grazing around water holes. Benchmark sites were compared to sites closer to waterholes; the PD54 index was used in conjunction with grazing models developed from prior research (Pickup, Chewings and Nelson, 1993).

South Africa, Mackay and Zietsman (1996) use GIS techniques to identify localized range condition based on fenceline contrasts. The technique employed the use of a Landsat TM image and various dissimilarity measurements of both field survey data and the digital satellite imagery. The authors also used a relatively unknown vegetation index called the Soil Adjusted Vegetation Index (Heute, 1987). Once again results from the analysis prove that distance based vegetation indices derived from medium resolution satellite data could be used to identify fenceline contrasts present in farming communities where management strategies influence vegetation cover.

4.2.3 Combining Coarse and Medium Resolution Satellite data

Bastin *et al* (1995) tested the utility of AVHRR data for land degradation assessment. Results from this study are especially important for the present research as the author used data derived from the same sensor. The assessment used the PD54 index. The aim was to see if the AVHRR data could be used in arid rangelands under commercial grazing using vegetation dynamics and animal grazing behaviour developed for Landsat MSS data. Results indicated that the AVHRR data is inappropriate for the reliable detection of grazing impacts. Problems include the inability of the data to detect fine scale landscape changes resulting from over grazing as well as misregistration of temporal images. They concluded that despite the low cost of the AVHRR data it is inappropriate for the reliable detection of grazing impact using grazing gradient methods (Bastin *et al.,* 1995). While the results from the above mentioned research may cast doubts on the use of AVHRR data for the assessment of rangeland dynamics, it should be noted that the study presented above assessed the validity of the AVHRR data in terms of methods developed using medium resolution satellite data, namely Landsat MSS. The grazing gradient methods developed around watering holes in arid regions of Australia are site and data specific. One would therefore expect the AVHRR data to perform badly given its coarse resolution. AVHRR data have been used at the continental scale in Australia with more success (Cridland 2000a, 2000b). In both studies AVHRR data was used at the continental scale to assess the state of vegetation growth and health as well as to identify extreme climatic events.

Marsh *et al* (1992) performed a similar study to Bastin *et al* (1995) where they used NOAA-AVHRR data and SPOT-XS to map land cover dynamics in the Sahel. Marsh *et al* (1992) found that the SPOT-XS data was useful for mapping local land cover, the AVHRR data however could not identify the difference between recession and irrigated agriculture, it was however useful for identifying riparian vegetation dynamics and did not provide any accurate information on the temporal assessment of vegetation dynamics (Marsh *et al.,* 1992). The results from the study indicate that AVHRR data were not adequate for mapping the various dynamic vegetation and agricultural types. The resolution of the sensor was cited as a major drawback, as well as its inability to identify temporal patterns associated with the agricultural growing seasons (Marsh *et al.,* 1992). These results are not surprising given that only five AVHRR images were used (it is interesting to see that the authors only used five images when they could have used as many as two images per day depending on availability). The advantage of using AVHRR data is the fine temporal resolution; a major disadvantage is the spatial resolution. Results would have been far more conclusive had the authors taken advantage of the temporal resolution and attempted to map the dynamics at the daily resolution or even at a ten-day resolution.

4.2.4 Moving Standard Deviation Index and Change Vector Analysis

Tanser and Palmer (1999, 2000) used digital satellite data in conjunction with Geographical Information Systems (GIS) to monitor degradation patterns in semi-arid regions of South Africa. They focused on measuring landscape heterogeneity using a moving standard deviation index (MSDI). The MSDI is calculated by moving a standard deviation filter across a Landsat TM band three image; they found that degraded or unstable landscapes exhibit higher MSDI values than undisturbed areas (Tanser and Palmer, 1999). The study also used fenceline contrasts as a means of identifying degraded or denuded areas pointing towards different management strategies being employed at the farm level. Tanser and Palmer (2000) also used the MSDI with various classification techniques to classify vegetation types in the Great Fish River Basin. They found that conventional classifications of temporal Landsat TM images proved ineffective in delineating the vegetation types present, but when combined with a textural classification index such as the MSDI they were able to produce a final vegetation classification at accuracy of 84 percent. Palmer *et al* (2001) also used the MSDI to substantiate findings using Landscape Function Analysis techniques. Once again the MSDI derived from Landsat TM data proved useful in identifying differences between communal and commercial rangelands. Another technique employed by Palmer and van Rooyen (1998) known as Change Vector analysis (CVA) has also reported interesting results. The CVA shows direction and magnitude of change between two anniversary data images and proved useful in a study conducted in the southern Kalahari (Palmer and van Rooyen, 1998).

4.3 Conclusion

Chapter 4 provided a brief introduction to the physical properties of vegetation indices. The chapter continued with a discussion of Slope-Based indices. Several Indices were outlined including the Ratio vegetation index and the Normalised Difference Vegetation index. Examples of published research were used as case studies. These included Ringrose *et al.,* (1990, 1996, 1999), Nicholson Davenport and Malo (1990) and Thiam (2003). The case studies were used to provide examples of how slope based vegetation indices have been used to assess vegetation phenology and potential degradation. Following the discussion on slope based vegetation indices, distance based vegetation indices were introduced and discussed. Slope based indices were originally developed to mitigate the effects of background soil reflectance. The principles of background soil reflectance were discussed along with a brief outline of indices developed to mitigate soil influences. These included the Soil Adjusted Vegetation Index, Perpendicular Vegetation index, and finally the PD54. Once again examples are used to highlight the use of VI's in vegetation studies. Additional examples are given where researchers have combined medium and coarse resolution data for vegetation studies. Finally two examples of landscape functional analysis are given. The Moving Standard Deviation index (Tanser and Palmer, 1999, 2000) and Change vector analysis (Palmer and van Rooyen, 1998). Both of the methods have proved useful when applied to medium resolution satellite data such as Landsat MSS, TM.

Chapter 4 has laid the foundation for a better understanding of vegetation indices and their respective applications as well as their limitations in terms of the chosen platforms. Chapter 5 will provide an in depth look at the satellite sensor used for the present analysis as well and the derivation of rainfall surfaces. The chapter also outlines the methodologies employed.

Chapter 5

Data and Analysis Methodologies

5.1 Introduction

Chapter 5 outlines data used in the analysis of intra-seasonal land surface change in the Succulent Karoo. It begins with an explanation of the primary data sources used. After a brief summary of both data types, the chapter continues with an outline of data processing techniques used to derive the Normalised Difference Vegetation Index and precipitation surfaces. Methodologies employed in analysing the relationship between rainfall and vegetation growth are outlined. These include the Spatio Temporal Correlation Filter (STCf), Principle Component Analysis (PCA) and Self Organising Maps (SOMS).

5.2 National Oceanic and Atmospheric Administration (NOAA) Advanced-Very-High-Resolution Radiometer (AVHRR)

5.2.1 A Brief History of the NOAA AVHRR platform

The NOAA series of satellites began in the early 1970's with the launch of NOAA-1. The satellite began as a meteorological imaging instrument designed to observe climatological phenomenon around the planet. The sensor, VHRR (Very-High-Resolution Radiometer), was the descendant of the TIROS (Television Infrared Observation Satellite) series which gave scientists their first synoptic scale view of the earth. NOAA-1 through NOAA-5 used the VHRR sensor and operated between 1972 and 1976 (Rees, 1999).

In 1978 NOAA-6 was launched. The satellite carried a new imaging sensor called the Advanced Very High Resolution Radiometer (AVHRR). The AVHRR sensor imaged the earth in four channels as opposed to the 2 channels of VHRR instrument. The four-channel sensor gave scientists the opportunity to derive vegetation indices using channel one and two. This was not possible on the VHRR sensor as the overlap between the visible and near-IR channels was such that ratio or normalised indices could not be computed (Tucker *et al,* 1985). NOAA-6 through NOAA-14 are known as the TIROS-N series of satellites. Accompanying the AVHRR instrument was the TIROS Operational vertical sounder (TOVS). This instrument included the following subsystems, a Microwave Sounding Unit (MSU), Stratospheric Sounding Unit (SSU) and the High Resolution Infrared Radiation Sounder (HIRS/2) (Kidwell, 1998). These units were standard on all TIROS-N satellites as well as the Advanced TIROS-N series. Later versions, NOAA-9 through NOAA-14 carried an Earth Radiation Budget Experiment (ERBE), Search And Rescue (SAR) instrument and the Solar Backscatter Ultraviolet system (SBUV). They were designed to operate in a near-polar, sun-synchronous orbit, with each orbit taking around 102 minutes to complete, giving the satellite 14.1 orbits per day.

In 1998 NOAA launched a new series of Polar Orbiting Environmental Satellites (POES). NOAA-K marked the beginning of a new and improved earth observation system, designed to take the NOAA series of satellites into the twenty first century. The system known as NOAA-KLM looks very similar to the old TIROS-N and ATN satellites, but nearly every subsystem changed. The KLM series of satellites were heavier than their predecessors with increased power needs and larger instruments. In particular the visible channels onboard the AVHRR/3 sensor allowed for improved, low energy / light detection. A sixth channel (3A) was added. Channel 3A allowed for greater snow and ice discrimination. The scan mechanism lifetime was improved with changes to the lubricating system as well as changes to the motor and bearings used. Satellites relevant to this study include NOAA-9 through to NOAA-16.

5.2.2 Sensor Characteristics, Calibration and Data Acquisition

The AVHRR sensor is a cross track scanning system similar to the VHRR system found on the ITOS series of satellites (Goodrum *et al,* 2000). NOAA-6 through NOAA-14 images the earth in four (NOAA-6, -8, -10) or five (NOAA-7, -9, -11, -12, -13, -14) channels depending on the satellite. The sensors image the visible, near-IR and thermal portions of the electromagnetic spectrum (Kidwell, 1998). The AVHRR/3 sensor flown onboard the NOAA-KLM series of satellites (NOAA-15, -16, -17, -N, N') images the earth in six channels (see table 4.1), three in the visible and near-IR and three in the thermal portion of the electromagnetic spectrum, with effective wavelengths around 0.63 micrometers (channel 1), 0.86 micrometers (channel 2) and 1.6 micrometers (channel 3A). The three remaining thermal channels are located in the atmospheric window regions in the infrared with wavelengths centred on 3.7 micrometers (channel 3B), 10.8 micrometers (channel 4) and 11.5 micrometers (channel 5) (Goodrum *et al,* 2000). While the satellite boasts six channels only five of the channels image at any one time of the day or night. Channels 3A (day time) and 3B (night time) are switched on and off depending on the time of day (Goodrum *et al,* 2000). All six channels are registered to measure the same place on earth at any one time. Signal amplitude of all channels is calibrated to measure radiance within each scene (Goodrum *et al,* 2000). Radiometric resolution is 10 bit, effectively giving an NDVI image 1025 classes (2^{10}) (Roderick *et al,* 1996). The Instantaneous Field of View (IFOV) at nadir is approximately 1.1 km^2 or 1.4 milliradians for a nominal altitude of 833 km. (Lillesand and Kiefer, 2000).

Table 5.1, Spectral Characteristics of recent versions of the AVHRR sensor (NOAA polar orbiters guide and KLM users guide)

Channel #	**TIROS-N**	**NOAA – 6, -8, -10**	**NOAA – 7, -9, -11, -12, -14 (-ATN)**	**NOAA –13**	**NOAA-KLM**	**IFOV (mr)**
1	0.55 – 0.9	0.58 – 0.68	0.58 – 0.68	0.58 – 0.68	(1) 0.58 – 0.68	1.39
2	0.725 – 1.10	0.725 – 1.10	0.725 – 1.10	0.725 – 1.10	(2) 0.725 – 1.0	1.41
3	3.55 – 3.93	3.55 – 3.93	3.55 – 3.93	3.55 – 3.93	(3A) 1.58 – 1.64	1.51
4	10.5 – 11.5	10.5 – 11.5	10.3 – 11.3	10.3 – 11.3	(3B) 3.55 – 3.93	1.41
5	Channel 4 repeated	Channel 4 repeated	11.5 – 12.5	11.4 – 12.4	(4) 10.3 – 11.3	1.30
NA					(5) 11.5 – 12.5	1.30

Calibration of the visible sensors is preformed prior to launch. The procedure involves the use of an integrating sphere as a source of illumination with a variety of 45-W and 150-W lamps mounted in a ring pattern (Goodrum *et al,* 2000). The integrating sphere is then used to illuminate the AVHRR sensors at various levels. The level of illumination is varied for different channels. Illumination levels used for calibration of channel one include 25 different levels of albedo or brightness. Channel

2 has sixteen levels and channel 3A is calibrated using eleven levels of illumination. Three thousand six hundred measurements are taken for each illumination step and converted to 10-bit digital counts. These digital counts are used to calibrate the channels. Pre-launch calibration results are provided in the form of a simple linear regression relationship between the measured AVHRR/3 (C_{10}) signal and the albedo of the integrating sphere (A) as shown in equation 4.1.

$$A = SC_{10} + I \tag{5.1}$$

The use of pre-launch calibration results will return the albedo value in percent under the assumption that pre-launch calibration is valid in orbit. Unfortunately no in-flight post-launch calibration occurs, prior experience gleaned from the TIROS-N series indicates that sensors will degrade in orbit. With the absence of on board calibration devices for the visible sensors, other methods are used. Calibration techniques developed by Rao and Chen (1995) for the TIROS-N series has been adapted to be used with the AVHRR/3 sensor.

Radiometric data are available at various resolutions depending on user needs (Campbell, 2002). The present study used the Local Area Coverage (LAC) data. This data are stored onboard and transmitted to a receiving station when the satellite is in the direct line of site of the station. NOAA and NESDIS (National Environmental Satellite, Data and Information Service) run two Command and Data Acquisition (CDA) stations, one on Wallops Island, Virginia and the second in Fairbanks Alaska. Data are recorded and retransmitted via satellite to Suitland, in Maryland, USA. Global Area Coverage (GAC) is also available. This data format is generated onboard using sampling techniques that select every third line of data in the full resolution data set. Four out of every five pixels are used to compute the average value used (Campbell, 2002). GAC coverage provides images with a pixel resolution of 4 km^2 at nadir. Data are also available via High Resolution Picture Transmission or HRPT, this data are continually transmitted at full resolution to ground receiving stations around the world.

5.3 Rainfall Surfaces

The Rainfall surfaces used in the analysis were derived from station data and interpolated to a 0.1° latitude/longitude grid using the *"Conditional Interpolation"* procedure (Hewitson and Crane, 2005). The interpolation technique was initially designed as a tool to create data sets that may be used to evaluate output from global climate models (GCM's). End users of model products consistently need to evaluate model output in terms of the spatial and temporal skill of the particular global climate model being used. The authors identified this as a primary reason for developing a new interpolation technique that did not suffer from problems associated with assumptions made by classical interpolation procedures when applied to precipitation. Methods used in the past (Inverse Distance Weighted, Kriging and Cressman) have over estimated the amount of rainfall, as well as its spatial distribution. Inherent in all interpolation procedures is the distance decay effect that states that the influence of a given station diminishes as one moves away in all directions from that station. When applying this to rainfall data it becomes problematic. Rainfall itself is not spatially continuous and many of the interpolation procedures fail to acknowledge this. Furthermore traditional interpolation procedures fail to include the role that topography plays in the distribution of rainfall, and that inter-station relationships can vary significantly as a function of the prevailing weather system. Thus Hewitson and Crane (2005) developed a procedure that attempts to mitigate the above-mentioned problems.

The procedure is termed *"Conditional Interpolation"* and estimates the spatial distribution of two variables central to the idea that rainfall is a bounded continuum and not a continuous surface. The interpolation technique uses all available information and attempts to mitigate the problems mentioned earlier. The two variables used in the derivation of rainfall surfaces via the *"Conditional Interpolation"* procedure are defined as the *phase* i.e. the spatial distribution of rain / no rain and the *magnitude* of the rainfall event. Hewitson and Crane (2005) argue that a given station response or value is determined by the regional synoptic state of the atmosphere. The conditional interpolation procedure recognizes that point / station observations represent a mixture of synoptic scale forcing shared with other stations in the immediate vicinity. The interpolation procedure derives the surfaces by first generating the phase or spatial distribution of the rainfall, once this has been calculated, the magnitude of the rainfall event is derived and the precipitation surface is created. Self Organising Maps (Kohenon, 1995) are used to classify the various synoptic phases. This form of artificial neural network (ANN's) has recently been introduced to Climatological studies (Hewitson and Crane, 2002). Section 5.6.3 provides an outline of the Self Organising Map procedure as applied in this thesis. Results from tests conducted by the authors indicate that conditional interpolation method derives surfaces that accurately predict the spatial extent of the precipitation field (Hewitson and Crane, 2005).

Rainfall data used in the analysis were extracted from the regional data set described by Hewitson & Crane (2005). Analysis methodologies necessitated the use dekadal (10 day) rainfall surfaces that match both the temporal and spatial resolution of the NDVI data. As discussed in section 5.4.1 the temporal and spatial resolution of the NDVI data are dekadal time steps with a resolution of ~1.1 km. The gridded rainfall data did not match these parameters. Interpolation procedures described by Hewitson and Crane (2005) developed a daily rainfall data set encompassing most of South Africa and Namibia at a resolution of ~10 km. This resolution was maintained as one should always default to the coarsest resolution. Once the NDVI and precipitation data had been windowed and processed to the desired dimensions analysis began.

5.4 Satellite Data Processing

5.4.1 AVHRR

Advanced Very High Resolution Radiometer data were downloaded by the Satellite Application Centre at Hartebeesthoek South Africa via High Resolution Picture Transmission. The data were then processed by the agricultural Research Council Institute for Soil, Climate and Water. Data for the period 1985 to 2003 were processed and calibrated to correct for sensor degradation and inter-sensor changes. Images were geometrically corrected using orbital parameters as well as an automated georeferencing system based on 300 ground control image subsets. Images were projected to the Plate Carree' projection with a resolution of 1 km^2. No atmospheric corrections were performed due to a lack of atmospheric water vapour and aerosol optical depth data. Clouds were masked out using channels one and four and the difference between channels four and five (Wessels *et al.*, 2004). (12)

Upon completion of the geometric and radiometric corrections daily Normalised

Difference Vegetation Index images were computed (see Chapter 4, section 4.2.1). These daily images were converted to 10-day composites using the Maximum Value Compositing technique (MVC) (Holben, 1986). The MVC technique takes the maximum NDVI value within a given time period and uses this pixel as the representative value for the previous 10-days. The method minimizes the effects of the atmosphere, scan angle and cloud contamination (Holben, 1986). Data used in the analysis were derived from NOAA - 9 through NOAA - 16. MVC NDVI images, for the period 1985 – 2003, were extracted from the ISCW archive. The data were not complete with several time steps either missing or of poor quality. Most notably, due to a fault on NOAA-13, no data were available for the year 1994. Missing data did not significantly impact the analysis. NDVI images were provided as 8-bit grey scale images in the Georeferenced Tagged Image Format (GEOTIFF). The resolution of the NDVI data was rescaled to match the precipitation data (10km^2). Chapter 4 outlined the derivation of vegetation indices as well as examples of research performed using remotely sensed data for vegetation change analysis and land degradation.

5.5 Methodologies

A core objective of this research is to identify *"zones of potential critical change"* in the Succulent Karoo biome of South Africa. Vegetation undergoes seasonal changes brought about by changes in climatic conditions (Roberts, 2002). This is a primary characteristic of vegetation phenology in any xeric or mesic environment (Woodward, 1986). The research seeks to use this response to identify areas where variance in the NDVI seasonal signal cannot be explained by rainfall. Data are analysed using several statistical analyses, designed to answer key questions that address both the spatial and temporal characteristics of vegetation growth within the biome as well as the relationships that exist between precipitation and vegetation growth. Firstly, the use of both NDVI and interpolated rainfall data in any statistical analysis necessitates the investigation of the spatial nature of seasonal vegetation growth. The question being, *where is seasonal vegetation change homogenous?* Secondly, *what is the seasonal nature of NDVI in the Succulent Karoo?* Finally, characterising the relationship between rainfall and vegetation growth is of utmost importance. Identifying when and where this relationship exists and is strongest necessitate the use of a classification algorithm that can handle the non-linear nature of rainfall and vegetation growth in the biome. Therefore, the final question posed is, *when and where is the relationship between rainfall and vegetation growth strongest?* Answering these questions using the above mentioned data would lead to a better understanding of the nature of intra-seasonal vegetation change in the Succulent Karoo. Sections 5.6.1, 5.6.2 and 5.6.3 describe the techniques used in the analysis of the NDVI and precipitation data. Figure 5.1 provides a graphical representation of the relative role each method plays in answering the research question posed in chapter one.

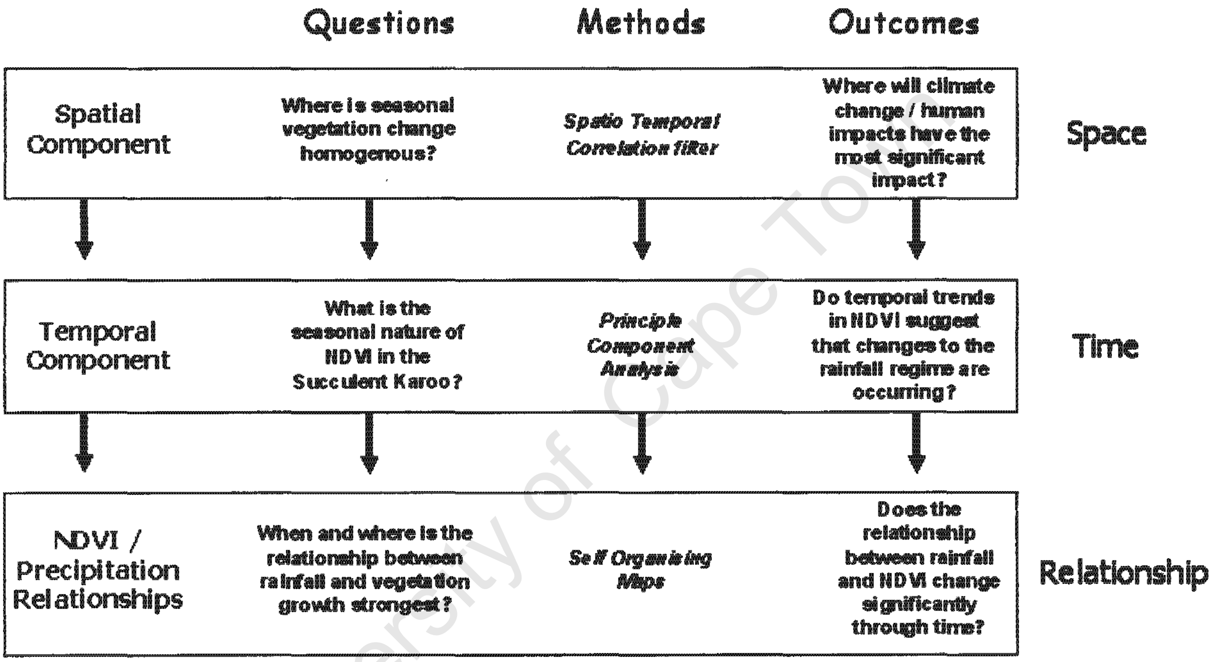


Figure 5.1, Figure describing the functions of analysis methodologies

5.5.1 Spatio Temporal Correlation Filter

When using rainfall surfaces in conjunction with NDVI data in any statistical analysis, results do not take into account local scale factors such as irrigation, topography or large river systems. Precipitation events in the Succulent Karoo biome are largely driven by weather systems associated with Westerly Waves (Tyson and Preston-Whyte, 2000). Thus rainfall is mostly non-convective in nature. This is important, as the cold fronts that bring the rain during the winter months are not localized events. Large areas receive their rainfall at much the same time. Given the nature of precipitation one would expect vegetation to respond in a fairly homogenous way. This, is however not the case, local scale factors such as agriculture, topography, large river systems and various land use types affect vegetation growth. Therefore if we want to perform any sort of meaningful statistical analysis using NDVI and Interpolated rainfall data we first need to determine the impact of local scale factors.

Time Series Analysis of the 14-year data set employed a Spatio Temporal Correlation Filter (STCf). Of interest is how a given pixel changes in relation to the pixels in the immediate vicinity. The method was applied to the NDVI data only, no rainfall data were used in the STCf analysis. A method was developed whereby a STCf was applied to the NDVI data. The filter calculates the Pearson Correlation Coefficient of the centre pixel through time with the surrounding NDVI pixels (3x3 kernel), returning effectively 8 correlation values for each group of pixels. The mean correlation value for the window is then assigned to the centre pixel in a new image. The filter then moves on and performs exactly the same operation on the adjacent pixel, much the same way a normal spatial filter would work. The rationale is that areas returning strong correlations are both spatially and temporally homogenous in terms of their particular response to atmospheric moisture. Two kernel sizes are used namely 3X3 and 5X5. The reason for using both sizes was to be able to perform the analysis at two separate resolutions namely 9 km and 25 km. Classes are defined in this manner as means of representing various levels of spatial correlation, thereby mapping the statistical correlation of both temporal and spatial seasonal vegetation change.

The analysis is stratified according to predefined seasons, namely December, January and February (DJF); March, April and May (MAM); June, July and August (JJA) and September, October and November (SON). The entire NDVI dataset is also processed using both kernels. Correlation results are extracted according to strength of the correlation. Four classes were created and plotted in a GIS (ArcGIS 8.3). Each of these classes represented a range of correlation values, Class 1 (<0.91), Class 2 (0.9 – 0.71) Class 3 (0.7 – 0.51) and finally Class 4 (0.5 - -0.5). Classes are defined in this manner as means of representing various levels of spatial correlation, thereby mapping the statistical correlation of both temporal and spatial seasonal vegetation change.

5.5.2 Principle Component Analysis (PCA)

Principal component analysis is a long-standing statistical technique used in many types of data analysis. PCA linearly transforms an original set of correlated variables into a smaller set of uncorrelated variables. At its most basic PCA attempts to understand, extract, and reduce the underlying dimensionality present in a data set. This is achieved by taking a set of correlated bands and linearly transforming them into a new set of uncorrelated bands, with each successive band explaining less and less variance in the original data set (Eastman and Faulk, 1992). The linear transformation uses a correlation matrix to derive the Eigenvalues and Eigenvectors (Eastman, 1996). While a covariance matrix has been used in the past, Eastman and Faulk (1992) report that using standardized components (correlation matrix) is far more effective at identifying significant change events in a large temporal data set. The transformation is achieved by rotating the axes of the original data set, using the Eigenvalues and Eigenvectors such that, the new origin and axes maximize the variance around the new axis. The first component is calculated and explains most of the variance in the data set. The second component is orthogonal to the first component and explains less of the variance in the data set. Successive components in a PCA analysis explain less and less variance until only noise is left. In the context of this thesis, PCA is used to detect change or trends through time and will identify any temporal / seasonal changes that may be attributed to a climatic change associated with global warming. Alternative trend analyses do exist and include Regression trend analysis (Fuller, 1998, Jin and Sader, 2005), autoregressive-moving average linear models (Piwowar and LeDrew, 2002) and Fourier models (Moody and Johnson, 2001). PCA was chosen for this particular analysis for the following reasons. Firstly, the method has been utilized by various authors for trend analysis and change detection (Eastman and McKendry, 1991; Eastman and Faulk, 1992, 1993; 1996; Jury *et al.*, 1997; Shabanov *et al.*, 2002). Secondly given that most remote sensing packages have PCA modules, which makes the analysis fairly easy to perform and finally results from several research papers have indicated that the method is sensitive to extreme climatic events such as droughts (Eastman *et al.*, 1997) and El Nino (Anyamba and Eastman; 1996).

Common uses of PCA include the reduction of data or data compression (Jensen, 1996). In many cases a data set may contain redundant data that is repeated or not needed. Jensen (1996) uses the example of a set of seven Landsat Thematic mapper bands. While each band may image and collect data in different portions of the electromagnetic spectrum, data duplication occurs, especially in the visible and infrared bands. PCA is used to reduce dimensionality and compress data from seven bands to three or four. Thus reducing the size of the data set and only retaining relevant data. Other uses of PCA in remote sensing include reducing the dimensionality of hyperspectral data sets such as MODIS or AVIRIS. Lee *et al* (1990) use a modified PCA transformation for data compression and noise reduction, in a 64-channel hyperspectral image. Again the sheer size of the data set and number of spectral bands means that data redundancy and duplication occur throughout the 64 channels.

The technique has been used extensively as a means of exploring the underlying dimensionality of NDVI time series imagery. Using PCA, authors have identified various seasonal phenomenons' in temporal NDVI data sets. These include: overall greenness, seasonality, sensor degradation, African Land-cover classification and even ENSO signals. Tucker *et al* (1985) used PCA for land cover classification in Africa. Their method used a covariance matrix of the spectral information. While they only used eight images, comprised of three-week composites, results indicated that component one had near equal Eigenvector weightings for all dates, the second component showed a quasi-sinusoidal structure with negative and positive values corresponding to wet and dry seasons in both African hemispheres (Tucker *et al*, 1985). Eastman and Faulk (1992, 1993) and Eastman and McKendry (1991) used PCA for time series analysis of temporal NDVI data. Their method used Standardised Principal Components as a change detection technique. Building on this work Eastman *et al* (1997) identified the spatial dimensions of drought precursors involving ENSO-related droughts in Southern Africa, again using PCA. Anyamba *et al* (2001) used temporal NDVI data to analyse NDVI anomalies over Africa during the 1997 / 1998 ENSO event. The methods used by the above mentioned authors are replicated in part in this thesis. All of the above mentioned authors utilise either monthly or annual NDVI images in their respective analysis. This research, however, is more ambitious as it uses dekadal (10 day MVC NDVI) images. Furthermore the above-mentioned authors used the IDRISI software package. Due to limits set in the afore-mentioned package it could not be used in this analysis (IDRISI only allows the analysis of up to 256 images). The author chose the ENVI 4.1 software package as there was no limit on the number of bands and the relevant Eigenvectors used to create the factor loading graphs are provided as part of the analysis output.

5.5.3 Self-Organising Maps (SOMS)

SOMS are an application of artificial neural networks (ANN), first introduced by Teuvo Kohonen (1995, 1997). They are primarily used in identifying recurring patterns in data sets using an unsupervised classification algorithm. Self Organising Maps have the ability to learn and train themselves without external help, hence the name Self Organising Maps (SOMS). The system is based on what is known as competitive learning where output nodes compete with one another to become the best matching node for data occupying a particular region of data space (Kohonen, 1997). SOMS provide an easy way to analyse and visualize high dimensional data on a two-dimensional array of points (Crane and Hewitson, 2003), representing a set of best features for approximating the underlying distribution of the input data.

A number of authors have used SOMS for various applications. Hewitson and Crane (2002) used SOMS to describe the multi-dimensional distribution function of a gridded sea-level pressure data set for the northeastern United States. They found that the SOM identified primary features of synoptic-scale circulation. Crane and Hewitson (2003) used SOMS to combine individual station data into a regional data set. They used the SOM to identify common regional variability from a locally forced precipitation data set. The SOM combined stations with common precipitation characteristics, thereby identifying precipitation regions that are temporally consistent at various spatial scales. Furthermore, Crane and Hewitson (2003) used a variation of the SOM to identify temporal modes in the precipitation record; these modes were then used to fill missing data in the station observations. Hewitson and Crane (2005) have also used SOMs in the derivation of a gridded area average daily rainfall data set.

Ji (2000) compared three classification techniques for land cover classification, the analysis included maximum-likelihood (ML), Back Propagation (BP) and the Kohonen Self-organizing Feature Map (KSOFM). The author reports that the KSOFM technique outperformed both the BP and ML and that if neighbouring pixels are taken into account, the classification accuracy increased. Luo & Tsang (2000) also use self-organizing feature maps for land cover classification using Multi-Spectral SPOT imagery, utilizing a three-stage approach. Firstly a spatial filter is used for multi-spectral feature extraction, secondly a supervised non-parametric self-organizing feature map is used for pattern similarity learning and finally a Learning Vector

Quantization (LVQ) network is combined with the Self Organising Feature Map (as a hidden layer) to classify land cover. The authors also reported that self-organizing maps are a viable alternative to traditional classification methodologies. Oja *et al* (2002) provide a concise bibliography of scientific papers using the SOM algorithm and should be consulted for a more detailed review of SOM's and neural network applications.

As mentioned earlier the SOM is an application of ANN. In essence an artificial neural network has the ability to learn from data using an iterative procedure whereby the algorithm learns or trains itself using parameters set by the user. The process has four components. Initialisation, Competition, Cooperation and finally Adaptation. Given a data set with *N*-dimensions, the SOM, will initially use a vector quantization algorithm (Kohonen, 1995) to place a number of reference / codebook vectors into the high dimensional data space, such that the distribution of these nodes are a good approximation of the multi-dimensional distribution function (Hewitson and Crane, 2002). The user determines the number of points placed into data space. Once these points have been identified they can then be *"trained"*. It is at this point that the competitive nature of the SOM becomes evident.

The nature of the training process is what makes the SOM algorithm so unique. While classical clustering algorithms attempt to place each input variable into a specific class, the SOM algorithm is not primarily focussed on classifying a data set. It merely attempts to place nodes into data space, such that these nodes describe the multi-dimensional nature of a given data set (Hewitson and Crane, 2003). The input nodes are defined by a given reference vector that is equal in dimension to the input data. These nodes are then presented to each of the input data records. The Euclidean distance between each node and data record is calculated. The node with the shortest Euclidean distance is identified as the winning node or best match node. The input node then has its reference vector altered such that the distance between the input data record and the SOM node is reduced. The user determines the amount of movement that takes place. The competitive nature of the SOM is now displayed; nodes are competing with one another to have the shortest Euclidean distance to the input data record (Ritter *et al.,* 1991). Cooperation now takes place between the neighbouring nodes. The winning node has had its reference vector altered such that the Euclidean distance between the winning node and the input data record has decreased. In contrast to other clustering algorithms the nodes in the immediate vicinity of the winning node are also updated and moved closer to the input data record. The distance that the surrounding nodes move is inversely proportional to their own distance from the winning node. The user determines the size and shape of this update kernel. Adaption is clearly evident here as the nodes work together to place themselves in regions where data density is highest, thereby accurately depicting the multi-dimensional nature of the input data set (Hewitson and Crane, 2003).

The SOM algorithm is utilised in the present research to classify the relationship between vegetation growth (NDVI) and precipitation. The non-linear relationship that exists between NDVI and precipitation necessitated the use of a classification algorithm that is able to deal with high dimensional data. Input data records in the present analysis are made up of the time series of each pixel in the study area. The time series consists of each of the input variables. The time series begins in February 1985 and ends in November 1999. The variables include NDVI, change in NDVI, concurrent precipitation, concurrent precipitation minus 10 days, minus 20 days and finally precipitation falling 30 days before concurrent precipitation. Each input record is therefore made up of the time series of each of the variables (6X537=3222). A 5 X 6 SOM array was used. The output from the SOM analysis consists of a code vector (COD) file (the final vector of each of the nodes, giving the position in data space) and a file of observation mappings (VIS) giving the node to which each pixel in the data set best maps to, with the associated quantization error). The (VIS) file is used to map the geographical position of each node and the cod file consists of the associated time series of each node. Results were imported into a GIS, with ancillary analysis performed on the time series data. Ancillary analysis included analysing the relationship between NDVI precipitation and temperature data derived from the NCEP reanalysis data set (Kalnay *et al,* 1996).

5.6 Conclusion

Chapter 5 discussed important aspects of this research project. It began with an introduction to the NOAA platform of satellites. These satellites, while primarily built for monitoring synoptic scale weather patterns, have proved extremely useful in studies relating to land surface change, vegetation phenology and degradation / desertification. A brief history of the AVHRR series of satellites highlights the development of the sensor. From the first satellite launched in 1970 to the most recent launched in 2004, the sensor has been the primary source of land surface data for numerous organisations (FEWS, USGS, Safari project etc). Sensor characteristics have remained largely unchanged; the sensor's primary mission is the monitoring of meteorological phenomenon around the globe. The advent of the ATN series (NOAA 8 onwards) marked a move towards an integrated system monitoring land surface radiance as well as earth's radiation budget, ozone concentration and search and rescue instruments. The NOAA-KLM series of satellites include major changes to the platform with the addition of an extra channel used for improved discrimination between snow and ice.

The chapter continued with an outline of the sensor characteristics. The latest series of AVHRR instruments image the earth in six channels, one in the visible three in the infrared and two in the thermal range of the electromagnetic spectrum. Obviously only channel one (visible 0.58-0.68 *um*, red) and channel two (0.725-1.10 *um*, near infra-red) are used in vegetation studies as they are combined to compute the slope-based indices discussed in chapter 4. Derivation of the rainfall surfaces utilizes a pioneering interpolation technique known as "conditional interpolation". This technique is outlined and discussed in section 5.3. Self Organising Maps are used in the interpolation and authors report that the technique is superior to classical interpolation procedures (Hewitson and Crane, 2004). Data pre-processing techniques are central to the undertaking of sound scientific analysis, hence processing techniques used to prepare the rainfall data and the NDVI surfaces are outlined. It should be noted that no derivation of the NDVI values was undertaken, and the data were prepared and processed by the Institute for Soil Climate and Water (Agricultural Research Council) into 10-day MVC composites and provided as 8-bit grey scale GEOTIFF images.

A central theme in this research is to identify *"zones of potential critical change"*; to do this the research has undertaken several methodologies. Each of the methodologies attempts to answer questions posed in the introductory chapter. Section 5.6 outlines the three analysis techniques used. The rationale behind each of the techniques is discussed as well as the statistical techniques employed. Each methodology is outlined giving the reader a sound understanding of the motivation for the technique chosen. The STCf analysis attempts to understand the spatial nature of seasonal vegetation growth in the Succulent Karoo. Principal Component analysis seeks to identify and understand the underlying dimensionality of the NDVI data set, as well as any changes in seasonal trends. Finally, Self Organising Maps (Kohenon, 1995) are discussed. The SOM technique is used in this analysis to classify the relationship between rainfall and vegetation growth. Its characteristics are discussed as well as the underlying methodology.

Chapter 6

Results

6.1 Introduction

Chapter 6 reports results from analyses performed. Analysis methodologies were designed to answer several questions. These questions, and their associated methodologies, were discussed in chapter 5 sections 5.6. A brief overview of the questions is presented first. The analysis using the STCF first sought to determine where seasonal vegetation growth, as a result of precipitation, displayed spatial homogeneity. In other words the analysis sought to find areas that respond to moisture in the same way. The rationale being that areas returning strong spatio-temporal correlations are those areas where local scale factors play less of a role in seasonal vegetation growth and hence are areas where climate change / variability are more likely to impact vegetation growth. Conversely areas that return weak to no correlation indicate that local scale factors are influencing vegetation growth. These local scale factors are predominantly human induced and therefore point towards areas susceptible to human induced degradation. Given that this research is attempting to identify *"zones of potential critical change"* using the relationship between rainfall and vegetation growth as a measure of ecosystem health, it is important to identify where these relationships exist.

Secondly, the PCA analysis is used to determine the seasonal / temporal nature of NDVI in the Succulent Karoo biome. While the biome is generally thought of as a winter rainfall region, rainfall patterns are not clearly defined. PCA of NDVI time series data have, in the past identified various seasonal phenomenon associated with summer winter rainfall dichotomy, general vegetation cover as well as spring and autumn vegetation growth (Eastman and Faulk, 1992). In the present research PCA is used to identify the spatial patterns associated with general vegetation cover, summer winter seasonality and autumn spring seasonality. Associated with these patterns are temporal factor loading graphs that provide insight into the temporal nature of NDVI. The temporal characteristics of NDVI will be used to determine if any long term changes are occurring in the biome. A long term decrease in NDVI would indicate a long term decrease in rainfall as NDVI is widely seen as a proxy measure for seasonal rainfall (Yang *et al.*, 1998; Jury & Weeks, 1997; Wang *et al.*, 2001).

Furthermore the inter-annual variability of rainfall will be reflected in the NDVI signal. Human induced changes will be more difficult to identify as degradation associated with human activities will not necessarily result in reduced vegetation cover.

Finally Self Organising Maps are used to classify the relationship between rainfall and vegetation growth. A method similar to Nicholson *et al* (1990) is used, whereby concurrent NDVI, delta-NDVI, concurrent precipitation, concurrent minus 10 days, concurrent minus 20 days and finally concurrent minus 30 days precipitation are presented to the SOM. The time series of each variable for each pixel in the study area were used as reference vectors in the SOM analysis. Outputs from the analysis are intended to give a better understanding of where and when the vegetation is responding to atmospheric moisture output from the SOM analysis are also subjected to a linear regression analysis with correlation and r-square values used to determine the strength of the relationships present. These strengths will then be used to determine how much variance in the NDVI signal is explained by rainfall. If the relationships are weak and precipitation does not account for NDVI variability then vegetation growth is being influenced by human activities, alternatively if the relationship is strong then climate change is likely to have an impact. Included in the linear regression analysis is an investigation of the relationship between NDVI and temperature for each of the output nodes.

6.2 Spatio Temporal Correlation filter (STCf)

6.2.1 Analysis Design

The STCf analysis was performed at two scales / resolution. A 3X3 and 5X5 kernel was used. Both kernels were applied to the entire data set. The analysis was then stratified to predefined seasons namely, DJF (summer), MAM (autumn), JJA (winter), SON (spring). Again both kernels were used in each of the analyses. Results were imported into a GIS (ArcView 8.3) where correlation classes were defined and mapped with appropriate colour palettes.

6.2.2 3X3 Kernel 1985-2003

Results from the 3 x 3 kernel are shown in figure 6.1. Starting with the entire data set (top left). The correlations are fairly strong throughout the biome. Class 1 (> 0.9) is found on the lowland areas of the biome. Small patches are also found in the

Hantam-Tanqwa-Roggeveld region. Class 1 is largely confined to areas north of the Olifants River and are completely absent in the Little Succulent Karoo. Class 2 (> 0.7) is found throughout the biome but seems to predominate on the high lying areas and areas of rough topography. In terms of geographical distribution class 3 (>0.5) is by far the smallest; it is located in close proximity to areas of no correlation and could be defined as a transition zone between areas of good correlation and weak correlation. Most notably the class is always found in close proximity to rivers. Class 4 is defined as areas where there is little or no correlation between adjacent pixels through time. The distribution of class 4 is associated with large river systems and areas of especially rough topography. Characteristics of the spatial distribution of correlation values derived from the entire 17-year data set are mirrored to some extent in the seasonal groupings.

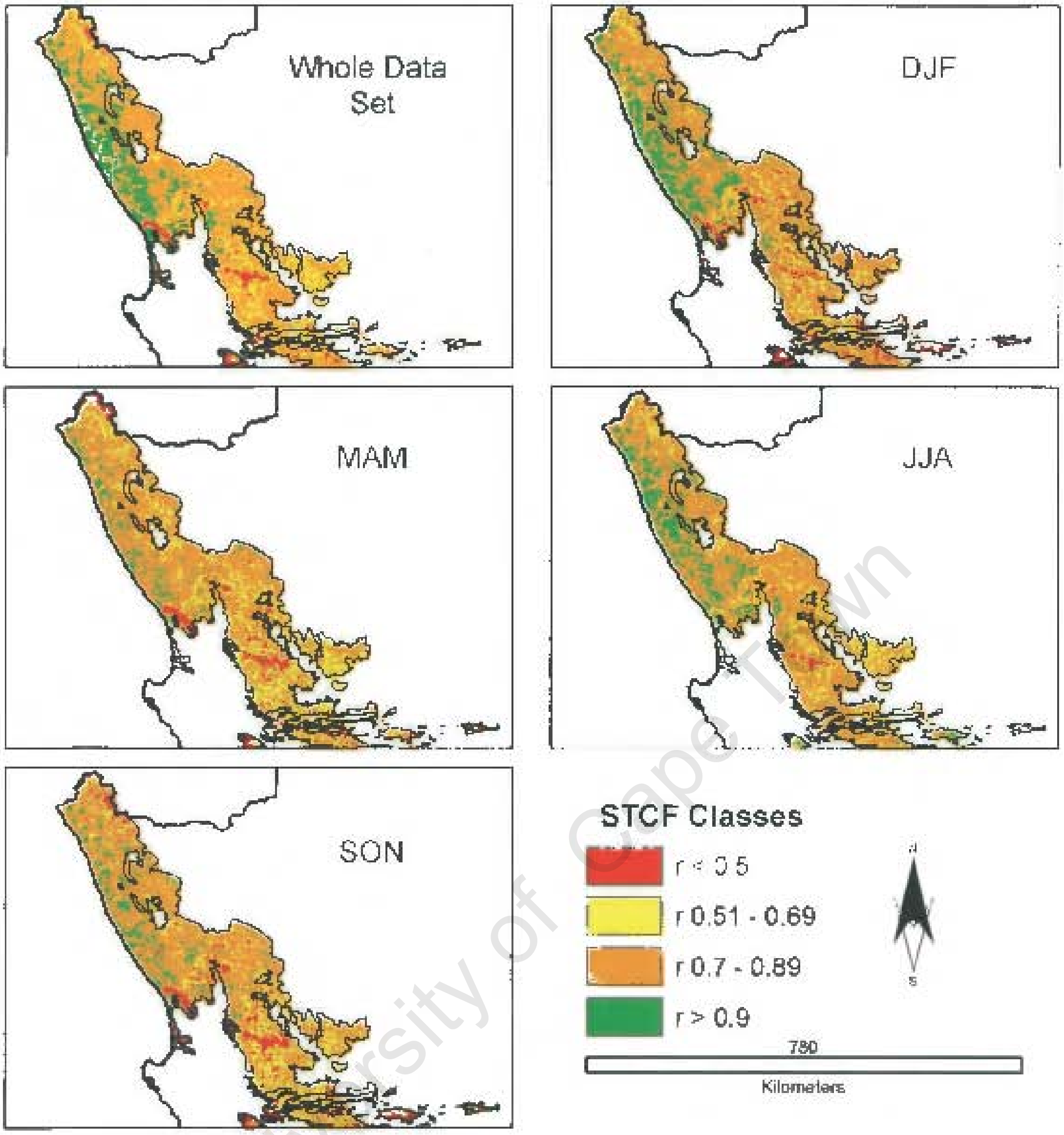


Figure 6.1 Results from STCf analysis (3X3 Kernel)

6.2.3 3X3 Kernel DJF (December, January, February) figure 6.1

The height of summer, desiccating berg winds and high summer aridity characterize this time period (Milton *et al.*, 1997). Some rain does fall, but it is largely confined to small areas either in the north of the biome or in the extreme south. In terms of the geographical distribution of classes, DJF seems to mirror the patterns already seen in the entire data set. Again class one and two dominate, class 1 is however, slightly smaller. Correlations of less than 0.7 (class 3) are once again found in close proximity to rivers, and in turn areas returning little or no correlation. Class 3 is always adjacent to class 4 and therefore also in close proximity to rivers. Additionally class 4 is always associated with large river systems, which is immediately evident looking at the Orange, Oliphants and Tanqwa rivers. These three river systems support large-scale agriculture, supplying water to farms in the immediate areas.

6.2.4 3X3 Kernel MAM (March, April, May) figure 6.1

Correlations returned for the autumn period of March April and May are seen in figure 6.1 (middle left). The regional distributions of correlation mirror the rest of the analysis results. Correlations are however, far lower in areas where class 1 dominated in DJF and the entire data set. Patches of class 1 still exist in the same areas but during this time of the year their areal distribution has decreased. General patterns still exist with class 2 dominating the biome. Class 3 and 4 are still found in close proximity to each other as well as large river systems.

6.2.5 3X3 Kernel JJA (June, July, August) figure 6.1

Most of the rainfall recorded in the biome falls within this period (Desmet and Cowling, 1999). The geographical distributions of classes are similar to previous seasons. Class 1 is once again found mostly on the lowland areas of the biome, but one does find small patches occurring in the Hantam-Tanqwa-Roggeveld region as well as the Little Succulent Karoo. The geographical distribution of class 2 incorporates the entire biome. Classes 3 and 4 have decreased significantly being replaced by class 2. This is especially evident in the areas around rivers, while class 3 and 4 are still found in close proximity to rivers, the areal extent of each class has diminished most notably the area around the Olifants River.

6.2.6 3X3 Kernel SON (September, October, November) figure 6.1

Class distributions for the SON period (spring) are largely the same as previous seasons. Class 1 is confined to low lying areas with small patches in the Hantam-Tanqwa-Roggeveld region as well as the Kamiesberg. A notable feature is that the distribution of class 1, which has become heterogeneous in nature. Class 2 dominates and is once again found in all regions of the biome. Classes 3 and 4 have once again returned to their familiar distribution. Class 4 is now more prevalent in the low-lying areas of the biome with small speckles seen in-between class 1 and 2.

The 3x3 kernel identified interesting trends and patterns within the study area. Variations in class distribution are evident between predefined seasons. Summer and winter, (DJF and JJA) return correlations that are less fragmented than the autumn and spring seasons. Correlations are also far higher on the lowland plains of the biome.

6.2.7 5X5 Kernel

Results from the 5X5 kernel (figure 6.2) are similar to the 3X3 kernel. Correlations are not nearly as strong as the smaller kernel. General geographical patterns are however similar to the 3X3 kernel. Class 1 is largely non-existent and is only seen in the entire data set output and during DJF. When class 1 does it occur, it is limited to the lowland regions of the biome. In all seasons, class 2 dominates the biome. Finally class 3 and 4 enjoy an increase in geographic as well as areal distribution.

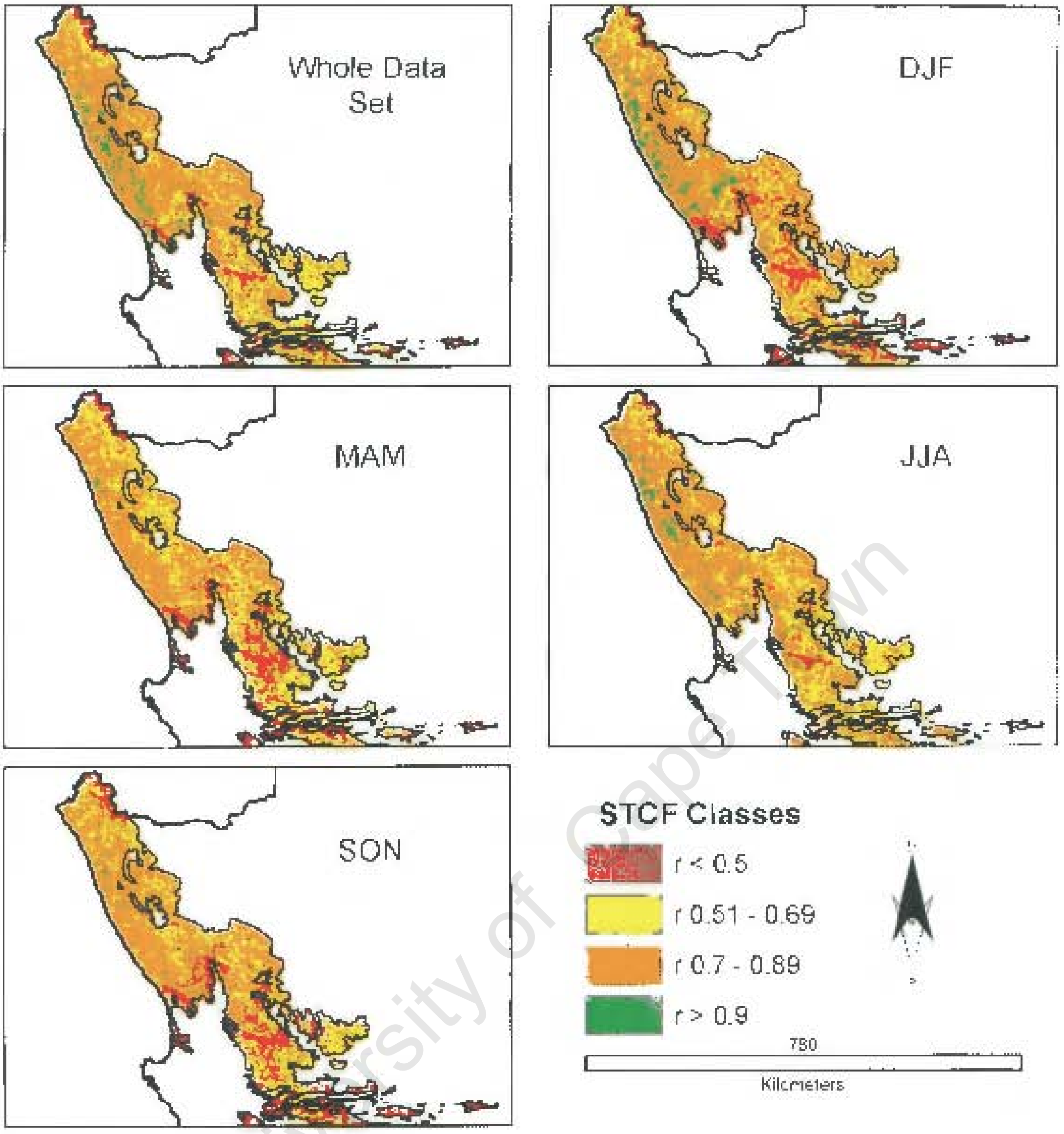


Figure 6.2 Results from STCf analysis (5X5 Kernel)

6.2.8 Ground Truthing / Field Work

Fieldwork / ground truthing was undertaken during March 2004. The fieldwork component of the research confirmed the results discussed above. Four sites were chosen for fieldwork. The sites were chosen to represent each of the four correlation classes mapped in the GIS.

Class 1 was ground truthed around Bitterfontein. This area returned strong correlations in the analysis. The vegetation of the area is largely undisturbed and occurs on the lowland plains of the Knersvlakte and Namaqualand. We therefore attributed class 1 to undisturbed homogenous plant cover. (See figure 6.3 for Geographic location).

Plate 6.1 Photograph taken at stop 2, Bitterfontein Class 1 ($r > 0.9$)

Class 2 was ground truthed in the Kamieskroon area. Elevation is well over 500m with topography being far more varied than the low-lying Knersvlakte. In several places along the road cropping was taking place. This cropping was limited to reasonably flat areas. Shrubs with signs of overgrazing dominated vegetation cover (See figure 6.3 for Geographic location).

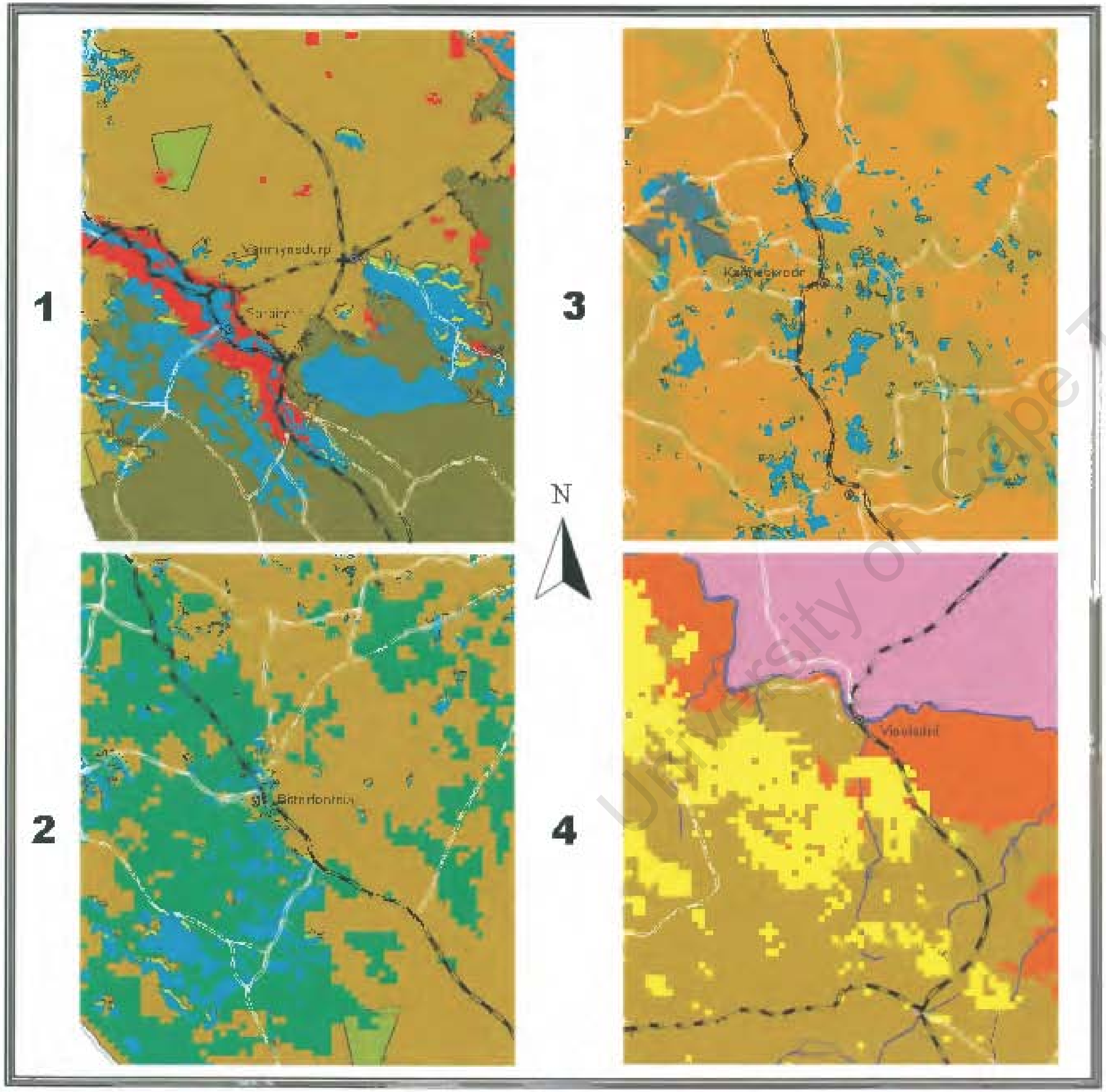
Plate 6.2 Photograph taken at stop 3, Kamieskroon Class 2 ($0.7 < r < 0.9$)

Class 3 was ground truthed south of Vioolsdrift approximately 40 km from the border between South Africa and Namibia. Land cover in this region is extremely sparse with little or no vegetation cover. The area was cropped until the late 1970's and has now been left fallow. (See figure 6.3 for Geographic location).

Plate 6.3 Photograph taken at stop 4, Vioolsdrift Class 3 ($0.5 < r < 0.7$)

Class 4 was ground truthed in the Spruitdrift area just south of Vanrhynsdorp. Here it was observed that the no correlation class was associated with agricultural activities located on the banks of the Olifants River. While large patches of no correlation are found elsewhere we concluded that reasons for the no correlation could be attributed to agriculture associated with large river systems and regions where topography is highly variable. Using spatial data in a GIS we concluded that the spatial distribution of class 4 in other areas was also associated with agriculture alongside rivers (See figure 6.3 for Geographic location).

Plate 6.4 Photograph taken at stop 1, Vanrhynsdorp Class 4 ($r < 0.5$)



Field Work Map

STOP 1

Vegetation Type: Strandveld of West Coast
Succulent Karoo
Fynbos

Elevation: 100m

Correlation Zone: -0,5 -- 0,5

Land use: Cropping and Homogenous Grazing

STOP 2

Vegetation Type: Succulent Karoo
Karoid Broken veld

Elevation: 368m

Correlation Zone: >0.9

Land use: Cropping and Homogenous Grazing

STOP 3

Vegetation Type: Succulent Karoo
Karoid Broken Veld
Mountain Renosterveld

Elevation: 764m

Correlation Zone. 0,7 – 0,9

Land use. Cropping and Homogenous Grazing

STOP 4

Vegetation Type: Western Mountain Karoo
Namaqualand Broken Veld
False Succulent Karoo

Elevation 500m

Correlation Zone: 0.5 -- 0.7

Land use: Homogenous Grazing

Figure 6.3 Fieldwork map

The STCf is used to determine the spatial nature of seasonal vegetation change in the Succulent Karoo Biome. Results from the analysis indicate that the filter is a useful tool for determining where atmospheric moisture drives seasonal vegetation change and where local scale factors such as rivers and irrigated agriculture influence vegetation growth.

6.3 Principle Component Analysis (PCA)

6.3.1 Analysis Design

Temporal analysis of 10 day MVC NDVI images was performed using Principle Component Analysis (PCA). Section 5.6.2 discussed the analysis methodology. The PCA analysis performed here used 10 day MVC NDVI images in the GEOTIFF format. Images were imported into ENVI 4.1 (Research Systems Incorporated) and analysis was performed using standardized principle components (correlation matrix). Six components were extracted along with their respective factor loadings graph. The factor loading graphs provide the correlation between each of the input images and the component being analysed (Eastman and Faulk, 1993), they also shed light on the temporal coherence of the spatial patterns identified in the component images and serve to highlight any long term trends that may be useful in identifying long term trends associated with climate change.

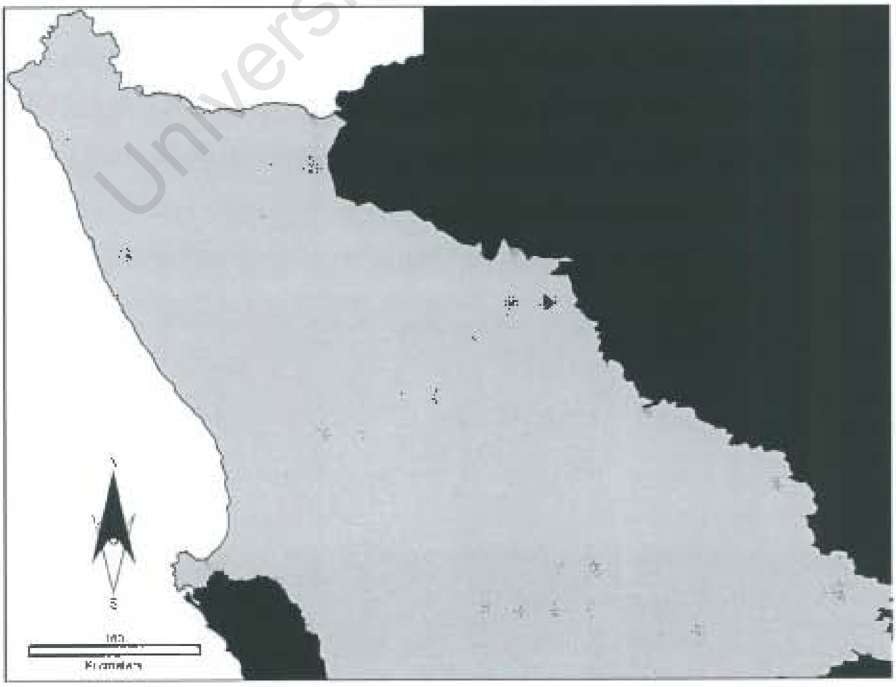
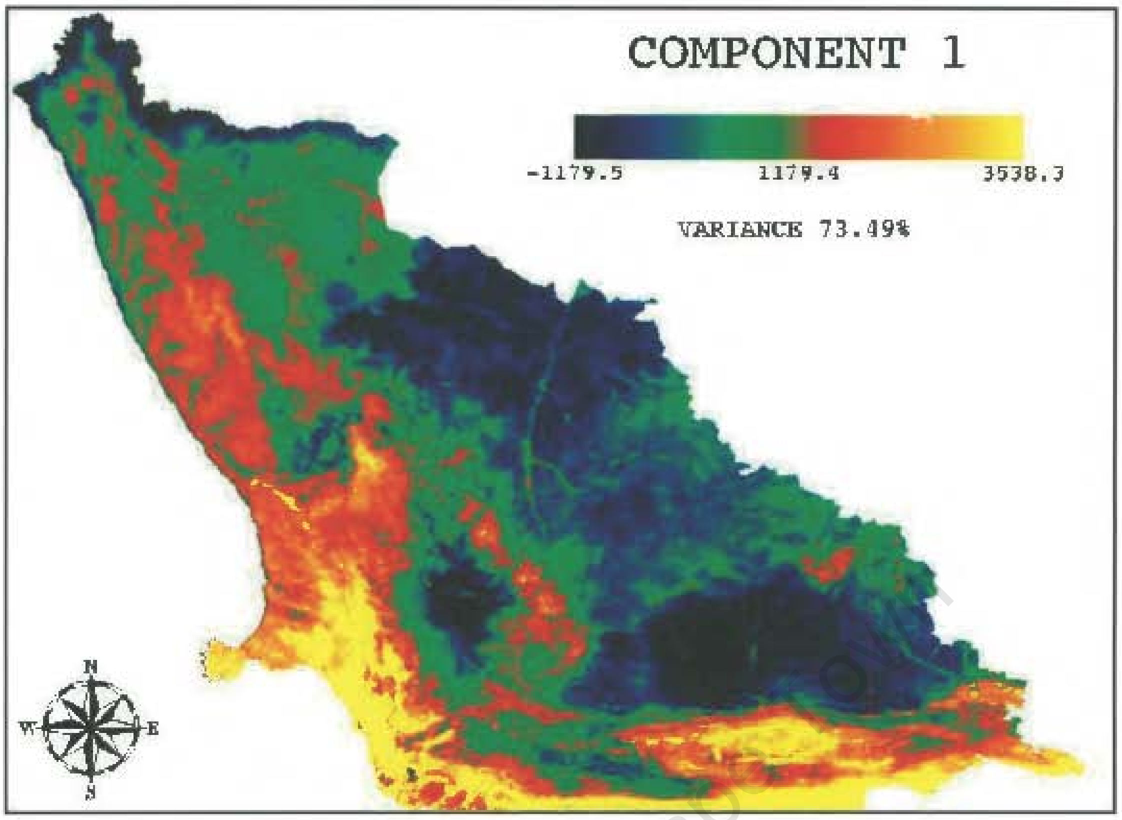


Figure 6.4 Reference Map for PCA analysis

6.3.2 Component One

Component 1 (See figure 6.5 below) represents the characteristic vegetation index for the entire time period. The component explains 73.49% of the variance found in the temporal NDVI data set used. The spatial distribution of NDVI anomalies indicates that component one represents the characteristic vegetation cover integrated over time. The component image also shows that the major element of variability in NDVI is that which occurs spatially i.e. the first change component. The spatial distribution of NDVI anomalies (high values) indicates where, throughout the year, photosynthesis is greatest. Elevated regions of the biome return higher values indicating denser vegetation cover. Low values are clearly seen as dark areas and correspond to regions of known low vegetation cover. The factor-loading graph (figure 6.5) for component 1 reveals that this component represents average vegetation cover and that the temporal correlation is reasonably good except for 1993. During the early months of 1993 correlations are low relative to the rest of the data. The factor loading graph indicates that no long term changes have occurred in the average vegetation cover found within the biome.



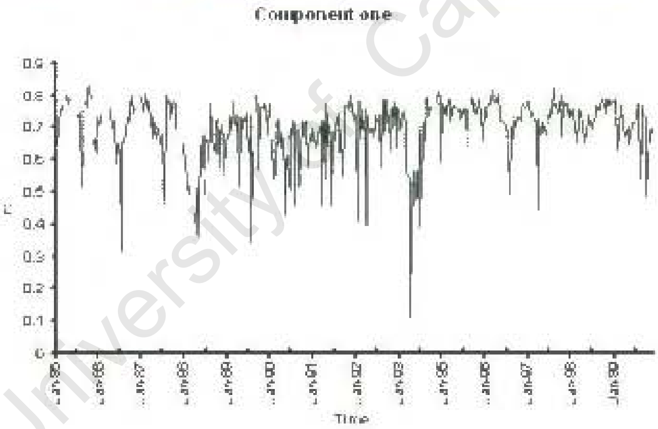


Figure 6.5 Component 1 and Graph

6.3.3 Component two

Figure 6.6 shows component 2 of the PCA analysis. The second component explains 8.34% of the variance found in the temporal data set. NDVI anomalies (high values) are found on the low and high lying areas of the central and northern Succulent Karoo, conversely lower values are found in the southern Karoo. The distribution of NDVI anomalies in component 2 reflects the strong seasonality found in the region. High anomalies are found in areas associated with winter rainfall, while low or negative values are associated with summer convective rainfall regions. The factor-loading graph (figure 6.6) confirms the seasonal nature of component 2 and indicates that the second major element of variability in the region is seasonal rainfall or summer winter rainfall dichotomy. Positive correlations are seen in the winter months of June July and August (traditional winter rainfall period) with negative correlations occurring in the summer months. The factor loading graph does not indicate any long term changes or significant decreases or increases in seasonal vegetation growth or changes to the timing of these growth events.

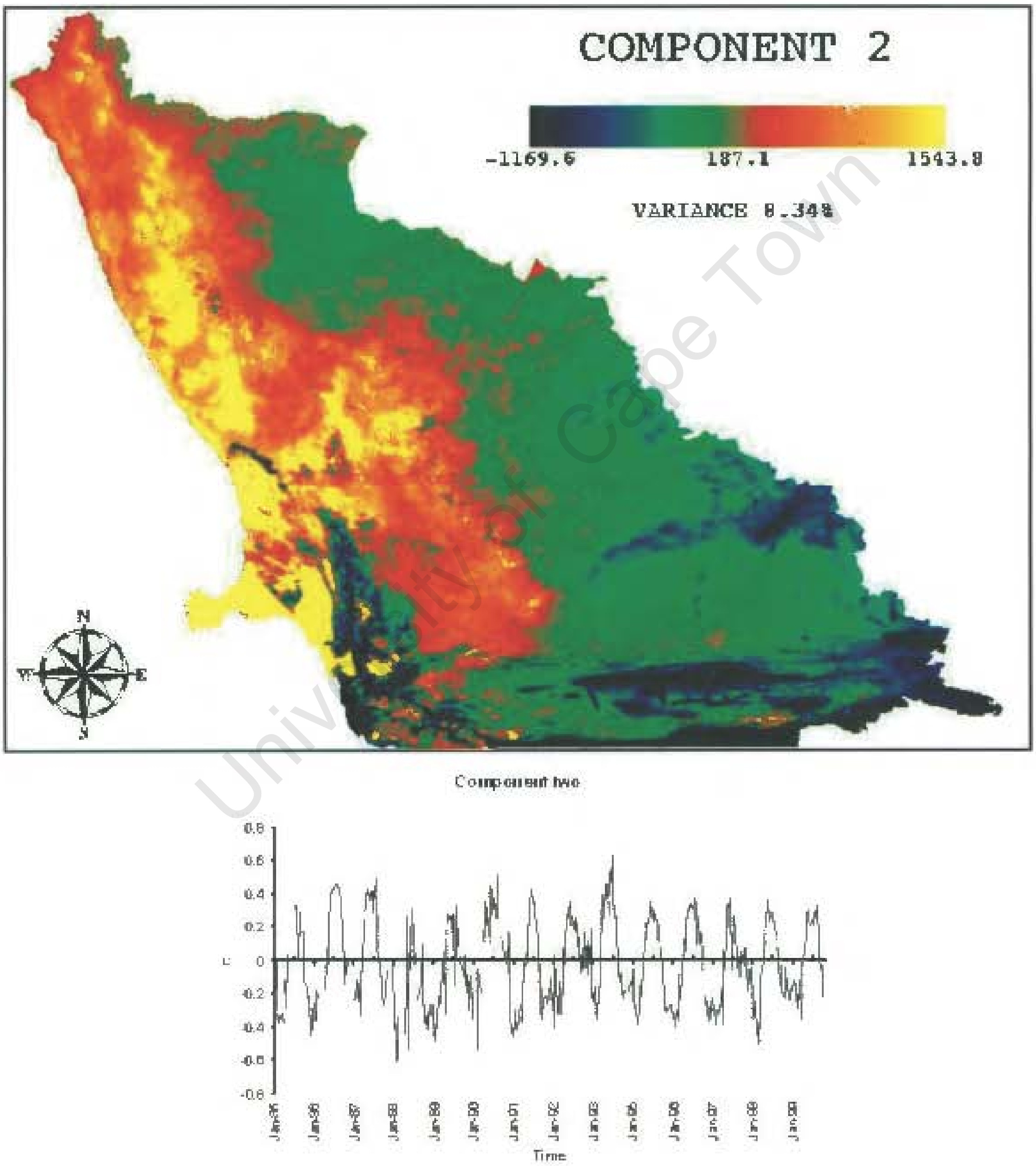


Figure 6.6 Component two and graph

6.3.4 Component three four five and six

While component 1 and 2 are relatively easy to explain components 3, 4, 5 and 6 are a little more difficult to interpret. Component 3 (figure 6.7) explains 1.37% of the total variance in the data set. Positive and negative NDVI anomalies in component 3 reflect a north south gradient, with positive NDVI anomalies found in the northern regions of the biome and low to very low NDVI anomalies in the south. The spatial distributions of NDVI anomalies do not reflect any known physical geographical phenomenon. The factor loadings of component 3's graph (figure 6.7) are also difficult to interpret, while component 1 and 2 returned definitive trends, component 3 does not indicate much in the way of seasonal phenomenon. The major element of variability seen in component 3 may have nothing to do with NDVI and may be related to the satellite system. Component's 4 (1.24% variance), 5 (1.14% variance) and component 6 (0.76% variance) reveal no significant trends or seasonal phenomenon. Likewise, the elements of variability associated with these bands cannot be attributed to any physical element in the biome (Component images and graphs are reported in Appendix A).

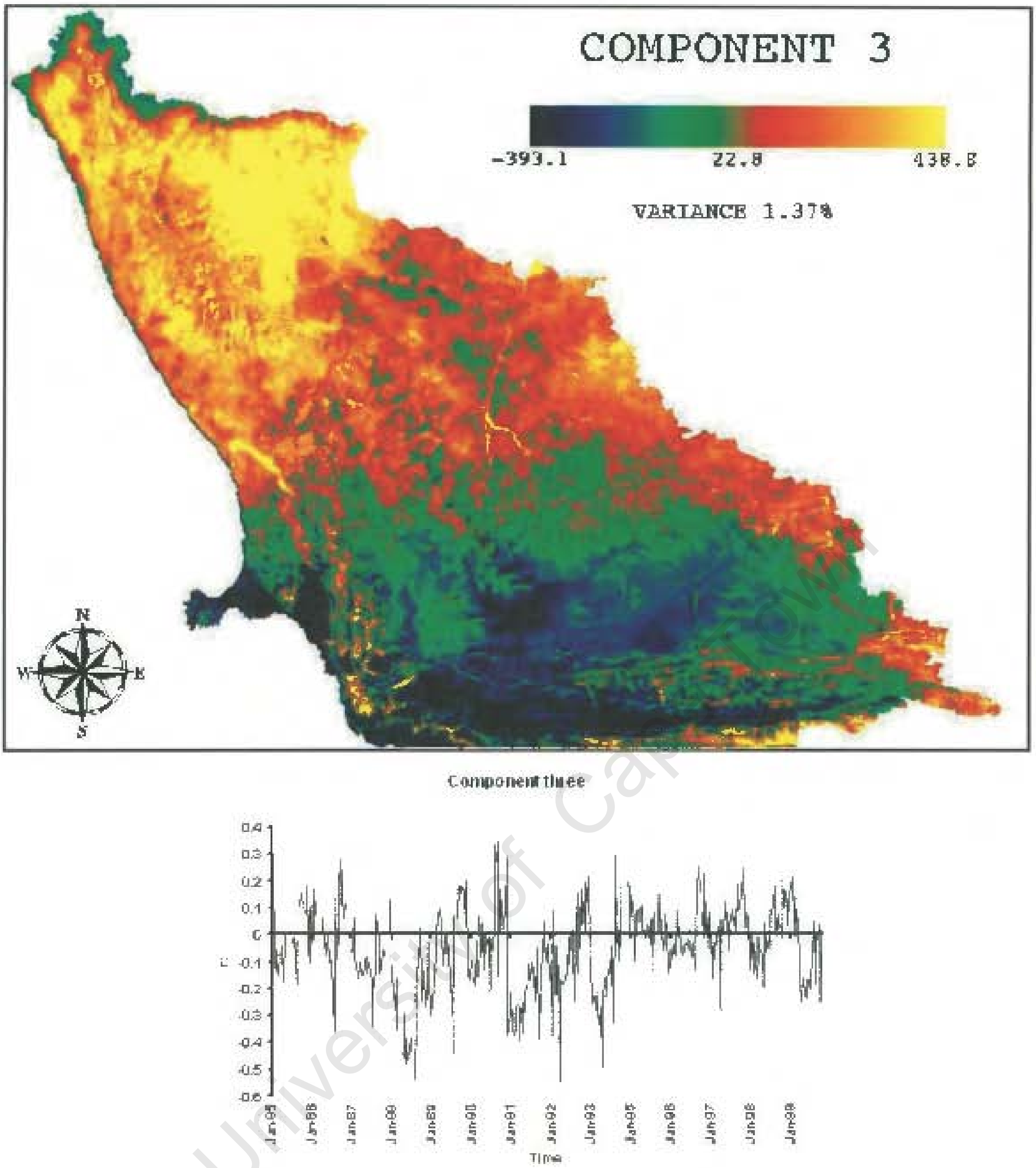


Figure 6.7 Component three and graph

The PCA identified key physical features pertinent to the study of intra-seasonal land surface change. Component images and their respective factor loading graphs highlighted the various change components associated with a long time series of NDVI satellite data. Most notably the analysis could not identify known physical features beyond the second change component. Factor loading graphs indicate that average vegetation cover has not changed during the study period and that no significant changes in vegetation phenology have occurred.

6.4 Self Organising Maps (SOM)

6.4.1 Analysis design

The purpose of the SOM analysis was to classify the relationship between rainfall and vegetation growth. Self-organizing maps provide an effective means of classifying and visualizing large multi-dimensional data sets. In the present research SOMs provide the perfect tool for this classification. SOM input, took the form of a text file made up of 4800 rows and 3222 columns. Each row consisted of the time series of each variable, while each column consisted of the spatial grid for that particular time step. The rows of the text file were used in the SOM as the input vectors. The classification is based on these input vectors. Random codebook vectors, for each node in the SOM array were defined as an initialisation for the subsequent iterative classification procedure or *training* of the SOM. The SOM output was evaluated using the sammon mapping technique (see figure 6.8) to assess whether the SOM effectively captures the span of the data space without topological folding. Once a reasonably good mapping was produced, outputs from the (COD and VIS) files were analysed. The (COD) file contained the reference vectors or final position in data space of each of the SOM NODES. The reference vectors for the NODES represent an archetypical time series of each variable, defined by the position of the NODE in multi-dimensional data space. Each of the variables were then analysed using scatterplots and linear regression, included in the linear regression analysis was temperature. Due to the lack of temperature data at the desired resolution temperature could not be included in the SOM analysis. Instead centroids of each of the Nodes were defined and those that fell within the study area were used to extract 10-day average maximum temperature from NCEP reanalysis data (Kalnay *et al.*, 1996)[1]. Output from the (VIS) file produced the SOM map seen in figure 6.9. This map and the associated scatterplots are the final analysis output. Only NODES whose reference vectors fall within the boundary of the study area (Succulent Karoo) as defined by Low and Rebello (1996). These include Node 0, 1, 2, 6, 7, 12, 13, 14, 18, 19 and 24. See figure 6.9 for a graphical description of the nodes that fall within the boundary of the Succulent Karoo.

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[1] NCEP reanalysis data are currently distributed at a 2.5° resolution. The present study is undertaken at the 10km resolution. The implications of this on the analysis are that the temperature data could not be included in the actual SOM analysis. It could however be included in ancillary regression analysis using nodal centroids.

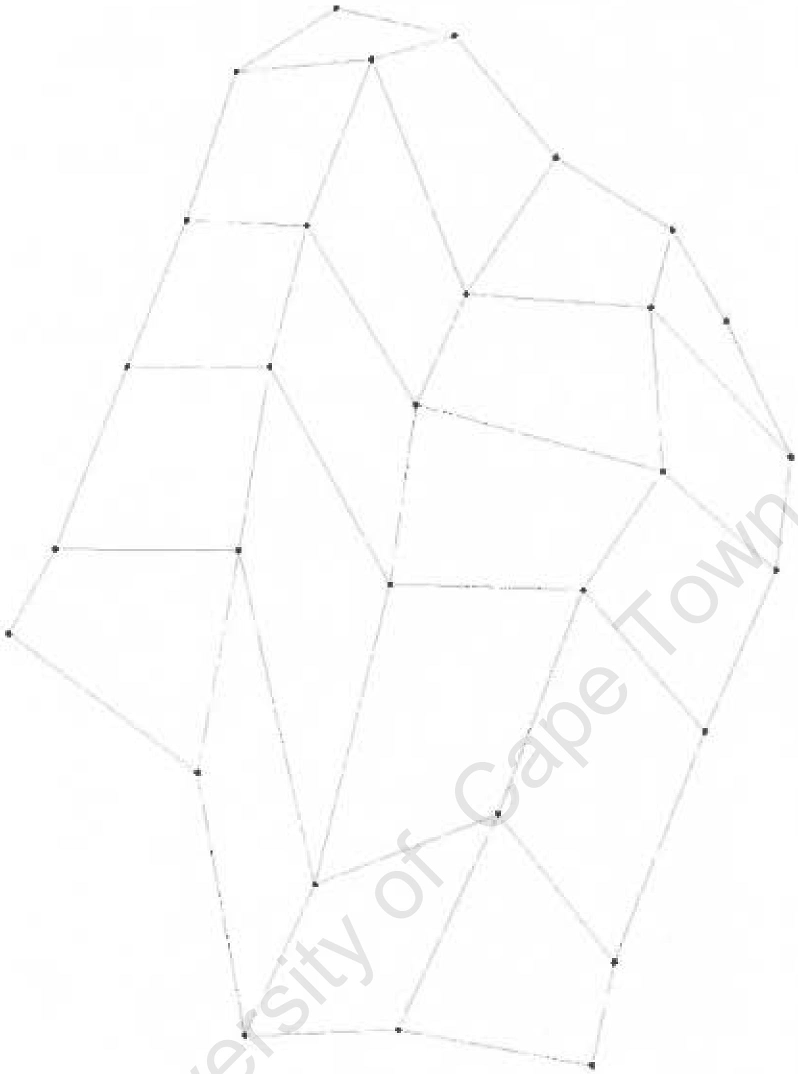

Figure 6.8 Sammon map

Graphical output from the SOM analysis is seen in figure 6.9. The map shows the geographical distribution from the SOM classification. Each pixel within the study area maps to a particular node. Each of these nodes represents a classification of the time series of each of the variables discussed in chapter 5. Nodes falling within the boundary of the Succulent Karoo are discussed. Their geographical distributions as well as associated scatterplots are also discussed. A complete table of correlation (r) values, r-square and variances can be found in Appendix C.

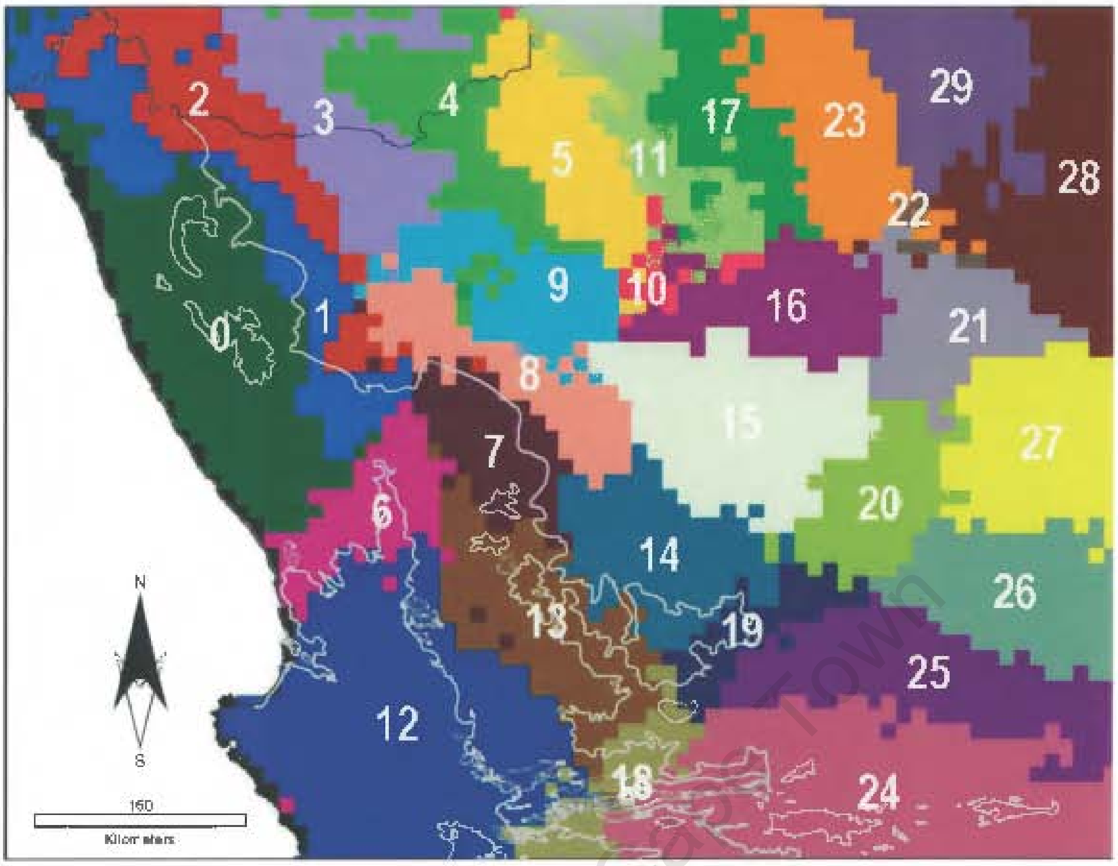

Figure 6.9 SOM output map

6.4.2 Node 0 (Figure 6.9 and Figure 6.10)

The geographical distribution of node 0 is limited to the Namaqualand region including the low-lying plains as well as higher lying regions of the Kamiesberg. Small patches are also seen along the coastline and in the southern regions of Namibia. The Node falls within the winter rainfall region of the biome and may receive much of its moisture in the form of dew and fog. The scatterplots of the SOM variables associated with Node 0 are seen in figure 6.10. The NDVI and precipitation variables return weak positive relationships with r-values of less than 0.3 for all precipitation variables. R-square values are small with variance in NDVI explained by the precipitation variables never reaching more than 6%. While precipitation does not seem to play a major role in vegetation growth, temperature is completely different. The temperature / NDVI scatterplot indicates that NDVI and temperature return moderate negative correlations with 20.48% of the variance in NDVI explained by temperature. This is far higher than precipitation and has important consequences for this research.

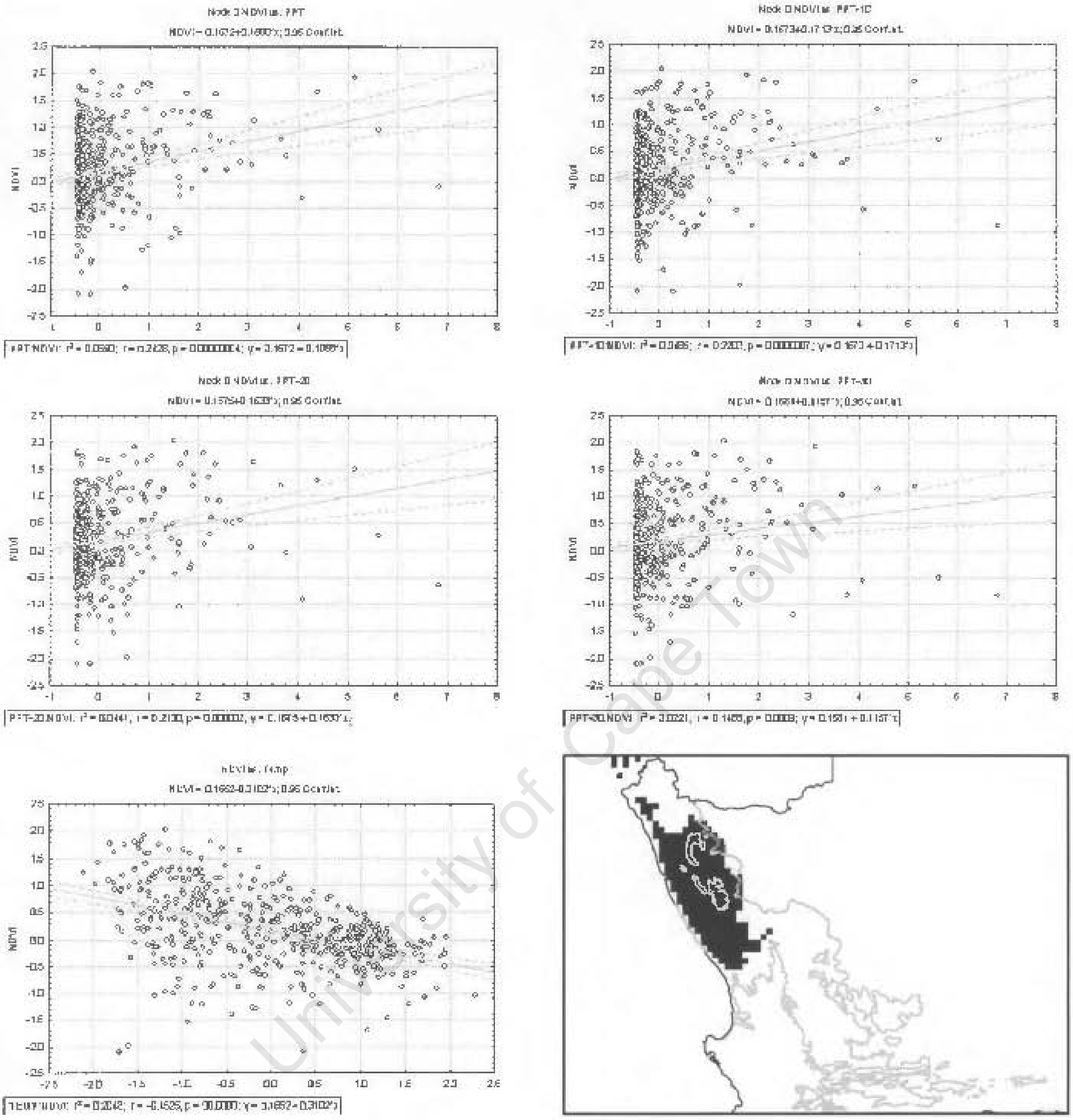

Figure 6.10 SOM node 0 scatterplots

6.4.3 Node 1 (Figure 6.9 and 6.11)

The geographical distribution of Node 1 follows the boundary of the Succulent Karoo and the Nama Karoo biome. The node is also found in the Northern parts of Namaqualand as well as the southern Namibia. The eastern parts of the node may fall within summer or non-seasonal rainfall regimes while the regions to the north of the biome ultimately fall within a winter rainfall regime. The scatterplots of NDVI precipitation variables and temperature are shown in figure 6.11. The relationship between NDVI and all the precipitation variables are once again positive with weak correlations of less than 0.25. On the other hand temperature returns a moderately weak negative correlation with an r-square value of 0.14, explaining almost 14% of variability in NDVI.

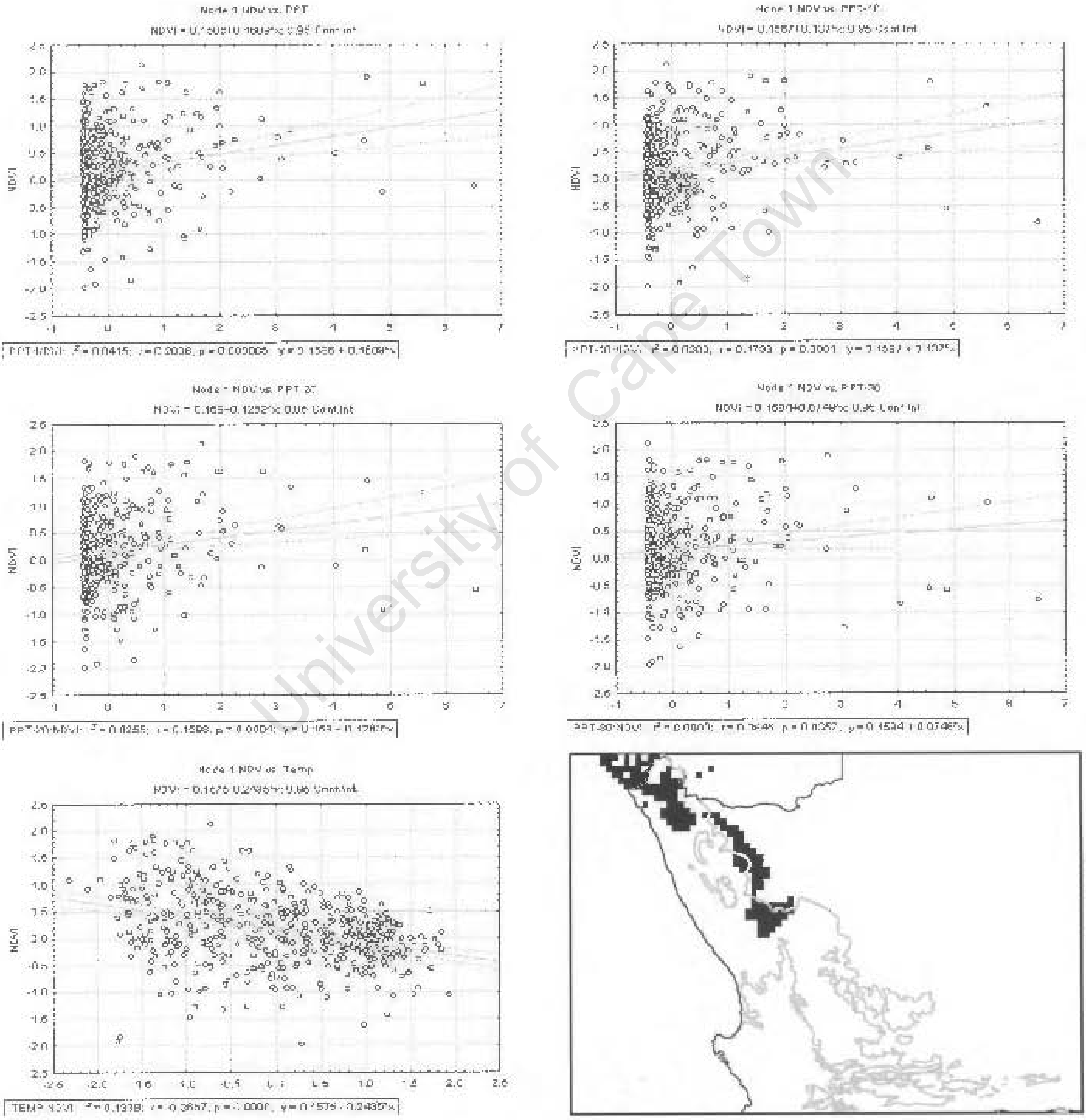

Figure 6.11 SOM Node 1 scatterplots

6.4.4 Node 2 (Figure 6.9 and 6.12)

Node 2 shares a similar geographic distribution to Node 1. In the Succulent Karoo the node occurs in the far northern region of the Richtersveld as well as on the coastline around the town of Alexander Bay. Scatterplots for Node 2 are shown in figure 5.12. Relationships between rainfall variables and NDVI are once again positive but very weak. Precipitation variables associated with node 2 show little relationship with NDVI. NDVI and temperature return a weak negative relationship with temperature explaining only 5% of the variability in NDVI.

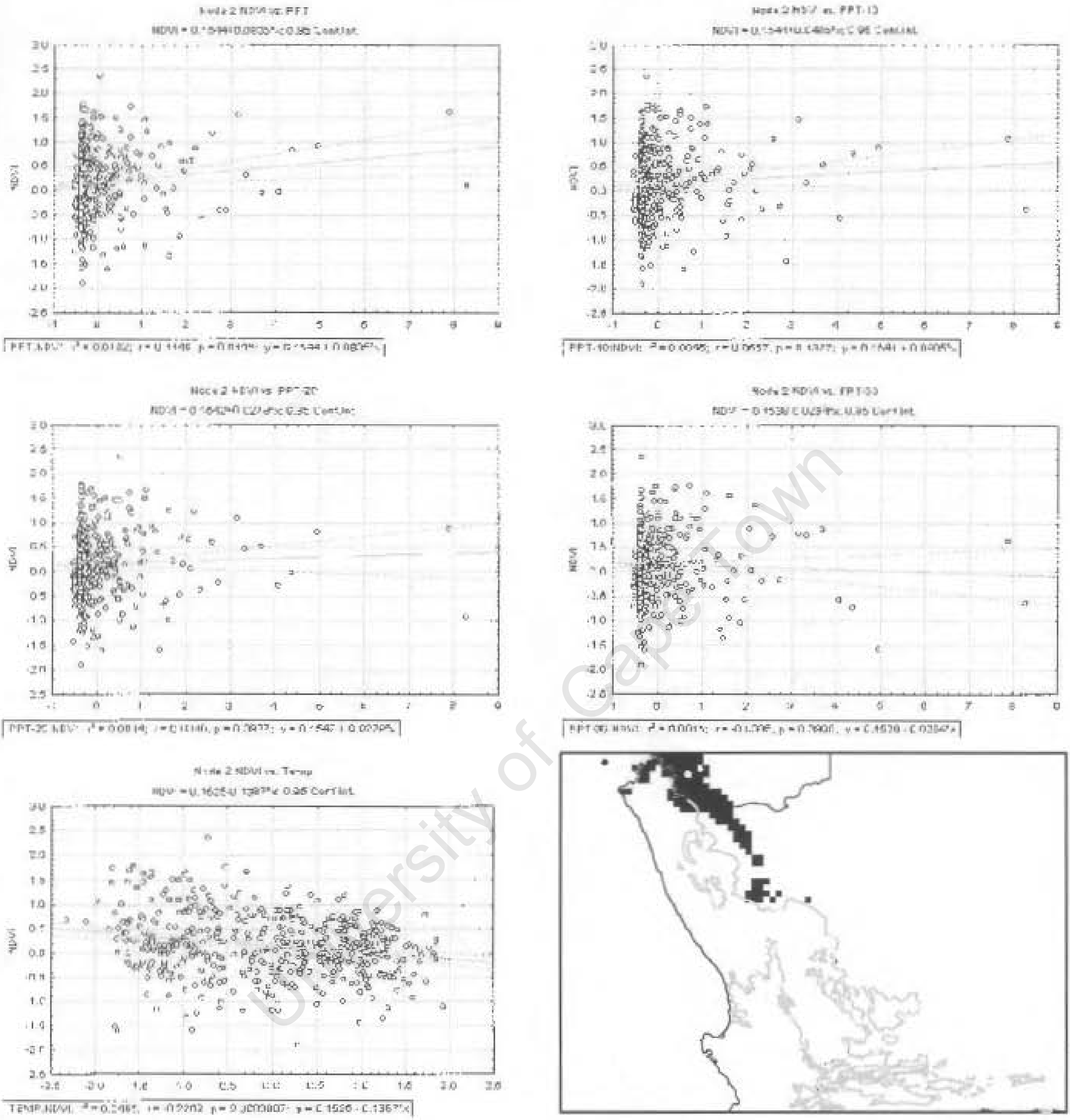

Figure 6.12 SOM Node 2 scatterplots

6.4.5 Node 6 (Figure 6.9 and 6.13)

Node 6 occupies a central region of the Succulent Karoo, which includes the Knersvlakte, Low-land Succulent Karoo and parts of the Bokkeveld. The node falls within the winter rainfall regime. Figure 6.13 illustrates the relationship between NDVI and rainfall as well as temperature. Relationships are once again positive but weak. Correlation coefficients (r) are all below 0.3 with less than 7% of the variability in NDVI explained by precipitation variables. Temperature returns moderately strong negative relationships with 16% of the variability in NDVI explained by temperature.

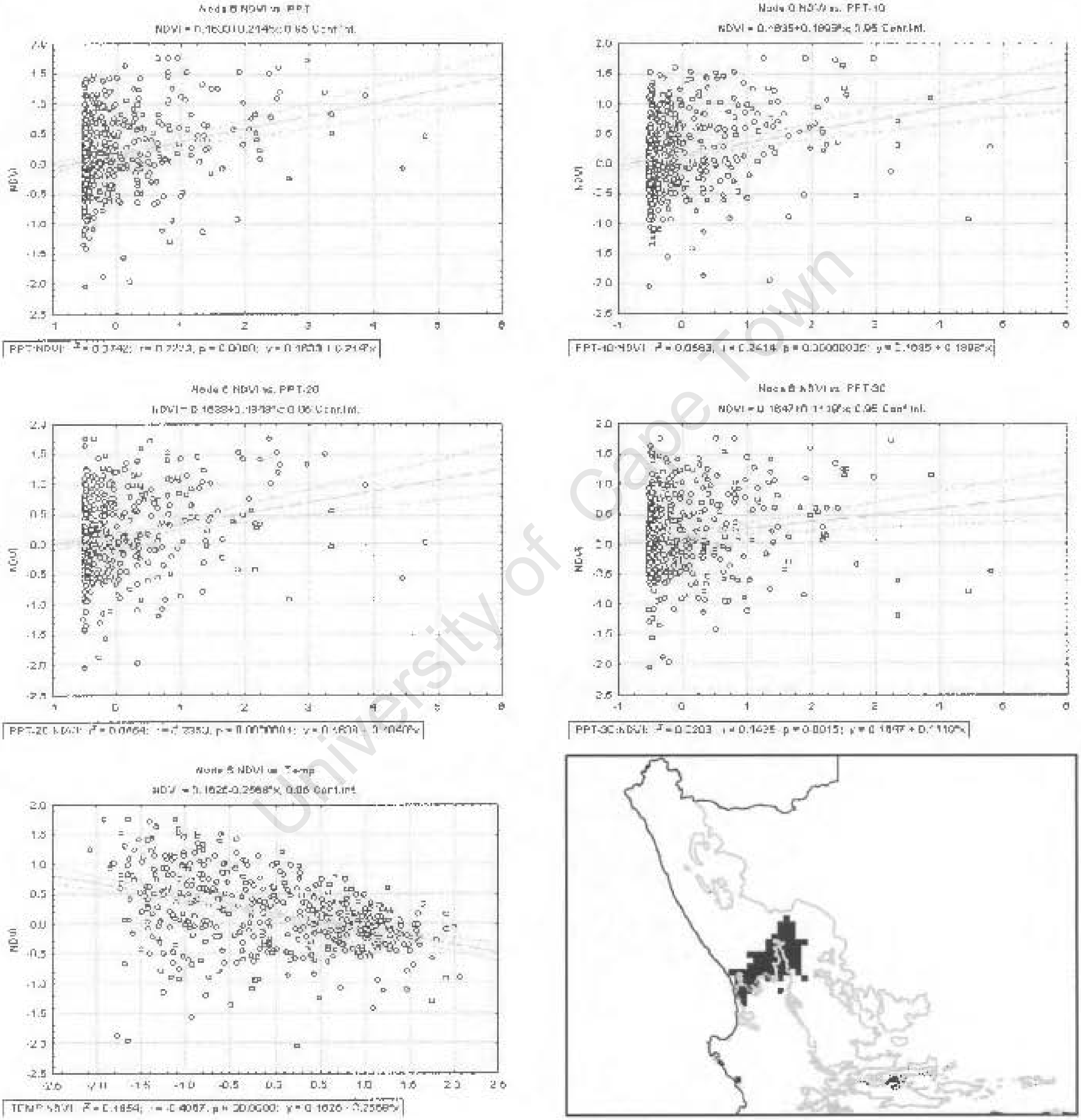

Figure 6.13 SOM Node 6 scatterplots

6.4.6 Node 7 (Figure 6.9 and 6.14)

Node 7 occupies a fairly small region around the town of Loeriesfontein. The node follows the eastern border of the Succulent Karoo. Figure 6.14 illustrates the relationship between NDVI and precipitation and NDVI and temperature. Familiar patterns are immediately evident. Weak relationships exist between NDVI and the precipitation variables used in the SOM analysis. Correlations are weak with the highest r-value of 0.1636. Little or no variance in the NDVI data is explained by any of the precipitation variables. Temperature also returns a weak r-value, but once again this relationship is negative with only 7.04% variability in NDVI explained by temperature.

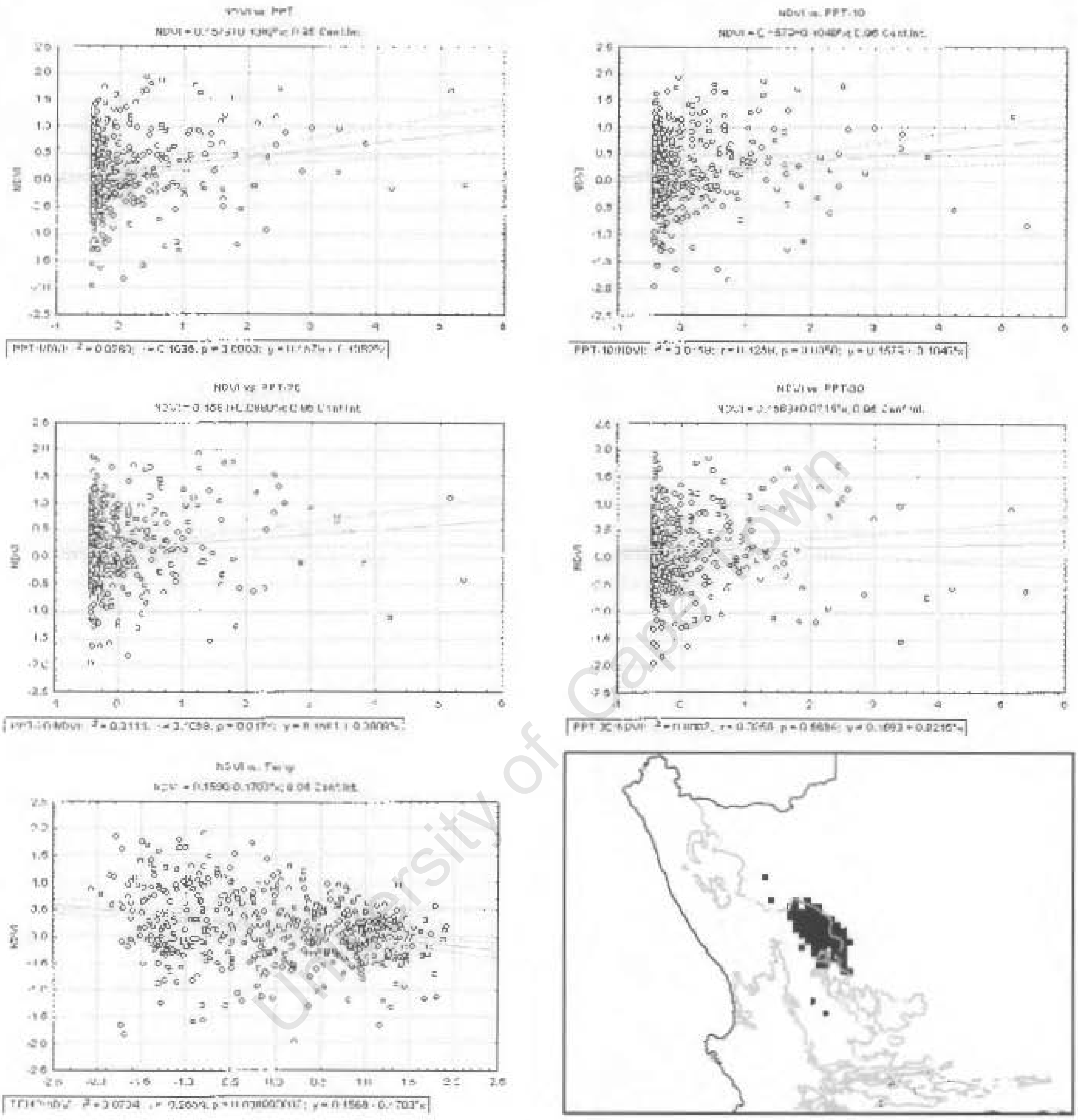

Figure 6.14 SOM Node 7 scatterplots

6.4.7 Node 12 (Figure 6.9 and 6.15)

Node 12 occupies the southern parts of the Hantam-Tanqua-Roggeveld region of the biome. The Node extends from the west coast (Cape Columbine) to the start of the Roggeveld Mountains. The node falls within a well-defined winter rainfall region that includes the Swartland. Figure 6.14 illustrates the relationships between NDVI and precipitation variables used in the SOM analysis. Correlation coefficients returned from Node 12 indicate weak to very weak relationships. Less than 2% of the variability in NDVI is explained by precipitation. Temperature returns a moderate correlation and explains more variability than precipitation (11.93%).

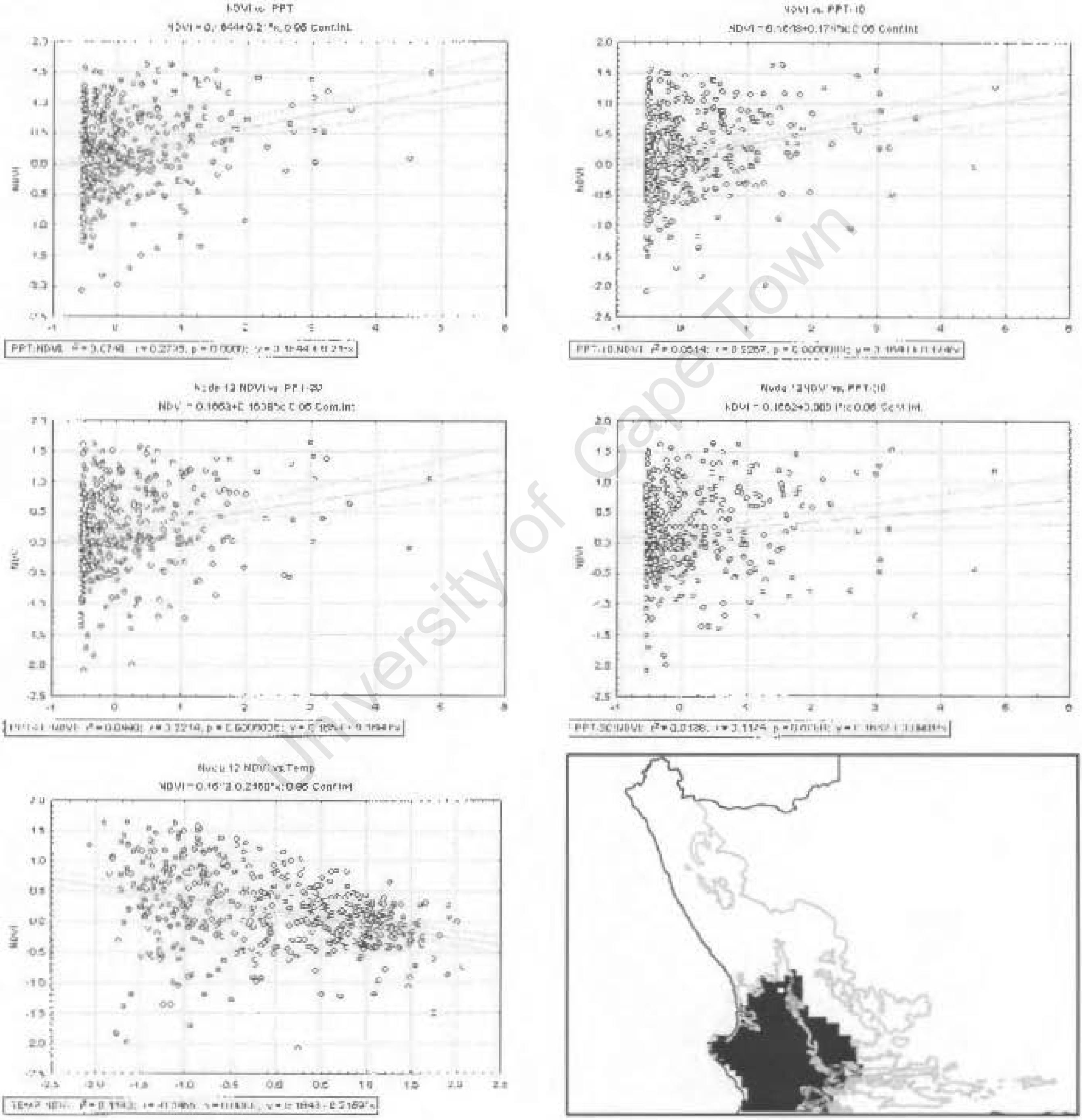

Figure 6.15 SOM Node 12 scatterplots

6.4.8 Node 13 (Figure 6.9 and 6.16)

Node 13 occupies the Roggeveld mountain range and lies northeast of Node 12. The region is well known as an extremely arid area prone to regular drought events. Figure 6.15 illustrates the graphical relationship between precipitation and NDVI and temperature and NDVI. Correlation coefficients are once again weak with r-values of less than 0.3 with variance in NDVI explained by precipitation only 4.44%. Temperature once again returns moderate negative r-values and explains a little over 11% of the variability in NDVI.

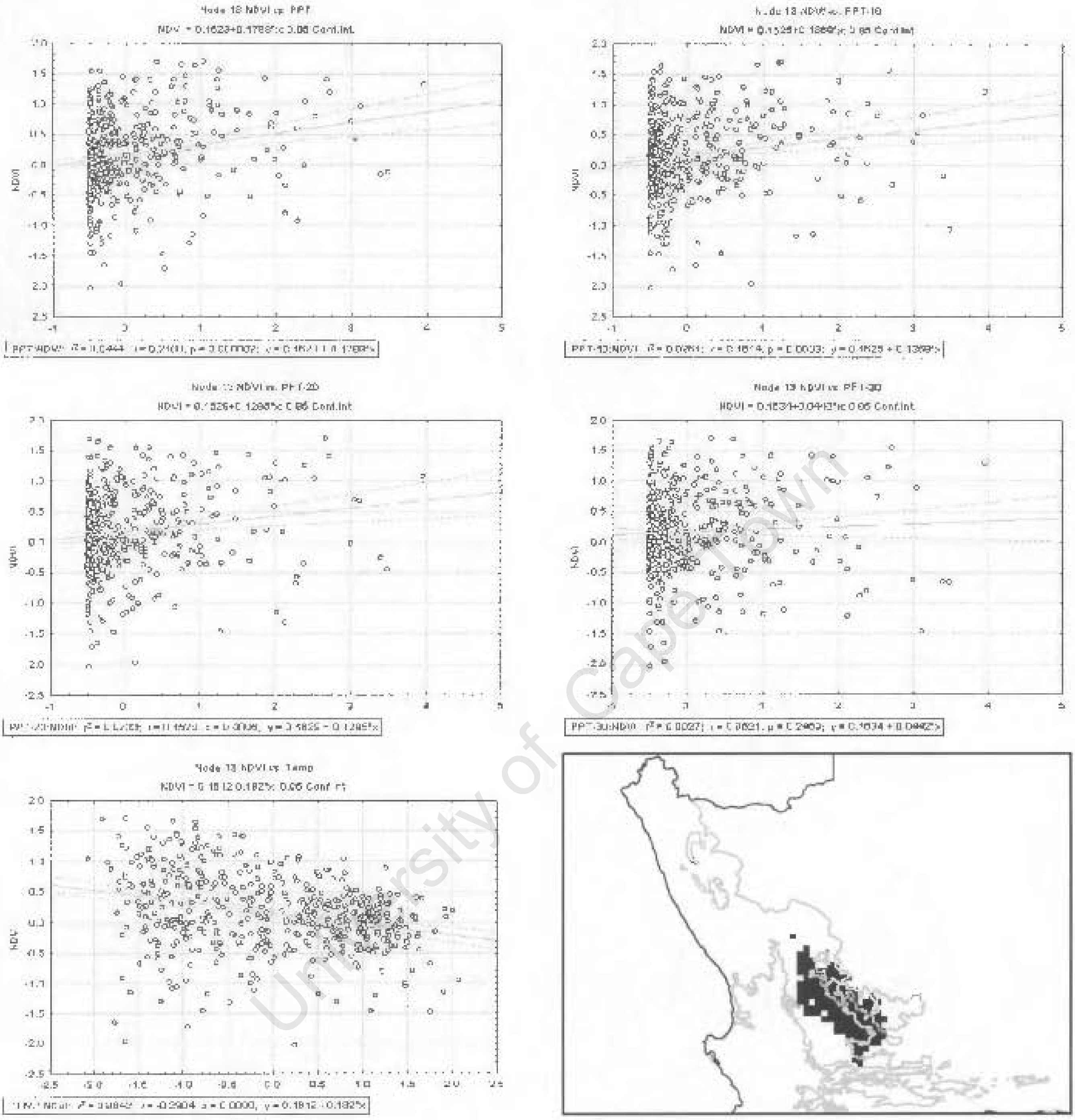

Figure 6.16 SOM Node 13 scatterplots

6.4.9 Node 14, 18, 19 and 24 (Appendix B)

Due to their limited spatial distribution and the fragmented nature of the Little Succulent Karoo the rest of the nodes will be discussed as one. Nodes 14, 18, 19 and 24 occupy the southeastern portion of the Succulent Karoo biome. Rainfall and

NDVI relationships are weak in this region. Scatterplots associated with these nodes can be found in Appendix B and illustrate the weak relationship between NDVI and precipitation as well as temperature.

6.5 Conclusion

Chapter 6 outlines the results of analysis methodologies discussed in chapter 5. Relevant maps and graphs were used to report the findings. Chapter 7 focuses on the interpretation of these results, with key results summarised below.

The STCf returned interesting results pertaining to the spatial nature of seasonal response to the input of atmospheric moisture. Results were reported for both the 3X3 and 5X5 kernels. Seasonal differences in vegetation response are most notable in the JJA season where on-the-ground correlations become spatially homogenous and less fragmented. The rest of the seasons all return similar patterns with variations associated with local scale factors. The methodology identified several regions where local scale factors such as rivers and agriculture impact on vegetation growth. These areas are loosely defined as regions where atmospheric moisture does not play a part in seasonal vegetation growth.

Time series analysis of the fourteen-year NDVI data set was undertaken using Principle Component Analysis. The PCA identified important spatial patterns as well as interesting trends with regards to seasonal phenomenon. Component one returned the general patterns of vegetation cover in the biome. The main element of variability in Principal Component 1 is that which occurs spatially. Component two returned the expected seasonal dichotomy between summer and winter rainfall. The study area is largely a winter rainfall area, but some regions do receive summer and non-seasonal rainfall events. This is especially true in the Little Karoo. The factor loading graph associated with component two confirmed that the main element of variability in Principal Component 2 is that which occurs seasonally. Components three, four, five and six are usually associated with autumn and spring, sensor characteristics and other elements of variability associated with the equatorial crossing time of the satellite as well as sensor degradation. These artefacts were, however not identified in any of the preceding components.

The classification of the relationship between rainfall and vegetation growth in the biome was undertaken using Self-Organising Maps. Each pixel within the study area was classified according to a pixels time-series consisting of six input variables. Nodes to which each pixel mapped to during the training phase of the analysis are seen in figure 6.8. Analysis of the time series output indicated that vegetation growth and precipitation return a weak but positive relationship. This is true for all nodes that fall within the study area. The weak relationships became progressively weaker as the lag in rainfall was increased. The relationship between NDVI and temperature was also tested. Temperature and NDVI returned moderately strong negative relationships with more variance in NDVI explained by temperature than by precipitation.

Results from the above analysis are interesting and thought provoking. Chapter 7 collates the results and discuss their relevance in terms of the problem statement and research questions posed in chapter one. Chapter 7 also discusses each methodology and relates results to the broad subject of Land Degradation. One of the key goals for this research project was to assess the methodologies used to identify *"zones of potential critical change"*. The ability of the methods to identify these zones will also be discussed. One critical issue is the impact of soil background reflectance on the NDVI signal; this is discussed and later mentioned in recommendations for future research projects. Implications for degradation assessment in the Succulent Karoo are also discussed with a special emphasis on combining digital remotely sensed information with extended fieldwork campaigns.

Chapter 7

Discussion

7.1 Introduction

Chapter 6 outlined results from the three analysis methodologies used. Each methodology was designed to answer a specific question regarding intra-seasonal land surface change in the study area. Chapter 6 discusses each of the analysis methodology outputs with regards to the questions they were designed to answer. Once the methodologies have been discussed and critiqued they are analysed and discussed in terms of their ability to identify potential critical change. The potential drivers of vegetation change are also discussed. Caveats and problems associated with the present research are outlined with recommendations left for the concluding chapter.

7.2 Spatio Temporal Correlation filter (STCf): Discussion

The main aim of the first of the three analyses performed was to identify where precipitation played a leading role in vegetation growth. This was achieved by determining the spatial nature of vegetation growth within the study area, using the STCf. Several distinct patterns are evident; correlations are far higher on the lowland areas of Namaqualand, small patches do occur in other areas, but their spatial extent is far smaller, fairly strong correlations dominate the rest of the biome with small patches of no correlation.

Areas of no correlation are largely limited to the southern portions of the biome with small speckles occurring in the northern parts as well as large areas associated with major rivers systems. Comparing the seasons highlights a very important feature. High correlations found on the lowland areas of Namaqualand and the Knersvlakte only occur during the DJF and JJA seasons. The spatial distribution of class 1 during the MAM and SON months is far smaller than the DJF and JJA periods. MAM and SON are associated with autumn and spring respectively. One could therefore call them transition zones between winter and summer. The low correlations during these months could be attributed to the changing of the seasons. This would indicate that stable climatic conditions associated with the summer and winter seasons influence the vegetation in a more homogenous or spatially explicit nature. Autumn and spring defined as MAM and SON are therefore far more variable than the summer and winter months leading to a variable vegetation signature. Perhaps with the change of seasons resources available for vegetation growth are spatially heterogeneous and limited.

Ground truthing provided the opportunity to verify results. Various geographic variables were assigned to each class. The use of a paper map (see figure 6.3) and a Global Positioning System (GPS) facilitated the identification of several local and regional scale factors driving intraseasonal land surface change. Attributes of each group were identified and tentative conclusions regarding class characteristics, beyond that of the correlation coefficients were made. Class 1 is largely made up of relatively undisturbed rangelands found on the flat low lying plains of the Knersvlakte and Hardeveld. Class 2 in most cases is associated with higher lying areas where topography and land use may influence the vegetation signal. Class 3 and 4 are generally found in close proximity to one another, as mentioned earlier class 3 is noted as being a transition zone between areas of strong correlation and areas where practically no correlation exists. Class 4 is undoubtedly associated with agriculture, major river systems and perhaps areas of steep topography. Ground truthing along both the Orange and the Olifants Rivers confirmed that these areas are influenced by both irrigated agriculture and riparian vegetation.

Correlation values returned from the analyses indicate that the spatial response of vegetation is reasonably homogenous. The 3X3 kernel seems to return better correlations than the 5X5 kernel. This is attributed to the potential for increasing levels of variance within the kernel window. The 3X3 pixel kernel returns only 8 correlation values whereas the 5X5 kernel returns 24 correlation values. The 5X5 kernel also includes pixels that are further away from the centre pixel, thus making it less likely for outer pixels to have strong relationships with the centre pixels. A from of distance decay effect in the relationships could be present.

7.3 Principle Component Analysis: Discussion

Results from the Principle Component Analysis reported in chapter 6, present interesting information regarding the nature of NDVI and vegetation growth in the study area. The broad aim of the analysis was to enquire about the seasonal changes occurring during the study period and relate these changes to either land use or climate change. Results were examined using component images in a progressive manner from most significant (component 1) too least significant (component 6). Associated with the component images was their respective factor loading graphs. Any change component identified needed to be both spatially and temporally coherent for it to be deemed change as apposed to inconsequential variation, thus component graphs were included and used to test the temporal coherence of the spatial patterns identified.

As mentioned in chapter 6, the first change component represents the characteristic vegetation index for the study area during the period 1985 to 1999. NDVI anomalies reflect the known moisture and topographical gradients present in the biome (Cowling, 1999). The Richtersveld and associated northern regions of the biome show relatively sparse vegetation cover. This is to be expected as rainfall in these areas is well below 50 mm per annum (Desmet and Cowling, 1999). Namaqualand and the Kamiesberg regions return high relative NDVI anomalies. Vegetation growth forms in this region are relatively standard across geographical gradients and one would expect fairly similar NDVI signals throughout the study period. The negative NDVI anomalies seen in the Namaqualand region are areas that have reduced vegetation cover relative to the positive NDVI anomalies. Physical environmental features such as vegetation type or soils may cause these areas of low to negative NDVI anomalies. Alternatively they may be the result of inappropriate land use practices associated with stock farming, cropping and dryland agriculture. As noted in Hoffman and Ashwell (2000) land degradation associated with inappropriate land use practices, manifests itself in localised areas where vegetation cover is not able to recover from grazing. Areas where vegetation cover is low to begin with are regions where land degradation is more likely to occur (Reich *et al.*, 2001).

Moving further south NDVI anomalies vary and could be dependent on topography and elevation. The Swartland (not part of this research) returns strong positive NDVI anomalies that are in stark contrast with the Hantam-Tanqwa karoo. The latter is one of the driest regions of the Western Cape with vegetation cover comparable to the northern regions of the Richtersveld (Desmet and Cowling, 1999). The Little Karoo region of the study area also returns a mixed NDVI anomaly signal. The component graph associated with the NDVI anomalies provides insight into the temporal coherence of the spatial patterns. It is plain to see that the patterns show temporal coherence throughout the study period save for 1993 where the correlation drops to below 0.4. Examining the component image and factor loading graphs for component one, it is clear to see that no significant changes have occurred to average / integrated vegetation cover during the fourteen years studied. If the component graph showed any sort of significant increase or decrease in correlation one would then postulate that vegetation cover within the biome were decreasing or increasing as a result of a change to climatic conditions.

Component 2 shows the second change component of the temporal NDVI data set. The element of variability seen in component 2 is the seasonal dichotomy between summer and winter rainfall. The geographic distributions of positive NDVI anomalies are strongly associated with the winter rainfall regime of the western and northern Cape. Positive NDVI anomalies are seen along the coastline from the Richtersveld down to Laingsburg in the south. This region receives most, if not all its rainfall during the winter months of the year (Schultze, 1997). Positive NDVI anomalies seem to outline the border of the Succulent Karoo and follow the biome into the central southern regions. The eastern border of the positive NDVI anomalies reflects the eco-tone between frontal-winter-rainfall-Succulent-Karoo and the convective-summer rainfall-Nama-Karoo. The Little Karoo displays contradictory results; here we see that the NDVI anomalies are low to negative, indicating that seasonal vegetation growth here is both summer and winter orientated.

The factor graph associated with component 2 reflects the cohesive nature of the seasonal dichotomy between summer and winter rainfall. Spacing between the peaks and troughs in the cycles accurately reflects the summer and winter rainfall cycles. The spatial pattern seen in component 2 has a strong correlation with the peaks in the component graph indicating that growth in the biome occurs during the winter months. The spatial nature of positive NDVI anomalies and the cohesive nature of the component graph reflect the reliability of rainfall in the biome. This reliability indicates that no significant change has occurred to the timing of rainfall events in the biome as indicated by the temporal nature of the factor loading graph (figure 6.6). If climate change were occurring within the biome an indication of this change would present itself as a shift in the timing of growth events driven by either a change in the timing of rainfall events or a change in the temperature regime.

Components three, four, five and six do not return immediately recognisable patterns. These components are more difficult to interpret. While they account for less than 5% of the total variance in the data set they may contain useful information pertaining to the satellite sensor. Eastman and Faulk (1993) found that later components contained information regarding sensor degradation; delays in equatorial crossing reflected in higher NDVI values in mid-latitudes and ENSO related patterns of drought. The authors noted that after general seasonal effects had been accounted for, the next element of variability is usually associated with the sensor system itself. Unfortunately, in the present analysis the patterns present do not present much in the way of trends. It was not possible to identify the autumn / spring seasonal dichotomy usually associated with component 3 nor was it possible to identify problems relating to orbital drift, equatorial crossing time and solar zenith angle of the NOAA-9 satellite platform (Eastman and Faulk, 1993). Finally given that the study area falls within a predominately winter rainfall region ENSO events were not considered.

7.4 Self-Organising Maps: Discussion

Results from the Self Organising Maps analysis were reported in Chapter 6 section 6.4. Results took the form of an output SOM map showing the geographical location of the various SOM nodes. These locations are of particular importance as they represent an area average of the time series of each variable mapped to an associated node (figure 6.9). The geographic distribution of each node therefore depicts a region that has similar rainfall and vegetation growth trends. Output from the SOM analysis included an area average time series of each input variable; these were used in the regression analysis. Vegetation growth relationships for each of the SOM nodes falling within the study area were tested using linear regression and scatterplots. The following paragraphs discuss the results with reference to the seasonal rainfall regime present as well as topography and soil classification (Watkeys 1999). Temperature data derived from the NCEP 2.5° data set (Kalnay *et al.,* 1996) were also regressed against vegetation growth and reveal interesting relationships within the biome.

The classification of the relationship between rainfall and vegetation growth returned a map of nodes depicting areas that responded to rainfall in the same way. This map (Figure 6.9) highlights interesting geographical relationships that seem to be governed by either topography, soil background reflectance or to a lesser extent, vegetation growth forms. Node 0 occupies the Namaqualand region of the biome. This area is well known for its endemic succulent species, high levels of plant diversity and winter rainfall. The node resides in both the lowland and the upland regions of Namaqualand where topography varies from gently sloping hills to the rough varied topography of the Kamiesberg. With regards to soils the node inhabits two broad soil zones defined by Watkeys (1999) as West Coast Region 1 and the Great Escarpment Region 6 (see chapter 2, section 2.4.2). Classification of this node seems to be determined by its winter rainfall status but may have more to do with temperature. The scatterplots for node 0 indicate that the role played by rainfall in vegetation growth is fairly weak. Temperature on the other hand seems to play a larger role in plant growth. It is well known that growth within the biome occurs in the winter (Esler *et al.*, 1999) when moisture combined with suitable growing conditions facilitates vegetation growth. This phenological trait is highlighted in the scatterplot of NDVI and temperature.

Nodes 1 and 2 fall within the summer / winter rainfall region, bordering on the Nama Karoo both nodes share geographic locations with both rainfall regimes. They are also mostly found within region 6 of the Watkeys (1999) classification but also traverse the topographical gradients between the higher lying regions of the great escarpment and the Richtersveld. The nodes also fall within the rain shadow created by Kamiesberg and could therefore be classified with the Northern Cape Richtersveld region on account of the low rainfall. Once again rainfall does not play a dominant role in vegetation growth with temperature demonstrating a fairly strong role, similar to that of node 0.

Nodes 6 and 7 occupy a very interesting and highly varied region of the biome. The geographical distribution of Node 6 is concomitant with the southern regions of the Knersvlakte. Node 7 is found on the high lying plains of the great escarpment. Both node 6 and 7 fall within the two dominant soil classifications of the region. Node 6 falls within region 1 and node 7 falls within region 6 as per Watkeys (1999). While node 6 falls within the dominant winter rainfall regime node 7 traverses both the summer and winter rainfall regions. The scatterplots indicate that in both nodes 6 and 7 rainfall typically explains less than 5% of the variance found in NDVI. Temperature plays a more significant role in vegetation growth than precipitation in both node 6 and 7. Classification of these nodes may be determined by soil structure and topography.

Nodes 12, 13 and 14 are also found in close proximity to each other. The geographic location of the three nodes reveals a diagonal orientation lying in a northeasterly direction. Nodes 12, 13 and 14 fall within region 4 of the Watkeys (1999) soil classification (Great Karoo). The areal distribution of the node occupies the

Swartland as well as the southern regions of the Tanqua Karoo. Rainfall within this node is winter orientated. Node 13 is found along the Roggeveld Mountains. The region is characterized by highly varied topography. Node 14 occupies a small region of the biome. Classification of this node may once again be determined by its close proximity to the Roggeveld Mountains. In all 3 nodes rainfall plays a limited role in vegetation growth. The scatterplots of temperature and NDVI for nodes 12, 13 and 14 reveal that as one moves inland temperature plays less of a role in vegetation growth. This is also true for the precipitation variables.

Nodes 18 and 19 occupy very small portions of the biome. Node 24 on the other hand occupies most of the Little Karoo. The Nodes fall within Region 4 and 5 of the Watkeys (1999) soil classification of the Karoo. Relationships between rainfall and vegetation growth in nodes 18 and 19 are weak, this is also true for the temperature variable. Rainfall within the three nodes is largely summer orientated and may display non-seasonal characteristics. Classification of these three nodes may be partly determined by soil type as defined by Watkeys (1999).

Results from the SOM analysis contributed to identifying climate change and human induced land degradation in several ways. Firstly, the output from the classification identifies areas where similar temporal trends are present, within each of the nodes vegetation change associated with climate change or human activities may be highlighted in the area average time series. Unfortunately the relationships that exist are weak and can not be used to determine whether or not vegetation change is taking place, regardless of the driving factor (climate vs. human activities). Secondly the ancillary analysis using temperature highlighted the fact that rainfall plays less of a role in vegetation growth. This is significant as most studies rely on the relationship between precipitation and vegetation growth as a means of climate / human induced vegetation change (Evans & Geerken, 2004). The present analysis has shown that in future studies of climate / human induced vegetation change both temperature and precipitation should be included in the analysis.

7.5 Review of Analysis Methodologies

Analysis methodologies discussed above were designed to answer three pertinent questions regarding vegetation growth in the study area. Firstly, *what is the spatial nature of seasonal vegetation response to atmospheric moisture?* Secondly, *what is* *the seasonal nature of vegetation growth in the biome* and finally *when and where is the relationship between rainfall and vegetation growth strongest?* Results from each of the analyses contribute to a better understanding of vegetation growth and seasonal changes in land surface characteristics within the Succulent Karoo biome. They also pose interesting questions regarding the role played by rainfall in vegetation growth. This section seeks to review each of the methodologies in terms of the question posed as well as collating the results and providing useful insight into the broad overarching goal of identifying *zones of potential critical change.*

The STCf returned interesting and useful results. Patterns of correlation reveal that most of the biome undergoes fairly homogenous spatio temporal vegetation change. This means that vegetation in the biome responds in much the same way during various times of the year. Most notably during JJA, patterns of correlation are significantly more homogenous (and higher) than the rest of the year. Growth occurs in the biome during the winter months, which explains why the correlations improve. This indicates that resources necessary for vegetation growth are more readily available during the winter months. In terms of the first question posed the STCf not only identifies where vegetation response to atmospheric moisture is homogenous, but also identifies the time of year when the spatial correlations are strongest.

The second question posed dealt with the seasonal nature of vegetation change in the study area. Principle Component Analysis was used to identify change components with decreasing significance. Component 1 identified the main element of variability as being that which occurs spatially. It also revealed the general vegetation cover found within the study area. The second change component identified the seasonal dichotomy between summer and winter rainfall. Component 2 revealed both the spatial and temporal nature of seasonal vegetation change in the biome. Positive NDVI anomalies were associated with the winter rainfall regions of the biome. The component graph further substantiated this with peaks associated with the winter months of the year. Component two reveals the biome is dependent on winter rainfall for growth to take place. This dependence occurs across the biome except for the southern regions where non-seasonal and summer rainfall patterns predominate.

The third question posed relates to when and where the relationship between rainfall and vegetation growth is strongest. This involved classifying the relationship between rainfall and vegetation growth using a Self-Organising Map. The geographical location of individual nodes is as important as groups of nodes mapping to similar locations. The nature of the SOM is such that nodes are placed in data space and moved around till their locations accurately reflect the multi-dimensional distribution function of the input data. The position of each node in a 2-dimensional array (figure 6.8) determines the nodes final position, relative to the rest of the nodes. The 2-dimensional array gives an indication as to which nodes are similar and which nodes are dissimilar. Basically if two nodes are close together then the nodes are more similar (Nodes 1 and 2) than two nodes that are far apart (Nodes 2 and 24). Nodal groupings seen in figure 6.9 can help to identify patterns and processes that have been identified by the SOM algorithm.

Figure 6.9 shows five broad groupings present. Nodes within each of these five groupings share similar features in terms of the variables used to classify them, but the SOM has split them and therefore each of the nodes is unique in terms of the relationship between rainfall and vegetation growth. Starting in the southern portions of the biome nodes 18, 19 and 24 are obviously summer rainfall nodes. Nodes 12, 13 and 14 occupy a transition zone where winter rainfall may dominate but influences such as topography and proximity to the coastline may play a smaller role in the classification of individual nodes. Nodes 6 and 7 clearly consist of the southern portions of Namaqualand including the Bokkeveld. Here topography may play a role in determining the geographical location of the nodes as well as soil type. Finally nodes 0, 1 and 2 occupy the central and northern regions of the biome. Here moisture in the form of Fog and Dew may influence the nodal locations as well as summer and winter rainfall patterns.

Unfortunately the relationship between rainfall and vegetation growth in all nodes is weak. R-squared values rarely rise above 0.0591. This is extremely important in terms of the original premise / paradigm defined in the problem statement. Plant growth in the Succulent Karoo is not, as first thought governed by precipitation alone. Ancillary analysis performed using temperature data suggests that temperature and not rainfall plays a dominant role in vegetation growth. This result is in stark contrast to the findings of a modelling study by Hahna *et al* (2005) where it was shown that vegetation growth on communal rangelands is dominated by rainfall variability. Results from the present analysis do not support the findings of Hahna *et al* (2005) nor do they refute them. The positive linear relationship between rainfall and vegetation growth seen in the nodal scatter plots (figure 6.11 – 6.16), and the temporal patterns seen in Appendix D support the finding that precipitation variability controls vegetation growth. Present results do however indicate that the role of temperature should be reassessed and perhaps included in future studies.

7.6 Land Degradation, Climate Change and Zones of Potential Critical Change

Chapter one introduced the idea that rangeland science in the past has failed to produce a generally accepted framework for assessing the sustainability of a rangeland in terms of the changes, and or pressures being imposed on the rangeland (Stafford Smith and Pickup, 1993). One of the over-arching problems is the relative contribution of land degradation and climate change to vegetation change in a xeric environment such as the Succulent Karoo. The focus of this research has been to identify where land use and climate change may impact on vegetation with a view to identifying so-called potential critical change. Each of the methodologies employed are discussed with regards to Land Degradation and Climate Change.

Regions returning strong correlations (Class one and two) are areas where large-scale environmental inputs govern vegetation growth, these inputs are more than likely governed by the regional climate system. Spatially, strong correlations are dominant on the low-lying regions of the biome. Small stock farming and strip mining along the coastline dominate land use on these plains. Cattle are sometimes kept in river valleys where riparian vegetation provides feed for the larger animals (Low and Rebello, 1996). On the lowland plains vegetation is susceptible to overgrazing if inappropriate management strategies are used. These inappropriate management strategies are reflected in the STCf as areas where spatio temporal correlations are low as over grazing and land degradation return fragmented temporal responses. The lowland plains are also susceptible to the potential effects of climate change. Given the unique plant biogeography of the biome any major changes to the climate may have a detrimental effect on the species distribution and indeed the species themselves (Rutherford *et al.,* 1999). Knock-on effects include a loss of biodiversity and a reduction in the winter feed for stock farmers, furthermore if stock farmers are not made aware of the potential impacts of climate change they may be forced to utilise marginal rangelands for feed, thereby exacerbating the problem and almost certainly contributing to degradation.

Regions returning weak correlations are far more problematic. Local scale factors such as topography, agriculture and river systems influence vegetation growth. Weak correlations are predominantly found on the higher lying areas and in close proximity to perennial rivers. Soils in these areas are low in plant nutrients and weakly developed (Watkeys, 1999). Any denudation resulting from either climate change or inappropriate land use practices may influence more than just the immediate environment. Loss of vegetation cover in these areas may result in increased run-off, leading to soil erosion and a modification of the hydrological system. The loss of above ground biomass may generate positive feedback loops that could impact not only the plant biogeography, but also the ability of these systems to support small-scale agriculture. The socio-economic implications may prove detrimental to those people who can least afford to mitigate a loss of their primary economic income. Furthermore areas where large-scale agriculture is present pose their own set of additional threats. While these areas only make up 6% (CEPF, 2003) of the total area of the biome they may yet prove to be major contributors to land surface change and subsequent loss of biodiversity. These areas should thus be noted as *zones of potential critical change* while areas returning moderate to strong correlations (class 1 and 2) should be conserved, managed and monitored appropriately.

Component 1 of the PCA analysis reveals interesting patterns that contribute to identifying *zones of potential critical change*. The major element of variability in the component 1 is that which occurs spatially, namely vegetation cover. Given that stock farming constitutes the major land use in the biome (CEPF, 2003), knowing where vegetation cover is greatest throughout the study period may give a resource manager / communal farming communities insight into effective management strategies. Areas where cover is sparser should be noted as being geographically marginal and not suited to intense stock farming. Component 1 (figure 6.5) reveals that vegetation cover is greatest in southern Namaqualand, parts of the Roggeveld mountain range and large areas of the Little Karoo. These regions are not always suitable for stock farming as sheep and cattle struggle to move around on the steep slopes. Farmers therefore tend to favour the flat low-lying regions where vegetation cover is sparser. Thus areas where vegetation cover is sparser (figure 6.5) should be monitored for signs of overgrazing. Component 2 identified the summer winter seasonal dichotomy. The major element of variability associated with Component 2 is that which occurs temporally. The shift between summer and winter rainfall areas is clearly evident. In terms of Climate Change the summer and winter rainfall regimes drive the unique plant diversity found in the Succulent Karoo. Thus any seasonal shift in rainfall and temperature patterns as a result of Climate Change may contribute to a loss of biodiversity as well as related impacts to agriculture.

Finally the SOM analysis revealed that in the Succulent Karoo Biome temperature plays a more significant role in vegetation growth than precipitation. In terms of Climate Change and Land Degradation this is a significant finding. If temperature is the dominant driving force in seasonal vegetation growth (see figure 7.1), any changes to the present climate may result in a loss of the plant assemblages that make the biome so unique. Esler *et al* (1999) showed that the unique plant assemblages found in the biome occur as a result of low but reliable winter rainfall and mild winter temperatures. Monitoring any changes in climate within the biome as well as the subsequent changes in vegetation patterns is of utmost importance. Results from the SOM analysis may be used to effectively monitor vegetation change in the biome. The SOM analysis identified thirty geographical areas that display similar relationships between precipitation and vegetation growth. Eleven of these nodes fell within the study area. They can be grouped into five broad geographical units. These groups are identified using the sammon map seen in figure 6.8 and may be used as management / monitoring zones. Within each of these zones vegetation change resulting from either Land Degradation or Climate Change can be identified and monitored using published methods such as Tanser and Palmer (2000); Mackay and Zietsman, (1996) or Pickup and Chewings (1988b).

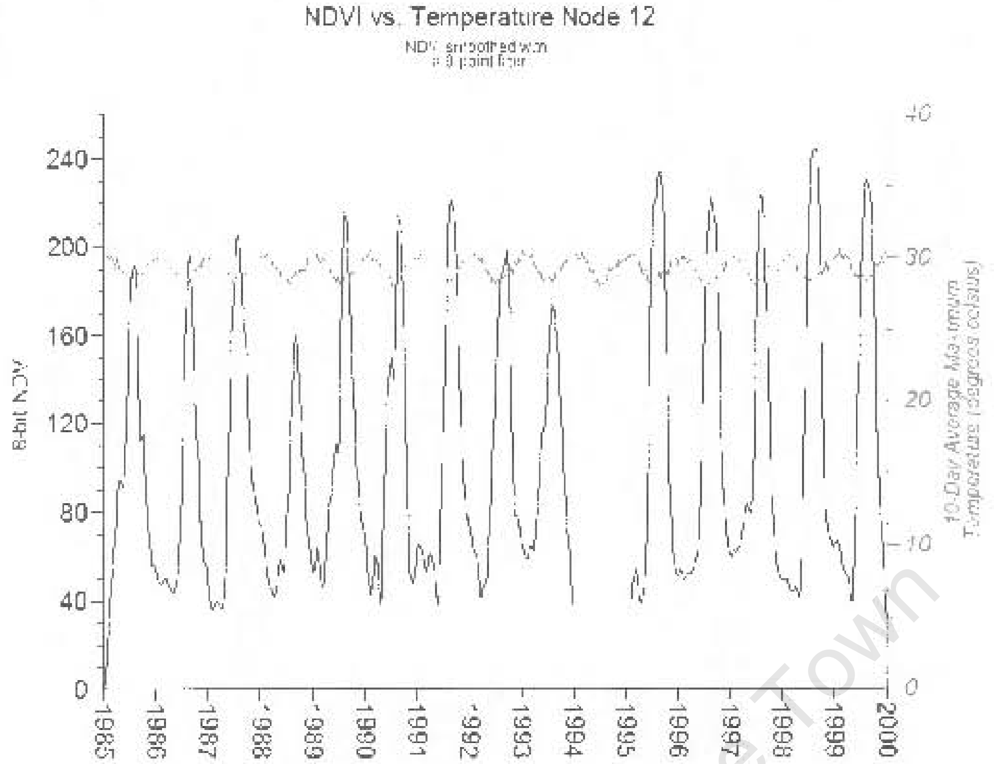

Figure 7.1 Graph of NDVI vs. Temperature through time

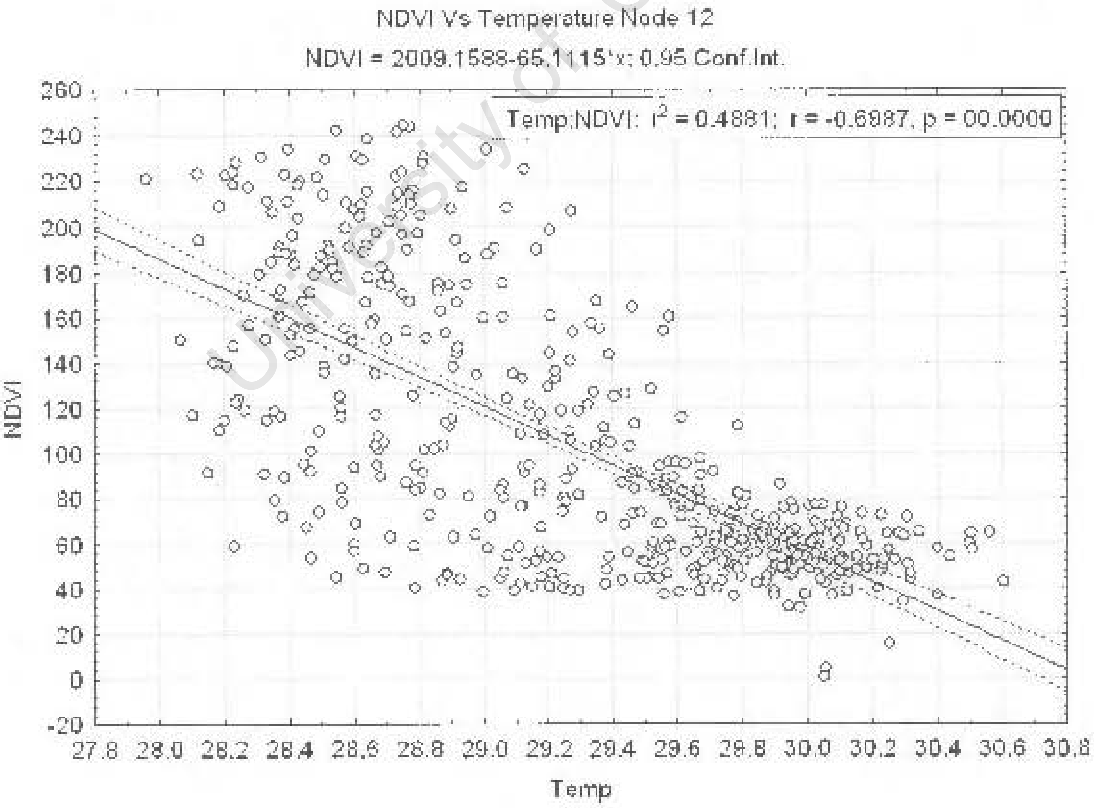

Figure 7.2 Scatterplot depicting relationship between temperature and NDVI

7.7 Caveats

When interpreting the results and discussion in the present research several caveats need to be outlined and discussed so as to avoid misinterpretation. The explanations given clarify the role each caveat played and the potential impacts that may have resulted from it. Solutions or recommendations for future research where these caveats may be mitigated are discussed in chapter 8 (section 8.3). Presently the author has identified several caveats that need to be outlined and discussed. They include soil background reflectance, the lack of a suitable land use map and reliable stocking rates as well as the size of the study area. Each of these caveats is introduced and discussed below.

7.7.1 Soils: Background reflectance

Implications of the background soil reflectance on the present study are as follows. Given the low annual rainfall (20 – 300mm p/a) much of the biome has a fairly sparse canopy cover. It follows that the spectra recorded by the satellite is a mixture of vegetation and soil background reflectance producing a mixed canopy / soil spectrum. This mixed canopy spectrum may produce a vegetation index that is partially contaminated by the background soil characteristics. These characteristics include colour (moisture), roughness, organic matter and mineral content (Rondeaux *et al.*, 1996; Heute 1988). Variations in each of these characteristics impact on the final NDVI measurement. In the Succulent Karoo soils are lightly coloured but may turn darker in the winter months directly after rainfall events, however soil moisture in the biome is fairly low as no significant soil moisture storage takes place (Esler *et al.*, 1999). Due to the low rainfall and sparse vegetation little organic matter remains on the soil surface (Watkeys, 1999), therefore influences related to organic matter are negligible. Finally mineral content in the soils is low save for the Knersvlakte where quartzite rocks dominate. Therefore the major soil characteristic contributing to background soil reflectance is soil colour. Within the biome soils are yellow to red in colour in the northern and central regions of the biome becoming progressively darker as one moves east (Watkeys, 1999). This means that the influence of soil background colour will decrease NDVI measurements in the central and northern regions of the biome and may increase measured NDVI in the eastern regions of the biome.

7.7.2 Land use map and stocking rates

In the IPCC (Intergovernmental Panel of Climate Change) third assessment (2001) it was noted that the impacts of Climate Change on rangelands was likely to be minor in comparison to land degradation. Given that stock farming constitutes the major land use in the biome (CEPF, 2003), land degradation, associated with overgrazing and inappropriate agricultural practices is of major concern. Presently there exists no definitive land use map of the Succulent Karoo biome. Several organisations (Chief Directorate of Surveys and Mapping, Succulent Karoo Ecosystem Program, Satellite Applications Centre) are currently working on land cover maps, as has an MSc student at the University of Cape Town (Jonas, 2004). A Land-Use-GIS database which contained up-to-date data concerning management practices, stocking rates and overall vegetation health would be a useful product with which to plan and manage future resource management.

7.7.3 Ground Truthing and GCP's

Fieldwork and ground truthing play a vital role in research using remotely sensed imagery. Unfortunately the author was only able to visit the study are on a single occasion. This meant that only one of the analysis methodologies could be properly ground truthed. The fieldwork was also performed during the height of summer when vegetation cover in the biome is at its sparsest. Furthermore only four sites were ground truthed. While these sites were representative of the results from the STCf, they could not be verified during the winter months, when most of the growth occurs within the biome. This research would have benefited greatly from extended fieldwork campaigns in both the summer and winter months. Furthermore only the central and northern parts of the biome were visited, the Little Succulent Karoo was not ground truthed and thus fieldwork data were not collected in this region. It should be noted that the study area is large and that fieldwork campaigns would have been expensive and time consuming.

7.7.4 Size of the study area

Finally the sheer size and environmental diversity present in the biome was in itself a caveat. Several regional environmental gradients exist within the biome making a study of vegetation change problematic. Mean annual rainfall varies from 300mm in the south to less than 20 mm in the north; furthermore the rainfall seasonality is split between summer in the south and winter in the central and northern regions (Desmet and Cowling, 1999). Topographical gradients exist on a west east orientation in Namaqualand with elevation ranging from sea level to 1500m. In the central and southern regions low land plains interspersed with Cape Fold Mountains characterize the topography (Low and Rebello, 1996). The analysis sought to identify *zones of potential critical change*; these zones are for the most part site specific. Given the environmental diversity present conclusions and recommendations should and will not be made across geographical gradients.

7.8 Conclusions

Chapter 7 discussed the results of analysis methodologies presented in chapter 6. The chapter began with a discussion of each methodologies result in the context the questions posed in chapter 1. The STCf identified the spatial nature of intraseasonal land surface change using correlation classes mapped in a Geographical Information System. The methodology accurately identified spatially and temporally homogenous land surface change with the 3X3 kernel returning the most useful results. The PCA identified both the integrated vegetation cover and the seasonal dichotomy between summer and winter rainfall regimes. Results contributed to a better understanding of the changes in seasonal rainfall in the biome and the general vegetation cover of the biome. The SOM analysis classified the relationship between rainfall and vegetation growth. The output nodes and associated map were discussed in terms of seasonal rainfall, soil type defined by Watkeys (1999) and topography. Most notably the SOM revealed that temperature plays a stronger role in vegetation growth than precipitation.

The chapter continued with a review of each of the methodologies in the context of the questions first posed in chapter 1. The STCf attempted to understand the spatial nature of intraseasonal vegetation response to atmospheric moisture. Results suggest that the methodology accurately identifies areas responding to large-scale environmental inputs associated with regional climate systems, furthermore the methodology also identified where local scale environmental inputs / features such as agriculture dictate seasonal vegetation growth. Question two related to the seasonal nature of vegetation growth in the biome. PCA analysis identified the underlying dimensionality of the data set and unpacked the integrated vegetation cover for the period of study as well as describing the seasonal dichotomy between summer and winter rainfall. Finally the SOM methodology classified the biome into 11 nodes. The

SOM attempted to identify where and when vegetation responded to rainfall, while 11 nodes / groups were identified subsequent analysis of the area average NDVI and precipitation variables showed that the relationship between rainfall and vegetation growth is weak. Temperature on the other hand showed a much stronger relationship.

Land degradation, climate change and *zones of potential critical change* were also discussed. Each methodology was reviewed and discussed in terms of their individual results. Regions seen as being susceptible to climate change included class 1 and 2 of the STCf. Positive NDVI anomalies seen in component 2 of the PCA analysis were also identified as being susceptible to climate change. Finally the fact that temperature plays a dominant role in vegetation growth means that any changes associated with global warming will have a negative impact on the biome. In terms of land degradation classes 3 and 4 of the STCf were identified as being susceptible to degradation associated with inappropriate agricultural practices, knock on effects were also identified. Component 1 of the PCA identified areas of reduced vegetation cover that, if heavily grazed could lead to the loss of above ground biomass and reduced economic potential.

Four caveats were identified and discussed; they included soil background reflectance, lack of an appropriate land use map, lack of adequate ground truthing and the size of the study area. Studies have shown that the background soil characteristics in partial vegetation canopies influence vegetation indices. Possible affects of soil background influence were discussed. Several studies on the effect of soil background influences were cited. Characteristics of the soil and ground litter present in the Succulent Karoo were discussed with the most significant contribution to soil background influence being the colour of the soils. It was concluded that the influence of background soils on the NDVI signal manifests itself as lower NDVI measurements. The second caveat discussed was the lack of an appropriate land use map. Analysis methodologies would have benefited from at least a general map of land use. Thirdly the lack of adequate fieldwork meant that the author only had field data for one of the three analysis methodologies. It was however noted that given the size of the study area, a comprehensive fieldwork campaign would have been costly and time consuming. Finally the size of the biome and environmental gradients within the biome were identified as potential caveats. While the analysis sought to identify *zones of potential critical change* at the 1 km resolution results should be seen in the light of a regional study.

Chapter 8 concludes the research by revisiting some of the issues outlined in the problem statement and commenting on the methodologies used as well as making several recommendations for future research. The chapter will collate the primary findings into a concise conclusion.

Chapter 8

Conclusion

8.1 Introduction

Chapter 8 concludes and summarises the relevant findings of the research reported on in this thesis. Section 8.2 summarises the key findings obtained from the three methodologies used. It begins with an outline of the results obtained from the STCf analysis, highlighting several key findings. This section also discusses the results in terms of their contribution to the identification of *zones of potential critical change*. The chapter continues with a summation of the Principal Component Analysis, outlining noteworthy results as well as linkages to the Self Organising Map analysis. Results obtained from the SOM analysis are then outlined and discussed. The SOM analysis sought to classify the relationship between rainfall and vegetation growth. Output from the analysis took the form of a map of nodal groupings and the time series of each variable used in the analysis. These outputs were used to analyse the relationship between rainfall and vegetation growth as well as contribute to the identification of *zones of potential critical change*.

The content of section 8.3 examines the implications of the results discussed in section 8.2 in terms of biome dynamics. The section focuses on the notable results acquired from the SOM analysis. In particular the section argues for a re-think of the present understanding of the role of precipitation and temperature within the Succulent Karoo. The section briefly comments on how a change in temperature may impact the flora regardless of changes in rainfall patterns. Section 8.4 introduces recommendations for future research. Briefly, it is suggested that future research projects wishing to assess vegetation changes in the Succulent Karoo (or any xeric environment) should focus their research on a specific region or area previously defined. When using remotely sensed images a soil insensitive index should be used, as canopy cover in arid regions tends to be sparse, which leads to a vegetation signal that is heavily contaminated by near-IR irradiance resulting in lower NDVI measurements. Furthermore the role of fog and dew as sources of moisture in the biome should be explored and finally the development of a land use map integrated into a Geographical Information System would greatly enhance future research projects.

Finally section 8.5 reviews the strengths and limitations of both the data and the methods used. The review is based solely on the results obtained and how they contribute to a better understanding of the "science" of the Succulent Karoo. The section comments on the use of satellite data for land surface change analysis citing the temporal resolution of NOAA AVHRR data as a strength, but also noting the limitations of the data (spatial resolution). The section ends with a short paragraph outlining the take home messages derived from this research project.

8.2 Abridgment / Summary

Results and conclusions reported on have identified several key outcomes relating to questions / problems mentioned in the opening chapter. In the present research, the varying response of vegetation to precipitation was used as a means of identifying areas that may be susceptible to the potential effects associated with in-appropriate Land Use and Climate Change. These areas were defined as *zones of potential critical change*. Vegetation response to precipitation was analysed using three separate yet interconnected methodologies. These methodologies were designed to answer three separate questions. Firstly, *where is seasonal vegetation growth in the Succulent Karoo homogeneous?* Secondly, *what is the seasonal nature of vegetation growth (NDVI)* and finally *when and where is the relationship between vegetation growth and precipitation strongest.* Results from each of the methodologies employed were discussed in chapter 5 and 6. What follows is a short summation of core findings.

Vegetation response to precipitation is fairly homogenous throughout the biome. Flat low-lying areas return a less heterogeneous response than higher lying regions where topography and rainfall as well as moisture associated with orographic fog contribute to vegetation growth. Agriculture associated with large river systems such as the Oliphants and Orange Rivers return a response that is heavily influenced by the land use around the rivers. In these areas vegetation growth seems to be highly variable returning a weak temporal correlation. Furthermore the months of June, July and August were identified as the time period where spatial vegetation response was most homogenous. Regions of weak correlation were identified as being susceptible to land degradation while those areas whose inputs are governed by the regional climate system were identified as being susceptible to the potential impacts of climate change. Spatially integrated vegetation cover for the study period was identified using a Principal Component Analysis. Component 1 revealed that the southern and central regions of the biome return the highest integrated vegetation cover, for the fourteen-year study period. Patterns of rainfall seasonality were identified in component 2, with much of the central and northern regions of the biome falling within a winter rainfall regime. The southern regions including the Little Karoo fall within a summer rainfall regime.

Finally the relationship between precipitation and vegetation growth was classified using Self Organising Maps. Eleven nodes / regions were identified as falling within the boundary of the study area. Within each of these regions temporal trends of vegetation growth and precipitation revealed that the two variables share a weak relationship (see maps and scatterplots in chapter 6). Furthermore, the weak relationships became even weaker as precipitation was lagged. Interestingly, present analysis suggests that temperature plays a more important role in vegetation growth. Results from the SOM analysis mirror that of the PCA in that both suggest that vegetation growth in the biome is governed by the timing of the winter rainfall as well as the temperature regime, indicating that any changes in temperature (Musil *et al.*, 2005) or rainfall may have a detrimental effect on biodiversity and endemism, as well as the agricultural potential of the biome. Currently the dominant land use in the biome is stock farming with ecotourism and mining also contributing to the local economy. Changes to the floristic composition of the region would alter the future economic potential and negatively impact the local inhabitants.

Zones of potential critical change were defined as both climate driven and land use driven. Key outcomes were used to identify *zones of potential critical change*. Classification zones identified in the SOM analysis divide the biome into eleven nodes; these nodes could be aggregated into five management / monitoring zones, which include; Namaqualand and the Richtersveld (nodes 0, 1, 2), Southern Namaqualand Knersvlakte and the Northern Bokkeveld (nodes 6, 7), Hantam-Tanqua-Roggeveld region (nodes 12, 13, 14), transition between summer and winter rainfall area (nodes 18, 19) and finally the Little Karoo (node 24). Within each of these aggregated nodes precipitation and vegetation growth share similar trends and or relationships. While these relationships are weak they are still significant and should be explored further. The role of dew and fog as sources of moisture should also be examined in future research projects with a focus on the role that each might play in factors such as soil moisture and nutrient cycling as well as the regional climatology.

Fragmented vegetation response identified by the STCf suggests that local scale factors are influencing seasonal vegetation change. These areas should be flagged as *zones of potential critical change* since inappropriate agricultural practices have the potential for perpetuating positive feed back loops negatively impacting on the livelihoods of local people. Similarly stock farming on the low land plains has the potential for overgrazing in an area where carrying capacity is extremely low. Agricultural exploitation of areas that have low vegetation cover should be avoided.

8.3 Implications for Biome Dynamics

Results from the present research impact directly on our understanding of the dynamic nature of the study area. Previous chapters introduced the idea that moisture is the limiting factor in plant growth and distribution (Woodward 1986), especially in arid and semi-arid regions such as the Succulent Karoo. Present research, however, suggests that this premise may not be entirely true. Our own understanding of the role that moisture and temperature play in the biome needs to be re-thought.

Established understanding recognises that growth within the Succulent Karoo occurs in winter months due to the presence of moisture and favourable growing conditions (Desmet & Cowling, 1999; Esler *et al.,* 1999; Cowling *et al.,* 1998). While mild winter temperatures have been identified as a primary driver of winter growth, it's role has, however, been overshadowed by the "low but reliable" rainfall regime. Present research suggests that temperature plays a more important role in vegetation growth than previously thought. Biome dynamics, especially growth and phenology, are thus more reliant on a particular temperature envelope as opposed to reliable rainfall. This temperature envelope encompasses the favourable conditions for vegetation phenology. Any changes in this envelope will certainly lead to changes in vegetation structure and diversity, regardless of changes in the regional rainfall patterns.

8.4 Recommendations for future research

Recommendations for ongoing research in the biome are gleaned from key outcomes and implications discussed above. They are divided into four broad recommendations. Firstly, future research projects within the biome using remotely sensed imagery should be site specific. While remotely sensed imagery covers large areas of the earth, the environmental inputs within these areas may differ significantly necessitating the modification of research methodologies to take these variations into account. This can be achieved by scaling down the size of the study area. Results from the Self Organising Map analysis could be used to define areas where future research could take place.

Secondly the use of a soil insensitive index such as the Soil Adjusted Vegetation Index (SAVI; Heute, 1988), Transformed Soil Adjusted Vegetation Index (TSAVI) or the Soil and Atmosphere Resistant Vegetation Index (SARVI; Kaufman and Tanre, 1992) is imperative. Present research results highlight the negative impact background soil influences may have on a study of vegetation change using temporal remotely sensed imagery. Minimising background soil reflectance in future studies is imperative if we are to accurately identify patterns of vegetation change brought about by either Climate Change or Land Use. Research should be focussed on the development of a soil insensitive index that is *specially tuned* for the Southern African arid zone. Rondeaux *et al* (1996) derived a constant *L* (see equation 4.4) value of 0.16 for the minimisation of background soil reflectance however; this constant may not be applicable to the southern African arid zone. The constant could be determined using climatological and environmental variables such as soil type or mean annual rainfall or a combination of both. Furthermore alternative satellite platforms such as MODIS, ASTER, SPOT 5 and Meteosat Second Generation should also be considered as viable sources of remotely sensed imagery.

Thirdly, results indicate that vegetation growth in the biome is driven by more than just precipitation. Future research into patterns of vegetation change within the Succulent Karoo biome should incorporate more environmental variables. Present research utilised NDVI and precipitation with ancillary analysis using temperature. Weak relationships indicate that precipitation is not the only driver of vegetation growth. While temperature and precipitation contribute to the vegetation phenology results indicate that they are by no means principal drivers. The role-played by other sources of moisture including fog and dew should be examined.

Finally, the monitoring of vegetation change associated with land use and climate change is dependant on intricate knowledge of the agricultural practices present in the biome. Mapping land use within the biome will allow future research to focus on particular agricultural practices known to cause environmental degradation. For example, livestock grazing currently constitutes the major land use (CEPF, 2003) utilising 90% of the biomes rangelands. Land use types within the stock farming industry include goat, sheep, ostrich and small game farming. Each of these land use types has their own set of impacts. If these land use types are mapped and documented, associated impacts may be readily attributed to the land use practice being employed. Furthermore, additional variables such as grazing strategies, stocking rates and land tenure should be included in the land use map. These variables are easily stored in a geographical information system maintained and updated by agricultural extension workers. In addition, the creation of a Geographical Information System containing land use data for the Succulent Karoo will greatly enhance the ability of scientists to pinpoint the drivers of land degradation and vegetation change.

8.5 Strengths and limitations

This research project entailed assessing intra-seasonal land surface change in the Succulent Karoo biome of South Africa. The core idea was to use vegetation response to the input of atmospheric moisture (precipitation) as a means of identifying degraded or degrading rangelands (*zones of potential critical change*). The project also looked at the role that land use and potential climate change might have on these zones, as well as what there combined effect may be.

An initial key outcome is the quality of the results obtained from the analysis. Methods and data used revealed interesting results that pose new questions about the "science" of the Succulent Karoo. Zones or nodal groupings identified by the Self Organising Map Analysis were discussed in section 7.6. These nodal groupings should be used to focus future research using similar geo-spatial data. The most interesting and compelling result of the present research relates to the analysis of the relationships between vegetation growth, precipitation and temperature. The fact that temperature has been identified as the dominant controlling factor in plant growth is significant. This result highlights the impact that future Climate Change will have on the biome. Regardless of the changes in rainfall patterns, if temperature were to change then the floral composition of the biome would change with potential negative impacts (Musil *et al.,* 2005).

Research questions posed, sought to understand the characteristics of vegetation growth in the study area as well as its relationship with precipitation. Questions were also designed to test the methodologies and the data sources selected. The core results suggest that remotely sensed imagery, albeit on a coarse resolution, provides useful data with which vegetation growth could be assessed. The strength of the data source is its temporal resolution while a limitation or weakness was the vegetation index used (see section 7.7.1) as well as the spatial resolution of the data. The methods used to analyse vegetation growth and precipitation are strengths themselves as each method built upon the last to contribute to the key outcomes of the research project. Furthermore, the scientific value of the results confirms that the analysis methodologies were well chosen.

The "take home message" of this project is that the Succulent Karoo biome is a highly diverse region where any number of factors contributes to the floral diversity and phenology. Monitoring the biome using coarse resolution satellite data is possible using a standard slope based index (NDVI), but results could be improved with the use of a soil insensitive index such as the Soil Adjusted Vegetation Index. Relationships between various biotic and abiotic factors can be used to characterise vegetation growth with thought provoking results. Identifying *zones of potential critical change* using methods presented in this research reveals that much of the biome is under threat from either Climate Change or inappropriate Land Use practices leading to Land Degradation.

8.6 Conclusion

Land degradation and the potential impacts of climate change in the Succulent Karoo biome place a heavy burden on biodiversity and endemism. Work presented in this research has identified several key findings that contribute to the science of Climate Change and Land Degradation within the Succulent Karoo. Firstly, weak relationships between rainfall and vegetation growth suggest that while precipitation may play a role in vegetation growth, it is by no means a principal driver. Other sources of moisture such as dew and fog should be explored as potential sources of moisture. Soil background reflectance was identified as a potential hindrance in the analysis due to irradiance in the near-IR portion of the electromagnetic spectrum, which may potentially be responsible for decreasing NDVI measurements.

Recommendations made include focussing research on a specific region of the biome; for example the Knersvlakte or Sandveld. The development of a soil insensitive index, incorporating more environmental variables in future analysis and finally the development of a land use map of the biome. These recommendations are made within the context of the study area. Future studies within this region will need to heed the recommendations made, if they wish to maximise the benefits of using temporal remotely sensed imagery for studies of vegetation change and Land Degradation.

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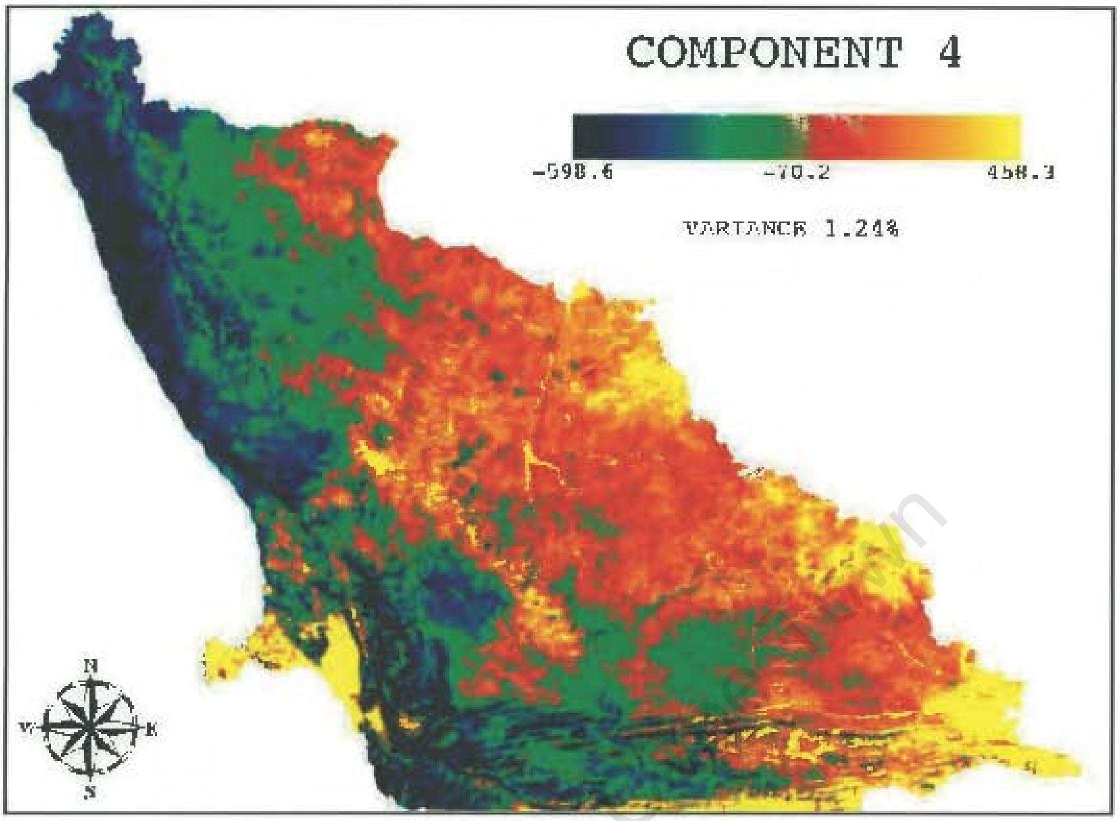
Appendix A



Component four

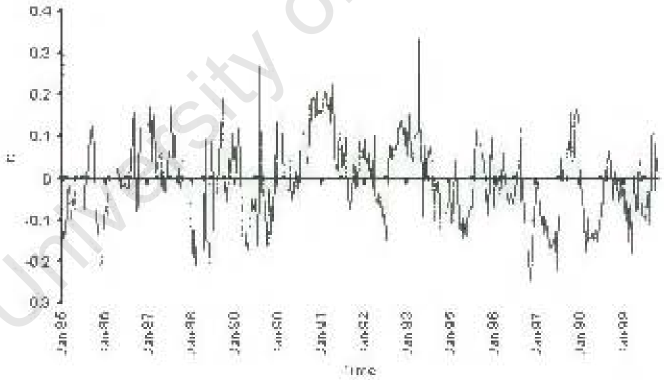
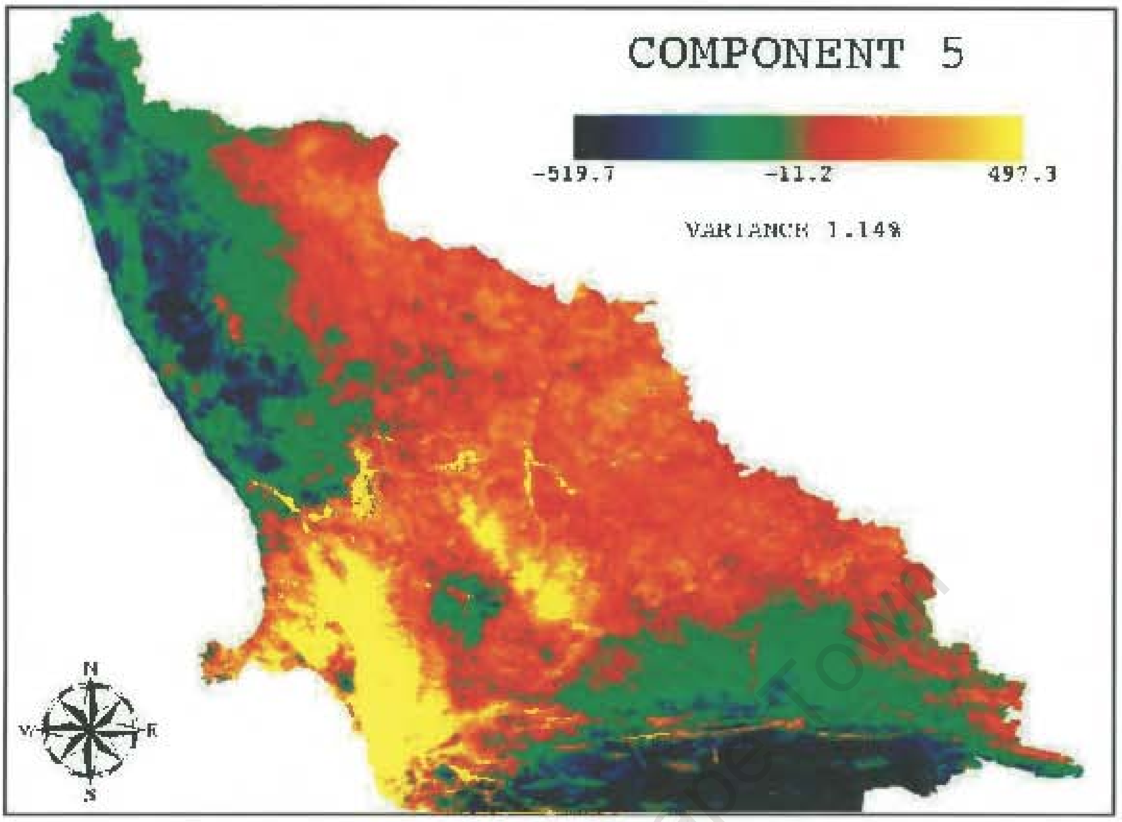


Figure A.1: Component 4 and graph



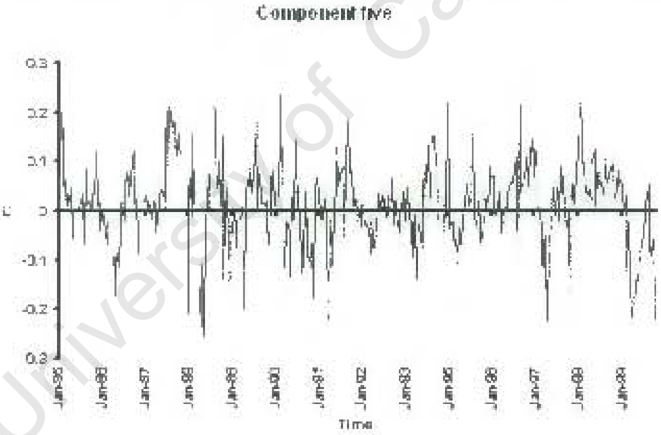


Figure A.2: Component 5 and graph

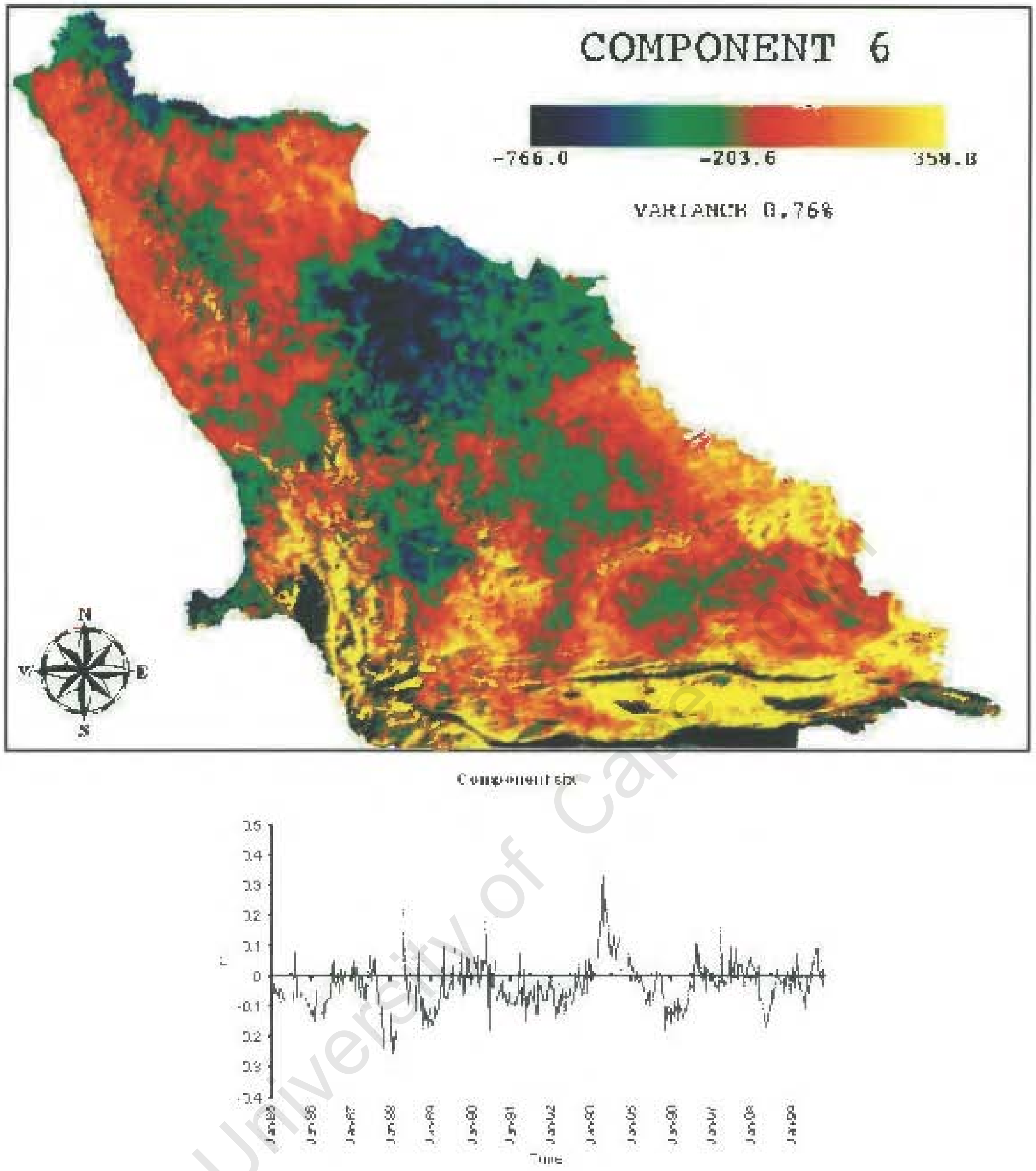


Figure A.3: Component 6 and graph

Appendix B

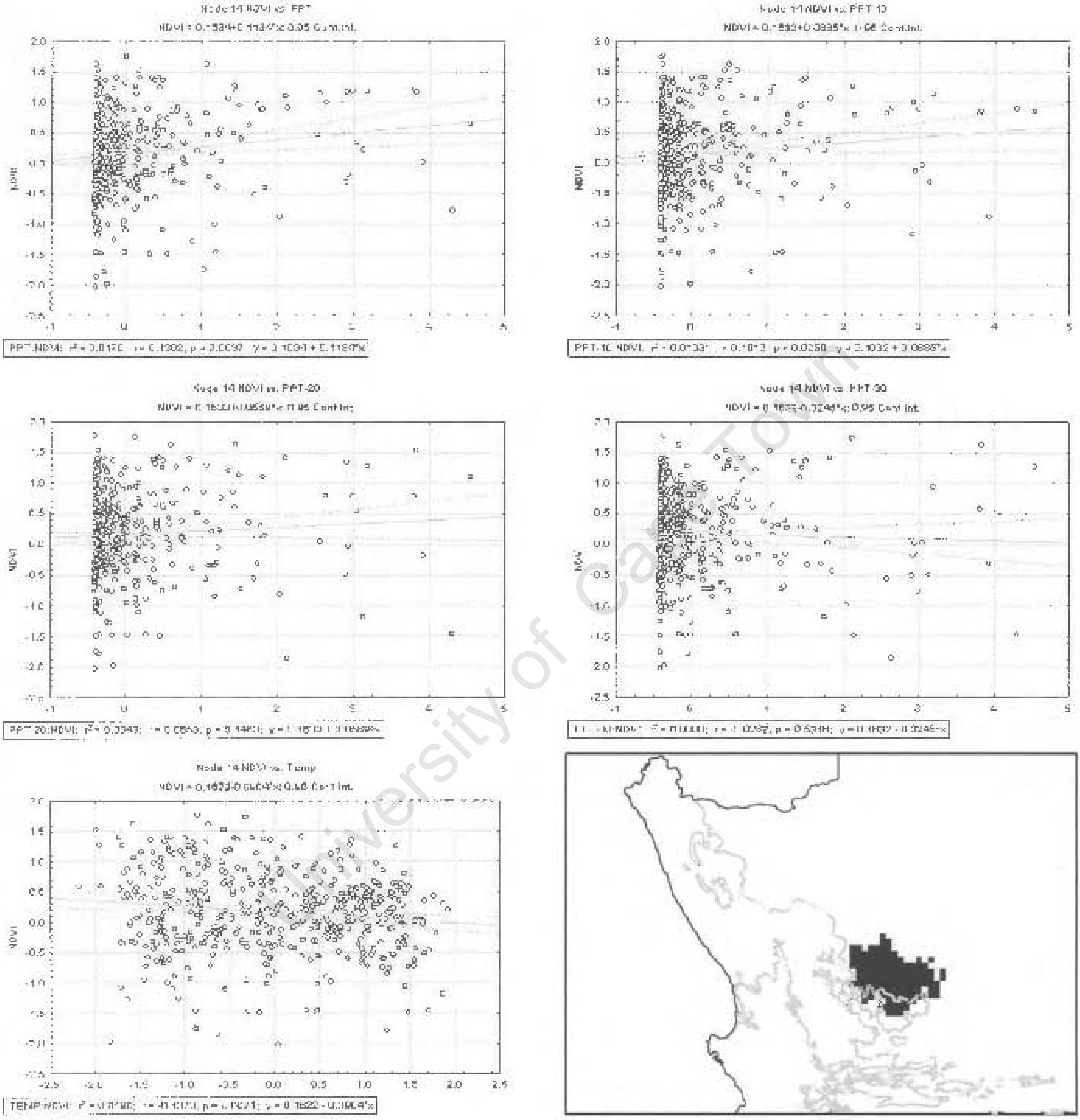


Figure B.1: Som Node 14 scatterplots

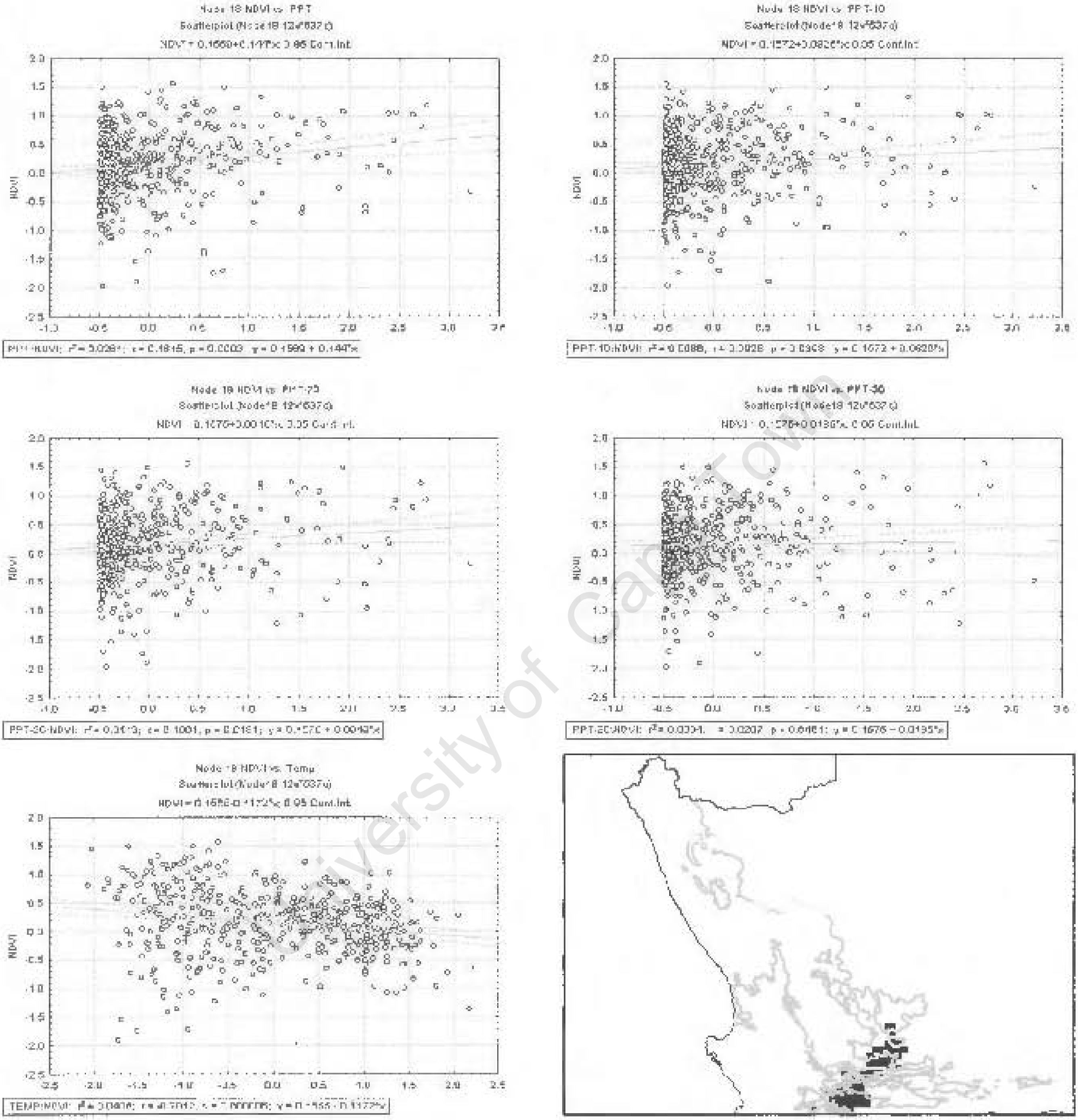


Figure B.2. Som node 18 scatterplots

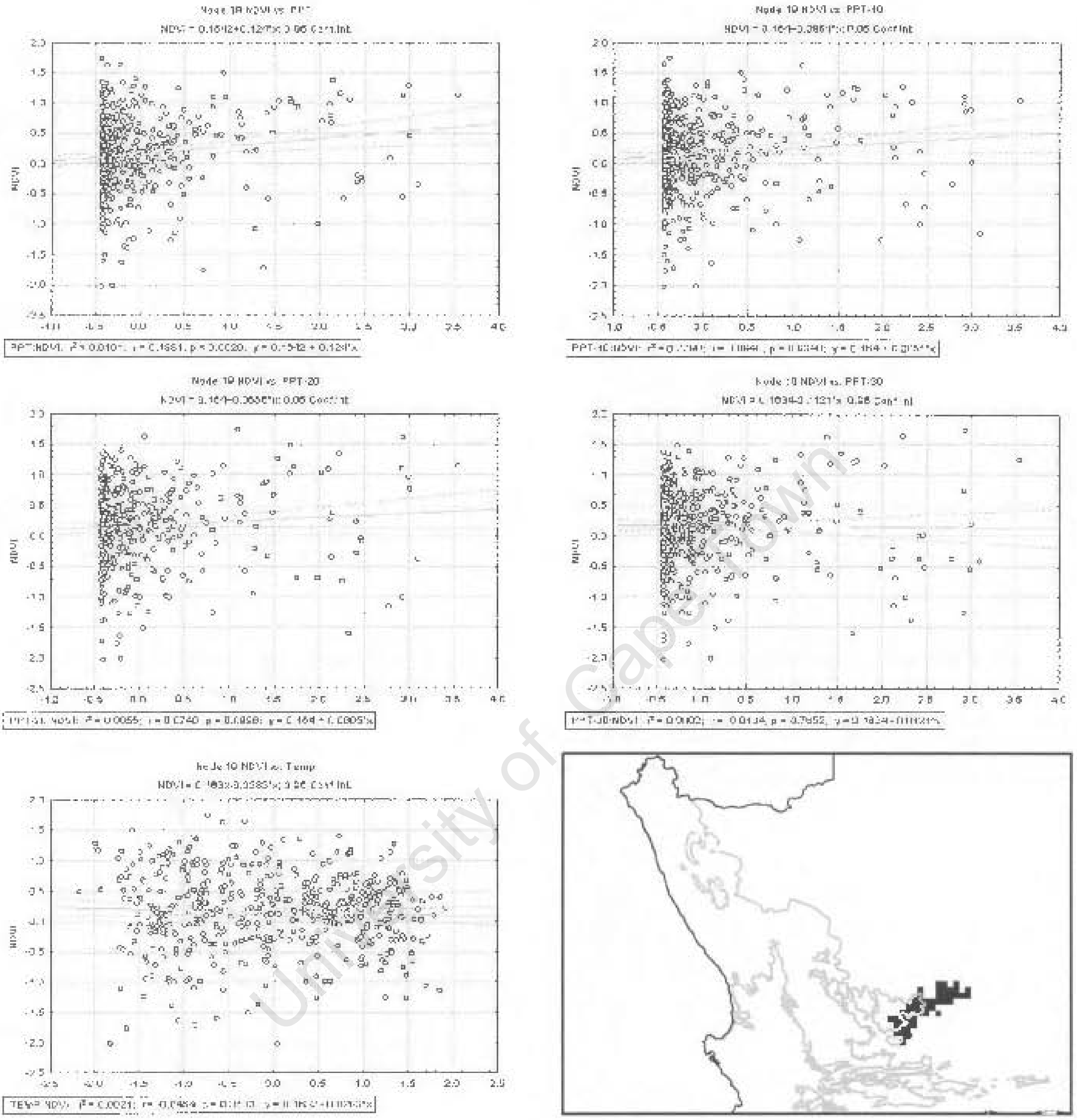
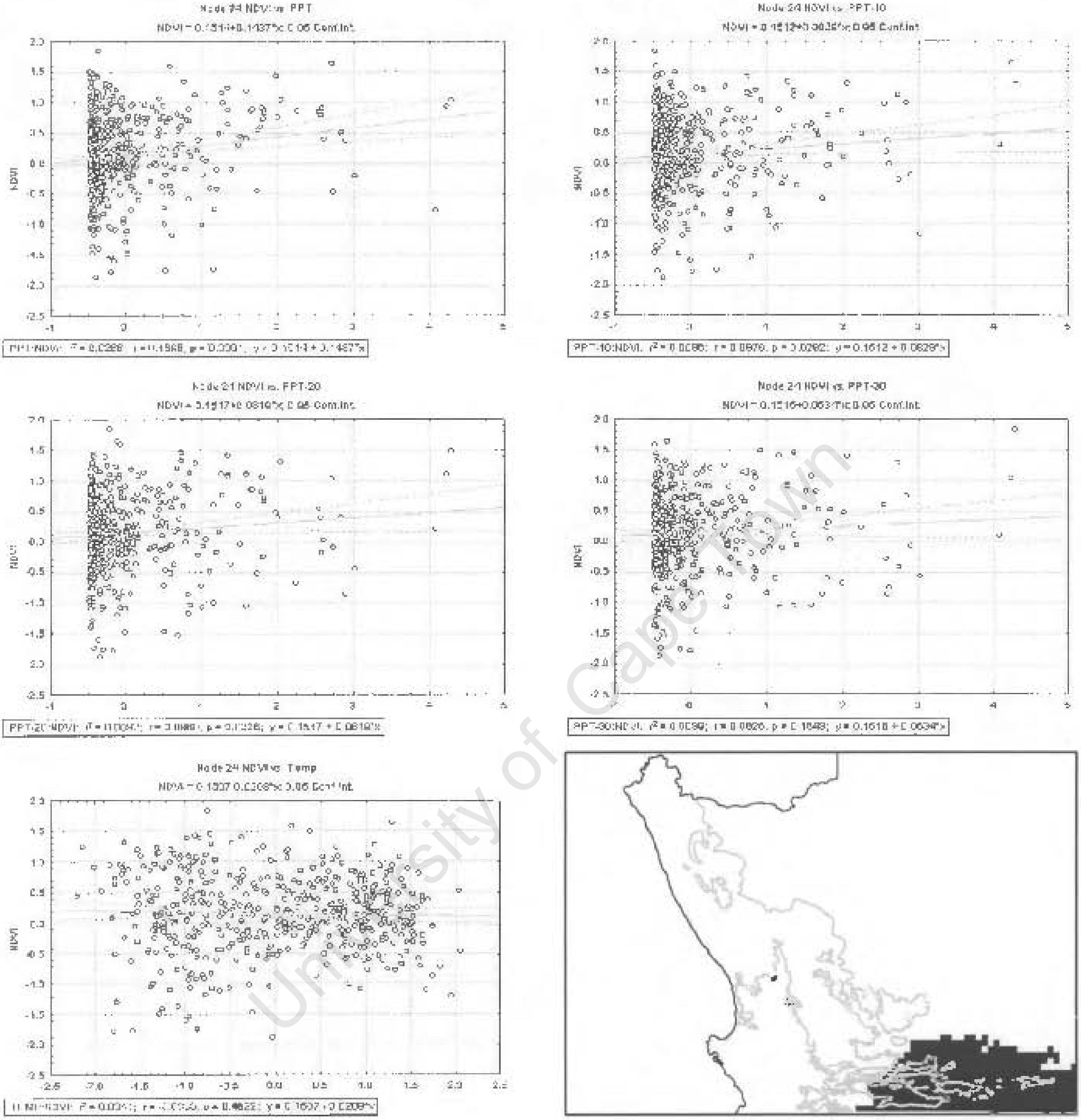


Figure B.3: Som node 19 scatterplots



Node 24 NDVI vs. PPT

NDVI = 0.1514+0.1487*x; 0.95 Conf.Int.

Node 24 NDVI vs. PPT-10

NDVI = 0.1512+0.0628*x; 0.95 Conf.Int.

Node 24 NDVI vs. PPT-20

NDVI = 0.1517+0.0819*x; 0.95 Conf.Int.

Node 24 NDVI vs. PPT-30

NDVI = 0.1516+0.0634*x; 0.95 Conf.Int.

Node 24 NDVI vs. Temp

NDVI = 0.1507 0.0208*x; 0.95 Conf.Int.

Figure B.4: Som node 24 scatterplots

Appendix C

Table C.1: Table of correlation, r-square and percent variance explained for SOM Analysis

Node	Variable	Sign	Correlation(r)	r-square	% Variance
0	PPT	+	0.2430*	0.0591	5.91%
	PPT-10	+	0.2204*	0.0486	4.86%
	PPT-20	+	0.2102*	0.0442	4.42%
	PPT-30	+	0.1490	0.0222	2.22%
	Temp	-	-0.4525*	0.2048	20.48%
1	PPT	+	0.2039*	0.0416	4.16%
	PPT-10	+	0.1733	0.0300	3.00%
	PPT-20	+	0.1601	0.0256	2.56%
	PPT-30	+	0.0949	0.0090	0.90%
	Temp	-	-0.3657*	0.1338	13.38%
2	PPT	+	0.1151	0.0132	1.32%
	PPT-10	+	0.0663	0.0044	0.44%
	PPT-20	+	0.0383	0.0015	0.15%
	PPT-30	-	-0.0384	0.0015	0.15%
	Temp	-	-0.2202*	0.0485	4.85%
6	PPT	+	0.2723*	0.0742	7.42%
	PPT-10	+	0.2414*	0.0583	5.83%
	PPT-20	+	0.2353*	0.0554	5.54%
	PPT-30	+	0.1425	0.0203	2.03%
	Temp	-	-0.4067*	0.1654	16.54%
7	PPT	+	0.1636	0.0268	2.68%
	PPT-10	+	0.1259	0.0159	1.59%
	PPT-20	+	0.1068	0.0114	1.14%
	PPT-30	+	0.0258	0.0007	0.07%
	Temp	-	-0.2654	0.0704	7.04%
12	PPT	+	0.2736*	0.0748	7.48%
	PPT-10	+	0.2267*	0.0514	5.14%
	PPT-20	+	0.2214*	0.0490	4.90%
	PPT-30	+	0.1174	0.0138	1.38%
	Temp	-	-0.3455	0.1193	11.93%
13	PPT	+	0.2106*	0.0444	4.44%
	PPT-10	+	0.1614	0.0261	2.61%
	PPT-20	+	0.1528	0.0233	2.33%
	PPT-30	+	0.0521	0.0027	0.27%
	Temp	-	-0.2904	0.0843	8.43%
14	PPT	+	0.1303	0.0170	1.70%
	PPT-10	+	0.1016	0.0103	1.03%
	PPT-20	+	0.0653	0.0043	0.43%
	PPT-30	-	-0.0281	0.0008	0.08%
	Temp	-	-0.1378	0.0190	1.90%
18	PPT	+	0.1615	0.0261	2.61%
	PPT-10	+	0.0926	0.0086	0.86%
	PPT-20	+	0.1061	0.0113	1.13%
	PPT-30	+	0.0207	0.0004	0.04%
	Temp	-	-0.2012*	0.0405	4.05%
19	PPT	+	0.1381	0.0191	1.91%
	PPT-10	+	0.0948	0.0090	0.90%
	PPT-20	+	0.0740	0.0055	0.55%
	PPT-30	-	-0.0134	0.0002	0.02%
	Temp	-	-0.0454	0.0021	0.21%
24	PPT	+	0.1684	0.0284	2.84%
	PPT-10	+	0.0986	0.0097	0.97%
	PPT-20	+	0.0951	0.0090	0.90%
	PPT-30	+	0.0616	0.0038	0.38%
	Temp	-	-0.0330	0.0011	0.11%

Appendix D

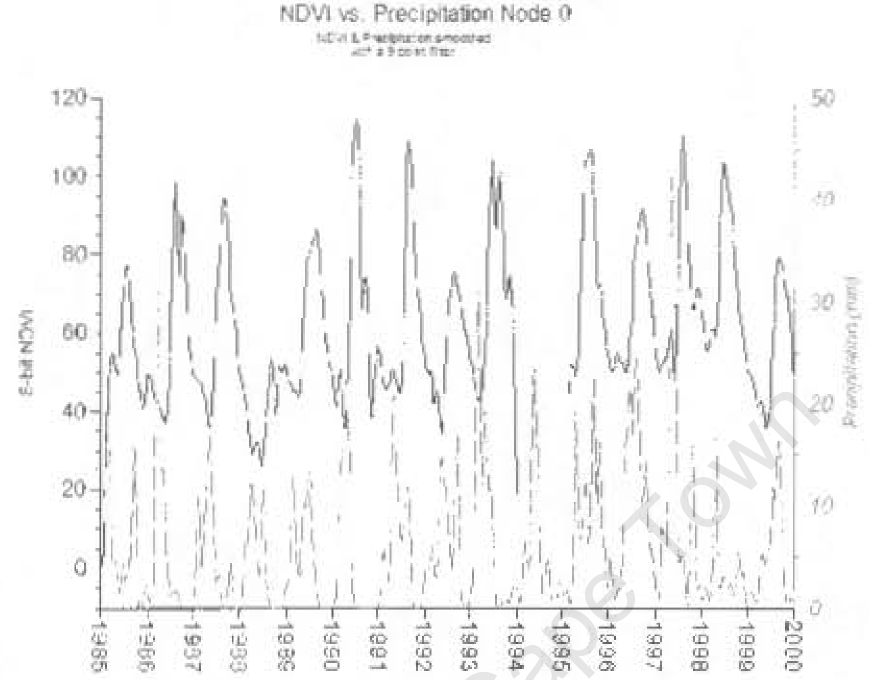


Figure D.1: Graph of NDVI and Precipitation through time for Node 0

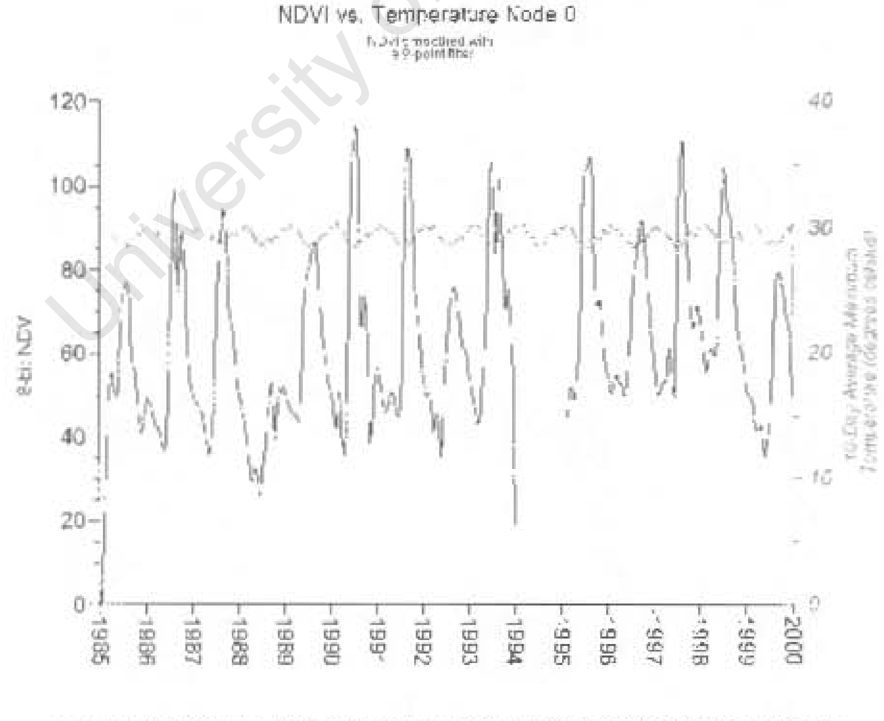


Figure D.2 Graph of NDVI and temperature through time for Node 0

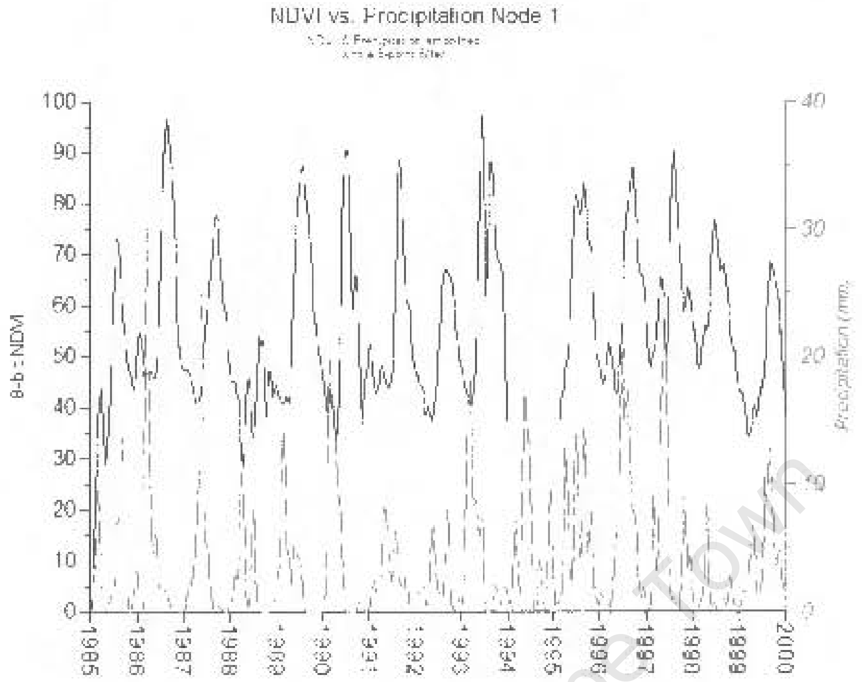


Figure D.3 Graph of NDVI and Precipitation through time for Node 1

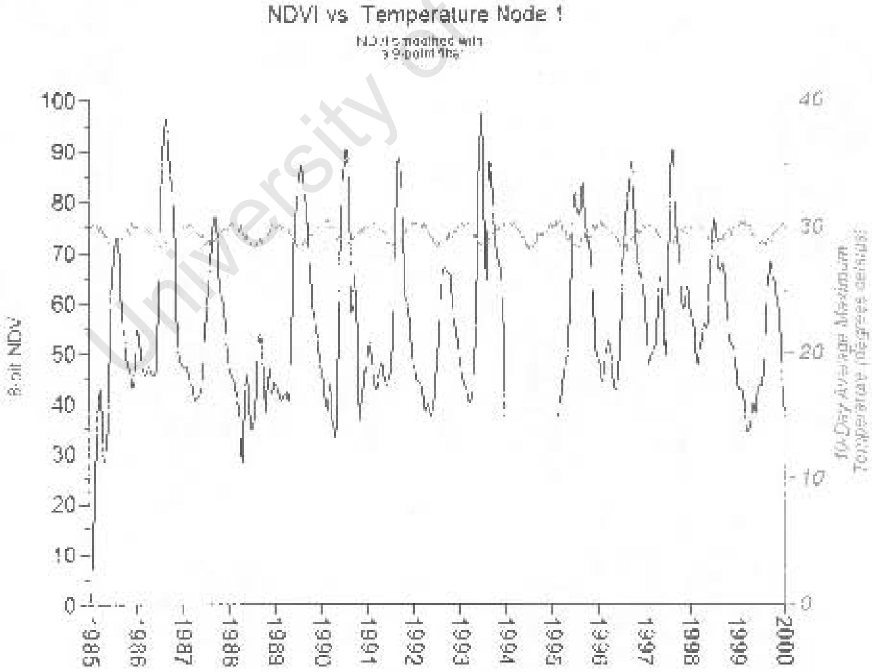


Figure D.4 Graph of NDVI and Temperature through time for Node 1

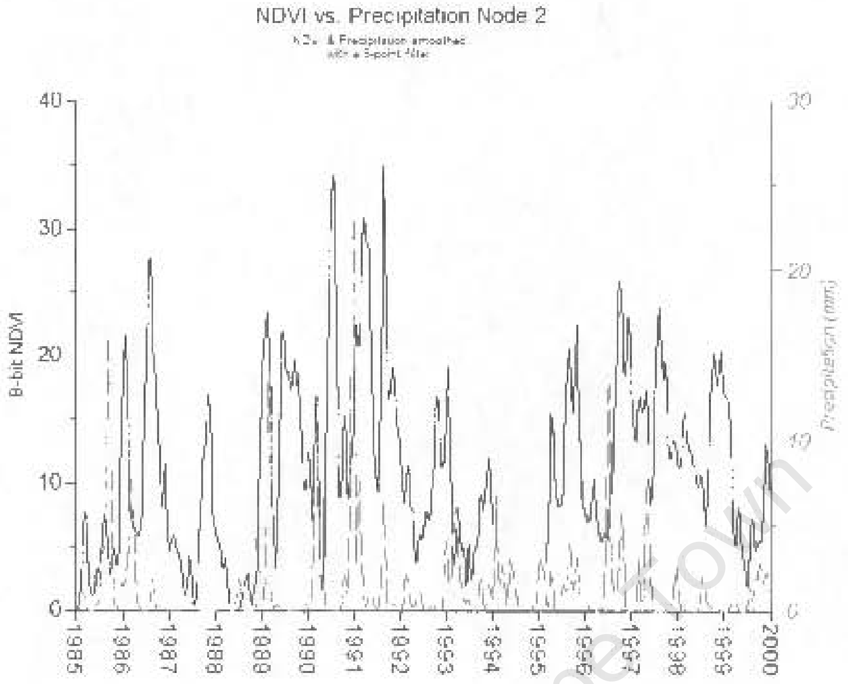


Figure D.5 Graph of NDVI and Precipitation through time for Node 2

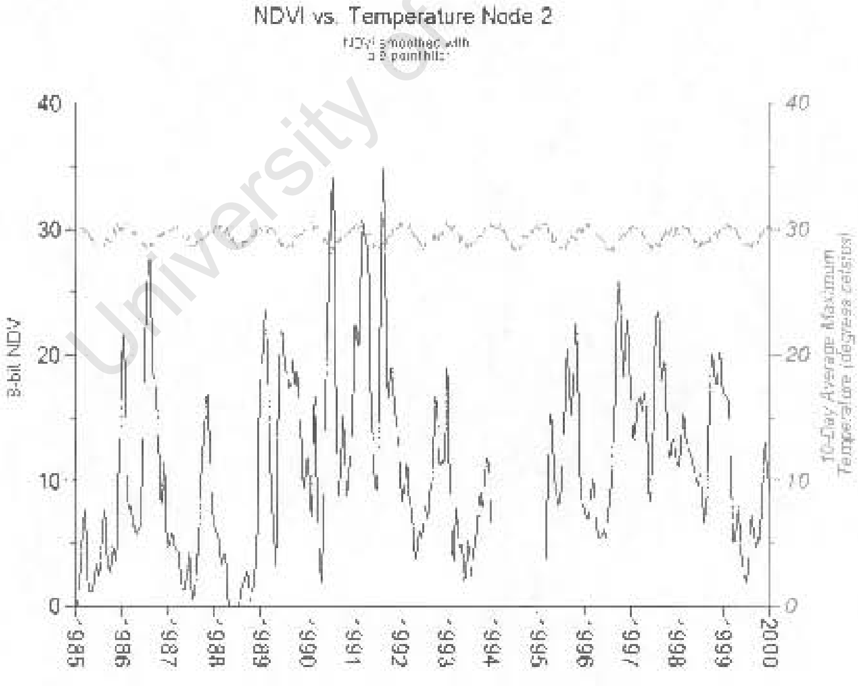


Figure D.6 Graph of NDVI and Temperature through time for Node 2

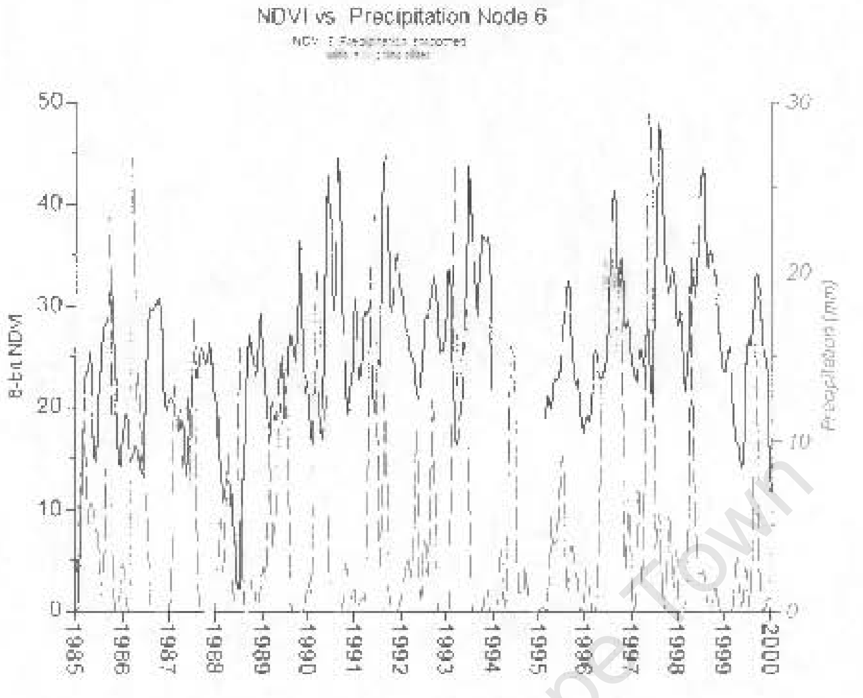


Figure D.7 Graph of NDVI and Precipitation through time for Node 6

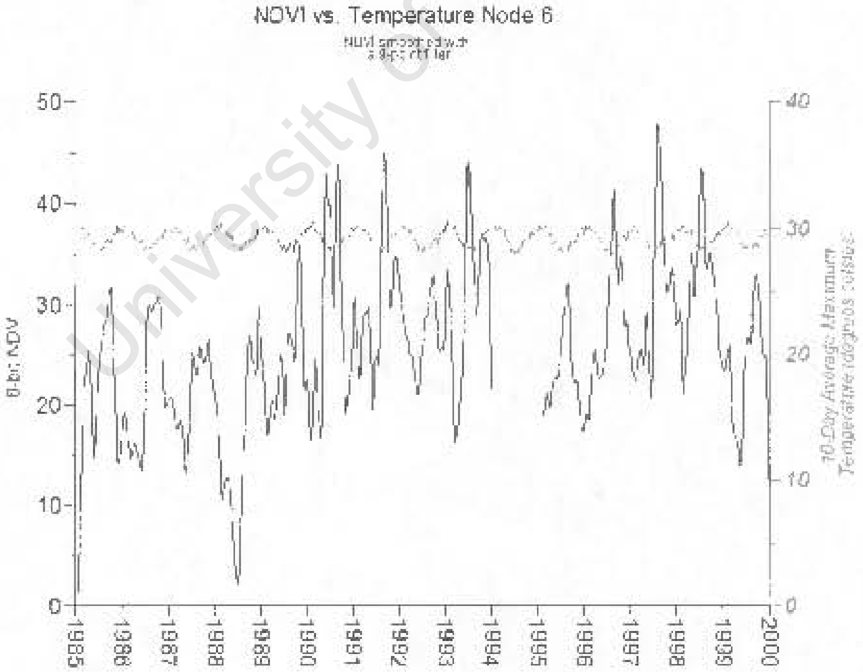


Figure D.8 Graph of NDVI and Temperature through time for Node 6

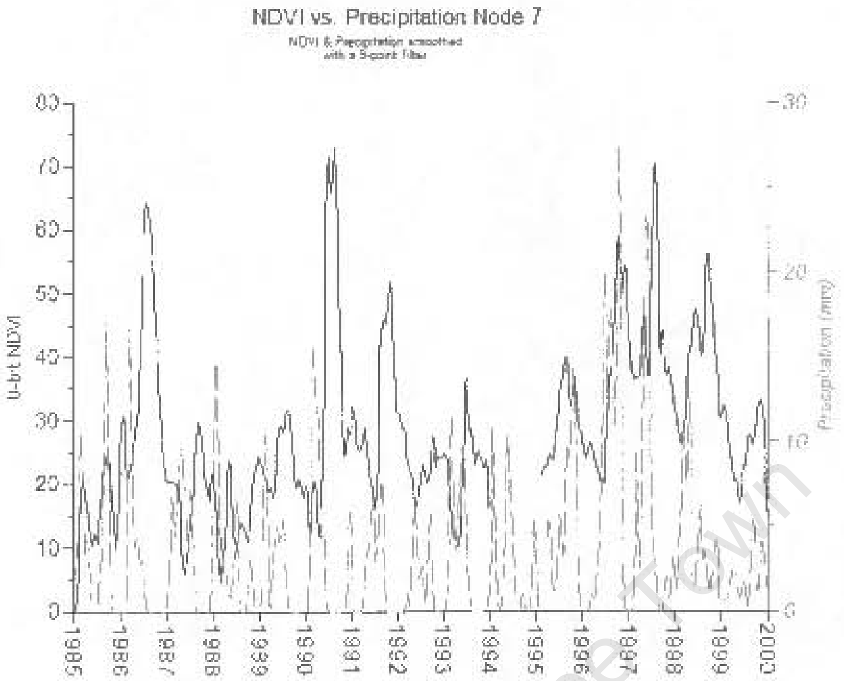


Figure D.9 Graph of NDVI and Precipitation through time for Node 7

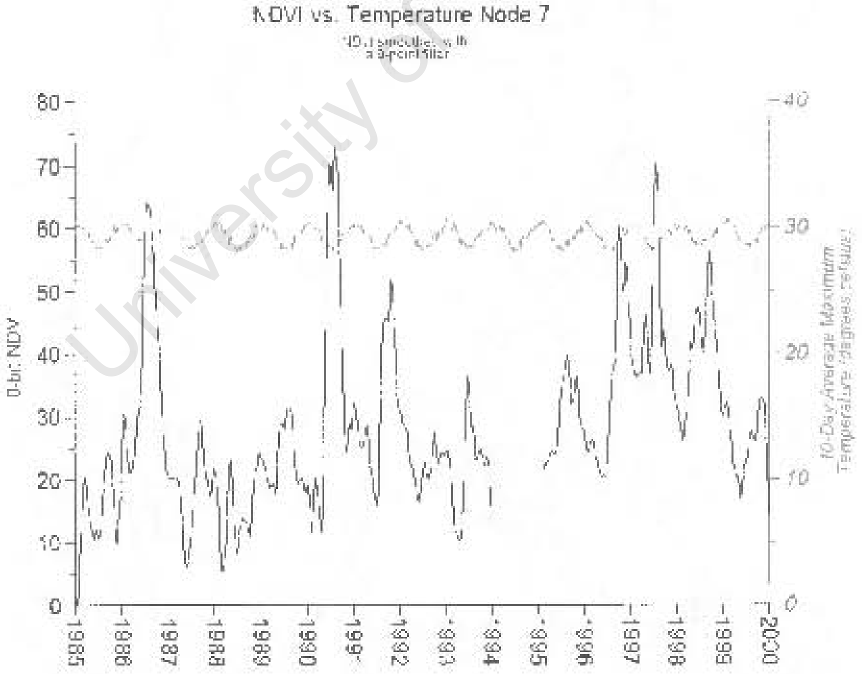


Figure D.10 Graph of NDVI and Temperature through time for Node 7

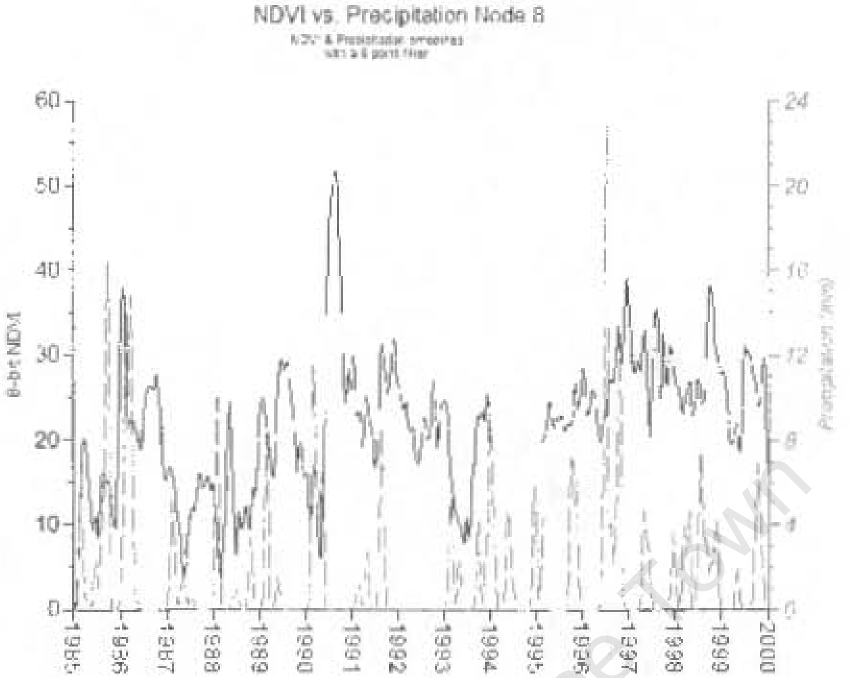


Figure D.11 Graph of NDVI and Precipitation through time for Node 8

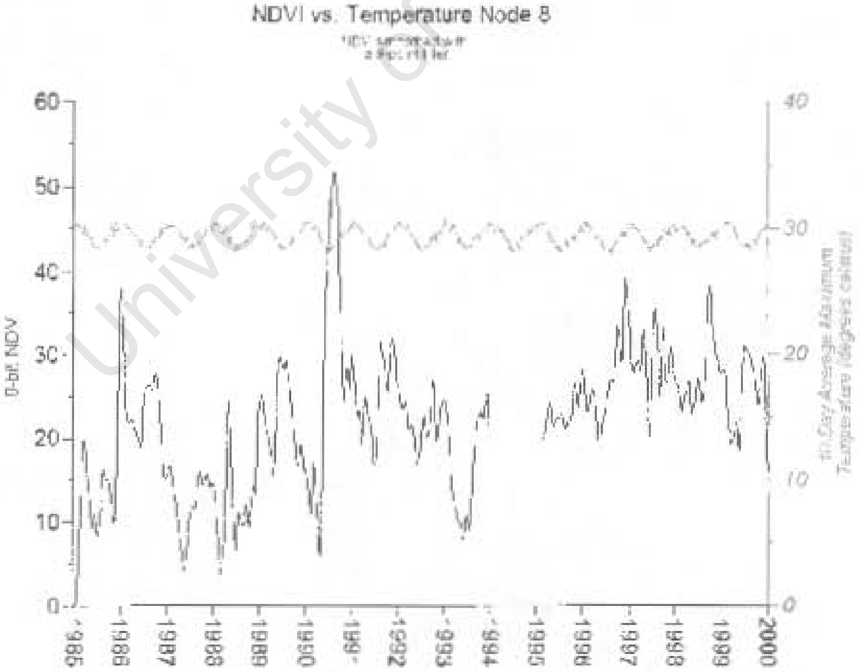


Figure D.12 Graph of NDVI and Temperature through time for Node 8

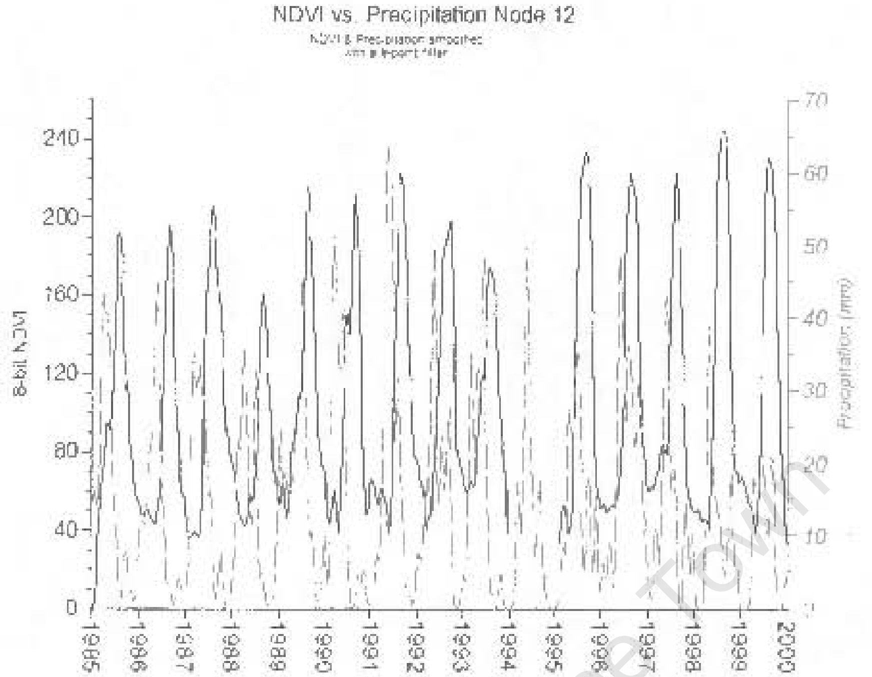


Figure D.13 Graph of NDVI and Precipitation through time for Node 12

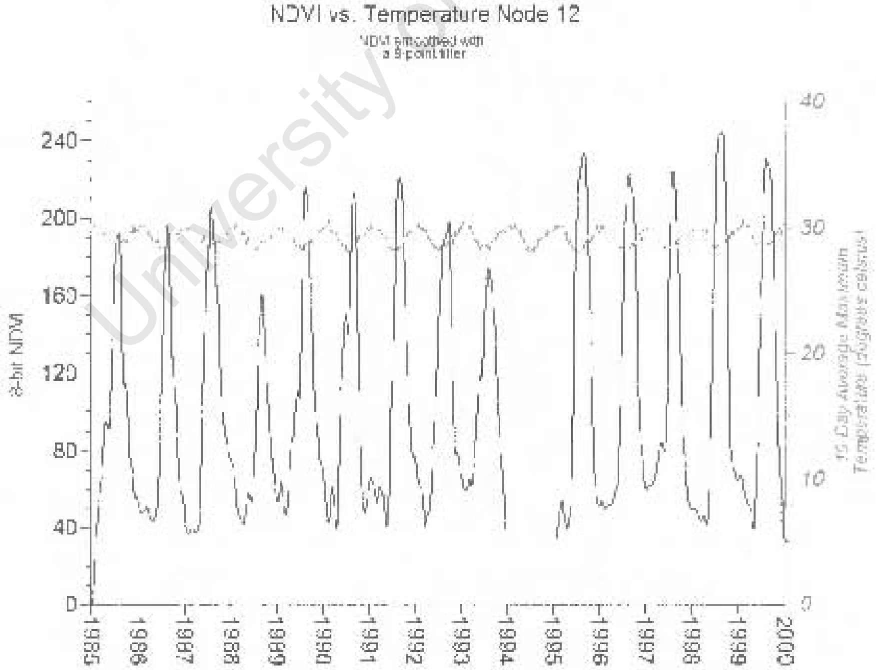


Figure D.14 Graph of NDVI and Temperature through time for Node 12

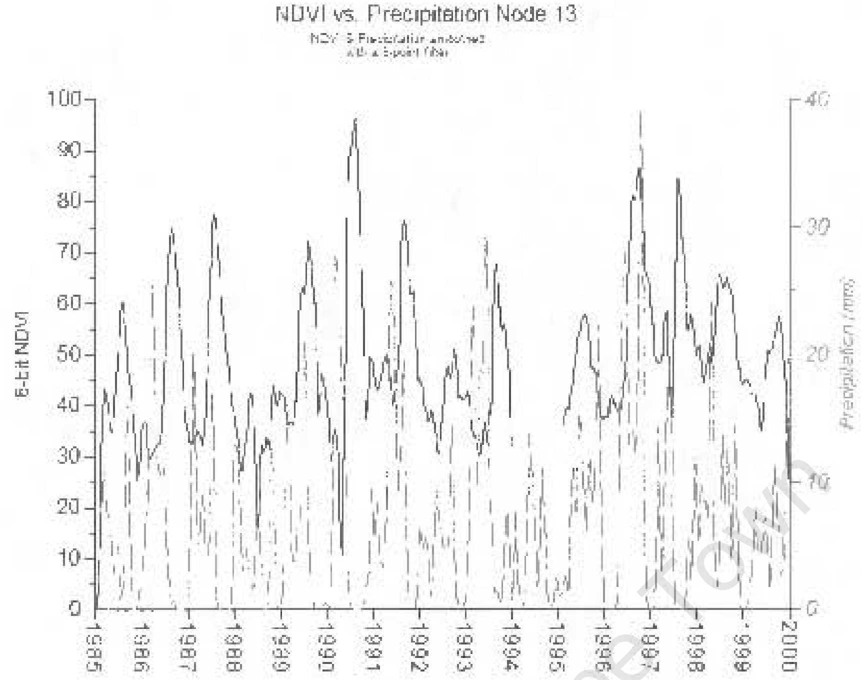


Figure D.15 Graph of NDVI and Precipitation through time for Node 13

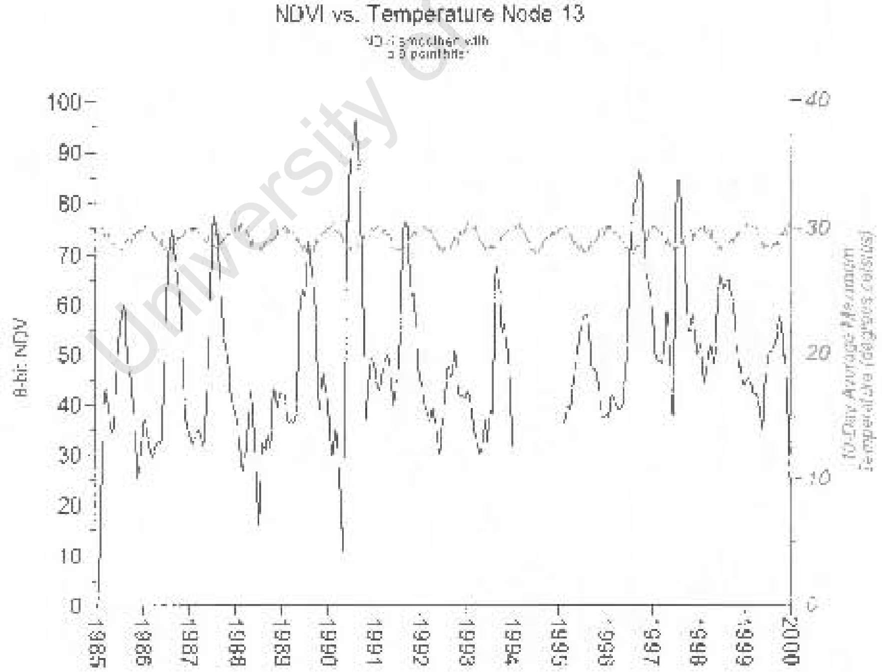


Figure D.16 Graph of NDVI and Temperature through time for Node 13

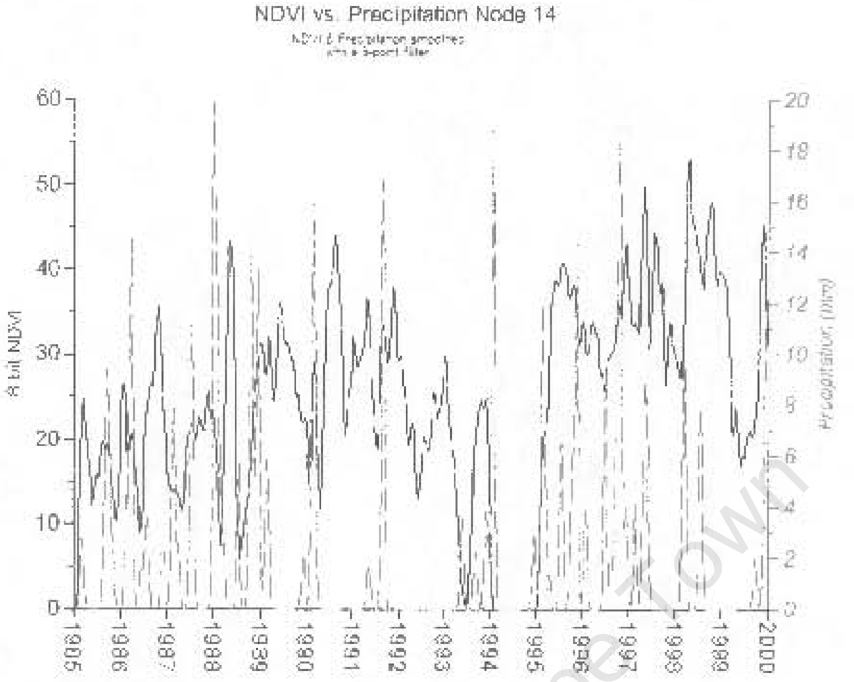


Figure D.17 Graph of NDVI and Precipitation through time for Node 14

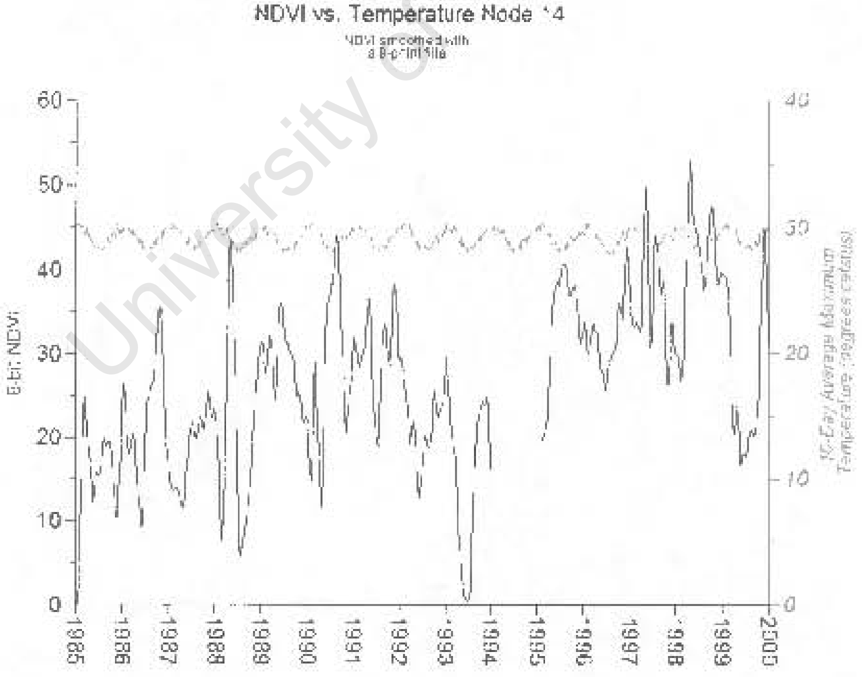


Figure D.18 Graph of NDVI and Temperature through time for Node 14

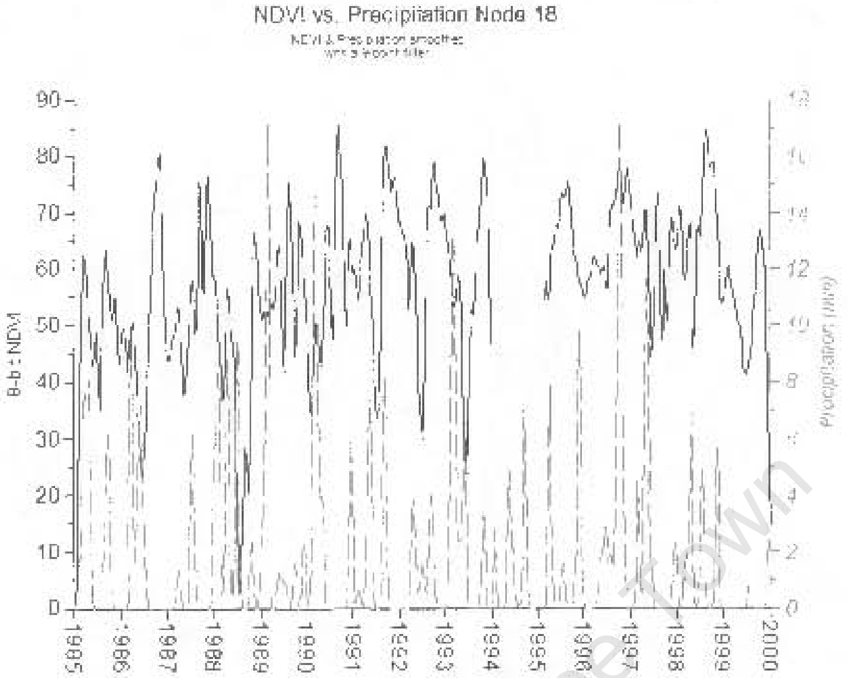


Figure D.19 Graph of NDVI and Precipitation through time for Node 18

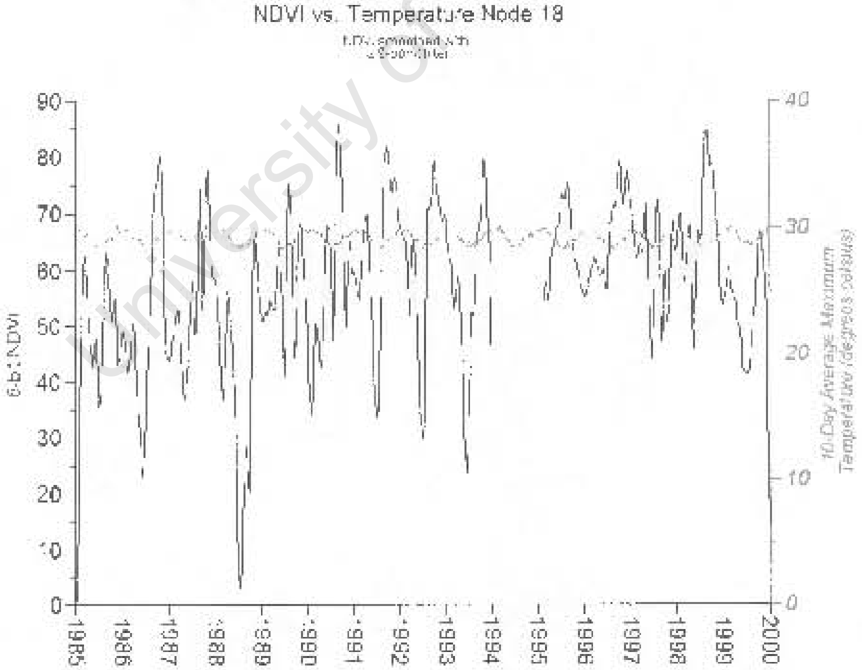


Figure D.19 Graph of NDVI and Temperature through time for Node 18

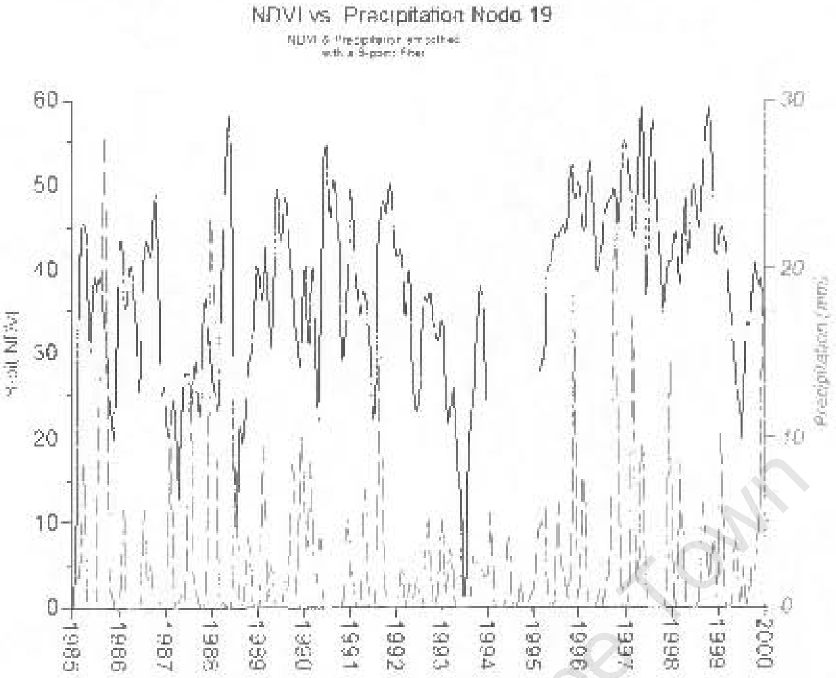


Figure D.20 Graph of NDVI and Precipitation through time for Node 19

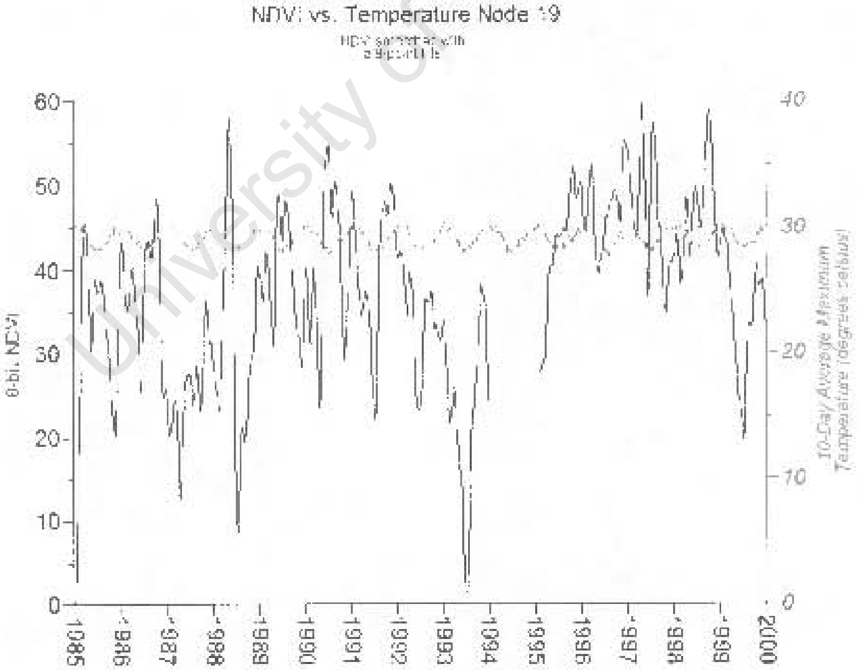


Figure D.20 Graph of NDVI and Temperature through time for Node 19

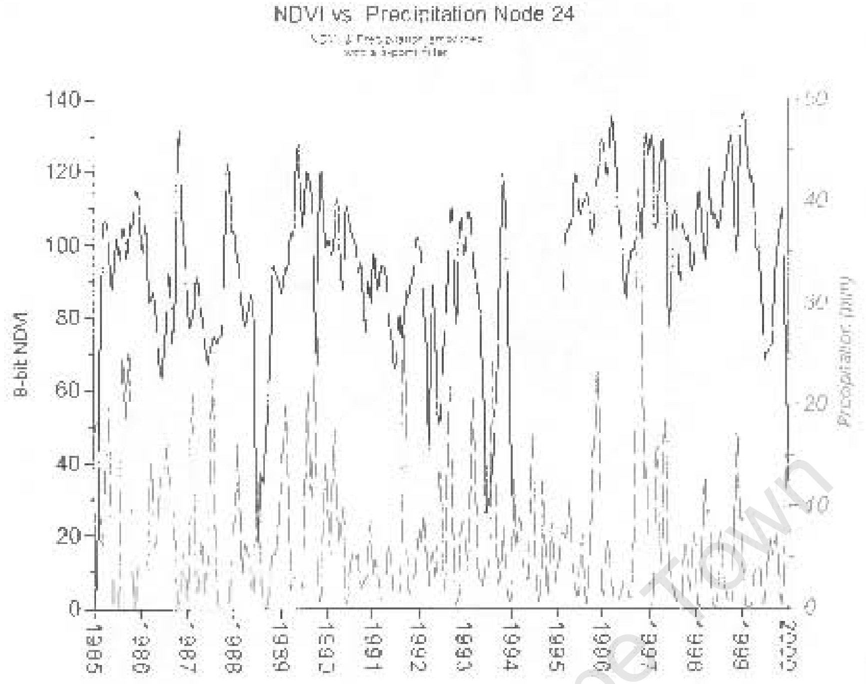


Figure D.21 Graph of NDVI and Precipitation through time for Node 24

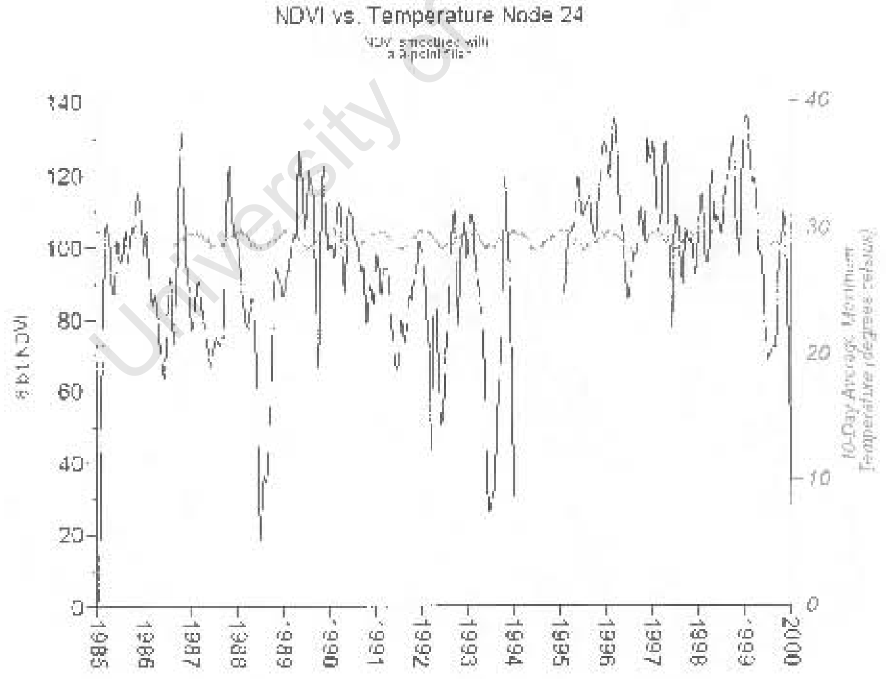


Figure D.22 Graph of NDVI and Temperature through time for Node 24