# The Application of a Landscape Diversity Index Using Remote Sensing and Geographical Information Systems to Identify Degradation Patterns in the Great Fish River Valley, Eastern Cape Province, South Africa

THESIS

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*To my wife Leonie, without whom there would not have been a thesis*

# ABSTRACT

Using a range of satellite-derived indices I describe, monitor and predict vegetation conditions that exist in the Great Fish River Valley, Eastern Cape. The heterogeneous nature of the area necessitates that the mapping of vegetation classes be accomplished using a combination of a supervised approach, an unsupervised approach and the use of a Moving Standard Deviation Index (MSDI). Nine vegetation classes are identified and mapped at an accuracy of 84%. The vegetation classes are strongly related to land-use and the communal areas demonstrate a reduction in palatable species and a shift towards dominance by a single species. Nature reserves and commercial rangeland are by contrast dominated by good condition vegetation types.

The Modified Soil Adjusted Vegetation Index (MSAVI) is used to map the vegetation production in the study area. The influence of soil reflectance is reduced using this index. The MSAVI proves to be a good predictor of vegetation condition in the higher rainfall areas but not in the more semi-arid regions. The MSAVI has a significant relationship to rainfall but no absolute relationship to biomass. However, a stratification approach (on the basis of vegetation type) reveals that the MSAVI exhibits relationships to biomass in vegetation types occurring in the higher rainfall areas and consisting of a large cover of shrubs.

A technique based on an index which describes landscape spatial variability is presented to assist in the interpretation of landscape condition. The research outlines a method for degradation assessment which overcomes many of the problems associated with cost and repeatability. Indices that attempt to provide a correlation with net primary productivity, e.g. NDVI, do not consider changes in the quality of net primary productivity. Landscape variability represents a measure of ecosystem change in the landscape that underlies the degradation process. The hypothesis is that healthy/undisturbed/stable landscapes tend to be less variable and homogenous than their degraded heterogenous counterparts. The Moving Standard Deviation Index (MSDI) is calculated by performing a 3 x 3 moving standard deviation window across Landsat Thematic Mapper (TM) band 3. The result is a sensitive indicator of landscape condition which is not affected by moisture availability and vegetation type. The MSDI shows a significant negative relationship to NDVI confirming its relationship to condition.

The cross-classification of MSDI with NDVI allows the identification of invasive woody weeds which exhibit strong photosynthetic signals and would therefore be categorised as good condition using NDVI. Other ecosystems are investigated to determine the relationship between NDVI and MSDI. Where increase in NDVI is disturbance-induced (such as the Kalahari Desert) the relationship is positive. Where high NDVI values are indicative of good condition rangeland (such as the Fish River Valley) the relationship is negative. The MSDI therefore always exhibits a significant positive relationship to degradation irrespective of the relationship of NDVI to condition in the ecosystem.

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# TABLE OF CONTENTS

# LIST OF FIGURES

# LIST OF PHOTOGRAPHS

# LIST OF PLATES

# LIST OF TABLES

# CHAPTER 1

# INTRODUCTION

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*"To gain control over the soil is the greatest achievement of which mankind is capable. The organization of civilized societies is founded upon the measures taken to wrest control of the soil from wild Nature, and not until complete control has passed into human hands can a stable superstructure of what we call civilization be erected on the land....Soil erosion is altering the course of world history more radically than any war or revolution. Erosion is humbling mighty nations, re-shaping the domestic and external policies and once and for all it has barred the way to the El Dorado that a few years ago seemed almost within reach."* (Jacks, 1939, pp. 313)

## 1.1 The Land Degradation Problem

Whilst land degradation has long been regarded as a major problem in South Africa's arid and semi-arid rangelands (Acocks, 1953; Acocks and Tidmarsh, 1951; Stocking, 1995), little is known of its true extent. Each year, it is estimated that South Africa loses approximately 300-400 million tons of soil as a consequence of soil erosion, making erosion in some areas the worst in the world (Huntley *et al.*, 1989). The day of reckoning is growing nearer. If the rate of degradation continues at the present rate, the country will eventually be unable to feed its people. The awesome danger South Africa faces is clear: while the demand for food is increasing by 3% per year, the agricultural capacity is cut by the same percentage for every centimetre of soil lost (Stocking, 1995).

The past decade has witnessed a growing concern regarding the phenomenal amount and severity of land degradation taking place throughout the world. With this growing concern comes not only an increasing need to monitor this phenomenon accurately but to predict which areas are in the infancy stages of desertification so that remedial action can be taken. This research demonstrates a method of monitoring degradation patterns that overcomes many of the disadvantages associated with conventional techniques and has the capability to predict which areas are prone to degradation or are in the early stages thereof.

### 1.1.1 Defining Desertification

Desertification is as old as civilization itself. Ancient Sumerian literature, dating back to 2000BC, tells how the felling of Mesapotamian forests turned the great ancient grain producing fields into wastelands (Mainguet, 1991). Nevertheless, it was only the devastating droughts of 1968-73 and the accelerated southward advance of the Sahara desert that led to international discussion regarding the crisis. This lead to the formulation of the United Nations Conference on Desertification (UNCOD). At a meeting convened in Nairobi, Kenya in 1978, UNCOD defined desertification as:

> *"Desertification is the diminution or destruction of the biological potential of land, and can lead ultimately to desert-like conditions. It has an aspect of the widespread deterioration of ecosystems, and has diminished or destroyed the biological potential, i.e. plant and animal production, for multiple use purposes at a time when increased productivity is needed to support growing populations in quest of development."* (UNCOD, 1978, pp. 43)

The 1970's and first half of the 1980's are considered the 'age of wrong perception' of desertification, with many authors subscribing to the 'myth of the encroaching desert'. This assertion reached its peak when Lamprey (1975), attempting to quantify the rate of advance of the Sahara desert margin, affirmed that the southern limit of the Sahara was advancing at a rate of 5.5 km $yr^{-1}$.

During the next 13 years various organisations, throughout the world, attempting to implement various aspects of the United Nations Plan of Action to Combat Desertification (PACD) and make quantitative assessments of desertification, found the above definition to be inadequate. In response, each group developed its own definition, which, not unexpectedly, lead to a significant amount of confusion. In addition, cyclic oscillations of vegetation productivity, related to climate fluctuations had been observed from satellite data (Ahlcrona, 1988). Ahlcrona (1988) concluded that Lamprey (1975) had not made a distinction between short-term drought effects and long-term trends. Furthermore, she observed on satellite images from Central Sudan, that there had been little change in the albedo index or the Normalised Difference Vegetation Index (NDVI). Her fieldwork demonstrated that behind the absence of quantitative change of vegetation a qualitative change was hidden: good pastures were being replaced by unpalatable species. Ahlcrona's conclusions were that degradation had occurred but a change to more desert-like conditions with less vegetation had not taken place. With some irony, Warren and Agnew (1988, pp.72) note "How could one measure the advance of the desert edge, when moreover the edge itself is ill-defined (to say nothing of the poverty of the data)?" The theory of the encroaching desert, which has now been scientifically rejected, is still a fixed idea in the minds of many governments, donors and journalists (Mainguet, 1991).

Mainguet (1991, pp. 4) offers the following definition on desertification:-

> *"Desertification, revealed by drought, is caused by human activities in which the carrying capacity of land is exceeded; it proceeds by exacerbated natural or man-induced mechanisms, and is made manifest by intricate steps of vegetation and soil deterioration which result, in human terms, in an irreversible decrease or destruction of the biological potential of the land and its ability to support population."*

Perhaps, the most significant aspect of this definition of desertification is its focus on 'human impact'. This differentiates the issue of desertification from simple climatic fluctuations, such as drought, that only play the role of 'revealer' of desertification. Etymologically, desertification refers to the change-over that takes place when semi-arid ecosystems become arid or hyper-arid landscapes. This evolution shows itself in two ways: *(1)* deteriorated vegetative cover and *(2)* truncated top soil or soil. This change is irreversible in human terms or within reasonable economical limitations. The concept of desertification is relative in connection with human activities.

### 1.1.2 The Global Extent of the Problem

The World Resources Institute (1992) reports that; over the past 45 years, approximately 11 percent of the Earth's vegetated soils became degraded to the point that their original biotic functions are damaged, and reclamation may be costly or in some cases impossible. It is estimated that between 50,000 and 70,000 $km^2$ of useful land is going out of production every year in the world as a consequence of desertification (Food and Agricultural Organsiation, 1984). Climatic models suggest that during the next century the average temperatures and precipitation values are likely to change over large areas of the globe (Emmanuel *et al.*, 1985) exacerbating the effects of human mismanagement; as a result widespread adjustments are likely to occur in the distribution of terrestrial vegetation (Schlesinger *et al.*, 1990). Areas that have been arid during the last several centuries cannot be said to have become 'desertified,' even if they are now further affected by human exploitation. Historical evidence shows that natural climatic patterns produce cycles of drought, followed by periods of higher rainfall (Nicholson, 1978). Losses of agricultural productivity and the associated social and economic disruptions during drought cannot be said to represent desertification unless the landscape is so altered that a full recovery during moist conditions is impossible. It is important to note that some authors for example Nelson (1988) expressed the view that desertification, as an irreversible state, has probably been exaggerated, although classifying it as a serious problem is correct. Topsoil lost to erosion can usually be rebuilt given time, and the well-known process of biological succession shows that forest ecosystems can replace an abandoned field given a few centuries (Nelson, 1988). Human effort can accelerate the regeneration of topsoil or ecosystems, shortening the need for regeneration, but this may require considerable economic expense. In extreme cases of degradation where the clay fraction of the soil is nearly completely lost or invading flora becomes too firmly entrenched, natural recovery to the original ecosystem will not occur.

## 1.2 Why Satellite Remote Sensing?

> *"Remote sensing is the science and art of obtaining information about an object, area or phenomenon through the analysis of data acquired by a device that is not in contact with the object, area or phenomenon under investigation."*(Lillesand and Kiefer, 1994, pp. 1).

The collective area of rangelands constitutes 40-50% of the global land surface and presents significant logistical challenges for obtaining ecological data for large, heterogeneous areas quickly, cheaply and with a significant level of accuracy. Rangelands are often too extensive, heterogeneous and inaccessible to effectively inventory or monitor by ground surveys. (Wessman *et al.*, 1995).

Problems with survey methodology arise as the most accurate techniques involve intensive measurement of soil or plant community properties (Foran *et al.*, 1986). These techniques are either too slow or too expensive for use at more than a few points in the landscape yet many locations must be surveyed to represent the highly diverse landscapes common in South African rangelands. Less intensive techniques such as air photo interpretation can provide better areal coverage but with far less accuracy and at the cost of sacrificing quantitative data for subjective assessment (Pickup and Chewings, 1994). Furthermore, these techniques are not sufficiently repeatable. Therefore, they are of little use in monitoring change over time. In particular, subjective assessments of land degradation during droughts indicate a far worse situation than if the assessment is made shortly after good rains, yet periodic droughts and 'times of plenty' are a normal part of the rangeland ecosystem (Freidel *et al.*, 1990). Further difficulties arise because natural processes can produce effects similar to grazing-induced land degradation. The loss of vegetation cover which occurs, even in minor droughts is regularly mistaken for the effects of soil erosion yet the vegetation may recover after the rain. There are also complex spatial patterns in the landscape that result from natural erosion (Pickup and Chewings, 1994).

Satellite remote sensing techniques have now become the single most effective method for land-cover and land-use data acquisition over extensive rangeland, providing accurate and cost-effectiveness assessment of range condition (Thompson, 1995). Remote sensing is relatively fast and economical for gross estimation when compared with any other method of surveying. Satellite data provides reliable, near real-time and unbiased information. Most ground-based range assessment procedures require information to be collected at a limited number of 'representative' or relatively homogenous points. These units are often incorrectly assumed, interpolated or extrapolated to represent the entire landscape. Remotely sensed data cover the entire landscape and allow it to be analysed as a unit. A further useful property of these data is the repeated coverage of an area they provide, which, with suitable correction procedures, can be used to make a quantitative assessment of change over time (Pickup and Chewings, 1994).

The use of remote sensing as a tool for analyses of environmental, cultural and natural resource management characteristics is well documented (Holtz, 1985; Jensen, 1986; Lillesand and Kiefer, 1994; Richason, 1983). In recent years many innovative techniques have been developed to sense remotely the physical and biological characteristics of the land surface. These are becoming increasingly important for monitoring arid environments, where sparse populations and inaccessibility often preclude the wide-scale use of conventional ground-based methods.

Satellite remote sensing offers a possible solution to the need to survey all corners of the globe with repeated, ongoing grand observations (Ray, 1995). However, believing that remote sensing can entirely supplant the use of ground observations, as widely believed in the 1970's and early

1980's would be incorrect. This was in part driven by the desire to find a world-wide unique idea of desertification, and to replace the need to investigate every corner of the planet with a general view (Mainguet, 1991). However, satellite remote sensing should provide a powerful adjunct to ground observations by extrapolating observations made at a single point in a given region and providing survey data to aid in targeting ground observations. In this way, ground observation is, in a sense, attached at both ends to the satellite observations, with the satellite remote sensing effectively multiplying the value of the data acquired on the ground and pointing out the places where additional and repeat ground surveys are most needed (Ray, 1995). Remote sensing supported by verifications on the ground are very important for a better perception of the extent and processes of degradation.

## 1.3 Research Objectives

The Mid Fish River Valley, Eastern Cape, South Africa is an exceedingly heterogeneous area. These 'heterogeneities' present significant problems to conventional techniques but provide an excellent opportunity to develop a landscape pattern index which defines the primary objective of the study.

The specific objectives of this study are to:-

- ♦ Identify and map the **contemporary vegetation types** occurring in the study area using the satellite data. A conventional classification and a multi-temporal approach will be utilised and the results of each will then be compared to determine whether the use of multi-temporal data can enhance the quality of the classification. The accuracy of the classification will then be determined by correlating surface reference data with that derived from the classification.
- ♦ Map the **vegetation production** in the study area using a vegetation index. The result will be statistically analysed to explore the relationship of the index to rangeland condition to establish whether vegetation indices can be used to reliably differentiate between good and poor condition rangeland. The relationship of the vegetation index to rainfall and altitude will be investigated and a preliminary investigation into the relationship of the vegetation index to green biomass will be conducted.

- The primary objective of the study is to determine whether other techniques using satellite data (which do not rely on the so-called 'green bump' used in all contemporary vegetation indices) can be used to predict rangeland condition. The technique will rely on the **relationships of pixels to their neighbours** and be sensitive to the underlying mechanisms of desertification and not absolute pixel reflectance and will utilise some findings from recent landscape pattern studies. The index's relationship to rangeland condition, vegetation production, vegetation type and the operation of the index in four other different ecosystems will be investigated to assess the repeatability of the index. It is envisaged that the findings of this research will help contribute significantly to the existing body of landscape pattern theory.

## 1.4 Conclusion

Most definitions of desertification contain explicit reference to drought as the basic cause, when drought in fact only plays the role of revealer and intensifier of the phenomenon. "We lack methods of analysing these effects and the scattered literature has no case studies differentiating between causes, processes and impacts and thereby identifying the levels at which solutions may be found" (Mainguet, 1991, pp. 5). The battle against desertification requires overlapping short-term physical and longer-term social strategies. It is beyond the scope of this study to recommend long-term social strategies for arresting desertification. However, remote sensing technologies provide a powerful means of monitoring degradation characteristics of large areas of land. To identify areas in the process of becoming desertified it is necessary to understand the mechanisms and processes of degradation that underlies the various forms of desertification. By understanding these processes and with the use of remote sensing technologies it is possible for indices, developed through the use of these techniques, to serve as an 'early warning' for areas that are susceptible to desertification.

Climate models suggest that future global warming may reduce soil moisture over large semi-arid regions of the globe (Emmanuel *et al.*, 1985). This climate change is likely to exacerbate the degradation of semi-arid lands that will be caused by rapidly expanding human populations during the next decade. Marginal areas are particularly sensitive to change, and therefore, studies of ecosystem function at the transition between semi-arid and arid ecosystems offer an effective index of human perturbation of the global system (Schlesinger *et al.,* 1990).

This research demonstrates how remote sensing can be used to understand and monitor land degradation in an area across three markedly different land-use categories and across a steep rainfall gradient. The overall complexity of the area provides an excellent opportunity to test a new index of rangeland condition and compare it with, as well as draw from, conventional techniques.

# CHAPTER 2

# THEORETICAL BACKGROUND

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The theoretical background presented here begins with an investigation into the processes of land degradation and factors that exacerbate the effects thereof. A description of the vital role of vegetation in any ecosystem and the part that remote sensing can play in the monitoring of vegetation characteristics is then presented. An overview of remote sensing is then discussed. The overview includes a description of the Landsat Thematic Mapper (TM) satellite and some commonly used broad techniques and concepts (such as image correction procedures, a supervised classification and an unsupervised classification and the theory behind vegetation indices). The last section of the chapter deals with existing landscape pattern theory which will be applied to the satellite data to derive an index of landscape condition.

## 2.1 Agents of Land Degradation

The United Nations Conference on Desertification (UNCOD) (1978, pp. 43) defined land degradation as follows:

> *"Degradation implies reduction of resource potential by one or a combination of processes acting on the land. These processes include water erosion, wind erosion and sedimentation by those agents, long-term reduction in the amount or diversity of natural vegetation, where relevant and salinization and sodication"* (UNCOD, 1978).

Mainguet (1991) lists the following as the 'paths to desertification:' wind erosion of soil, salinisation of soil, vegetative degradation, water erosion of soil, soil crusting and compaction and reduction in soil organic matter. Through these different processes, the land is made barren, and may effectively become a desert, even without climatic change. Before continuing further to consider how to assess and monitor land degradation, this section will look briefly at some of these processes. Water is the major agent of erosion in Southern Africa and therefore soil erosion will be the major process discussed. This brief examination of the processes and mechanisms of degradation, provides the basis for the monitoring of the spread of desertification

### 2.1.1 Water Erosion

Soil erosion is the removal of soil from the land surface and its associated transport and deposition in a different location. The World Resources Institute (1992) indicates that water erosion is the most serious form of land degradation at the global scale. Beckedahl *et al.* (1988) conclude that accelerated erosion is a manifestation of ecological disequilibrium. The fine fraction of the soil and the absorbed chemical bases are the most readily removed parts of the soil. Increased erosion can undermine the root systems of plants, and the development of gullies by the erosive power of water can render the land unsuitable for cultivation and ultimately reduce its grazing potential (Dregne, 1983).

Water erosion begins with raindrops striking the ground. The World Meteorological Association (1992) stated that a 4-mm diameter raindrop will strike the ground with enough energy to throw a 0.1 $cm^3$ volume of sand having a density of 2.65 $gcm^{-3}$ to a height of 6 cm. Ellinson (1944) demonstrated that the impact of raindrops also contributed to soil compaction. A raindrop striking a soil aggregate will violently compress the air in the aggregate's pores causing the soil aggregate to explode. Finally, the droplets that raindrops split into when they strike the soil will plug pores in the soil, thereby in cooperation with the soil compaction caused by the raindrop impact, decreasing the permeability of the soil and preventing the infiltration of water (Mainguet, 1991).

Three characteristic forms of water erosion exist namely; sheet, rill and gully erosion. Sheet erosion involves the progressive removal of a relatively thin layer of soil from the surface of the land. The severity of this erosion is closely related to the transporting ability of the flow. This form of erosion, under rangeland conditions, tends to go unnoticed and its effects on productivity manifest only gradually. Consequently this form of land degradation is seldom viewed with concern and is often accepted as a natural process; of interest only in geomorphic terms (Chappell and Brown, 1993). Sheet erosion is normally preceded by more subtle signs of land-degradation, such as an increase in unpalatable species and a decline in vegetation production.

Rill erosion involves the flow of water in 'mini channels' and is usually associated with cultivated lands. Rills are responsible for the passage down the slope of considerable amounts of soil during a season, which results in the general lowering of the arable land.

Gully erosion occurs when the flow in a system of rills becomes large enough to gouge out a channel of significant size, termed a gully. A gully differs from a natural stream in that the water flow is intermittent and only occurs during periods of heavy rain. Unlike a river gullies are not stable landforms, tending to grow in size with time rather than settling into a harmonious balance with the environment. (Ciskei Department of Agriculture and Forestry, 1994). Gullies can gauge to 10 to 15 m deep and extend as much as 30 m in width.

The role played by the soil resource in maintaining the integrity of rangelands systems is widely recognised. Chappell and Brown (1993) claim that the importance of soil overrides the importance of changes in the biotic component in maintaining range productivity.

Broadly speaking, soil erosion results in two major problems:

- Reduced land productivity;
- Silting up of water courses and dams.

The value of land is reduced due to the lowering of the depth of soil available for the growth of crops and natural vegetation. In addition, when gullies are formed, access into lands by vehicles is hampered and cultivation operation within lands restricted. Fields become divided into very small parcels that are inefficient to farm. Gullies become drainage ditches that reduce available soil moisture and lower the water table of adjoining lands. They act as 'quick response' drainage systems resulting in limited water availability. The soil washed off the land is then deposited when the water transporting it slows, for example when it enters a dam. Eventually it is possible for such dams to become completely silted up thereby destroying their usefulness. The sediment loads of the Keiskamma River are among the highest in Southern Africa, with annual sediment volumes reaching almost 1% of the mean annual runoff (Ciskei Department of Agriculture and Forestry, 1994). This poses an economic threat to several major dams. Siltation also increases the danger of flash floods.

Soil erosion is a naturally occurring process; however, where slopes have been cultivated with inadequate conservation measures, a thousand fold increase in soil loss has been measured

(Ciskei Department of Agriculture and Forestry, 1994). Therefore, differentiating between 'natural' erosion and accelerated forms of soil loss is necessary. Weaver (1989) calculated soil erosion rates in the Roxeni Basin, Ciskei, as 113.7 t $ha^{-1}y^{-1}$ in abnormally high years (1983 to 1986). Smith and Stamey (1965) have suggested guidelines for soil erosion rates, in terms of what farmers are likely to achieve in cultivated lands, on slow forming erodible soils. They indicated that for acceptable soil conservation practice the upper limit is 2 t $ha^{-1}y^{-1}$. To reduce this loss of soil to nearer the acceptable limit, it is necessary to locate the most severely eroded areas and apply soil conservation methods.

Weaver (1989) attributes the high rates of erosion in the former Ciskei to bad cultivation practices, overstocking and the occurrence of abnormally high rainfall and runoff following successive years of low rainfall and runoff. Other factors that may increase the rate of soil erosion are the effect of burning and the occurrence of soils with low clay content and large amounts of fine sand.

### 2.1.2 The Effects of Domestic Herbivores

The husbandry of domestic herbivores is widespread in Southern Africa. Domestic animals may have detrimental impacts on the lands that they graze, but the type and degree of the impact are dependent on the type of animal, the length of grazing period and type of land that they are allowed to graze.

Domestic herbivores have many effects on the landscape ranging from the subtle to more obvious at the microscopic or macroscopic scales. It is generally the more obvious macroscopic effects that are observable via remote sensing and since this study is concerned ultimately with remote sensing observables, these will be treated here. However domestic herbivores can graze lands that are otherwise uncultivable, thus increasing the economic value of this land (Okin, 1995).

Domestic herbivores have a major impact on the soils in arid and semi-arid rangelands. The primary contributor to soil quality degradation in all landscapes is the direct action of animals compacting the soil (Jacobs, 1988). This has drastic effects on the microorganisms that are present in the soil. These organisms play a crucial role in the development and maintenance of soils and soil quality. Compaction of soil by domestic animals disrupts the habitats of soil organisms and weakens soil health and long-term viability (Ferguson and Ferguson, 1983). This is especially important in arid and semi-arid regions where soils are thinner, less robust, and less organic-rich than their more humid counterparts. In these regions, soils can be destroyed by trampling which decreases soil porosity and makes soil less permeable to water. This affects soil microbe health and is a major contributor to soil erosion in grazed lands (Okin, 1995).

When soil permeability is reduced through compaction, water is less able to penetrate the surface. Therefore, runoff water flows at the surface, which increases a soil's susceptibility to erosion (Rifkin, 1992). This is especially dangerous in a semi-arid environment such as the Great Fish River Valley where the coefficient of rainfall is very high and precipitation events can be sudden and severe. Arid and semi-arid lands grazed by domestic herbivores are therefore more prone to severe soil erosion than ungrazed areas. For example, grazed watersheds in Colorado, USA produce up to 76% more sediment than ungrazed areas (Ferguson and Ferguson, 1983).

Domestic herbivores have a direct effect on water quality where their faeces are allowed to enter streamflows. This introduces microorganisms, such as *Giardia lamblia*, into the water supply fouling it for downstream use. Domestic herbivory also have a direct impact on riparian areas. These are vital in supporting healthy landscapes since in arid lands, most of the flora and fauna species are concentrated here. In their quest for water and shade, the animals trample and disrupt riparian areas.

In addition, the increased erosion in grazed lands affects water quality in the grazed area. Increased erosion causes increased sediment loads in the streams and rivers that drain the area. This, in turn, alters the stream ecosystems by changing water temperature and chemistry. Higher sediment loads in water channels increases the temperature of the water since the sediment particles intercept more sunlight. Higher water temperatures combined with cattle waste, diminishes the dissolved oxygen content of the water, and thus changes the biotic potential of the system (Ferguson and Ferguson, 1983).

Selective herbivory can have major effects on the distribution of plant species in a landscape.

Most obviously, selective herbivory will lead to a reduction of the biomass of the desirable species relative to the undesirable ones. The overall biomass however, may not be reduced but simply transferred from palatable to non-palatable species. However, selective herbivory may have more subtle and insidious effects. For example, in the arid Journada Basin in western New Mexico, what was 100 years ago a uniform grassland has become a Creosote and Mesquite shrubland. This transformation seems to have been triggered by grazing of the basin by cattle (Schlesinger *et al.*, 1990). The herbivores selectively choose the grasses and succulents over the woody shrubs, giving the shrubs a competitive edge. Once the woody shrubs gain a foothold, the microclimatic effects around the shrubs such as cooler soil temperatures and accumulation of plant debris near the base of the shrubs due to leaf-fall and wind movement further boosts the competitiveness of the shrubs over the grasses.

The distribution of species in a semi-arid landscape can be affected by the spatial preferences of grazing animals. Sheep graze preferentially near water sources, and only move away from water as food resources are depleted (Pickup and Chewings, 1994). This means that over a period of time, more herbivory has taken place near the water than further away causing a grazing gradient that is observable via remote sensing (Perkins and Thomas, 1993). There is also an associated trampling and nutrient gradient, where sheep trample and enrich the soil closer to the water sources than away from them simply because they spend more time near the water sources. In the case where the water is concentrated at a point source, grazing gradients can be observed as concentric circles around the point source. These circular gradients are observed regularly in arid central Australia, and often represent permanent land damage (Pickup and Chewings, 1994). More dramatically, circular areas up to 40 km wide centred on village water sources have turned to sand in the Sudan due to grazing pressures (Pimental and Hall, 1989).

## 2.2 Vegetation

### 2.2.1 The Vital Role of Vegetation.

Vegetation has been identified as one of the most important biophysical parameters of terrestrial surfaces due to its specific role in geosphere-biosphere-atmosphere interactions (Yang *et al.*, 1995). Vegetation regulates the energy (including water) exchanges between the earth-atmosphere interface, and dominates the functioning of hydrological processes through modification of interception, infiltration, surface runoff, and its effects on surface albedo, roughness, evapotranspiration and root system modification of soil properties. The vegetation abundence controls the partitioning of incoming solar energy into sensible and latent heat fluxes and consequently changes in vegetation cover will result in long term changes in the local and global climates, which in turn will affect the vegetation growth as a feedback (Qi, 1996). One measure of land degradation is therefore the degradation of vegetation (Dregne, 1983), but a brief examination reveals that the state of vegetation is a powerful indicator of where additional degradation will occur (Ray, 1995).

Common thought has it that it is the roots of vegetation that are responsible for controlling erosion. The argument is that the roots provide an interlocking framework that holds the soil particles in place. However, soil can easily be removed from within the root network by flowing water, especially when the soil fraction of fine clay and silt is low. The most important function of plants in erosion control is their ability to break the flow of erosive agents. The discussion of water erosion (section 2.1.1) showed that the impact of raindrops on the soil surface was one of the most fundamental causes of soil degradation. As early as 1877, the German scientist Wollny recognised that plant canopies and surface mulch protected soil from water erosion primarily by breaking the fall of raindrops (Mainguet, 1991). Rangeland is currently the single most important economic resource of the arid and semi-arid regions of Southern Africa. The monitoring of rangeland characteristics such as the extent and intensity of degradation present is therefore vital to facilitate informed management decisions.

### 2.2.2 Vegetation Mapping and Condition Assessment

A number of methods have been used in the past to map accurately the contemporary vegetation. Aerial photographs are used extensively to identify vegetation units in the field and trace them onto the photographs. Response surfaces have been used to predict the expected vegetation at a specific site and the results analysed statistically (Palmer 1990; Palmer and van Staden, 1992). There are many ways whereby rangeland condition can be assessed. Definition of the condition of the rangeland may be in terms of ground cover; vegetative biomass; productivity or yield; species composition and diversity; or degradation of vegetation and/or soil, or a combination of some or all of these factors (Mackay and Zietsman, 1996).

### 2.2.3 Vegetation Mapping Using Remote Sensing

As indicated by the extensive volume of literature on this subject, an increasingly popular method for acquiring vegetation information over large areas is satellite remote sensing (Anderson *et* al., 1993; Baret *et al.*, 1989; Clevers, 1988; Crippen, 1990; Franklin, 1991; Freidel *et al.*, 1993; Friedl *et al.*, 1995; Mackay and Zietsman, 1996; Malo and Nicholson, 1990; Palmer, 1990; Palmer *et al.*, 1997; Pickup and Chewings, 1994; Qi *et al.*, 1994; Ray, 1995; Richards, 1984; Richardson and Everitt, 1992; Richardson and Wiegand, 1977; Tanser, 1996a; Tanser, 1996b; Tanser and Palmer, 1997; Tueller, 1991; Ustin *et* al., 1986; Westfall and Malan, 1986).

Milford (1989) points out that the feature that one is interested in is rarely directly sensed by satellite; it usually has to be deduced. However, remote sensing involving water, plants and soils is very complicated due to the extreme complexity of biological materials and soils. Although remote sensing has been successful when applied to understanding vegetation and community ecology (Goetz *et al.*, 1985) our ability to interpret spectral information remains especially limited in arid environments, where the vegetation is sparse and shrub communities with similar physiographic properties often differ markedly in species composition and ecology (Ustin *et al.*, 1986).

## 2.3 Remote Sensing: An Overview

The purpose of this section is to provide an overview of general concepts and methodologies in remote sensing.

### 2.3.1 Landsat Thematic Mapper

The Thematic Mapper sensor on the Landsat series satellites records radiance in six spectral bands and thermal emittance in one band, for an area on the earth's surface corresponding to 812 $m^2$. Landsat imagery provides a synoptic view of an area of approximately 34,000 $km^2$ (185 x 185 km) and it has a monitoring capability due to the repetitive coverage (every 16 to 18 days) in a relatively short time. Satellite imagery can be thought of as a large multivariate data set in which there are a number of spectral measurements for every location (Franklin, 1991). For example, in the study area there are approximately 10 million measurements (for all seven spectral bands) in an area of 2065 $km^2$. The characteristic reflectance properties of different materials such as vegetation and soil allow for the correlation of satellite spectral measurements with biophysical variables such as herbaceous biomass, canopy temperature, soil moisture and surface albedo (Table 2.1).

***Table 2.1: The Landsat Thematic Mapper spectral bands (adapted from the United States Geological Survey, 1996).***

| Band | Wavelength ($\mu$m) | Spectral Regions | Sensitivity to landscape features |
|---|---|---|---|
| 1 | 0.45 - 0.52 | Blue | Provides increased penetration of water bodies as well as supporting analyses of land use, soil, and vegetation characteristics. The shorter-wavelength cutoff is just below the peak transmittance of clear water, while the upper-wavelength cutoff is the limit of blue chlorophyll absorption for healthy green vegetation. Wavelengths below 0.45$\mu$ are substantially influenced by atmospheric scattering and absorption. |
| 2 | 0.52 - 0.60 | Green | Spanning the region between the blue and red chlorophyll absorption bands, this band corresponds to the green reflectance of healthy vegetation. |
| 3 | 0.63 - 0.69 | Red | This red chlorophyll absorption band of healthy green vegetation is one of the most important bands for vegetation discrimination. It is also useful for soil-boundary and geological boundary mapping. Band 3 may exhibit more contrast than bands 1 and 2 because of the reduced effect of the atmosphere. The 0.69$\mu$ cutoff represents the beginning of a spectral region from 0.68 to 0.75$\mu$ where vegetation reflectance crossovers occur that can reduce the accuracy of vegetation studies. |
| 4 | 0.76 - 0.90 | Near Infra Red | For reasons discussed above, the lower cutoff for this band was placed above 0.75$\mu$. This band is especially responsive to the amount of vegetation biomass present in a scene. It is useful for crop identification, and emphasizes soil-crop and land-water contrasts. |
| 5 | 1.55 - 1.75 | Mid infra-red | This reflective-IR band is sensitive to turgidity (the amount of water in plants). Turgidity is useful in drought studies and plant vigor studies. In addition, this band can be used to discriminate between clouds, snow, and ice (important in hydrological research) as well as being able to remove the effects of thin clouds and smoke. |
| 6 | 10.4 - 12.5 | Thermal | This band measures the amount of infrared radiant flux (heat) emitted from surfaces. The apparent temperature is a function of the emissivities and true (kinetic) temperatures of surface objects. Therefore, band 6 is used in locating geothermal activity, thermal inertia mapping, vegetation classification, vegetation stress analysis, and in measuring soil moisture. |
| 7 | 2.08 - 2.35 | Mid infra-red | This important band is used to discriminate among various rock formations. It is particularly effective in identifying zones of hydrothermal alteration in rocks. |

The accuracy of the data is very high because of relatively low planimetric and image distortions amenable to correction procedures (Kaushalya, 1992). Thematic Mapper (TM) data have several advantages over Multi-Spectral Scanner (MSS) data. For example, TM has a higher spatial resolution which facilitates enlargement on a scale of 1:50 000. Ground features can be better perceived in TM due to digital clusters, whereas in MSS feature delineation is difficult due to a lower resolution. Radiometric quality of TM is better than that of MSS. TM thus provides better contrast and better perception of images as a result of its 8-bit quantisation and light segregation.

### 2.3.2 Image Correction Procedures

Raw digital images contain **geometric distortions** so significant that they cannot be used as maps. The sources of these distortions range from variations in altitude, attitude and velocity of the sensor platform, to factors such as panoramic distortion, earth curvature, atmospheric refraction, relief displacement, and linearities in the sensor's Instantaneous Field of View (IFOV) (Lillesand and Kiefer, 1994). The intent of geometric correction is to compensate for the distortions introduced by these factors so that the corrected image will have the geometric integrity of a map.

As with geometric correction, the type of **radiometric correction** applied to any given digital image data set varies widely among sensors. All things being equal, the radiance measured by any given system over a given object is influenced by factors such as changes in scene illumination, atmospheric conditions, viewing geometry, and instrument response characteristics (Lillesand and Kiefer, 1994). Some of these effects such as viewing geometry variations, are reduced in the case of satellite image acquisition as opposed to airborne data collection. It is often necessary to generate mosaics of images taken at different times or to study the changes in reflectance of ground features at different times or locations. In such applications it is necessary to apply *a* **sun elevation correction** and an **earth-sun distance correction.**

### 2.3.3 Multi-Spectral Techniques

Classification of digital imagery involves grouping together pixels on the basis of similar spatial reflectance values in order to identify the areas or information of interest (Harrison and Jupp, 1990; Lillesand and Kiefer, 1994; Richards, 1986; Tueller, 1989). Classification is achieved by two basic methodologies. These are supervised, unsupervised or a mixture of both. The image-processing tool used in this study is IDRISI, therefore the methods used in obtaining multi-spectral classifications will taken from IDRISI.

An **unsupervised classification** is automated for the computer-assisted interpretation of remotely sensed imagery. The computer routine achieves this by identifying typical patterns in the reflectance data. These patterns are then identified by undertaking site visits to a few selected examples to determine their interpretation. Because of the mathematical technique used in this process, the patterns are usually referred to as clusters. An unsupervised classification is performed using the IDRISI module CLUSTER. CLUSTER uses a histogram peak technique of cluster analysis. This is equivalent to looking for the peaks in a one-dimensional histogram, where a peak is defined as a value with a greater frequency than its neighbours on either side. Once the peaks have been identified, all possible values are assigned to the nearest peak and the divisions between classes fall at the midpoints between peaks. A three-dimensional histogram is used as the composite image is derived from three bands. A peak is thus a class where the frequency is higher than all of its neighbours (Eastman, 1995). The CLUSTER algorithm used is modified from a histogram peak technique described by Richards (1986).

A **supervised classification** consists of three basic steps. In the *training stage* (1), the analyst identifies representative training areas and develops a numerical description of the spectral attributes of each land cover type of interest in the scene. Next, in the *classification stage* (2), each pixel in the image data set is categorised into the land cover class it most closely resembles. If the pixel is insufficiently similar to any training data set, it is usually labelled 'unknown'. The category label assigned to each pixel in this process is then recorded in the corresponding cell of an interpreted data set as an output image. Thus, the multidimensional image matrix is used to develop a corresponding matrix of interpreted land cover category types.

Numerous mathematical approaches to spectral pattern recognition have been developed whose discussion falls beyond the scope of this chapter. However, the pattern recognition algorithm that will be used is the maximum likelihood classification using the module MAXLIKE. MAXLIKE undertakes a Maximum Likelihood classification of remotely sensed data based on information contained in a set of signature files. The Maximum Likelihood classification is based on the probability density function associated with a particular training site signature. Pixels are assigned to the most likely class based on a comparison of the probability that it belongs to each of the signatures being considered. MAXLIKE is the slowest of the classification routines provided, but when supplied with good training site data, it tends to be the most accurate (Eastman, 1995). In essence, the maximum likelihood classifier delineates ellipsoidal 'equi-probability contours' (Lillesand and Kiefer, 1994). IDRISI offers an extension of the maximum likelihood approach in the form of the Bayesian classifier. This technique applies two weighting factors to the probability estimate. First, the analyst determines the '*a priori* probability', or the anticipated likelihood of occurrence for each class in the given scene. The weighting minimises the 'cost' of misclassifications, resulting in a theoretically optimum classification (Lillesand and Kiefer, 1994). MAXLIKE allows exclusion of a set proportion of the least likely pixels from any classification. This causes the pixels with the least likelihood of belonging to any of the classes for which one has signature data to be left unclassified. This proportion is specified with the aid of a Chi-Squared distribution table (a value of 0% ensures all pixels are classified). After the entire data set has been categorised, the results are presented in the *output stage* (3).

### 2.3.4 Image Enhancement Techniques

Raw image data are often not visually interpretable and may need to be enhanced in order to extract features of interest to the user. Enhancement may be one of two broad types, spectral or spatial (Harrison and Jupp, 1990; Richards, 1986).

**Spectral enhancement** also known as contrast stretching, entails selectively adjusting individual pixel values in order to increase feature contrast. This involves taking pixel values within a given spectral range and spreading them over a different range. This may result in pixel values that are outside of the initial range, thus losing contrast. Various techniques can be used to stretch pixel values selectively in differing spectral ranges in order to highlight the feature of interest.

**Spatial enhancement** entails adjusting individual pixel values according to the values of neighbouring pixels. This is performed in order to highlight or manipulate differences in the spatial frequency of the set of image pixels. Various filters are used to detect, enhance or smooth edge features.

### 2.3.5 Principal Components Analysis

A Principal Components Analysis (PCA) is an ordination technique for projecting multi-dimensional bands into a space of fewer dimensions. The resulting components are by definition uncorrelated with each other (Richards, 1986). In this technique, principal axes are calculated through the measurements of multidimensional (multi-spectral) space. A covariance matrix is computed from the spectral measurement vectors associated with each pixel in the image. Then the eigenvectors are computed. The eigenvalues and associated eigenvectors represent the variance along the principal axes. In successive steps the variance is maximised, and the next axis is orthogonal to the previous one. In this way, new axes are defined as linear combinations of the original spectral axes. The coefficients in each of the eigenvectors are used to transform the original data into the new data of which each component is uncorrelated with successive components. The high interband correlation ensures that most of the variance is contained in the first few transformed bands, so that fewer than the original number of bands can be used in subsequent analysis. However, interpretation of the meaning of the transformed axis can be difficult and this is true for principal components of any complex data set (Franklin, 1991). The first three components commonly contain 99% of the variance contained within the data with the latter components highlighting areas of change between the images.

### 2.3.6 Vegetation Indices

Soil tends to reflect in all visible and near infra-red wavelengths as a function of its colour, whilst vegetation absorbs strongly in the photosynthetically active visible wavelengths and reflects near infra-red radiation proportional to the amount of green vegetation present. Mid-infra red reflectance is related to soil and vegetation moisture content (Table 2.1). For photosynthesising vegetation there is a significant differential in reflectance and absorption of electromagnetic radiation when the border between visible and near-infrared wavelengths is transgressed. These differences have led to the development of several multi-spectral band ratios and indices that involve both the red/infra-red differences and coefficients derived from several bands. These ratios and indices are indicative of the quantity of green and senescent vegetation. Soil background conditions and shadows often influence the signal and complicate the use of these indices for evaluating vegetation on rangelands. An ideal vegetation index for use on arid lands would be highly sensitive to vegetation, insensitive to soil background changes and only slightly influenced by atmospheric path radiance (Jackson *et al.*, 1983). On rangelands the ideal index would have the capability of sorting out the influence of shadow, the influences of the great variety of leaf reflectances as well as the standing dead vegetation and litter (Tueller, 1991).

The differential reflection of green vegetation in the red and near-infrared(NIR) portions of the electromagnetic spectrum (Figure 2.1) provides the theoretical basis for vegetation indices.

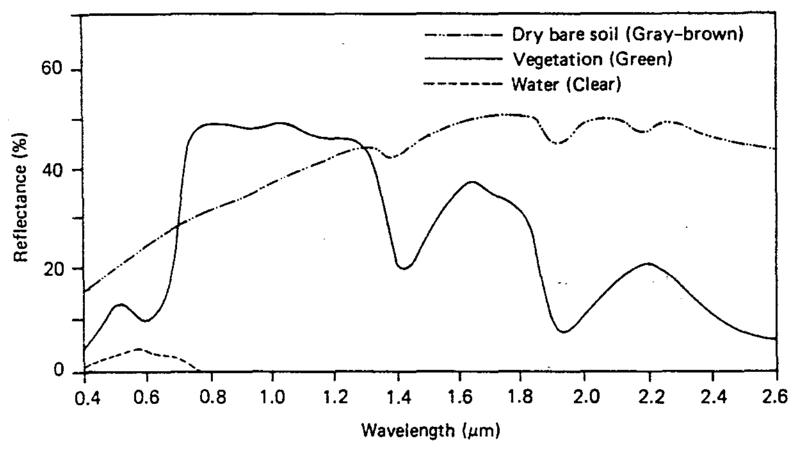



**Figure 2.1:** Spectral reflectance curves for soil vegetation and water (Adapted from Lillesand and Kiefer, 1994)

The cells in plant leaves are very effective scatterers of light because of the high contrast in the index of refraction between the water-rich cell contents and the intercellular air spaces (Ray, 1995). Vegetation is very dark in the visible (0.4 - 0.7$\mu$m) because of the high absorption of pigments which occur in leaves (chlorophyll, protochlorophyll and xanthophyll). There is a slight increase in reflectivity around 0.55$\mu$m (visible green) as the pigments are least absorptive in this range. In the spectral range 0.7 - 1.3$\mu$m plants are very bright as this is a spectral 'no-man's land' between the electronic transitions which provide absorption in the visible and molecular vibrations which absorb in the longer wavelengths. There is no strong absorption in this spectral range, but the plant scatters strongly as mentioned above (Ray, 1994). From 1.3 - 2.5$\mu$m vegetation is relatively dark, primarily because of the absorption by leaf water. Cellulose, lignin, and other plant materials absorb in this spectral range. Thus vegetation reflects brightly in any band covering 0.7 - 1.3$\mu$ and minimal reflectance is encountered in the range 0.4 - 0.7$\mu$m and 1.3 - 2.5$\mu$m. In order to accentuated this difference and to delineate photosynthesising vegetation a band located at a portion of the electromagnetic spectrum where vegetation appears bright is ratioed with a satellite band located at a portion of the electromagnetic spectrum where vegetation appears dark.

An assumption is made with vegetation indices that all bare soil in an image will form a line in spectral space. Nearly all of the commonly used vegetation indices are only concerned with the red-near-infrared space, so a red-near-infra-red line for bare soil is assumed. This line is considered to be the line of zero vegetation. At this point, there are two divergent lines of thinking about the orientation of lines of equal vegetation (isovegetation lines), namely;

- All isovegetation lines converge at a single point. The indices that use this assumption are the 'ratio-based' indices, which measure the slope of the line between the point of convergence and the red-NIR point of the pixel. An example of this type of index is the Normalised Difference Vegetation Index (NDVI) (Rouse *et al.*, 1973).
- All isovegetation lines remain parallel to the soil line. These indices are typically referred to as 'perpendicular' indices. They measure the perpendicular distance from the soil line to the red-near-infra-red point of the pixel. An example of this type of index is the Greeness Vegetation Index (GVI).

The first ratio-based vegetation index was described by Jordan (1969) and was termed the Ratio Vegetation Index (RVI) and is simply calculated as the ratio of NIR to Red. The Normalised Difference Vegetation Index (NDVI) (Rouse *et al.*, 1973) is calculated by dividing the value of the NIR band minus the red band by the value of the NIR band plus the red band.

The perpendicular indices originated from Kauth and Thomas (1976). They proposed a transformation that used linear combinations of four Landsat MSS bands to produce four indices: brightness, greeness, yellowness and non-such. The soil spectra in four dimensional Landsat MSS signal space was found to be distributed along a plane, known as the plane of soils. This observation led to the Soil Brightness Index (SBI). The SBI is measured as the vector distance in the direction of the soil baseline. The Greeness Vegetation Index (GVI) is defined as the measured distance perpendicular to the soil base line towards a point of all vegetation (Kauth and

Thomas, 1976). Reflectance variations of developing vegetation grow perpendicularly out of this plane of soils. The perpendicular Vegetation Index (PVI) is a combination of infrared and red bands (Richardson and Wiegand, 1977) and is essentially the two-dimensional equivalent of the indices proposed by Kauth and Thomas (1976). The PVI is defined as the orthogonal distance of a given spectral point from the soil baseline. The PVI, unlike ratio-based indices, minimises the influence of the soil background for the assessment of green biomass (Elvidge and Lyon, 1985).

Some indices, such as the Soil Adjusted Vegetation Index (SAVI) proposed by Huete (1988) attempt to be a hybrid between the ratio-based indices and the perpendicular indices. The reason behind this index acknowledges that isovegetation lines are not parallel, and they do not all converge at a single point. The initial construction of this index was based on measurements of cotton and range grass canopies with dark and light soil backgrounds, and the adjustment factor L was found by trial and error until a factor that gave equal vegetation index results for the dark and light soils were discovered. The result is a ratio-based index where the point of convergence is not the origin. The correction factor L varies from 0 for very high vegetation cover to 1 for very low vegetation cover. SAVI reduces to NDVI when the L factor is 0. A summary of commonly used ratio-based and perpendicular vegetation indices is presented (Table 2.2).

***Table 2.2: Commonly used Vegetation indices***

| Vegetation Index | Formula | Author |
|---|---|---|
| **Normalised Difference** | $\frac{NIR-Red}{NIR+Red}$ | Rouse *et al.*(1973) |
| **Infrared Percentage** | $\frac{NIR}{NIR+Red}$ | Crippen (1990) |
| **Difference** | $NIR-Red$ | Lillesand and Kiefer (1987) |
| **Perpendicular** | $Sin(a)NIR-Cos(a)Red$<br>a - angle between the soil line and the NIR axis | Richardson and Wiegand (1977) |
| **Weighted Difference** | $NIR-g*Red$<br>g - slope of the soil line | Clevers (1988) |
| **Soil Adjusted** | $\frac{NIR-Red}{NIR+red+L}(1+L)$<br>L - Correction factor (L=0 for very high vegetation cover and 1 for very low vegetation cover) | Huete (1988) |
| **Modified Soil Adjusted** | $\frac{NIR-Red}{NIR+red+L}(1+L)$<br>L = 1- 2*s*ndvi*wdvi<br>s = Slope of the soil line. | Qi *et al.* (1994) |
| **Transformed Soil Adjusted** | $\frac{s(NIR-s*red-a)}{(a*NIR+red-a*s+x*(1+s*s)}$<br>**a** - Soil line intercept<br>s - Soil line slope<br>**x** - Soil adjustment factor (0.08 in original papers) | Baret *et al.* (1989) |

## 2.4 Landscape Pattern - The Key to Monitoring Desertification

Landscapes can be observed from many points of view, and ecological processes in landscapes can be studied at different spatial and temporal scales (Risser, 1987). 'Landscape' commonly refers to the landforms of a region in the aggregate (Webster's New Collegiate Dictionary, 1980) or to the land surface and its associated habitats at scales of hectares to many square kilometres. Most simply, a landscape can be considered a spatially heterogeneous area. Three landscape characteristics useful to consider are structure, function, and change (Forman and Godron, 1986). 'Structure' refers to the spatial relationships between distinctive ecosystems, that is, the distribution of energy, materials and species in relation to the sizes, shapes, numbers, kinds and configurations of components. 'Function' refers to the interactions between the spatial elements, that is, the flow of energy, materials and organisms among the component ecosystems. 'Change' refers to alteration in the structure and function of the ecological mosaic through time. As this study is concerned predominantly with the distribution of vegetation and nutrients in the landscape the primary landscape component under investigation will be 'structure'. Landscape ecology emphasises broad spatial scales and the ecological effects of the spatial patterning of ecosystems. Specifically, it considers:-

- The development and dynamics of spatial heterogeneity;
- Interactions and exchanges across heterogenous landscapes;
- The influences of spatial heterogeneity on biotic and abiotic processes;
- The management of spatial heterogeneity.

Landscape ecology has a long tradition of interest in the spatial patterning and geographic distribution of organisms. Throughout the nineteenth century the emerging view was that strong interdependencies among climate, biota and soil lead to long-term stability of the landscape in the absence of climatic changes (O'Neill *et al.,* 1986). The early biogeographical studies also influenced Clements' theory of successional dynamics, in which a stable endpoint, the climax vegetation, was determined by macroclimate over a broad region (Clements, 1936). Clements stressed temporal dynamics but did not emphasise spatial patterning. Gleason (1917) argued that spatially heterogeneous patterns were important and should be interpreted as individualistic responses to spatial gradients in the landscape. The development of gradient analysis allowed description of the continuous distribution of species along environmental gradients. Abrupt discontinuities in vegetation patterns were believed to be associated with abrupt discontinuities in the physical environment (Whittaker, 1975), and the spatial patterns of climax vegetation were believed to reflect localised intersections of species responding to complex environmental gradients.

A revised concept of vegetation patterns in space and time was presented by Watt (1947). The distribution of the entire temporal progression of sucessional stages was described as a pattern of patches across a landscape. The orderly sequences of phases at each point in space accounted for the persistence of the overall pattern. The complex spatial pattern across the landscape was constant but this constancy in the pattern was maintained by the temporal changes at each point (Turner, 1989). Thus, space and time were linked by Watt (1947) for the first time at the broader scale that is now termed the landscape. The concept of the shifting steady state mosaic (Bormann *et al.,* 1979), which incorporates natural disturbance processes, is related to Watt's conceptualisation. Consideration of spatial dynamics in many areas of ecology has received increased attention during the past two decades (Allen and Starr, 1982; Mooney and Godron, 1983; Pickett and White, 1985; Schlesinger *et al.*, 1990).

This brief overview demonstrates that a long history of ecological studies provides a basis for the study of spatial patterns and landscape-level processes. However the emphasis previously was on describing the processes that created the patterns observed in the biota. The explicit effects of spatial patterns on ecological processes have not been well studied (Turner, 1989). This research will therefore focus on the characterisation of landscape patterns via the use of satellite imagery and their effects on ecological processes; particularly desertification.

### 2.4.1 The Consideration of Scale

The effects of spatial and temporal scale must be considered in landscape ecology (Meentemeyer, 1978). Landscapes are spatially heterogeneous areas (i.e. environmental mosaics) and therefore the structure, function and change of landscapes are themselves scale-dependent. The measure of spatial pattern and heterogeneity is therefore dependent upon the scale at which the measurements are made (Turner, 1989). The scale at which humans perceive boundaries and patches in the landscape may have little relevance to flows or fluxes. For example, in a particular organism it is unlikely that discernment of the important elements of structure will be possible unless an organism-centred view of the environment is adopted (Whittaker, 1975). Similarly, abiotic processes such as gas fluxes may be controlled by spatial heterogeneity that is not intuitively obvious to the human observer. Finally, changes in landscape structure or function are scale-dependent. For example, a dynamic landscape may exhibit a stable mosaic at one spatial scale but not at another (Turner, 1989). The scale at which studies are conducted or in the case of remote sensing the resolution of the imagery used may profoundly influence the results. Processes and parameters important at one scale may not be as important or predictive at another scale. For example, most of the variance in litter decomposition rates at local scales is explained by properties of the litter and the decomposer community, whereas climatic variables explain most of the variance at regional scales (Meentemeyer, 1984). Thus, conclusions or inferences regarding landscape condition must be drawn with acute awareness of scale (Turner, 1989).

### 2.4.2 Characterising Landscape Structure

Landscape structure must be identified and quantified in meaningful ways before the interactions between landscape patterns and ecological processes can be understood. The spatial patterns observed in landscapes result from complex interactions between physical, biological and social forces (Turner, 1989). Most landscapes have been influenced by human use, and the resulting landscape mosaic is a mixture of natural and human-managed patches that vary in size, shape and arrangement (for example Krummel *et al,* 1987; Turner and Ruschner, 1988). This spatial patterning is a unique phenomenon that emerges at the landscape level.

### 2.4.3 Quantifying Landscape Patterns

Quantitative methods are required to compare different landscapes, identify significant changes through time, and related landscape patterns to ecological function. Considerable progress in analysing and interpreting changes in landscape structure has already been made. Landscape indexes derived from information theory have been applied in several landscape studies. Indices of landscape richness, evenness and patchiness were calculated for a subalpine portion of Yellowstone National Park, USA and related to fire history and diversity of the site (Romme, 1982). These indexes were later adapted by Hoover (1986) and applied to six study areas in Georgia. The study revealed a general trend of decreasing landscape diversity from the mountains to the coastal plain.

Shapes and boundaries in the landscape have been quantified by using fractals, which provide a measure of the complexity of the spatial patterns. Fractal geometry (Mandelbrot, 1983) was introduced as a method to study shapes that are partially correlated over many scales. Fractals have been used to compare simulated and actual landscapes (Gardner *et al.,* 1987; Turner, 1987a), to compare the geometry of different landscapes, and to judge the relative benefits to be gained by changing scales in a model or data set (O'Neill *et al.,* 1988; Turner and Ruschner, 1988). It has been suggested that human-influenced landscapes exhibit simpler patterns than natural landscapes, as measured by the fractal dimension (O'Neill *et* al., 1988; Turner and Ruscher, 1988). Landscapes influenced by natural rather than anthropogenic disturbances may respond differently, with natural disturbances increasing landscape complexity. Landscape complexity has not been shown to be constant across a wide range of spatial scales (i.e self-similarity). This lack of constancy probably reflects the effects of processes that operate at different scales; however, it remains a focus of current research (Turner, 1989). Applying predictions made at one scale to other scales may be difficult if landscape structure varies with scale (Milne, 1987).

The use of three complementary landscape indexes (dominance, contagion, and fractal dimension) in the eastern United States discriminated between major landscape types, such as urban, coastal, mountain forest and agricultural areas (Milne, 1987). The three indices furthermore appeared to provide information at different scales, with fractal dimension and dominance indices reflecting broad scale pattern and the contagion index reflecting the fine-scale attributes that incorporate the adjacency of different habitats. This type of scale sensitivity could prove useful in selecting measures of patterns that can easily be monitored through time by means of remote sensing and related to different processes (Turner, 1989).

The size and distribution of patches in the landscape is another measure of landscape structure. A patch is defined as a group of pixels of similar type that have at least one edge in common. These characteristics may be of particular importance for species that require habitat patches of a minimum size or specific arrangement. The potential effects that the changes in patch structure created by forest clear-cutting patterns have on the persistence of interior and edge species were analysed by Franklin and Forman (1987). Patch size and arrangement may also reflect environmental factors, such as topography or soil type. The size and isolation of forest patches in southern Wisconsin, USA were correlated with groups of environmental variables - for example, soil type, drainage, slope and disturbance regime (Sharpe *et al.*, 1987).

A variety of other techniques are available for quantifying landscape structure. The extent of edge between different landscape elements may be important for the movement of organisms across boundaries (Turner and Bratton, 1987; Wiens *et al.*, 1985), and the importance of edge habitat for various species is well known (Leopold, 1933). Thus, it may be important to monitor changes in edges when one quantifies spatial patterns and integrates pattern with function (Turner, 1989).

The quantitative measures described above, although not designed specifically for remotely sensed data, could easily be applied to satellite data, this would then permit broad-scale monitoring of landscape changes. However, both classification and scale must be carefully considered in analyses of landscape structure.

Turner (1989) identifies four important questions that still remain regarding landscape patterns and their changes:

- What constitutes a significant change in landscape structure?
- What measures best relate to ecological processes?
- How do the measurements of pattern relate to the scale of the underlying processes?
- Is it possible to derive an index of structure that serves as an 'early warning'?

Answers to these questions are necessary for the development of broad scale experiments and for the design of strategies to monitor landscape responses to global change (Turner, 1989).

### 2.4.4 Landscape Heterogeneity and Disturbance

The spread of disturbance across a landscape is an important ecological process that is influenced by spatial heterogeneity (Romme, 1982; Turner, 1987b). Disturbance can be defined as "any relatively discrete event in time that disrupts ecosystem, community or population structure and changes resources, substrate availability, or the physical environment" (Pickett and White, 1985, pp. 5). Disturbances operate in a heterogeneous manner in the landscape. Gradients of frequency, severity, and type are often controlled by physical and vegetational features. The differential exposure to disturbance, in concert with previous history and edaphic conditions, leads to the vegetation mosaic observed in the landscape (Turner, 1989). In semi-arid or arid ecosystems such as the Great Fish River Valley, Eastern Cape the relationship between reflectance and biophysical variables will change over space and time. This is because any biophysical variables are superimposed on the landscape and each has its own pattern of spatial and temporal heterogeneity. In semi-arid Africa the land cover consists of varying mixtures of woody and herbaceous vegetation cover on different soil types. Complex land use practices and overgrazing impose their own pattern on the landscape. The majority of satellite derived indices lack some needed measures of landscape structure (for example texture) (Baker and Cai, 1992). If vegetation change is to be monitored, for the purposes of practical management or research, the different scales of temporal variability must be recognised as well as landscape heterogeneity, otherwise imposed effects will be undetectable (Freidel *et al.*, 1993).

Estimation of the cumulative impacts of disturbances in a landscape is important for protecting sensitive habitats or environmental health. A comparison of the Arctic landscape in 1949 and 1983 demonstrated that indirect impacts of anthropogenic disturbances may have substantial time lags (Walker *et al.*, 1987). This suggests a strong need for comprehensive landscape planning through the use of current technologies such as remote sensing to address such synergistic disturbance effects (Turner, 1989).

The spatial spread of disturbance may be enhanced or retarded by landscape heterogeneity. This relationship depends on the mode of propagation. The mode of propagation can be divided into: *(a)* those that spread *within* the same habitat type (for example the spread of a species specific parasite through a forest); and *(b)* those that cross boundaries and spread *between* different habitat types (for example landscape degradation). Whether landscape heterogeneity enhances or retards the spread of disturbance may depend on which of these two modes of propagation is dominant. If the disturbance is likely to propagate *within* a community, high landscape heterogeneity should retard the spread of a disturbance. If the disturbance is likely to move between communities, increased landscape heterogeneity enhances the degradation of the landscape. Furthermore, the rate of disturbance propagation should be directly proportional to landscape heterogeneity for disturbances that spread *between* communities, but inversely proportional for disturbances that spread *within* the same community (Turner, 1989). Satellite imagery is generally concerned with identifying disturbances in the landscape as a whole and not disturbances peculiar to a specific habitat type, therefore it is hypothesised that increasing heterogeneity will show a marked correlation with increasing disturbance/degradation.

"The relationship between landscape pattern and disturbance regimes must be studied further particularly in light of potential global climatic change" (Turner, 1989, pp. 183). Disturbances operate at many scales simultaneously, and their interactions contribute to the observed landscape mosaic. The interactive effects of disturbances are not well known, partly because single disturbances are often studied rather than multiple disturbances in whole landscapes. "A better understanding of how disturbance regimes vary through time and space is needed" (Turner, 1989, pp. 183).

### 2.4.5 The Need for Satellite-Derived Indices of Landscape Structure

The data from remote sensing satellites cannot always distinguish between different types of vegetation cover, and therefore degradation has to be defined in terms of temporal and spatial patterns (Pickup and Chewings, 1994). An alternative to indices based on absolute pixel reflectance, indices based on landscape heterogeneity may yield more sensitive measures of the changes in ecosystem function that underlie various forms of desertification.

Current research suggests that different landscape indexes may reflect processes operating at different scales. The relationships between indexes, processes and scale needs more study to understand *(a)* the factors that create pattern and *(b)* the ecological effects of changing patterns of processes. "Of paramount importance is the development and testing of a general body of theory relating pattern and process at a variety of spatial and temporal scales" Turner (1989, pp. 191). It is the aim of this research to develop and test an index of landscape structure based on the landscape pattern theory discussed above to monitor rangeland condition using remote sensing technologies and Geographic Information Systems (GIS). The technique will try to determine whether a relationship between heterogeneity and degradation does exist and whether via the use of remote sensing and GIS it can be quantified. It is envisaged that the results obtained in the study will help contribute significantly to the existing body of landscape pattern theory.

## 2.5 Summary

The nature, causes and effects of soil erosion have been broadly outlined in this chapter as well as the effect of domestic herbivores in accelerating degradation. A discussion on the role of vegetation in the ecosystem is presented and a brief examination into field-based methods of assessing rangeland condition. Mention is made of the large volume of literature on the use of remote sensing to predict vegetation characteristics. Some broad concepts in remote sensing such as the characteristics of the Landsat TM series satellite as well as commonly used techniques, such as vegetation indices and supervised and unsupervised approaches, to mapping vegetation are addressed. Existing landscape pattern theory that has been used in several studies to investigate ecosystem dynamics has been outlined and the need for satellite-derived indices of landscape pattern discussed.

# CHAPTER 3

# THE STUDY AREA

*"The relationship between people and nature in most of Africa has been extractive: people took crops, and wood, and put nothing back, but gave nature time and space to restore herself. That relationship depended on an abundance of land and forests. But as population density grew, that abundance could no longer be taken for granted. Nature is no longer given time to restore herself. Her capital of resources is being depleted, and the whole system grinds gradually downhill."* (Harrison, 1987, pp. 380)

*"Nowhere is this more dramatically visible than in the Mid Fish River Valley, Eastern Cape, where the Great Fish River Nature Reserve, a natural paradise, meets an ecological disaster zone. Inside the reserve's fences are lush green hills, outside is nothing but bare dongas"* (L'ange, 1996, pp. 48).

## 3.1 Introduction

The region defined for the present study is the Mid Great Fish river basin in the Eastern Cape, South Africa and occurs on the border of South Africa and the former Ciskei Homeland (Figure 3.1) - an area of approximately 2065 km$^2$. The geographic region defining the study area extends from 32°54' S, 26°35' E to 33°17' S, 27°08' E. The most salient features of the study area are that it is heterogeneous, semi-arid and marginal, and that it consists of four markedly different units of land management and population densities. Furthermore, it is located in a peripheral area of the South African space-economy (Ainslie *et al.*, 1994). The description of the study area presented here describes the existing physical attributes and the human factors contributing to those attributes as it soon became apparent that the socioeconomic factors are so closely interwoven with the physical that they could not be neglected. A false colour composite (using Landsat TM bands 3,4 and 5) of the study area is depicted (Plate 1).

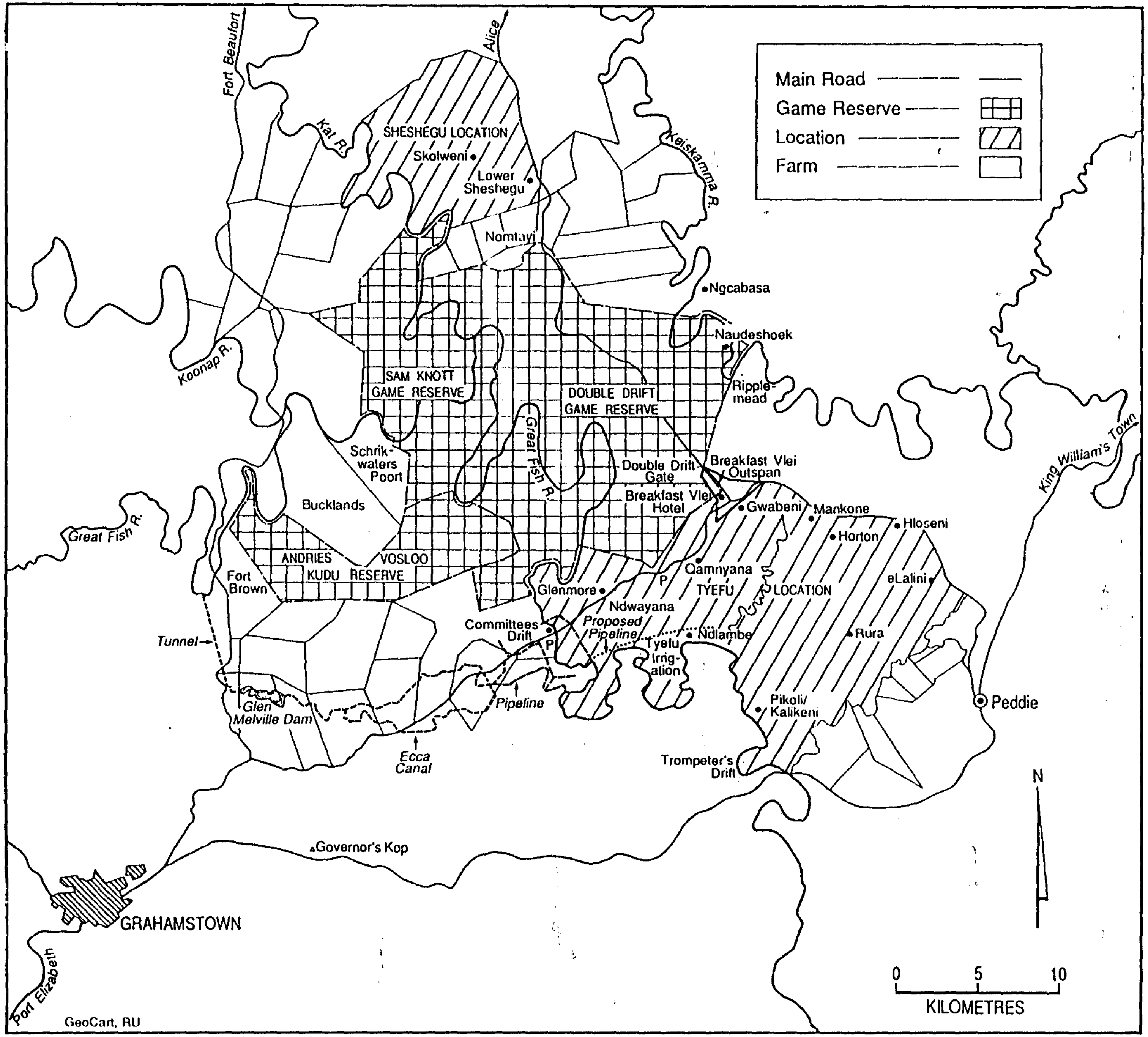



**Figure 3.1:** Map of study area and surrounds.

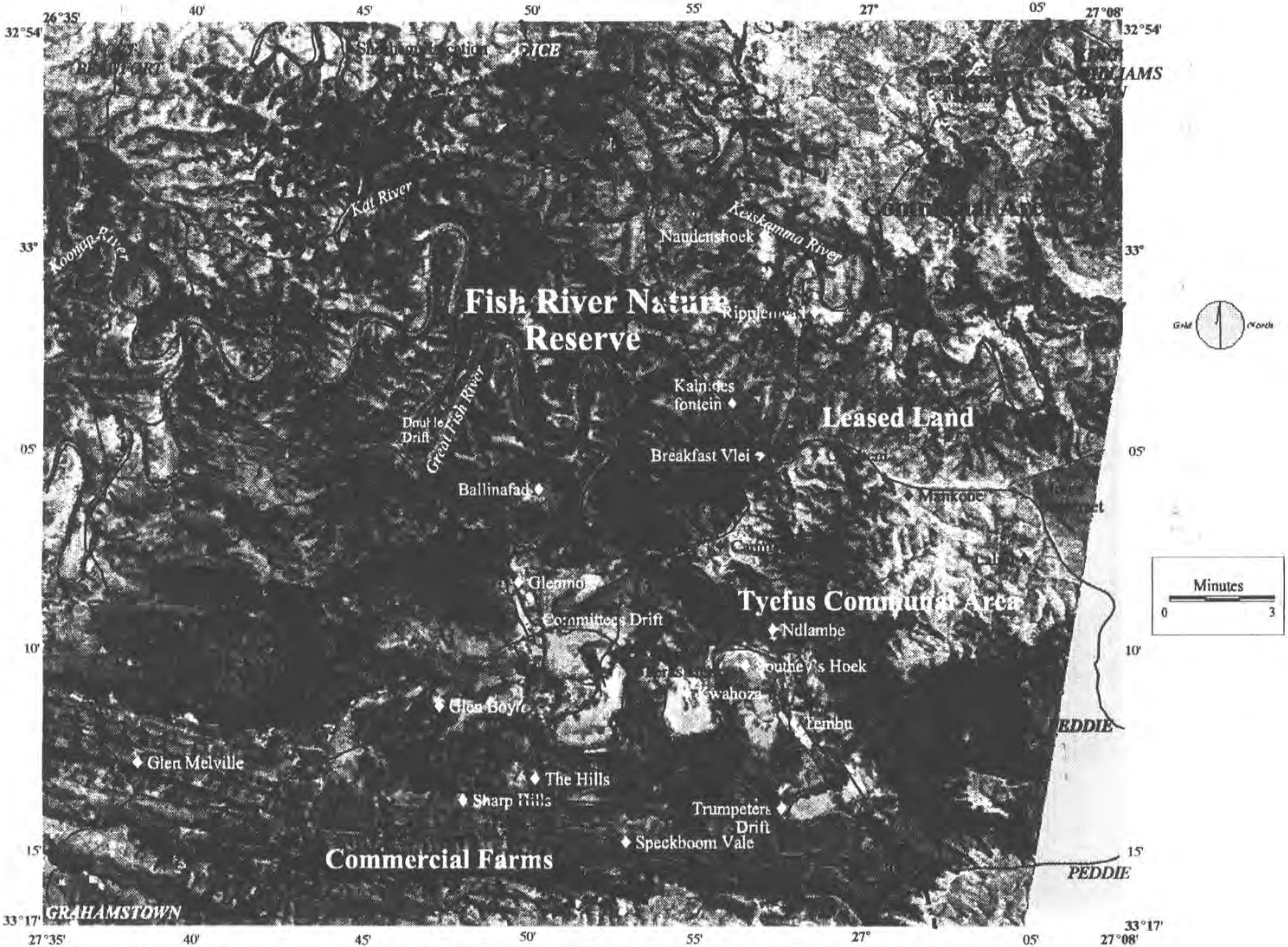



*Plate 1: False Colour Composite of the Study Area (bands 3,4,5 displayed as blue, green and red respectively)*

## 3.2 The Human Landscape

### 3.2.1 Introduction

The demographic pattern of the study area bears stark witness to the policies of the past regime, which forced people to live in defined areas without adequate resources or infrastructure provision. Areas inhabited by black people have been systematically underdeveloped through apartheid policies. Of the 18 500 people in the study area 16 500 live in 25% of the area (Tyefu and Glenmore) and the remaining 2000 are dispersed throughout the commercial farms and nature reserves (these figures do not include Sheshego which falls under the Alice district and for which no reliable census data exists) (Ainslie *et al.*, 1994). The population density therefore differs markedly in the study area: there is a density of 71 persons $km^{-2}$ in Tyefu Location but only 2-6 persons $km^{-2}$ for the remainder of the study area.

### 3.2.2 History

The history of land occupancy is a major causal factor to the degradation patterns observed as it has impacted on the distribution of the people, the distribution and types of settlement, land tenure systems, land management, and ultimately the use of resources which characterise the study area. The original division of land into white and black-owned dates back to 1825 when neutral territory was ceded to 'loyal fingos'. The rest of the study area was successively divided up into white farms on either side of the Great Fish River. With the Native Land Act (1912), Fingo's location became a sheduled area, while the Native Trust and Land Act (1926) established the possibility of 'released' land being made available for black occupancy beyond the scheduled areas. African farmers thus became tenants of the South African Native Trust. The National States Act of 1971 and 1975 consolidation proposals pre-empted Ciskei's independence in 1982. This saw the incorporation of white-owned farms into the Ciskei, particularly those farms north of the Committees Drift. Some of these farms were later to form part of Double Drift Game Reserve.

The Andries Vosloo Kudu Reserve, consisting of former white farms, was proclaimed in 1972. It was extended in 1977 and 1984. The relocation of 4500 people from 'black spots' around the Eastern Cape, to Committee's farm (just over the Fish River) occurred in 1979 and subsequently Glenmore was established.

By 1982, the South African Government had bought all the formerly white-owned farms between the Great Fish and Keiskamma Rivers. These were subsequently transferred from the South African Trust to the Ciskei Government and most of these were to become Double Drift Game Reserve in 1982. In 1987 the Sam Knott Nature Reserve was established from a bequest by Mr M.T. Knott to the World Wildlife Fund for Nature.

### 3.2.3 Land-Use

The study area can be divided into four using historical and political criteria. These criteria have determined subsequent patterns of settlement, population distribution, land-use and management systems.

#### 3.2.3.1 Communal Areas

Tyefu and Sheshego are the areas which were reserved for black settlement in the apartheid eras. The land is used as sub-subsistence rangeland with limited dryland cultivation practised on land allocated on a communal basis. Population densities are very high (over 70 persons $km^{-2}$) for such a poor resource base. Tyefu has an irrigation scheme, developed by the South African and Ciskei Governments, utilising the alluvial terraces along the Great Fish River and water made available from the Orange-Fish river scheme. Glenmore is the other main population concentration, it is located adjacent to Tyefu and is a resettlement community on a released white farm. The Glenmore community have access to an irrigation scheme associated with the Orange-Fish river scheme.

More than 90% of the livestock in the communal areas is owned by 22% of the people. This means there are wide disparities in livestock holdings and this has an influence on the management of the rangeland. 72% of the livestock owned on communal areas consist of cattle and the remaining 28% consists of sheep and boer or indigenous goats. Continuous heavy grazing in the area has led to a decline in palatable plants, and a transformation of productive shrub and grasslands to unproductive Karroid dwarf shrubland (Palmer and Avis, 1994). Consequently, the natural vegetation, which has a low resilience compared to other savannas, has been severely affected. Although both the high-lying and the low-lying areas are generally unproductive and erosion prone, especially on the steep slopes, most of the high-lying areas which fall within the fences of the nature reserves have relatively higher production rates (Palmer and Avis, 1994).

Approximately 40% of the area is estimated to be degraded to some degree (Tanser, 1994). The tribal custom of considering cattle a form of wealth is often blamed for the degradation problem.

Nevertheless, fencing, overpopulation and a breakdown in traditional social systems are the real culprits. The problem is compounded as the distribution of livestock does not correspond with the distribution of the productive high-elevation vegetation (Palmer and Avis, 1994). As a result, the communal areas are characterised by environmental degradation in a number of ways, primarily severe soil erosion, the deterioration of rangeland and the loss of biodiversity. The fragile environment and limited natural resources call for strategies which will ensure the future sustainability of the system.

#### 3.2.3.2 Released Farms

Released farms were incorporated into the contiguous area of Ciskei in the 1970s and 1980s. Population densities are in the order of 2-6 persons $km^{-2}$ and the land is consequently in a far better condition. As these released farms are adjacent to the communities mentioned above there is obvious pressure for expansion either of people or livestock into these areas. For the purposes of this study the vegetation characteristics of 'released farms' will generally be considered as a component of Nature Reserve vegetation as few significant differences exist.

#### 3.2.3.3 Nature Reserves

Several independent game reserves namely Double Drift, Andries Vosloo and Sam Knott recently amalgamated to form the Fish River Nature Reserve. Prior to being proclaimed conservation areas, the land currently comprising the reserves were composites of former white farms and which were previously managed as commercial rangeland. Some parts of this farm land were heavily grazed whilst other parts degraded. The Fish River Nature Reserve contains a greater variety of plant, reptile and arthropod species than the communal grazing lands (Fabricius *et al.*, 1995). The reserves also contain a higher vegetation biomass and greater abundance of palatable species than the surrounding rangelands (Palmer and Avis, 1994)

Differences in species composition and richness is directly attributable to land management, and specifically grazing intensity. The conservation areas protect a variety of rare or spectacular large herbivores which are not found on surrounding land. These areas also ensure the long-term survival of Valley Bushveld, only 16% of which is regarded as 'pristine' (LaCock *et al.*, 1990). Population densities are broadly similar to those of released land i.e. 2-6 persons $km^{-2}$.

#### 3.2.3.4 Commercial Farms

These are still farmed largely as rangeland (approximately 80% of the livestock are Angora goats and 5% are cattle) with private irrigation of crops, particularly lucerne, on the alluvial terraces of the Great Fish River. Population densities and settlement patterns are similar to those of the last two categories. The commercial farms have performed noticeably better than the communal areas and the resources of the area are managed in broadly sustainable ways (Palmer and Avis, 1994).

## 3.3 Physical Variables

### 3.3.1 Climate

The annual rainfall of the study area is low and variable due to the topographic range and high evaporation rates which give rise to a water deficit throughout the year. The inter-annual variability in rainfall is high (co = 29%), with a tendency towards a cyclical pattern of drought sequences interspersed with higher rainfall periods so that strategies for coping with drought are of major concern in the area (Ainslie *et al.*, 1994). The mean annual precipitation of the study area is approximately 434 mm with peaks in October and March. The departure from mean annual precipitation from 1970 to 1994 (Figure 3.2) and the mean monthly precipitation (Figure 3.3) are shown. The spatial distribution of rainfall (Plate 2) which is highly correlated with elevation (Plate 4) is shown.

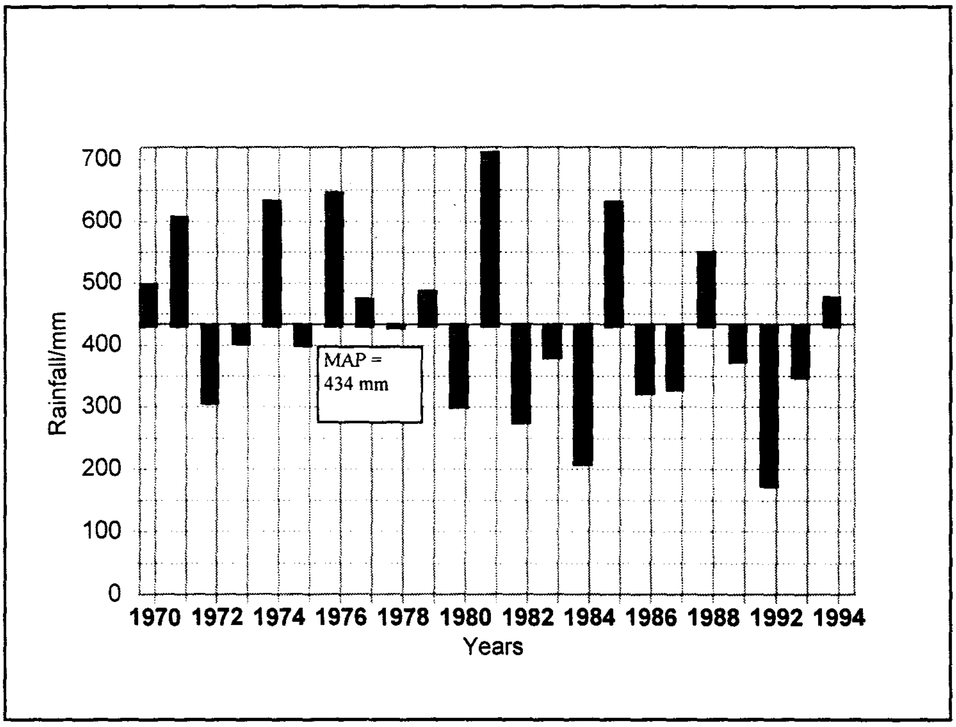



**Figure 3.2:** Departure from Mean Annual Precipitation (1970 - 1994)

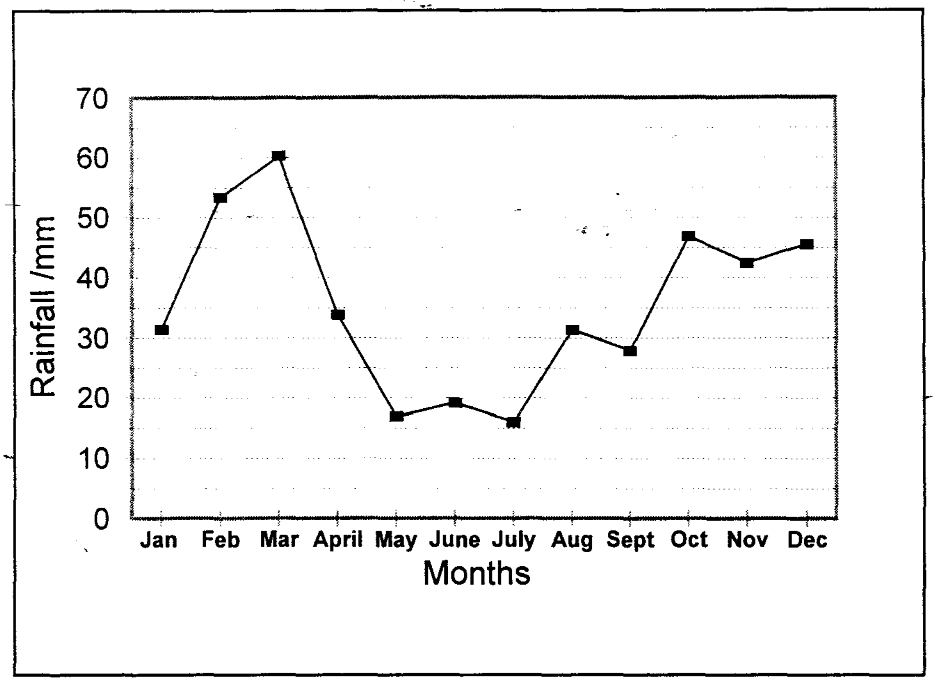



**Figure 3.3:** Mean Monthly Precipitation for the Study Area (1970-1994).

According to the Köppen classification the climate of the study area may be described as *Cfa*, where C = warm temperate climate - coldest month 18 °C to -3 °C; f = sufficient precipitation during all months; a = maximum temperature over 22 °C. Rainfall totals are markedly affected by ranges in elevation (section 3.3.2) and range from 250 mm to 850 mm.

### 3.3.2 Topography and Elevation

The study area is topographically complex (Plate 3) and this results in a complex climatic environment. Elevation ranges from 170 metres above sea level (m.a.s.l.) at the Great Fish River to some 560 m.a.s.l on the dividing ridge between the Great Fish and Keiskamma rivers (Plate 4). This range in elevation has an influence on the temperature and rainfall patterns within the study area. The low elevation sites along the Great Fish River experience lower mean annual rainfall as well as higher mean annual temperature, resulting in a hot semi-arid environment. The higher elevation sites are wetter (mean annual rainfall >500mm) and cooler, with lower January maximum temperatures (Palmer and Avis, 1994). Throughout the study area, small variations in climate may be attributed to differences in aspect and slope, with southern slopes experiencing cooler, moisture conditions; and north facing slopes being warmer and drier. Palmer and Avis (1994) cite the most significant variable controlling the vegetation as being altitude which has a close correlation with rainfall (Marker, 1990).

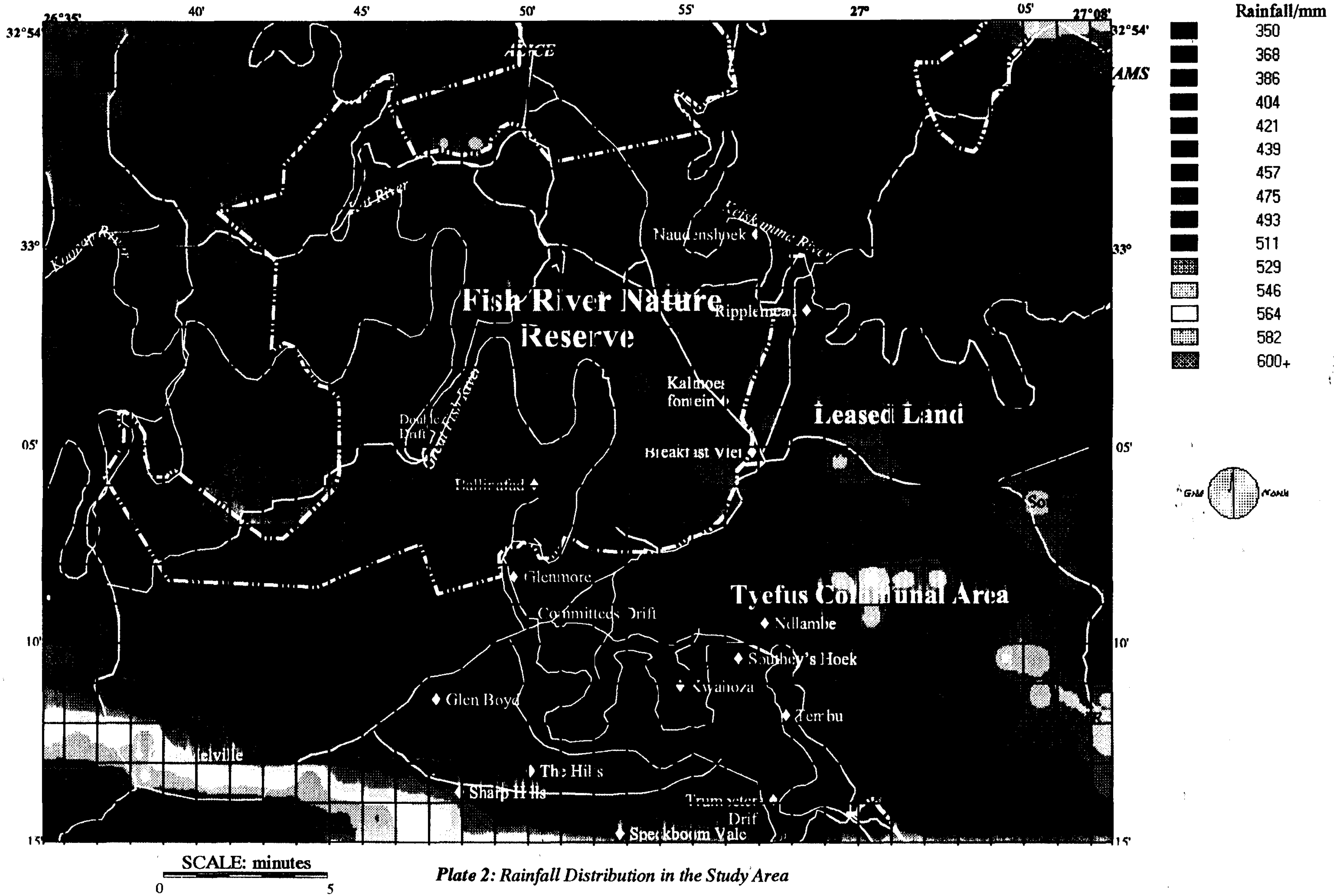



*Plate 2: Rainfall Distribution in the Study Area*

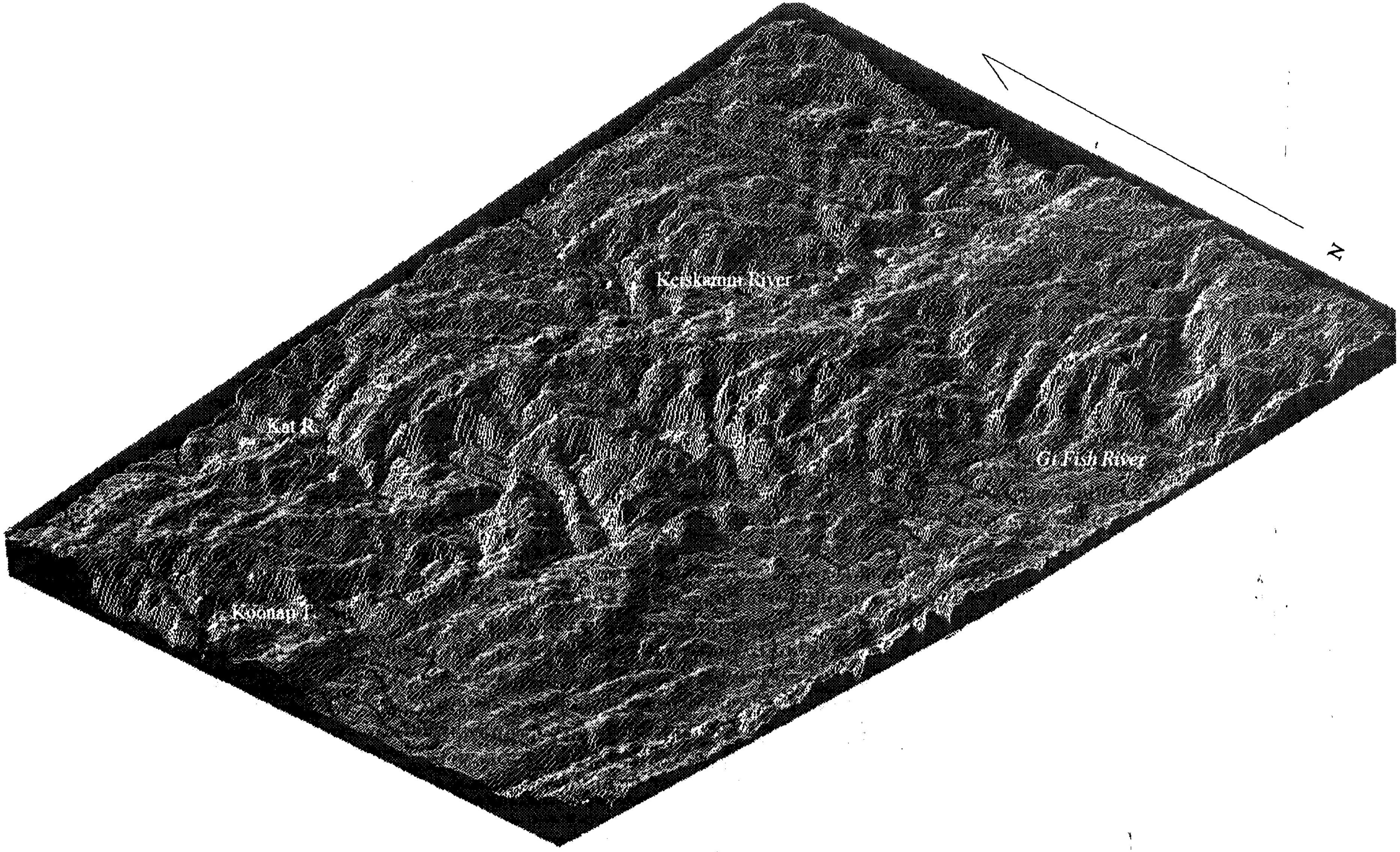
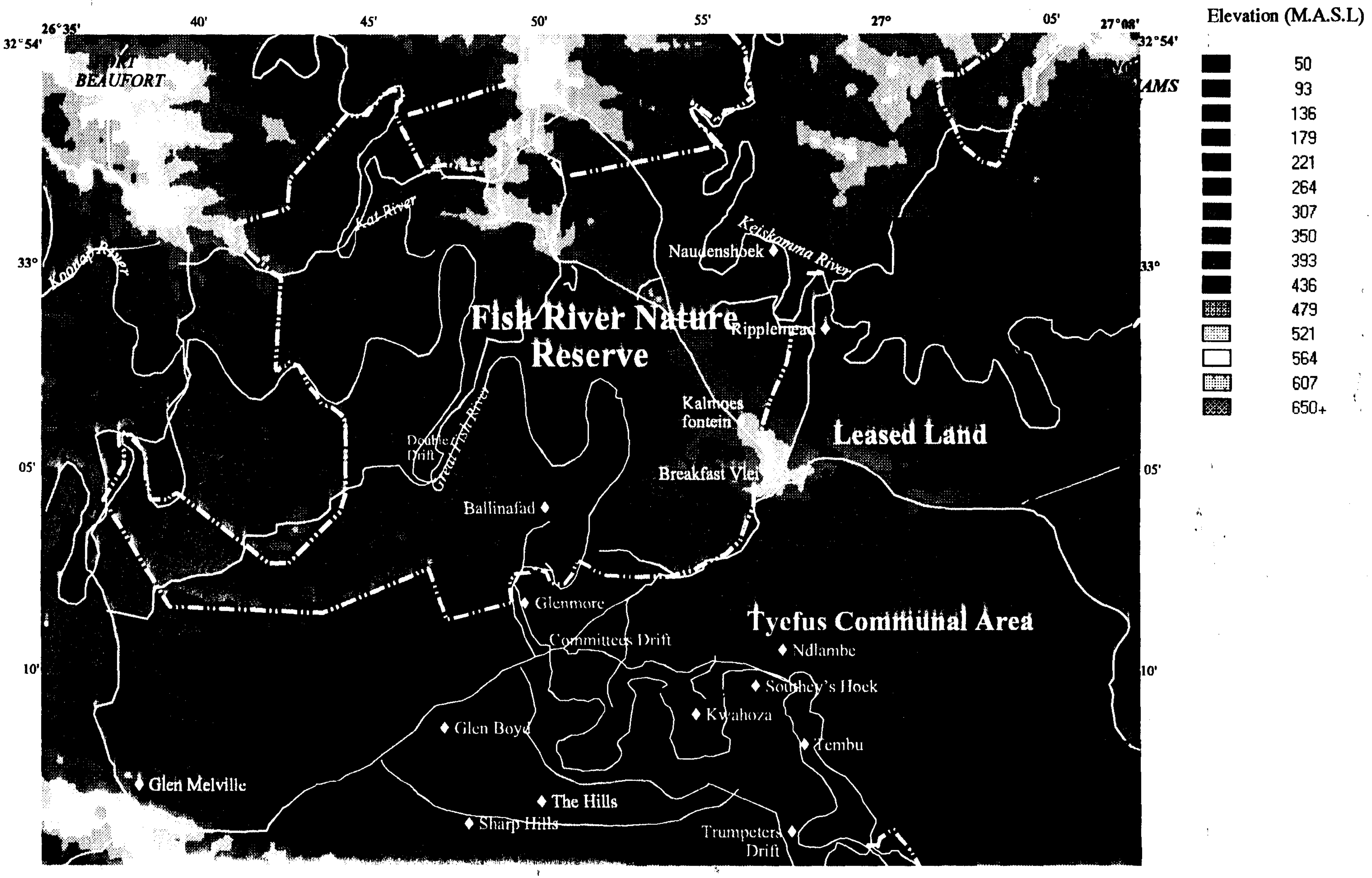



***Plate 3:*** *Shading Enhanced orthographical view of the study area showing the complex topography.*




SCALE: minutes
0 5

***Plate 4: Elevation Values for the Study Area***

### 3.3.3 Geology and Soils

Johnson and Keyser (1976) describe the geology of the study area as predominantly grey and 'red' mudstone, and sandstone of the Middleton formation (Adelaide subgroup: Karroo supergroup), with sandstone dominating the formation. The landscape consists of inter-basin ridges, with steep river valleys. The inter-basin ridges consist of the more resistant sandstone of the Middleton formation.

In the valleys nutrient-rich mudstones are exposed and are susceptible to erosion. Isolated dolerite dykes of post Karroo age exist in parts of the study area (Mountain, 1937). The koppies are features related to the more resistant rocks of the upper division of the Ecca series (Mountain, 1946). The shales are of varying character, interbedded with blueish mudstone, the beds gently dipping northwards (Mountain, 1937).

The soils, derived from the erosion of the Adelaide subgroup, are generally yellow/brown, apedal, sandy clay loams or clay loams overlying either mudstone, sandstone or parent rock, the latter being most common. The soils generally have a low dryland crop potential. Over most of the study area the soils are eutrophic, greyish, brown and light brown, shallow litholic and derived from the Beaufort and Ecca sediments (Loxton, Hunting and Associates, 1979). In the Committees Drift to Breakfast Vlei areas, and further west, rock outcrops cover approximately 25% of the landscape, and slopes are predominantly between 15% and 20%, but steeper slopes are not uncommon. Further south and west of Peddie similar soils occur but more arable eutrophic, well-drained red soils derived from Karroo sediments and alluvium are common at lower elevations. These soils have a moderate to low dryland arable potential, whereas the greyish brown soils have a low to very low potential (Loxton, Hunting and Associates, 1979).

### 3.3.4 Vegetation

The vegetation has been described previously by Acocks (1988) as a semi succulent thorny scrub, about 2 m high. Acocks (1953) classified the Fish River scrub as a variant of his Valley Bushveld. He regarded *Euphorbia bothae* as an invading species, and distinguished four variations which he related to successional gradients. These variations are:-

- Dense, succulent scrub with some grass (climax);
- Open succulent scrub with much grass;
- Open, succulent scrub with thorny shrubs and succulents, and Karroo bushes invading the grassland;

- Succulent, thorny scrub with karroo bush and little grass.

A detailed floristic analysis has been undertaken by Palmer (1981) in the Andries Vosloo Nature Reserve. This study provides useful information on natural vegetation that has not been exposed to domestic herbivory. In the study Palmer (1981) recognised three orders, based on the presence of differentiating species:

- *Walafrida geniculata - Felicia muricata* community of the drainage lines and now succulent bushclump savanna. Two variations, each with two sub-variations were recognised;
- *Portulacaria afra - Barleria obtusa* community of the succulent bushclump savanna and thicket. Two variations and five sub-variations were recognised;
- *Hippobromus pauciflorus - Schotia latifolia* community of dry forests.

A structural vegetation analysis of the area was undertaken by Palmer and Avis (1994). Using Landsat TM data and a technique developed by Westfall and Malan (1986) four vegetation classes were identified and mapped.

- Short Succulent thicket
- Bushclump Savanna
- Medium Succulent Thicket
- Riparian

The most recent floristic vegetation analysis has been undertaken by Evans *et al.* (1996) who used a direct gradient analysis approach to classify the vegetation into homogenous units. The results showed four major plant communities present, namely;

- Short succulent thickets
- Medium succulent thickets
- Mesic bushclump Savanna
- Grasslands of the mesic bushcamp Savanna.

The vegetation units were subdivided into the three different landuses. All four classes were defined in the commercial rangelands and nature conservation areas but only the classes Dwarf shrubland and Grassland were established on communal rangelands.

The results revealed a definite grazing gradient which showed that an increase in grazing intensity resulted in a transformation from vegetation synonymous to a mesic environment towards that found in an arid environment. As grazing pressure increased there was a decrease in palatable grasses, succulents and herbaceous species and an increase in dwarf Karroid Shrubs.

#### 3.3.4.1 Communal Rangeland

The rangelands near traditional villages at low elevations (<250 m) and low rainfall (<290mm) on mudstone substrata are dominated by unpalatable and poisonous plants (to domestic livestock) and weedy annuals. Although the amount of wet season photosynthesis is similar to that of underutilised areas where the same conditions prevail, production of plant species suitable for domestic herbivores has declined. In addition, in the friable, nutrient rich substrata of the Ecca series mudstones, erosion has removed the thin layer of overlying soil (Palmer and Avis, 1994).

At moderate elevations (250-500 m) and rainfall (290-450mm) sites near traditional villages, the change is manifested by an increase in annual grasses and a reduction in palatable leaf succulents (for example *Portulacaria afra* and woody shrubs). The surviving shrubs include unpalatable woody species (for example *Ptaeroxylon obliquum*; *Euclea undulata*) and *Euphorbia triangularis*, which are either tolerant of herbivory or unpalatable to domestic stock. The herbaceous layers consist of annual grasses and Karroid dwarf shrubs. These sites continue to provide some sustenance to the herbivore, as they are usually further away from villages, occurring on the more steeply sloping land. However, the collecting of wood-fuel continues to destroy old, well-established woody shrubs which would otherwise continue to contribute significantly to high quality herbage (Palmer and Avis, 1994).

At high elevation (>500 m.a.s.l) and rainfall (450-600mm), the degraded rangeland near traditional villages comprises Karroid shrubs (*Pteronia incana*), annual grasses (*Aristida sp.*) and leaf succulents (*Aloe ferox*).

#### 3.3.4.2 Commercial Rangeland

Palmer and Avis (1994) identified commercial rangeland condition at low elevation and low rainfall to be moderate to good. There was some evidence of dominance by Karroid dwarf shrubs but this did not deviate significantly from their expectation based on topo-moisture classes. At moderate elevation and rainfall, succulent shrubs had a high cover, with many of the desirable species (for example *Capparis sepiaria, Boscia oleoides, Phyllanthus verucossus*) being well represented.

#### 3.3.4.3 Nature Reserve Vegetation

In the conservation areas, the low elevation and rainfall sites were quite uncommon but did not differ significantly from expectation based on topo-moisture classes (Palmer and Avis, 1994). At moderate elevations and rainfall, a reduction in the height of the desirable species was experienced. This could be explained by the wider range of herbivores which utilize this vegetation, particularly bushbuck, kudu and black rhinoceros (Palmer and Avis, 1994). A large proportion of the high-potential grazing land occurs within the western section of the Fish River Nature Reserve (formerly Double Drift Nature Reserve) and was extremely grassy, with a high cover of perennial grasses (for example *Themeda sp., Digitaria sp.* and *Panicum sp.*). Condition of the high performance land varied from poor on the Andries Vosloo Nature Reserve, where high buffalo numbers have reduced grassiness, to extremely good on the Double Drift Nature Resererve (Palmer and Avis, 1994)

## 3.4 Selection of the Study Area

The preceding sections have described the existing human and physical landscape of the Mid Fish River Valley, Eastern Cape. The history of the area which has resulted in the current landscape mosaic has been described, as well as the characteristics of the different land-use categories. The associated environmental variables (climate, topography and elevation, geology and soils) and the effects these variables have on the vegetation of the area in concert with the effects of different land-use treatments was also described by a brief literature review of previous vegetation surveys.

Throughout the chapter the heterogeneous nature of the study area has been alluded to. These 'heterogeneities' provide significant obstacles to many conventional remote sensing techniques. The study area was therefore selected to enable the development and testing of a landscape pattern index which will operate reliably across the heterogenous land-uses, climatic gradients, differing soils and geology and complex topography. This will enable a thorough assessment of the performance of the index.

# CHAPTER 4

# DATA COLLECTION AND METHODS OF ANALYSIS

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*"... remote sensing is a reality ... whose time has come. It is too powerful a tool to be ignored in terms of both its information potential and the logic implicit in the reasoning processes employed to analyse the data. We predict it could change our perceptions, our methods of data analysis, our models and our paradigms."* (Estes *et al.*, 1980, pp. 43)

This chapter commences with a description of the surface reference data (collected to corroborate ground features with the satellite data) and the rationale for the collection of this data. A description of the available imagery and its characteristics is presented. The registration of the images to a geographic reference base and the feasibility of undertaking some form of change detection analysis is then examined. The methods used in obtaining a vegetation classification, determining the environmental characteristics associated with each vegetation type and the methods used for assessing accuracy of the classification are then described. The vegetation index to be used in the study is described as well as the methods to be used to establish the vegetation index's relationship to condition, biomass and rainfall are presented. The final section describes the method used to derive an index of landscape pattern and the relationship of the index to vegetation condition, vegetation production, vegetation type as well as the operation of the index in other ecosystems.

## 4.1 Collection of Surface Reference Data

To facilitate the mapping of landscape characteristics it was necessary to have extensive surface reference data to verify that the components of the landscape being identified by the satellite were in fact the objects under investigation and not background 'noise'. To this end an extensive field survey comprising 180 sites was undertaken. Due to financial constraints there was a two-year lapse between the capturing of the most recent (1994) image and the collection of surface reference data. The assumption is therefore made that no change has taken place between the two events. To compensate for this all surface reference data were collected at a near anniversary date to the wet season image (February - March 1996). This ensures that vegetation characteristics are as similar as possible to the those of the vegetation at the time of image capture. The time lapse between the capturing of the image and collection of field data was not characterised by any 'abnormal' conditions such as very high rainfall and therefore no major differences in landscape condition were expected to exist between the two events. The sites were chosen to represent homogenous units in the study area. Information recorded at each sample site are listed (Table 4.1) and a concise summary of all surface reference data provided (Appendix 1).

***Table 4.1: Surface Reference Data***

| Data | Method | Notes |
|---|---|---|
| **Latitude and Longitude** | Obtained using a Magellan Global Positioning System (GPS) | Using the high precision WGS 84 geodetic reference system |
| **Vegetation** | A combination of Edwards (1983) classification (Appendix 2) and the classifications used in other vegetation surveys (Evans *et al.*, 1996; Palmer, 1981; Palmer and Avis, 1994) as well as other vegetation categories observed in the field. | The broad category *Dwarf shrubland* and a succulent component were added to Edwards (1983) existing classification. |
| **Geology** | Johnson and Keyser (1976) 1:250 000 maps as well as an *in situ* assessment | Sandstone, Mudstone, Dolerite, Shales |
| **Land-use category** | 1:50 000 maps | Commercial, Communal, Nature Reserve |
| **Overall cover components** | Estimated | % shrub, % grass, % bare |
| **Average height of classifying component** | Estimated | |
| **Aspect** | Compass | Where slope was < 5 ° the slope was not considered to have an aspect and -1 was entered |
| **Altitude** | Avocet Baroaltimeter | |
| **Slope** | Abney Level | |
| **Erosion Status** | An adaption of Norton *et al.*, 1984. Handbook of Standardised Monitoring Techniques for Cape Nature Reserves. (Appendix 3) | Categories 2,3 combined into 'moderate' |
| **Soil** | **Type** (Loxton, Hunting and Associates, 1976), **colour** (Munsell colour charts) and **texture** (gauged *in situ*) | |

It was decided to adopt a structural approach to the mapping of the vegetation for a number of reasons. Firstly, direct biophysical remote sensing of floristic vegetation types has only been successful in homogenous environments with relatively uniform or predictable surface properties (Sellers, 1987) or in controlled experiments (Franklin, 1991). Secondly, a structural vegetation map would be of more use to decision makers. Thirdly, there are marked associations between floristic and structural components in the study area. On this basis ten vegetation classes were identified and described.

### 4.1.1 Error Minimisation

The magnitude of error in the collection of location data using a Global Positioning System (GPS) is a common source of debate in the remote sensing community (Ardö and Pilesjö,1992; Koh and Edwards, 1996). The GPS system is owned by the United States Department of Defence. The system comprises a constellation of 24 satellites that orbit the Earth every 12 hours. Each satellite transmits two carrier signals termed L1 and L2 respectively. Modulated onto the L1 signal are two pseudo-random binary code sequences known as the Coarse Acquisition (C/A) code and the Precise (P) code. The use of pseudo -random binary code sequences enable all satellites to transmit on the same frequency without creating a garbled mess of radio interference. The C/A code is intended to assist with the acquisition of the P code for approximate position measurements and civilian use, whereas the P code is intended for the military and is more precise by an order of magnitude (Koh and Edwards, 1996).

Ardö and Pilesjö (1992) demonstrated that the maximum error encountered was 44m from a known fixed point using a single GPS. In order to minimise errors in fieldwork the following steps were taken. Sampling was only carried out on sites where the properties under investigation were of a large areal extent (approximately 90m x 90m or greater). However, in the vegetation type *Riparian forest* this was not possible due to its elongated nature and small extent. Secondly, all GPS readings were averaged over a period of five minutes. This reduces, but does not eliminate, the errors. Ideally differential correction is obtained using two GPS systems. One is positioned at a known point of reference such as a trigonometric beacon. The user of the second GPS then remains in contact with the user of the static GPS and the magnitude of deviation from the known point is noted and subtracted from the reading taken in the field. Using this method it is possible to obtain sub-metre accuracy readings. However, monetary constraints did not allow for the use of multiple GPS and hence the need to average the readings. During the field survey, a trigonometric beacon of known geographic position was visited on several occasions to determine errors in the roving GPS positions. Sub-pixel errors were obtained during all these visits.

## 4.2 The Available Satellite Imagery

### 4.2.1 The Imagery Characteristics

The satellite data available for the study are shown (Table 4.2).

***Table 4.2: Satellite Data Available for the Study.***

| Type of Data | Scene ID | Date | Bands | Season | Correction level |
|---|---|---|---|---|---|
| Thematic Mapper | 170-083 | 11/05/92 | 1 - 7 | Dry | 5[1] |
| Thematic Mapper | 170-083 | 26/02/94 | 3 - 5 | Wet | 5 |

The data was received in the form of an EXABYTE cartridge in band interleaved format. The exabyte cartridge was then read in the Unix operating system using the GRASS Geographic Information System. The resulting images were then imported into IDRISI where all image processing took place.

Ancillary data available for the study are shown (Table 4.3).

***Table 4.3: Ancillary Data Available for the Study***

| Type of Data | Resolution | Source |
|---|---|---|
| Digital Terrain Model | 200m | Director General, Surveys and Mapping |
| Median Annual Rainfall | 60 pixels per degree | Dent *et al.*, 1989 |

To facilitate any form of comparison between images acquired on different dates, such as change detection analysis (Michalek *et al.*,1993), it is necessary to correct the data for seasonal variations such as preceding rainfall events, differences in the amount of haze present and cloud cover. The preceding rainfall events in the year leading up to the capturing of the image are shown (Figure 4.1 and 4.2). An analysis of the graphs shows that any form of direct comparison or change detection is impossible due to the different seasons that the images were captured in and the dissimilar preceding rainfall events. The dry conditions that prevailed during the capturing of the 1992 image (Figure 4.1) are clearly shown with no precipitation recorded during the image acquisition month of May. The capturing of the 1994 image by contrast took place in a year of above average rainfall (Figure 4.2 ) and with the greatest percentage of that rainfall occurring in the 3 months prior to the capturing of the image.

[1] The imagery is radiometrically corrected. Geometric corrections are applied in both the across-scan and along-scan directions using spacecraft orbital and attitude information. The scene is not corrected to a projection and the orientation is not changed.

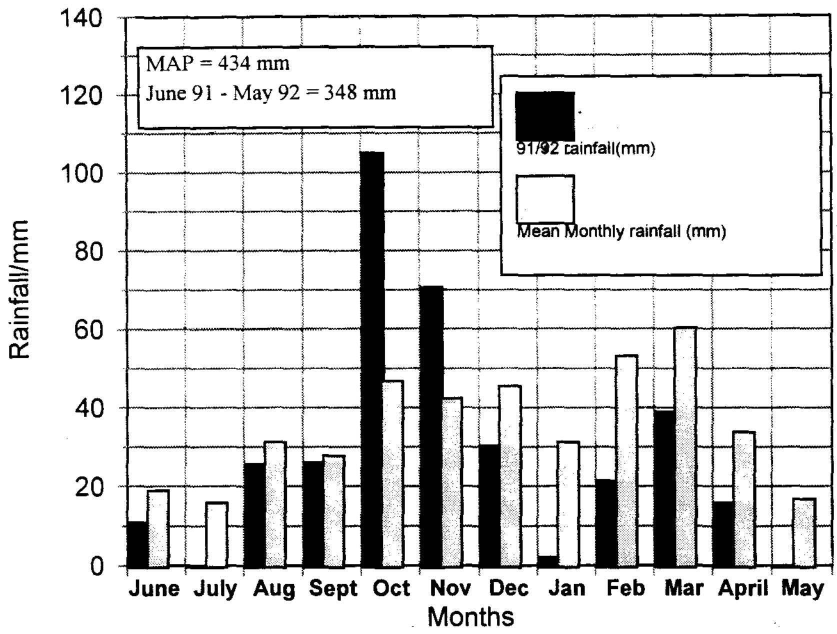



**Figure 4.1:** Rainfall events preceding the capturing of the 1992 data to illustrate the dry conditions under which the image was captured.

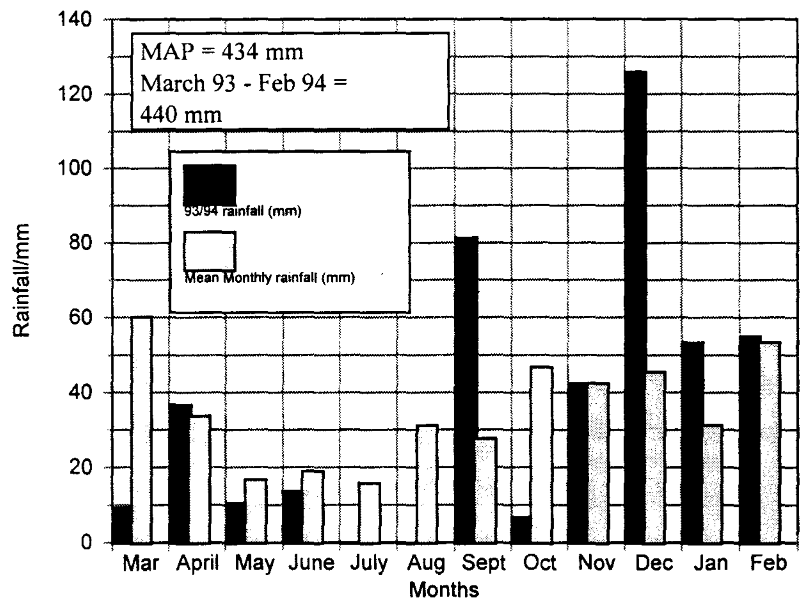



**Figure 4.2:** Rainfall events preceding the capturing of the 1994 image to illustrate the moist conditions under which the image was captured.

The dissimilar preceding rainfall events clearly rule out any form of direct comparison between the images. However, this may be an advantage in the discrimination of vegetation types as temporal differences in plant phenology can enhance the satellite's ability to delineate vegetation types (Richards, 1984).

### 4.2.2 Image Registration and Projection

Image registration is carried out by locating identifiable points in all images and geometrically transforming the image using a 'rubber sheeting' procedure so that the coordinates match. Control points were located interactively on the screen and in the field using a GPS. The GPS readings were averaged over a period of five minutes during which 10 readings were taken to minimise the random fluctuations imposed by the United States Department of Defence. Recognisable features such as road intersections and stream confluences are used. The module RESAMPLE [2] is then applied to compute a matrix of transformation coefficients using the control points and the least squares regression. If the sum of the root mean square (r.m.s.) errors for all control points are greater than the user-specified tolerance (1.0 pixel was used), the control point having the largest r.m.s. error is eliminated, and the coefficients are recomputed until the total r.m.s is less than the tolerance. In this case 20 control points were identified interactively on the screen and using a GPS, and 9 of these were subsequently used (6 discarded). The remaining 5 points were retained to validate the quality of the rectified image. The transformation coefficients are used to convert the coordinates of each image into the coordinate system of the new registered image.

The data were transformed with a first order (linear) transformation matrix. A higher order polynominal can be used but linear transformation was deemed adequate for two images from the same sensor. Other 'resampling' algorithms could be applied such as bilinear interpolation or cubic convolution, but nearest neighbour was chosen so that the integrity of the radiometric measurements would be preserved during registration. Slightly smaller sub-images of the registered images were selected and used in subsequent analysis to avoid the problem of misregistration that tends to occur at the edge of the image, outside the grid of control points. The images were then projected into a Universal Transverse Mercator Projection using the Cape Datum. The other parameters used in this transformation are listed (Appendix 4).

To further confirm the accuracy of the transformation an independent data set consisting of roads and rivers digitized from 1:50 000 maps was overlayed onto the images. In all cases the accuracy of the data was found to be within a pixel. The quality of the georeferencing was then further validated using the remaining 5 points identified prior to the rectification (these points were not used for the rectification). All were found to be within one pixel.

---

[2] Modules expressed in capital letters are taken from IDRISI.

## 4.3 The Vegetation Classification

A preliminary vegetation classification undertaken by Tanser (1995) yielded 5 vegetation classes. Field investigations revealed that the classification had not distinguished between succulent and woody vegetation communities and was only accurate in the high rainfall regions of the study area Therefore the succulent component was added to the existing field classes.

Tueller (1989) states that, on rangelands, unsupervised classification appears to produce the most accurate results. O'Neill (1989) found that in heterogeneous areas of high variability unsupervised classification was far more accurate than a supervised approach but that a combination of both produced the best results. To delineate the dominant vegetation types in the study area the results of a broad unsupervised classification and a multi-temporal classification will be compared. Classes that are not obtained by either approach will be extracted using a supervised classification.

### 4.3.1 The Unsupervised Classification

An unsupervised classification was performed on wet season TM bands 3,4 and 5. The wet season imagery was chosen following a visual inspection of the images and a standard deviation histogram analysis (Figure 4.3) revealed that the wet season bands contained substantially more spectral information than those of their dry season counterparts. The differences in standard deviation reflect the greater contrast in reflectance encountered in a wet season image due to the greater variation of photosynthetic patterns observed during a wet season in semi-arid areas. This contrasts strongly with the redundant information and lack of contrast displayed in the dry season images. The combination of bands 3,4 and 5 has been found to be very effective in monitoring tropical deforestation in the Amazon rain forests as typically these three bands account for 95% of the variance encountered in all bands (Lillesand and Kiefer, 1994).

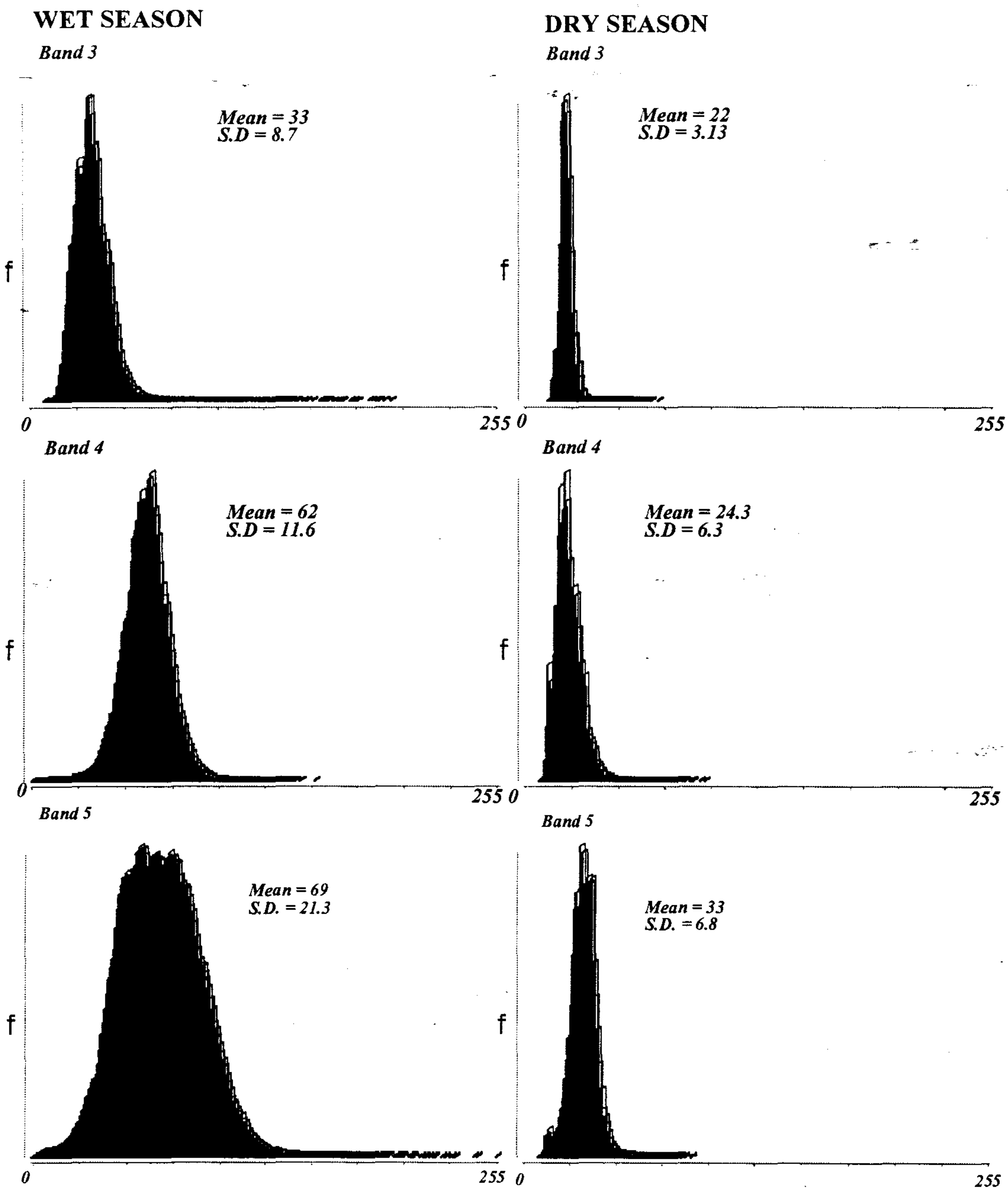



**Figure 4.3:** A comparison of wet and dry image frequency histograms.

To perform the unsupervised classification a composite image was produced using bands 3,4 and 5 (assigned to blue, green and red respectively) using the linear stretch with 2.5% saturation option (Plate 1). A broad unsupervised classification with clusters occupying less than 1% of the image dropped from the classification was performed on the data. In the broad classification, a class must contain a frequency higher than all of its non-diagonal neighbours. Where classes were too broad and contained more than one class or where it was necessary to delineate a small vegetation class a supervised classification was performed on the remainder of the data. Additional classes derived from other classifications will be added to the existing classification using the COVER option in the OVERLAY module. This allows an image to be overlain on another image where all non-zero values on the top image replace those on the bottom image.

### 4.3.2 The Use of Multi-temporal Vegetation Spectra

The satellite's ability to map vegetation types can be enhanced with the aid of seasonal variations in plant phenology (Franklin, 1991; Richards, 1984). The 10 bands of multi-temporal data (7 wet season bands and 3 dry season bands) were combined into a set of discrete bands and inputted into a composite image and an unsupervised classification performed using a Principal Components Analysis (PCA). The first three components were then transformed into byte binary data by linear stretching. The minimum and maximum values were determined by the values occurring at the 'shoulder' and not the edge of the histograms to encourage maximum differentiation of the digital numbers. The components were combined into a composite image where principal component 1-3 represent the green, blue and red band respectively. An unsupervised classification was then performed identical to the one described in the previous section 4.3.1. A similar technique has been used successfully by Richards (1984) to map vegetation classes in the Sahel.

### 4.3.3 Accuracy Assessment

A standard method for evaluating thematic maps produced from remotely sensed digital images is to compare them with either a sample of ground-control points or a reference map produced by photo-interpretation.. The accuracy of the final classification image was assessed based on the sites that were surveyed in the field. Cross-tabulations were made of the sites surveyed in the field and arranged in a classification error matrix.

In this study accuracy was assessed by three measures in order to demonstrate the variability in estimates of error based on these estimates. The measures were:

- ♦ *Commission error* - the proportion of points assigned to a class that were actually in another class (diagonals divided by row totals).
- ♦ *Omission error* - the proportion of points in a class that were incorrectly assigned to another class (diagonals divided by column totals).
- ♦ *The Kappa coefficient of agreement* (Congalton and Mead, 1983; Hudson and Ramm, 1987; Rosenfeld and Fitzpatrick-Lins, 1986).

The Kappa index measures the actual agreement between the two maps minus chance agreement. A value of 1 means perfect agreement (a matrix with entries only on the diagonal). The Kappa index is based on all entries in the table, and is therefore considered a single index expressing both omission and commission error (Franklin, 1991).

### 4.3.4 The Environmental Characteristics of the Vegetation Types

The Digital Terrain Model (DTM) and median annual rainfall were resampled to the same resolution as the satellite data (30m) using the module RESAMPLE. This facilitated a preliminary investigation into the conditions associated with each vegetation types (elevation, rainfall, aspect and slope). The module SURFACE was used to calculates slope and aspect images from the DTM. SURFACE determines the slope by calculating the maximum slope around each pixel from the local slopes in X and Y. Only the neighbours above, below, and to either side of the pixel are accounted for in this procedure. Aspects use standard azimuth designations, 0 - 360, clockwise from north. In regions where the surface is perfectly flat with slope = 0, aspect is assigned a value of -1. The aspect and slope images are shown (Plate 5 and Plate 6 respectively).

To identify environmental characteristics of the vegetation types, a stratified random sampling approach was employed. Two thousand sites were sampled in the study area and were selected using the module SAMPLE. To sample from large areas of representative vegetation roads, large rivers (Fish, Keiskamma and Koonap) and boundaries between the respective land-use categories were buffered by 5 pixels. The buffer zones were assigned a value 0 whilst the remainder of the study area was assigned a value 1. The final vegetation classification was interrogated by the module GROUP to determine contiguous groupings of identically valued integer cells in an image. Cells belonging to the same contiguous grouping are given a unique integer identifier, numbered consecutively in the order found. The module AREA was then used to calculate the area of the individual identifiers assigned by GROUP. All values less than 100 pixels were then assigned a value 0 whilst the rest of the image was assigned the value 1. It was not possible to do this with *Riparian forest* as it has a small areal extent and is elongated along drainage lines. This class was assigned a value one and added to the AREA image using COVER. The SAMPLE image was then multiplied with the BUFFER image and the AREA image to create a final sampling image. The final sampling image consisted of only those values that are not within 5 pixels of a road, river or land-use boundary and occur only in vegetation types consisting of an area of 100 pixels or greater (except in the case of *Riparian forest*). This eliminates the possibility of isolated small areas of unrepresentative vegetation being sampled.

The rainfall, slope and elevation values (obtained from the sample image) were graphed to produce three-dimensional environmental 'envelopes' for each vegetation type. Aspect histograms of the individual vegetation types were analysed separately in conjunction with field data to ascertain if a preferred aspect existed.

### 4.3.5 The Relationship of Vegetation Type to Land-Use

To assess the impact of land-use on vegetation type, the percentage of each vegetation type (derived from the final vegetation classification) occurring in each of the land-use classes (taken from digitized polygons) was calculated using the module AREA.

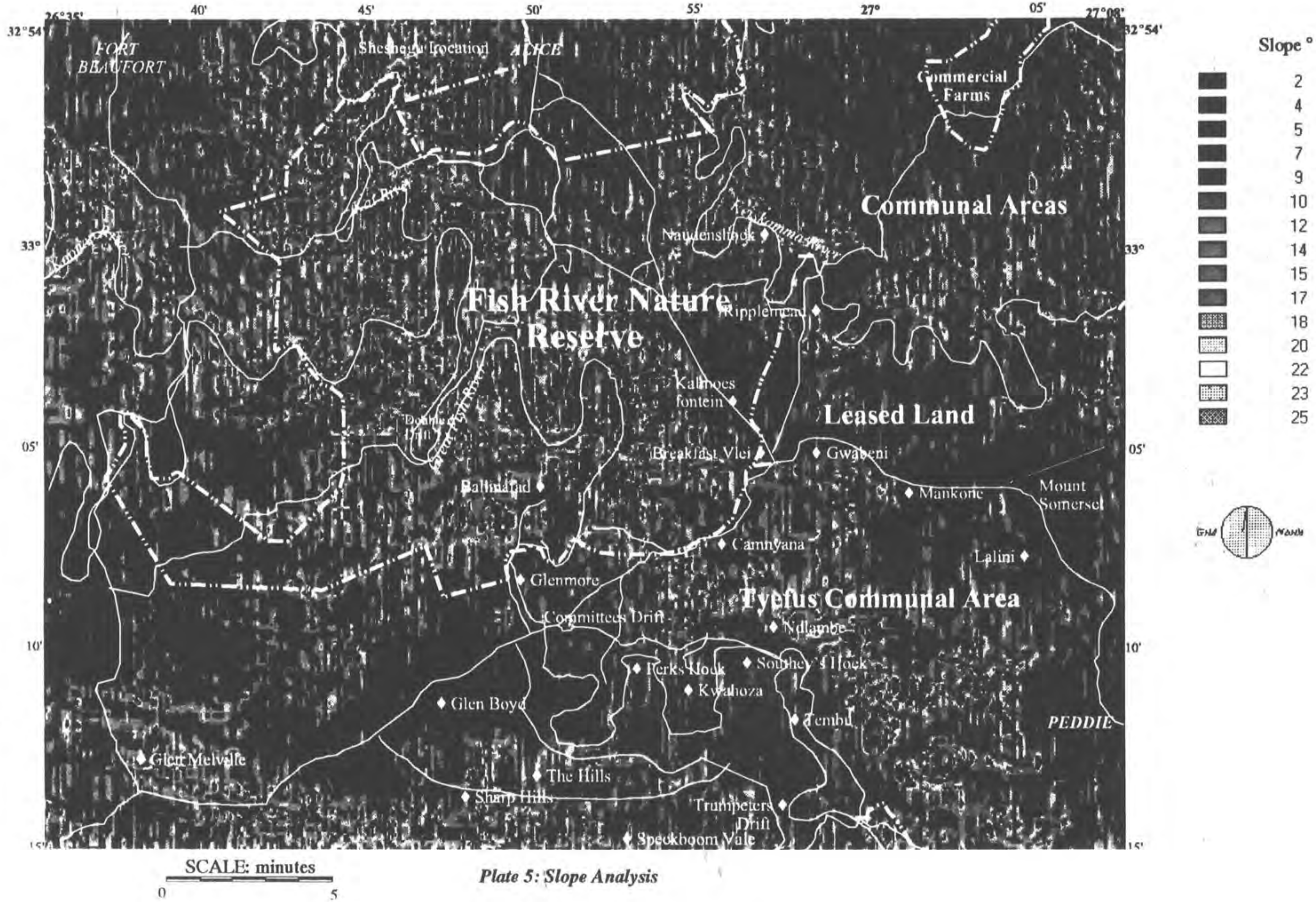



*Plate 5: Slope Analysis*

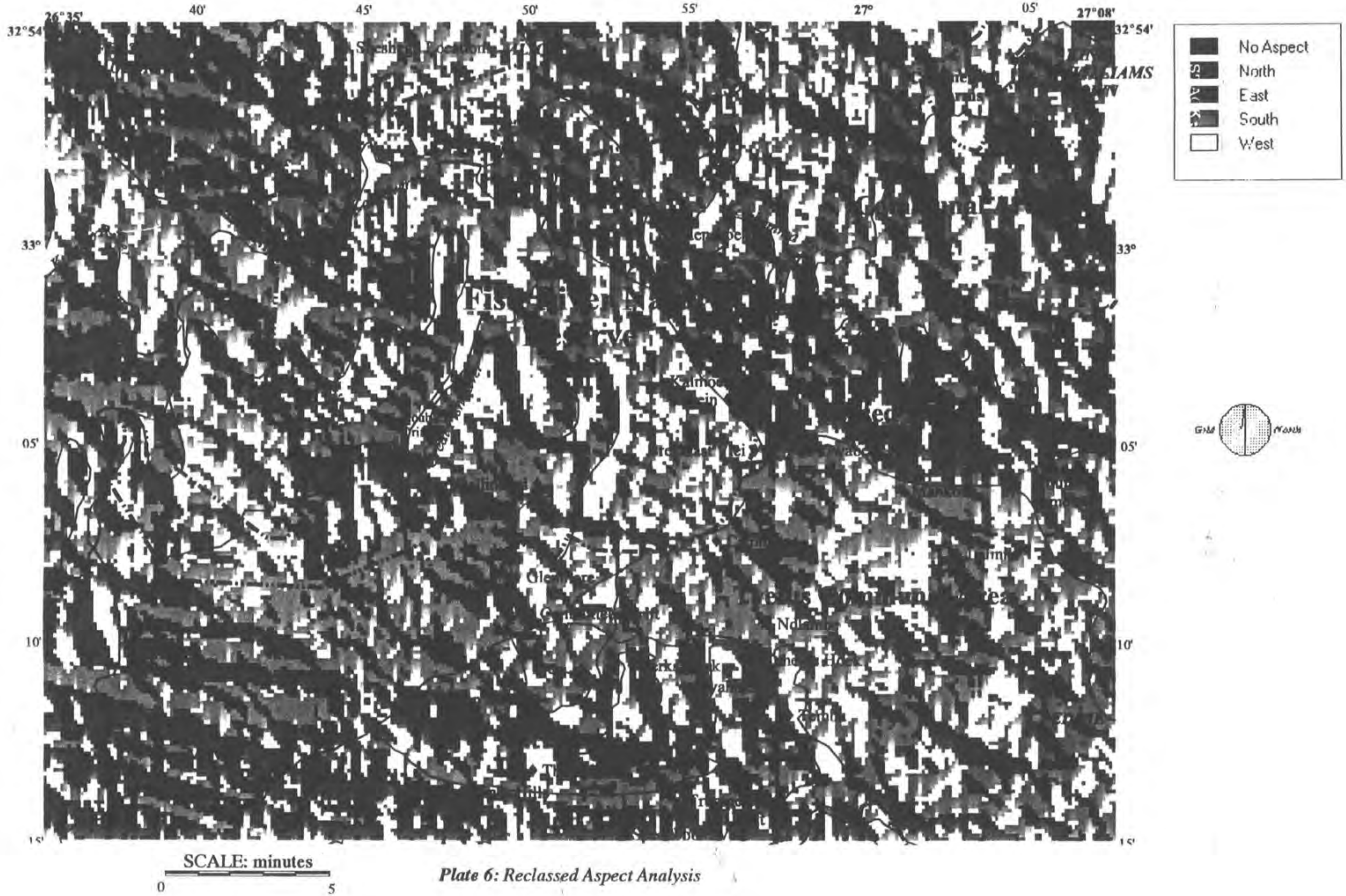



*Plate 6: Reclassed Aspect Analysis*

## 4.4 Vegetation Production

A large percentage of the research area consists of very low cover and it is therefore necessary to correct for the influence of background soil noise. Indices such as the Soil Adjusted Vegetation Index (SAVI) (Huete, 1988) were considered. This index has recently been used by Mackay and Zietsman (1996) to identify fence-line contrasts in the Ceres region of South Africa. Elvidge and Chen (1995) investigated how the performance of the Normalised Difference Vegetation Index (NDVI), the Ratio Vegetation Index (RVI), the Soil Adjusted Vegetation Index ( SAVI), the Perpendicular Vegetation Index (PVI) and the Difference Vegetation Index ( DVI) in related to leaf area index (defined as the total area of leaves per ground area) and percentage green cover (the percentage of the ground area which is covered by photosynthetic canopy materials). Using pinyon pine (*Pinus edulis*) and trays filled with different gravel backgrounds, they found that SAVI and PVI consistently provided better estimates of Leaf Area Index and percentage green cover than did NDVI or RVI. They also discovered that there was a steady improvement in all of these vegetation indices as narrower and narrower bands were used for NIR and red reflectances, with SAVI being the best index at the very narrowest bandwidth.

The adjustment factor L for SAVI depends on the level of observed vegetation cover. The vegetation cover must be determined before calculating the vegetation index. The amount of cover varies from 0% in the degraded communal areas to 100% in the nature reserves and it was therefore decided to use the Modified Soil Adjusted Vegetation Index (MSAVI) (Qi *et al.*, 1994). The MSAVI provides a variable correction factor L (as to opposed to the static correction factor for SAVI). The correction factor used is based on the product of NDVI and the Weighted Difference Vegetation Index (WDVI). The MSAVI is calculated using the following formula:-

$$MSAVI = \frac{NIR - Red}{NIR + Red + \mathbf{L}}(1 + \mathbf{L})$$

*Where* $\mathbf{L} = 1 - 2 * \mathbf{s} * NDVI * WDVI$

*Where* $\mathbf{s}$ *= the slope of the soil line*

The second MSAVI (used for this study) developed by Qi *et al.*(1994) was a recursion of the first MSAVI and computationally less intensive as the need to precalculate the WDVI and NDVI and the need to find the soil line are eliminated and is calculated using the following formula :-

$$MSAVI_2 = \frac{2NIR + 1 - \sqrt{(2NIR + 1)^2 - 8(NIR - Red)}}{2}$$

The MSAVI (IDRISI algorithm included in Appendix 5) has been shown by Qi *et al.* (1994) to increase the dynamic image of the vegetation signal while further minimising the soil background influences, resulting in greater vegetation sensitivity as defined by a 'vegetation signal' to 'soil noise' ratio. The MSAVI was shown to operate better than the NDVI, SAVI and WDVI (Qi *et al.*, 1994).

Although the MSAVI was chosen as the primary vegetation index to be used in the study a NDVI (Rouse *et al.*, 1973) was also performed on the data to facilitate comparison of MSAVI values with a well utilised index. The results were compared across the differing vegetation types (obtained from the vegetation classification of the satellite imagery). A NDVI was calculated using the following formula:

$$NDVI = \frac{NIR - red}{NIR + red}$$

This well documented index (Goward, 1991; Malo and Nicholson, 1990; Tucker *et al.*, 1981) is preferred to a simple vegetation index as it helps compensate for changing illumination, surface slope, aspect and other extraneous conditions. Numerous investigators have related the NDVI to several vegetation phenomena. These phenomena have ranged from vegetation seasonal dynamics at global and continental scales, to tropical forest clearance, leaf area index measurement, biomass estimation, percentage ground cover determination and photosynthetically active radiation estimation. In turn these vegetation attributes have been used in various models to study photosynthesis, carbon budgets, water balance and related processes (Goward, 1991).

### 4.4.1 The Relationship of Vegetation Indices to Rangeland Condition

In order to assess the reliability of the MSAVI to predict rangeland condition a number of fence-line contrasts were investigated during a field survey. If each site on either side of the fenceline is treated as a sample set of pixel values then two independent samples can be tested using the t-test as described by Snedecor and Cochran (1967). Masks were defined on either side of the fence using module POLYRAS and the means and standard deviations for each sample calculated. Using these values, the differences in sample means at the 99% confidence limit were calculated for each pair of samples. The null hypothesis is that there is no significant difference between the two sample means (for two images on opposite sides of the fence). This is in fact what would be expected if rangeland is of identical condition on either side of the fence-line given that rainfall, temperature and other environmental/ natural determinants of rangeland condition will not change abruptly. However, if the difference in the means of the two samples is greater than the critical t-test value at the 99% confidence level, then the null hypothesis is rejected. It could then be said that the samples do differ beyond chance with a confidence level of 99%.

### 4.4.2 The Relationship of Vegetation Indices to Biomass

The relationship between vegetation indices and biomass has been a topic of much discussion over several years. Numerous studies have found significant relationships between vegetation indices and green biomass (Bedard and Lapointe, 1987; Deering and Haas, 1980; Hardisky *et al.*,1984; Pearson *et al.*, 1976), while others have reported little or no relationship (Anderson and Hanson, 1992; Waller *et al.*, 1981). The results of these studies indicate that vegetation indices do respond to varying levels of green biomass in homogenous areas. However, in heterogeneous areas this relationship is confounded by factors such as standing dead biomass, foliar cover, adaptations of semi-arid shrubs to the water-poor environment and background soil reflectance (Anderson and Hanson, 1992; Bedard and Lapointe, 1987; Hardisky *et al.*, 1984; Holben, 1986; Jasinski, 1990; Ray, 1995; Richardson and Everitt, 1992; Waller *et al.*, 1981). The success of vegetation indices to predict green biomass levels in semi-arid rangelands has therefore been limited (Anderson *et al.*, 1993).

Although it was not a primary aim of this research to establish the relationships of vegetation indices to biomass, a brief investigation into the relationship was deemed necessary. As discussed previously, the Fish River Valley is an exceedingly heterogeneous area and therefore the study will adopt a stratification approach. This involves stratifying the image on the basis of vegetation type (established from the multi-spectral classification) and examining the relationship between MSAVI and biomass for each of the 10 vegetation types. To estimate relative biomass five geo-coded photographs were taken for each vegetation type and average stem diameters and heights of the tree/shrub components of the vegetation measured. A combination of the photographs and the stem and height measurements were then used to rate the biomass on a scale of 1 to 10 (10 representing the largest amount of living biomass associated with the vegetation type). Absolute biomass estimation techniques (Rutherford, 1982; Catchpole and Catchpole, 1993) were considered. However, only the direction and strength of the relationship (and not absolute biomass) needed to be quantified and therefore a rating technique was considered adequate for the purposes of this study.

### 4.4.3 The Relationship of Vegetation Indices to Rainfall

Several studies have suggested that a good correlation exists between rainfall and vegetation indices (Choudhury and Tucker, 1987; Malo and Nicholson, 1990; Rogers and Randolph, 1991; Tucker and Dregne, 1990). Malo and Nicholson (1990) found a strong linear relationship between NDVI and rainfall in the semi-arid Sahel region of West Africa. The best correlation occurring in the concurrent plus two previous months. Their study also suggests that the phenology of vegetation indices appears to reflect soil moisture availability. The relationship of MSAVI and NDVI to rainfall was therefore investigated to validate that the improved sensitivity of MSAVI to vegetation reflectance results in a better estimate of production and therefore better relationship to rainfall. This was performed by extracting a stratified random sample from the study area using the module SAMPLE and comparing the average rainfall of the naturally occurring vegetation types against the average MSAVI and NDVI values.

## 4.5 A Landscape Pattern Index to Monitor Degradation

The redistribution of matter and nutrients across heterogeneous landscapes is not well documented. However, recent work in semi-arid rangelands (Miles and Johnston, 1990; Pickup 1985; Schlesinger *et al.*, 1990; Tongway, 1990) has shown that land degradation may result in increased runoff and increased soil and water redistribution within an area. This leads to changes in the distribution pattern of vegetation cover of different types and not necessarily a reduction in biomass. Biomass may be relocated in the roots and woody plants which are less desirable to the domestic herbivores. This in turn leads to an increase in landscape heterogeneity or variability, with the nutrients and moisture being concentrated in small runon or deposition areas supporting an increasingly dense cover of unpalatable trees and shrubs. The rest of the landscape maintains a cover which is sparser than that existing before degradation occurred.

Degraded arid-zone landscapes can be highly patterned due to extensive erosional activity. In turn, vegetation change is often spatially variable because of the redistribution of water and sediment (Freidel *et al.*, 1993). "When degradation of productive rangelands occurs, a relatively uniform distribution of water, nitrogen, pH and other soil resources is replaced by an increase in their spatial and temporal heterogeneity. Heterogeneity of soil resources promotes invasion by woody shrubs and excessive herbivory favours less palatable species. This leads to further localisation of soil resources under shrub canopies. In the barren area between shrubs, soil fertility is lost by erosion and gaseous emissions. This leads to desertification of formerly productive areas." (Schlesinger *et al.*, 1990, pp. 1043).

Extenuating circumstances such as livestock grazing disrupt the tight connection of soil and plant processes and leads to a decline in the cover of grasses in semi-arid regions. Nutrients are transported by these grazing animals across landscapes and between patches. Large animals are important as they typically graze (and remove nutrients) from patches containing high quality forage and may return nutrients (by means of defecation) to areas in which they rest or sleep. The redistribution of water by overland flow results in heterogeneity in the spatial distribution of soil moisture. "The cover of shrubs then increases as a direct result of nonuniform distributions of water in space and time. "(Schlesinger *et al.*, 1990, pp. 1044). Shrubs can then exploit the additional soil moisture that infiltrates under intermittent streambeds and in local areas where water accumulates during runoff. "Shrub cover and net primary production is often greatest in these areas" (Schlesinger *et al.*, 1990, pp. 1044). Shrub dominance leads to further heterogeneity of soil properties because effective infiltration of rainfall is confined to the area under shrub canopies, whereas barren intershrub spaces generate overland flow, soil erosion by water and wind resulting in nutrient loss. Another factor contributing to the variability is that in degraded areas single shrubs grow better when competition is removed.

The underlying assumption of the heterogeneity index is that a healthy landscape is less variable than a degraded landscape. Degraded arid-zone landscapes can be highly patterned due to extensive erosional activity. In turn, vegetation change is often spatially variable because of the redistribution of water and sediment (Freidel *et al.*, 1993). When an increase in spatial heterogeneity is observed the landscape has moved from a state of equilibrium to non-equilibrium and can be said to have become 'dysfunctional' (Ludwig and Tongway, 1997).

To calculate an overall index of landscape condition a heterogeneity image was produced by calculating standard deviation images for bands 3-5 (wet season) and the Ratio Vegetation Index(RVI) (band 4/band3). Moving standard deviation images were calculated by passing a 3 x 3 moving filter across the image (Baker and Cai, 1992). The moving window calculates the standard deviation for the nine pixels and assigns that value to the middle pixel. The standard deviation is then placed into a new map at the same location as the target pixel. The window is then moved to the right one pixel (and then down one row at the end of the row) and the process is repeated. The algorithm written in IDRISI for calculating the moving standard deviation is included (Appendix 6). Standard deviation was calculated according to the following formula;

$$\sigma = \sqrt{\frac{\sum x_{ij}^2 - \frac{(\sum x_{ij})^2}{n}}{n}}$$

*Where* $n = 9$, $x_{ij}$ *= Digital Numbers*

The standard deviation image that exhibits the best relationship to condition will be referred to as the Moving Standard Deviation Index (MSDI).

### 4.5.1 The Relationship Between Heterogeneity and Rangeland Condition

To investigate the relationship between heterogeneity and rangeland condition the fence-line contrasts, established during a field survey, were interrogated using the method described in section 4.4.1. In addition to this, the MSDI was classified into low, moderate and high categories and the results compared against the assessment of degradation undertaken at all sites based on the technique developed by Norton *et al.* (1984).

### 4.5.2 The Relationship Between Heterogeneity and Vegetation Type

A crucial question has to be answered in determining the performance of the MSDI, namely can it be applied across different vegetation types? Provided the vegetation types are undisturbed the MSDI values should all be low irrespective of species composition, rainfall, substrate and other variables. Inherent variability (high MSDI) in an undisturbed vegetation community would necessitate stratification prior to determining rangeland condition. To test whether undisturbed vegetation types displayed any inherent variability (i.e. high MSDI values) the associated average standard deviation values for each of the vegetation types were calculated. The sample derived in section 4.3.4 was used in the comparison to facilitate sampling from large areas of representative vegetation.

### 4.5.3 The Relationship Between Heterogeneity and Production

In order to quantify the relationship between heterogeneity and production the results of the NDVI were compared against the standard deviation images of the various bands. The NDVI was subjected to a 3 x 3 mean filter to transform the data into the same effective resolution as the MSDI. NDVI was used in preference to MSAVI for the reason that it is a widely used and accepted vegetation index. It is hypothesised that the correlation between the heterogeneity and NDVI should be high as both indices are highly correlated with the condition of the landscape. This was measured using the Spearman's Rank Correlation Coefficient to establish firstly, whether significant correlations exist and secondly, the extent of these correlations. The data that was used to examine the correlation was extracted from the four fence-line contrasts (using the method described in section 4.4.1) that were established during the field survey. The non-parametric Spearman's Rank Correlation Coefficient was used to determine if a correlation existed for two reasons;

- The value of one variable (either MSDI or NDVI) does not affect the other i.e both variables are from an independent data set and therefore some form of correlation and not regression was required.
- The data failed the Kolmogorov-Smirnov test (with Lilliefors' correction) to test data for normality of the estimated underlying population. The test is used to determine if a parametric test such as Pearsons Product Moment Correlation Coefficient (which assumes a normal distribution of data) can be performed on the data.

The NDVI and MSDI were reclassed into low, medium and high MSDI and NDVI values (determined from surface reference data) on the basis of NDVI and MSDI. The reclassed images were then cross-classified and the resulting nine classes described.

### 4.5.4 The Operation of the Index in Other Ecosystems

To validate the usefulness of the MSDI in the assessment of degradation the index's operation in other ecosystems was investigated. To do this satellite data were obtained for sites with contrasting land-use patterns namely; the southern Kalahari desert, Mpumalanga, Cathedral Peak and Namaquland. Fence-line contrasts were established in the Kalahari by Palmer *et al.* (1997) and the MSDI values statistically analysed (using the technique described in section 4.4.1). The relationships of MSDI to NDVI were investigated for the four ecosystems using Spearman's Rank Correlation Coefficient.

## 4.6 Summary

The collection of surface reference data, and the steps taken to reduce error in the collection of the data has been described as well as available satellite imagery. The methods used for geo-referencing and projection of the satellite images are outlined and the accuracy of the resulting images determined. The methods used to derive a final vegetation classification are then described and the methods used to assess the accuracy of the classification. A technique to derive the environmental determinants of each vegetation type is described. The methods used to calculated the MSAVI and establish the relationship of the index to condition, biomass and rainfall have been presented. The final section explains the derivation of a variability index (MSDI) and how the relationship of the index to rangeland condition, vegetation type, vegetation production and the operation of the index in other ecosystems will be investigated.

# CHAPTER 5

# RESULTS

*"Our ability to interpret spectral information remains especially limited in arid environments, where the vegetation is sparse and shrub communities with similar physiographic properties often differ markedly in species composition and ecology"* (Ustin *et al.*, 1986, pp. 446).

The purpose of the chapter is to describe the results obtained from the vegetation classification, the Modified Soil Adjusted Vegetation Index (MSAVI) and the Moving Standard Deviation Index (MSDI). A description of the vegetation classes identified in the field and the mapping of the classes using various image manipulation techniques is described. The environmental and spectral characteristics associated with each of the vegetation classes are then identified. The MSAVI is depicted and the relationship of the MSAVI to rangeland condition, biomass and rainfall and altitude explored. The chapter then examines the results of the most significant element of this research, namely, the use of a landscape diversity index to map rangeland condition. The relationship of the index to rangeland condition, vegetation type, vegetation production and the operation of the index in other ecosystems is examined.

## 5.1 The Vegetation Classification

### 5.1.1 Field Identification of Vegetation Classes

A diagram of the classification system used to categorise vegetation communities in the field is shown (Figure 5.1.) The associated symbols (used for the remainder of the study) and colour that the vegetation type appears as on the final vegetation classification (Plate 8) are listed (Table 5.1).

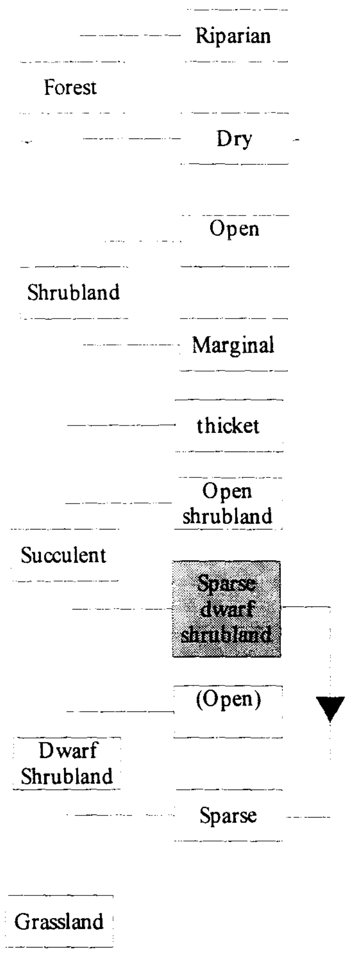



**Figure 5.1:** Diagram of Vegetation categories used in the field.

***Table 5.1: Vegetation types and associated symbols (used for the remainder of the study)***

| Vegetation Type | Symbol | Colour |
|---|---|---|
| *Riparian forest* | RiFr | Dark Blue |
| *Dry forest* | DrFr | Brown |
| *Open shrubland* | OpSh | Light Blue |
| *Marginal shrubland* | MaSh | Grey |
| *Succulent thicket* | SuTh | Dark Green |
| *Open succulent shrubland* | OpSuSh | Light Green |
| *Sparse succulent dwarf shrubland* | SpSuDwSh | Red[1] |
| *Dwarf shrubland* | DwSh | White |
| *Sparse dwarf shrubland* | SpDwSh | Red |
| *Grassland* | Gr | Yellow |

### 5.1.2 The Unsupervised Classification

The unsupervised classification of bands 3,4 and 5 produced good results. Eight of the ten structural vegetation types that were mapped using this technique agreed strongly with those visited and described in the field. *Riparian forest* and *Sparse succulent dwarf shrubland* were not delineated; *Riparian forest* due to its small areal extent and *Sparse succulent dwarf shrubland* due to its similar spectral response to that of the *Open succulent shrubland.*

### 5.1.3 The Multi-Temporal Classification

The results of the 10 dimensional multi-temporal principal components analysis (Plate 7) illustrates the varying spectral information contained in the different principal components. Components 1 - 7 and the composite of components 1-3 as well as wet season bands 3-5 and the false colour composite thereof are depicted. The associated eigen values and correlation matrix are provided (Appendix 7). The first 3 components accounted for 92% of the variance of the components. The loadings of the first four principal components (the fourth component is included for comparison purposes) are depicted (Figure 5.2). The loadings express the correlation between the component produced and the original data. They can be interpreted as the degree to which the original bands contribute to the component.

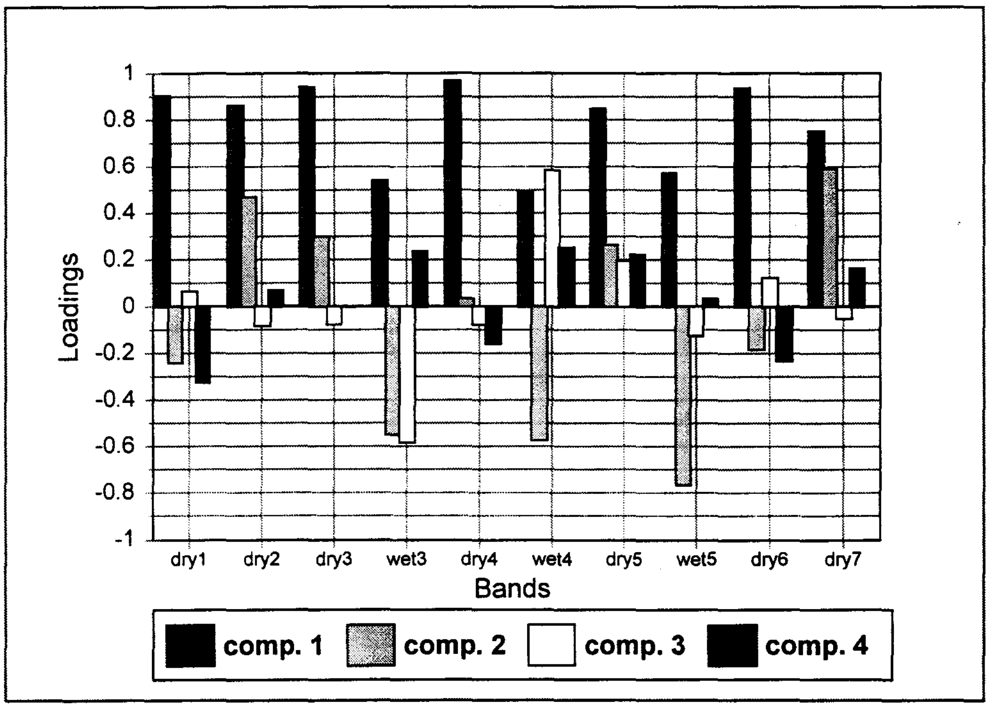



**Figure 5.2**: Graph depicting the loadings of the original bands in the PCA.

Overall this technique produced disappointing results and contributed no extra classes to the classification.

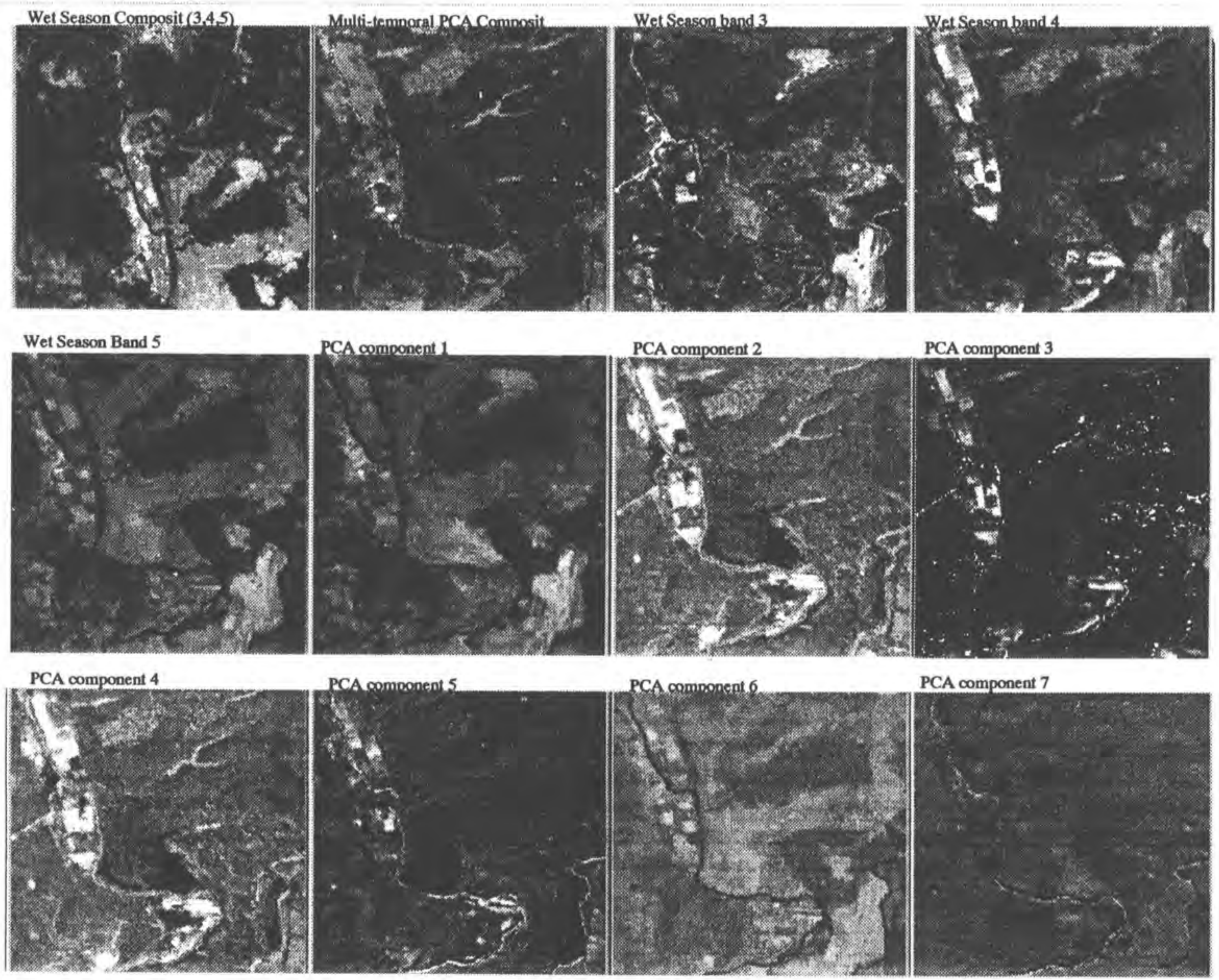



***Plate 7:** A comparison of the different spectral data contained in the components of the multitemporal classification, the composite thereof and a conventional false colour composite*

### 5.1.4 Derivation of the *Riparian Forest* Class

The derivation of the *Riparian forest* was achieved using a maximum likelihood supervised classification of wet season bands 3,4 and 5 (assigned to blue, green and red respectively) with a $\chi^2$ value of 5%.

### 5.1.5 Derivation of the *Sparse Succulent Dwarf Shrubland* Class

The *Sparse succulent dwarf shrubland* could not be identified using either the unsupervised or the supervised approach. Attempts to separate this vegetation unit from the *Open succulent shrubland* using a supervised approach was unsuccessful and resulted in 'speckling'. This was due to the spectral signatures being almost identical across all bands. A supervised approach utilising all 10 bands of multi-temporal data similarly produced no discrimination between the two vegetation types.

The derivation of the class was achieved using a cross-classification with Moving Standard Deviation Index (MSDI). The logic used to distinguish it from the *Open succulent shrubland* a good condition class will be discussed extensively in section 5.3. Essentially however, the *Sparse succulent dwarf shrubland* exhibited higher red spectral variation than the good condition *Open succulent shrubland.*

### 5.1.6 The Final Vegetation Classification

A flow diagram illustrating the methods used to derive the final vegetation classification is depicted (Figure 5.3). The final vegetation classification comprised 8 classes from the broad unsupervised classification. These were *Dry forest, Open shrubland, Succulent thicket, Grassland, Marginal shrubland, Dwarf shrubland, Sparse dwarf shrubland* and a *'Succulent shrubland'* (a combination of *Open succulent shrubland* and *Sparse succulent dwarf shrubland*).

The supervised classification was used to distinguish *Riparian forest* and a cross-classification of the *'Succulent shrubland'* class (delineated using the broad unsupervised classification) and MSDI distinguished the class *Sparse succulent dwarf shrubland.* These two new classes were overlayed onto the existing classification using the COVER option in the OVERLAY module. It was decided to reclass the *Sparse succulent dwarf shrubland* into the broad category *Sparse dwarf shrubland* as land management strategies required for these two vegetation classes are identical. In all cases *Riparian forest* coincided with the vegetation group previously delineated as *Dry forest* using the broad unsupervised classification.

The multi-temporal classification contributed no extra vegetation types to the classification although it would have been possible to delineate 5 of the 8 classes already discriminated using the conventional unsupervised classification.

A post-classification mode filter (3 x 3 window) was then applied to smooth the image. This filter is applied to qualitative data such as vegetation types to remove single, isolated pixels and replaces the pixel with the most common or majority value of surrounding pixels. The mode filter improves the visual appearance of the vegetation map with insignificant loss of information content from a management perspective and ensures that the recognised minimum mapping unit is approximately one hectare (Lillesand and Kiefer, 1994). The image was then further visually enhanced by applying a edge enhancement and 'sharpening' procedure to provide the final vegetation classification (Plate 8).

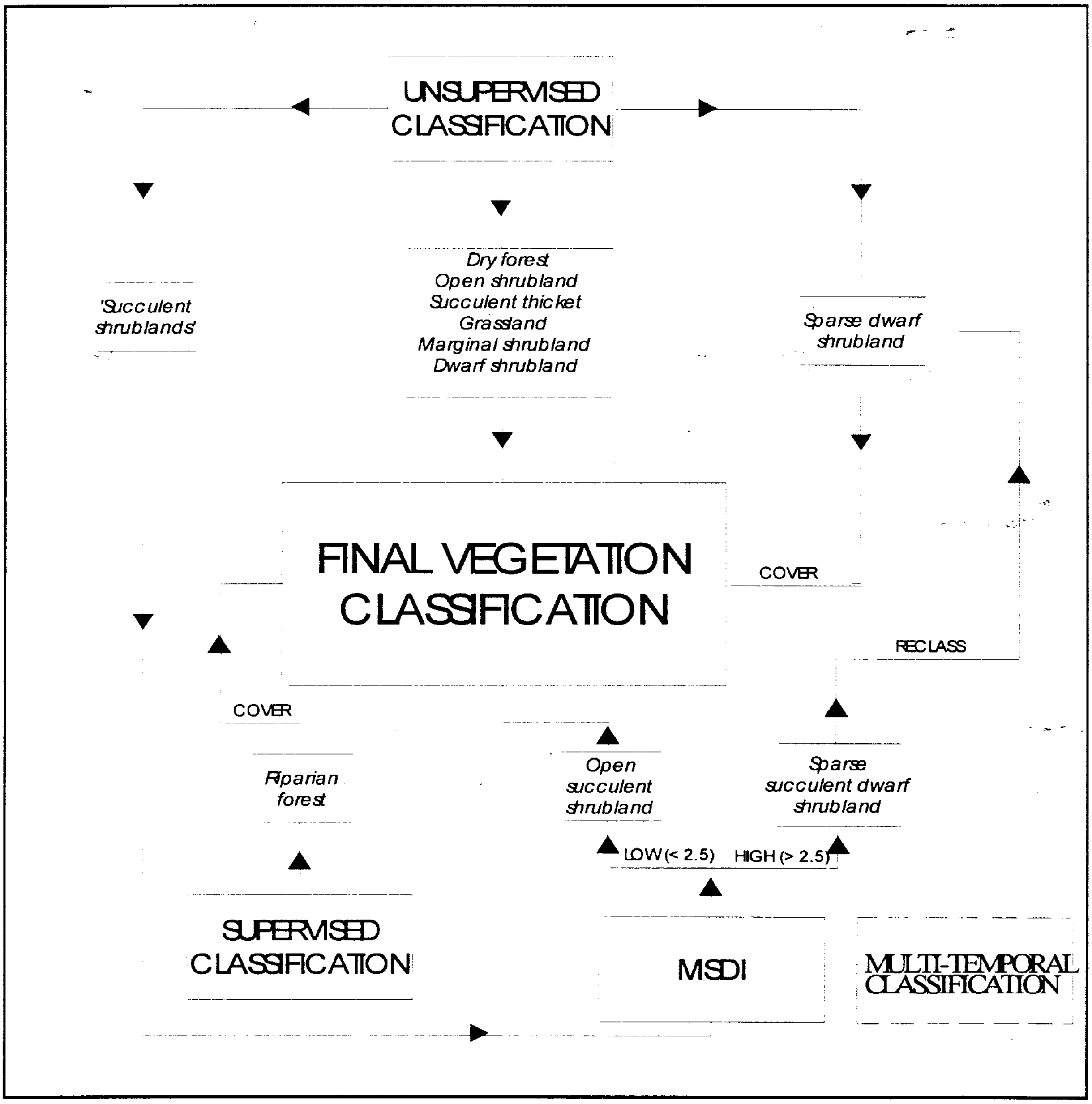



**Figure 5.3**: Flow diagram depicting the methods used to derive the final vegetation classification.

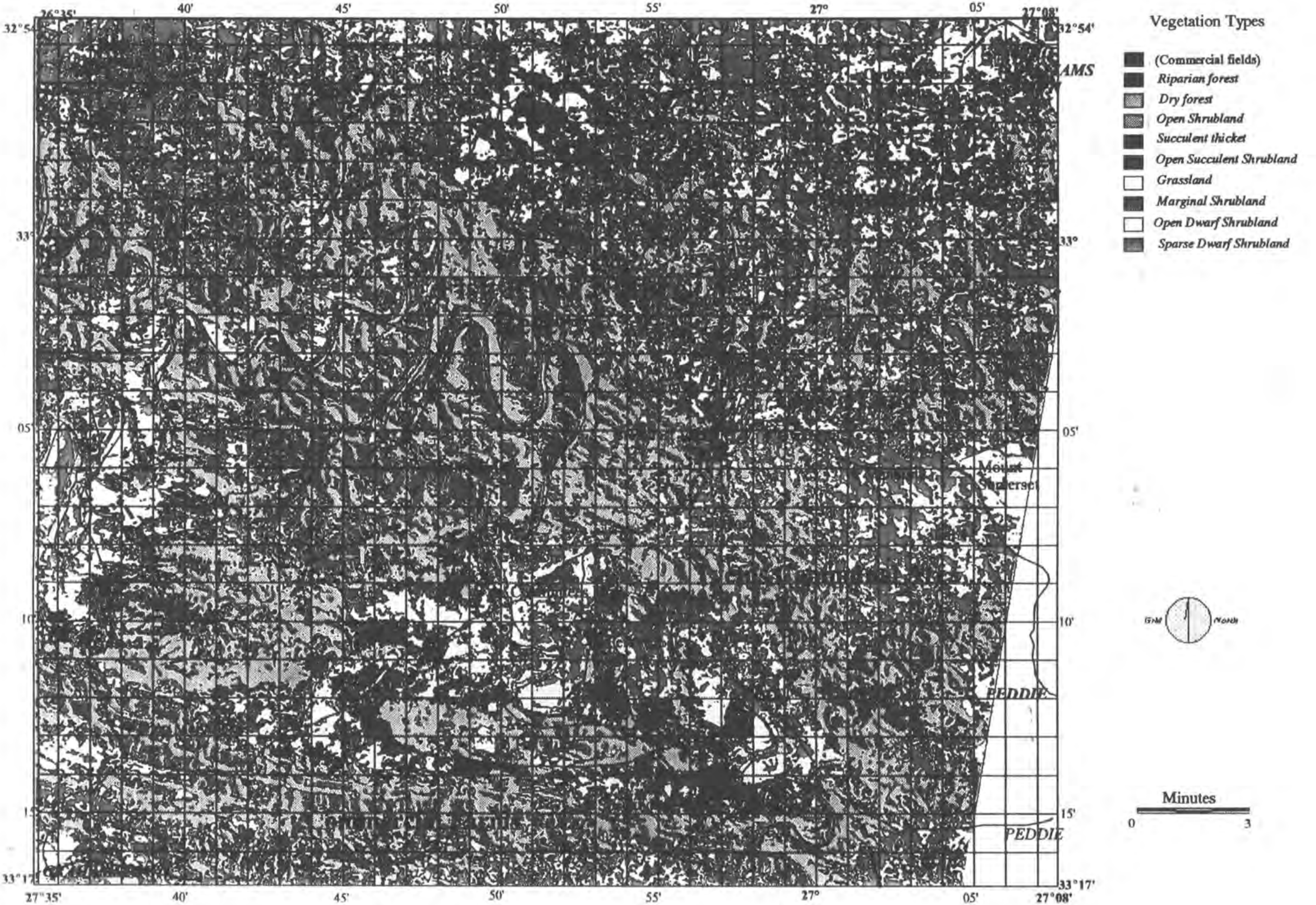



*Plate 8: Final Vegetation Classification*

### 5.1.7 Descriptions of the Vegetation Units

The purpose of the vegetation descriptions presented here is to briefly describe the diagnostic features of each vegetation type and is not intended to be a detailed botanical review. Similarly, the environmental variables depicted (Figures 5.5 - 5.13) serve only to illustrate the range of conditions associated with each vegetation type and not to draw any firm conclusions about preferred vegetation habitats. A detailed species list of each vegetation type is provided (Appendix 8). The associated average shrub/tree, grassy and bare components for each vegetation type are depicted (Figure 5.4).

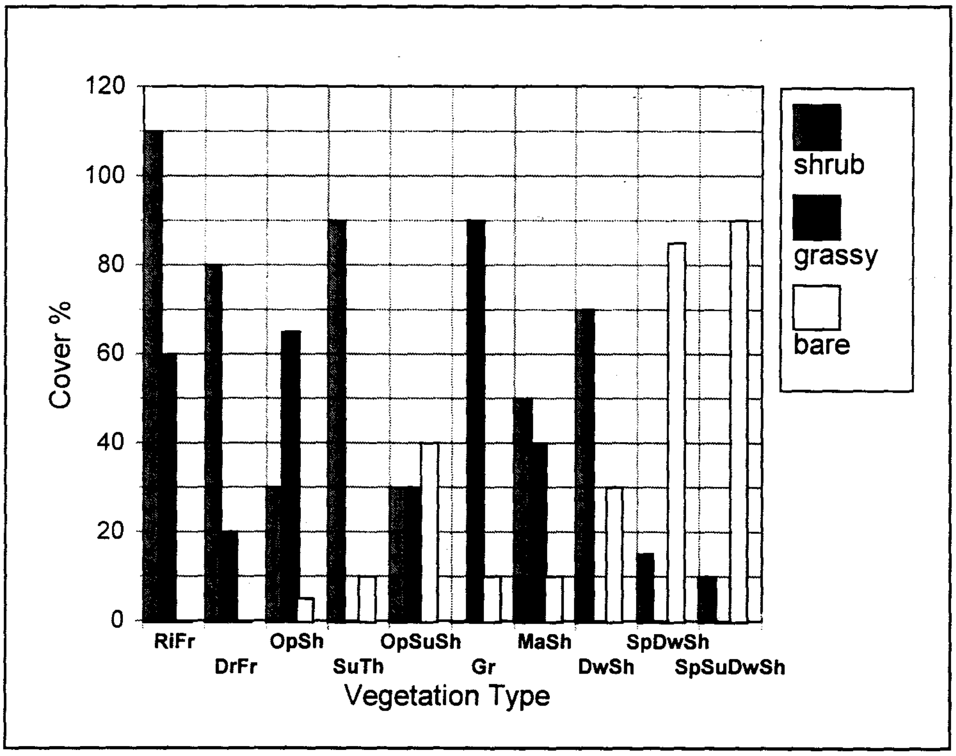



**Figure 5.4:** Average shrub, grassy and bare components of the vegetation types

#### 5.1.7.1 *Riparian Forest* (RiFr)

This vegetation type (Photograph 1) is found in close proximity to rivers and is associated with a wide range of conditions (Figure 5.5). It is characterised by a tall dense forest canopy consisting of trees higher than 10 m (predominantly *Schotia latifolia* and *Vepris undulata*), a middle canopy consisting of shrubs of approximately 5 m (predominantly *Euphorbia triangularis* and *Euphorbia tetragona*) and a ground canopy consisting of grasses such as *Panicum maximum* and *Panicum deustum*. It has no preferred aspect and is generally found on steep slopes exceeding 10°. The dense cover leads to low reflectance values in all bands although less so in the NIR (Figure 5.5).

**Photograph 1:** A *Riparian forest*

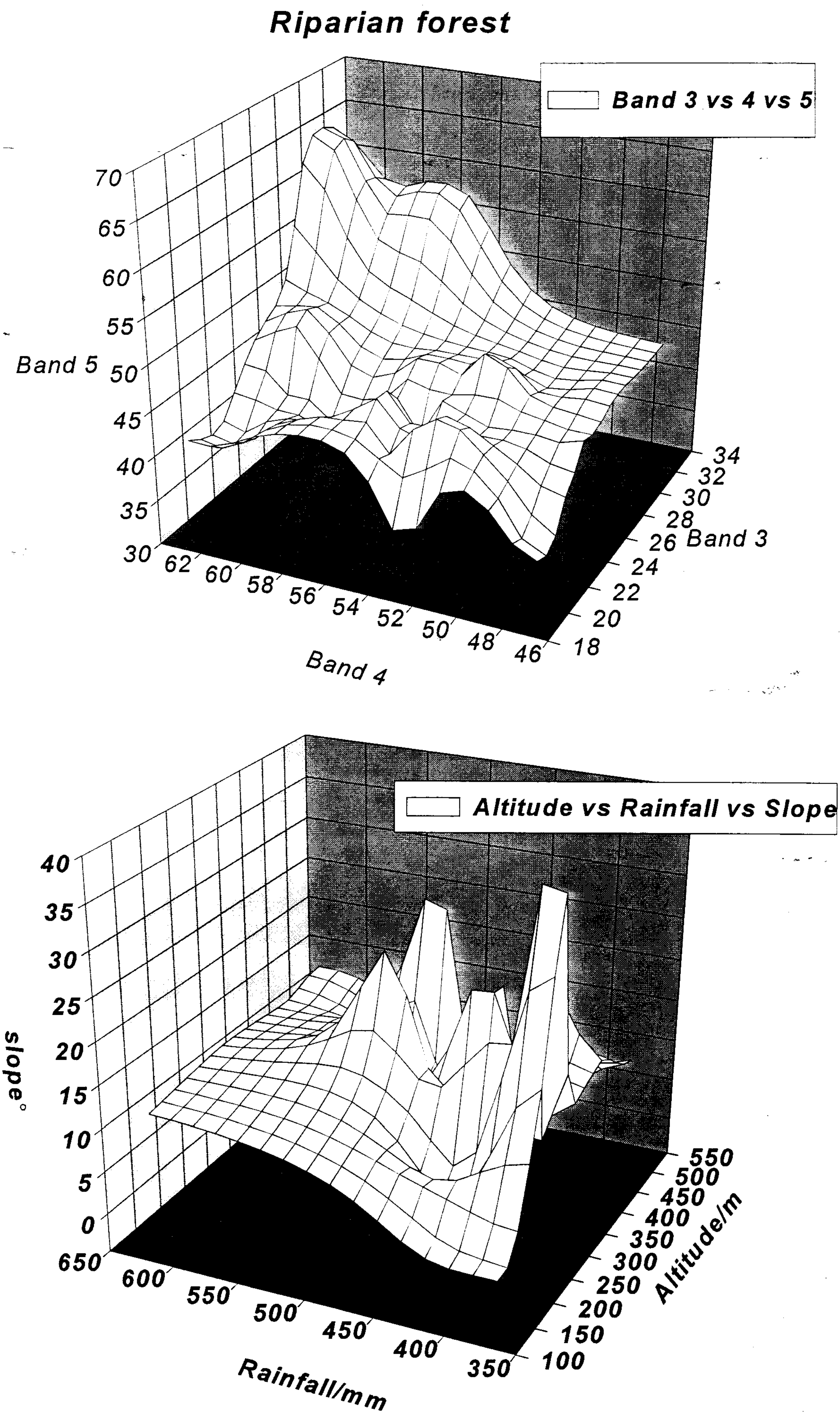
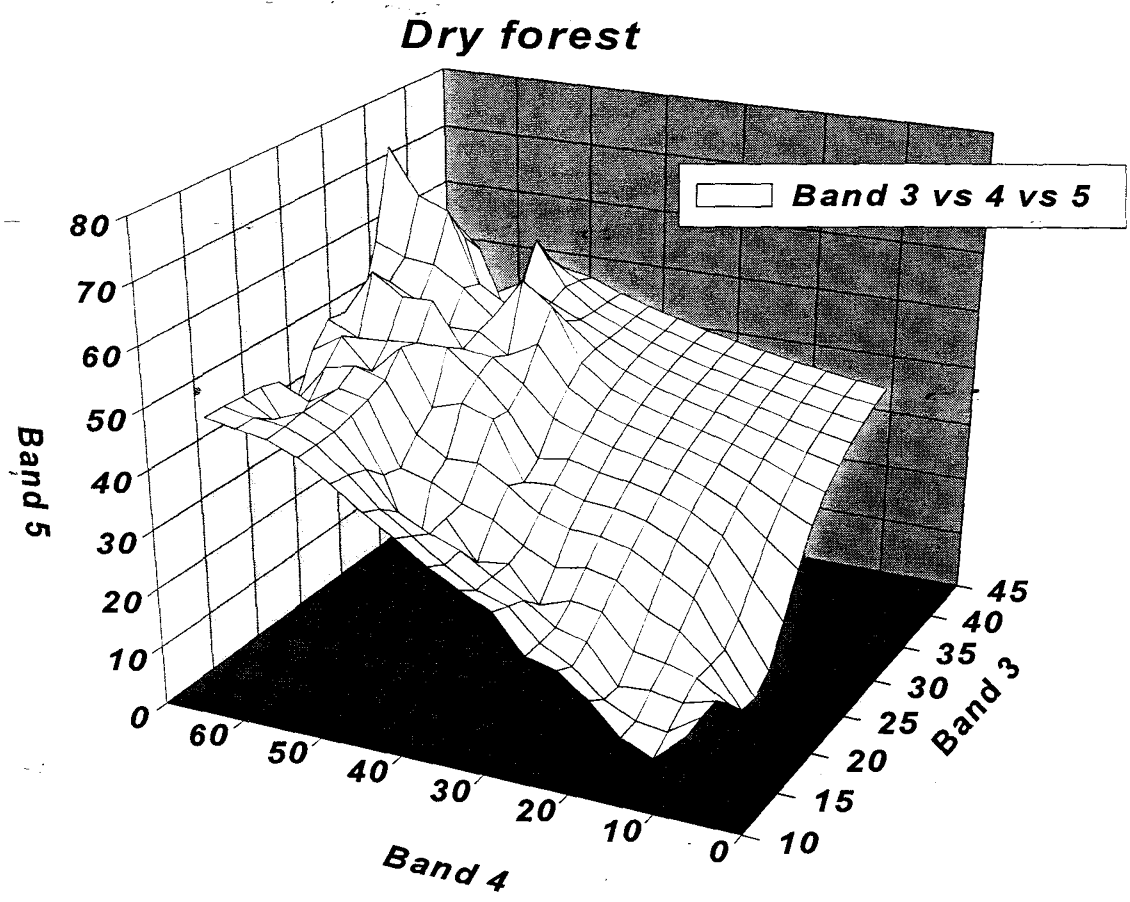



**Figure 5.5:** Spectral and environmental characteristics of a *Riparian forest.*

### 5.1.7.2 *Dry Forest* (DrFr)

This vegetation type (Photograph 2) first described by Palmer (1981) consists of a 75% cover of approximately 5-8 m high shrubs characterised by the dominance of *Euphorbia triangularis* and *Euphorbia tetragona*. The remaining cover consists of grasses and small shrubs such as *Phyllanthus verucossus*. It is tolerant of diverse conditions and is thus widespread (Figure 5.6). It is resilient to grazing pressures and therefore it is also found in communal areas. It occurs on the steep slopes (above 10°) with a marked southern aspect. This is probably due to the elevated moisture status and reduced radiation levels that occurs on the cooler southern slopes. Spectrally it is very similar to *Riparian forest* exhibiting low values in all bands (Figure 5.6 ) and therefore is associated with low vegetation index values.

**Photograph 2:** A *Dry forest*



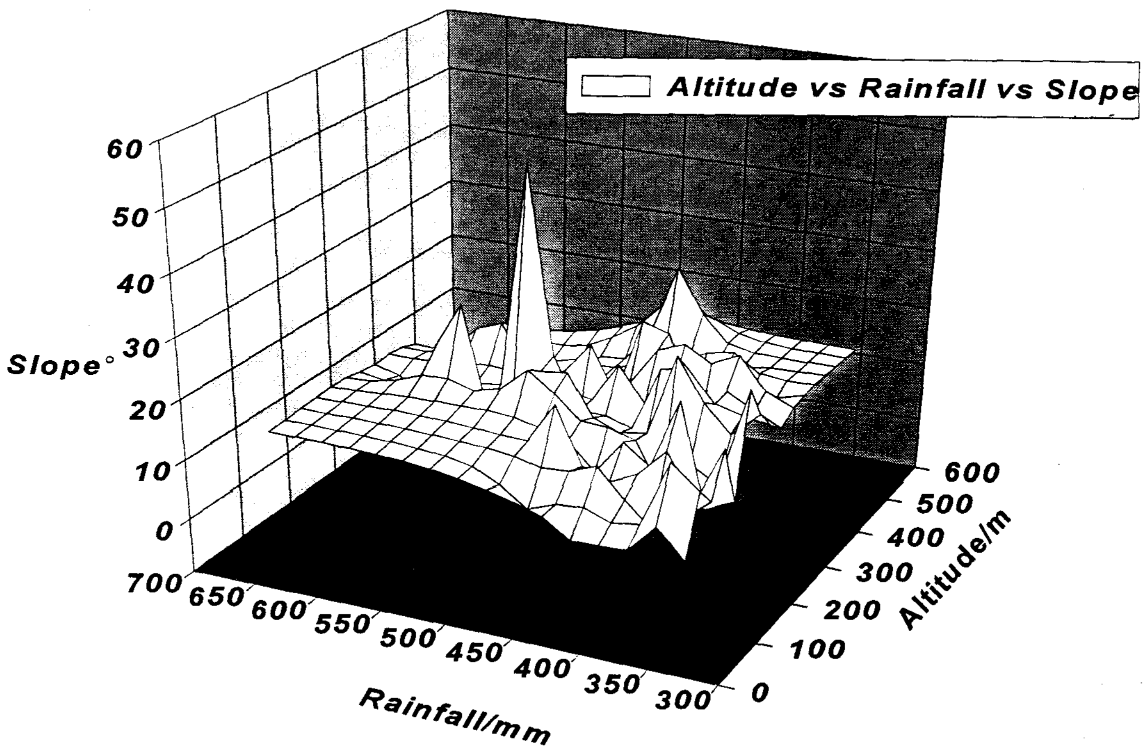
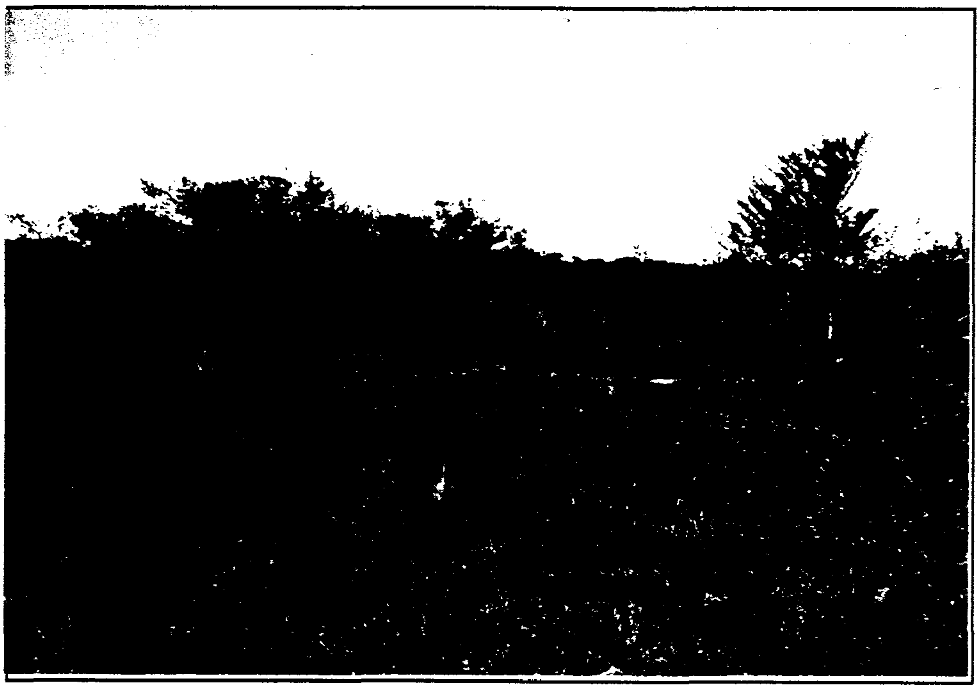




**Figure 5.6:** Spectral and environmental characteristics of a *Dry forest*

### 5.1.7.3 *Open Shrubland* (OpSh)

This vegetation community (Photograph 3) previously classified as Bushclump savanna by Palmer (1981) consists of 1 - 2 m high shrubs (approximately 25% of the cover) consisting mainly of *Acacia karroo* with the remaining 75% comprising grasses such as *Digitaria* and *Themeda.* It normally occurs in the wetter high altitude regions of the study area (Figure 5.7) but is also found in a more dense form in riparian zones. Aspect analysis revealed that it has a northern aspect preference opting for the hotter, drier northern slopes with increased radiation levels where the *Acacia karroo* can out-compete less resilient species. The high photosynthetic activity of the grasses and the fact that this vegetation type is often found in riparian zones contributes to very high NIR value (Figure 5.7) leading to high vegetation index values. It can be classified as good condition rangeland.



**Photograph 3:** An *Open shrubland*

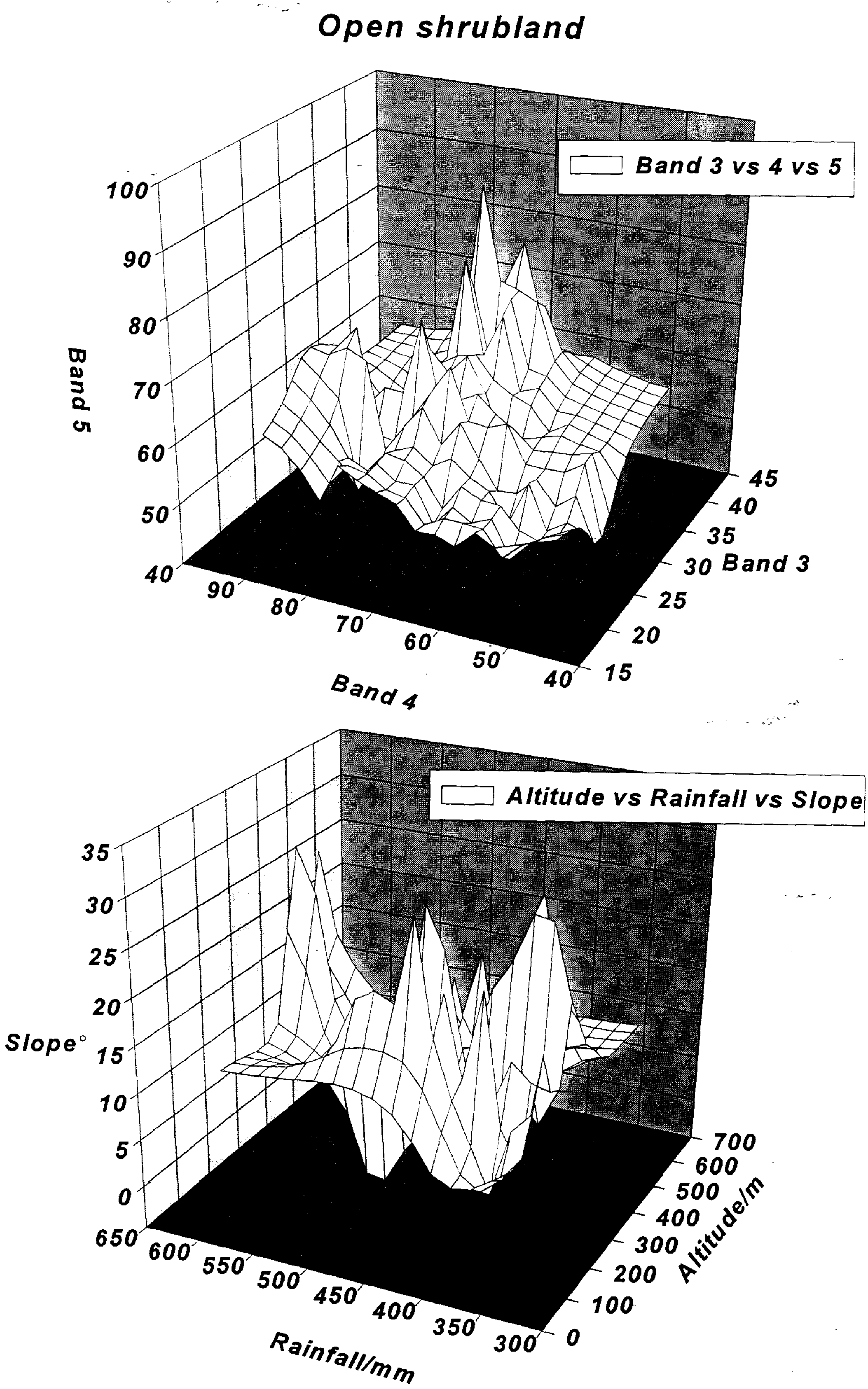
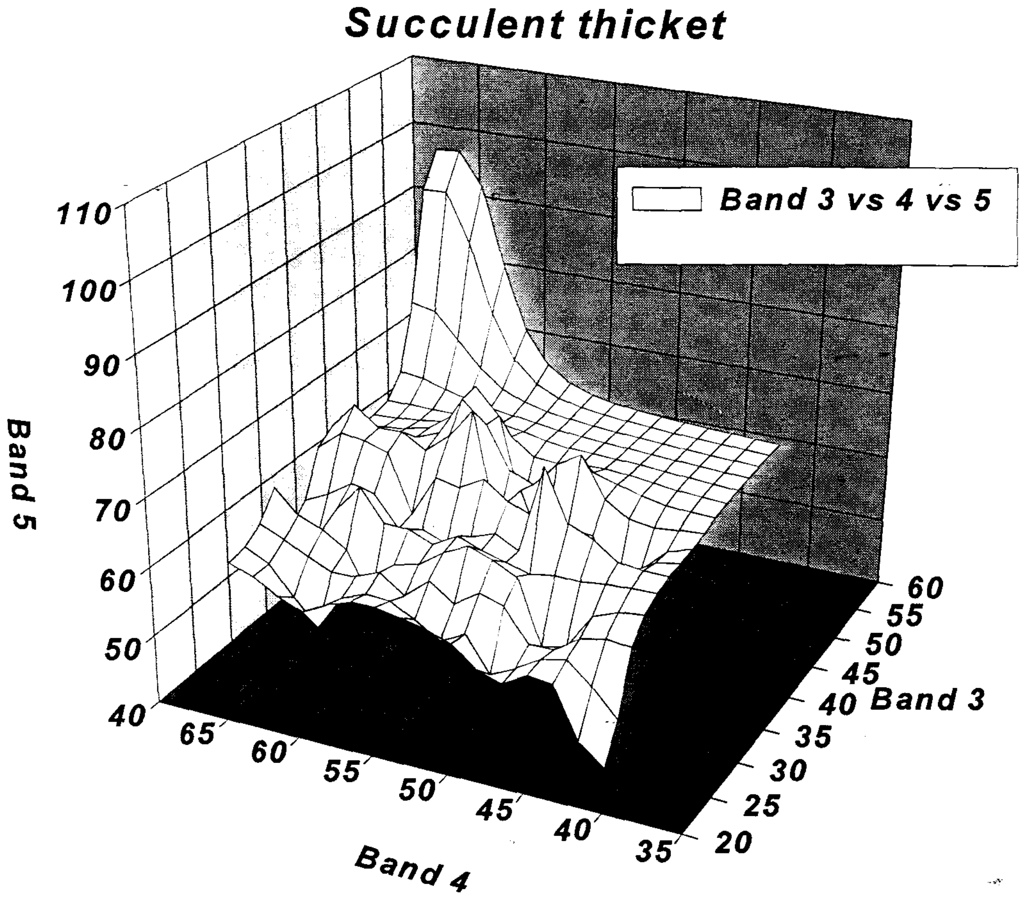



**Figure 5.7:** Spectral and environmental characteristics of an *Open shrubland*

### 5.1.7.4 *Succulent Thicket* (SuTh)

A *Succulent thicket* (Photograph 4) is characterised by the abundance of *Portulacaria afra* and corresponds to Acocks (1988) Fish River Valley Bushveld. The total cover of this class is typically 80 - 90% with *Portulacaria afra* comprising 90% of the species present. Other commonly occurring species include *Grewia robusta, Rhigozum obovatum, Pappea capensis* and *Boscia oleoides*. The average height of the shrubs are between 1 - 2.5 m. It is found in the lower altitude, lower rainfall (350 - 400 mm), semi-arid parts of the study area (Figure 5.8) and as a result has a characteristically low NIR reflectance (Figure 5.8) and therefore low vegetation index values. This is probably due to its semi-arid adaptations (Ray, 1995) and diminished moisture availability of the underlying Ecca Shales (Palmer *et al.*, 1988). It is also found dominantly on steeply sloping terrain.

**Photograph 4:** A *Succulent thicket*



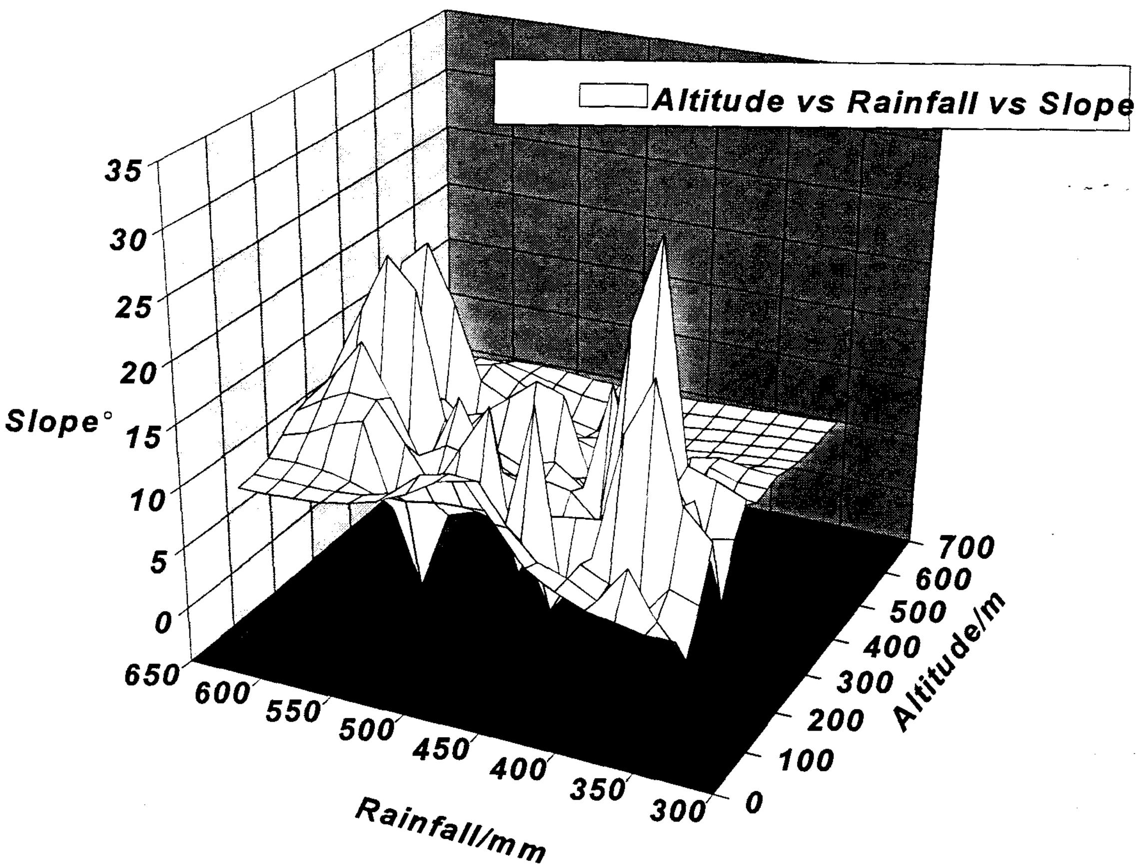




**Figure 5.8:** Spectral and environmental characteristics of a *Succulent thicket*.

### 5.1.7.5 *Succulent Shrublands*

The two succulent shrublands namely, *Open succulent shrubland* and *Sparse succulent dwarf shrubland* (reclassed as *Sparse dwarf shrubland* in the final classification) are spectrally and environmentally inseparable and therefore will be discussed together. Both vegetation types occur exclusively in the low rainfall, low altitude semi-arid parts of the study area (Figure 5.9) and both are found only on the Ecca Shales (Palmer, 1981). They are both associated with very low photosynthetic reflectance (Figure 5.9 ) possibly due to the low cover and arid adaptations of the plants and the dominance of the spectral response pattern by the reflectance of the underlying Ecca Shales. While the environmental and spectral characteristics are very similar the relative condition of these two vegetation types differs markedly.

The *Open succulent shrubland* (OpSuSh) is good condition rangeland and is characterised by 0.5 - 2m high bushclumps separated by succulent dwarf shrubs, grasses and bare patches (Photograph 5). The clumps typically consist of *Euphorbia bothae* and *Maytenus polyacantha* whilst the inter-clump areas consist of grasses such as *Panicum maximum* and dwarf shrubs such as *Protasparagus suaveolens*. The total vegetation cover is approximately 75%.

The *Sparse succulent dwarf shrubland* (SpSuDwSh) (Photograph 6) is characterised by very low cover (5-10%) even after good rainfall due to the degradation that has taken place. It is found almost exclusively in communal areas. The dominant species are dwarf succulent shrubs less than 30 cm in height such as *Euphorbia bothae* and *Rhigozum obovatum*.

**Photograph 5:** An *Open succulent shrubland*

**Photograph 6:** A *Sparse succulent dwarf shrubland*

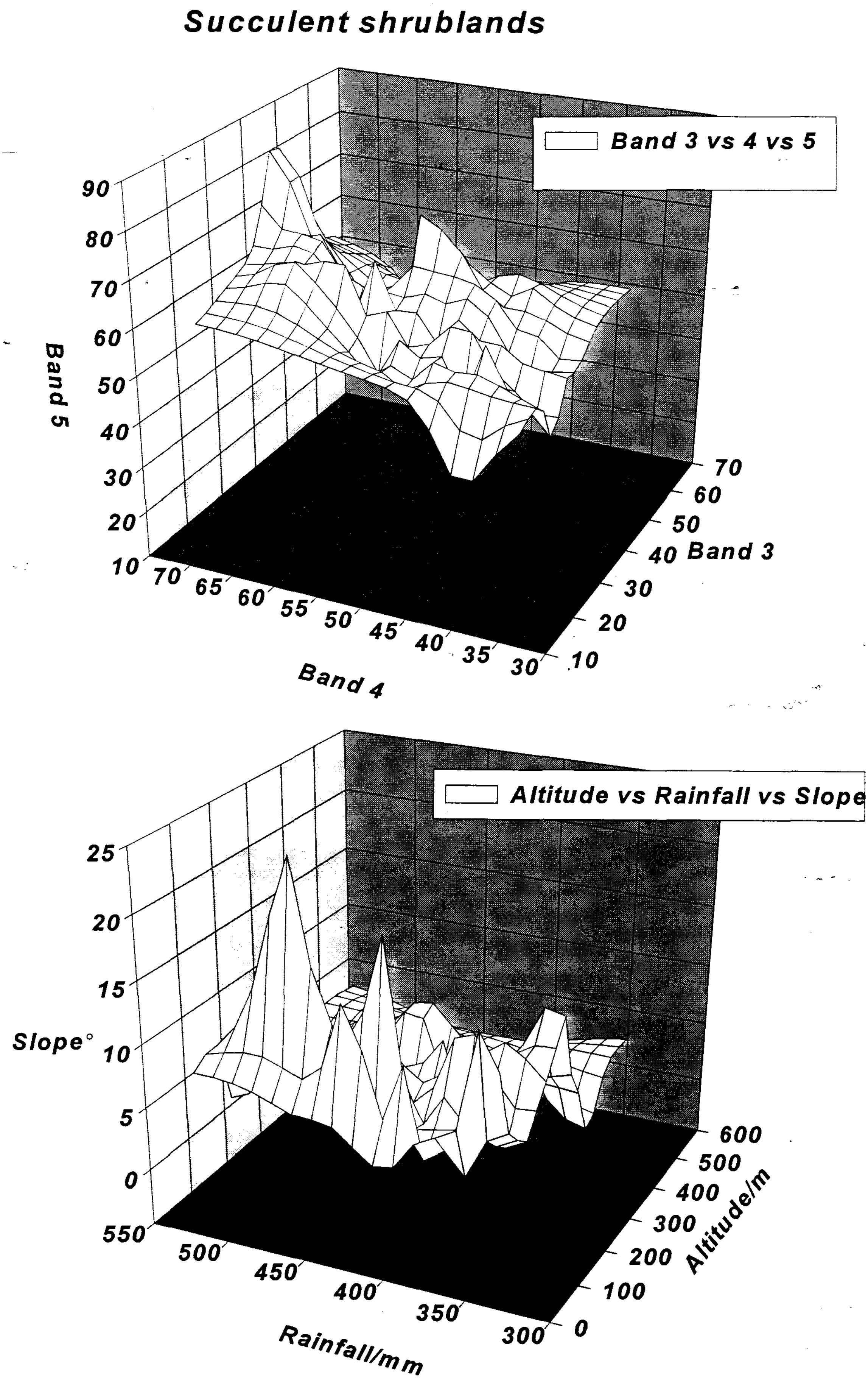
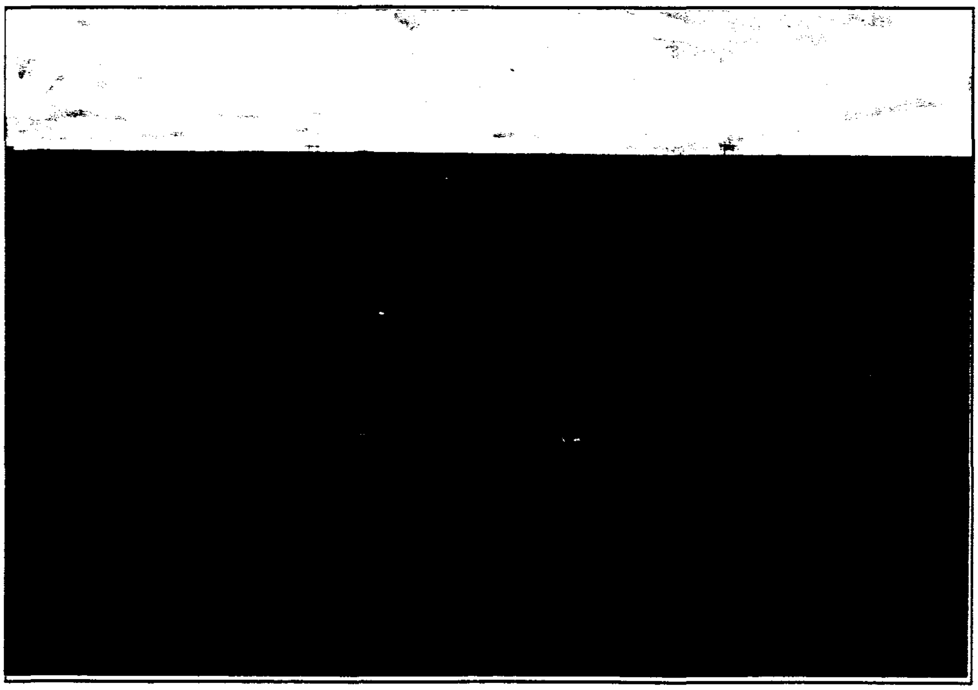


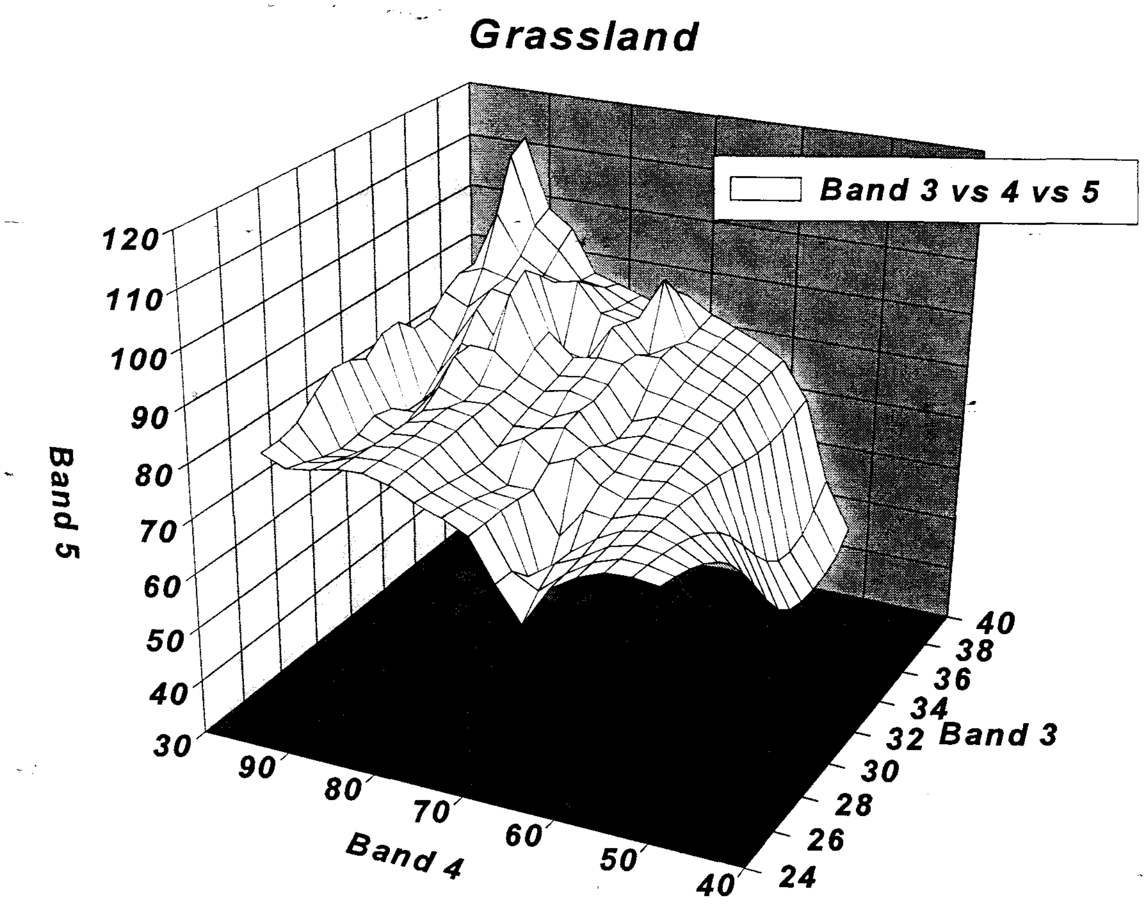

**Figure 5.9:** Spectral and environmental characteristics of *Succulent shrublands*.

### 5.1.7.6 *Grassland* (Gr)

The *Grasslands* (Photograph 7) occur exclusively on the high altitude, high rainfall (Figure 5.10) non-disturbed areas mainly on sandy loam soils. They are characterised by the highest average NIR reflectance value of any vegetation type (Figure 5.10) and consequently high vegetation index values. *Grasslands* are perhaps the vegetation types most sensitive to disturbance. This has been revealed by an aerial photographic analysis of the study area over the last 50 years where large *Grassland* areas have been invaded by woody shrubs such as *Acacia karroo* as soon as the fragile equilibrium is disturbed by domestic herbivores. Consequently the *Grasslands* that remain in the study area occur on land that has not been subjected to intensive herbivory. There are however patches of remnant *Grasslands* throughout the study area occurring mainly around homesteads where domestic herbivores are prevented from grazing. Heights of grasses vary from as little as a few centimetres to a metre and cover from 65 - 100%. The dominant grass species include *Digitaria eriantha, Themeda triandra, Sporobolus africanus* and *Aristida congesta.*



**Photograph 7:** A *Grassland* (taken at Mount Somerset)



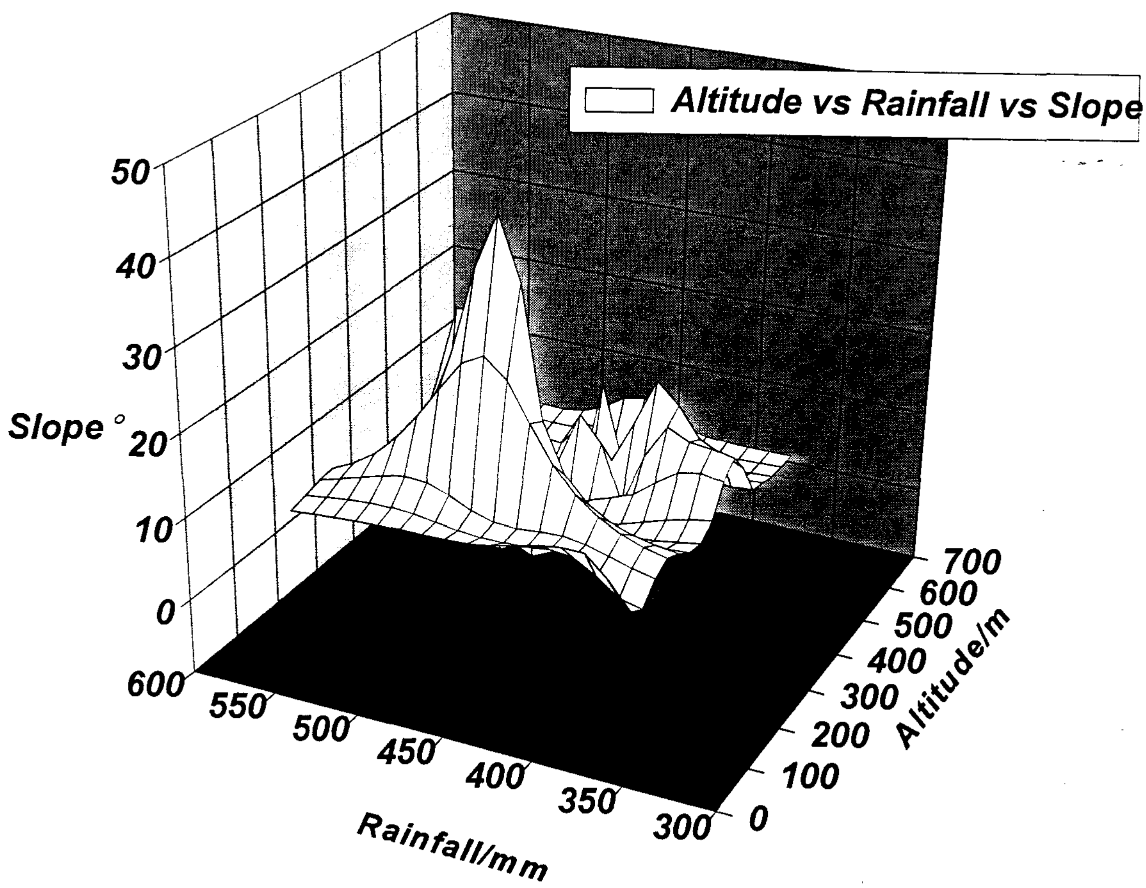
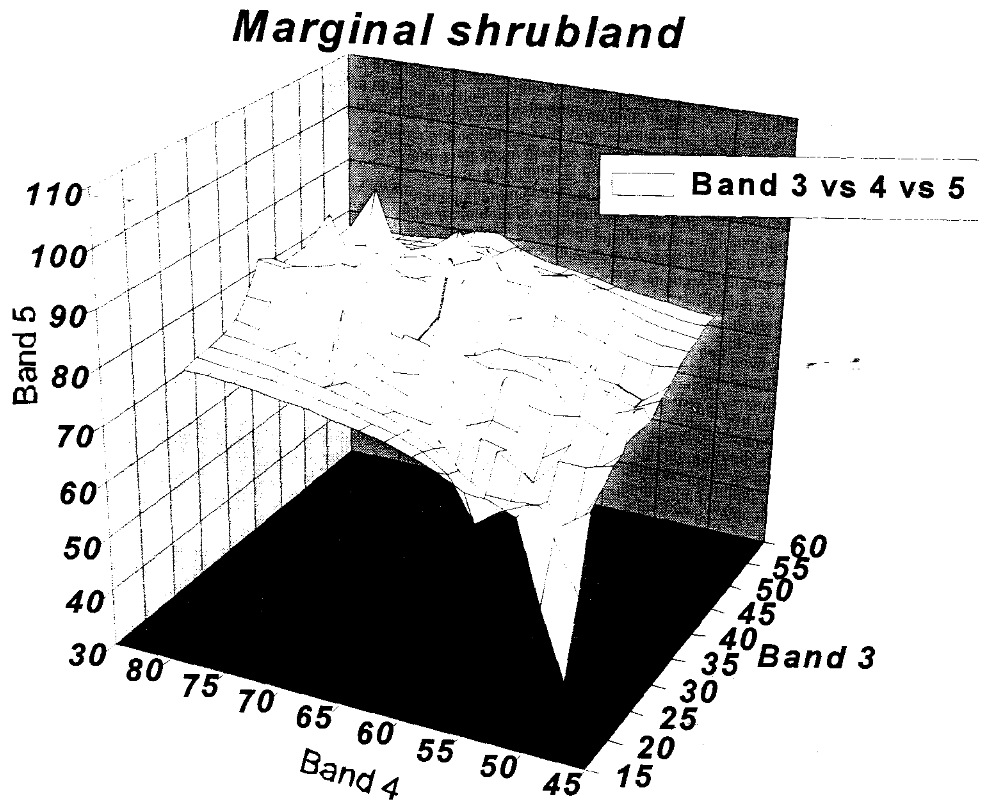




**Figure 5.10:** Spectral and environmental characteristics of *Grasslands*.

### 5.1.7.7 *Marginal Shrubland* (MaSh)

This vegetation type (Photograph 8) represents the intermediate phase between an *Open shrubland* and a *Dwarf shrubland;* consequently many of the palatable grasses have been replaced by dwarf shrubs such as *Pteronia incana.* The structure may be described as an open clumpy shrubland. The clumps consist of shrubs between 1 - 1.5m tall such as *Aloe ferox* and *Pteronia incana.* The inter-clump area comprises unpalatable grasses such as *Erogrostis plana* and dwarf shrubs such as *Pteronia incana.* It is generally found on moderate slopes (Figure 5.11). Basal cover is approximately 70-80% with shrubs dominating. A large proportion of this vegetation type occurs on the released farms that suggests it was originally an *Open shrubland* which has since been exposed to excessive herbivory leading to the reduction in palatable species. It occurs in high altitude, high rainfall areas (Figure 5.11) and has a preferred northern aspect. These factors present further evidence to suggest that it was originally an *Open shrubland.* As a consequence of the degradation that has taken place the NIR reflectance is diminished and the red reflectance value is increased (Figure 5.11).

**Photograph 8:** A *Marginal shrubland*



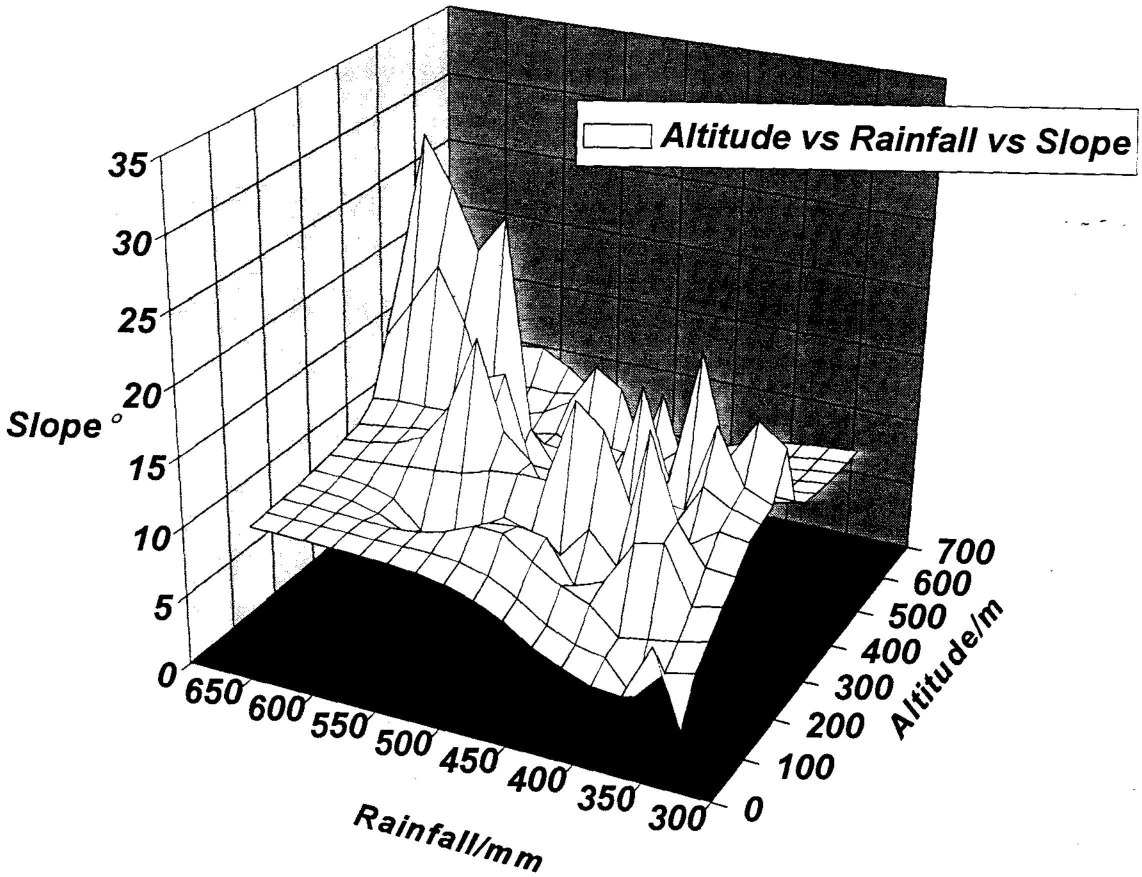
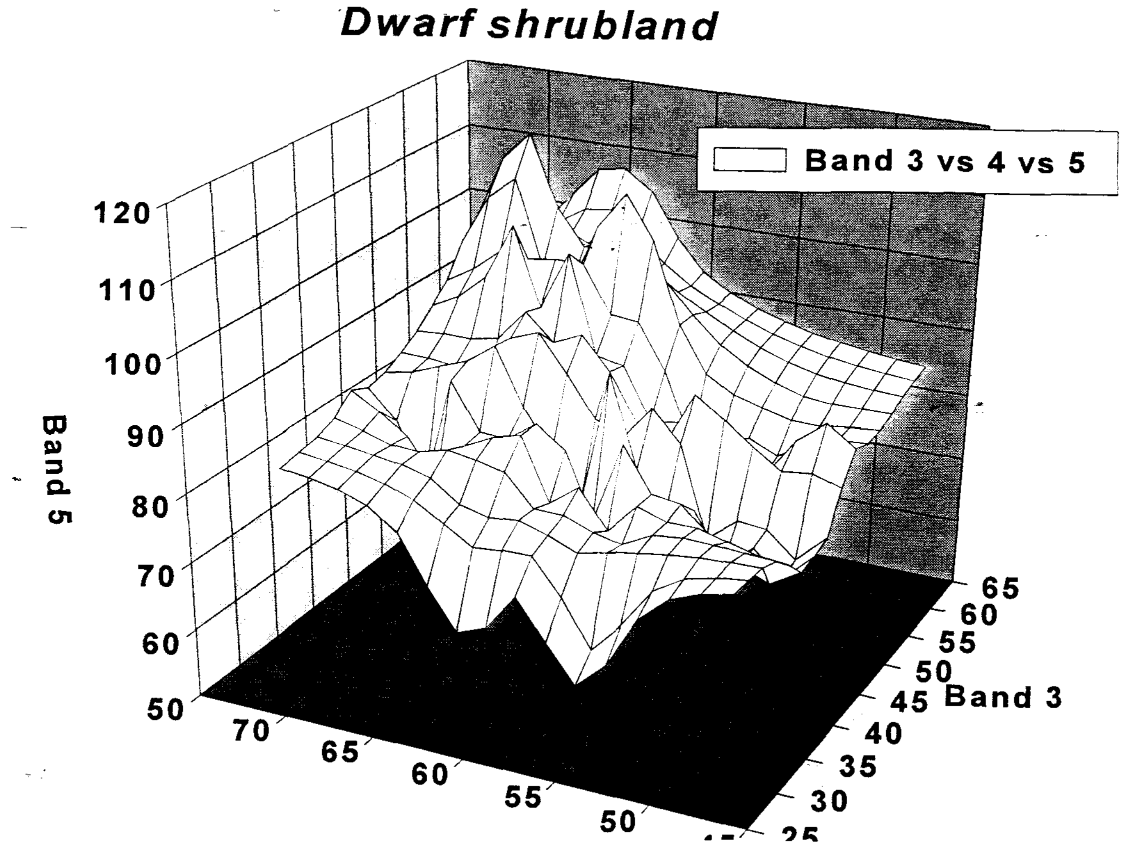




**Figure 5.11:** Spectral and environmental characteristics of a *Marginal shrubland.*

### 5.1.7.8 *(Open) Dwarf Shrubland* (DwSh)

*Dwarf shrublands* (Photograph 9) represent vegetation types where the palatable species have been replaced by karroid dwarf shrubs. Typically the basal cover is approximately 30% and may therefore be classed as an *Open dwarf shrubland*, however cover may be as high as 90%. On the mudstones and sandstones the dominant species are *Pteronia incana* and *Aloe ferox*. Where it occurs on the Ecca Shales the dominant species are *Pentzia incana* and *Aristida congesta*. Spectrally it is characterised by moderate values in all bands (Figure 5.12) and occurs across a wide range of rainfall and altitude conditions (Figure 5.12) wherever excessive herbivory has taken place.

**Photograph 9:** A *Dwarf shrubland*



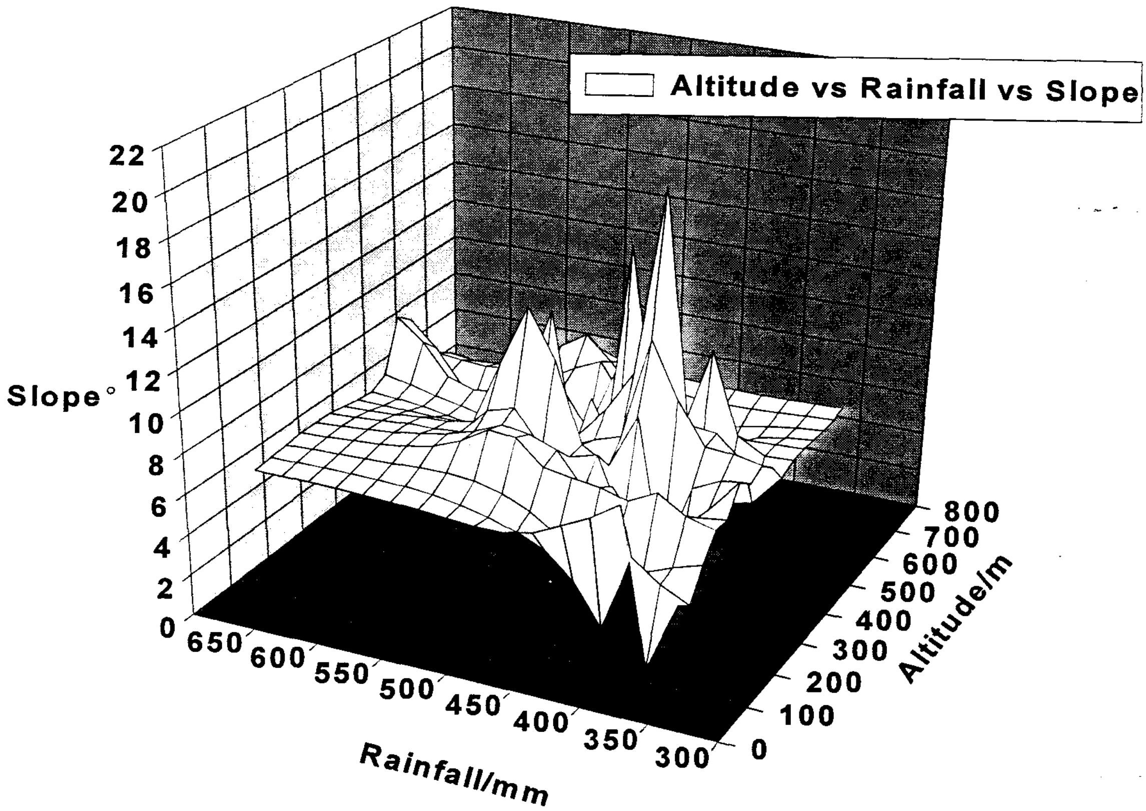
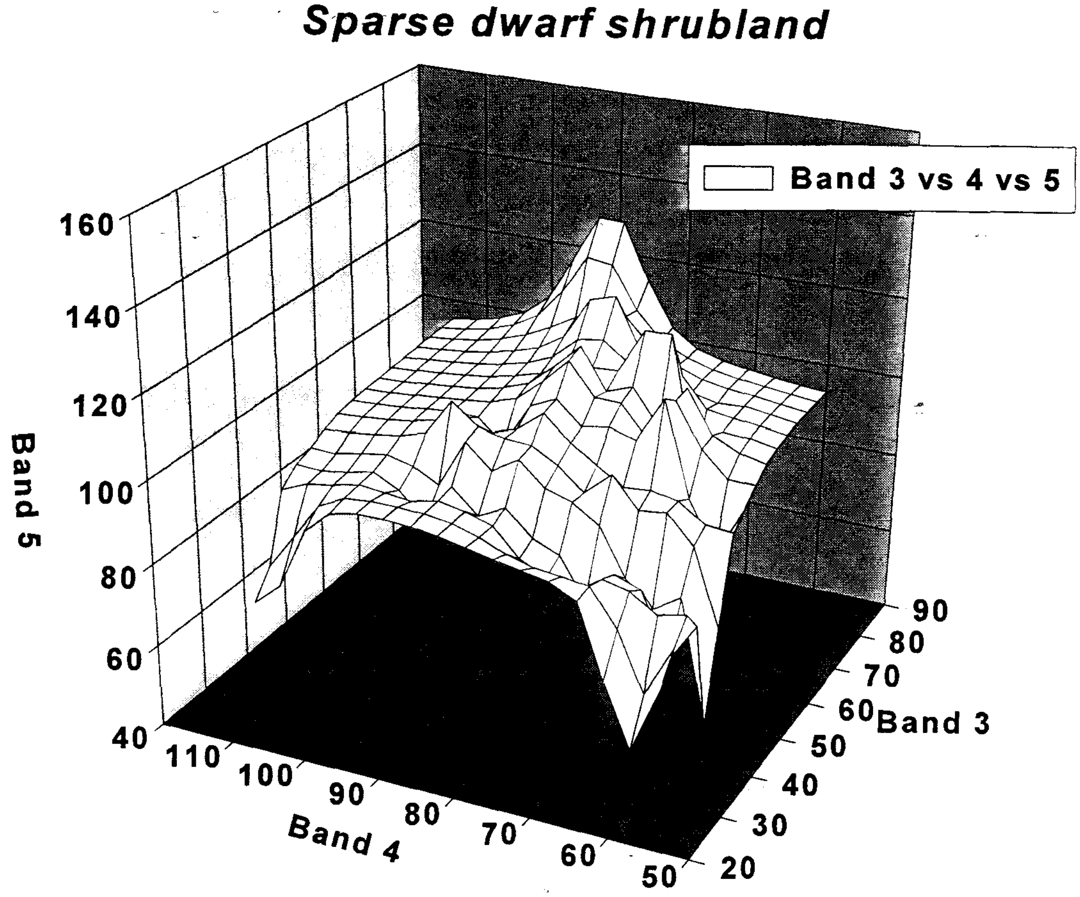




**Figure 5.12:** Spectral and environmental characteristics of an *Dwarf shrubland.*

### 5.1.7.9 *Sparse Dwarf Shrubland* (SpDwSh)

This vegetation type (Photograph 10) represents areas that have been severely degraded and any cover of vegetation largely removed. The ability of these areas to support vegetation is minimal. The overall vegetation cover is between 0 - 30%. It occurs almost exclusively in the communal areas and is dominated by *Pteronia incana*, *Aloe ferox* and *Acacia karroo*. The background reflectance of light coloured sandstone and mudstone contributes to elevated NIR values (Figure 5.13) leading to an exaggerated photosynthetic signal. This vegetation type occurs across a wide range of environmental conditions (Figure 5.13) wherever excessive degradation has taken place.

**Photograph 10:** A *Sparse dwarf shrubland*



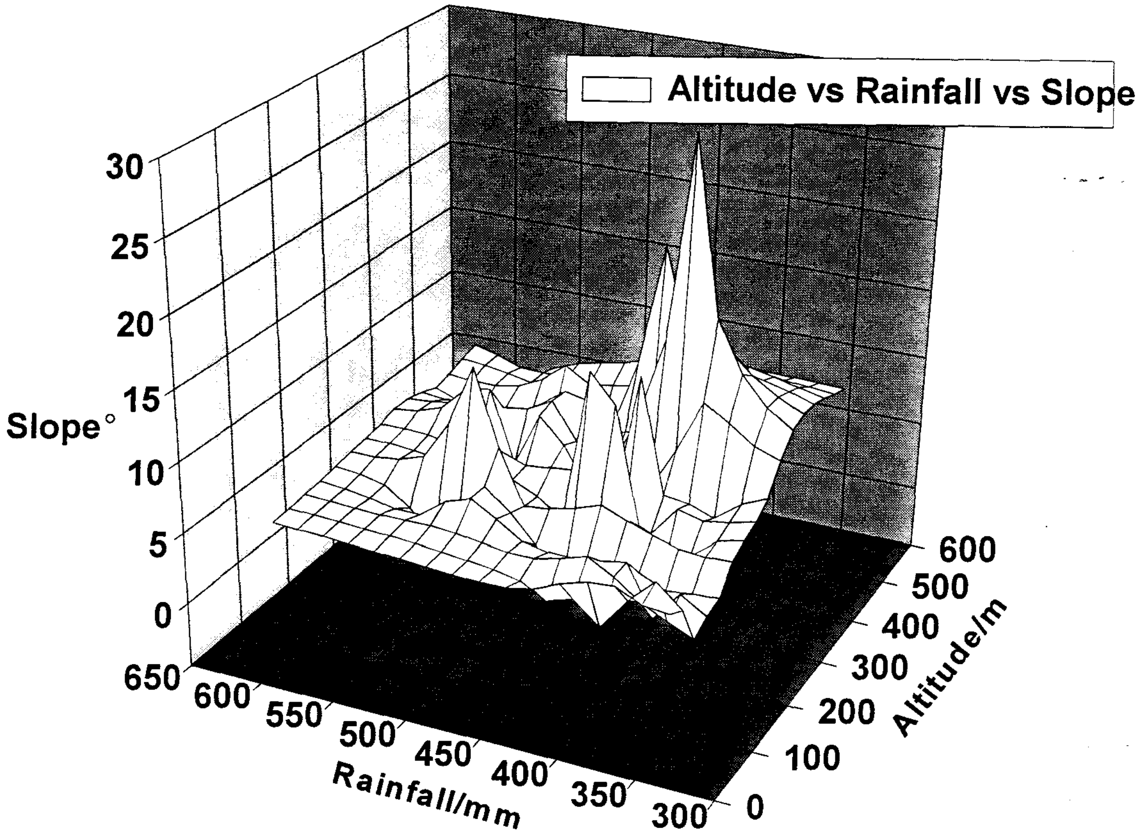




**Figure 5.13:** Spectral and environmental characteristics of a *Sparse dwarf shrubland.*

### 5.1.8 Accuracy Assessment

The error matrix of satellite-derived classes versus field-derived classes is shown (Table 5.2). The columns correspond to the 'true' (sites surveyed in the field) and the rows to the mapped (image-derived) category. The diagonal represents points that were correctly classified. The omission and commission errors as well as the Kappa Index of agreement are shown.

### 5.1.9 The Relationship of Vegetation to Land-Use

The area of each vegetation type occurring in the study area and the percentage of each vegetation type occurring in the various land-uses is provided (Table 5.3).

***Table 5.3: Area of each vegetation type and associated occurrences in the different land-uses***

| Vegetation Type | Area ($km^2$) | Area (%) | Commercial (%) | Nature Reserve (%) | Communal (%) |
|---|---|---|---|---|---|
| *Riparian forest* | 54.8 | 2.7 | 42 | 52 | 6 |
| *Dry forest* | 381.7 | 18.8 | 50 | 34 | 17 |
| *Open shrubland* | 313.2 | 15.4 | 48 | 32 | 20 |
| *Succulent thicket* | 179.4 | 8.8 | 74 | 21 | 4 |
| *Open succulent shrubland* | 92.5 | 4.6 | 73 | 10 | 16 |
| *Grassland* | 117.1 | 5.7 | 64 | 11 | 25 |
| *Marginal shrubland** | 405.9 | 20.0 | 44 | 24 | 32 |
| *Dwarf shrubland** | 196.3 | 9.6 | 32 | 12 | 56 |
| *Sparse dwarf shrubland** | 287.8 | 14.2 | 21 | 3 | 76 |
| **Undisturbed Vegetation** | 1046.2 | 51.0 | 14 | 75 | 11 |
| **Disturbed Vegetation** | 982.6 | 49.0 | 17 | 11 | 72 |

* Disturbed vegetation types

*Table 5.2: Vegetation Classification error matrix of sample sites.*

| | | FIELD CLASS | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | ***RiFr*** | ***DrFr*** | ***OpSh*** | ***SuTh*** | ***OpSuSh*** | ***Gr*** | ***MaSh*** | ***DwSh*** | ***SpDwSh*** | ***Total*** | ***Commision Error*** | ***Kappa**** |
| **I** | ***RiFr*** | *7* | *2* | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *9* | *0.222* | *0.763* |
| **M** | ***DrFr*** | *3* | ***26*** | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *29* | *0.103* | *0.878* |
| **A** | ***OpSh*** | *2* | *0* | ***19*** | *0* | *0* | *0* | *2* | *0* | *0* | *23* | *0.174* | *0.804* |
| **G** | ***SuTh*** | *0* | *0* | *0* | ***11*** | *0* | *0* | *0* | *0* | *0* | *11* | *0* | *1* |
| **E** | ***OpSuSh*** | *0* | *0* | *0* | *0* | ***9*** | *0* | *1* | *0* | *0* | *10* | *0.100* | *0.895* |
| | ***Gr*** | *0* | *0* | *0* | *0* | *0* | ***15*** | *0* | *0* | *0* | *15* | *0* | *1* |
| **C** | ***MaSh*** | *0* | *0* | *2* | *0* | *0* | *0* | ***19*** | *3* | *0* | *24* | *0.208* | *0.764* |
| **L** | ***DwSh*** | *0* | *0* | *0* | *0* | *0* | *0* | *0* | ***13*** | *5* | *18* | *0.278* | *0.687* |
| **A** | ***SpDwSh*** | *0* | *0* | *0* | *0* | *0* | *0* | *0* | *5* | ***42*** | *47* | *0.106* | *0.858* |
| **S** | ***Total*** | *12* | *28* | *21* | *11* | *9* | *15* | *22* | *21* | *47* | ***186*** | | |
| **S** | ***Ommison Error*** | *0.417* | *0.071* | *0.095* | *0* | *0* | *0* | *0.136* | *0.381* | *0.106* | | ***0.094*** | |
| | ***Kappa**** | *0.562* | *0.915* | *0.891* | *1* | *1* | *1* | *0.843* | *0.578* | *0.858* | | | ***0.843*** |

* Adjusted for chance agreement

## 5.2 Vegetation Production

The MSAVI (Plate 9) depicts the high production values associated with good condition vegetation (in the high rainfall areas), riparian zones, commercial crops (such as the centre pivot fields of lucerne near Perks Hoek) and the *Grassland* areas (such as those at Mount Somerset). The highest values in the study area are derived from riverine *Acacia karroo*. Low values are associated with degraded areas ( Sheshego, Gwabeni, Ndlambe and Glenmore and large parts of Tyefu) and the semi-arid regions in the south east of the study area. The frequency histogram of the MSAVI is shown (Figure 5.14).

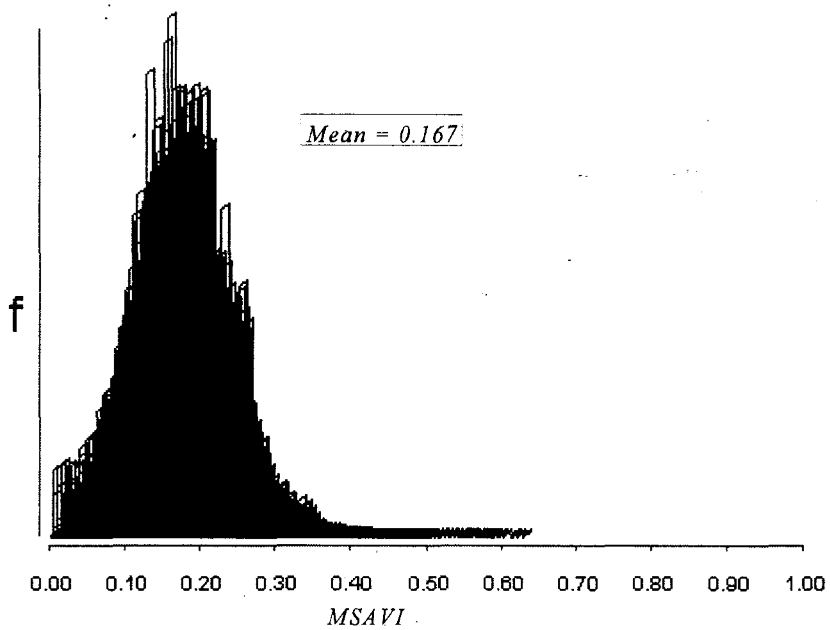



**Figure 5.14:** MSAVI frequency histogram

### 5.2.1 The Relationship of Vegetation Indices to Condition

The Student's t-test performed on paired MSAVI values is shown (Table 5.4). All results in the higher rainfall areas showed significant differences in MSAVI across the fence-line. One site (Ndlambe) taken from the arid Ecca shales area showed no significant difference at the 99% confidence level.

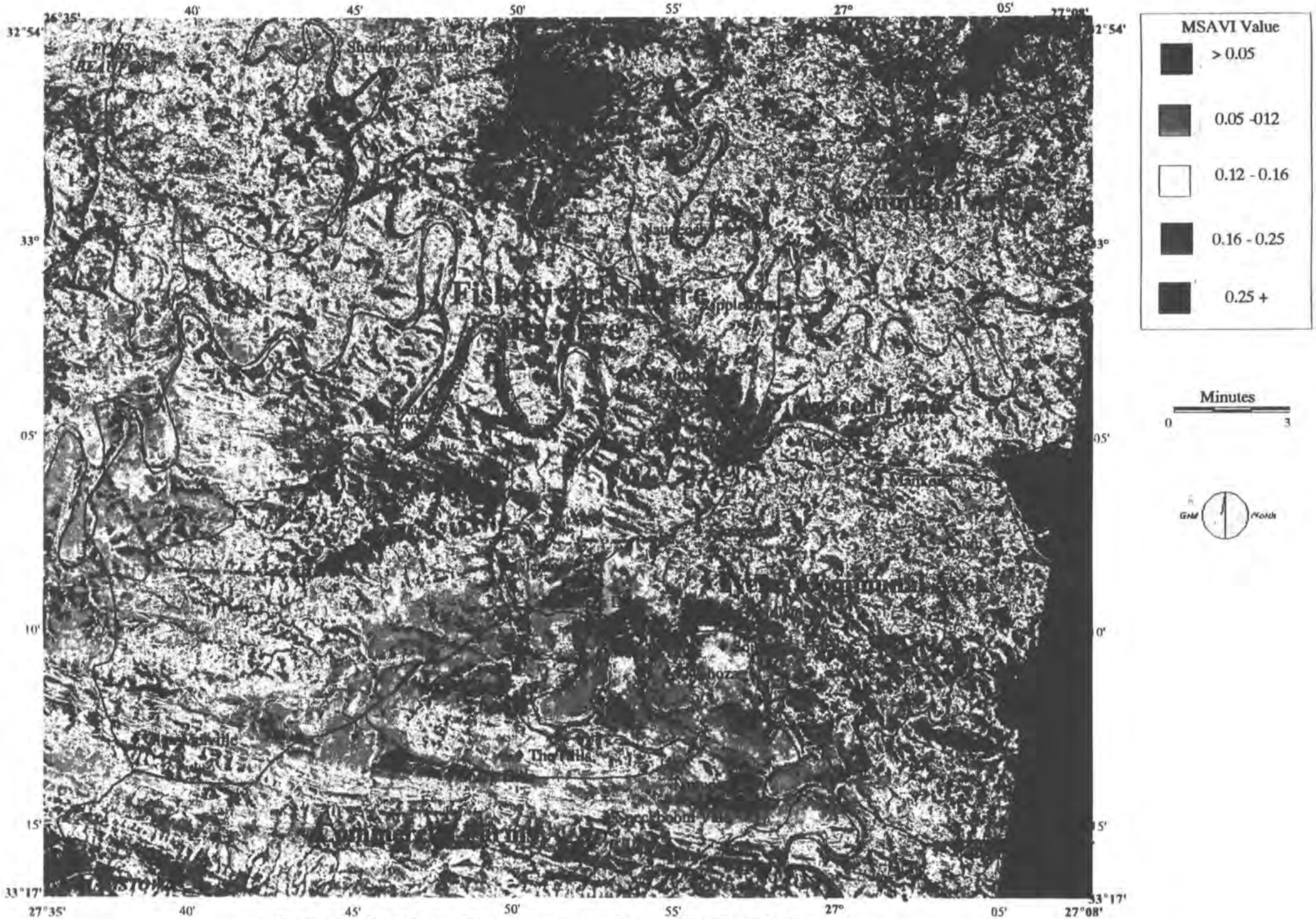



***Plate 9:** Modified Soil Adjusted Vegetation Index (MSAVI) of the Study Area*

*Table 5.4:* ***Results of the Student's t-test performed across four fence-lines to determine significant differences in MSAVI.***

| **Sample** | **Mean MSAVI** | **Standard Deviation** | **Degrees of Freedom** | **P value** |
|---|---|---|---|---|
| *Gwabeni (degraded)* | *0.12* | *0.031* | *1024* | *0.000* |
| *Good condition* | *0.22* | *0.014* | *1015* | *$H_0$* rejected* |
| *Tyefu (degraded)* | *0.098* | *0.031* | *997* | *0.000* |
| *Mount Somerset* | *0.25* | *0.022* | *1214* | *$H_0$ rejected* |
| *Sheshego (degraded)* | *0.096* | *0.025* | *1421* | *0.000* |
| *Good condition* | *0.21* | *0.013* | *1002* | *$H_0$ rejected* |
| *Ndlambe* | *0.09* | *0.019* | *1104* | *0.185* |
| *Good Condition* | *0.092* | *0.015* | *989* | *$H_0$ accepted* |

* No significant differences in MSAVI exist at 99% confidence level. Any differences that do exist are purely as a result of chance

## 5.2.2 The Relationship of Vegetation indices to Biomass

A comparison of the ranked average NDVI and MSAVI for the vegetation types is presented (Figure 5.15) (the corresponding ranks are labelled next to each value).

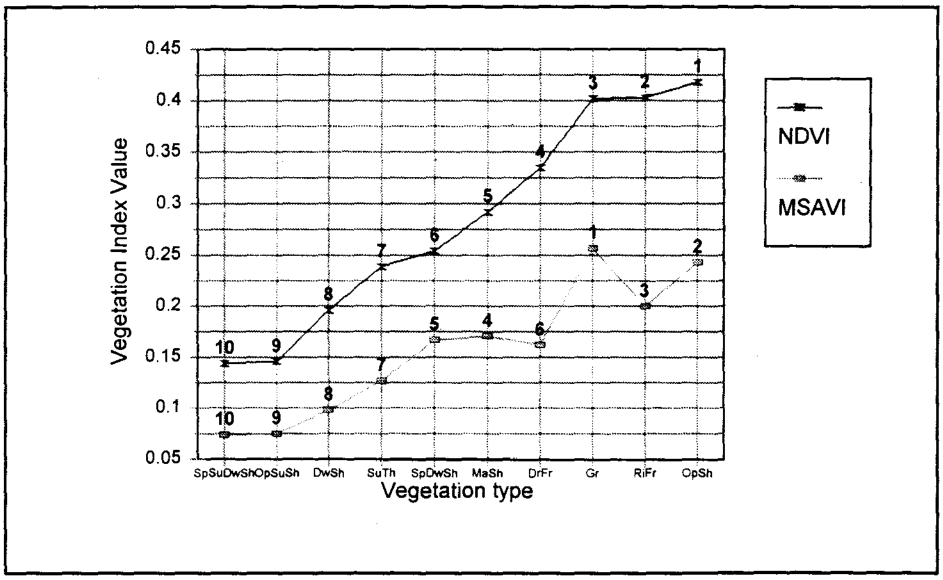



**Figure 5.15:** Comparison of MSAVI and NDVI values for the vegetation types

The biomass-MSAVI relationships for the 10 vegetation types and associated regression lines are depicted (Figure 5.16).

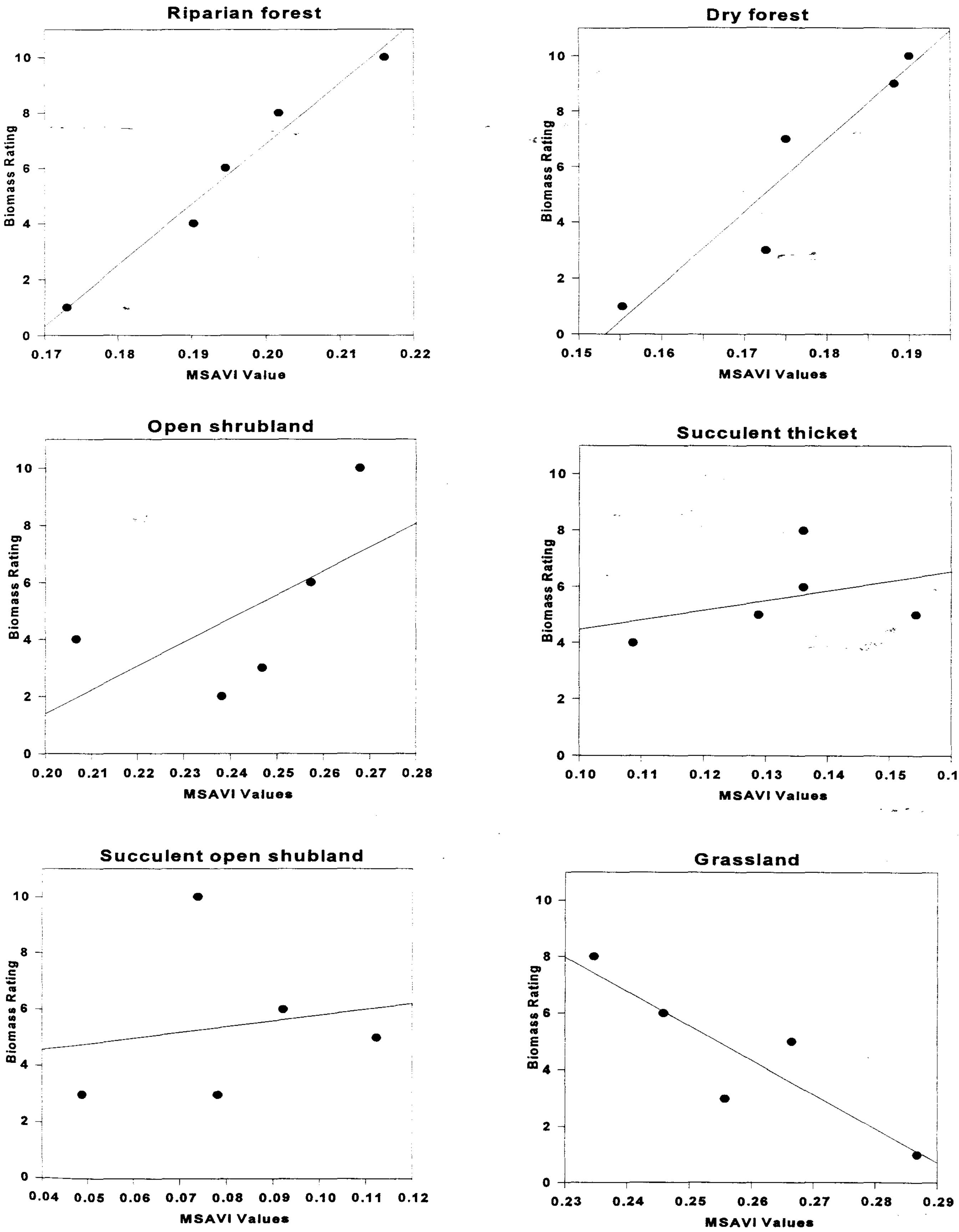



**Figure 5.16**: Biomass - MSAVI relationships for the different vegetation types.

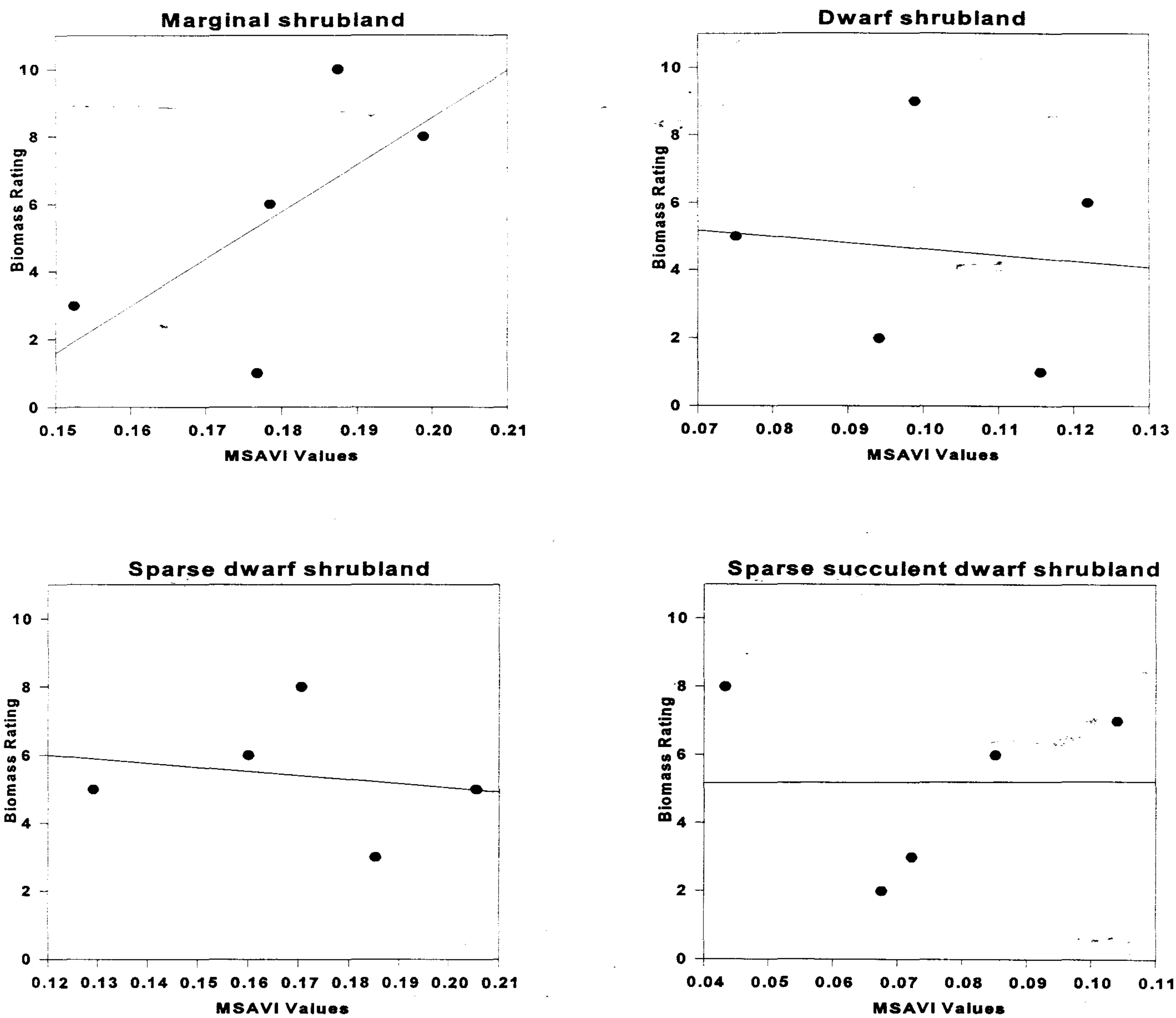



**Figure 5.16**: Biomass - MSAVI relationships for the different vegetation types.

Portions of a large homogenous grassland at Mount Somerset (Photograph 11) and the Fish River Nature Reserve (Photograph 12) (taken in a similar season to the capturing of the satellite data and after similar preceding rainfall events) are compared. The photographs illustrate the inconsistent relationship of vegetation indices to biomass. The associated MSAVI and NDVI values are given(Table 5.5).

***Table 5.5: The Associated NDVI and MSAVI values for Photograph 11 and 12***

| Photograph | Locality | NDVI | MSAVI |
|---|---|---|---|
| Photograph 11 | Mount Somerset | 0.481 | 0.271 |
| Photograph 12 | Fish River Nature Reserve | 0.468 | 0.232 |

**Photograph 11:** A young *Digitaria/Themeda Grassland* (taken at Mount Somerset).

**Photograph 12:** A senescent *Grassland* (taken in the Fish River Nature Reserve)

### 5.2.3 The Relationship of Vegetation Indices to Rainfall

The relative rainfall, MSAVI and NDVI characteristics of the five naturally occurring vegetation types (not brought about as a result of disturbance) are shown (Figure 5.17). Vegetation types caused by poor land management are omitted from the analysis.

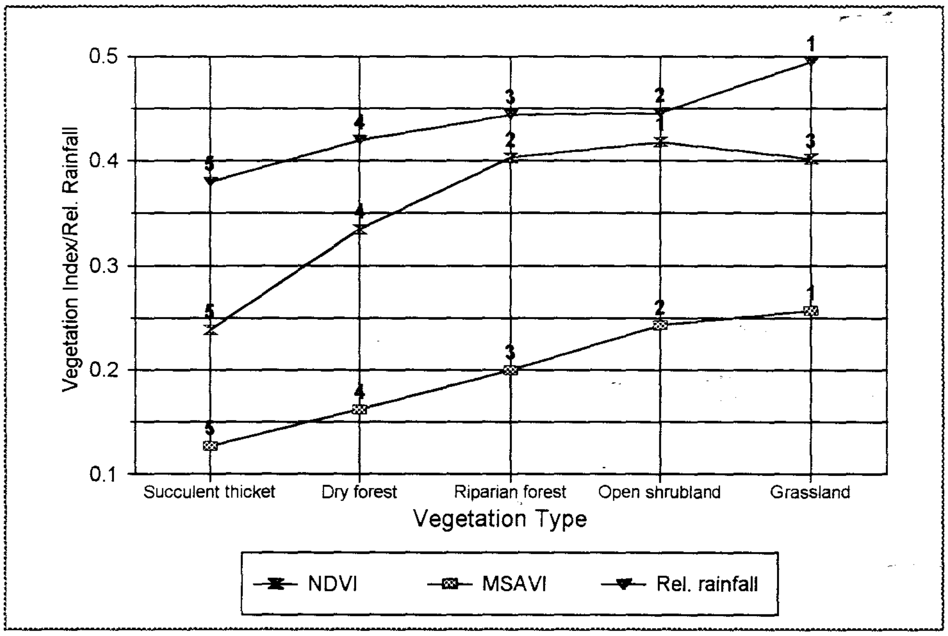



**Figure 5.17:** MSAVI and NDVI relationships to average rainfall (calculated for the naturally occurring vegetation types).

Rainfall is highly correlated with altitude in the study area (Evans *et al.*, 1996; Palmer, 1981; Palmer and Avis, 1994). The relationship of MSAVI to altitude was tested using a cross-section from the south east to the north west of the study area and plotting the corresponding MSAVI and altitude values (Figure 5.18). A marked association is observed.

A random sample of MSAVI values for the vegetation types *Open shrubland* and *Succulent thicket* are shown (Figure 5.19.). Both vegetation types contain similar weights of green biomass and cover and can be described as good condition vegetation types. The only difference being that the *Succulent thicket* is found dominantly in the lower rainfall Ecca shales whereas the *Open shrubland* occurs dominantly in the higher rainfall, sandstone/mudstone areas. The *Succulent thicket* is characterised by significantly lower MSAVI values.

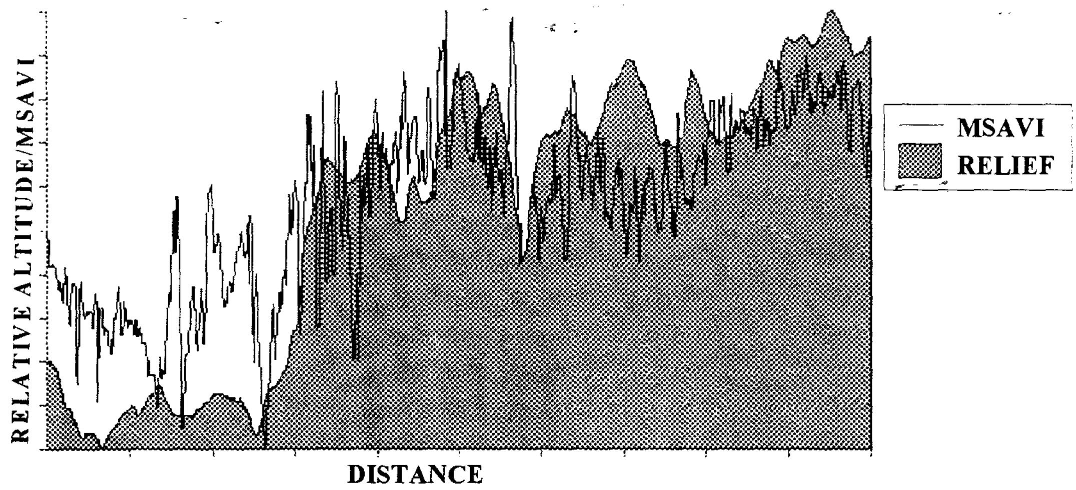



**Figure 5.18:** Cross-section from the south east to the north west of the study area showing the marked correlation between MSAVI and altitude/rainfall.

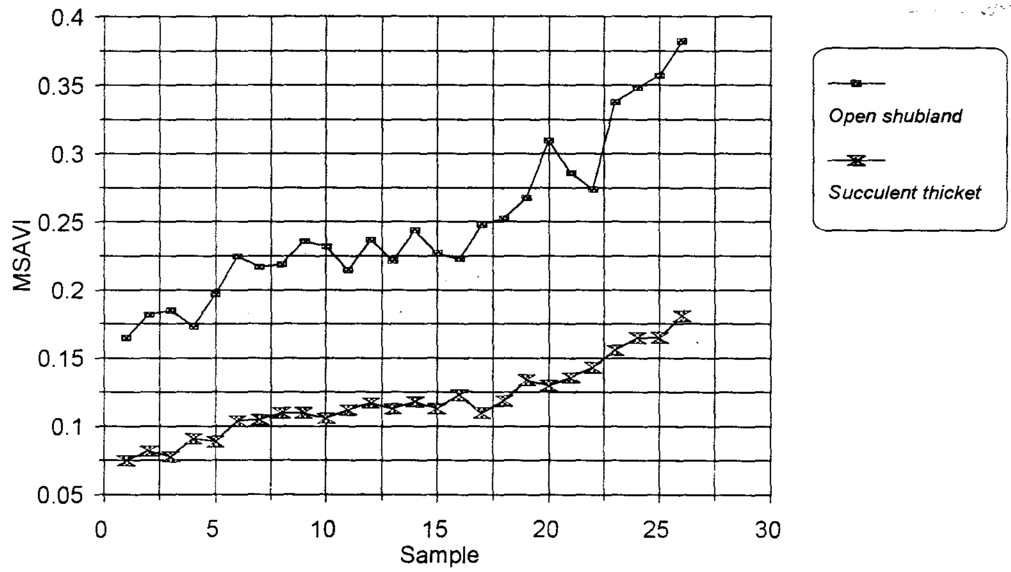



**Figure 5.19:** Comparison of *Succulent thicket* and *Open shrubland* MSAVI values.

## 5.3 Landscape Heterogeneity

A visual inspection of the moving standard deviation images produced demonstrated that TM band 3 (red) and TM band 5(mid-infrared) were the only bands that exhibited a good correlation with rangeland condition. TM band 4 (NIR) standard deviation image proved too sensitive to changes in vegetation type and resulted in large changes in standard deviation in the nature reserves and the degraded communal areas. The standard deviation image of the RVI similarly showed extreme variations in standard deviation in good condition areas and degraded areas when crossing vegetation boundaries. Band 3 showed significant changes in standard deviation across fence-lines and did not show major deviations in values when good condition vegetation type boundaries were crossed. The moving standard deviation of band 3 will be referred to as the Moving Standard Deviation Index (MSDI) for the remainder of the study.

The MSDI image (Plate 10) shows that the large rivers, the roads and some communal areas and other marginal areas exhibit the highest MSDI values. The degraded communally managed rangeland also falls into this category, particularly those areas with a long history of communal management (Gwabeni, Sheshego, Tyefu). The areas of commercial crops (centre pivot irrigation fields in Perks Hoek) and less disturbed/good condition areas (large parts of the Fish River Nature Reserve) exhibit low MSDI values. It is interesting to note that even large areas which have been severely eroded until little or no vegetation remains exhibit high MSDI values. This confirms the original hypothesis that variability of the landscape as a whole is a sensitive indicator of the amount of degradation that has been imposed on the landscape. The image frequency histogram is shown (Figure 5.20).

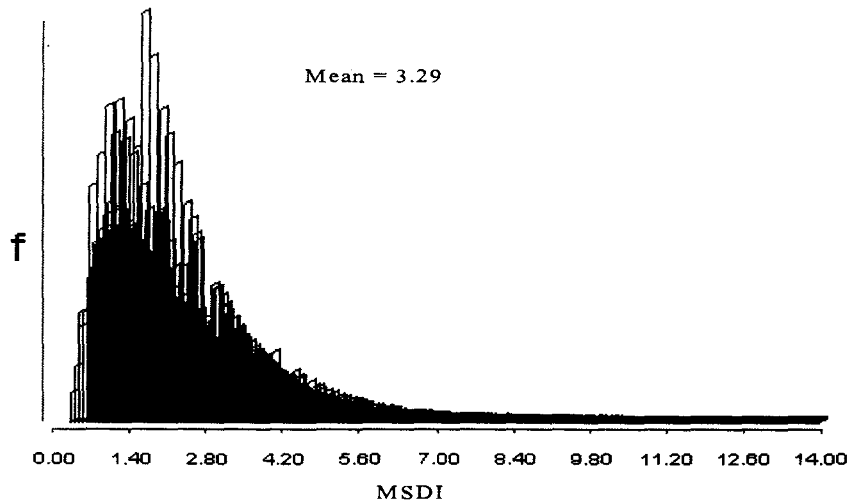



**Figure 5.20:** MSDI frequency histogram

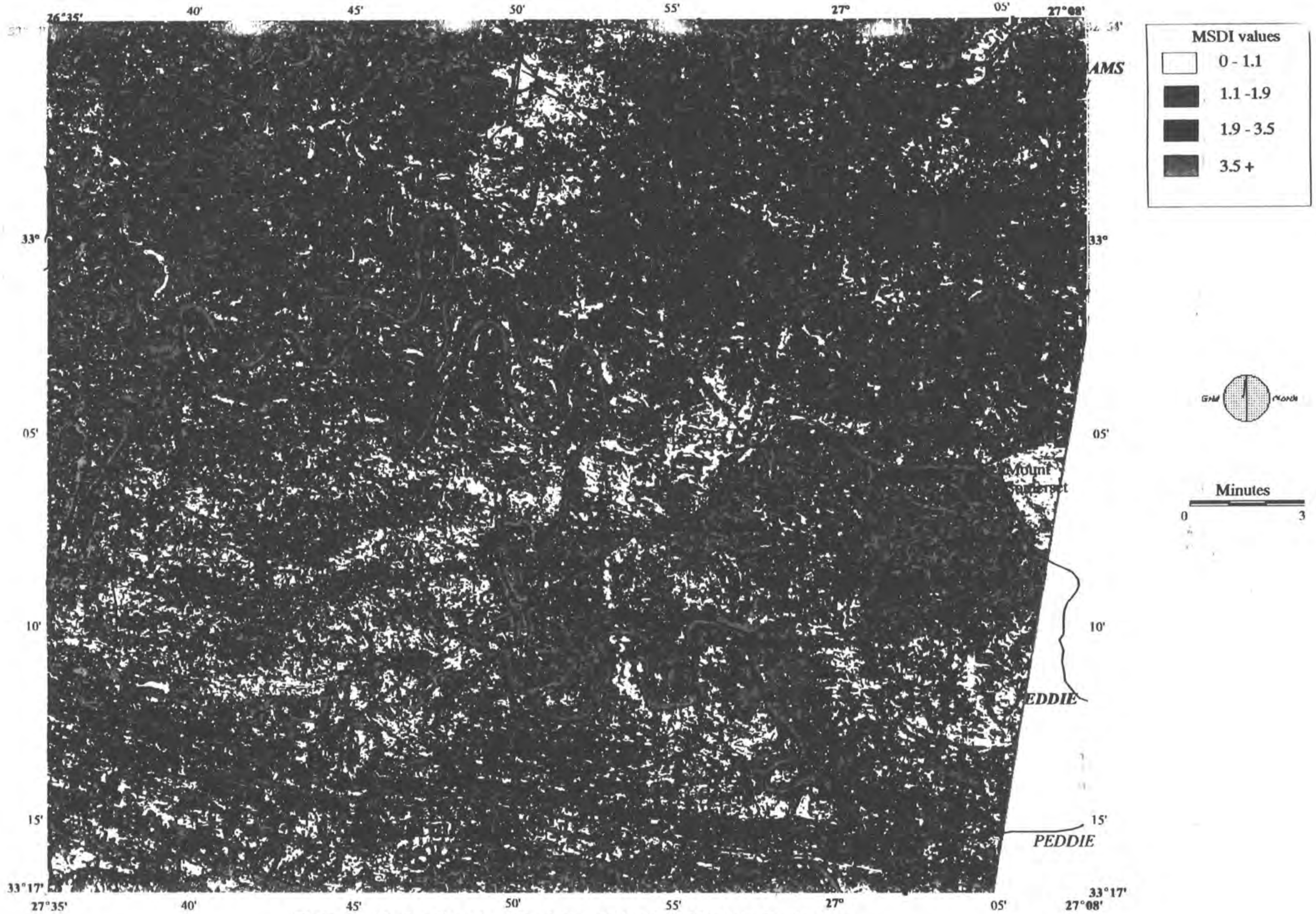



*Plate 10: Moving Standard Deviation Index (MSDI) of the Study Area*

### 5.3.1 The Relationship of MSDI to Rangeland Condition

The results of the Student's t-test for significant difference in MSDI across condition boundaries is shown (Table 5.6). All pairs displayed a significant difference between treatments, with the MSDI being highest on all communal land, or land with a history of communal management.

***Table 5.6: Results of the student's t test performed across 4 fence-lines.***

| Sample | Mean NDVI | Standard Deviation | Mean MSDI | Standard Deviation | Degrees freedom | P value of MSDI |
|---|---|---|---|---|---|---|
| *Gwabeni (degraded)* | *0.18* | *0.044* | *5.01* | *0.9* | *1024* | *0.000* |
| *Good condition* | *0.38* | *0.028* | *1.37* | *0.5* | *1015* | $H_o$* *rejected* |
| *Tyefu (degraded)* | *0.13* | *0.031* | *4.38* | *0.83* | *997* | *0.000* |
| *Mount Somerset (good condition)* | *0.42* | *0.03* | *0.95* | *0.2* | *1214* | $H_o$ *rejected* |
| *Sheshego (degraded)* | *0.12* | *0.038* | *4.65* | *0.65* | *1421* | *0.000* |
| *Good condition* | *0.32* | *0.019* | *1.59* | *0.4* | *1002* | $H_o$ *rejected* |
| *Ndlambe (degraded)* | *0.15* | *0.025* | *6.7* | *0.9* | *1104* | *0.00* |
| *Good Condition* | *0.17* | *0.015* | *1.08* | *0.38* | *989* | $H_o$ *rejected* |

*No significant difference in values at the 99% confidence level. Any differences observed are purely a result of chance

During the collection of field data each site was assigned an assessed degree of transformation based on the method described by Norton *et al.* (1984) (Appendix 3). An error matrix (Table 5.7) of the field data collected versus the MSDI (including the areal extent of each category) is presented (sites occurring within 30m of rivers and roads have been omitted from the analysis).

*Table 5.7: Error matrix of MSDI categories (and areas) versus field data.*

| | Degree of Transformation | Low | Moderate | Severe | Total | Commision Error | Kappa* |
|---|---|---|---|---|---|---|---|
| | | **FIELD DATA SAMPLE SITES** | | | | | |
| M | Low (< 0.5) (782.6 $km^2$) | 37 | 5 | 0 | 42 | 0.119 | 0.813 |
| S | Moderate (0.5-25) (535 $km^2$) | 8 | 16 | 11 | 35 | 0.543 | 0.322 |
| D | High (> 2.5) (701 $km^2$) | 2 | 7 | 55 | 64 | 0.141 | 0.735 |
| I | Total | 47 | 28 | 66 | 141 | | |
| | Ommission Error | 0.212 | 0.429 | 0.167 | | 0.234 | |
| | Kappa* | 0.692 | 0.430 | 0.695 | | | 0.6337 |

* Adjusted for chance agreement

### 5.3.2 The Relationship of MSDI to Vegetation Type

The associated average MSDI values for each of the vegetation units in the study area are shown (Figure 5.21). Undisturbed Vegetation values clearly exhibit markedly lower MSDI values.

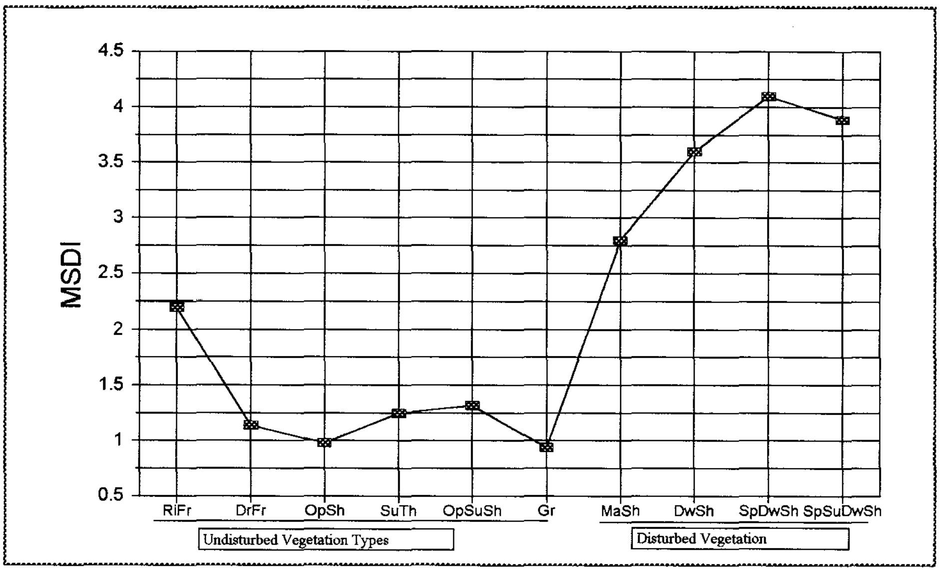



**Figure 5.21:** Average MSDI/vegetation type relationships

### 5.3.3 The Relationship of MSDI to Production

The correlations of the various standard deviations to NDVI are listed (Table 5.8)

***Table 5.8: Spearman's Rank Correlation Coefficients for standard deviation images versus NDVI***

| Band Used | Spearman's Rank Correlation Coefficient | P Value of Correlation | Significance of correlation |
|---|---|---|---|
| *Band 3 (MSDI)* | *-0.58* | *0.00* | $H_o$* *Rejected* |
| *Band 4* | *-0.29* | *0.22* | $H_o$ *Accepted* |
| *Band 5* | *-0.44* | *0.01* | $H_o$ *Rejected* |
| *RVI* | *-0.18* | *0.31* | $H_o$ *Accepted* |

*No significant correlation at the 99% confidence level. Any correlation that is observed is purely a result of chance.

The graph of the correlation between the NDVI and MSDI computed for the four fence-line contrasts investigated in section 5.3.1 is presented (Figure 5.22). The correlation is negative in the study area where a high NDVI generally indicates good condition rangeland. The five basic combinations of vegetation condition are shown (Figure 5.22) and can be described as follows:-

- A site exhibiting a high NDVI and low MSDI is indicative of a good condition highly photosynthesising site and is associated with the good condition vegetation types such as *Grassland, Open shrubland, Dry forest* and *Riparian forest.*
- A site exhibiting low NDVI values and high MSDI values is indicative of a highly degraded site. Where spatial patterning is high and photosynthetic activity is low. These areas commonly occur in communal areas and surrounding watering points and are normally associated with disturbed vegetation types such as *Dwarf shrublands.*
- A site exhibiting high NDVI values and high MSDI values indicates an area which has been subject to a disturbance. Natural or man-induced disturbance allows invasive/highly competitive vegetation to out-compete less resilient species. Typical man-induced disturbances include over-grazing and degradation from soil surface disturbance (for example ploughing). These sites are typified by a reduction in palatable grasses and shrubs and an increase in unpalatable dwarf shrubs. Natural disturbances include the influence of rivers, geological features (for example the existence of a dolerite dyke in an otherwise sedimentary geological environment) or the occurrence of seep lines. Sediment surrounding river courses is often covered by *Acacia karroo* which exhibits a powerful highly variable NIR signal and as a result a high MSDI.

- A site exhibiting low MSDI values and low NDVI values is typical of the healthy arid vegetation types. These sites typically occur on the Ecca Shales where the NIR reflectance is low and the patterning of the landscape is also low as a consequence of the low level of disturbance. Another feature plotting in this region of the graph are fallow fields.
- Areas plotting elsewhere on the graph indicate an area in moderate condition.

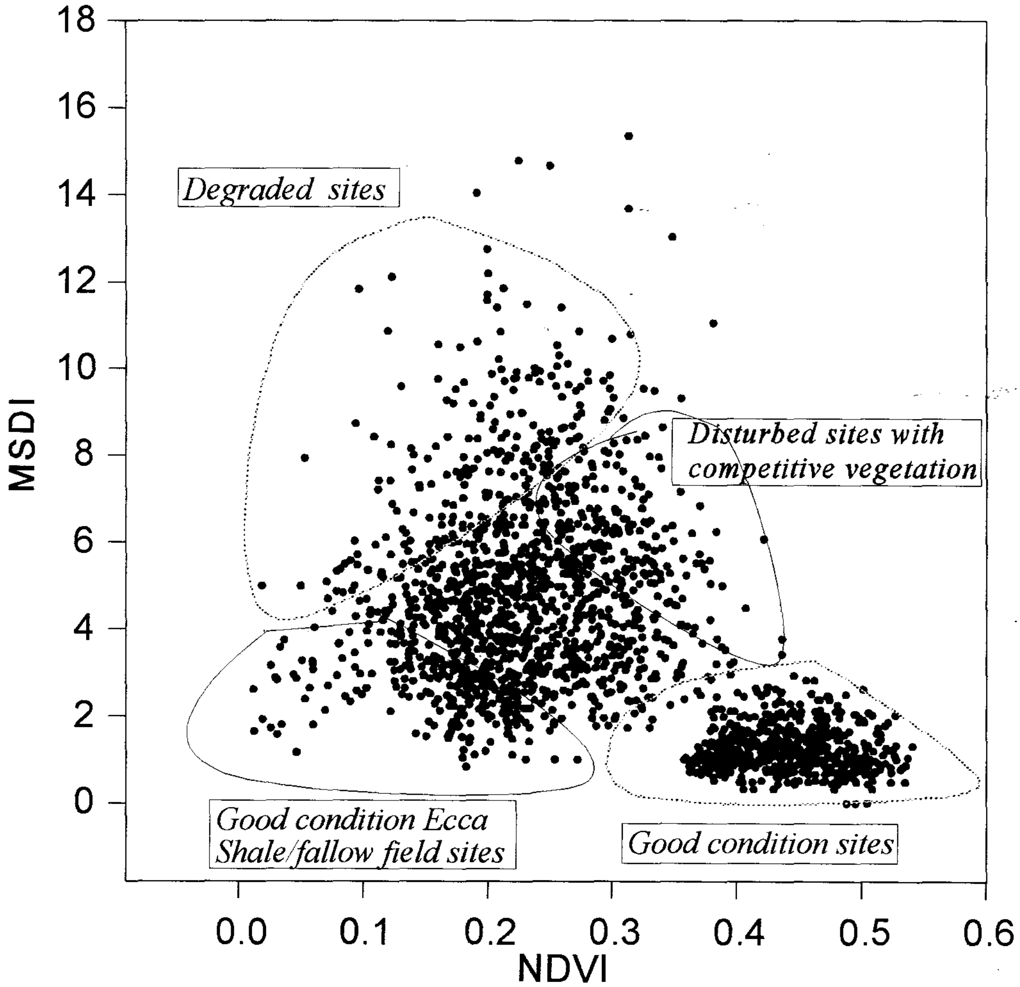



**Figure 5.22:** MSDI/NDVI relationships in the study area.

Although the graph of MSDI versus NDVI for the four fence-line contrasts (Figure 5.22) shows moderate correlation, the samples are taken over a wide range of rainfall, temperature and altitudinal gradients. These variations have a profound effect on the NDVI (Malo and Nicholson, 1990; Rogers and Randolf, 1991). The correlation is therefore improved when a sample is taken in a small area where rainfall, temperature and soils are identical and only rangeland conditions change. This is true provided the vegetation index in question is correlated with vegetation condition. A contrast in correlations between MSDI and NDVI in a semi-arid area(Ndlambe)and a high rainfall (Mount Somerset) part of the study area is presented (Figure 5.23).

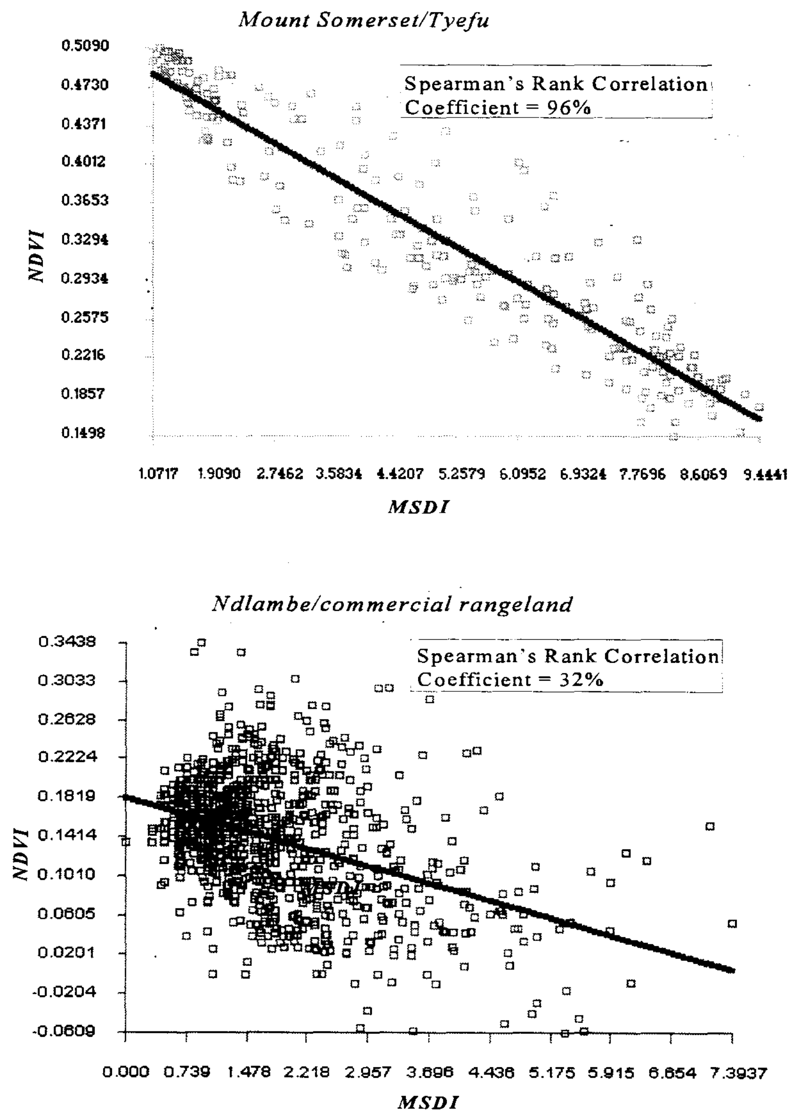



**Figure 5.23:** Comparisons of the correlations between MSDI and NDVI in a high rainfall, non-succulent area (Mount Somerset) with a low rainfall, succulent area (Ndlambe).

The image produced by performing a cross-classification of the categorised NDVI and MSDI values is presented (Plate 11 and the resulting classes described (Table 5.9).

***Table 5.9: Descriptions of the MSDI:NDVI cross-classification***

| | *Low NDVI (1)* (>0.2) | *Moderate NDVI (2)* (0.2 - 0.3) | *High NDVI(3)* (< 0.3) |
|---|---|---|---|
| ***Low MSDI (1)*** (> 0.5) | ***119.1 km²*** <br> *1. Good condition arid/fallow fields sites* | ***156.5 km²*** <br> *2. Moderately good condition (typical of areas on the periphery of nature reserves)* | ***507.0 km²*** <br> *3. Very good condition (typical of nature reserves)* |
| ***Moderate MSDI (2)*** (0.5 - 2.5) | ***83.3 km²*** <br> *4. Degraded (typical of communal areas)* | ***169.3 km²*** <br> *5. Moderate condition (typically transition vegetation types such as Marginal shrubland)* | ***282.3 km²*** <br> *6. Good condition (often riparian zones)* |
| ***High MSDI (3)*** (> 2.5) | ***154.0 km²*** <br> *7. Very Degraded (typically sparse dwarf shrublands of the communal areas)* | ***243.1 km²*** <br> *8. Degraded (typical of average vegetation in communal areas)* | ***303.9 km²*** <br> *9. Competitive/invasive /disturbed vegetation (often surrounding roads, Acacia karroo in degraded areas and surrounding river courses)* |

Note how the Fish River Nature Reserve is dominated by class 3 whereas the degraded communal areas (for example Glenmore, Gwabeni, Tyefu and Ndlambe) are dominated by class 7. The good condition arid areas (for example commercial rangeland in the south of the study area)are dominated by class 1. Areas of highly photosynthesising highly competitive/invasive vegetation (often surrounding disturbance areas such as homesteads) are dominated by class 9. The image presents a visual perspective of the strong correlation between heterogeneity and production.

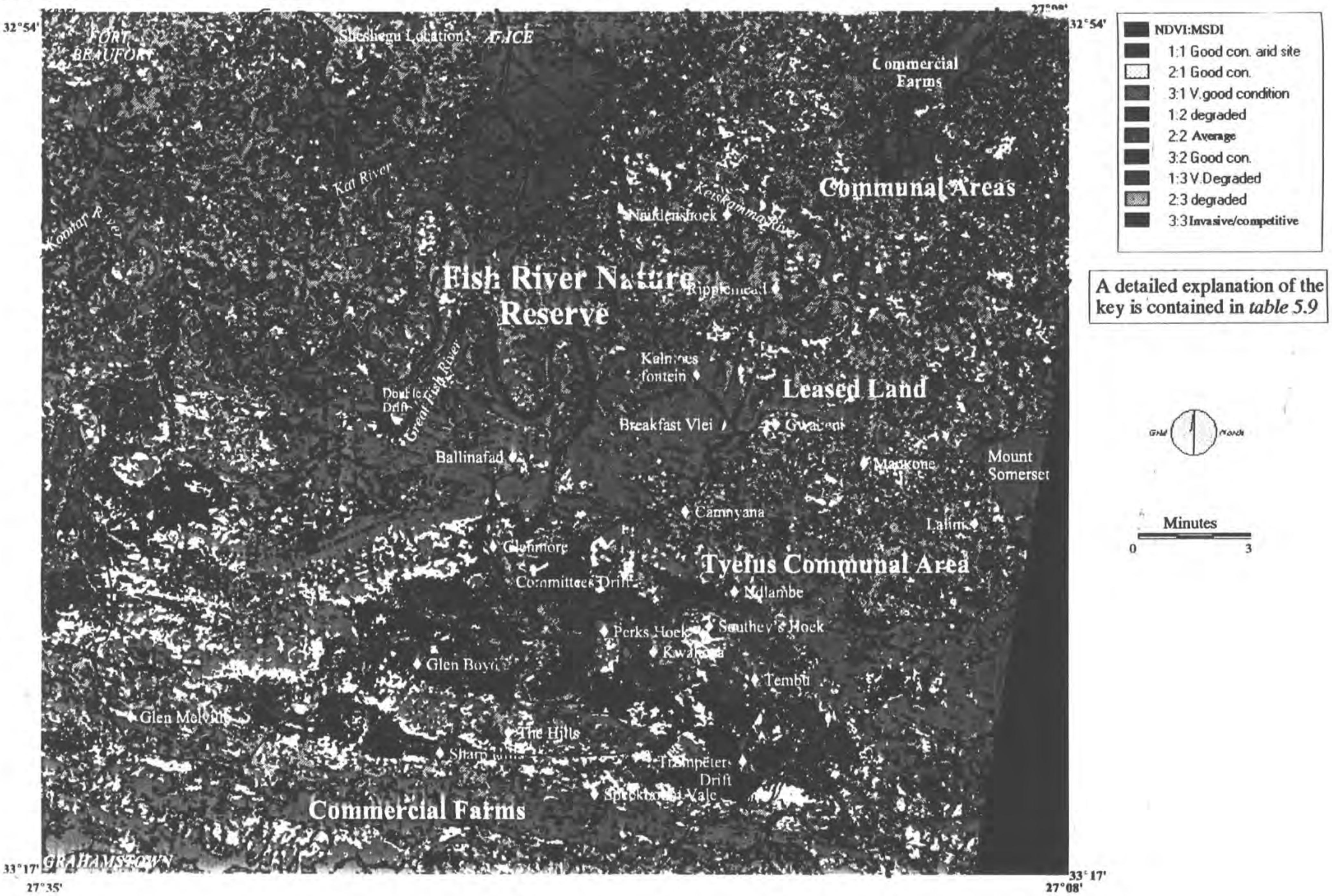



***Plate 11:*** *The Image Derived from the NDVI:MSDI cross-classification*

### 5.3.4 The MSDI in Other Ecosystems

The Spearman's Rank Correlation Coefficient and test for significance of correlation for the five ecosystems investigated as well as a brief description of the landscape dynamics associated with each ecosystem is presented (Table 5.10). The correlations for the five ecosystems are all significant at the 99% confidence level. However, the direction of the correlation differed.

***Table 5.10: NDVI:MSDI relationships in five different ecosystems***

| Locality | Spearmans NDVI:MSDI | Vegetation Dynamics and Relationship to Production | P Value of Correlation |
|---|---|---|---|
| *Fish River, Eastern Cape* | *-0.49* | *High production values are generally associated with good condition rangeland except in very specific instances.* | *0.0000* *$H_o$* rejected* |
| *Sabie Sand Game Reserve, Mpumalanga* | *0.47* | *High production values are normally disturbance-induced and represent alteration to the original functioning of the ecosystem.* | *0.0000* *$H_o$ rejected* |
| *Southern Kalahari Desert* | *0.46* | *High production values are associated with the invasion of indigenous grasslands with encroaching woody shrubs such as Acacia mellifera* | *0.0000* *$H_o$ rejected* |
| *Cathedral Peak, Natal* | *-0.38* | *High production values are associated with good condition mesic grasslands whilst low values are indicative of degraded areas.* | *0.001* *$H_o$ rejected* |
| *Lillefontein, North Western Cape* | *-0.42* | *High production values associated with good condition succulent mountain rangeland.* | *0.0005* *$H_o$ rejected* |

*No significant correlation at the 99% confidence level. Any correlation observed is purely a result of chance.

The southern Kalahari data was interrogated further to validate that the MSDI is still related to condition when the relationship to NDVI is positive. Fence-line contrasts were established by Palmer *et al.* (1997) and tested for significant differences in MSDI (Table 5.11).

*Table 5.11:* ***Student's t test performed on three Paired MSDI and NDVI fence-line Contrasts in the Kalahari Desert***

| Sample | Mean NDVI | Standard Deviation | Mean MSDI | Standard Deviation | Sample size | P value of MSDI |
|---|---|---|---|---|---|---|
| *Degraded* | *0.317* | *0.0387* | *2.05* | *1.289* | *1412* | *0.00* |
| *Good condition* | *0.306* | *0.0284* | *1.43* | *0.946* | *1029* | $H_o$* *rejected* |
| *Degraded* | *0.336* | *0.0453* | *2.3* | *1.564* | *729* | *0.00* |
| *Good condition* | *0.304* | *0.0285* | *1.687* | *0.878* | *690* | $H_o$ *rejected* |
| *Degraded* | *0.302* | *0.031* | *1.79* | *0.985* | *1569* | *0.00* |
| *Good condition* | *0.318* | *0.0189* | *1.344* | *0.542* | *1458* | $H_o$ *rejected* |

*There are no significant differences in MSDI at the 99% confidence level. Any differences are purely a result of chance.

The graph of MSDI versus NDVI for the Kalahari data is shown (Figure 5.24). The relationship is clearly positive.

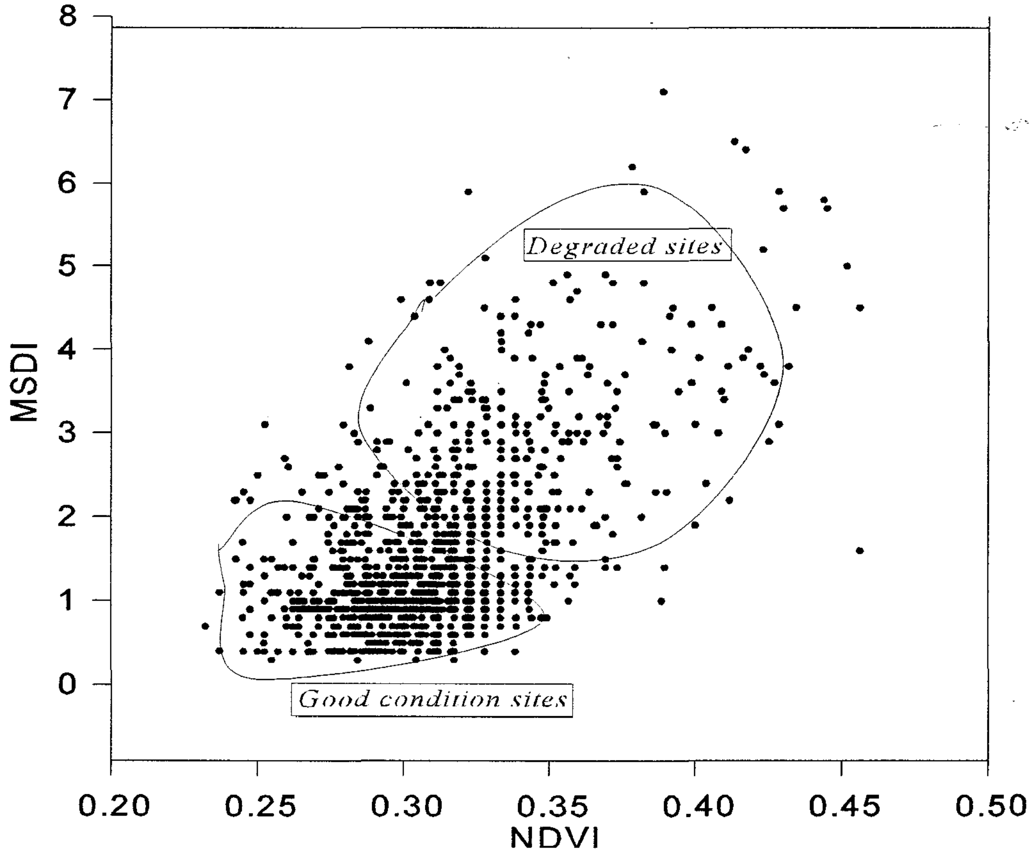



**Figure 5.24:** MSDI/NDVI relationship in the Southern Kalahari Desert.

## 5.4 A Visual Comparison

The purpose of this section is to demonstrate how the vegetation classification, the MSAVI, the MSDI and cross-classification can be used in concert with one another to derive a good understanding of the character of the landscape. A typical area of relatively undisturbed nature reserve and a degraded communal area are examined to investigate the spatial relationships of the MSDI and NDVI and vegetation from an orthogonal perspective. A summary of the characteristics of the two sites to be compared is presented (Table 5.12).

***Table 5.12: Summary data for the nature reserve and communal area compared in Plates 12 and 13***

| Category | Communal Area | Nature Reserve |
|---|---|---|
| ***Level and nature of herbivory*** | *High (Cattle, sheep and goats)* | *Low (Kudu, Black Rhinoceros)* |
| ***Land History*** | *1912 proclaimed communal area* | *Prior to 1982 commercial rangeland* |
| ***Population pressure*** | *high (70 persons km $^{-2}$)* | *Nil(<2 persons km $^{-2}$)* |
| ***Average Rainfall*** | *525 mm yr $^{-1}$* | *504 mm yr $^{-1}$* |
| ***Altitude*** | *450 m.a.s.l.* | *500 m.a.s.l.* |
| ***Substrate*** | *Sandstone/Mudstone* | *Sandstone/Mudstone* |
| ***Degradation*** | *Severe* | *Minimal (except on steep slopes)* |

The potential vegetation based on rainfall, altitude and substrate is very similar (Palmer and van Staden, 1992). The NDVI and MSDI (Plate 12) and the vegetation and cross-classification (Plate 13) are depicted overlain on the corresponding Digital Terrain Model (DTM). The MSDI and NDVI frequency histograms (Figure 5.25) refer to Plate 12 and the vegetation and cross-classification bar graphs (Figure 5.26) refer to Plate 13.

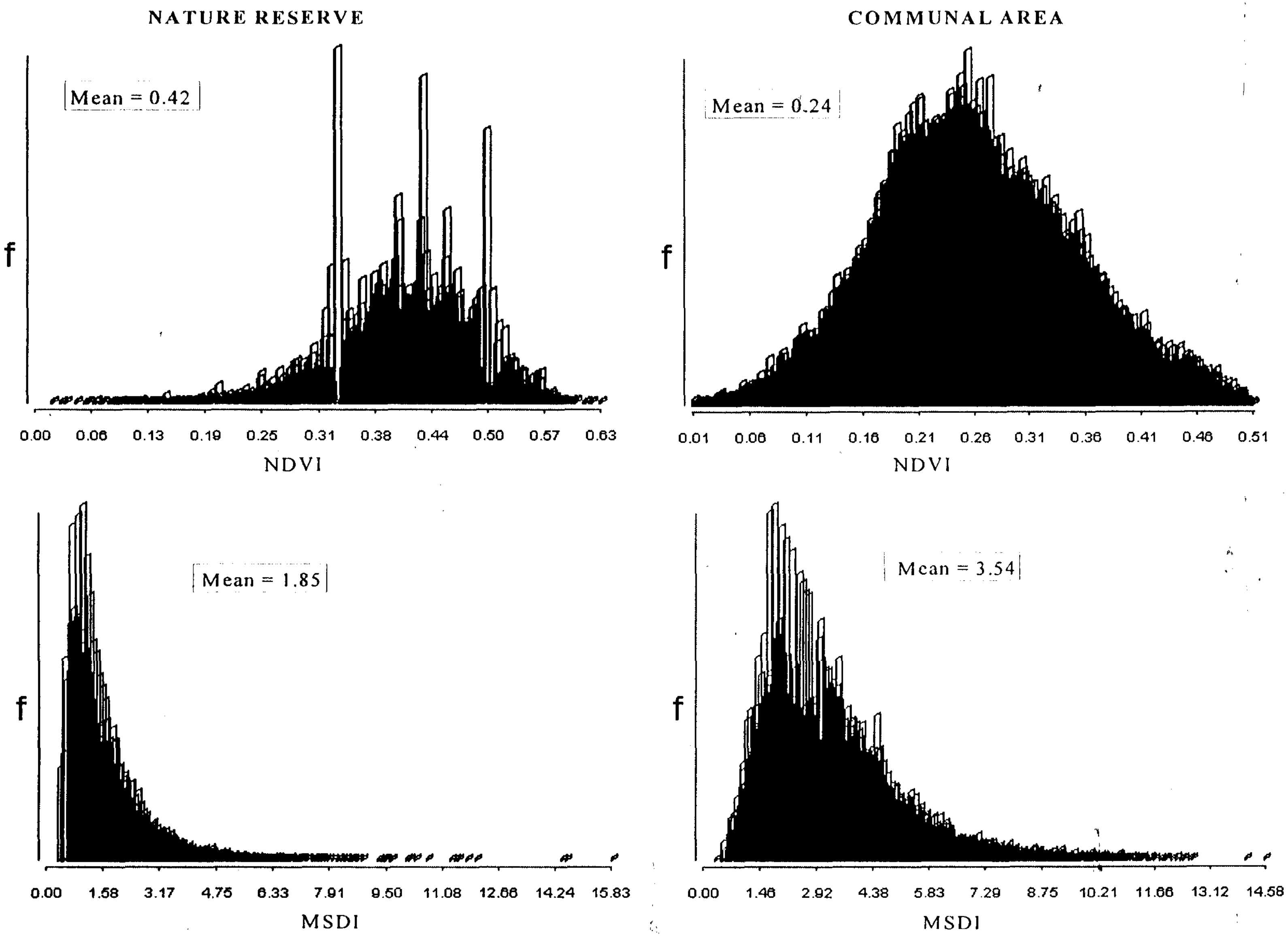



**Figure 5.25:** Comparative NDVI and MSDI frequency histograms of the communal area and nature reserve depicted in Plate 12.

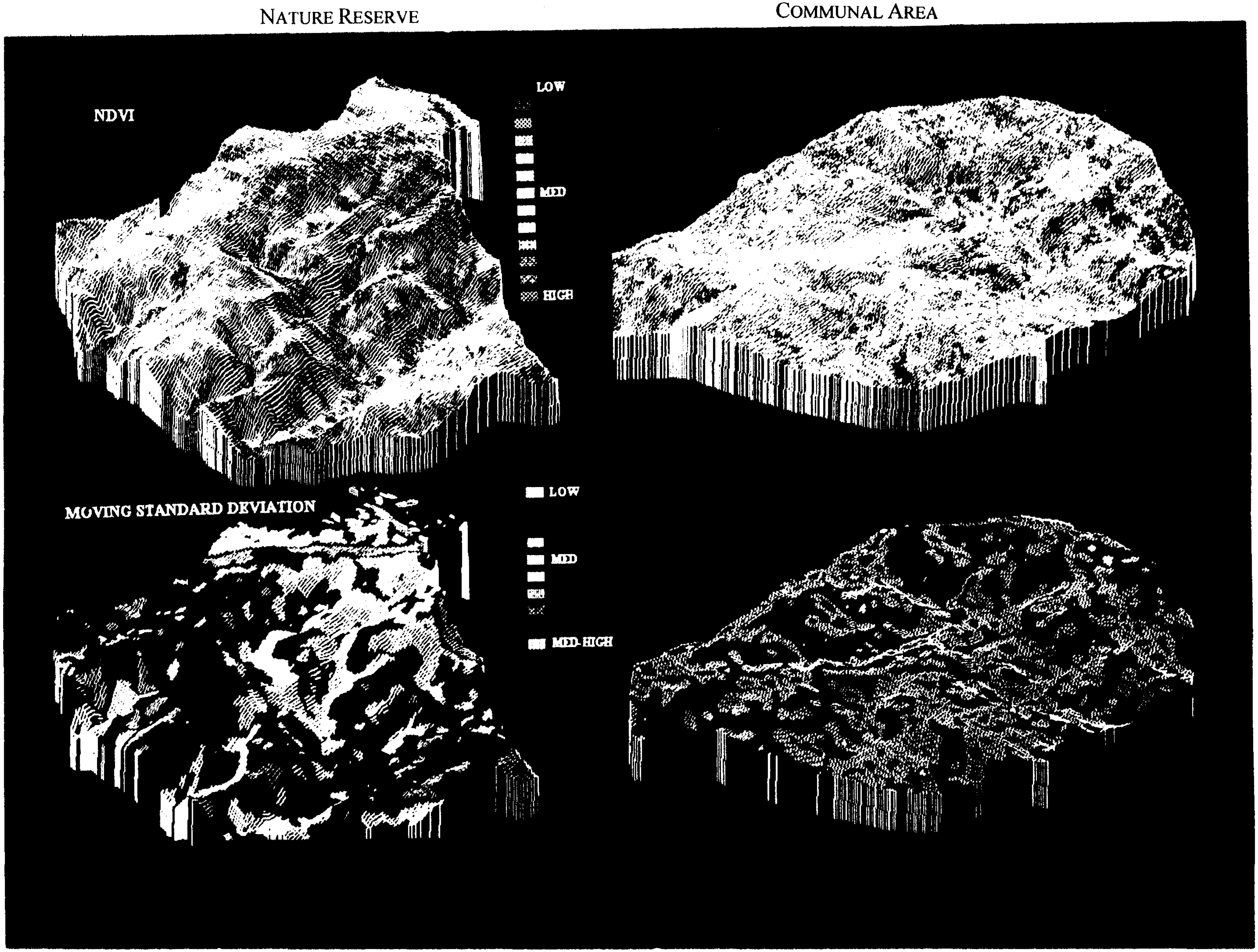



**Plate 12:** An orthographic comparison of the NDVI and MSDI values for a typical Communal area and Nature reserve.

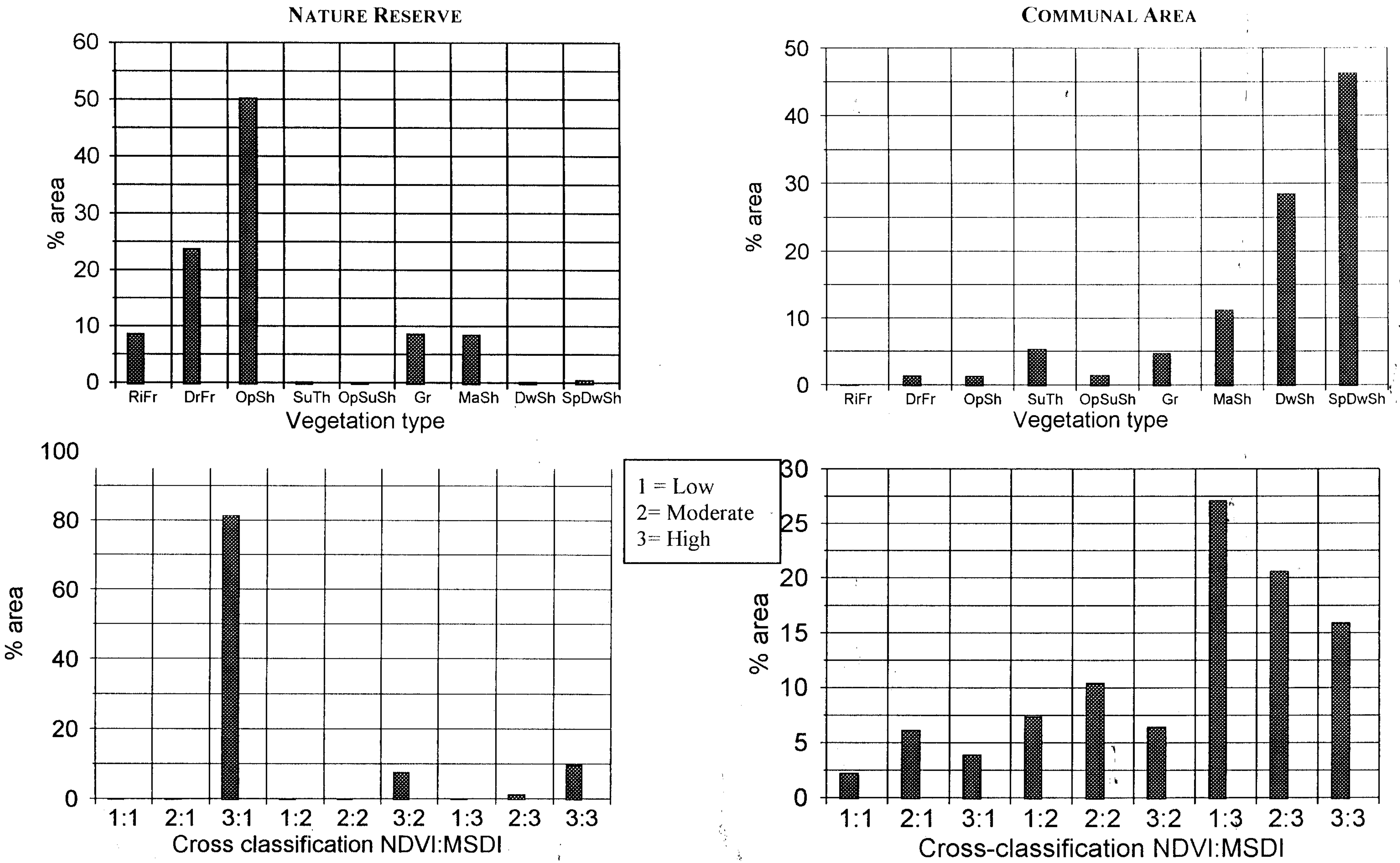



**Figure 5.26**: Comparative vegetation classes and cross-classification classes of the nature reserve and communal area depicted in Plate 13.

NATURE RESERVE | COMMUNAL AREA

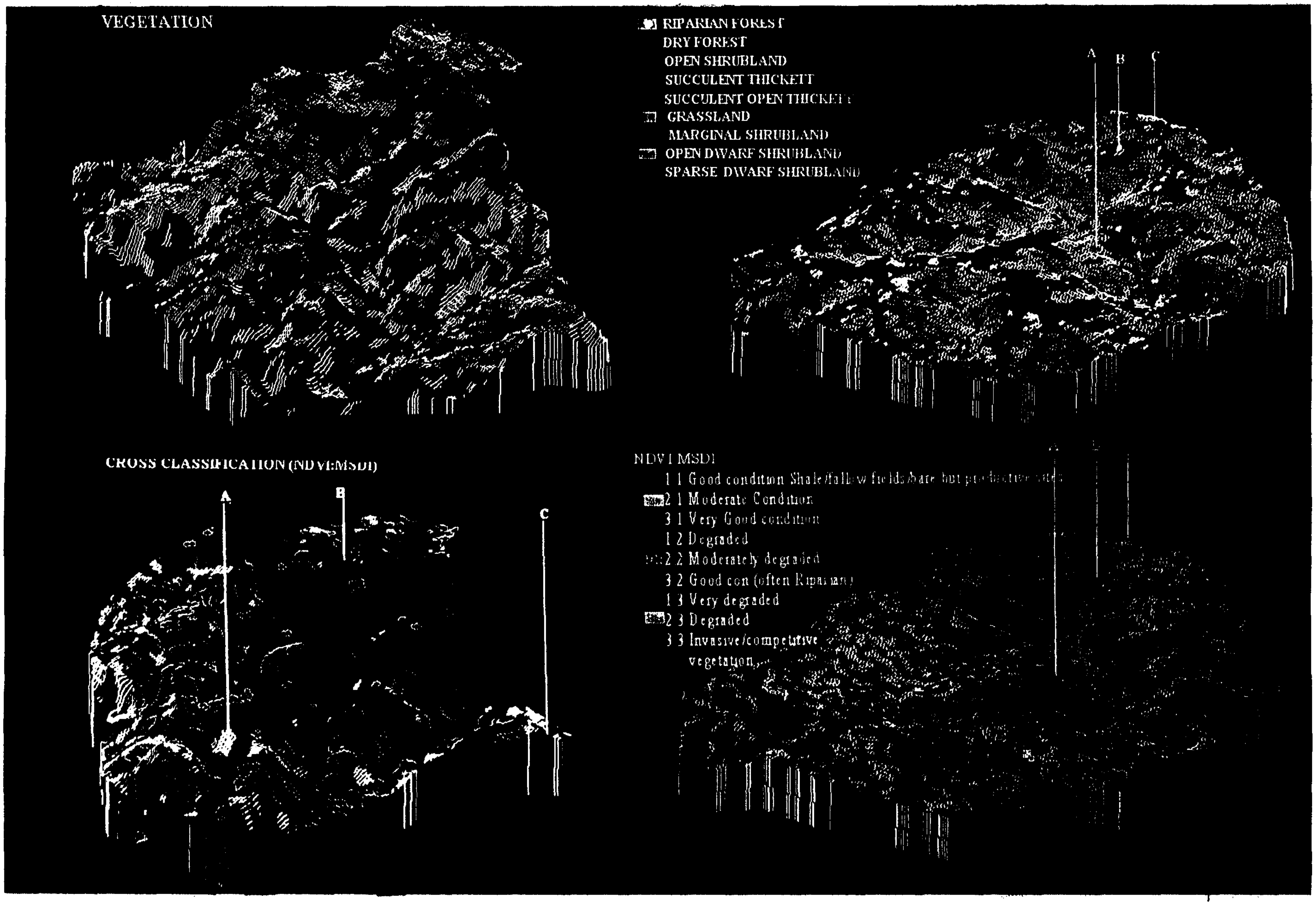



**Plate 13:** An orthographic comparison of the vegetation and cross-classification classes (NDVI:MSDI) for a typical Communal area and Nature reserve.

# CHAPTER 6

# DISCUSSION

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*Remote sensing has long been an important tool in regional studies of natural resources, but its potential for understanding ecological patterns and processes has not been fully realised* (Roughgarden *et al.*, 1991; Wickland, 1991).

The purpose of this chapter is to discuss the results obtained in chapter 5. The results of the vegetation classification in relation to the multi-temporal classification versus the conventional approach are presented. The final vegetation classification, its accuracy and relationship to land-use is presented. The relationship of the Modified Soil Adjusted Vegetation Index (MSAVI) to rangeland condition, biomass and rainfall are then analysed as well as the limitations of vegetation indices in predicting health that have been elucidated in the study. The findings of the Moving Standard Deviation Index (MSDI) and its relationship to condition, vegetation type, production and the operation of the index in other ecosystems are then discussed. The significant differences in the nature reserve and communal area compared (in terms of vegetation type, production and variability) are discussed to illustrate how the classifications may be used in conjunction with one another.

## 6.1 Vegetation Classification

### 6.1.1 The Multi-temporal Classification

Whilst a PCA is helpful in understanding the underlying dimensionality and character of the images it is sometimes helpful to make known the major contributors to the overall reflectance pattern observed in terms of the original input variables. The following discussion of the results obtained in section 5.1.3 refers to the components of the Principal Components Analysis (PCA) displayed in Plate 7 and the loadings of the components (Figure 5.2).

As is typical with a PCA on satellite data principal component (PC) 1 is characterised by positive loadings of all bands and is equivalent to a total brightness image. Densely vegetated areas and areas situated on the Ecca Shales are characterised by lower values than their sparsely vegetated counterparts in all bands. Grassy vegetation types such as the *Open shrubland* and *Grasslands* form the intermediate values.

PC 2 is characterised by positive loadings of all dry bands excepting band 1 and 6 (blue, thermal band respectively) and negative loadings in all wet bands. The most significant positive loading is encountered in the dry season band 7. PC2 was the most difficult to interpret and seemed to contain even less valuable information than PC3. It represents the discrimination between green vegetation/Ecca shale sites and brown vegetation/degraded sites. A high value indicated either green vegetation cover in a dry season (i.e. *Riparian forest*, *Dry forest*) or Ecca shale sites whilst a low value indicated degraded sites on the sandstones/mudstones or grassy areas. The high values associated with the Ecca shale sites is probably caused by their dark background reflectance giving rise to low values in the wet season imagery.

Although the PC 3 image (Plate 7) gives the impression of minimal contribution to the overall classification, it is very informative in the sandstone/mudstone higher elevation areas. The characteristics of PC3 belong to the wet season imagery with a high value being associated with a strong NIR signal and a low red reflectance value. A high value therefore equates to healthy photosynthesising vegetation and has an inconsequential value in all dry season bands. The high value 'speckling' encountered on the roads, rivers and communal areas probably represents the highly reflective areas in both the wet season and dry season images.

When the conventional composite (obtained using wet season bands 3-5) is compared with the multi-temporal composite (derived from the 10 dimensional multi-temporal principal component analysis) (Plate 7) the latter proves very powerful in mapping active areas of change, for example rotated commercial crops (Plate 7). Overall however, the technique produced disappointing results in attempting to enhance the spectral consequences of differences in plant phenology on a seasonal basis. Most noticeable was the failure of the technique to discriminate between *Grassland* and other grassy vegetation types such as *Open shrubland.* This was possibly due to the similar spectral properties of grasses (due to the lack of moisture) and degraded vegetation in a dry season. Overall therefore the dry season images had a 'diluting' effect on the spectral content in the images. In particular the delineation of grassy vegetation types proved difficult.

For the PCA technique to be useful, it is necessary that the subscenes include a substantial region of relatively no change. This is important to ensure that the inclination of the first (and thus subsequent) principal axes is determined by variance associated with stationary cover types (Richards, 1984). In this instance the only areas that showed relatively little change between the scenes were the large riparian zones that occupy a very small proportion of the study area. Richards (1984) concludes that this technique is of most value in situations where the variance attributable to static cover types dominates that associated with changing covers. The dry images contained so little valuable data that it is likely that a significant amount of haze was present in the images thus diminishing the spectral content of the data. It should be noted that the technique still holds considerable promise for vegetation discrimination in future research; but the selection of the season during which data capture took place and the analysis of preceding rainfall events is of paramount importance. I would recommend that; data should be selected from the peak rainfall months (in this case October and March) to provide a high degree of discrimination between green and degraded vegetation types as well as provide significant differences between the two dates to enhance the delineation of the vegetation types.

### 6.1.2 Accuracy Assessment of the Final Classification

The results obtained from the final vegetation classification (Plate 8) were good (Kappa index of agreement 84%) (Table 5.2). All pixels that were incorrectly classified were assigned to similar vegetation types. For example several *Dry forest* pixels were assigned to *Riparian forest*. These assignments are mainly due to the vegetation classes being defined by arbitrary discontinuities that in reality form a continuum (that may be difficult to classify in the field), rather than as discrete entities that strongly contrast (Franklin, 1991).

*Grassland* and *Succulent thicket* recorded 100% accuracy in both the commission and omission categories whilst *Open succulent shrubland* showed no omissions. These vegetation types are perhaps the easiest to identify in the field implying that the errors encountered in other classes are predominantly not due to georeferencing and positional error but rather to incorrect classification of the vegetation type in the field. This suggests that it is an important part of any remote sensing application to survey large areas of representative vegetation to ground-truth images.

The largest errors encountered were the omission error of 0.417 in the category *Riparian forest* and 0.381 in the category *Dwarf shrubland.* There were a number of reasons that could account for the omission errors observed in the category *Riparian forest.* Firstly, to the strict $\chi^2$ value used in the supervised classification (5%). Secondly, to the *Riparian forest-Dry forest* continuum problem. Thirdly, obtaining large areas of representative *Riparian forest* was impossible due to its elongated areal extent (because of its close proximity to drainage lines) and therefore GPS and geo-referencing errors need to be borne in mind. The errors encountered in the *Dwarf shrubland* and *Marginal shrubland* categories are probably also a result of the 'continuum problem'.

### 6.1.3 The Relationship of Vegetation to Land-use

The results (Table 5.3) show that land-use has a major effect on the type of vegetation that exists in the study area where incorrect grazing management practices have resulted in a decrease in the production potential of rangelands. Of the 2065 $km^2$ in the study area 49 % has been degraded to some degree with communal areas consisting of 72% disturbed vegetation types predominantly *Dwarf shrubland* and *Sparse dwarf Shrubland.* In several of the communal areas (which were formerly *grasslands*) there is approximately the same biomass as that before over-grazing, but it is arranged as shrubby clumps instead of a uniform carpet of grass. A large proportion of the biomass has also been transferred to the roots which are therefore not available to domestic herbivores. The response of the vegetation to intensive sustained herbivory has been a shift towards single dominance by unpalatable species, with a concomitant decline in production (Palmer and Avis, 1994).

## 6.2 Vegetation Production

### 6.2.1 The Relationship of Vegetation Indices to Rangeland Condition

The results (Table 5.4) showed that the MSAVI operated very well in the higher cover, higher rainfall areas exhibiting significant differences across condition boundaries. However, there was no significant difference in MSAVI values encountered across a condition fence-lines in the semi-arid parts of the study area. The result demonstrated that contemporary vegetation indices, using contemporary satellite data, are not of sufficient spatial or spectral resolution to enable the detection of significant differences in condition in semi-arid areas and concurs with other authors such as Ray (1995).

### 6.2.2 The Relationship of Vegetation Indices to Biomass

The results (Figure 5.15) showed there to be no absolute relationship to biomass. *Grasslands* had the highest average MSAVI values and the *Sparse dwarf shrubland* (the most degraded of the vegetation types with the lowest overall cover and lowest biomass) ranks 5th highest in the MSAVI and 6th highest in the NDVI. The signal is dominated by the highly reflective sandstone that contributes to elevated NIR values. Another explanation for the elevated production values observed is that degraded shrubs grow better when the competition from grasses is removed contributing to higher NIR reflectance.

An interesting feature of the graph (Figure 5.15) is the low ranking of the *Dry forest* (6th in the MSAVI and 4th in the NDVI). This is probably because despite having the second highest amount of green biomass, it occurs in a far wider range of rainfall conditions. It therefore has a lower average rainfall leading to a depressed level of moisture availability and lower vegetation index value. Another factor contributing to the low value is that this vegetation type is very resistant to herbivory and is not grazed by any animals (Palmer, 1981). This allows vegetation production to progress unaltered at a slow rate leading to comparatively lower NIR values. By contrast areas that have been grazed or purposefully cut exhibit high photosynthetic values.

The stratification of biomass (on the basis of vegetation type) and its relationship to MSAVI (Figure 5.16) produced mixed results. The results revealed a decreasing correlation with biomass as percentage woody vegetation cover and rainfall decreased. The categories *Riparian forest*, *Dry forest, Open shrubland* and *Marginal shrubland* showed good positive correlations between MSAVI and biomass. *Grassland* showed a marked negative correlation to biomass (Figure 5.16) as a result of the high rate of production associated with young grasses. A photographic comparison (Photograph 11, 12) of a young and mature grass and the associated NDVI and MSAVI values (Table 5.5) confirmed this relationship. Many examples occur throughout the study area which exhibit the same inverse correlations to biomass or cover, especially outside homesteads where cut lawns give very high production values.

### 6.2.3 The Relationship of Vegetation Indices to Rainfall

The improved sensitivity to vegetation and minimisation of background soil reflectance cause the MSAVI to have a significant relationship to rainfall (Figure 5.17). The NDVI however, is more sensitive to the background soil reflectance and therefore does not exhibit such an association. The relationship is further confirmed by the significant association between MSAVI and altitude (Figure 5.18).

Neither the MSAVI nor NDVI performed well in the lower rainfall, arid regions of the study area and showed no increase between the *Open succulent shrubland* (good condition) and the *Sparse succulent dwarf shrubland* (degraded). These vegetation types both occur on the Ecca shales but exhibit major differences in biomass and production. This serves to highlight the ineffectiveness of vegetation indices in semi-arid areas. The arid adaptions of plants in water-poor environments make arid and semi-arid vegetation hard to detect unless it is observed during periods of relatively abundant water where a new set of adaptions to maximise plant productivity take effect. The comparison of MSAVI values for the *Open shrubland* and *Succulent thicket* (Figure 5.19) demonstrates that although biomass and cover conditions are the same for these two vegetation types the MSAVI values are markedly different. This is probably due to the arid adaptions of plants in water-poor environments described by Ray (1995).

### 6.2.4 The Limitations of Vegetation Indices in Predicting Condition

During the course of the study a number of disadvantages have been elucidated in connection with the use of contemporary vegetation indices to establish rangeland condition. This section will describe some of these limitations.

- Although desertification is often assumed to result in a reduced level of plant growth, Ludwig (1986) found net primary productivity to be similar in the native grasslands and invasive shrub communities in southern New Mexico. However changes in the quality of net primary production with shrub invasion lower the economic potential of the landscape, especially as rangeland (Schlesinger *et al.*, 1990). Thus total net primary production that is correlated with vegetation indices such as NDVI may not always be the best measure of the magnitude of the desertification process. For example, in the Kalahari desert invasive woody vegetation encroaching onto grasslands exhibit higher NDVI values than the surrounding grasses (Palmer *et al.*, 1997).

- In areas of low cover and in dry seasons a correction factor has to be applied for background soil noise. Vegetation indices such as the Perpendicular Vegetation Index (Richardson and Wiegand, 1977), the Soil Adjusted Vegetation Index (Huete, 1988), the Transformed Soil Adjusted Vegetation Index (Baret *et al.*, 1989) and the MSAVI (Qi *et al.*, 1994) attempt to minimise this interference. However, these correction factors are often subjective in nature and repeatability is limited.
- Direct comparison between non-textural vegetation indices of different years requires calibration of the vegetation index based on factors such as preceding rainfall events and sensor aging (Friedl *et al.*, 1995; Guyot and Gu, 1994; Olsson, 1993).
- The arid adaptions of semi-arid plants in the study area ensure that NIR values are diminished limiting the ability of the vegetation index to identify differences in rangeland condition in semi-arid/arid vegetation types (Pickup and Chewings 1988; Ray, 1995).

It is therefore not feasible to cite vegetation indices as an index of landscape condition/health in heterogeneous areas. Ideally an index is required that will compensate for the problems mentioned above. As an alternative, landscape variability may be a more sensitive measure of the changes in ecosystem function that underlie various forms of desertification.

## 6.3 Landscape Heterogeneity

### 6.3.1 The Relationship of MSDI to Condition

All four fence-lines established showed significant differences in MSDI (higher values being associated with degraded areas) at the 99% confidence level (Table 5.6). This difference could be explained by invoking the Walker and Noy-Meir (1982) model of savanna ecosystem function. As the grass cover is reduced by domestic herbivory more moisture is available to the deep-rooted woody shrubs. This results in a greater variation in pixel values. The result is meaningful as the arid site (Ndlambe) displayed no significant differences in MSAVI at the 99% confidence level thus highlighting the effectiveness of the MSDI in areas where production indices do not operate well.

The contingency table of reclassed MSDI versus the field degradation assessment (Norton *et al.*, 1984) (Table 5.7) produced moderate results (Kappa index of agreement 63%). It was encouraging to note that none of the sites categorised as severely degraded in the field were characterised as good condition using the MSDI. In addition only 2 sites out of 47 (4%) assigned as severe using MSDI were described as good condition in the field. Future research will focus on the derivation of breakpoints on the MSDI continuum, allowing the accurate categorisation of ground condition.

This result obtained (Table 5.7) also elucidates one of the disadvantages of the MSDI, namely, the effective resolution of the index. The index is obtained by performing a 3 x 3 filter on the original data and therefore the effective resolution of the image is diminished (by nine times) causing the accuracy of point data on the ground to decline. An example will serve to illustrate this point. Assume an assessment of veld condition is made at a point less than 30m from an a disturbance, for example a homestead or road. Although the condition of the vegetation may be good the difference in pixel values between the disturbance and vegetation would be such that a high MSDI value is obtained, classing the pixel as disturbed. This is a disadvantage when attempting to correlate point estimates with areal data but may not be a disadvantage in the final analysis. This is because the index produces a realistic estimate of the amount of healthy vegetation present in an area. It does not allow isolated pockets of 'unutilisable' healthy vegetation to contribute to over-estimates. Degradation is thus defined in terms of spatial patterning and therefore the result consists of degraded areas as well as areas most likely to become degraded (i.e areas near a disturbance).

If disturbance is defined on the basis of MSDI; the result (Table 5.7) indicates that 62% of the area has been degraded to some degree. When this is compared with the 49%[1] disturbance figure (Table 5.3) obtained using the vegetation classification it highlights the sensitivity of the index to degradation.

### 6.3.2 The Relationship of MSDI to Vegetation Type

The low average MSDI values of the vegetation types (Figure 5.21) suggest that no inherent variability in undisturbed vegetation types exists in the Fish River Valley vegetation environment. *Riparian forest* (Figure 5.21) has a slightly elevated value due to its elongated nature and small areal extent. The vegetation types brought about by poor land-management conversely are characterised by higher MSDI values (Figure 5.21). The result demonstrates that the MSDI is also not affected by geological or soil boundaries (provided the unit in question is not of small areal extent) as vegetation types occurring on mudstones or sandstones show negligible differences in MSDI from those occurring on the Ecca Shales.

It must be noted that in clumpy vegetation, where the average inter-clump distance is greater than the effective pixel size, research still has to be conducted to assess the performance of the MSDI.

### 6.3.3 The Relationship of MSDI to Production

The highest Spearman's Rank Correlation Coefficient (MSDI versus NDVI) of -0.58 for TM band 3 (Table 5.8) confirms the selection of band 3 to be used as the MSDI. The radiometric or physiographic reason for red component of the electromagnetic spectrum exhibiting the best relationship to landscape condition is not clearly understood. I would suggest that the red band is sensitive to vegetation (the chlorophyll absorption band) as well as being useful for soil-boundary and geological mapping (Coleman *et al.*, 1993). Furthermore, the red band demonstrates a significant reduction in atmospheric noise. This spectral region is therefore sensitive to heterogeneity of the landscape as a whole and not sensitive to a particular component

[1] The class *Sparse succulent dwarf shrubland* (disturbed) had it not been derived using MSDI would have been classified as undisturbed. The 49% disturbance figure would therefore have been reduced to 42%.

of the landscape.

The relative strength of the correlations (between NDVI:MSDI) compared across fence-line contrasts (Figure 5.23) demonstrates that the correlation is markedly improved in higher rainfall non-succulent areas. Thus, the more reliably the vegetation index is an indicator of landscape condition (usually in the higher rainfall areas) the greater the correlation between the vegetation index and MSDI.

### 6.3.4 The MSDI in Other Ecosystems

The results (Table 5.10) have shown that the MSDI had significant correlations to NDVI in all of the five ecosystems investigated. Significant differences in MSDI were detected across condition boundaries in all sites in the Kalahari Desert (Table 5.11). The MSDI has also been successfully applied in the Sabie Sand Nature Reserve, Mpumalanga Provinces to identify areas of *Acacia* encroachment (Fortescue, 1997). The relationship of NDVI to condition for the Mpumalanga data is similar to that of the Kalahari Desert (high NDVI values are disturbance-induced) (Table 5.11).

The direction of the relationship of MSDI to production however, although in all cases highly significant (Table 5.11) is ecosystem-specific. Where increase in NDVI is indicative of a favourable scenario on the ground (such as the majority of the Great Fish River valley), the relationship of heterogeneity to production is negative. However, where increase in NDVI is indicative of invasion of undisturbed vegetation with competitive vegetation types (such as invasion of grasses by woody species, as in the Kalahari Desert), production clearly exhibits a positive relationship to heterogeneity. MSDI therefore always demonstrates a positive relationship to degradation irrespective of the relationship of NDVI to condition. The differing direction of correlation between the two indices proves that the relationship is not purely a mathematical one.

### 6.3.5 The Advantages and Disadvantages of the MSDI

The purpose of this section is to list the advantages and disadvantages of the MSDI some of which have been eluded to during the course of this study.

The advantages of the use of the MSDI are listed below.

- The MSDI is a very sensitive indicator of rangeland condition and performs well in areas where vegetation indices to do not operate such as arid/semi-arid areas.
- It is possible to distinguish between healthy vegetation (low MSDI) and invading vegetation (high MSDI) both exhibiting high NDVI values by cross-classification of the two indices.
- It is not necessary to apply a correction for background soil noise, preceding rainfall events and sensor imbalance as the MSDI does not depend on absolute reflectance.
- Natural 'buffer zones' surround marginal areas where the variability in these zones is effectively 'projected' onto the surrounding areas. Thus degradation is not seen as a localised phenomena but is defined on the basis of the variability in the landscape surrounding it. This results in a realistic estimate of the amount of healthy vegetation present in an area and does not allow isolated pockets of seemingly healthy vegetation to contribute to over-estimates.
- Where this technique is used to monitor large areas of land and where cost is a factor the use of only one band of data will reduce the cost of this type of endeavour substantially.

The disadvantages of using the MSDI to monitor degradation relate primarily to the effective resolution of the index and are listed below.

- The accuracy of point data collected on the ground when related to this index is diminished.
- An entity exhibiting different spectral properties to those surrounding it will only be classed as good condition if its areal extent is greater than 90m x 90m.
- Rangeland within 30m of a disturbance cannot be classed as good condition using the MSDI.
- The MSDI results in increased values when a vegetation, soil, land-use boundary is encountered. This effectively means that the accuracy of the index is diminished on the boundaries of landscape units.

## 6.4 A Visual Comparison

The purpose of the following section is to describe the results of the comparison between a degraded communal area and a good condition nature reserve (compared in section 5.4). The differences in vegetation, vegetation production (NDVI), spatial heterogeneity (MSDI) and the cross-classification of NDVI and MSDI will be described.

The nature reserve (Figure 5.24 and Plate 12) is dominated by high NDVI values. The lower NDVI values occur only on the steeper slopes and the lower right of the image (Plate 12) (where the image borders a communal area). The substantially lower NDVI values of the communal rangeland (Figure 5.24 and Plate 12) occur as a result of severe degradation that has robbed the landscape of the majority of its vegetation cover (whether it is natural vegetation or alien shrubs).

The lower MSDI values in the nature reserve are clearly depicted (Figure 5.24 and Plate 12). This is due to the low landscape variability that is observed in undisturbed/well managed areas. Higher MSDI values are associated with steep slopes (particularly in the top left of the image - Plate 12), riparian zones and disturbances such as the Peddie-Alice gravel road in the top of the image (Plate 12). The communal area by contrast is associated with high MSDI values due to the high variability that exists in a degraded landscape.

The dominant vegetation (Figure 5.25 and Plate 13) in the nature reserve is shown to be *forests* and *Open shrubland* (82%). The communal area by contrast is dominated by *Dwarf shrubland* and *Sparse dwarf shrubland* (75%) (such as Feature 'A'). These areas can be said to have become desertified as their ability to support vegetation is almost non-existent. The *Grassland* patches (such as Feature 'B') in the communal area represent remnant patches of large *Grassland* areas and are typically found outside homesteads where cattle are prevented from grazing. A portion of good condition *Grassland* (Mount Somerset) is included on the periphery of the image for comparison purposes (Feature 'C').

The cross-classification (NDVI:MSDI) (Figure 5.25 and Plate 13) shows the nature reserve to be dominated by high NDVI: low MSDI values (81%). The steep slopes (such as Feature 'A'), the riparian zones, the degraded communal area (extreme bottom right of the image - Feature 'C') and the Alice-Peddie road (Feature 'B') are the only exceptions. The communal area is dominated by low NDVI: high MSDI values (27%) although moderate and high NDVI coupled with high MSDI are also prominent (Figure 5.24 and Plate 13). The *Dwarf shrublands* (for example Feature 'A') are all characterised by low NDVI: high MSDI values. The areas exhibiting high NDVI:low MSDI in the communal area are patches of remnant *Grasslands* (for example Feature 'B') as well as the Mount Somerset *Grassland* (Feature 'C').

## 6.5 Summary

The results of the multi-temporal classification (including a description of the principal components), the final vegetation classification, the production index (MSAVI) and the variability index (MSDI) have been discussed. The classification of the vegetation was performed using an unsupervised approach, a supervised approach and a cross-classification on the basis of MSDI. The overall Kappa index of agreement (between field classes and satellite-derived classes) was 84%. The vegetation communities showed a strong relationship to land-use with the communal areas characterised by disturbed vegetation types.

The MSAVI relationship to condition was found to be significant in the high rainfall regions of the study area but not in the semi-arid areas. The relationship to biomass was similarly found to be significantly positive in the higher rainfall parts of the study area where the vegetation consisted dominantly of shrubs/trees. There was no obvious relationship in the semi-arid areas and *Grassland* exhibited a strong negative relationship. The ranked average rainfall values of each vegetation community demonstrated a good relationship to rainfall. The limitations of vegetation indices in predicting condition are then presented.

The MSDI/condition relationship was found to be highly significant. All fence-line contrasts interrogated for differences in MSDI were significant at the 99% confidence level. Significant differences were detected across a wide range of varying climatic gradients. The MSDI was not affected by differences in vegetation composition or structure. Significant negative correlations between MSDI and NDVI were observed and were most marked in the higher rainfall areas. This resulted in the performing of a cross-classification between low, moderate and high NDVI and MSDI values to produce nine classes. The resulting classes included invasive/competitive vegetation and good condition semi-arid vegetation. The MSDI was then applied to four other markedly different ecosystems. Significant correlations between MSDI/NDVI were observed in all ecosystems (although the direction of correlation differed) and significant differences obtained for all fence-line contrast sites in the southern Kalahari. The relative advantages and disadvantages of using the MSDI were presented.

The last section of the chapter discussed the results of the comparison between the communal area and nature reserve. Significant differences in vegetation, NDVI and MSDI were detected.

# CHAPTER 7

# CONCLUSIONS

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"*The relationship between landscape pattern and disturbance regimes must be studied further, particularly in light of potential climatic change.*" (Turner, 1989, pp. 183)

The primary objective of this study was to answer the question whether or not an index of landscape heterogeneity could be developed and related to landscape condition using satellite - derived data. This would enable several theories of landscape ecology to be tested and quantified. The other indices applied in this study were used primarily to investigate the relationships to the MSDI but also constitute significant results in their own right.

The objectives that were set-up to apply an index of variability and map the prevailing characteristics of the Mid Fish River Valley are outlined in chapter 1. All of these objectives have been met within the limits of this study. The principle objectives were:-

- to identify, describe and quantify vegetation communities as well as conduct a preliminary investigation into their relationship to environmental factors as well as land-use.
- to quantify and map the amount of vegetation production taking place in the area and relate it to vegetation condition, biomass and rainfall.
- to develop an index of landscape pattern (using the relationship of pixels to their neighbours) which related to landscape condition and overcame a number of the disadvantages associated with the use of vegetation indices. The indices robustness was to be tested by investigating the relationship of the index to rangeland condition, vegetation type and vegetation production. The repeatability of the index was also to be assessed by investigating the operation of the index in four other ecosystems.

During the study, as a consequence of the techniques employed to map the prevailing conditions in the study area, it became evident that spectral properties alone were not enough to complete the vegetation classification. This was therefore accomplished by cross-classifying certain classes with MSDI to produce the final result.

## 7.1 The Vegetation Classification

The final vegetation classification of nine classes was achieved using an unsupervised classification, a supervised classification and a textural discrimination using the Moving Standard Deviation Index (MSDI). The results of the final vegetation classification (84% accuracy) in this study have to some extent confirmed current findings (O'NeiH, 1989; Tueller, 1989) who propose that in heterogeneous areas of high variability an unsupervised classification is more accurate than a supervised approach but a combination of both produces the best results. However, spectral reflectance properties alone failed to map vegetation classes in the semi-arid succulent areas necessitating the use of MSDI. The need to employ some form of textural discrimination in classifying satellite imagery has been widely advocated (Baker and Cai, 1992; Rosenfeld, 1980; Sali and Wolfson, 1992; Shin and Schowengerdt, 1983; Wang, 1983). Although Richards (1984) found that dry season imagery in the Sahel improved spectral discrimination, the dry season data used in this study contained little significant information and did not contribute in any way to the final result.

The structural approach (Edwards, 1983) ensured that vegetation was relatively simple to classify in the field and satellite discrimination improved. This is in contrast to the lack of success when attempting to map floristic vegetation communities (Palmer, 1990; Sellers, 1987). Overall accuracy of the point data was also improved by taking stringent measures in the field to ensure that spatial errors were minimised. These included the use of averaged GPS readings (Ardö and Pilesjö, 1992; Koh and Edwards, 1996) and the surveying of large areas of similar vegetation. This ensured that a one pixel error in any direction was allowed for.

Disturbed vegetation types constituted 49% of the study area with differences in vegetation type directly attributable to land-use. Communal areas were dominated by disturbed vegetation types (dominantly *Dwarf shrublands*) and nature reserves/commercial rangeland associated with undisturbed vegetation types. The results are consistent with other studies (Evans et al., 1996; Palmer and Avis, 1994; Palmer *et al.*, 1988).

## 7.2 Vegetation Production

The Modified Soil Adjusted Vegetation Index (MSAVI) had a good relationship to vegetation condition in the higher rainfall, higher cover areas but could not reliably detect differences in condition in semi-arid areas; thereby illustrating that the vegetation indices cannot be reliably used to detect differences in condition. The result was consistent with the findings of Ray (1995) who concluded that contemporary vegetation indices using contemporary imagery are not of sufficient spectral resolution to capture the vegetation characteristics of semi-arid/arid vegetation. Mackay and Zietsman (1996) however used vegetation indices to successfully detect differences in rangeland condition in the semi-arid Ceres region of South Africa.

The MSAVI demonstrated a significant relationship to rainfall which was in accordance with the results of other studies (Choudhury and Tucker, 1987; Malo and Nicholson, 1990; Rogers and Randolf, 1991; Tucker and Dregne, 1990). No overall relationship between MSAVI and biomass was found to exist. This was consistent with the findings of some studies in semi-arid rangelands (Anderson and Hanson, 1992; Anderson *et al.*, 1993; Ray, 1995; Waller *et al.*, 1981) however, inconsistent with others (Bedard and Lapointe, 1987; Deering and Haas, 1980; Hardisky *et al.*, 1984). The stratification of MSAVI (on the basis of vegetation type) and the relationship to biomass revealed good positive correlations to biomass in the high rainfall areas where a high cover of woody vegetation existed. However, other vegetation types demonstrated little or no positive correlation whilst *Grassland* demonstrated a significant negative correlation.

## 7.3 Landscape Heterogeneity

The MSDI proved to be a very powerful and sensitive indicator of landscape condition in all areas irrespective of moisture availability or vegetation type. The result confirmed the hypotheses of several authors (Miles and Johnson, 1990; Pickup, 1985; Schlesinger *et al.*, 1990; Tongway, 1990) who suggest that any process that leads to an increasing heterogeneity of soil resources in space and time is likely to lead to the degradation of a landscape. Fabricius *et al.* (1995) hypothesised that increase in coefficient of variation (essentially a dimensionless form of standard deviation)of satellite data indicated an increase in vegetation structure and biodiversty and therefore health. This research finds this hypothesis to be incorrect. Rather the degraded areas and highly populated areas tend to be characterised by high MSDI values (therefore high coefficient of variation), whereas good condition areas such as nature reserves and commercial agricultural areas have low MSDI values. The MSDI - degradation relationship is only applicable in rangeland of areal extent exceeding 90m x 90m and does not extend to urban areas and small heterogeneous fields of commercial agriculture. The results of the MSDI indicate that 62% of the study area is degraded to some degree with communal areas constituting the bulk of that figure.

An interesting aspect of the research has been the relationship of MSDI to the Normalised Difference Vegetation Index (NDVI). The relationship was strongly negative and significant at the 99% confidence level. The strength of the relationship increased as moisture availability (and the ability of vegetation indices to predict rangeland condition) increased. The cross-classification of NDVI:MSDI produced nine classes including highly photosynthesising invasive vegetation and good condition semi-arid vegetation.

Significant differences in MSDI were detected across condition boundaries in the southern Kalahari Desert (which exhibits markedly different vegetation dynamics to that of the Fish River Valley) illustrating the diverse conditions under which the image can operate. The relationship of the MSDI to NDVI in four other ecosystems revealed that all correlations were significant (99% confidence level) but the direction of the correlation differed. Negative correlations reflect areas where increase in NDVI is indicative of a favourable scenario on the ground (such as the Fish River Valley). Positive correlations reflect areas where increase in NDVI is disturbance-induced (such as the Mpumalanga data). Palmer *et al.* (1997) suggest that the direction of correlation is dependent on soil depth, with the positive correlation occurring in the deeper (>1m) soils of Mpumalanga and the Kalahari. The landscape dynamics responsible for these differences are not clearly understood and deserve further investigation.

Automated procedures for calculating moving standard deviation do exist such as the r.le programs in the GRASS Geographic Information System (Baker and Cai, 1992). However there is a dearth of literature in interpreting this index and relating it to landscape condition. Textural indices such as standard deviation have not been used as an overall determinant of vegetation condition as far as the author is aware except by Fabricius *et al.* (1995).

Emmanuel *et al.* (1985) predict a 17% increase in the world area of desert during the climatic changes expected with a doubling of atmospheric $C0_2$ and population pressures. Any directional shift to a greater area of arid land potentially represents a permanent loss in the productive capacity of the biosphere on which all life depends. The MSDI constitutes a potent tool that can used in the global battle against desertification in the monitoring and quantification of this phenomenon. I would therefore like to propose that the MSDI be used in any satellite analysis of degradation as an index of the magnitude of the desertification process and as a powerful adjunct to contemporary satellite-derived indices.

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# APPENDICES

# APPENDIX 1
## Surface Reference Data

| Site Num | latitude | longitude | Veg Type | Geology | Land Use | Cover %Shrubs | %Grass | %Bare | Edwards Number | height/m | aspect° | Altitude MASL | slope° | Erosion | Soils |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 26.61555 | -32.9093 | 7 | SS | 0 | 75 | 0 | 25 | 12 | 0.2 | -1 | 448 | 3 | mod | Sl |
| 2 | 26.62086 | -32.9288 | 4 | SS | 2 | 40 | 60 | 0 | 5 | 1 | 98 | 431 | 10 | none | Sl |
| 3 | 26.62250 | -32.9206 | 7 | SS | 0 | 75 | 0 | 25 | 12 | 0.2 | 114 | 181 | 9 | mod | Sl |
| 4 | 26.62822 | -32.9158 | 7 | SS | 0 | 60 | 5 | 35 | 12 | 0.2 | -1 | 117 | 1 | Sev | Sl |
| 5 | 26.62904 | -32.9076 | 7 | SS | 2 | 75 | 0 | 25 | 12 | 0.2 | 127 | 441 | 6 | mod | Sl |
| 6 | 26.63395 | -32.9336 | 7 | SS | 1 | 60 | 5 | 35 | 12 | 0.2 | 253 | 349 | 20 | Sev | Sl |
| 7 | 26.63763 | -32.9113 | 9 | MS | 1 | 50 | 5 | 45 | 14 | 0.2 | 278 | 502 | 5 | Sev | Cl |
| 8 | 26.63967 | -32.9086 | 9 | SS | 1 | 50 | 5 | 45 | 14 | 0.2 | 180 | 400 | 10 | Sev | Sl |
| 9 | 26.66175 | -32.9093 | 9 | SS | 2 | 50 | 5 | 45 | 14 | 0.2 | 109 | 210 | 7 | Sev | Sl |
| 10 | 26.71776 | -32.9141 | 8 | SS | 2 | 50 | 5 | 45 | 13 | 0.2 | -1 | 348 | 3 | Sev | Sl |
| 11 | 26.72185 | -32.913 | 9 | SS | 2 | 15 | 5 | 80 | 14 | 0.2 | 85 | 330 | 8 | Sev | Sl |
| 12 | 26.73575 | -33.2234 | 4 | Shale | 0 | 50 | 40 | 10 | 5 | 1 | -1 | 198 | 4 | none | Sh |
| 13 | 26.73902 | -33.0956 | 3 | SS | 2 | 30 | 70 | 0 | 7 | 1.5 | -1 | 382 | 1 | none | Sl |
| 14 | 26.74393 | -33.2268 | 4 | Shale | 1 | 60 | 30 | 10 | 5 | 1 | -1 | 429 | 2 | Mod | Sh |
| 15 | 26.75047 | -32.9158 | 9 | SS | 2 | 15 | 5 | 80 | 14 | 0.2 | 104 | 443 | 12 | Sev | Sl |
| 16 | 26.75211 | -33.2142 | 5 | Shale | 0 | 40 | 0 | 60 | 8 | 1 | -1 | 470 | 3 | Mod | Sh |
| 17 | 26.75579 | -33.085 | 2 | SS | 2 | 45 | 70 | 0 | 3 | 3 | 250 | 391 | 10 | none | Sl |
| 18 | 26.75906 | -33.0877 | 2 | SS | 2 | 75 | 35 | 0 | 2 | 4 | 270 | 435 | 11 | none | Sl |
| 19 | 26.75947 | -32.9093 | 8 | SS | 0 | 58 | 5 | 37 | 13 | 0.2 | -1 | 411 | 3 | Sev | Sl |
| 20 | 26.76110 | -33.1946 | 5 | Shale | 0 | 40 | 30 | 30 | 7 | 0.5 | -1 | 559 | 4 | none | Sh |
| 21 | 26.76151 | -32.9062 | 9 | SS | 0 | 5 | 5 | 90 | 14 | 0.2 | 270 | 145 | 5 | Sev | Sl |
| 22 | 26.76315 | -33.0785 | 1 | MS | 2 | 60 | 60 | 0 | 2 | 5 | 221 | 470 | 17 | none | Cl |
| 23 | 26.76928 | -33.2166 | 5 | Shale | 1 | 30 | 20 | 50 | 7 | 1 | 127 | 231 | 6 | none | Sh |
| 24 | 26.77091 | -33.0847 | 3 | SS | 0 | 60 | 40 | 0 | 7 | 2 | 275 | 198 | 8 | none | Sl |
| 25 | 26.77132 | -33.098 | 2 | SS | 1 | 75 | 45 | 0 | 2 | 4 | -1 | 157 | 2 | none | Sl |
| 26 | 26.77255 | -33.1878 | 4 | Shale | 1 | 45 | 35 | 20 | 5 | 1 | 51 | 280 | 10 | none | Sh |
| 27 | 26.77255 | -32.9141 | 9 | SS | 0 | 15 | 5 | 80 | 14 | 0.2 | -1 | 117 | 1 | Sev | Sl |
| 28 | 26.77500 | -33.1943 | 5 | Shale | 2 | 35 | 35 | 30 | 7 | 1 | -1 | 437 | 4 | Mod | Sh |
| 29 | 26.77623 | -33.2234 | 5 | Shale | 0 | 40 | 0 | 10 | 7 | 0.5 | -1 | 139 | 0 | Mod | Sh |
| 30 | 26.77827 | -33.1902 | 5 | Shale | 0 | 40 | 40 | 20 | 7 | 1 | 290 | 492 | 9 | none | Sh |
| 31 | 26.77827 | -33.0778 | 2 | SS | 0 | 40 | 70 | 0 | 3 | 3 | -1 | 122 | 3 | none | Sl |
| 32 | 26.77950 | -33.083 | 2 | SS | 1 | 60 | 40 | 0 | 3 | 3 | 312 | 235 | 7 | none | Sl |
| 33 | 26.78032 | -33.0929 | 2 | SS | 1 | 60 | 50 | 0 | 3 | 3 | 180 | 210 | 7 | none | Sl |
| 34 | 26.78236 | -33.0802 | 3 | SS | 1 | 50 | 50 | 0 | 7 | 2 | -1 | 205 | 2 | none | Sl |
| 35 | 26.78236 | -33.0723 | 2 | SS | 1 | 60 | 40 | 0 | 3 | 3 | 98 | 227 | 10 | none | Sl |
| 36 | 26.78563 | -33.2313 | 4 | Shale | 1 | 60 | 10 | 30 | 5 | 1 | 246 | 231 | 16 | none | Sh |
| 37 | 26.78604 | -32.9117 | 9 | SS | 0 | 50 | 5 | 45 | 14 | 0.2 | 73 | 223 | 20 | Sev | Sl |
| 38 | 26.78890 | -33.0963 | 1 | SS | 2 | 60 | 50 | 0 | 1 | 5 | 114 | 439 | 24 | none | Sl |
| 39 | 26.78890 | -33.1792 | 5 | Shale | 1 | 58 | 2 | 40 | 7 | 1 | -1 | 283 | 1 | Mod | Sh |

| Site Num | latitude | longitude | Veg Type | Geology | Land Use | Cover %Shrubs | %Grass | %Bare | Edwards Number | height/m | aspect° | Altitude MASL | slope° | Erosion | Soils |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 40 | 26.78972 | -33.0703 | 6 | MS | 0 | 20 | 70 | 10 | 10 | 0.3 | 70 | 479 | 9 | none | Cl |
| 41 | 26.79258 | -33.2234 | 2 | Shale | 1 | 58 | 42 | 0 | 3 | 3 | 132 | 220 | 11 | none | Sh |
| 42 | 26.79340 | -33.0562 | 2 | SS | 0 | 40 | 60 | 0 | 3 | 3 | 172 | 171 | 11 | none | Sl |
| 43 | 26.79504 | -33.0627 | 3 | SS | 1 | 30 | 70 | 0 | 7 | 1.5 | 270 | 321 | 7 | none | Sl |
| 44 | 26.79667 | -33.1758 | 4 | Shale | 1 | 40 | 60 | 0 | 5 | 1 | 138 | 223 | 19 | none | Sh |
| 45 | 26.80199 | -32.9117 | 9 | SS | 0 | 15 | 5 | 80 | 14 | 0.2 | -1 | 123 | 3 | Sev | Sl |
| 46 | 26.80240 | -33.1806 | 4 | Shale | 2 | 45 | 55 | 0 | 5 | 1 | -1 | 450 | 4 | Mod | Sh |
| 47 | 26.80240 | -33.0381 | 2 | SS | 0 | 40 | 70 | 0 | 3 | 3 | -1 | 109 | 2 | none | Sl |
| 48 | 26.80240 | -33.0511 | 3 | SS | 1 | 40 | 60 | 0 | 7 | 2 | -1 | 279 | 1 | none | Sl |
| 49 | 26.80280 | -32.913 | 9 | SS | 1 | 50 | 5 | 45 | 14 | 0.2 | 180 | 202 | 5 | Sev | Sl |
| 50 | 26.80894 | -33.0251 | 2 | SS | 0 | 60 | 60 | 0 | 3 | 3 | 84 | 437 | 15 | none | Sl |
| 51 | 26.81262 | -33.2344 | 4 | Shale | 1 | 60 | 40 | 0 | 5 | 1 | 268 | 269 | 19 | none | Sh |
| 52 | 26.81589 | -32.9726 | 6 | SS | 0 | 10 | 85 | 5 | 9 | 0.2 | -1 | 189 | 4 | none | Sl |
| 53 | 26.81957 | -32.9815 | 6 | MS | 1 | 0 | 100 | 0 | 9 | 0.2 | 78 | 514 | 18 | none | Cl |
| 54 | 26.82284 | -32.9589 | 6 | MS | 1 | 0 | 100 | 0 | 9 | 0.1 | 124 | 528 | 8 | none | Cl |
| 55 | 26.82529 | -32.9802 | 3 | MS | 1 | 15 | 85 | 0 | 8 | 1 | 80 | 499 | 21 | none | Cl |
| 56 | 26.82815 | -33.0155 | 2 | MS | 1 | 60 | 40 | 0 | 3 | 3 | -1 | 506 | 1 | none | Cl |
| 57 | 26.83020 | -33.0559 | 2 | SS | 1 | 60 | 50 | 0 | 3 | 3 | 288 | 340 | 18 | none | Sl |
| 58 | 26.83061 | -32.9469 | 6 | SS | 1 | 0 | 100 | 0 | 9 | 0.3 | 270 | 207 | 40 | mod | Sl |
| 59 | 26.83183 | -33.0463 | 2 | MS | 0 | 58 | 42 | 0 | 3 | 3 | -1 | 518 | 3 | none | Cl |
| 60 | 26.83306 | -33.1799 | 5 | Shale | 0 | 40 | 20 | 40 | 8 | 0.5 | 259 | 521 | 12 | Mod | Sh |
| 61 | 26.83388 | -32.9394 | 6 | SS | 0 | 30 | 60 | 10 | 10 | 0.2 | -1 | 85 | 0 | none | Sl |
| 62 | 26.83429 | -33.1758 | 5 | Shale | 0 | 50 | 0 | 40 | 7 | 1 | -1 | 500 | 1 | Mod | Sh |
| 63 | 26.83551 | -33.0624 | 2 | SS | 0 | 40 | 70 | 0 | 3 | 3 | -1 | 84 | 0 | none | Sl |
| 64 | 26.83633 | -32.9994 | 2 | SS | 1 | 60 | 40 | 0 | 3 | 3 | 256 | 240 | 28 | none | Sl |
| 65 | 26.84246 | -33.0422 | 3 | SS | 1 | 30 | 70 | 0 | 7 | 1.5 | 228 | 409 | 15 | none | Sl |
| 66 | 26.84287 | -32.9171 | 3 | SS | 1 | 10 | 85 | 5 | 8 | 1 | 82 | 304 | 33 | none | Sl |
| 67 | 26.84328 | -33.1614 | 8 | Shale | 0 | 60 | 5 | 35 | 13 | 0.2 | -1 | 543 | 1 | Sev | Sh |
| 68 | 26.84451 | -33.0528 | 3 | SS | 2 | 40 | 60 | 0 | 7 | 2 | -1 | 105 | 3 | none | Sl |
| 69 | 26.84901 | -32.9884 | 6 | SS | 1 | 0 | 100 | 0 | 9 | 0.2 | 85 | 286 | 38 | mod | Sl |
| 70 | 26.84941 | -33.1987 | 8 | Shale | 0 | 50 | 5 | 45 | 13 | 0.2 | 70 | 463 | 10 | Sev | Sh |
| 71 | 26.85473 | -33.0473 | 3 | SS | 2 | 40 | 60 | 0 | 7 | 2 | 270 | 80 | 5 | none | Sl |
| 72 | 26.85473 | -33.1991 | 8 | Shale | 1 | 58 | 5 | 37 | 13 | 0.2 | -1 | 155 | 4 | Sev | Sh |
| 73 | 26.85800 | -33.0114 | 2 | SS | 2 | 40 | 60 | 0 | 3 | 3 | -1 | 97 | 1 | none | Sl |
| 74 | 26.85923 | -33.1484 | 3 | Shale | 1 | 15 | 85 | 0 | 8 | 1.5 | -1 | 367 | 2 | none | Sh |
| 75 | 26.86045 | -33.0021 | 2 | SS | 2 | 75 | 25 | 0 | 2 | 4 | 278 | 118 | 5 | none | Sl |
| 76 | 26.86250 | -33.2001 | 8 | Shale | 1 | 45 | 5 | 50 | 13 | 0.2 | 217 | 445 | 5 | Sev | Sh |
| 77 | 26.86413 | -33.1384 | 9 | Shale | 2 | 15 | 5 | 80 | 14 | 0.2 | 180 | 92 | 5 | Sev | Nil |
| 78 | 26.86454 | -33.158 | 9 | Shale | 2 | 5 | 5 | 90 | 14 | 0.2 | 239 | 175 | 6 | Sev | Nil |

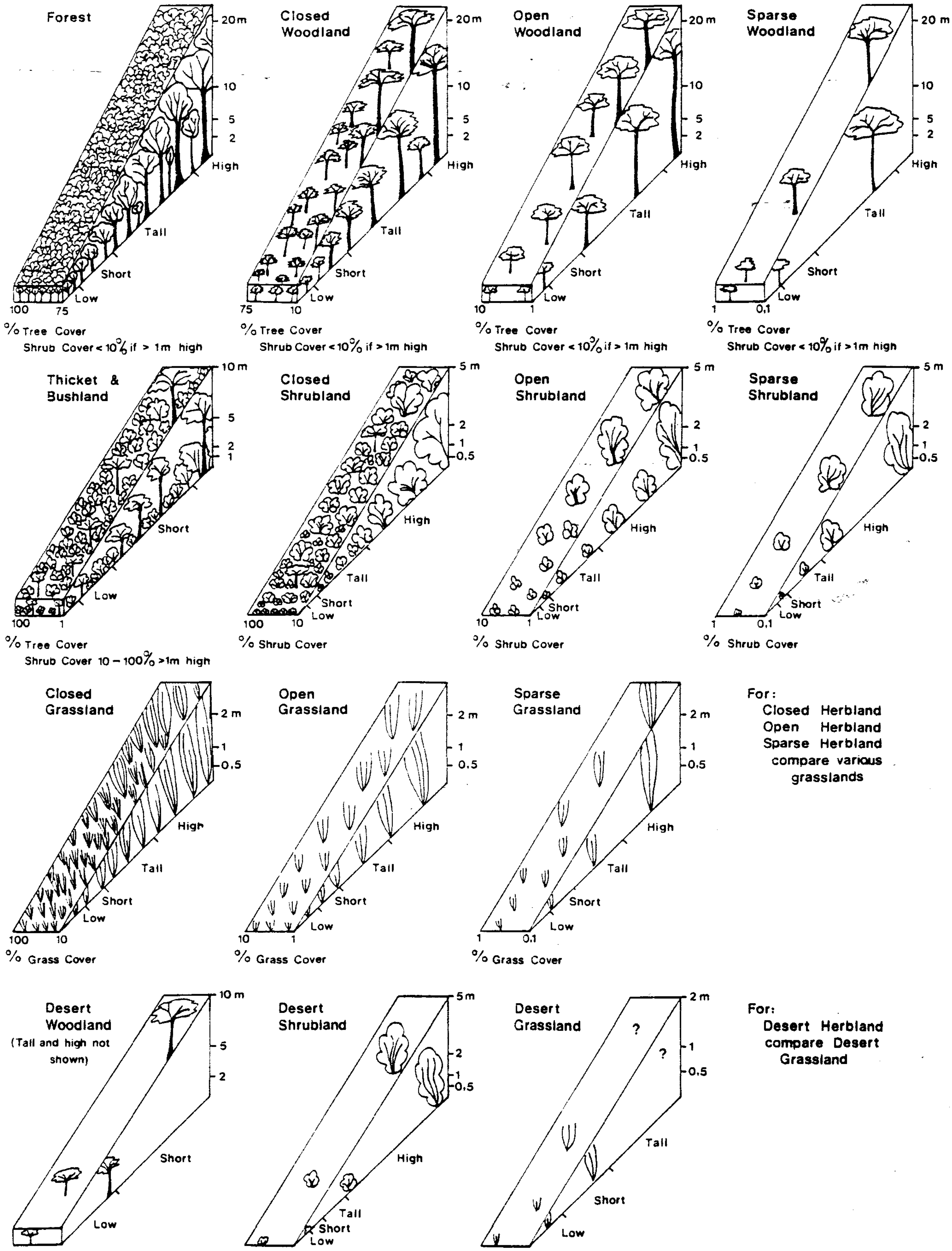
| Site Num | latitude | longitude | Veg Type | Geology | Land Use | Cover %Shrubs | %Grass | %Bare | Edwards Number | height/m | aspect° | Altitude MASL | slope° | Erosion | Soils |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 79 | 26.86904 | -33.0141 | 2 | SS | 2 | 40 | 70 | 0 | 3 | 3 | -1 | 149 | 2 | none | Sl |
| 80 | 26.87149 | -32.9404 | 6 | SS | 0 | 15 | 75 | 10 | 10 | 0.5 | -1 | 439 | 2 | none | Sl |
| 81 | 26.87149 | -32.9994 | 7 | MS | 0 | 100 | 0 | 0 | 12 | 0.2 | 86 | 498 | 11 | mod | Cl |
| 82 | 26.87313 | -33.1905 | 9 | Shale | 1 | 15 | 5 | 80 | 14 | 0.2 | 96 | 408 | 15 | Sev | Nil |
| 83 | 26.87354 | -33.1844 | 9 | Shale | 2 | 15 | 5 | 80 | 14 | 0.2 | 128 | 68 | 8 | Sev | Nil |
| 84 | 26.87436 | -33.1607 | 9 | Shale | 2 | 5 | 5 | 90 | 14 | 0.2 | 103 | 61 | 7 | Sev | Nil |
| 85 | 26.87476 | -33.1785 | 9 | Shale | 2 | 13 | 5 | 82 | 14 | 0.2 | -1 | 152 | 3 | Sev | Nil |
| 86 | 26.87763 | -33.1354 | 8 | Shale | 2 | 10 | 5 | 85 | 13 | 0.2 | 103 | 60 | 7 | Sev | Sh |
| 87 | 26.87844 | -33.1419 | 8 | Shale | 2 | 33 | 5 | 62 | 13 | 0.2 | -1 | 199 | 0 | Sev | Sh |
| 88 | 26.87926 | -33.1515 | 8 | Shale | 2 | 50 | 5 | 45 | 13 | 0.2 | 90 | 186 | 5 | Sev | Sh |
| 89 | 26.88335 | -33.135 | 7 | Shale | 2 | 60 | 5 | 35 | 12 | 0.2 | 105 | 182 | 8 | Sev | Sh |
| 90 | 26.88417 | -32.9634 | 7 | MS | 0 | 60 | 5 | 35 | 12 | 0.2 | 77 | 468 | 10 | Sev | Cl |
| 91 | 26.88621 | -33.084 | 2 | SS | 1 | 60 | 50 | 0 | 3 | 3 | -1 | 423 | 1 | none | Sl |
| 92 | 26.88907 | -33.0237 | 2 | SS | 1 | 60 | 40 | 0 | 3 | 3 | 257 | 286 | 32 | none | Sl |
| 93 | 26.89398 | -33.1306 | 2 | Shale | 1 | 75 | 35 | 0 | 2 | 4 | 239 | 390 | 6 | none | Sh |
| 94 | 26.89562 | -33.1758 | 8 | Shale | 2 | 43 | 5 | 52 | 13 | 0.2 | 257 | 280 | 27 | Sev | Sh |
| 95 | 26.89643 | -33.0257 | 7 | SS | 2 | 60 | 5 | 35 | 12 | 0.2 | 287 | 56 | 5 | Sev | Sl |
| 96 | 26.90011 | -33.0302 | 7 | MS | 1 | 85 | 0 | 15 | 12 | 0.2 | 264 | 464 | 19 | mod | Cl |
| 97 | 26.90339 | -33.1319 | 3 | Shale | 1 | 30 | 70 | 0 | 7 | 1.5 | 257 | 430 | 7 | none | Sh |
| 98 | 26.90420 | -33.1809 | 8 | Shale | 2 | 58 | 5 | 37 | 13 | 0.2 | 106 | 230 | 37 | Sev | Sh |
| 99 | 26.90420 | -33.1943 | 9 | Shale | 2 | 5 | 5 | 90 | 14 | 0.2 | 90 | 64 | 5 | Sev | Nil |
| 99 | 26.90584 | -33.0747 | 1 | SS | 2 | 60 | 60 | 0 | 2 | 3 | 256 | 95 | 12 | none | Sl |
| 100 | 26.90584 | -33.1981 | 9 | Shale | 1 | 15 | 5 | 80 | 14 | 0.2 | 284 | 455 | 15 | Sev | Nil |
| 101 | 26.90706 | -33.1888 | 9 | Shale | 2 | 5 | 5 | 90 | 14 | 0.2 | 266 | 63 | 11 | Sev | Nil |
| 102 | 26.90829 | -33.1802 | 9 | Shale | 2 | 5 | 5 | 90 | 14 | 0.2 | 198 | 87 | 5 | Sev | Nil |
| 103 | 26.91034 | -33.0788 | 6 | SS | 2 | 10 | 80 | 10 | 9 | 0.3 | -1 | 109 | 3 | none | Sl |
| 104 | 26.91034 | -33.0391 | 3 | MS | 1 | 15 | 85 | 0 | 8 | 1.5 | 90 | 468 | 20 | none | Cl |
| 105 | 26.91483 | -33.0648 | 7 | MS | 1 | 100 | 0 | 0 | 12 | 0.2 | 66 | 475 | 9 | mod | Cl |
| 106 | 26.91606 | -33.197 | 9 | Shale | 1 | 15 | 5 | 80 | 14 | 0.2 | 18 | 447 | 5 | Sev | Nil |
| 107 | 26.91892 | -33.1165 | 2 | SS | 2 | 40 | 60 | 0 | 3 | 3 | -1 | 80 | 4 | none | Sl |
| 108 | 26.91892 | -33.1909 | 9 | Shale | 1 | 15 | 5 | 80 | 14 | 0.2 | -1 | 389 | 4 | Sev | Nil |
| 109 | 26.92056 | -33.0497 | 3 | SS | 2 | 57 | 43 | 0 | 7 | 2 | -1 | 62 | 3 | none | Sl |
| 110 | 26.92383 | -33.122 | 4 | MS | 1 | 75 | 0 | 25 | 5 | 1 | -1 | 466 | 2 | none | Cl |
| 111 | 26.92424 | -33.0641 | 2 | SS | 2 | 50 | 70 | 0 | 3 | 3 | 256 | 340 | 15 | none | Sl |
| 112 | 26.92751 | -33.1299 | 9 | MS | 1 | 70 | 5 | 25 | 14 | 0.2 | -1 | 456 | 2 | mod | Cl |
| 113 | 26.93037 | -33.123 | 8 | SS | 2 | 60 | 5 | 35 | 13 | 0.2 | -1 | 354 | 1 | Sev | Sl |
| 114 | 26.93078 | -33.1693 | 9 | Shale | 2 | 50 | 5 | 45 | 14 | 0.2 | 236 | 345 | 8 | Sev | Nil |
| 115 | 26.93200 | -33.0871 | 2 | SS | 0 | 60 | 40 | 0 | 3 | 3 | 262 | 89 | 5 | none | Sl |
| 116 | 26.93405 | -33.0627 | 3 | SS | 1 | 15 | 85 | 0 | 8 | 1.5 | 33 | 442 | 6 | none | Sl |

| Site Num | latitude | longitude | Veg Type | Geology | Land Use | Cover %Shrubs | %Grass | %Bare | Edwards Number | height/m | aspect° | Altitude MASL | slope° | Erosion | Soils |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 117 | 26.93528 | -33.108 | 2 | MS | 1 | 75 | 35 | 0 | 2 | 4 | -1 | 492 | 2 | none | Cl |
| 118 | 26.93650 | -33.1032 | 2 | SS | 1 | 60 | 50 | 0 | 3 | 3 | -1 | 377 | 2 | none | Sl |
| 119 | 26.93732 | -33.1282 | 9 | SS | 1 | 70 | 5 | 25 | 14 | 0.2 | -1 | 409 | 2 | mod | Sl |
| 121 | 26.93773 | -33.0737 | 6 | SS | 2 | 25 | 70 | 5 | 10 | 0.2 | -1 | 339 | 4 | none | Sl |
| 122 | 26.93814 | -33.0888 | 1 | MS | 0 | 85 | 15 | 0 | 1 | 5 | 253 | 503 | 5 | none | Cl |
| 123 | 26.93855 | -33.1213 | 9 | MS | 0 | 50 | 5 | 45 | 14 | 0.2 | 289 | 465 | 7 | Sev | Cl |
| 124 | 26.93896 | -33.0497 | 7 | SS | 2 | 75 | 0 | 25 | 12 | 0.2 | -1 | 364 | 4 | mod | Sl |
| 125 | 26.93936 | -33.1155 | 8 | SS | 1 | 45 | 5 | 50 | 13 | 0.2 | 307 | 434 | 6 | Sev | Sl |
| 126 | 26.93977 | -33.1686 | 9 | Shale | 2 | 5 | 5 | 90 | 14 | 0.2 | 114 | 358 | 7 | Sev | Nil |
| 127 | 26.94018 | -33.0758 | 6 | SS | 0 | 25 | 60 | 15 | 10 | 0.2 | 42 | 88 | 5 | none | Sl |
| 128 | 26.94386 | -33.1306 | 9 | Shale | 0 | 50 | 5 | 45 | 14 | 0.2 | 251 | 504 | 7 | Sev | Nil |
| 129 | 26.94468 | -33.1004 | 3 | SS | 2 | 50 | 50 | 0 | 7 | 2 | -1 | 358 | 2 | none | Sl |
| 130 | 26.94672 | -33.0768 | 3 | SS | 1 | 15 | 85 | 0 | 8 | 1.5 | 51 | 309 | 10 | none | Sl |
| 131 | 26.94672 | -33.071 | 7 | MS | 0 | 100 | 0 | 0 | 12 | 0.2 | -1 | 511 | 3 | mod | Cl |
| 132 | 26.94672 | -33.1676 | 9 | Shale | 1 | 50 | 5 | 45 | 14 | 0.2 | -1 | 505 | 3 | Sev | Nil |
| 133 | 26.94672 | -33.1244 | 9 | SS | 0 | 50 | 5 | 45 | 14 | 0.2 | 59 | 61 | 6 | Sev | Sl |
| 134 | 26.94836 | -33.0884 | 3 | SS | 2 | 30 | 70 | 0 | 7 | 1.5 | 180 | 309 | 5 | none | Sl |
| 135 | 26.95040 | -33.086 | 6 | MS | 0 | 0 | 100 | 0 | 9 | 0.2 | 280 | 519 | 8 | none | Cl |
| 136 | 26.95245 | -33.0871 | 6 | MS | 0 | 0 | 100 | 0 | 9 | 0.1 | -1 | 516 | 1 | none | Cl |
| 137 | 26.95735 | -33.06 | 4 | MS | 0 | 75 | 25 | 0 | 5 | 1 | -1 | 518 | 3 | none | Cl |
| 138 | 26.95817 | -33.0336 | 2 | SS | 1 | 60 | 40 | 0 | 3 | 3 | -1 | 432 | 4 | none | Sl |
| 139 | 26.95981 | -33.0545 | 7 | SS | 1 | 85 | 0 | 15 | 12 | 0.2 | 259 | 370 | 19 | mod | Sl |
| 140 | 26.96144 | -33.0816 | 1 | SS | 0 | 60 | 60 | 0 | 2 | 5 | 0 | 227 | 9 | none | Sl |
| 141 | 26.96308 | -33.0946 | 9 | MS | 0 | 50 | 5 | 45 | 14 | 0.2 | 66 | 462 | 5 | Sev | Cl |
| 142 | 26.96512 | -33.0857 | 8 | MS | 2 | 15 | 5 | 80 | 13 | 0.2 | 106 | 478 | 13 | Sev | Cl |
| 143 | 26.96553 | -33.0422 | 9 | MS | 2 | 15 | 5 | 80 | 14 | 0.2 | -1 | 501 | 0 | Sev | Cl |
| 144 | 26.96758 | -33.0963 | 9 | SS | 1 | 50 | 5 | 45 | 14 | 0.2 | -1 | 424 | 1 | Sev | Sl |
| 145 | 26.96798 | -33.049 | 7 | SS | 2 | 75 | 0 | 25 | 12 | 0.2 | 87 | 441 | 16 | mod | Sl |
| 146 | 26.97166 | -33.0854 | 9 | SS | 1 | 50 | 5 | 45 | 14 | 0.2 | -1 | 441 | 3 | Sev | Sl |
| 147 | 26.97166 | -33.0901 | 8 | MS | 2 | 33 | 5 | 62 | 13 | 0.2 | -1 | 475 | 4 | Sev | Cl |
| 148 | 26.97493 | -33.0963 | 9 | SS | 2 | 15 | 5 | 80 | 14 | 0.2 | 129 | 421 | 10 | Sev | Sl |
| 149 | 26.97902 | -33.086 | 9 | SS | 2 | 15 | 5 | 80 | 14 | 0.2 | 128 | 378 | 8 | Sev | Sl |
| 150 | 26.98597 | -33.0799 | 7 | SS | 2 | 85 | 0 | 15 | 12 | 0.2 | 180 | 370 | 9 | mod | Sl |
| 151 | 26.98884 | -33.0782 | 3 | MS | 2 | 40 | 60 | 0 | 7 | 2 | 265 | 465 | 8 | none | Cl |
| 152 | 26.99252 | -33.0716 | 1 | MS | 0 | 75 | 35 | 0 | 1 | 5 | 270 | 472 | 8 | none | Cl |
| 153 | 26.99987 | -33.0788 | 7 | SS | 0 | 100 | 0 | 0 | 12 | 0.2 | 289 | 429 | 14 | mod | Sl |
| 154 | 27.00601 | -33.0867 | 9 | MS | 0 | 70 | 5 | 25 | 14 | 0.2 | -1 | 451 | 3 | mod | Cl |
| 155 | 27.01706 | -33.097 | 9 | MS | 0 | 70 | 5 | 25 | 14 | 0.2 | 93 | 457 | 14 | mod | Cl |
| 156 | 27.01950 | -33.0898 | 7 | MS | 2 | 85 | 0 | 15 | 12 | 0.2 | -1 | 463 | 1 | mod | Cl |

| Site Num | latitude | longitude | Veg Type | Geology | Land Use | Cover %Shrubs | %Grass | %Bare | Edwards Number | height/m | aspect° | Altitude MASL | slope° | Erosion | Soils |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 157 | 27.02481 | -33.1038 | 8 | SS | 0 | 50 | 5 | 45 | 13 | 0.2 | 318 | 436 | 5 | Sev | Sl |
| 158 | 27.02972 | -33.0912 | 7 | SS | 2 | 75 | 0 | 25 | 12 | 0.2 | 100 | 428 | 8 | mod | Sl |
| 159 | 27.03953 | -33.0963 | 9 | SS | 0 | 70 | 5 | 25 | 14 | 0.2 | 270 | 428 | 5 | mod | Sl |
| 160 | 27.04199 | -33.1035 | 9 | SS | 0 | 15 | 5 | 80 | 14 | 0.2 | -1 | 171 | 4 | Sev | Sl |
| 161 | 27.05221 | -33.0987 | 7 | SS | 2 | 75 | 0 | 25 | 12 | 0.2 | -1 | 424 | 1 | mod | Sl |
| 162 | 27.05671 | -33.1148 | 8 | SS | 2 | 60 | 5 | 35 | 13 | 0.2 | 106 | 442 | 13 | Sev | Sl |
| 163 | 27.05712 | -33.0915 | 7 | SS | 2 | 75 | 0 | 25 | 12 | 0.2 | 278 | 333 | 5 | mod | Sl |
| 164 | 27.06284 | -33.097 | 9 | SS | 0 | 50 | 5 | 45 | 14 | 0.2 | -1 | 427 | 3 | Sev | Sl |
| 165 | 27.06611 | -33.1165 | 8 | SS | 2 | 15 | 5 | 80 | 13 | 0.2 | -1 | 426 | 2 | Sev | Sl |
| 166 | 27.06938 | -33.0977 | 9 | SS | 2 | 5 | 5 | 90 | 14 | 0.2 | -1 | 341 | 2 | Sev | Sl |
| 167 | 27.06979 | -33.1062 | 9 | SS | 2 | 70 | 5 | 25 | 14 | 0.2 | -1 | 441 | 3 | mod | Sl |
| 168 | 27.06979 | -33.1254 | 4 | SS | 2 | 50 | 40 | 10 | 5 | 1 | -1 | 431 | 1 | none | Sl |
| 169 | 27.07102 | -33.1114 | 8 | SS | 2 | 35 | 5 | 60 | 13 | 0.2 | 283 | 346 | 10 | Sev | Sl |
| 170 | 27.07224 | -33.0925 | 7 | SS | 1 | 85 | 0 | 15 | 12 | 0.2 | 52 | 226 | 8 | mod | Sl |
| 171 | 27.07592 | -33.1059 | 8 | SS | 0 | 43 | 5 | 52 | 13 | 0.2 | -1 | 428 | 1 | Sev | Sl |
| 172 | 27.08001 | -33.1052 | 9 | SS | 2 | 10 | 5 | 85 | 14 | 0.2 | -1 | 416 | 2 | Sev | Sl |
| 173 | 27.08574 | -33.1134 | 8 | SS | 2 | 60 | 5 | 35 | 13 | 0.2 | -1 | 417 | 2 | Sev | Sl |
| 174 | 27.08982 | -33.1097 | 6 | SS | 2 | 0 | 100 | 0 | 9 | 0.5 | -1 | 423 | 4 | none | Sl |
| 175 | 27.09228 | -33.1196 | 9 | SS | 0 | 50 | 5 | 45 | 14 | 0.2 | 80 | 427 | 8 | Sev | Sl |
| 176 | 27.09269 | -33.1069 | 3 | SS | 0 | 57 | 43 | 0 | 7 | 2 | -1 | 408 | 3 | none | Sl |
| 177 | 27.09269 | -33.1117 | 6 | SS | 0 | 0 | 100 | 0 | 9 | 0.2 | -1 | 410 | 2 | none | Sl |
| 178 | 27.09718 | -33.1295 | 9 | SS | 0 | 45 | 5 | 50 | 14 | 0.2 | 83 | 415 | 11 | Sev | Sl |
| 179 | 27.09964 | -33.1354 | 9 | Shale | 2 | 15 | 5 | 80 | 14 | 0.2 | -1 | 401 | 4 | Sev | Nil |
| 180 | 27.10086 | -33.0939 | 3 | SS | 1 | 40 | 60 | 0 | 7 | 2 | -1 | 237 | 4 | none | Sl |

# Appendix 2

## Edwards (1983) Structural Vegetation Classification



# APPENDIX 3

## An Adaption of Norton *et al.* (1984) method for determining Erosion Status

*Table A-1: An adaption of Norton et al. (1984) method for determining erosion status*

| Erosion Status | Description |
|---|---|
| 1 | Soil mantle intact. No evidence of soil movement |
| 2 | Moderate soil movement occurred recently; surface seal may be formed in bare areas; occasional plants on pedestals; some sediment deposits behind minor obstructions. |
| 3 | Soil erosion evidence is active and slightly advanced; Signs of soil loss due to sheeting; Some dongas in weak points of landscape; Points on pedestals; drifted soil and debris noticeable against obstructions; Drainage areas show soil deposition. |
| 4 | Severe soil erosion conditions; Topsoil loss by sheeting; exposed subsoil; Gullies active and extensive drainage channels have large deposits of soil and debris; wind forms small dunes in sandy soils. |

# APPENDIX 4

## Variables Used to Project the Satellite Data

**ref.system** : My Area
**projection** : Transverse Mercator
**datum** : Cape
**delta WGS84** : -136 -108 -292
**ellipsoid** : Clarke 1880
**major s-ax** : 6378249.145
**minor s-ax** : 6356514.869
**origin long** : 27
**origin lat** : 0
**origin X** : 500000
**origin Y** : 10000000
**scale fac** : 0.9996
**units** : m
**parameters** : 0

# APPENDIX 5

## Algorithm Used to Calculate MSAVI

```
overlay x 2 nir red 31
scalar x 31 32 3 8
delete x 31.img
delete x 31.doc

scalar x NIR 21 3 2
scalar x 21 22 1 1
scalar x 22 23 5 2
delete x 21.img
delete x 21.doc
delete x 22.img
delete x 22.doc
scalar x NIR 11 1 1
scalar x 11 12 3 2
delete x 11.img
delete x 11.doc

overlay x 2 23 32 whole1
scalar x whole1 whole2 5 0.5
overlay x 2 12 whole2 whole3
scalar x  whole3 msavi2 3 0.5

delete x 23.*
delete x 32.*
delete x whole.*
```

# APPENDIX 6

## Algorithm Used to Calculate MSDI

```
Scalar x band3 x2 5 2
Filter x x2 sx2 6 1 1 1 1 1 1 1 1 1
Delete x x2.img
Delete x x2.doc

Filter x band3 sx 6 1 1 1 1 1 1 1 1 1
Scalar x sx 2sx 5 2
Delete x sx.img
Delete x sx.doc

Scalar x 2sx 2sxdn 4 9
Delete x 2sx.img
Delete x 2sx.doc

Overlay x 2 sx2 2sxdn top
Delete x sx2.doc
Delete x sx2.img
Delete x 2sxdn.doc
Delete x 2sxdn.img

Scalar x top var 4 9
Delete x top.img
Delete x top.doc

Scalar x var sd3 5 0.5
Delete x var.doc
Delete x var.img
```

# APPENDIX 7

## Associated Eigen Values and Correlation Matrix for the Multi-temporal PCA

| VAR/COVAR | dry1 | dry2 | dry3 | dry4 | dry5 | dry6 | dry7 | wet3 | wet4 | wet5 |
|---|---|---|---|---|---|---|---|---|---|---|
| dry1 | 177.09 | 95.96 | 57.17 | 96.65 | 83.12 | 289.39 | 164.27 | 59.63 | 84.86 | 189.77 |
| dry2 | 95.96 | 127.66 | 60.52 | 76.31 | 87.44 | 176.95 | 275.36 | 26.02 | 19.34 | 39.86 |
| dry3 | 57.17 | 60.52 | 31.09 | 41.89 | 45.28 | 102.11 | 124.77 | 18.88 | 17.12 | 37.36 |
| dry4 | 96.65 | 76.31 | 41.89 | 64.09 | 59.70 | 165.94 | 144.05 | 36.44 | 36.75 | 87.24 |
| dry5 | 83.12 | 87.44 | 45.28 | 59.70 | 91.28 | 159.64 | 186.67 | 22.09 | 44.09 | 52.83 |
| dry6 | 289.39 | 176.95 | 102.11 | 165.94 | 159.64 | 513.81 | 322.84 | 95.27 | 151.83 | 311.48 |
| dry7 | 164.27 | 275.36 | 124.77 | 144.05 | 186.67 | 322.84 | 647.51 | 29.85 | 17.30 | 15.06 |
| wet3 | 59.63 | 26.02 | 18.88 | 36.44 | 22.09 | 95.27 | 29.85 | 76.47 | 31.36 | 141.35 |
| wet4 | 84.86 | 19.34 | 17.12 | 36.75 | 44.09 | 151.83 | 17.30 | 31.36 | 139.32 | 159.19 |
| wet5 | 189.77 | 39.86 | 37.36 | 87.24 | 52.83 | 311.48 | 15.06 | 141.35 | 159.19 | 456.54 |

| COR MATRX | dry1 | dry2 | dry3 | dry4 | dry5 | dry6 | dry7 | wet3 | wet4 | wet5 |
|---|---|---|---|---|---|---|---|---|---|---|
| dry1 | 1.000000 | 0.638215 | 0.770381 | 0.907223 | 0.653794 | 0.959373 | 0.485096 | 0.512418 | 0.540260 | 0.667415 |
| dry2 | 0.638215 | 1.000000 | 0.960594 | 0.843624 | 0.810054 | 0.690932 | 0.957763 | 0.263385 | 0.145020 | 0.165117 |
| dry3 | 0.770381 | 0.960594 | 1.000000 | 0.938318 | 0.849943 | 0.807811 | 0.879321 | 0.387150 | 0.260164 | 0.313598 |
| dry4 | 0.907223 | 0.843624 | 0.938318 | 1.000000 | 0.780559 | 0.914433 | 0.707144 | 0.520521 | 0.388941 | 0.509987 |
| dry5 | 0.653794 | 0.810054 | 0.849943 | 0.780559 | 1.000000 | 0.737154 | 0.767850 | 0.264448 | 0.390958 | 0.258812 |
| dry6 | 0.959373 | 0.690932 | 0.807811 | 0.914433 | 0.737154 | 1.000000 | 0.559706 | 0.480636 | 0.567489 | 0.643114 |
| dry7 | 0.485096 | 0.957763 | 0.879321 | 0.707144 | 0.767850 | 0.559706 | 1.000000 | 0.134142 | 0.057598 | 0.027691 |
| wet3 | 0.512418 | 0.263385 | 0.387150 | 0.520521 | 0.264448 | 0.480636 | 0.134142 | 1.000000 | 0.303849 | 0.756519 |
| wet4 | 0.540260 | 0.145020 | 0.260164 | 0.388941 | 0.390958 | 0.567489 | 0.057598 | 0.303849 | 1.000000 | 0.631195 |
| wet5 | 0.667415 | 0.165117 | 0.313598 | 0.509987 | 0.258812 | 0.643114 | 0.027691 | 0.756519 | 0.631195 | 1.000000 |

| COMPONENT | C 1 | C 2 | C 3 | C 4 | C 5 | C 6 | C 7 | C 8 | C 9 | C 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| % var. | 64.11 | 20.11 | 7.69 | 3.77 | 1.96 | 1.29 | 0.51 | 0.30 | 0.14 | 0.11 |
| eigenval. | 6.41 | 2.01 | 0.77 | 0.38 | 0.20 | 0.13 | 0.05 | 0.03 | 0.01 | 0.01 |
| eigvec.1 | 0.357425 | -0.167811 | 0.073526 | -0.518604 | 0.048474 | -0.067899 | 0.213192 | -0.713785 | 0.078226 | 0.041364 |
| eigvec.2 | 0.340299 | 0.329880 | -0.090671 | 0.112476 | -0.306748 | -0.041739 | -0.113723 | -0.011894 | 0.613371 | -0.519008 |
| eigvec.3 | 0.371545 | 0.211871 | -0.083278 | 0.001094 | -0.048305 | -0.172252 | -0.395429 | 0.087768 | 0.200833 | -0.757445 |
| eigvec.4 | 0.382882 | 0.023504 | -0.084081 | -0.248203 | 0.064717 | -0.314796 | -0.435379 | 0.178459 | -0.569446 | -0.367720 |
| eigvec.5 | 0.335514 | 0.186158 | 0.224291 | 0.362518 | 0.734003 | 0.331767 | -0.046769 | -0.117155 | -0.007754 | -0.079041 |
| eigvec.6 | 0.369631 | -0.123997 | 0.140272 | -0.364103 | 0.088281 | 0.113774 | 0.481947 | 0.649770 | 0.137407 | 0.040703 |
| eigvec.7 | 0.297046 | 0.417077 | -0.055317 | 0.267972 | -0.433963 | 0.201997 | 0.419112 | -0.119617 | -0.481466 | 0.109738 |
| eigvec.8 | 0.212957 | -0.381884 | -0.660212 | 0.384788 | 0.178197 | -0.334761 | 0.281283 | -0.018680 | 0.039692 | 0.002938 |
| eigvec.9 | 0.194695 | -0.401477 | 0.665883 | 0.411900 | -0.229479 | -0.367012 | 0.015177 | -0.015304 | -0.004539 | 0.002216 |
| eigvec.10 | 0.226073 | -0.535326 | -0.141582 | 0.057188 | -0.278822 | 0.674018 | -0.325931 | -0.000641 | -0.026613 | -0.004329 |

| LOADING | C 1 | C 2 | C 3 | C 4 | C 5 | C 6 | C 7 | C 8 | C 9 | C 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| dry1 | 0.905002 | -0.237996 | 0.064488 | -0.318483 | 0.021452 | -0.024392 | 0.048210 | -0.123536 | 0.009340 | 0.004320 |
| dry2 | 0.861638 | 0.467849 | -0.079525 | 0.069073 | -0.135748 | -0.014995 | -0.025717 | -0.002059 | 0.073239 | -0.054210 |
| dry3 | 0.940753 | 0.300484 | -0.073041 | 0.000672 | -0.021377 | -0.061881 | -0.089420 | 0.015190 | 0.023980 | 0.079115 |
| dry4 | 0.969460 | 0.033334 | -0.073745 | -0.152426 | 0.028640 | -0.113090 | -0.098454 | 0.030886 | -0.067994 | -0.038408 |
| dry5 | 0.849523 | 0.264016 | 0.196719 | 0.222628 | 0.324825 | 0.119186 | -0.010576 | -0.020276 | -0.000926 | -0.008256 |
| dry6 | 0.935909 | -0.175857 | 0.123029 | -0.223602 | 0.039068 | 0.040873 | 0.108984 | 0.112457 | 0.016407 | 0.004251 |
| dry7 | 0.752123 | 0.591514 | -0.048517 | 0.164566 | -0.192045 | 0.072567 | 0.094775 | -0.020702 | -0.057489 | 0.011462 |
| wet3 | 0.539208 | -0.541603 | -0.579054 | 0.236304 | 0.078859 | -0.120262 | 0.063607 | -0.003233 | 0.004739 | 0.000307 |
| wet4 | 0.492970 | -0.569390 | 0.584028 | 0.252954 | -0.101553 | -0.131848 | 0.003432 | -0.002649 | -0.000542 | 0.000231 |
| wet5 | 0.572419 | -0.759220 | -0.124178 | 0.035120 | -0.123389 | 0.242139 | -0.073704 | -0.000111 | -0.003178 | -0.000452 |

# APPENDIX 8

## Species lists of Dominant Vegetation Communities

### 1. *Riparian forest*

*Chaetacme aristata*
*Olea europaea*
*Ficus sur*
*Heteromorpha arborescens*
*Plumbago auriculata*
*Diospyros sp.*
*Maytenus heterophylla*
*Dovyalis sp.*
*Euphorbia triangularis*
*Schotia latifolia*
*Solanum sp.*
*Hypoestes verticillaris*
*Azima tetracantha*
*Panicum deustum*
*Scutia myrtina*
*Coddia rudis*
*Vepris undulata*
*Tecomaria capensis*
*Rhus longispina*
*Ptaeroxylon obliquum*
*Panicum sp.*
*Abutilon sp.*
*Coddia rudis*
*Jasminum multipartitum*

### 2. *Dry forest*

*Euphorbia tetragona*
*Pappea capensis*
*Azima tetracantha*
*Grewia occidentalis*
*Hypoestes venigullous*
*Lycium schizocalyx*
*Lycium oxycarpum*
*Panicum maximum*
*Panicum deustum*
*Capparis sepiaria*
*Protasparagus plumosus*
*Protasparagus sp.*
*Lantana rugosa*
*Cussonia spicata*
*Euclea undulata*
*Carissa haematocarpa*

### 3. Open shrubland

*Acacia karroo*
*Sporobolus africanus*
*Digitaria sp.*
*Themeda sp.*
*Rhus incisa*
*Rhus undulata*
*Digitaria eriantha*
*Cynodon dactylon*
*Lantana rugosa*
*Selago corymbosa*

### 4. Succulent thicket

*Portulacaria afra*
*Grewia robusta*
*Cussonia spicata*
*Lycium oxycarpum*
*Crassula ovata*
*Ptaeroxylon obliquum*
*Brachylaena ilicifolia*
*Sarcostemma viminale*
*Maytenus polyacantha*
*Rhoicissus tridentata*
*Plumbago auriculata*
*Heteromorpha arborescens*
*Diospyros whyteana*
*Rhus undulata*
*Capparis sepiaria*
*Aloe speciosa*
*Crassula muscosa*
*Crassula rogersi*
*Cotyledon sp.*
*Delosperma calycinum*
*Euclea undulata*
*Cussonia spicata*

### 5. Open succulent shrubland

*Euphorbia bothae*
*Mestoklema sp.*
*Rhigozum obovatum*
*Lycium schizocalyx*
*Panicum maximum*
*Felicia filifolia*
*Pentzia incana*
*Euphorbia bothae*

*Maytenus polyacantha*
*Brachylaena ilicifolia*
*Schotia afra*
*Grewia robusta*
*Panicum maximum*
*Digitaria eriantha*
*Euclea undulata*
*Protasparagus suaveolens*
*Protasparagus densiflorus*
*Aizoon glinoides*
*Delosperma calycinum*

**6. Grassland**

*Themeda triandra*
*Eragrostis plana*
*Sporobolus africanus*
*Aristida congesta*
*Acacia karroo*
*Protasparagus sp.*
*Chrysocoma ciliata*
*Indigofera sp.*
*Eustachys mutica*
*Eragrostis obtusa*
*Heteropogon contortus*
*Selago sp.*
*Scutia myrtina*
*Eragrostis curvula*
*Hyparrhenia hirta*
*Coddia rudis*

**7. Marginal shrubland**

*Elytropappus rhinocerotis*
*Pteronia incana*
*Aloe ferox*
*Aristida congesta*
*Rhus undulata*
*Coddia rudis*
*Rhus incisa*

**8. Dwarf shrubland**

*Pteronia incana*
*Aloe ferox*
*Chrysocoma tenuifolia*
*Teucrium africanum*
*Sutera pinnatifida*
*Helichrysum rosum*
*Aizoon glinoides*
*Coddia rudis*

*Lycium schizocalyx*
*Anthospermum aethiopicum*
*Leucas capensis*
*Ruellia cordata*
*Hermannia althaeoides*
*Plumbago auriculata*
*Cynodon dactylon*

**9. Sparse dwarf shrubland**

*Chrysocoma ciliata*
*Felicia muricata*
*Aristida congesta*
*Cynodon dactylon*
*Sutera pinnatifida*
*Helichrysum rosum*
*Coddia rudis*
*Exomis michrophylla*
*Pentizia incana*
*Eragrostis plana*
*Cynodon dactylon*
*Acacia karroo*
*Pteronia incana*
*Aloe ferox*

**10. Sparse succulent dwarf shrubland**

*Euphorbia bothae*
*Rhigozum obovatum*
*Protasparagus suaveolens*
*Aristida congesta*
*Pentzia incana*
*Anthospermum aethiopicum*
*Euphorbia mauritanica*
*Leucas capensis*
*Digitaria eriantha*
*Sporobolus nitens*
*Gnidia cuneata*
*Sutera pinnatifida*
*Eragrostis obtusa*
*Jatropha capensis*