THE USE OF REMOTE SENSING AND GEOGRAPHIC INFORMATION SYSTEM (GIS) TECHNIQUES, TO INTERPRET SAVANNA ECOSYSTEM PATTERNS IN THE SABI SAND GAME RESERVE, MPUMALANGA PROVINCE

BY

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ABSTRACT

This thesis explores techniques which ultimately strive to optimize production systems in rangeland areas of southern Africa. By linking spatially significant, satellite derived data to practical measurements of vegetation structure, valuable insight has been derived on processes of ecosystem function, in the Sabi Sand Game Reserve.

A broad ecosystem response mechanism has been established from a conventional Normalized Differentiation Vegetation Index (NDVI). By responding to increases in production, which are driven by disturbance, this index has allowed quantitative systems theory in savanna to be tested and refined.

Methods of biomass and production estimation which are specifically designed to reduce the cost and time involved with the more conventional method of destructive harvesting have been tested in the savanna at the Sabi Sand Game Reserve. Results from these estimates relate well with data derived through destructive harvesting in structurally similar savanna. Moreover, by relating the above-ground woody production estimates to remote sensing indices, it was possible to demonstrate that the problem of extrapolation, universal to most biomass and production studies can be overcome.

Since remote sensing encompasses an array of tools fundamental to rangeland inventory, monitoring and management, valuable spatially significant information pertaining to ecosystem structure and function has been provided for managers in the Sabi Sand Game Reserve.

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CHAPTER 1

INTRODUCTION

"Every nation is faced with the responsibility of managing the natural resources at its disposal. Effective natural resource management rests on sound decision making, which in turn depends on the acquisition of accurate information regarding the resource" (Lourens, 1990, pp 1).

1.1 INTRODUCTION

Parker, (1988) suggest that ecology is a dialogue between the scientist and the environment. Rangeland ecologists often use ground-based monitoring as a tool, in order to achieve this dialogue (Wessman *et al.*, 1995). Recent developments in landscape ecology have however reemphasised the important relationship between spatial patterns and ecological processes (Turner, 1989). This presents a major concern to ecologists, as ground-based monitoring seldom allows spatial awareness of data. Given the inherent spatial variability of arid and semi-arid landscapes (Pickett and White, 1985), the non-uniform impact of grazing animals and the impact of redistribution processes which transmit soils, water, seed and nutrients across the terrain, the potential for error from a limited number of ground-based point assessments is immense (Friedel, 1990; Pickup, 1989; Stafford Smith and Morton, 1990; Tueller, 1989). Furthermore, ground-based monitoring is rarely possible on a regular basis due to the limited funds and personnel available for monitoring large expanses of land.

Remote sensing offers a possible solution to these problems as it encompasses an array of tools for collecting data fundamental to rangeland inventory, monitoring and management (Bryant *et al.*, 1990; Colwell, 1983; Eidenshink and Hass, 1992; Haas, 1992; Nicholson *et al.*, 1990). It is inexpensive and uses the attributes of multispectral information, rather than suffering from the loss of spatial information. By responding to the primary productive functioning of plants, remote sensing indices provide a measure that is difficult to produce in any other way. Rather than being a substitute for many other measurements, remote

sensing indices provide a unique measure of vegetation that will be of value to many users for many applications (Maxwell, 1983). Moreover, it can be used as an important data source for the development and refinement of models and can be used to validate models of landscape change (Quattrochi and Pelletier, 1991). Used within a Geographic Information System (GIS) framework, remote sensing has the potential to generate spatially significant data, and therefore can play a crucial role in the scientist-environment dialogue.

The present study attempts to participate in this dialogue by applying spatial data derived from satellite imagery to spatial patterns in the landscape at the Sabi Sand Game Reserve, Mpumalanga, South Africa. Remote sensing techniques are used within a GIS framework so as to explore several key issues pertinent to the savanna of the Mpumalanga lowveld. These issues are described below (sections 1.2-1.4).

1.2 RESOURCE UTILIZATION

Over the past two decades, consumptive and non consumptive utilization of resources in the savannas of the Mpumalanga lowveld, has increased exponentially. Research has yielded much needed information relevant to conservation, but there is a general lack of data regarding wildlife as a potentially utilizable resource. Such deficiencies have, in many cases, resulted in the widespread deterioration of the natural resource base of the region due to its mismanagement (Ben-Shahar, 1995; Scholes and Walker, 1993). Furthermore, management of natural resources in conservation areas in southern Africa have traditionally depended upon *ad hoc* decisions by management staff. Consequently, the objectives of these decisions cannot be guaranteed, as the actions initiated to solve specific problems often generate additional problems or undesirable effects. It is therefore imperative that environmentally significant natural resource information, defined in terms of spatially significant patterns and processes in the landscape, be made available to the decision makers.

This study will review current management practices in the Sabi Sand Game Reserve as well as their effects on the landscape (chapter 3). Spatially significant data, which may be used by decision makers to isolate and address these effects, will also be provided. This information will include:

1. A map of the contemporary vegetation communities in the Sabi Sand Game Reserve.
2. The proportional extent and estimates of basal cover for each vegetation community.
3. The extent of sodic patches in the Sabi Sand Game Reserve.
4. A map of water points which are being heavily utilised.
5. A Digital Elevation Model (DEM) which describes the topography of the area at a resolution 500 m by 500 m.

1.3 ANNUAL PRODUCTION OF ABOVE-GROUND BIOMASS

One of the leading problems facing the earth is the increased demand on the natural resource base, specifically vegetation for food, fibre, fuel and shelter. Consequently, the measurement of standing crop biomass and the annual production of biomass has taken on worldwide importance (Maxwell, 1983). Improvements, or ultimately, optimization of animal production systems in the natural rangeland areas of southern Africa can only be realized if reliable primary production estimates are available (Grossman, 1982).

Rangeland primary production has not been investigated in southern Africa to the extent that it has been in other biogeographical regions (Singh *et al.*, 1975). Furthermore, production estimates in southern Africa have been based on "shrewd guesses", "simplifications" "appropriate adjustments" and "predictable ratios" (Rutherford, 1978, pp. 624). Interpretation, and evaluation of primary production estimates is therefore extremely difficult.

The most widely used method in production studies is the destructive harvest method (Rutherford, 1978). The problems encountered, using this technique have been extensively reviewed (Grossman, 1982). Perhaps however, the most universal problem in the use of this technique has been overlooked; cost and extrapolation to larger areas. Although innovative methods have been devised to increase the cost-efficiency and time involved in estimating

biomass and above-ground production (Catchpole and Catchpole, 1993; Rutherford, 1982 a; b), extrapolation remains a problem.

Rutherford's (1982 a) technique for estimating an Annual Production Fraction (APF) of above-ground woody biomass (appendix 1) and Rutherford's (1982 b) method for estimating above-ground woody biomass (appendix 1) were designed for *Burkea africana-Ochna pulchra* savanna which exhibits similar structural characteristics to the sand savanna in the Sabi Sand Game Reserve (Acocks, 1988). These techniques were therefore used in the Ground Control Point (GCP) data collection programme. The results will be validated by comparison with APF estimates converted from Biomass Accumulation Ratios (BAR) for shrubland and woodland biome types, and biomass estimates derived through the destructive harvest method in southern African savannas respectively. The relationship between these estimates and remote sensing indices, which have been successfully related to above-ground biomass (Tucker *et al.*, 1976; 1983) and above-ground production (Reich and Hussin, 1993), will also be determined in an attempt to override the problem of extrapolation.

1.4 QUANTITATIVE SYSTEMS THEORY IN SAVANNA

The term 'savanna' has a wide range of meanings among bioecologists, sometimes referring to flat and open landscapes, and other times referring to the vegetation that characterizes that landscape (Sarmiento, 1984). Some definitions are given below.

> 'A mixed formation of grasses and woody plants in any geographical area' (Dansereau, 1957)

> 'An ecologically homogenous grassland upon which woody plants are more or less evenly distributed' (Walter, 1973).

> 'A tropical community with a continuous herbaceous layer, usually dominated by C_4 grasses and a discontinuous woody layer of shrubs and trees' (Belsky, 1995).

Savannas are unique, differing from other ecosystems primarily as they allow for the co-existence of trees and grasses. The large scale, long term pattern, shows this co-existence to be one of remarkable stability (Scholes and Walker, 1993). In almost all other ecosystems, trees and grasses have evolved very dissimilar patterns of environmental interaction, (i.e. usually only the one is dominant) (Belsky, 1995). The form and distribution of the vegetation types within these ecosystems is usually determined by key environmental variables; temperature, light and rainfall. The proportion of trees and grasses in savanna vegetation is however not predictable from environmental conditions, nor are they stable over time (Belsky, 1995). The determinants of savanna vegetation are considerably more complex, and have in fact created a considerable debate between ecologists over the last century. Sarmiento, (1984) refers to this as the 'savanna problem'.

Until the middle of this century, woodlands and forests dominated much of sub-Saharan Africa. In the 1950's and 1960's thousands of square kilometres of woodlands were converted to open savanna. In an extensive review on spatial and temporal patterns in African savannas, Belsky (1995) notes that the driving forces behind this conversion is mainly attributed to fire (Frost and Robertson, 1987; Lock, 1977; Norton-Griffiths, 1979; Phillips, 1974) and elephants (Agnew, 1968; Croze, 1974; Glover, 1963; Lamprey *et al.*, 1967; Laws *et al.*, 1970; Norton-Griffiths, 1979). Drought (Greenway and Vesey-Fitzgerald, 1969), insect eruptions (Walker, 1981), fluctuations in water tables (Western and van Praet, 1973), senescence of even aged stands (Young and Lindsay, 1988) and catenary structure (Bell, 1970; Tinley, 1982) were also cited as being equally or more important driving forces.

Many scientists in the 1960's and 1970's viewed this loss of woodlands as a permanent catastrophic event (Beuchner and Dawkins, 1961; Laws, 1970). Others proposed that these vegetational changes were short lived or essentially cyclic in nature. As a consequence, several theoretical mechanisms were proposed in order to explain or allow for the co-existence of apparently competing species (grasses and trees).

A major challenge in remote sensing applications lies with assessing ecosystem function from spectral measurements of ecosystem structure (Wessman *et al.*, 1995). The increased attention on spatial dynamics has highlighted the need for new quantitative methods that can analyze patterns, determine the importance of spatially explicit processes, and develop reliable landscape models (Turner and Gardner, 1991). Future research in landscape ecology should be orientated towards the testing of such models, using spatial data (Turner and Gardner, 1991; Wiens, 1976). Remote sensing, which incorporates spatial, data can be used for the development, refinement and validation of landscape change models (Quattrochi and Pelletier, 1991). Since an understanding of the patterns of vegetation production is essential in determining whether a transition state exists and in evaluating the nature of any steady state (Vitousek, 1985), remote sensing indices of production will be related to savanna ecosystem function. In so doing, savanna co-existence models will be tested and refined. The fundamental principles on which these models are based are discussed in chapter 4.

1.5 RESEARCH CONTEXT

This study forms part of a research programme which was launched in 1989 in the Mpumalanga lowveld, South Africa, by the Game Production Unit (GPU) of the Department of Agricultural Development (DAD). This unit is now housed in the Range and Forage Institute (RFI) of the Agricultural Research Council (ARC). The research programme is entitled 'Towards a predictive understanding of savanna ecosystem dynamics in the Mpumalanga lowveld' and currently extends over some 250 000 ha. It includes the Sabi Sand Game Reserve (± 60 000 ha), Timbavati Private Nature Reserve (± 68 000 ha), Umbabat Private Nature Reserve (± 14 000 ha), Manyeleti Game Reserve (± 23 000 ha) and 23 privately owned ranches (17 units) in the Hoedspruit area (± 40 000 ha).

1.6 RESEARCH AIMS AND OBJECTIVES

The present study is limited to the Sabi Sand Game Reserve and attempts to explore key issues pertinent to the savanna of the Mpumalanga lowveld, using remote sensing techniques within a GIS framework. The research aims and objectives are summarised below.

1. To review current management practices in the Sabi Sand Game Reserve and their effects on the landscape.
2. To provide a map of the contemporary vegetation communities in the Sabi Sand Game Reserve from satellite derived data which will include:
   - the proportional extent of each vegetation community.
   - an estimate of basal cover for each vegetation community.
   - the extent of sodic patches in the Sabi Sand Game Reserve.
3. To provide a map of water points which are being heavily utilised.
4. To determine and verify above-ground woody biomass estimates in the Sabi Sand Game Reserve.
5. To determine and verify Annual Production Fraction (APF) estimates of above-ground woody biomass in the Sabi Sand Game Reserve.
6. To determine the relationship between these estimates and remote sensing indices of biomass and production.
7. To review theories on co-existence of apparently competing species (trees and grasses) in the savanna at the Sabi Sand Game Reserve.
8. To relate remote sensing indices of production to stability in the savanna at the Sabi Sand Game Reserve and so test and refine these co-existence theories.

1.7 THESIS OUTLINE

The thesis is organized as follows:

In chapter 2, a physical description of the study area is presented. A review of key management decisions adopted in the Sabi Sand Game Reserve, as well as their effects on the landscape, forms the substance of chapter 3. Existing theories of co-existence in savanna are reviewed in chapter 4. Methods of analysis used in data processing and GCP data collection together with a description of the software and data sources used in the study are discussed in chapter 5. In chapter 6 the results are presented. The information derived from the study is applied to management decisions in the Sabi Sand Game Reserve, and quantitative systems theory of savanna, in chapter 7. Conclusions and recommendations to management are provided in chapter 8. The techniques used in Ground Control Point (GCP) data collection are described in chapter 1. A review of remote sensing and image processing techniques is provided in appendix 2, for readers with a limited knowledge of the fundamental principles involved in remote sensing, and a sample data set is supplied in appendix 3.

CHAPTER 2

THE STUDY AREA

2.1 INTRODUCTION

The study was carried out in the Sabi Sand Game Reserve, situated in the lowveld of the Mpumalanga Province, South Africa. The reserve consists of twenty nine privately owned, adjoining properties and was proclaimed a private nature reserve in January 1965. The reserve is bordered in the east and south by the Kruger National Park, in the north by the Manyeleti game reserve and in the west by Mpumalanga province grazing lands and sisal plantations. It occurs on either side of the Sand River near its confluence with the Sabie River. The reserve covers an area of about 570 km^2, (57 000 ha) and is situated between latitudes 24°42'S and 24°59'S and longitudes 31°20'E and 31°33'E (figures 2.1, 2.2 and 2.3).

2.2 ABIOTIC FACTORS

2.2.1. Topography

The Sabi Sand Game Reserve lies in an intermediate position between the sub-tropical lowveld plain and the foothills of the Mpumalanga great escarpment. The landscape has been described as one which is composed of moderately dissected, gently undulating, hill country (Tinley, 1979). A single range of hills (granite topped inselbergs underlain by dolerite dykes) are to be found on the western border of the reserve, the highest of which is 579 metres above mean sea level (mamsl). Altitude varies from 518 mamsl in the west to 420 mamsl in the east and 305 mamsl in the south east. Essentially, the hill country rises 100 to 200 m above the floor of the Sand River valley (figure 2.4).

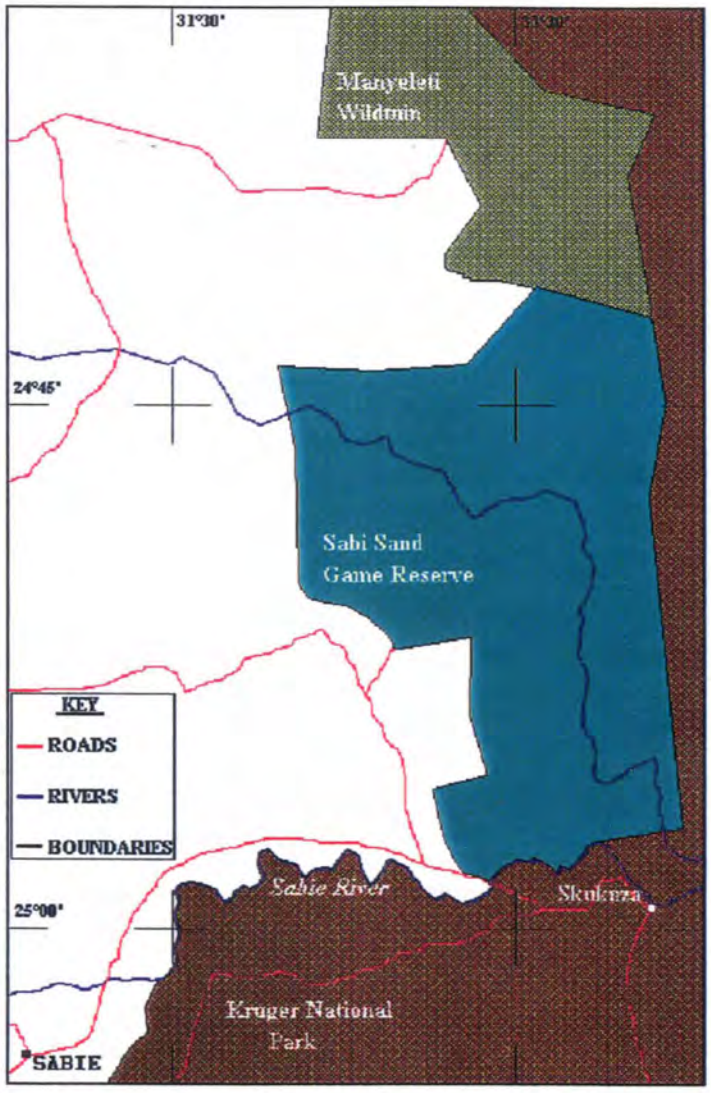

Figure 2.1 Location of the study area in the Mpumalanga lowveld - shown in green

Figure 2.2 Location of the study area in relation to southern Africa.

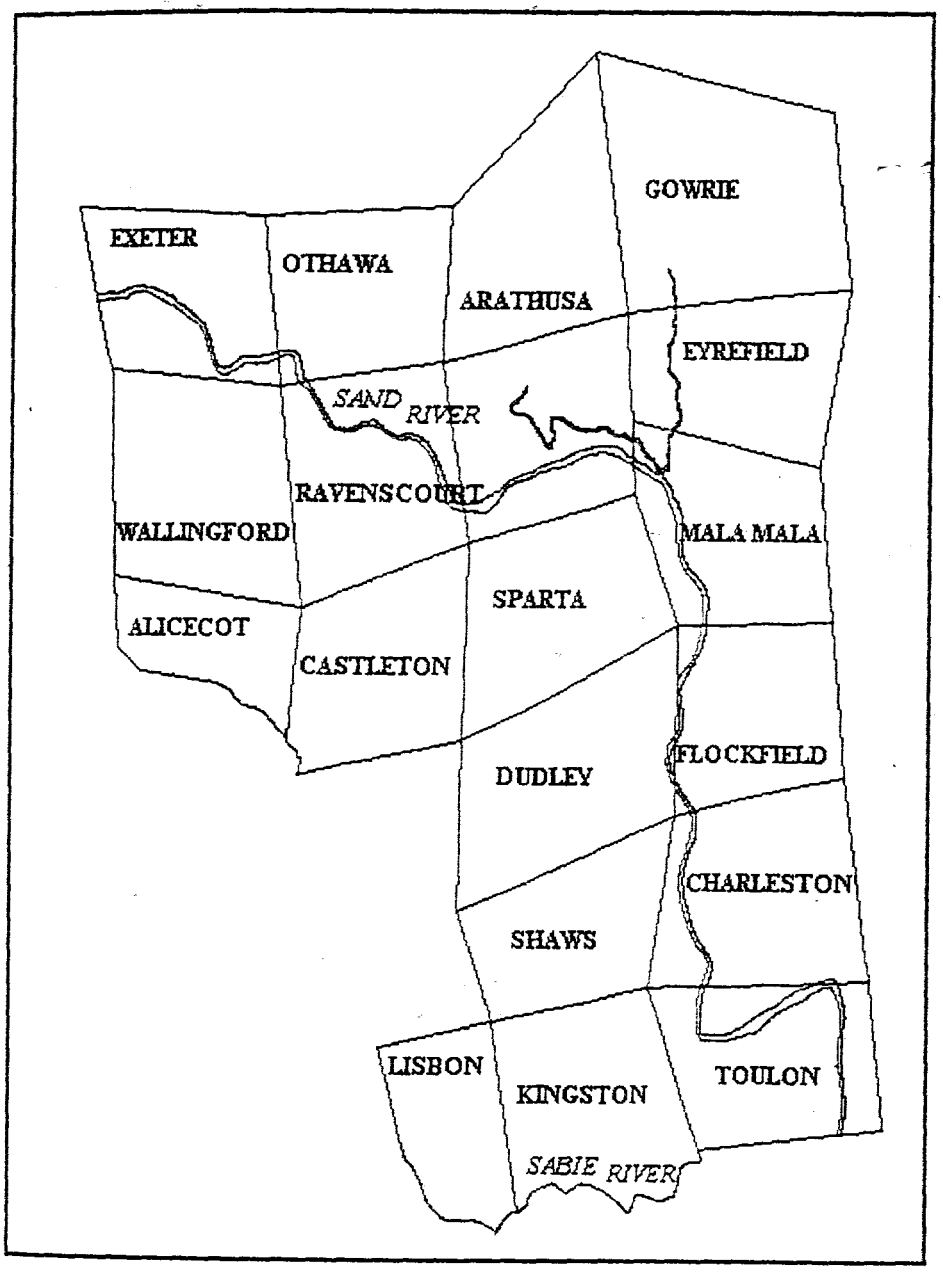

Figure 2.3 Position of original properties in the Sabi Sand Game Reserve.

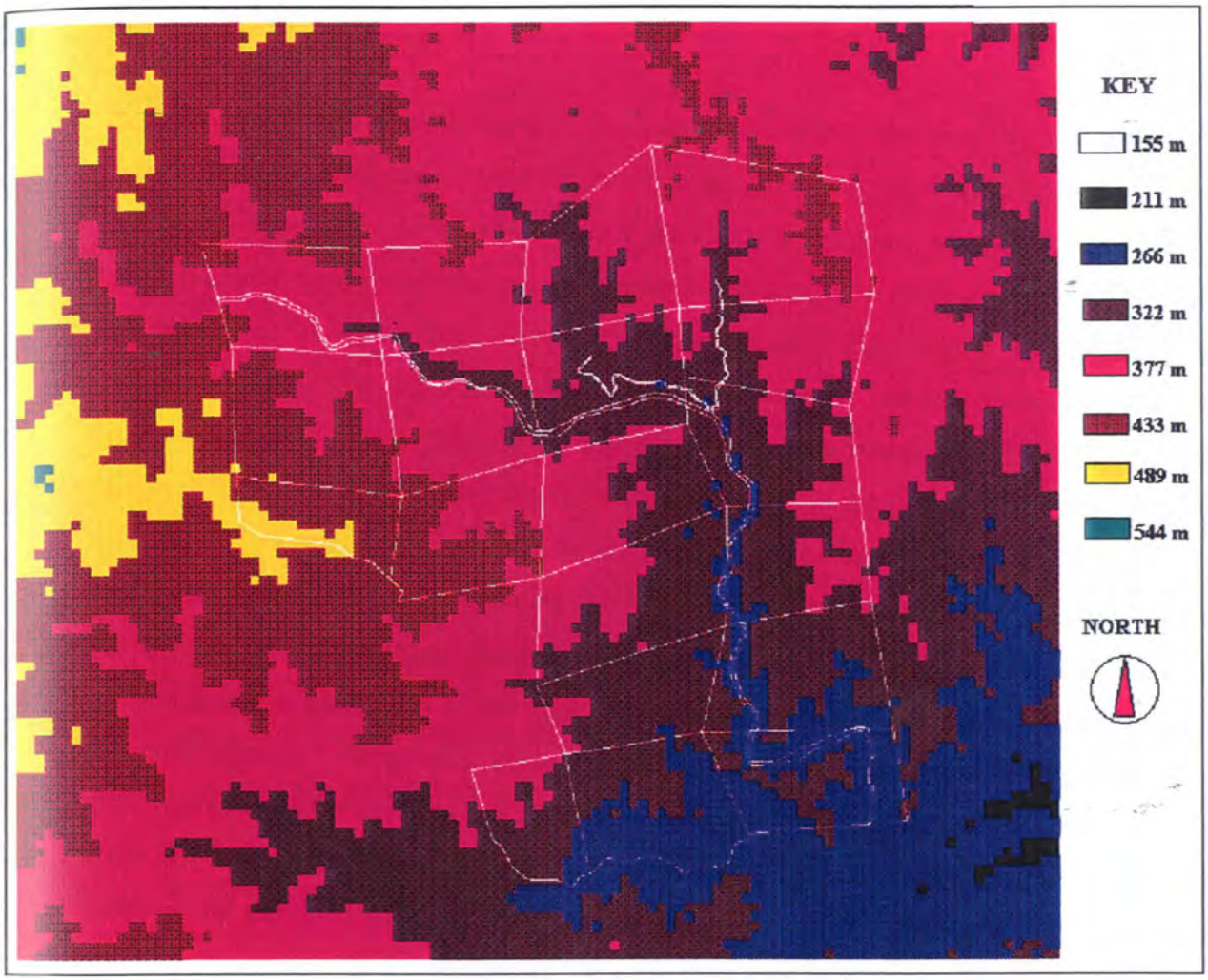

Figure 2.4 Digital Elevation Model (DEM) of the Sabi Sand Game Reserve depicting mean height classes, (note the clear distinction of drainage lines).

2.2.2. Drainage

The main water source for the area is the Sand River which traverses the reserve from the north west to the south east along a 52 km frontage. The only other significant water source in the area is the Sabie River which forms the southern boundary with the Kruger National Park. It is a perennial river providing 12 km of frontage. The drainage lines are shown by low elevations in figure 2.4. Both rivers are incised with narrow floodplains which incorporate a thin strip of riparian vegetation on either bank. In the study area, the rivers flow predominantly over granites, which creates a characteristic, fine network of small valleys. Their sources originate on the escarpment, which receives a mean annual rainfall upward of 1500 mm per annum, with three dry months from June to August. The Sand River bed is often broad and placid allowing the deposition of sand bars. These reaches typically support reed beds (*Phragmites* species). It has been suggested that the absence of floods, due to dams and pine plantations in the upper reaches of the catchment, has aided the deposition and establishment of these sand bars (Scholes, 1985). A few permanent springs occur, the most significant of which rises from the dolerite sill on the farm Dudley (Tinley, 1979). Some of the contour seeplines ooze water perennially in the high rain years but are dry when mid-summer droughts occur or in years with less than mean annual rainfall. The dolerite waters are generally brak (containing between 500 and 30 000 parts per million sodium chloride) whilst those from the seeplines are acidic.

2.2.3. Geology

The area is predominantly of granite-gneiss belonging to the Nelspruit Granite Suite, an acidic intrusive rock dated more than 3 090 Myr old (Bristow and Venter, 1986). Red sands derived from weathered granite cap the hills and interfluves across most of the reserve. The granites are cut through by dolerite basic volcanic intrusions (the Timbavati Gabbro), forming a grid of dykes trending east-west and north-south and a large sill in the Castleton area (figure 2.5).

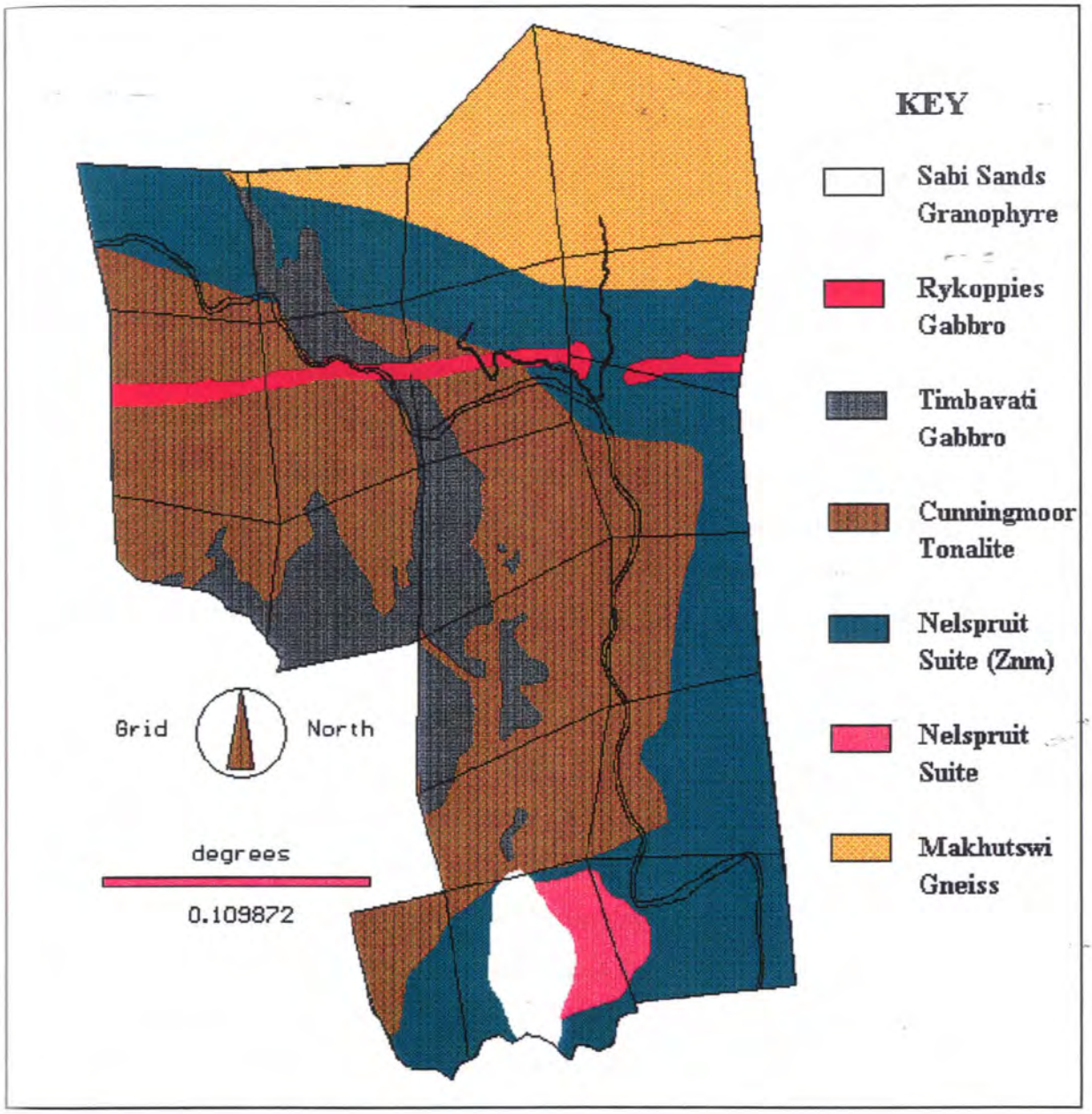

Figure 2.5 Geology of the Sabi Sand Game Reserve digitized from the 1:250 000 geological series for Pilgrims Rest.

2.2.4 Soils

Most of the soils found in the lowveld of Mpumalanga are underlain by granite and therefore consist of sand, clay and salt. The soils are generally deep, infertile, and dominated by 'low activity' clays such as kaolinites and aluminium oxides (Scholes and Walker, 1993). Soils derived from weathered granite are usually slightly acidic (Webber, 1979). The granites often contain sodium rich feldspar which play a major role in the formation of sodic patches (Scholes, 1985). These soils are characteristically bare and are highly impermeable. Areas underlain by basic lavas, such as basalts and dolerites, weather to produce soils that are fertile. They have high initial mineral contents and are dominated by 'high activity clays' such as the smectite group (Scholes and Walker, 1993). However, they tend to be arid soils due to their high clay content and are usually slightly to moderately alkaline (Webber, 1979).

The Land type series for Pilgrims Rest (1986) shows the occurrence of four land types within the Sabi Sand Game Reserve (figure 2.6). Land types Fb167 and Fb185 are described as pedologically young landscapes, that produce Mispah and/or Glenrosa soil forms (MacVicar *et al.*, 1977). Lime in these soil types is either rare or absent in upland areas, but widespread in the bottomlands due to the high rates of leaching. Soil depth is generally low (100 - 400 mm for Fb167 and 100 - 150 mm for Fb185). Land type Ea92 is described as one or more vertic, melanic, red structured diagnostic soil horizons. This soil type denotes dark and/or red coloured soils, usually clay, associated with basic parent materials. Land type Hb1 is composed of deep grey sandy soils, typically of the Fernwood form. Constantia, Shepstone and Villafontes soil forms also occur.

Tinley (1979) produced an extensive description of the soils in the Sabi Sand Game Reserve. He described the present Sabi Sand landscape as being derived from a gently undulating plainsland of sand convexities with intervening flat vlei drainage lines, known as dambos in south Central Africa. Incision and headward erosion was the cause for many of these dambos to be striped away, exposing the contact between the deep red sands capping the hills and the underlying weathering front (saprolite zone) of the granite. The granite saprolite forms an impermeable layer and consists of rotten rock fragments in a matrix of poorly drained saline

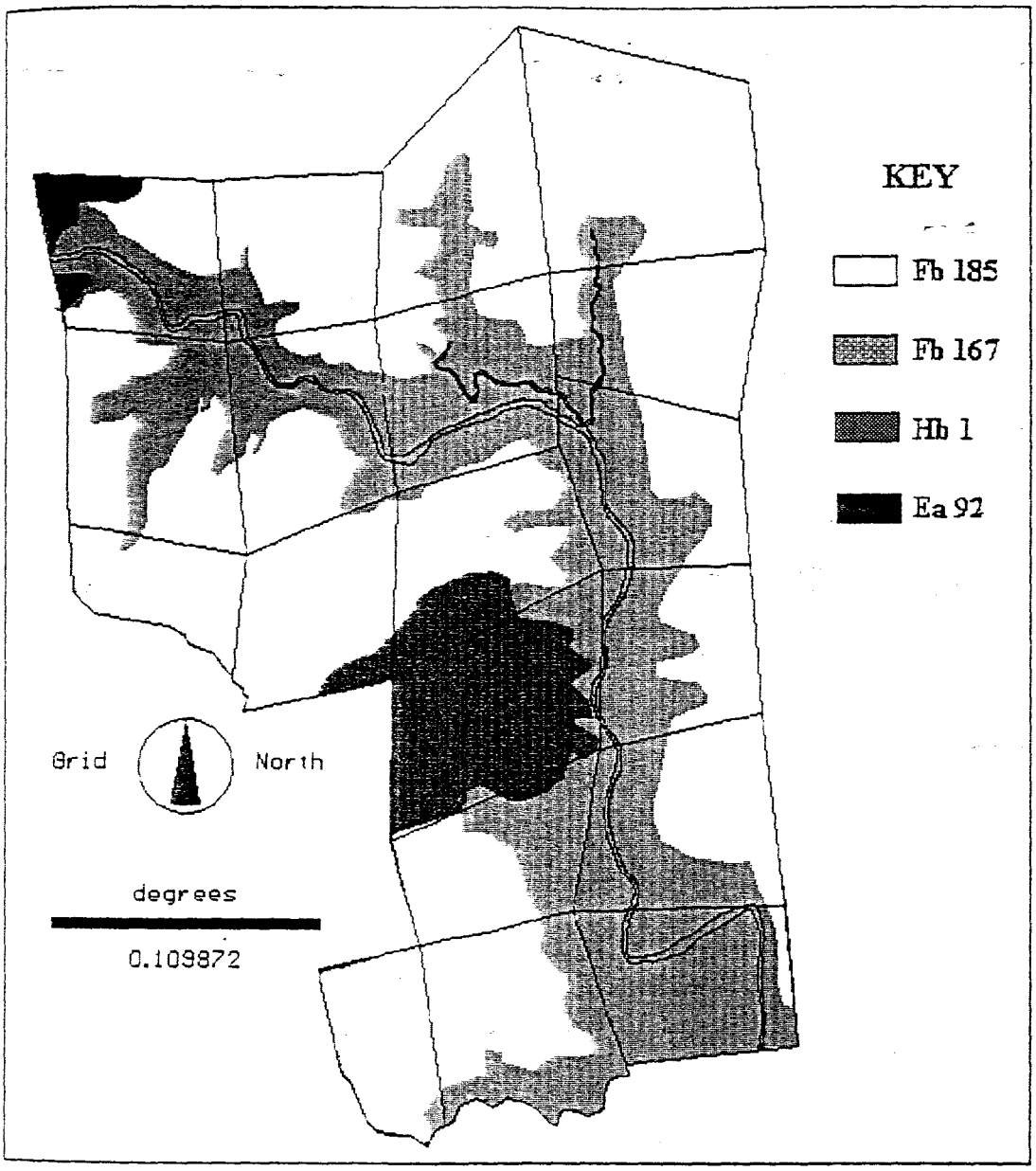

Figure 2.6 Digitized map of the 1:250 000 land type series for Pilgrims Rest.

sandy clay. The red sands therefore absorb all the rainfall which is then forced to drain laterally when it meets the saprolite zone. The groundwater permeates to the surface on the slopes of the hills parallel with the contour, forming characteristic seepage lines. The seepage line is composed of two distinct soil types; an upper zone of acid white leached sands and a lower zone of base saturated grey-brown clays (plate 1). The soils of these areas are described as a very saline (pH - 10) Sterkspruit series (Fraser, 1983). These brackish flats

appear to be a common feature of the granitic terrain as similar areas have been described in the Kruger National Park (Fraser 1983; Webber, 1979). Further down the slope towards the stream gullies is either a shallow continuation of calc-brak clays or 10 - 25 cm of dark grey skeletal, sandy, often stoney, excessively drained soils (Tinley, 1979). In the stream valleys a variety of sedimentary soils derived from colluvium and alluvium co-exist. These are sandy, silty or black clays.

Tinley (1979) describes this sequence of hill-crest sands, composite seepline grassland soils and clay-skeletal valley-slope slopes and bottomland alluvia as a repetitive series referred to as a catena. Overlying this basic catena sequence is the grid of dolerite dykes which weather to form red turf clays and black base saturated clays. Lime rich sandy clay islands of subsoil formed by hill-building termites are also common features of the area (Scholes, 1985).

2.2.5 Climate

In terms of Köppen's and Thornthwaite's Climatic Classifications (Schulze, 1947; 1958), the vast majority of the area in the Mpumalanga province lowveld incorporating the Sabi Sand Game Reserve forms one climatic region. In Koppen's Classification the reserve fits into the B Shw category, exhibiting a hot, dry, steppe climate with a dry winter and a mean annual temperature of over 18°C. According to Thornthwaite's criteria, the reserve has a semi-arid, warm climate (Db-d). Both classification systems show that the entire area is deficient in moisture in all seasons, (i.e. potential evapotranspiration exceeds precipitation, even in the rainy season).

The area experiences a unimodal sub-tropical savanna climate with a single rainy season in summer (October-April), followed by a single dry season in winter (May-September). Midsummer droughts often disrupt the rainfall sequence as exemplified by the 1978/79 and 1981/82 summers. The reserve is situated between the 700 mm isohyet in the south and the 550mm isohyet in the north, and thus falls into the transition between the arid and moist savanna biomes (Huntley, 1982). The area also experiences hot summers and cool to cold winters. Daily maximum temperatures average 30°C in summer and 23°C in winter. Daily

minimum temperatures average 18°C in summer and 8°C in winter (Schulze, 1965). Extreme temperatures have been recorded at -3°C in July and 44.5°C in November. The reserve is generally frost free, but in low lying areas frost may occur, usually in July. Mean annual evaporation (S-pan) is 1 600 mm and mean annual runoff is estimated at 10 to 20 mm (Midgley *et al.*, 1990)

2.2.6 Rainfall

Rainfall, in that it influences soil moisture and nutrient availability to plants, is a major factor in determining variation in the structure and composition of savannas. Long term annual rainfall records, exemplified by 34 year records for Skukuza, Kruger National Park, are shown in figure 2.7. Moist-arid sequences are also provided in figure 2.8. Two arid periods occur in the rainfall record; 1962 to 1970 and 1986 to 1994. The recent (1996) floods experienced in the area, suggest that this latter arid period may have ended. Smoothing of the annual data (5 year moving mean) gives the impression that the variation has a cyclic pattern with a period of between 16 and 20 years (figure 2.9). This cycle has been described as a consistent feature of the summer rainfall interior regions of southern Africa (Tyson, 1986). Proving its existence beyond reasonable doubt is difficult, given the short data record that is available, but tree ring studies have shown that it has been present for at least 300 years (Scholes and Walker, 1993).

The shorter term seasonal alternation of summer rains and autumn-winter-spring dry seasons epitomising the unimodal rainfall distribution is provided in figure 2.10.

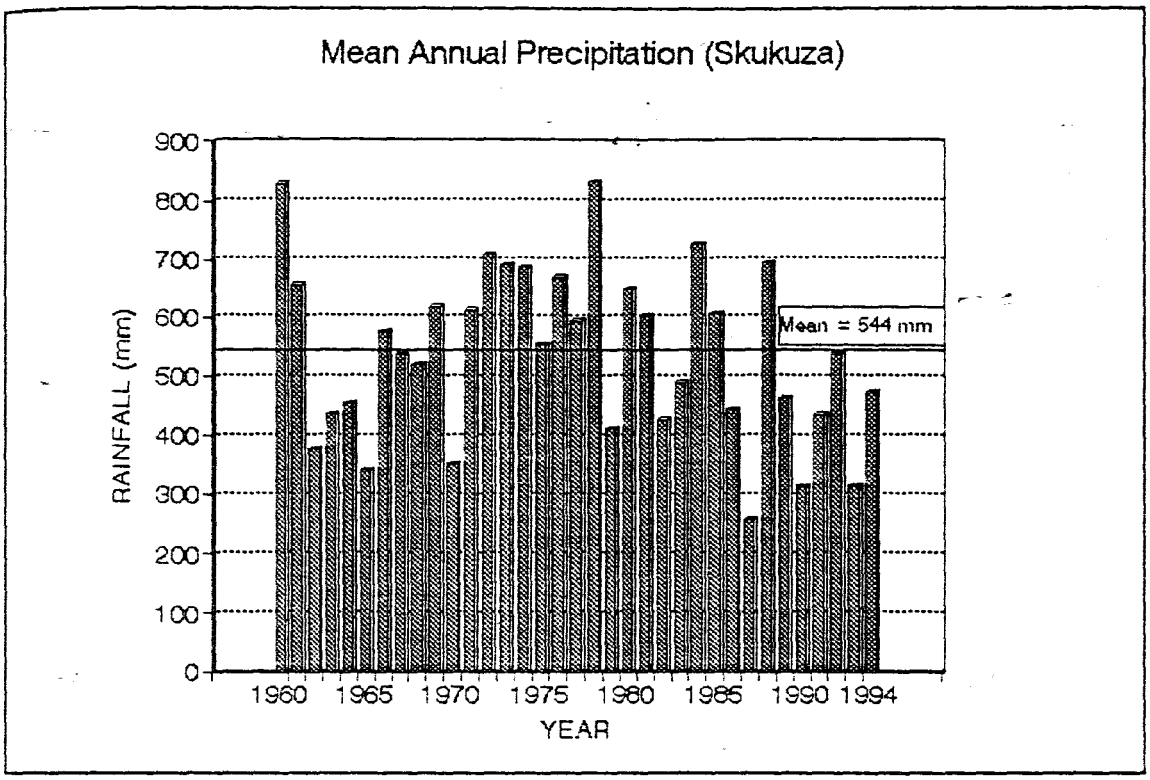

Figure 2.7. Long term rainfall record (34 years) for the Skukuza station.

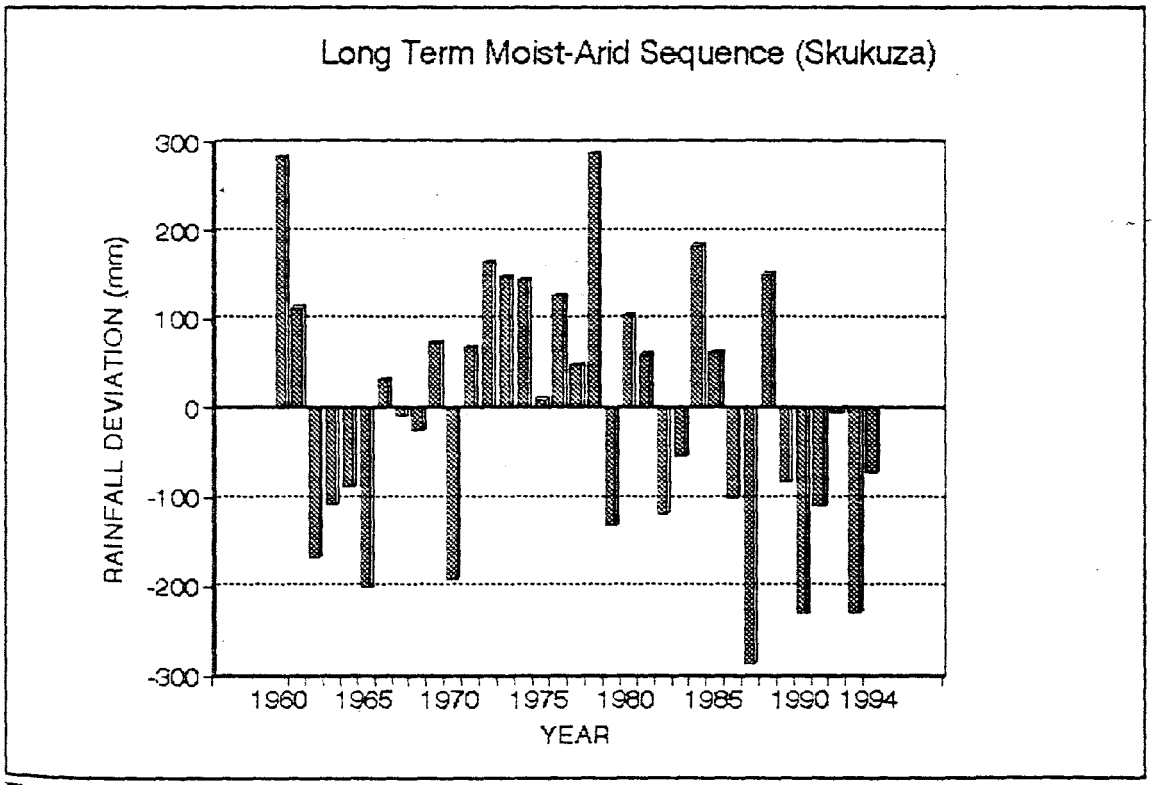

Figure 2.8. Long term moist-arid sequence for the Skukuza station.

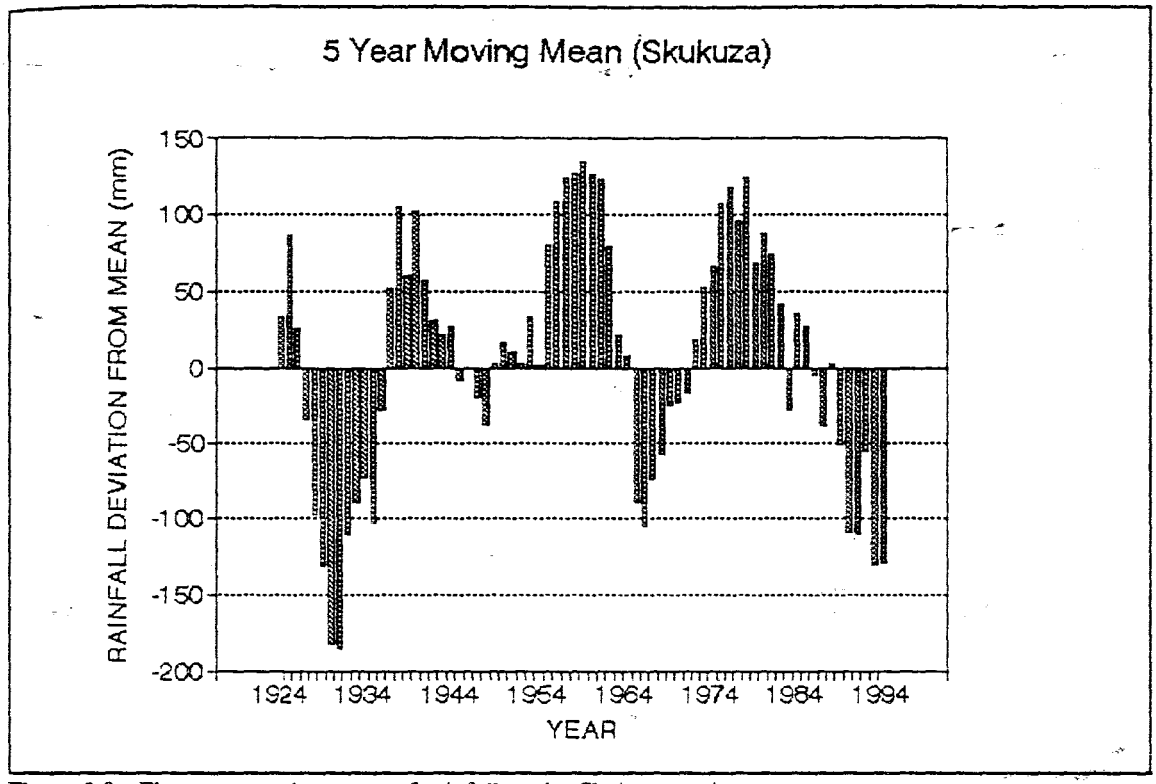

Figure 2.9. Five year moving mean of rainfall at the Skukuza station

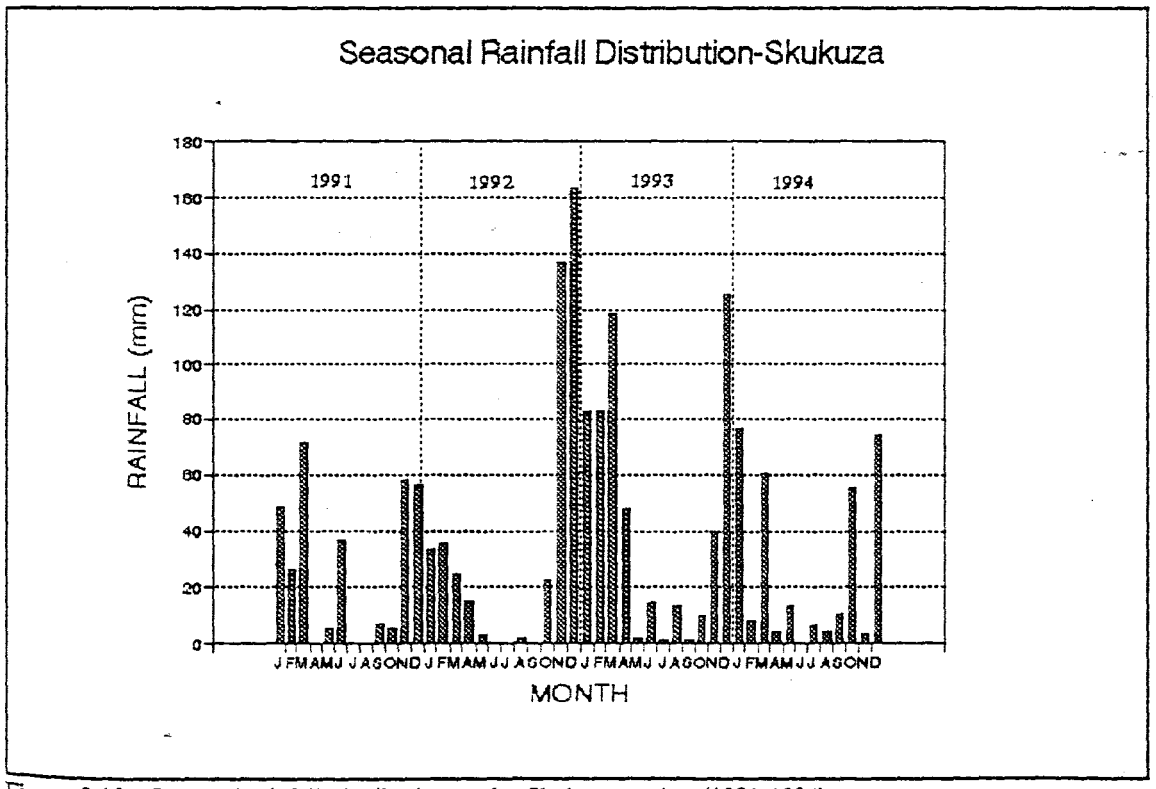

Figure 2.10. Seasonal rainfall distribution at the Skukuza station (1991-1994).

2.3 BIOTIC FACTORS

2.3.1. History

The pre-colonial landscape is often perceived to be free of the influence of human disturbance. However, hunter-gatherers and pastoralists occupied the area since at least the Middle Stone Age, more than 20 000 years ago, impacting on the landscape through burning and the use of wood (Scholes and Walker, 1993).

Between 1870 and 1890 the area was used extensively for hunting by white farmers. This initiated a period of wildlife decimation which was completed by rinderpest between 1896 and 1898, killing approximately 95 per cent of the cattle and antelope species (Scholes, 1985). Ironically, the rinderpest outbreak was also responsible for freeing the lowveld of the tsetse fly. Once malaria had been combatted by the liberal use of insecticides such as DDT in the early 1900's, the lowveld was finally transformed from an inhospitable wilderness to a region highly favourable for human settlement.

In 1922 the Transvaal Consolidated Land and Exploration Company began extensive cattle ranching (it is said that up to 2500 cattle were run at a time by 1934) in the area (Peel, 1991). In 1965, the Sabi Sand Game Reserve was finally proclaimed. Most of the reserve is now run on a commercial basis (mainly eco-tourism). It is used intensively and man-made changes to the landscape have been inevitable as a consequence of management decisions such as road construction, burning policies, bush clearing, and the construction of artificial water points.

2.3.2 Vegetation

The Sabi Sand Game Reserve incorporates the lowveld and arid lowveld veld types (Acocks, 1988). A description of the major systems and plant communities in the Sabi Sand Game Reserve is provided in table 2.1 (Tinley, 1979).

Table 2.1 Description of the major systems and plant communities in the Sabi Sand Game Reserve.

VEGETATION COMMUNITY	DESCRIPTION
AQUATIC COMMUNITIES	Running waters (streams, rapids)
	Still waters (pools, dams)
	Acid seepline bogs
GRASS COMMUNITIES	Floodplain
	Contour seepline
	Turf
	Termitaria
	Old fields and clearings
SAVANNA COMMUNITIES	Sand savanna (*Sclerocarya caffra/Combretum* spp.)
	Turf savanna (*Acacia nigrescens*)
	Mixed tree savanna of valley sides
	Short valley thorn savanna a. *Acacia tortilis/Acacia senegal.* b. *Acacia nilotica.*
THICKET COMMUNITIES	Riparian
	Calc-brak
	Termitaria
	Tree-base
	Rock outcrop

(Source: Tinley, 1979)

Four main plant community relationships have been identified in the Sabi Sand Game Reserve (Tinley, 1979). These include *Acacia nigrescens* turf savanna, sand savanna, contour seepline grasslands and sodic patches.

Acacia nigrescens turf savannas occur on shallow (not more than 80 cm deep), black clay soils derived from basalt. The dominant vegetation species are *Acacia nigrescens, Acacia robusta, Lannea stuhlmannii, Themeda triandra* and *Panicum coloratum*. Two variations of turf savanna can be distinguished; red and black turfveld (Acocks, 1988). The former is a fairly dense thornveld with brownish black soils, while the latter tends to be more open thornveld on black soils (plate 1).

Sand savannas occur on coarse, deep, acidic sands derived from granite. Generally, broad-leafed *Combretum* spp. occur on the upper slopes while *Acacia* spp. are found lower down the slope (van Wyk, 1972). The dominant tree types include *Combretum apiculatum, Combretum collinum, Combretum suluense* and *Combretum zeyheri* (Tinley, 1979). The largest trees tend to be scattered *Sclerocarya caffra. Acacia nigrescens* may also occur on Glenrosa soils (Webber, 1979). The main grasses are medium to long sour varieties including *Hyperthelia dissoluta, Perotis patens, Eragrostis rigidor, Pogonarthria squarrosa* and *Digitaria pentzili* (Tinley, 1979; Webber, 1979).

Contour seepline grasslands are part of the successional dynamics across topo-catena sequences developed on granite in the Mpumalanga lowveld (plate 2). They are characteristic seasonally waterlogged open bands of seepline grassland which occur along contours, where impervious saline sandy clays (derived from the weathering front of granite) come to the surface on the hill slope, from beneath a 2 to 3 metre mantle of red sand capping the hills (Tinley, 1982). The soils at the sand/clay contact are duplex acid white sands (groundwater podzols) on which seasonal sedge peat bogs develop in high rainfall years (Tinley, 1982).

Sodic patches (section 3.5) are also important pastures for wild ungulates. They are almost always bare of woody species, but are susceptible to encroachment by *Acacia exuvialis* and, to a lesser extent, *Euclea divinorum* (plate 3).

Plate 1. *Acacia nigrescens* turf savanna vegetation community. Note the dark clay soils derived from basalt.

Plate 2. Contour seepline grassland vegetation community. Note the invasion by the *Acacia* species from down catena on the right.

Plate 3. A typical example of a sodic site. Note the coppiced *Acacia* species on the right.

2.3.3 Wildlife

The main animal species which occur in the Sabi Sand Game Reserve are briefly described below. A more detailed account is given in Tinley (1979) and Peel (1991).

The main animal species in the Sabi Sand Game Reserve can be divided into three trophic groups (Tinley, 1979):

1. Short grass feeders which include impala, white rhino, wildebeest, waterbuck, hippo and warthog.
2. Medium to tall grass feeders which include buffalo, zebra and elephant.
3. Browsers and mixed feeders which include giraffe, kudu, and elephant.

Due to their efficient soil moisture balance the most important pastures are the black turf grasslands and the contour seepline grasslands, providing green grass deep into the dry season (Tinley, 1979; Webber, 1979). Buffalo, zebra, impala and white rhino mainly utilise the contour seepline grasslands whilst wildebeest and giraffe have a greater preference for the *Acacia nigrescens* turf savanna. Sodic patches are also utilised as the grasses growing on their characteristically sodium-rich soils accumulate high levels of this element in their leaves (Bailey, 1990). Animals are also known to lick the soil to compensate for salt deficiencies (Weir, 1971).

2.4 SUMMARY

The Sabi Sand Game Reserve experiences a unimodal semi-arid warm climate with a single rainy season in summer, followed by a single rainy season in winter. It occurs at a low elevation on predominantly granite-gneiss bedrock, between the sub-tropical lowveld plain and the foothills of the escarpment. Soils are generally deep, infertile and slightly acidic but may be dominated by 'high activity clays' where they occur on basic lavas. The vegetation is relatively homogenous and supports a wide diversity of wildlife.

CHAPTER 3

KEY MANAGEMENT DECISIONS AND THEIR EFFECTS IN THE SABI SAND GAME RESERVE

"African game parks have lost their innocence - either they are too small and are surrounded by fences, or they are subject to increasing pressures from human population on their borders. Under these circumstances, a game park is not a pristine, natural ecosystem, but a human artifice, and management decisions need to be justified" (Starfield and Beloch, 1991, pp 24).

3.1 INTRODUCTION

A key issue facing game reserve management is whether or not regulation should be applied to sites (Scholes, 1985). As game parks in African savannas are partly, if not totally, fenced in, the decision to regulate often has to be adopted. Human pressures on the borders of the reserves and economic factors influence the decisions to regulate. This decision has a profound effect on the environment. To learn the extent and effect of these regulations, managers therefore require crucial spatially significant information regarding landscape patterns and processes.

This chapter deals with the types of regulations adopted in the Sabi Sand Game Reserve. The effects of these regulations on the landscape, and the relevant information required by managers to determine their respective functioning at the landscape scale are also reviewed.

3.2 CROPPING

Migrations of large herds of ungulates were once a common feature of African savannas (Starfield and Beloch, 1991). Today, fences either restrict migrations or prevent them altogether. These migratory restrictions demand regulation in the form of cropping (culling or removal) of certain animal species in the Sabi Sand Game Reserve in order to:

- prevent predators from moving out of the reserve. An increase in predator numbers may cause some to leave the reserve in search of prey. This can create unwanted conflicts with surrounding farmers;
- protect a rare animal or plant species (for example roan antelope introduced on various properties);
- prevent animal species that have been too successfully protected from damaging their environment (for example impala);
- control disease;
- finance the maintenance of the park (for example professional hunters pay to cull on various properties).

Herbivore numbers are limited, not by the total amount of plant material produced by the ecosystem, but by the quantity of nutritious palatable and accessible food (Scholes, 1985). The assessment of veld condition and the use of this measurement to estimate an approximate stocking rate incorporates information on species composition and abundance, basal cover, topography and soil erodibility (Tainton, 1981).

3.3 THE CONSTRUCTION OF ARTIFICIAL WATER POINTS

Fences not only restrict animal migration but also cut off natural water supplies, and as a result, artificial water points often have to be constructed. In the Sabi Sand Game Reserve, this problem was overcome when the Sabi Sand management decided to remove the fences on the southern and eastern borders thereby incorporating it into the Kruger National Park, albeit with separate management policies. Although this allowed renewed access to many natural, permanent water supplies such as the Sabie, Olifants, Crocodile and Letaba rivers,

artificial water supplies are still extensively used. Most wild herbivores are concentrated within five to six kilometres of surface water (Scholes, 1985) and being the major tourist attraction, the game are thereby encouraged to remain close to the water sources in the reserve. Artificial water supplies also allow the wildlife to fully utilise the natural resource base, sometimes to the extent that they become over utilised. When this occurs, there is a resultant loss in topsoil that accelerates soil erosion to unnatural levels (Scholes, 1985). This is a direct consequence of increased herbivore activity around the water point which effectively reduces the vegetation cover.

3.4 THE USE OF FIRES

There is no such thing as a savanna which does not burn: the only management choice is between planned and unplanned fires (Scholes and Walker, 1993). Fire used judiciously in combination with grazing, can improve species diversity (Hartnett *et al.*, 1996), ameliorate overgrazed patch formation (Andrew, 1986), and maintain a desirable range condition (Llorens, 1996). There is well-documented literature suggesting that fires suppress woody vegetation while enhancing grass production. (Scholes and Walker, 1993; Starfield and Beloch, 1991; Tinley, 1982). Fires also promote coppicing and lower the mean height of the tree canopy, thereby increasing the amount of leaf available to browsers (Barnes, 1982; Scholes and Walker, 1993). Furthermore, fires remove the moribund grass layer, which stimulates the production of a fresh flush of nutritious grass for grazers (Starfield and Beloch, 1991).

Natural fires (principally caused by lightning), were once a common feature of African savannas (Scholes and Walker, 1993). Increasing pressures by human populations have negated the extent of natural fires in recent times. Decision makers in the Sabi Sand Game Reserve have therefore been forced to adopt burning policies. The decision to burn is usually adopted if active bush encroachment has taken place or if sufficient moribund grass biomass is available to warrant the decision (Starfield and Beloch, 1991). Managers need accurate information regarding changes in shrub density as well as the extent to which grasses have become moribund to assist in their decisions.

3.5 MECHANICAL BUSHCLEARING

Woody plants increase in savannas at the expense of grasses when the grazing pressure is increased and the frequency and the intensity of burning is reduced (Scholes and Walker, 1993). This tendency can be halted, but is not easy to reverse, even with reduced grazing and increased burning. Managers therefore need to conduct mechanical bushclearing and burning and reduce animal numbers. In the Sabi Sand Game Reserve this decision is primarily adopted to repress bush encroachment, but often includes ulterior motives, which are influenced by underlying economic factors.

These factors stem from the fact that the Sabi Sand Game Reserve consists of twenty nine privately owned farms, most of which offer exclusive accommodation in game lodges. This has created an economically competitive environment where lodges try to guarantee tourists sightings of the 'Big Five'. The dense bush cover of the savanna in the reserve is however not conducive to suitable game viewing. Mechanical bushclearing is therefore adopted primarily to prevent bush encroachment, but also to concentrate game into 'viewing friendly' sites, which can be up to 25 ha in extent. It involves the systematic removal of woody species and is often combined with the mowing of grass species and the introduction of water points

The reduction of woody plant cover mechanically, together with the loss of grass cover by heavy grazing, results in erosion and inevitably a loss in topsoil (Chappell and Brown, 1993). On bottomlands and footslopes with granitic soils this process can continue until the entire A-horizon is eroded, resulting in the formation of sodic patches. Following the loss of topsoil the exposed clays of the B-horizon do not provide a suitable seedbed for the reestablishment of grass cover and these areas appear as bare open patches in the landscape (Scholes, 1986). Numerous observations in the form of game tracks that cross and recross these areas, the formation of wallows, the abundant deposits of dung and in many instances the formation of large middens, indicate that these areas are favoured by many species of game, even when grass cover has been reduced to less than 10 per cent (Chappell and Brown, 1993).

Areas that have reduced grass cover allow for maximal penetration and retention of rain and here dense woody plant invasion of thicket can occur (Tinley, 1982). Shrub encroachment is a function of soil moisture change when the grasses are removed from competition by overgrazing (Walter, 1971; Walter and Volk, 1954). In sodic patches in the Sabi Sand Game Reserve, encroachment by *Acacia exuvialis* is particularly common. The reduction in grass cover, the concentration of nutrients from dunging and the fact that this species is usually unpalatable or not preferred, are the collective causes its invasion.

Acacia exuvialis is controlled by bushcutting, which results in coppicing (Barnes, 1982). The process often continues until the opportunity cost of reclearing is too high. In such cases, dense thickets form which concentrate nutrients in the canopy, effectively out-competing the grasses and thus reduce the diversity and carrying capacity of the landscape. Burning as a regulatory control for these thickets is complicated by the high resistance of this species to fire and the lack of a grassy fuel load (Palmer, *pers.comm.*, 1995).

Any management practice that promotes high grazer concentrations on these sites has the potential for accelerating the destruction of the grass cover and promoting sodic patch expansion (Chappell and Brown, 1993). It is thus vital that managers in the Sabi Sand Game Reserve, acquire an impression of the extent of sodic patch formation.

3.6 SUMMARY

Climatic, edaphic and topographic factors may have major influences upon the spatial distribution, composition and productivity of the vegetation in an area (Wiens, 1985). Superimposed on these basic environment-vegetation patch dynamics are the effects of disturbances. Most disturbance of an existing environment-vegetation mosaic is through erosion by water or wind, fire or the actions of animals in disturbing the soil. In the Sabi Sand Game Reserve, the latter is induced by mechanical bushclearing, mowing and the introduction of water points. This has a marked effect on the landscape, often resulting in the loss of topsoil or the invasion of thicket. Managers thus require spatial information concerning the processes that drive these negative impacts.

CHAPTER 4

CO-EXISTENCE MODELS IN SAVANNA: A REVIEW

Future research in landscape ecology should be orientated toward the testing of hypotheses and spatial models, using spatial data (Turner and Gardner, 1991).

4.1 INTRODUCTION

Until the middle of this century, woodlands and forests dominated much of sub-Saharan Africa. In the 1950's and 1960's thousands of square kilometres of woodlands were converted to open savanna. Many scientists in the 1960's and 1970's viewed this loss of woodlands as a permanent catastrophic event (Beuchner and Dawkins, 1961; Laws, 1970). Others proposed that these vegetational changes were short lived or essentially cyclic in nature. As a consequence, several theoretical mechanisms have been proposed in order to explain or allow for the co-existence of apparently competing species (grasses and trees). These theories can effectively be divided into two groups; equilibrium and disequilibrium models.

The following sections will review these theories and provide a description of the fundamental principles on which they are based.

4.2 DISEQUILIBRIUM MODELS

Co-existence in disequilibrium models is usually explained by the domination of one competitor. Multiple stable-state models and cyclic models are two examples.

4.2.1 Multiple Stable-State Models

Multiple stable-state models represent the long dominant view of East African savanna, in which several stable vegetation types exist (figure 4.1). Catastrophic events (disease or uncontrolled population growth of a dominant herbivore) are seen to cause one vegetation type to be replaced by another, which remains unchanged until the next catastrophic event. An example is the uncontrolled growth of elephant numbers in the Serengeti National Park, Kenya which was probably the main cause for woodlands to be converted to grasslands (Lamprey *et al.*, 1967).

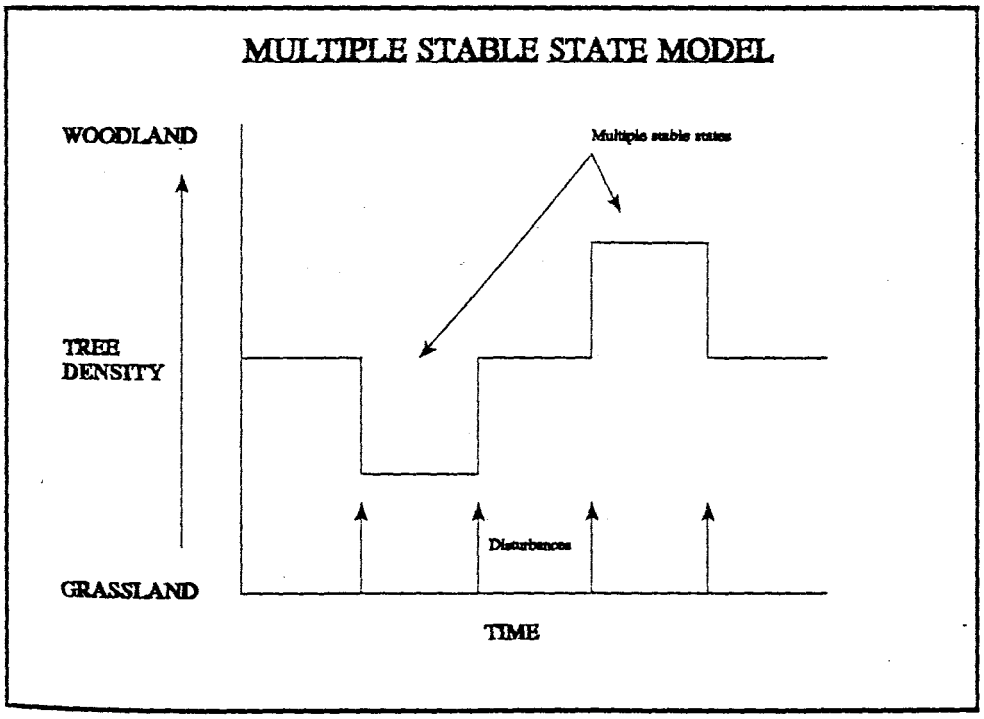

Figure 4.1 Multiple stable-state model, explaining temporal fluctuations between grasslands and woodlands. Adapted from Belsky, (1995).

4.2.2 Cyclic Models

Cyclic models suggest that populations or communities cycle continuously between various phases (figure 4.2). Caughley (1976) suggested that African woodland ecosystems, that include elephants, can never reach a natural stable equilibrium. This occurs when high elephant numbers cause woodlands to be destroyed and as a direct result cause their own numbers to decline, as their food source slowly starts to diminish. With lower elephant numbers, the woodlands regenerate creating an improved habitat for the elephants. As the elephant numbers subsequently increase the whole cycle is repeated again. The main feature of these models is that vegetation fluxes between several types.

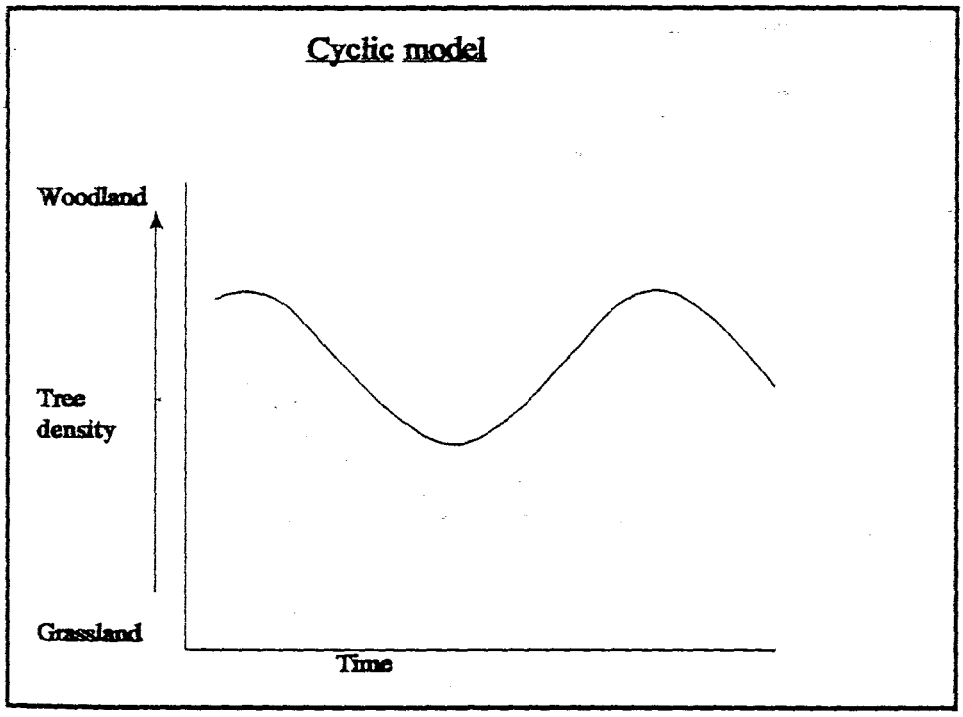

Figure 4.2 Cyclic model explaining temporal fluctuation between grasslands and woodlands. Adapted from Belsky, (1995).

The principal problem with disequilibrium models is the fact that they generally imply local disequilibrium and tend to neglect the fact that on a larger scale, the landscape as a whole may be in equilibrium.

4.3 EQUILIBRIUM MODELS

4.3.1 The Walter Model

The classic equilibrium model for co-existence in savanna is that proposed by Walter (1971). It states that the essential feature of savanna vegetation is the alternating wet and dry soil phase and that grasses are superior in surface horizons of soils, with trees having exclusive access to deeper layers. Walter (1971) perceived savannas as 'natural' systems, rather than a tree-grass vegetation mixture anthropogenically derived from woodlands. The conditions necessary for the existence of these natural savannas are shown in figure 4.3.

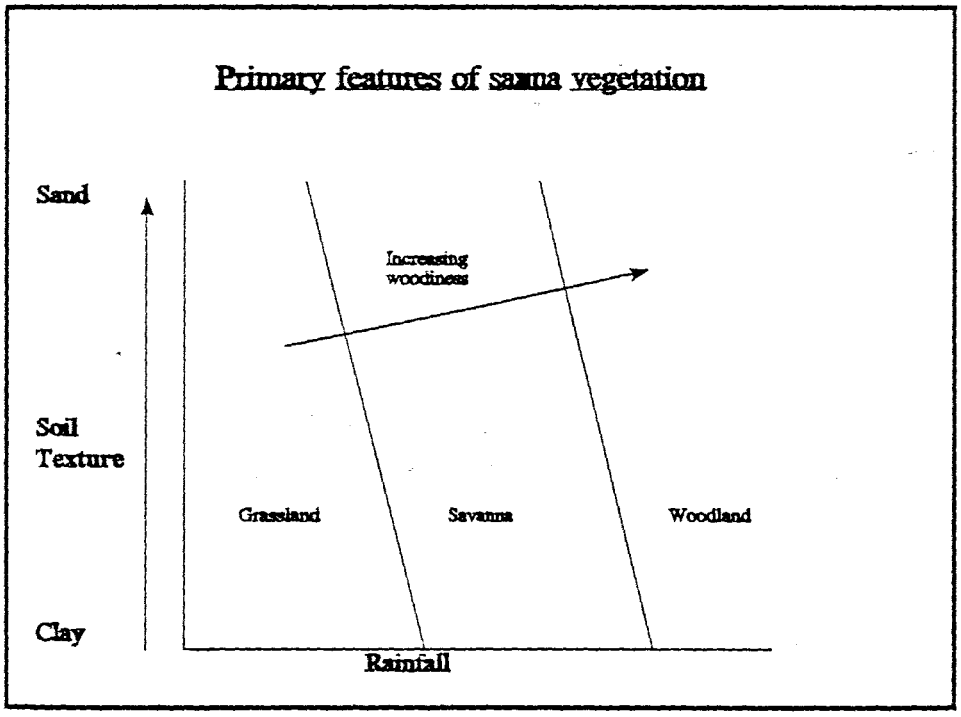

Figure 4.3 The soil and rainfall conditions required for natural savannas as proposed by Walter (1973).

4.3.2 Refinement of the Walter Model

The Walter (1973) hypothesis was modified by Walker and Noy-Meir, (1982) who modelled interspecific competition between herbaceous and woody species for available soil water. They essentially suggest that grasses out-compete woody plants in the topsoil, owing to the nature of their root systems, and woody vegetation out-competes grasses where topsoil is lacking (for example rocky slopes), or where the soil has a very low water holding capacity (for example deep sands). They demonstrated the existence of dual equilibrium states in systems where the soil infiltration capacity declined with reduced grazing cover. One state is a tree-grass mixture whilst the other is a thicket with virtually no grass. They attributed deflections of the system away from these equilibrium positions to disturbances (fire, drought, intensive grazing) and contended that the savanna vegetation eventually returns to the equilibrium position (figure 4.4)

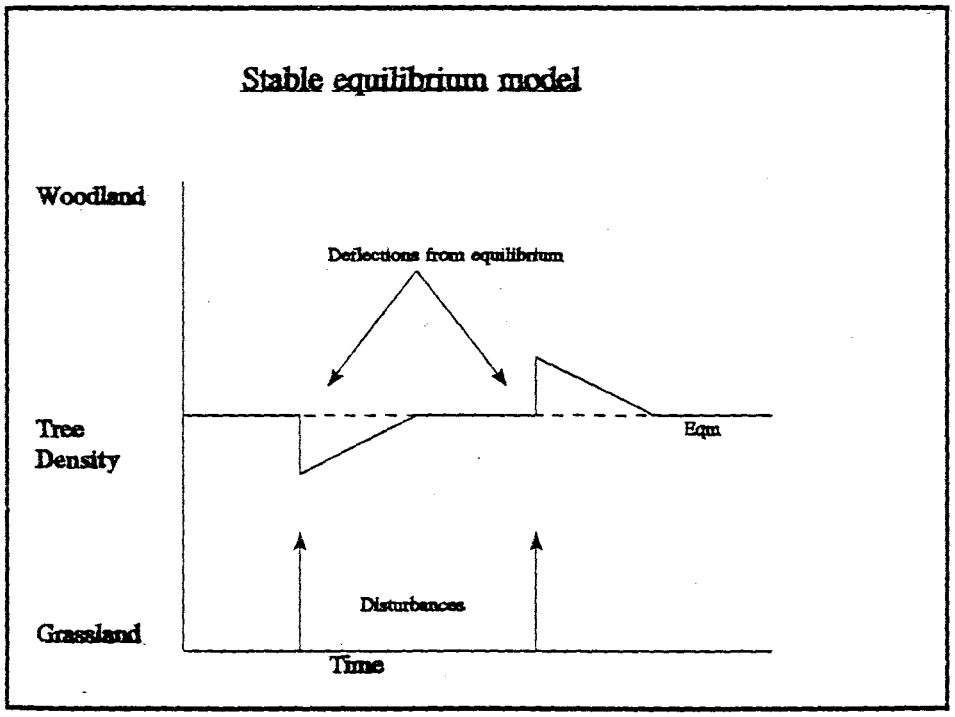

Figure 4.4 Stable equilibrium model proposed by Walker and Noy-Meir (1982).

4.4 ALTERNATIVE MODELS

Scholes and Walker (1993) showed that the models described above were generated under the conventional view of ecosystems, which was one of reasonably stable entities when left to their own devices. They contend that at present, savannas are seen as frequently being far from equilibrium with a structure and function largely driven by disturbance.

Their model is based on research conducted by Knoop and Walker (1984) who found that in both broad and fine leafed savanna, grass roots were able to use subsoil water as effectively as tree roots and that tree roots dried out the topsoil as rapidly and completely as grass roots alone. Scholes and Walker (1993) used their savanna hydrology model to show that there is strikingly little separation between the depth at which grasses and trees extract their water, but significant differences in temporal patterns (figures 4.5 and 4.6). The temporal tree water use niche totally includes the grass temporal niche at the whole season scale (figure 4.6). Scholes and Walker (1993) contend that this situation can lead to an equilibrium solution for co-existence only if the competitor with the included niche has a much higher resource use efficiency than the competitor with the broader niche. Results from their data suggest that there is little difference between trees and grasses with respect to water use efficiency. Furthermore savannas, with their tree components removed, have never been found to have higher productivity than the combined tree and grass system (Scholes, 1987).

Scholes and Walker (1993) therefore reject the 'Walter Hypothesis'. They contend that water enters the soil from above, and that most storms only wet the surface horizons. As a consequence, trees and grasses are forced to use the same water source for the bulk of their needs. The fact that trees have deeper roots than grasses merely aids them in survival during severe water deficiencies, as in times of drought.

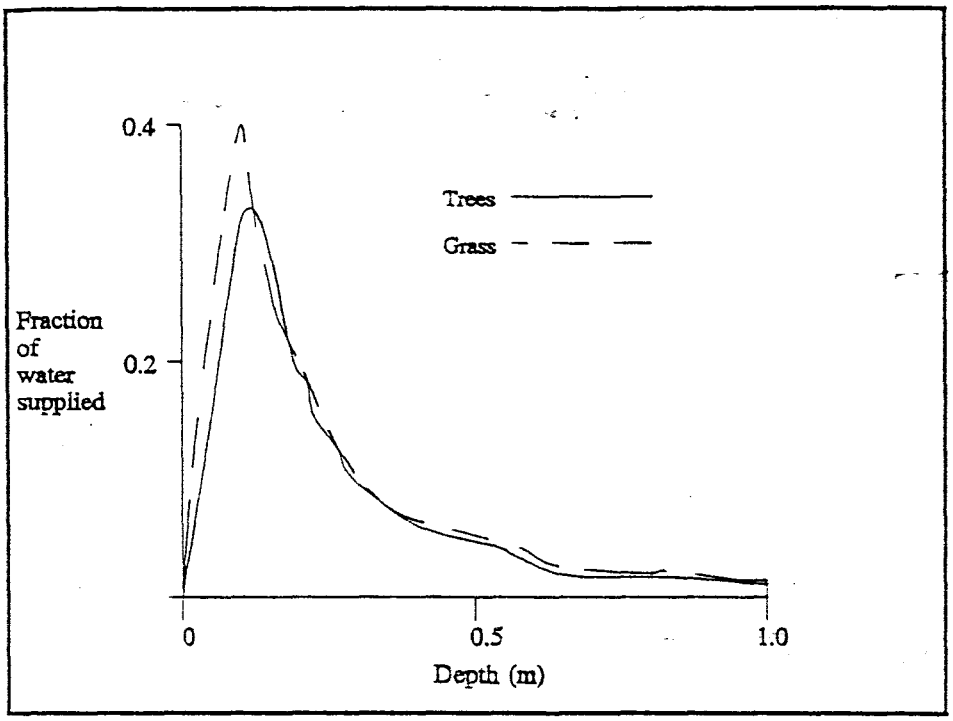

Figure 4.5 Spatial patterns of water use by trees and grasses as depicted by the Scholes and Walker (1993) savanna hydrology model.

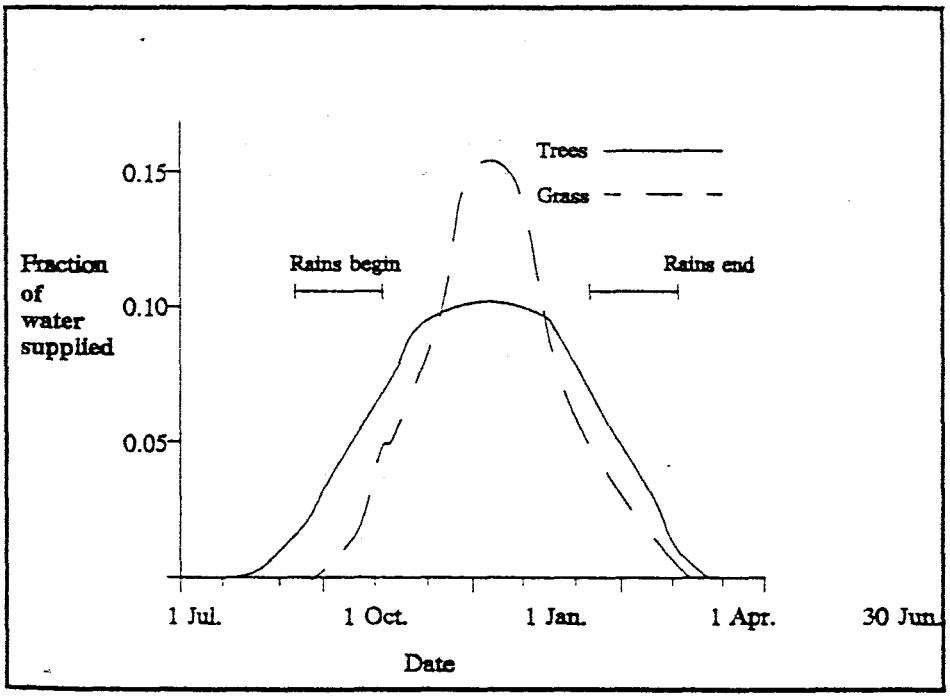

Figure 4.6. Temporal patterns of water use by trees and grasses as depicted by the Scholes and Walker (1993) savanna hydrology model.

Scholes and Walker (1993) further question the assumption that water is the common limited resource on which the tree grass co-existence mechanism depends. Evidence presented in their work suggests the following:

1. Water acts as an on-off switch to savanna processes and therefore controls the duration of growth, not the rate.
2. Production in savanna plants is not constrained by their carbon metabolism, but their nitrogen metabolism.
3. Nitrogen assimilation is controlled by the nitrogen mineralisation rate which is in turn controlled by water availability.

They argue that the immediate limiting resource in the broad leafed savanna at Nylsvley, Mpumalanga and possibly many other savannas as well, is nitrogen, and the key effect of water is to control the availability of inorganic nitrogen, not the control of photosynthesis. They explain that this would go a long way to explaining the non-linear relationship between grasses and trees. It would also explain why the degree of non-linearity of this relationship increases as the productive potential of the site declines. Scholes and Walker (1993) therefore adopt the alternative view of co-dominance which is that the tree-grass mixture in savanna is inherently unstable. Woodiness will increase in the absence of disturbances which control woody plant biomass until growth is limited by competition with other trees. Trees have a suppressive effect on grass production but grasses only have a suppressive effect on tree seedlings and not mature trees. When the grass layer is reduced by heavy and continuous grazing tree seedlings can grow beyond the control of grass competition and fire, and the result is bush encroachment. Other research carried out in the savanna of the lowveld tends to concur with the notion that stability is rarely attained (Shackleton, 1993).

4.5 THRESHOLD MODELS

Several studies have suggested that the landscape has critical thresholds at which ecological processes will show dramatic qualitative changes (Gardner *et al.*, 1987; Gosz and Sharpe, 1989; Krummel *et al.*, 1987; O'Neill *et al.*, 1988; Rosen, 1989). This concept was developed in savanna as early as the mid 1970's. Holling (1973) recognized the possibility of one or more distinct domains of attraction, to explain the co-existence of trees and grasses. Holling (1973) proposed that tree-grass co-existence occurs within threshold levels, which once crossed, cause the system to move into a new domain of attraction. He notes that there may be one or more domains of attraction in which the important point is not so much how stable they are within the domain, but how likely it is for the system to move from one domain into another and so persist in a changed configuration.

4.6 SUMMARY

There are many conflicting theories which attempt to explain the co-existence of grasses and trees in savannas. These theories need to be quantified, understood and interpreted in order to glean a better understanding of the functional aspects of ecosystem dynamics. One approach is to explicitly link remote sensing information of actual vegetation structure to biogeochemichal models thereby using information on ecosystem structure to drive models of ecosystem function (Wessman *et al.*, 1995). Although this principal is only applied to the savanna at the Sabi Sand Game Reserve, it is hoped that its general potential in other savannas and possibly even other biomes can be established.

CHAPTER 5

METHODS

Variance generated by patch dynamics is likely to be one of the most important constraints on non-experimental sampling strategies, although this factor has seldom been considered in designing field sampling projects (Pickett and White, 1985).

5.1 INTRODUCTION

This chapter deals with the data sources and methods undertaken in the research. There are three parts; data sources, digital image processing methods and Ground Control Point (GCP) data collection methods. The reader is referred to appendix 2 for a review of the fundamental principles involved with image processing.

5.2 DATA AND SOFTWARE

5.2.1 Satellite Imagery Used in the Study

This study concentrated on the use of remotely sensed data obtained from a multispectral sensor on an orbiting space platform. The imagery type used was LANDSAT Thematic Mapper (TM). An overview of remote sensing and the LANDSAT series is provided in appendix 2. Attributes of the imagery are described in table 5.1.

Table 5.1. Imagery available for the study

Satellite Sensor	Date of Capture	Scene ID Number	Processing Level	Cloud Cover
LANDSAT TM	1989/04/19	168-0-077	5	0

The imagery was purchased from the Satellite Applications Centre (SAC) in Pretoria at a processing level of 5 (table 5.2). Geometric corrections therefore had to be applied to the data and will be discussed in section 5.3.1

Table 5.2. Corrections applied at each processing level

Processing level	Corrections Applied
4	Radiometrically corrected. Geometric corrections are applied in the along-scan direction only. The scene is not corrected to a projection and the orientation is not changed
5	Radiometrically corrected. Geometric corrections are applied in both the along-scan and across-scan directions using spacecraft orbital and attitude information. The scene is corrected to a map projection, but the orientation is not changed.
6	Radiometrically corrected. Geometric corrections are applied in both the along-scan and across-scan directions, using GCPs. The scene is corrected to a map projection, but the orientation is not changed
8	Radiometrically corrected. Geometric corrections are applied in both the along-scan and across-scan directions, using spacecraft orbital and attitude information. The scene is corrected and aligned to a map projection.
9	Radiometrically corrected. Geometric corrections are applied in both the along-scan and across-scan directions, using GCPs. The scene is corrected and aligned to a map projection

(Source: SAC MIKOMTEK, 1995)

5.2.2 Geographic Information Systems (GIS)

As satellite images are captured on a pixel by pixel basis, the raster based GIS, IDRISI (Eastman, 1992) was used. IDRISI is designed to provide professional-level geographic research tools on a low-cost non-profit basis. ARCINFO a vector based GIS was also applied when capturing cadastral information such as farm boundaries, roads and rivers from topographic maps.

5.2.3 Ancillary Data Sources

5.2.3.1 Scanned Map

Tinley (1979) produced a vegetation map of the Sabi Sand Game Reserve from án extensive ground survey conducted between 1977 and 1978. This map was used as an independant data source to assess the accuracy of the multispectral classification. It was scanned on a Genius colour page 1, 24-bit scanner at a resolution of 300 dots per inch with 256 colours.

5.2.3.2 Topographic Maps

There are six 1:50 000 topographic maps (15' S by 15' E) which cover the Sabi Sand Game Reserve, 2431 CA, 2431 CB, 2431 CC, 2431 CD, 2431 DA and 2431 DB. They were used to obtain the following information:

- GCPs for use in the geometric correction (section 5.3.1 and appendix 2) of the satellite imagery and the scanned map.
- Farm boundaries, roads and rivers. These were captured through digitizing using ARCINFO. The vectors were later converted to IDRISI using the ARCIDRIS module. They serve not only to enhance the information on the final output, but also act as an independant data set for the accuracy assessment of the geometric corrections applied to the imagery.

In addition to these maps, the 1:250 000 geological and land use maps were used to describe the geology (section 2.2.3) and soils (section 2.2.4) respectively.

5.2.3.3 Rainfall Data

Rainfall data acquired from the Computing Centre for Water Research (CCWR), Pietermaritzburg were used to determine how the monthly precipitation recorded at the time of image capture compared with the mean monthly precipitation recorded over the past decades. The year 1989 was a relatively dry year deviating below the mean by more than 100 mm (figure 2.8). The scanned map (Tinley, 1979) was produced between 1971 and 1972;

both relatively wet years of above mean rainfall (figure 2.8).

5.2.3.4 Aerial Photographs

Eleven aerial photographs captured in July, 1984 were used in the study for various visual interpretations such as verification of the bare sodic patches.

5.2.3.5 Digital Elevation Model (DEM)

A DEM of the study area was acquired from the Director General, Surveys and Mapping, in Mowbray, Cape Town. The raster data were extracted from spot heights every 400 m from 1:20 000 orthophoto maps (figure 2.4).

5.3 DIGITAL IMAGE PROCESSING METHODS

5.3.1 Image Rectification

The RESAMPLE module of IDRISI (Eastman, 1992) was used to register the LANDSAT Thematic Mapper (TM) data, as well as the scanned vegetation map produced by Tinley (1979). RESAMPLE undertakes a 'rubber-sheet' transformation of an image using a linear, quadratic or cubic polynomial equation (Eastman, 1992). The equation is used in the transformation of data from one grid to the other by a nearest neighbour or a bilinear interpolation technique. RESAMPLE requires information from three grid systems; the input grid, an intermediate reference grid, and an output grid. For convenience, the reference grid chosen for this study was the Gauss Conform projection, which is the standard for the 1:50 000 South African map series. A representative sample of twenty GCPs was collected from the relevant 1:50 000 map sheets, incorporating road intersections, farm boundary intersections and airstrips. The GCPs were deliberately chosen so that a somewhat greater number of well distributed control points occurred around the edges of the input image. This is essential for the provision of a 'stable fit' (Eastman, 1992). Of the twenty GCPs collected, only ten were used in the actual resampling of the imagery, the remainder being required to

check the accuracy of the resampled image.

RESAMPLE uses the GCP data to establish a polynomial 'mapping function' to relate positions in the input image with corresponding positions in the output image (Eastman, 1992). The lowest order of polynomial; linear, was chosen as the effect of poor control point specification gets dramatically worse as the order of equation used increases. Although the linear polynomial only requires a minimum of three GCPs, at least double is recommended by Eastman (1992).

Once the polynomial has been solved, the output image is created. The process works by moving through each output pixel and determining its position within the input image to establish an appropriate output value. Since it is unlikely that the centre of the output pixel exactly corresponds with the position of the centre of a pixel in the input image, a new value is derived by one of two techniques. In a nearest neighbour interpolation, the value of the closest input cell to the position of the output cell is transferred. In the case of a bilinear interpolation, a linear distance-weighted average of the four closest cells is used (Eastman, 1992).

The bilinear interpolation process was chosen for this study as it produces a smoother result (Bernstein, 1983). Although this process modifies output digital numbers (DNs) from their original DNs, this did not present a problem, as the image enhancement and information extraction components were all carried out on the resampled images.

The ten GCP's used to check the accuracy of the image rectification showed a root mean square (RMS) error of less than 30m (1 TM pixel) for both the TM data and the Tinley (1979) scanned map. This degree of accuracy is considered to be acceptable (Bernstein, 1978). An ARCINFO vector file, containing farm boundaries digitised from 1:50 000 map sheets, was also used as an external data set to visually assess the accuracy of the rectification. This is demonstrated in fig 6.13.

5.3.2 The Use of Vegetation Indices

5.3.2.1 Normalized Differentiation Vegetation Index (NDVI)

The NDVI is an index which is sensitive to photosynthetically active, green vegetation. It is based on the fact that photosynthetically active plants reflect more light in the near infra-red part of the spectrum than less active plants (Rouse *et al.*, 1973; Wessman *et al.*, 1995). Ground-based NDVI measurements are well correlated with canopy absorbed photosynthetically active radiation (APAR) (Asrar *et al.*, 1984; Bartlett *et al.*,1990; Hartfield *et al.*, 1984), leaf area index (Asrar *et al.*, 1986), biomass (Tucker *et al.*, 1976; 1983) and above-ground production (Reich and Hussin, 1993). NDVI values range between negative one and positive one. Negative values are generally insignificant as they depict areas of high reflectance. Positive values however, represent increasingly active sites of vegetation as they approach the value of one. While the pixel scale value of the NDVI can be significantly influenced by plant canopy geometry, vegetational fractional cover and variation in background, several studies have shown its general utility for large scale extrapolations of APAR (Fortescue, 1994; Lourens, 1990; Sellers *et al.*, 1992).

The NDVI is defined by the following equation:

$$NDVI = (IR - Red) / (IR + Red)$$

where: IR = TM band 4
Red = TM band 3

The Normalized Ratio option of the OVERLAY module in IDRISI was used to create NDVI images for both sets of imagery. The HISTO option was used to determine the histogram of the NDVI images with the mean and standard deviation values. NDVI values were determined for corresponding GCPs using the QUERY option. Query allows pixels defined by GCP co-ordinate data, to be extracted to an output file. The output file is then combined into the spreadsheet with the GCP data (appendix 3).

5.3.2.2 Determination of Mean NDVI Values Around Water Points

Ground data was collected from 55 water points scattered throughout the four vegetation communities; open and closed sand savanna, sodic patches and turf savannas. In order to determine the extent of disturbance around these water points, mean NDVI values were determined for the 8, 24 and 48 surrounding pixels, corresponding to distances of 45 m, 75 m and 105m respectively (figure 5.1). This was achieved by producing three window images for each water point. Mean values were calculated using the HISTO module in IDRISI.

The average for the 8 pixels was compared to the mean NDVI value for the vegetation community in which the water point occurred. As managers require information on water points which are being heavily utilised, 8 pixel mean values which fell below the respective vegetation community averages were not included in the results section. This was based on the fact that high NDVI values depict areas of disturbance or degradation (section 7.2.3). Where water points were greater than 1 TM pixel (30 m), the 24 pixel means were utilised for this purpose. NDVI gradients with distance from water points are therefore only provided for water points which are heavily utilised (section 6.1.2).

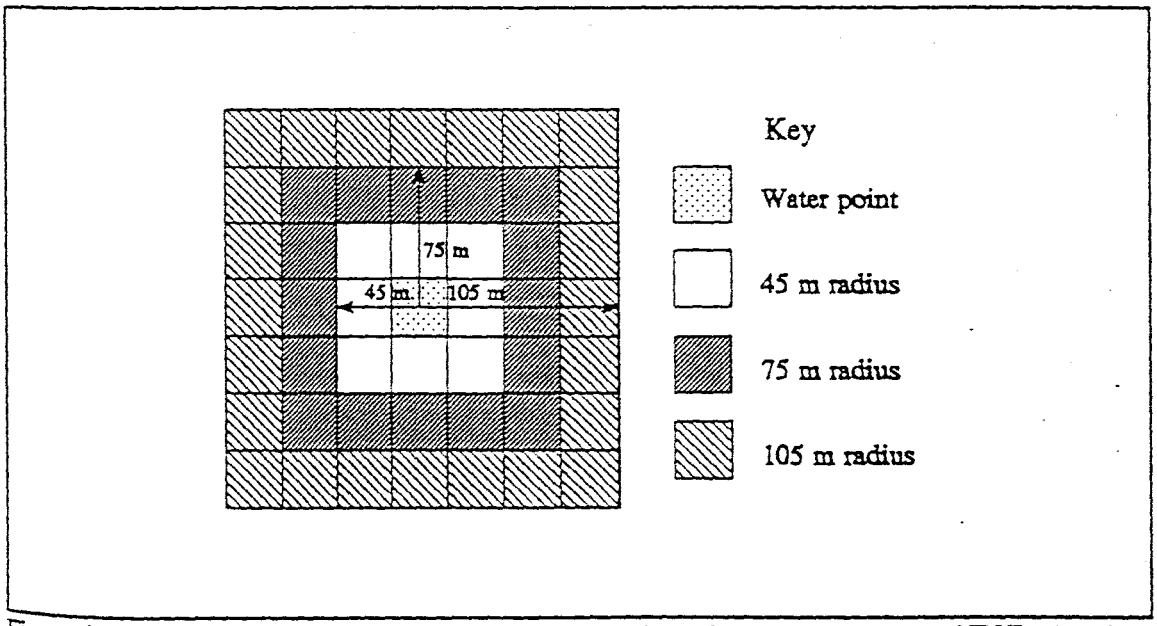

Figure 5.1 Diagrammatic representation of the method employed in extracting the mean NDVI values from the 8, 24 and 48 pixels surrounding water points.

5.3.2.3 Landscape Diversity Indices

The standard deviation index is a landscape diversity index which describes landscape spatial variability in order to interpret landscape condition, using the standard deviation of attributes of pixels in the sample area (Baker and Cai, 1992). It is based on the hypothesis that healthy/undisturbed/stable landscapes tend to be less variable and homogenous than their degraded heterogenous counterparts. This is attributed to the redistribution of water and nutrients that occurs when a landscape moves out of equilibrium and tends towards a non-equilibrium state (Ludwig and Tongway, 1997).

Tanser (1997), demonstrated in the eutrophic semi-arid savanna of the Eastern Cape, South Africa, that degraded areas exhibit high Moving Standard Deviation Index (MSDI) values whilst undisturbed or well managed areas exhibit low MSDI values. It was also noted that the MSDI, in conjunction with conventional vegetation indices, can assist in the identification of invading shrubs, woody weeds and less palatable grasses which do not necessarily demonstrate a reduction in production and are therefore not identified by non-textural vegetation indices exclusively.

The MSDI was used in order to determine if there is any significant relationship between NDVI and MSDI values. A positive relationship would imply that high NDVI values occur in degraded or disturbed patches and low NDVI values occur in undisturbed or well managed areas. In preparing the MSDI a moving 3 x 3 window is moved across LANDSAT TM band 3. The window is moved pixel-by-pixel across each row calculating the standard deviation for the 3 x 3 window and assigning the standard deviation value to the middle pixel.

The standard deviation is defined by the following formulae:

$$S=\sqrt{\frac{\sum_{i=1}^{N}(X_1-X)^2}{N}}$$

where:

X_1 = middle pixel

X = mean of 8 surrounding pixels + middle pixel

N = 9 pixels

5.3.3 Unsupervised Classification

The unsupervised classification was achieved by producing a False Colour Composite image (FCC), being a cross-classification of 3 bands of LANDSAT Thematic Mapper (TM) byte binary imagery. The COMPOSIT module in IDRISI was used with TM bands 2, 3 and 4 specified as the blue, green and red bands respectively. User experience with the compositing algorithm has shown that pixels with digital values at the extremes of the data set are usually insignificant (for example dark water bodies or bright clouds). In order to reject these features, a linear saturation of 2.5% was specified in the compositing procedure.

The peaks in the histogram of the FCC were analyzed to determine the distribution of clusters and thereby classes (figure 5.2). This was achieved using the CLUSTER module in IDRISI, which provides two options. The first option is a choice between a broad or a fine classification. The broad classification achieves a general picture whilst the fine classification gives intricate details. The second option allows one to drop the least significant clusters or retain all the clusters. Fine generalization retaining all the clusters usually results in an unmanageable number of classes and is only suited to small scale analyses. Broad generalization dropping the least significant clusters on the other hand, often results in the loss of spatially insignificant classes which may be vital to decision makers (for example sodic patches which only occupy a small fraction of the image). Broad generalization retaining all the clusters from the FCC was therefore chosen.

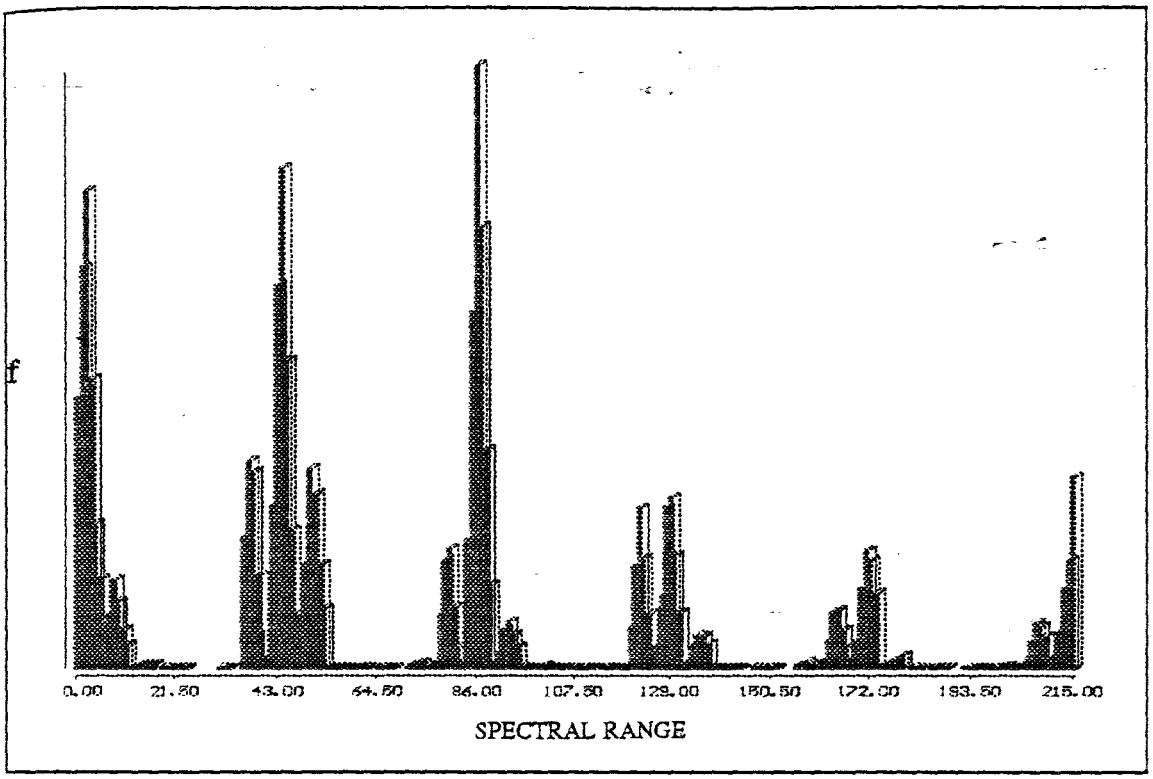

Figure 5.2 Histogram of the False Colour Composite (FCC) showing the six spectrally distinct classes.

The classes defined by the histogram peaks which the FCC produced required further interpretation. Interpretation was accomplished by determining the relationship of the reclassified image with known locations of vegetation communities on the ground from GCP's. In order to show this relationship, a contingency table is provided (table 6.3). Areas in hectares and square kilometres for each class were determined using the AREA module in IDRISI.

5.3.4 Assessment of Classification Accuracy

There are several measures of classification accuracy, among these are: the determination of errors of omission and commission, the overall accuracy, the mean class accuracy and the Kappa measure (Drake *et al.*, 1987). The Jaccard Coefficient (Sneath and Sokal, 1973) was used to determine the accuracy of the classification in this study. The Jaccard coefficient is a measure of association which is easy to determine while providing a sound measure of accuracy. It is defined by the following formulae:

$$J = \frac{\text{Positive matches}}{\text{Positive matches} + \text{Omission} + \text{Commission}}$$

where:

Positive Matches = Number of pixels mapped in field survey correctly classified

Omission = Number of pixels mapped in field survey not classified

Commission = Number of pixels incorrectly classified

In many cases the optimum sample size is too large to collect in the limited time that exists between collection of the remotely sensed data and changes in the state of the surface being observed. This presents a serious problem when assessing classification accuracy with a limited number of GCP's (Curran, 1985; Thomas and Alcock, 1984).

Traditional botanical survey, which uses aerial photography and extensive ground-based information to describe and map spatial patterns in the landscape, can provide remote sensing scientists with an expected vegetation type under 'ideal' environmental conditions (Palmer and van Staden, 1992). If the classification of the satellite derived data concurs in part, with an expected model from a traditional survey, true classification accuracy can then be determined. Moreover, if the satellite derived classes which deviated from expectation can be explained, using land-use and event data, then the value of these data is further enhanced. The capacity to predict can then be used as an important tool in change detection.

The vegetation map of the study area, produced by Tinley (1979), was used to assess the accuracy of the unsupervised classification. The hypothesis is that the Tinley (1979) map represents the expected vegetation type. Not all classes defined in the expected vegetation map corresponded with the classes defined in the unsupervised classification. This is due to the expected vegetation map being derived from an extensive floristic ground-based survey (Tinley, 1979) and the unsupervised classification being derived from a multispectral analysis of the reflectance of vegetation communities. Sand savannas, *Acacia nigrescens* turf savannas, contour seepline grasslands and open grasslands were however classified in both data sets, allowing for accuracy assessments of these vegetation communities.

The expected vegetation map (Tinley, 1979) distinguished between upland and slope savanna communities. This was based on topographic position of the savanna vegetation community on the landscape. Although the multispectral classification enabled the distinction between high cover and low cover savanna (section 6.2), the spectral similarity between upland and slope savanna defined in the expected vegetation map could not be distinguished. It was anticipated that this could be achieved by overlaying the multispectral classification with the Digital Elevation Model (DEM), however the high resolution of this data (500 m x 500 m) did not permit this to any degree of accuracy. The upland and slope savanna communities from the expected vegetation map, as well as the high and low cover savanna vegetation communities from the multispectral classification, were therefore modified through reclassification into one vegetation class respectively. An accuracy assessment could therefore only be conducted for the combined sand savanna vegetation community, irrespective of percentage cover and topographic position on the landscape.

The CROSSTAB module in IDRISI was used to cross-tabulate the classes in the unsupervised classification with the classes in the expected vegetation map. The result of this operation is a table output as well as an image output that can be likened to a multiple overlay showing the location of all combinations of the categories in the expected and multispectral vegetation maps. CROSSTAB was conducted on two sub-scene image windows which together, incorporated the combined sand savanna, *Acacia nigrescens* turf savanna, contour seepline grassland and open grassland vegetation communities. By determining the total number of pixels classified for each class (from the unsupervised classification sub-scene) and the number of pixels correctly classified (from the crosclassification sub-scene), it was possible to determine Jaccard coefficients for each of these vegetation communities

5.4 THE COLLECTION OF GROUND CONTROL POINT (GCP) DATA

The type of investigation and the time scale of GCP data collection are closely related. Ideally, the collection of GCP data would have been undertaken at the time of image capture. However, economic factors limited the availability of imagery. In order to compensate for this, the GCP data was collected on the anniversary date of the imagery.

Data were collected for over four hundred sites in the study area. Data collected at sites is summarised in table 5.3.

Table 5.3. Data and sources collected at GCPs

DATA COLLECTED AT EACH SITE	SOURCE
1. Latitudinal and Longitudinal coordinates	Magellan GPS at high precision WSGS 84 geodetic setting
2. Veld type	Acocks (1988)
3. Dominant species	Palmer (*pers.comm.*)
4. Percentage of woody, grass and bare cover	Estimates from two independent field assistants
5. Soil texture	(Appendix 1)
6. Geology	1:250 000 Geological series map as well as an in situ assessment
7. Erosion	Handbook of standardised monitoring techniques for Cape nature reserves (Appendix 1)
8. History and disturbance	Personal communications with various management and staff at the Sabi Sand Game Reserve
9. Structural diversity	(Appendix 1)
10. General vegetation utility	In situ assessment based on number of middens and amount of, grazed and browsed vegetation
11. Vegetation structure	Edwards (1983) (Appendix 1)
12. Annual production fraction estimate	Rutherford (1982 a) (Appendix 1)
13. Above-ground woody biomass estimate	Rutherford (1982 b) (Appendix 1)

GCP data was collected for 9 vegetation classes. These classes were based on *a priori* stratification of the vegetation (Acocks, 1988; Tinley, 1979; Vogt, 1992) in conjunction with Edwards (1983) structural classification scheme. The classes are described in table 5.4.

Table 5.4 Vegetation classes defined in the GCP data collection programme.

VEGETATION CLASSES	DESCRIPTION
Open savanna woodland	Dominated by *Sclerocarya caffra* and *Combretum apiculatum* on sandy soils derived from granite (greater than 60% woody cover and above 10 m in height)
Closed savanna woodland	Dominated by *Sclerocarya caffra* and *Combretum apiculatum* on sandy soils derived from granite (less than 60% woody cover and above 10 m in height)
Acacia nigrescens woodland	Dominated by *Acacia nigrescens* on dark clay soils derived from basalt (less than 60% woody cover and above 10 m in height)
Acacia thicket	Dominated by *Acacia exuvialis* (greater than 60% woody cover and below 10m in height)
Mature, closed *Acacia* woodland	Dominated by *Acacia exuvialis* and *Acacia nylotica* (greater than 60% woody cover and above 10 m in height)
Open grassland	Dominated by *Themeda triandra* and *Panicum maximum* (less than 60% grass cover)
Dambo	Dominated by *Panicum coloratum* and *Themeda triandra* on dark clay soils derived from basalt.
Seepline	Dominated by *Eragrostis gummiflua*. These features form characteristic narrow bands on hillslopes which tend to follow contours.
Sodic patch	Sparse patches of *Euclea divinorum* with bare open patches of highly sodic soils.

The size of plots was set at 30 m^2, (the size of one TM pixel). In order to compensate for Global Positioning System (GPS) inaccuracies, which can be as much as 30 m (Koh and Edwards, 1996), plots were chosen within representative homogenous areas greater than 60 metres in extent. The true coordinates for Trig. Survey Beacon number 16 on the 1:50 000 topographical map sheet 2431CD Newington, was acquired from the Director of surveys and mapping. GPS data collected from this spot height showed deviations of not more than 20 m.

5.5 SUMMARY

A wide variety of techniques, specifically designed for determining landscape patterns and processes, have been employed in this study. They include image processing techniques (rectification, classification and the use of vegetation indices) and GCP data collection techniques. By combining these two data sets into a GIS, it was possible to derive spatially significant information regarding ecosystem structure and function. Ancillary data was used as independant data sources for the testing of these data.

CHAPTER 6

RESULTS

6.1 VEGETATION INDICES

6.1.1 Normalized Differentiation Vegetation Index (NDVI)

The NDVI image output is presented in figure 6.1. High NDVI values are shown in red and yellow whilst low NDVI values are shown in black and white. NDVI pixel values range from -0.69 to 0.63 with most of the distribution falling above zero (figure 6.2). The mean for all pixels is 0.062 with a standard deviation of 0.12.

Sodic patches, *Acacia* thickets and seeplines exhibit high average NDVI values which occur above the mean (figure 6.3). Open and closed sand savanna, mature *Acacia* thicket, turf savannas and open grassland vegetation communities show low average NDVI values of below mean (figure 6.3). Actual values are presented in table 6.1.

Table 6.1. Mean NDVI values for each class with respective standard deviations about the mean.

VEGETATION COMMUNITIES	MEAN NDVI VALUES	STANDARD DEVIATION VALUES
Sodic patches	0.12	0.035
Open sand savanna	0.039	0.034
Closed sand savanna	0.040	0.033
Acacia thicket	0.105	0.021
Mature *Acacia* thicket	0.056	0.024
Acacia nigrescens turf savanna	0.022	0.014
Seeplines	0.113	0.041
Open Grassland	0.068	0.034
Average for all communities	**0.075**	**0.021**

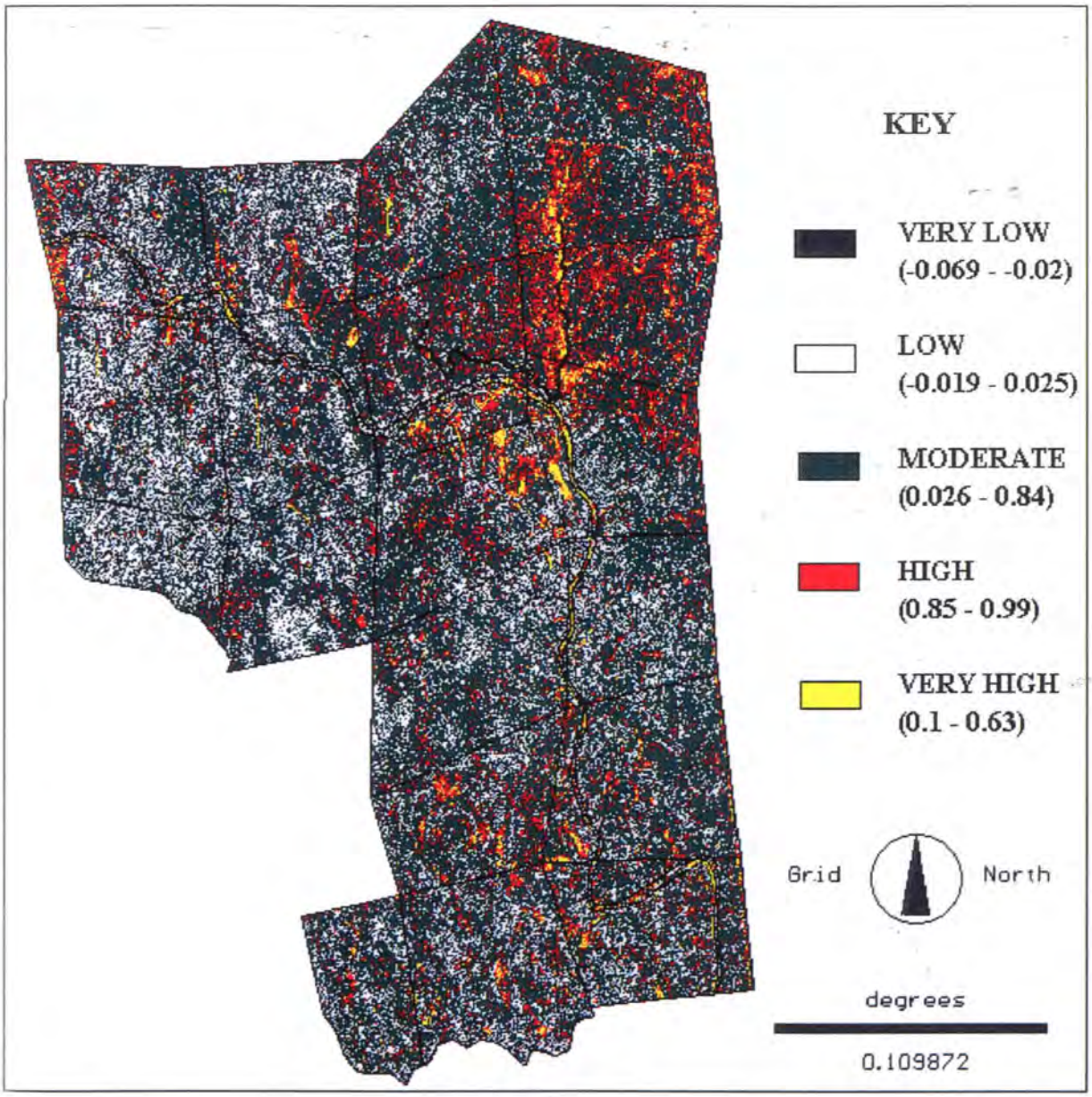

Figure 6.1 Normalized Differentiation Vegetation Index (NDVI) image output.

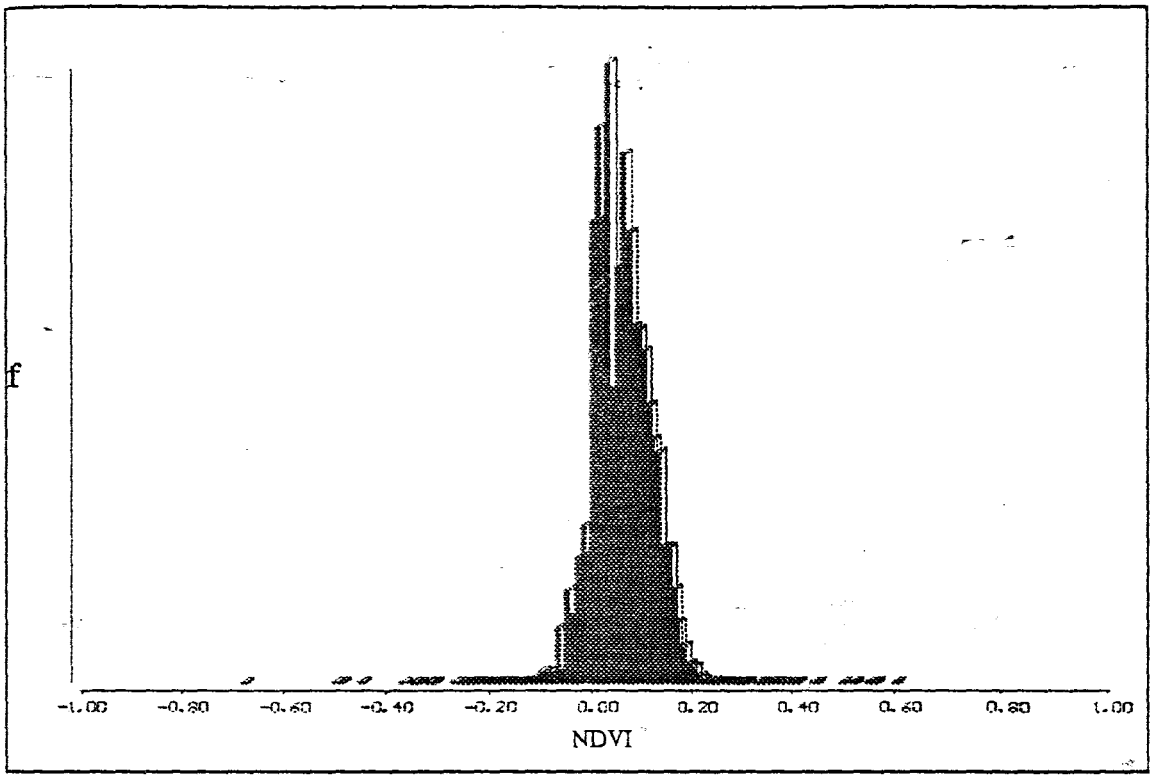

Figure 6.2 Histogram depicting the distribution of NDVI pixel values between -1 and 1.

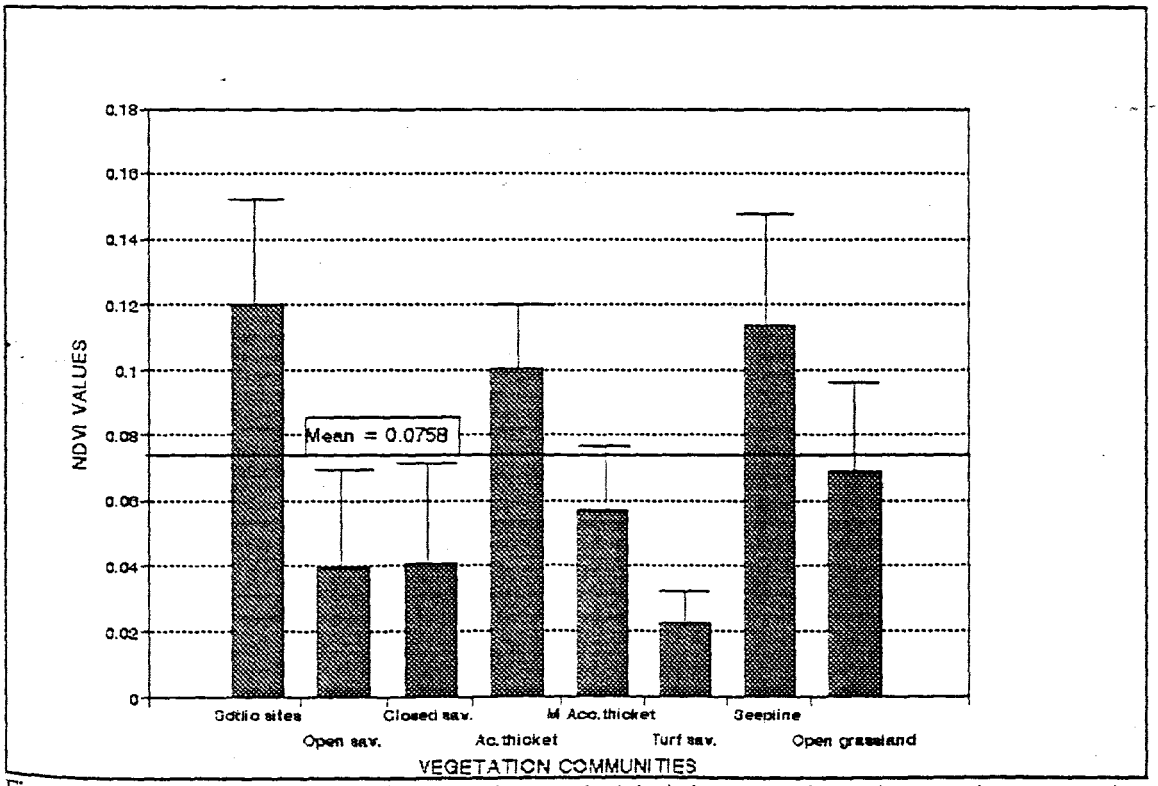

Figure 6.3 Average NDVI values with respective standard deviation values for each vegetation community

6.1.2 NDVI Values Around Water Points

The NDVI gradients around water points in each vegetation community are shown in figures 6.4-6.8. Only water points with 8 pixel mean values above the average for the respective vegetation community (table 6.1) are shown. Values which fell below the mean NDVI value for each community were omitted on the assumption that they are under utilised or relatively undisturbed. The sites shown in these figures therefore represent heavily utilised water points only and labels correspond with the labels in figure 6.9.

NDVI values at water points are always low. This is due to the high reflectance of water in all wavebands (Barrett and Curtis, 1992). Water points which occur in open and closed sand savanna and turf savannas all show a rapid increases in NDVI values for neighbouring pixels (45m distance) (figures 6.4-6.8). With distance from water points, average NDVI values decrease. Where these values decrease below the average NDVI value for the respective community, disturbance is limited to the maximum distance shown on the graphs (site 12 in figure 6.4, sites 17 and 18 in figure 6.5 and sites 18 and sites 29 and 30 in figure 6.8). Where these values decrease to some value above the mean for the respective vegetation community, disturbance and degradation occur up to at least 105m from the water source.

Rapid increases in NDVI values for neighbouring pixels also occur in sodic patches (figure 6.7). The gradual decrease in these values with distance from the water point, which is observed in other vegetation communities, is however not as obvious. In fact, NDVI values often increase with distance from the water point (sites 19, 20, 21 and 24). This is due to these sites being influenced by other disturbances, such as bushclearing, mowing and intensive grazing.

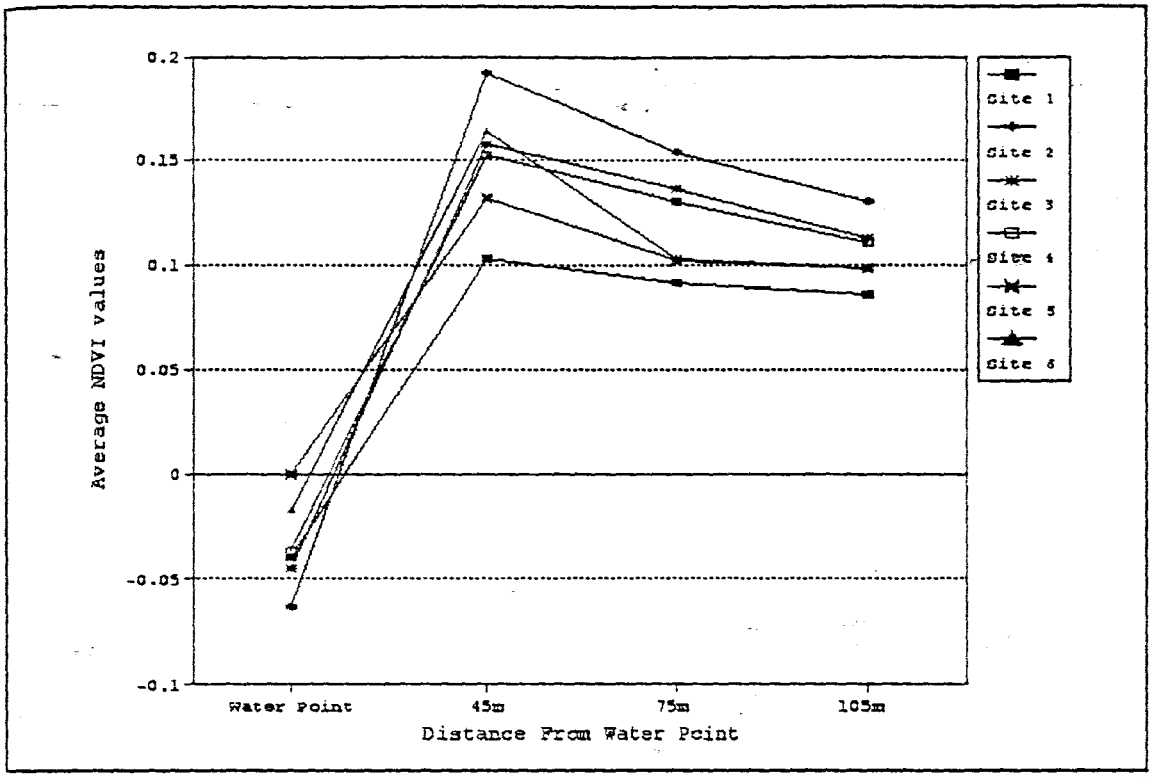

Figure 6.4 Average NDVI values with distance from water points in the closed savanna vegetation community. Sites 1-6 correspond with respective sites in fig 6.9.

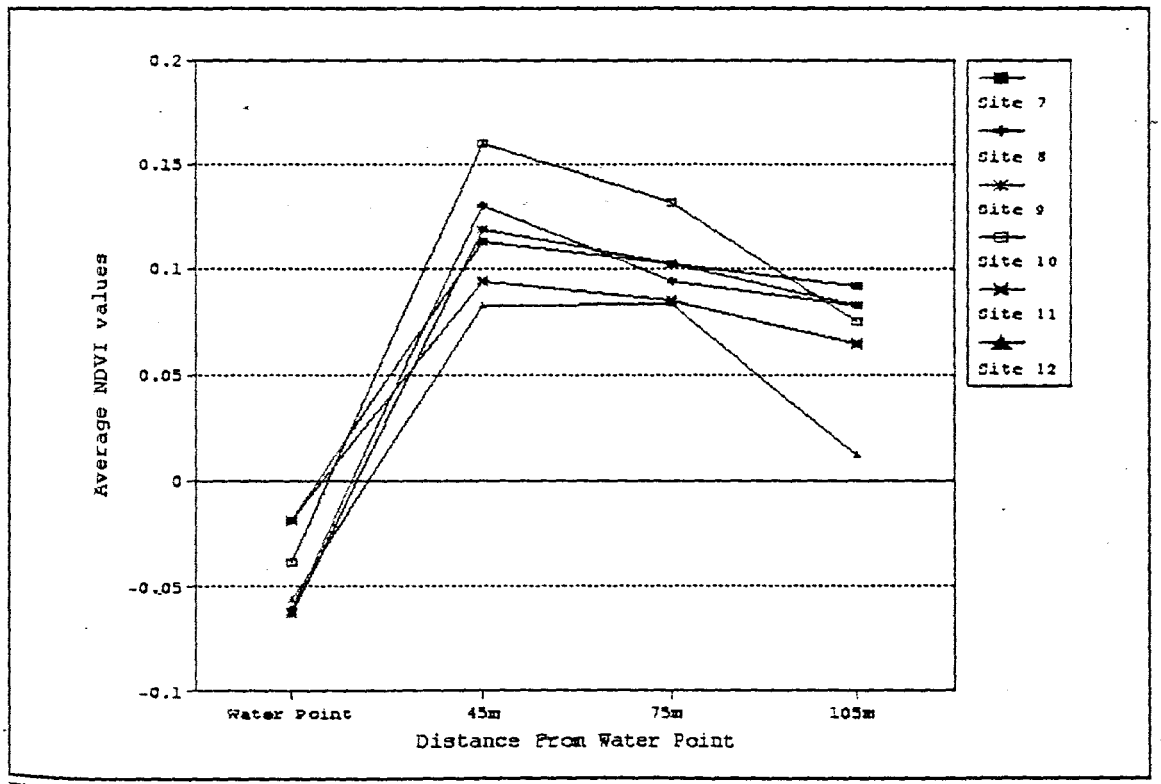

Figure 6.5 Average NDVI values with distance from water points in the closed savanna vegetation community. Sites 7-12 correspond with respective sites on fig 6.9.

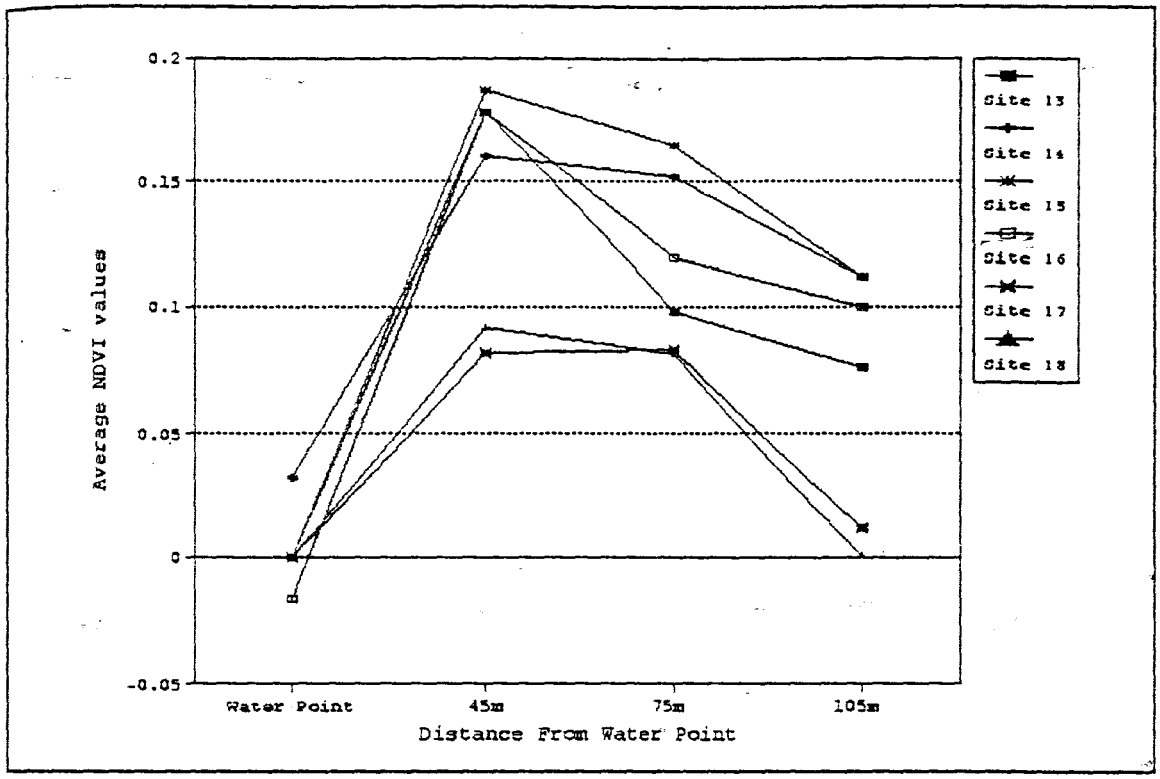

Figure 6.6 Average NDVI values with distance from water points in the open savanna vegetation community. Sites 13-18 correspond with respective sites in fig 6.9.

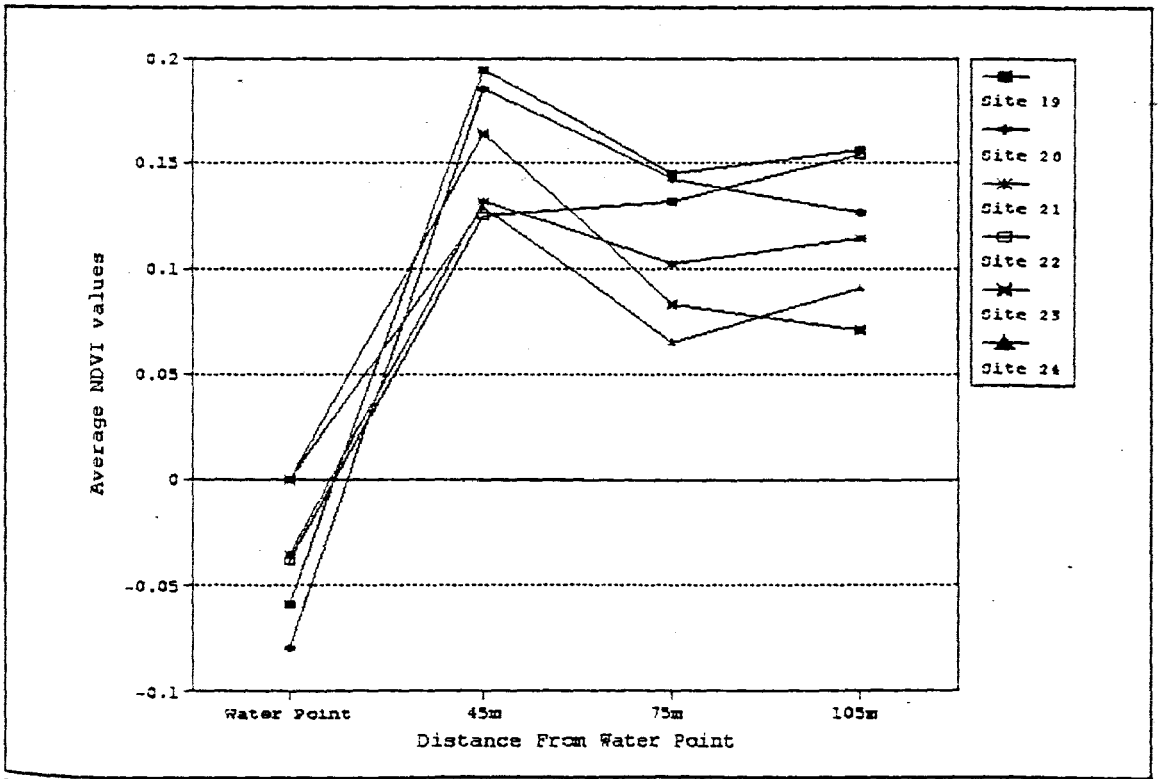

Figure 6.7 Average NDVI values with distance from water points on sodic sites. Sites 19-24 correspond with respective sites on fig 6.9.

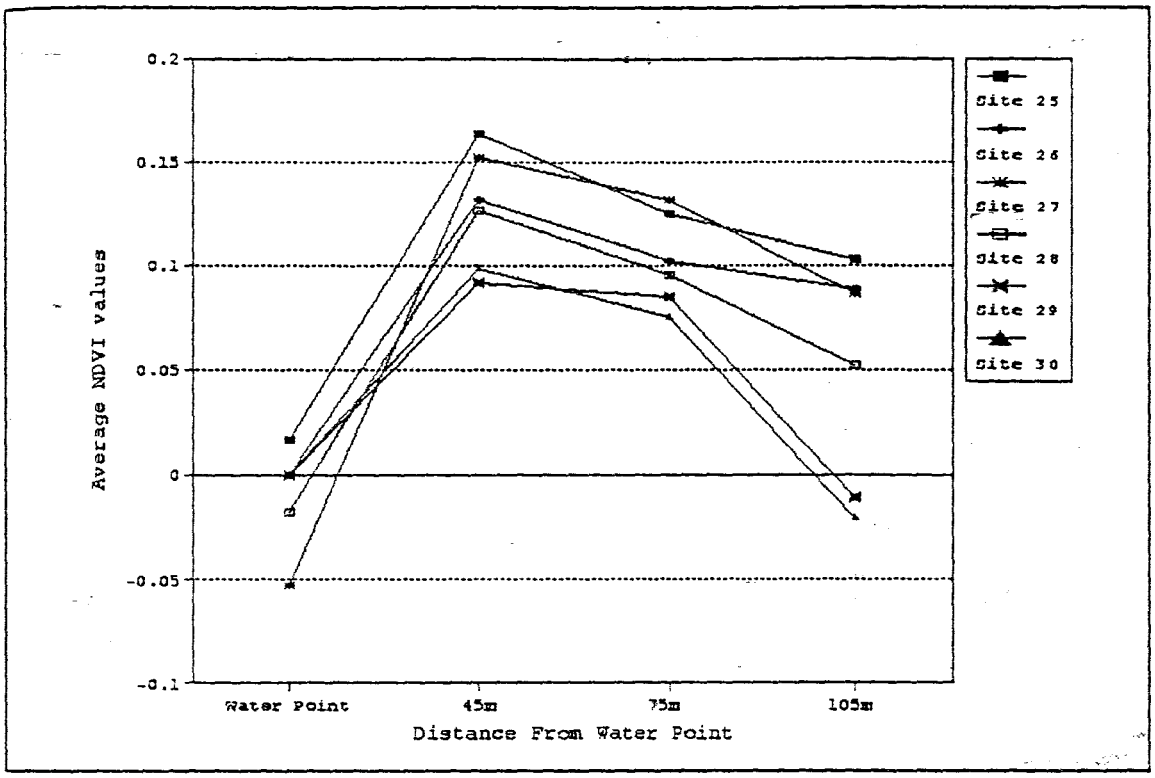

Figure 6.8 Average NDVI values with distance from water points on turf savannas. Sites 25-30 correspond with respective sites on fig 6.9.

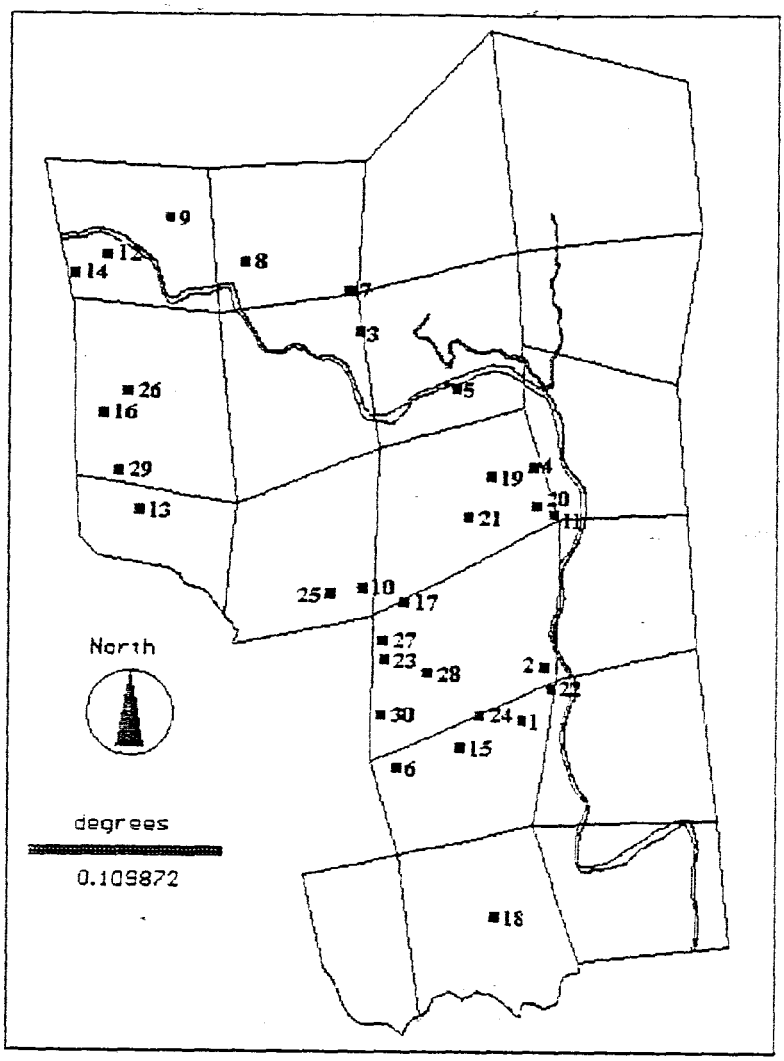

Figure 6.9 Map of heavily utilised water points. Labels correspond with those on figures 6.4-6.8.

6.1.3 Landscape Diversity Index

The moving standard deviation index (MSDI) image is presented in figure 6.10. High values are depicted in red and yellow whilst low values are depicted in black and white.

The histogram of the MSDI image showing the distribution of MSDI pixel values ranging between 0 and 255 is provided in figure 6.11. The histogram is strongly positively skewed with a mean of 15.449 (0.15449) and a standard deviation of 11.292 (0.1129). The mean MSDI values for each vegetation community defined in the GCP collection programme are shown in figure 6.12. Actual values are provided in table 6.2.

Table 6.2. Average MSDI values for each vegetation community as well as the average MSDI value for all vegetation communities

VEGETATION COMMUNITIES	AVERAGE MSDI VALUE	STANDARD DEVIATION VALUES
Sodic patches	3.019	0.986
Open sand savanna	1.293	0.82
Closed sand savanna	1.034	0.343
Acacia thicket	2.959	0.869
Mature *Acacia* thicket	1.326	0.415
Acacia nigrescens turf savanna	0.968	0.532
Seeplines	2.664	0.932
Open grasslands	1.222	0.491
Average for all communities	**1.963**	**0.664**

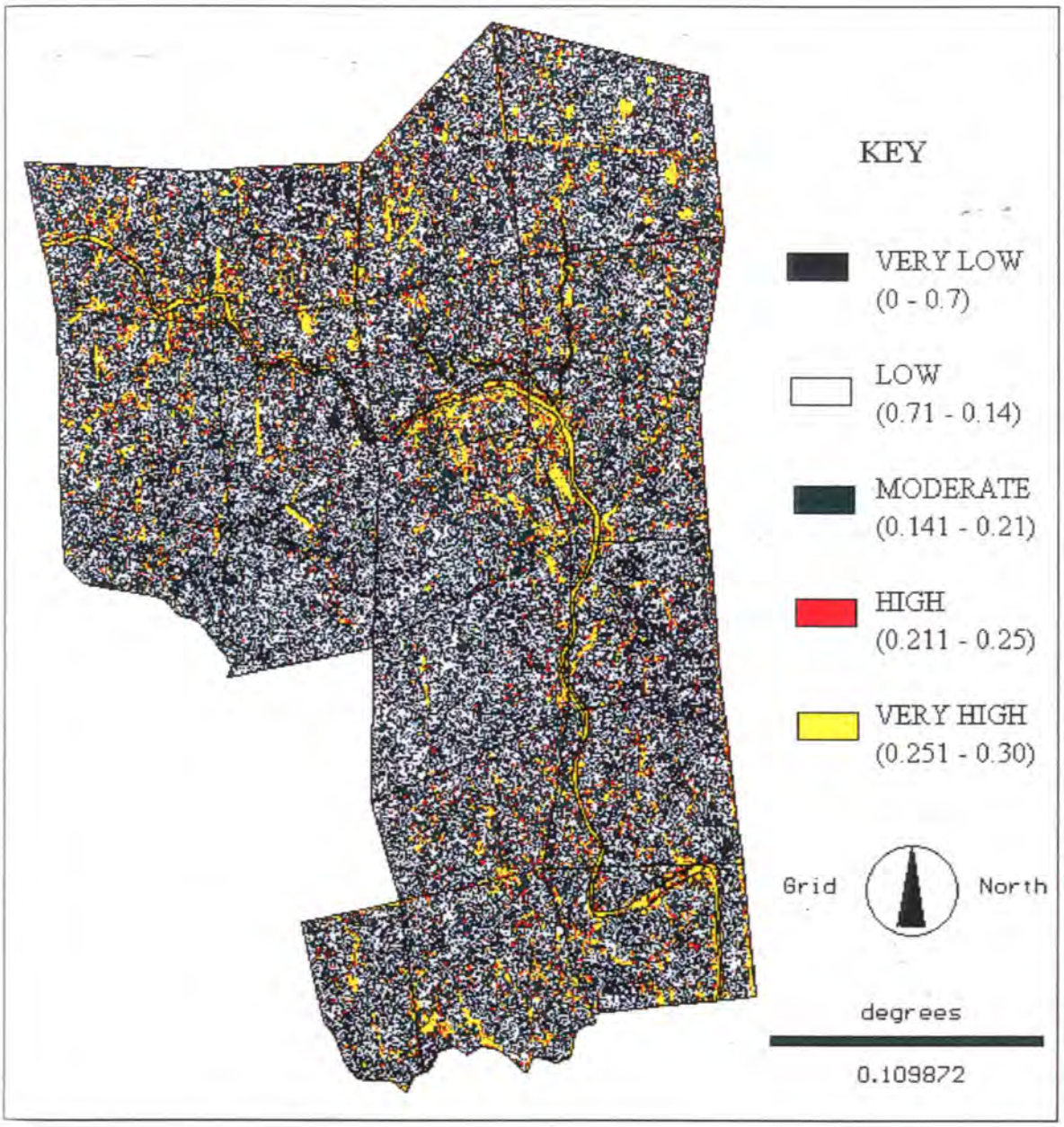

Figure 6.10 Moving Standard Deviation Index (MSDI) image.

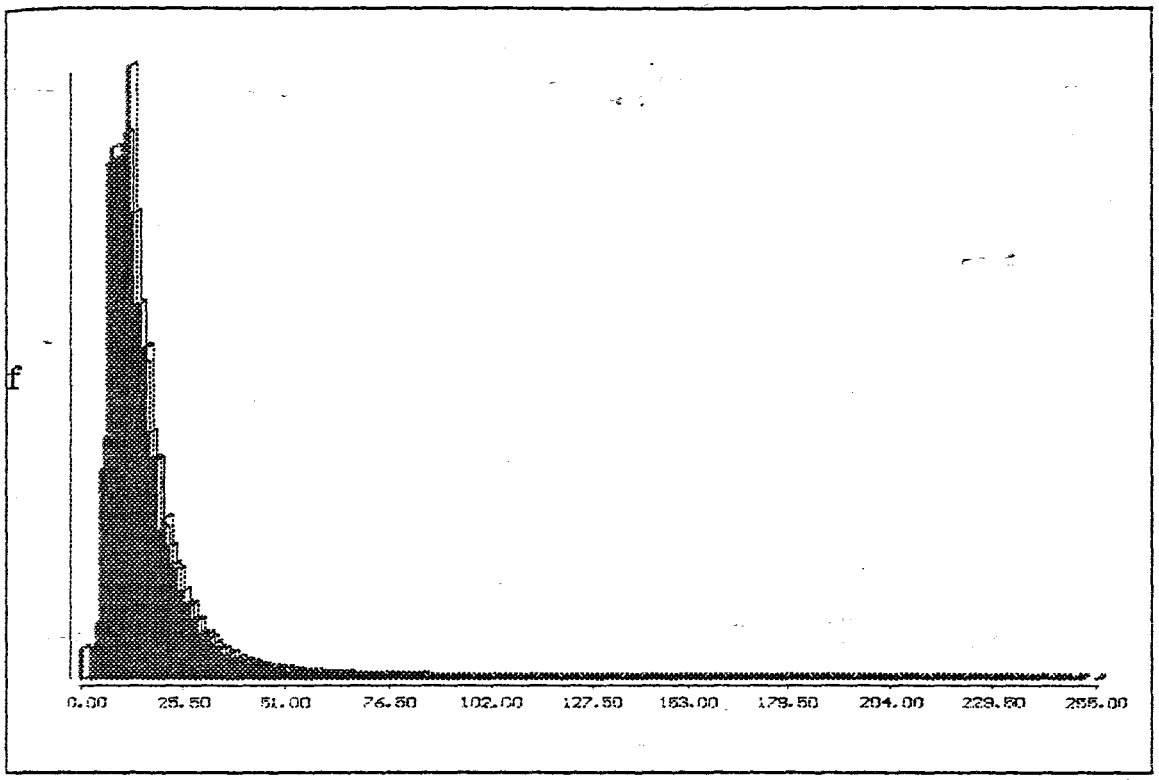

Figure 6.11 Histogram of the MSDI image. Values were multiplied by a factor of 10 to aid visual display.

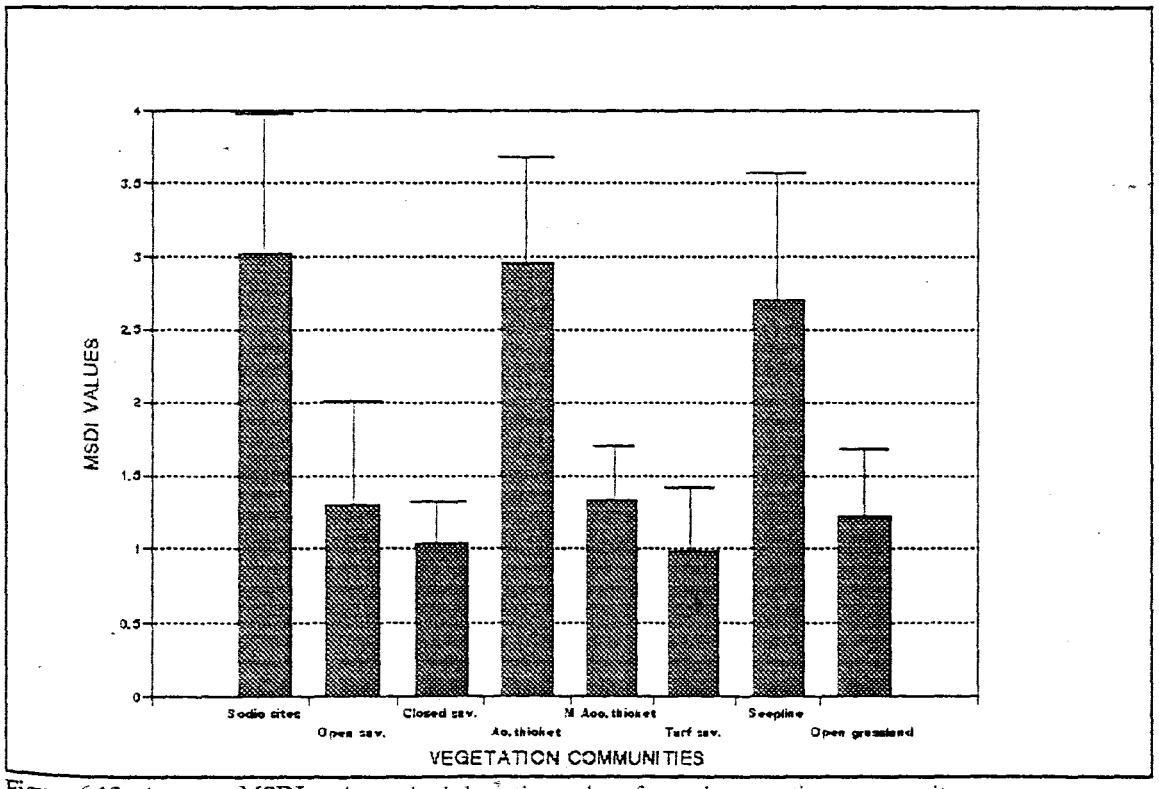

Figure 6.12 Average MSDI and standard deviation values for each vegetation community.

As is the case with NDVI values, sodic patches, *Acacia* thickets and seeplines/open grasslands all display high average MSDI values whilst open and closed sand savannas, mature *Acacia*-thickets, *Acacia nigrescens* turf savannas, and open grasslands display low average MSDI values.

A correlation coefficient of 0.8803 was calculated for high MSDI and NDVI values. The correlation coefficient was determined by running the CROSSTAB module between the MSDI and NDVI images. In order to allow for cross-tabulation, both images had to be reclassified so that high values were shown as 1 and low values as 0. Threshold values were determined for both images using the histograms generated from the HISTO module (figures 6.2 and 6.11 respectively). The threshold value for high values was defined as everything above 0.85 and 0.35 for the NDVI and MSDI images respectively.

6.2 UNSUPERVISED CLASSIFICATION

The unsupervised classification yielded six spectrally distinct classes. Both classes five and six correlated well with the *Acacia nigrescens* turf savanna vegetation community and these classes were therefore reclassified so that together, they represent one class.

A classification matrix was used to show the vegetation communities represented by the classes derived from the unsupervised classification (table 6.3). These classes correlate well with the vegetation communities defined in the GCP data collection programme, particularly in the case of the *Acacia nigrescens* turf savanna.

In the unsupervised classification image (figure 6.13), closed sand savanna is depicted in blue, open sand savanna in green, seeplines/open grasslands in red, sodic patches in yellow, *Acacia nigrescens* turf savanna in black and *Acacia* thicket in pink. The *Acacia* thicket was an addition to the image and will be discussed in section 6.3 Contour seeplines and open grasslands could not distinguished in the classification and are therefore represented as one class. Seeplines do however exhibit a characteristic shape, occurring as narrow bands (about 100 m wide) which follow the contours. They can therefore be distinguished visually.

Table 6.3 Classification matrix showing the relationship between classes defined from the unsupervised classification and those defined in the GCP data collection programme. Bold values represent the percentage of GCPs correctly classified in the multispectral classification.

		GROUND DATA				
	Vegetation Community	Closed Sand Savanna	Open Sand Savanna	Seeplines/ open grasslands	Sodic Patches	*Acacia nigrescens* turf savanna
IMAGE DATA	Closed Sand Savanna	(22/26) **81.48%**	(4/33) 12.12%	(1/32) 3.13%	(3/68) 3.85%	(4/86) 4.59%
	Open Sand Savanna	(5/26) 18.51%	(28/33) **84.84%**	(4/32) 12.5%	(2/68) 2.56%	(1/86) 1.15%
	Seeplines/open grasslands	-	(1/33) 3.03%	(26/32) **81.25%**	(10/68) 12.82%	(2/86) 2.29%
	Sodic Patches	-	-	(1/32) 3.125%	(62/68) **69.48%**	(1/86) 1.15%
	Acacia nigrescens turf savanna	-	-	-	(1/68) 1.28%	(69/86) **90.8%**

The unsupervised classification was used to determine the area in ha and km^2 for each vegetation community in the Sabi Sand Game Reserve (table 6.4).

Table 6.4 Area occupied by each class in hectares and square kilometres.

Vegetation Community	Area occupied in the Reserve (hectares)	Area occupied in the Reserve (Kilometres squared)
Closed sand savanna	26414.3	264.1
Open sand savanna	20139.6	201.4
Seeplines or open grasslands	11243.3	112.4
Sodic Patches	609.3	6.1
Acacia nigrescens turf savanna	566.0	5.8
Acacia thicket	396.0	4.0

Since the *Acacia nigrescens* turf savanna and *Acacia* thicket vegetation communities collectively represent only 1.62 % of the total area classified their distribution is difficult to determine from the unsupervised classification image. An additional map has therefore been provided in order to isolate these vegetation communities (figure 6.14).

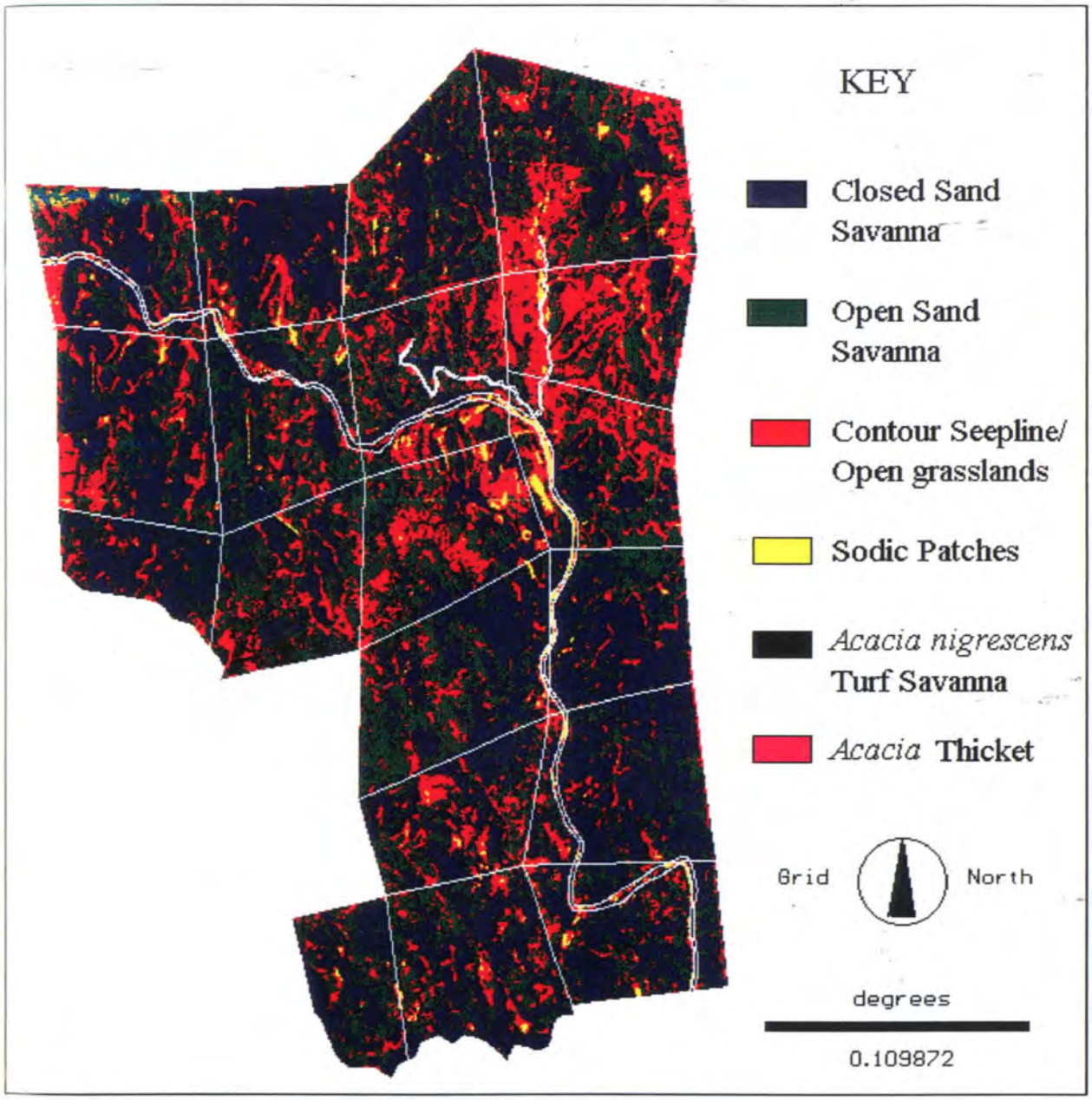

Figure 6.13 Vegetation map of the Sabi Sand Game Reserve derived from an unsupervised classification of LANDSAT TM data.

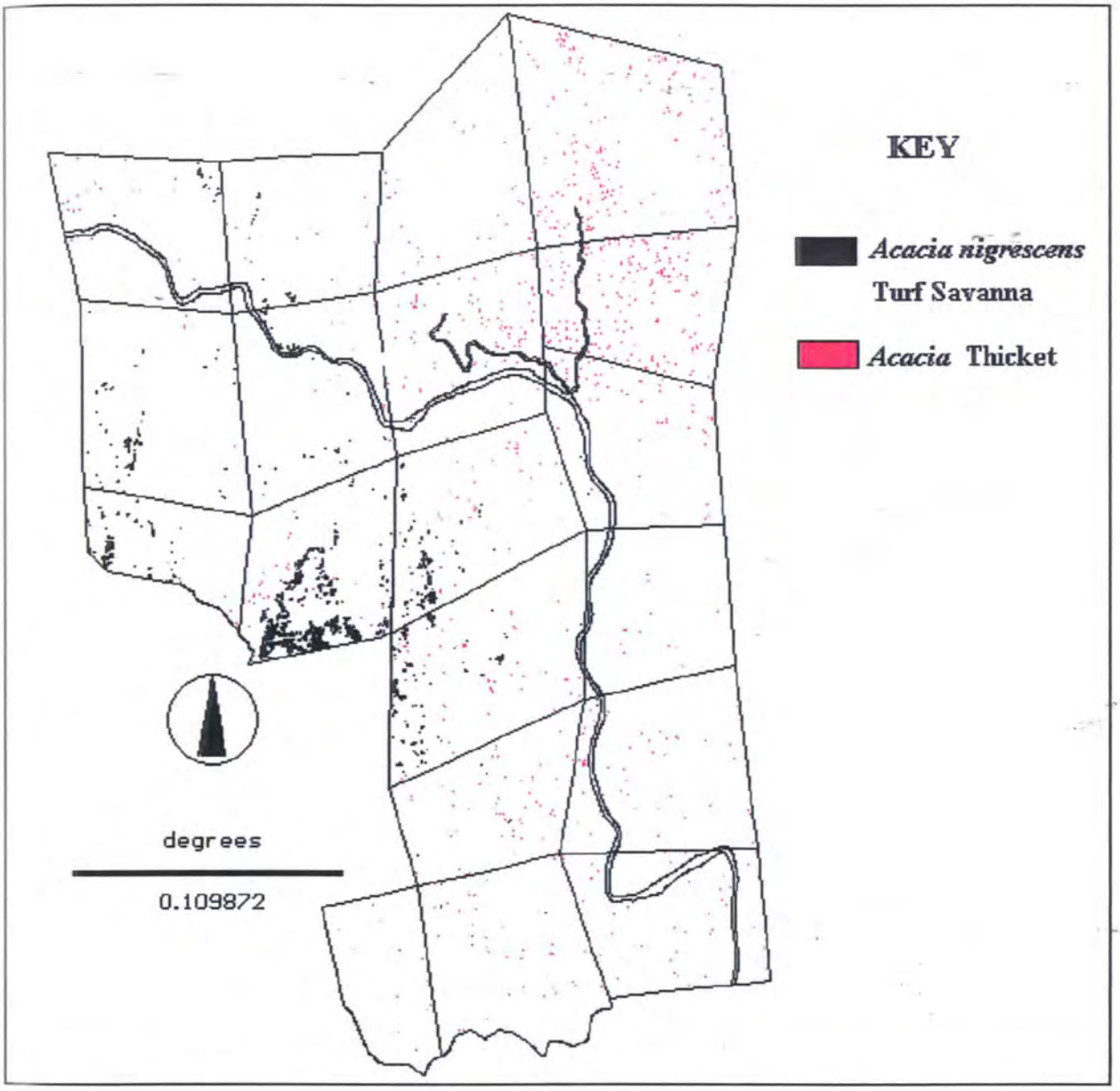

Figure 6.14 The distribution of *Acacia nigrescens* turf savanna and *Acacia* thicket in the Sabi Sand Game Reserve.

6.3 ADDITION OF THE *ACACIA* THICKET CLASS TO THE UNSUPERVISED CLASSIFICATION

Interpretation of the unsupervised classification showed the absence of the *Acacia* thicket class defined in the field. This probably occurred as a result of spectral similarity with the high cover, closed sand savanna vegetation community. The *Acacia* thicket, although occupying a small representative area of the reserve, is an important indicator of degradation for managers (section 3.5). It was therefore necessary for this class to be included in the multispectral classification.

Field data from GCP's revealed that the *Acacia* thickets exhibit high annual production fractions (section 6.5.5). An assessment of the NDVI values from the image confirmed this assumption. High NDVI values only occur in *Acacia* thickets sodic patches and contour seepline grasslands (figure 6.3). *Acacia* thickets can be distinguished between sodic patches on the basis of woody cover. Since high cover sand savanna was distinguished in the unsupervised classification and since the *Acacia* thicket community exhibits spectral similarity with this community, it was possible to produce a new image showing only where pixels with high cover sand savanna occurred in conjunction with high NDVI values. In so doing, it was possible to map the incidence of the *Acacia* thicket community defined in the GCP programme. The following steps were followed:

1. A critical threshold NDVI value was determined in order to distinguish high NDVI values from moderate and low values. The optimum threshold value (0.85) was determined from the mean NDVI value + half the standard deviation.
2. The NDVI image was then reclassified so that all values above 0.85 were assigned a new value of two and values below 0.85 were assigned a new value of zero.
3. The unsupervised classification image was reclassified so that the closed sand savanna class was assigned a new value of one and the other classes a new value of zero.
4. The reclassed unsupervised classification image was then subtracted from the reclassed NDVI image, so that a new image was created with values of one depicting areas where high NDVI values occur in conjunction with the closed sand savanna community.

5. This new image was further reclassified so that values of one were assigned a new value of six.
6. This image was then covered over the original unsupervised classification. The sixth class represents *Acacia* thicket.

6.4 RESULTS FROM CLASSIFICATION AFTER THE ADDITION OF THE *ACACIA* THICKET CLASS

The classification matrix after the addition of the *Acacia* thicket class is presented in table 6.5.

Table 6.5 Classification matrix showing the association of field data with image pixel values from the unsupervised classification after the addition of the young *Acacia* thicket class. Bold values represent the percentage of GCPs correctly classified in the multispectral classification.

		FIELD DATA					
	Vegetation Community	Closed Sand Savanna	Open Sand Savanna	Seeplines / open grasslands	Sodic Patches	*Acacia nigrescens* turf savanna	Young *Acacia* Thicket
IMAGE DATA	Closed Sand Savanna	(2/26) **81.48%**	(4/33) 12.12%	(1/32) 3.13%	(3/68) 3.85%	(4/86) 4.59%	(2/49) 4.08%
	Open Sand Savanna	(2/26) 6.4%	(28/33) **84.84%**	(4/32) 12.5%	(2/68) 2.56%	(1/86) 1.15%	(1/49) 2.04%
	Seeplines / open grasslands	-	(1/33) 3.03%	(26/32) **81.25%**	(8/68) 10.25%	(2/86) 2.29%	(4/49) 8.16%
	Sodic Patches	-	-	(1/32) 3.125%	(62/68) **69.48%**	(1/86) 1.15%	(1/49) 2.04%
	Acacia nigrescens turf savanna	-	-	-	(1/68) 1.28%	(69/86) **90.8%**	-
	Young *Acacia* thicket	(3/26) 11.11%	-	-	(2/68) 2.56%	-	(41/49) **83.66%**

6.5 ASSESSMENT OF CLASSIFICATION ACCURACY

Jaccard coefficients confirm that all classes defined in the unsupervised classification, and modification, are strongly associated with the Ground Control Point (GCP) data (table 6.6).

Table 6.6 Jaccard coefficients of association showing accuracy of classification. Values depicted in bold represent the correlation of correctly classified pixels with GCP data

VEGETATION COMMUNITY	JACCARD COEFFICIENT
Closed sand savanna	0.81
Open sand savanna	0.84
Seeplines	0.81
Sodic Patches	0.69
Acacia nigrescens turf savanna	0.91
Young *Acacia* thicket	0.84

The Jaccard coefficients derived from the cross-classification between the two image sub-scenes of the expected vegetation map (Tinley, 1979) and the unsupervised classification for the combined sand savanna, *Acacia nigrescens* turf savanna, seepline and open grassland vegetation communities are presented in table 6.7. These data represent a classification accuracy assessment, using an independent data set in contrast to the GCP data, used in defining the unsupervised classification.

Relatively high Jaccard coefficients for the combined sand savanna, *Acacia nigrescens* turf savanna and open grassland vegetation communities confirm the accuracy of the multispectral classification for these classes. Low Jaccard coefficients for the contour seepline grassland vegetation community can be attributed to invasion of woody species and will be dealt with in the discussion (chapter 7).

Visual interpretation between the expected vegetation map (Tinley, 1979) and the multispectral classification for the two image sub-scenes reflects these high Jaccard

coefficients (figures 6.15, 6.16 and 6.17, 6.18 for sub-scenes 1 and 2 respectively)

Table 6.7 Jaccard coefficients derived from cross-tabulation of the expected versus the contemporary vegetation maps.

Image sub-scene	Vegetation Communities	Jaccard coefficient (J)	Positive matches (from cross-classification image)	Commission (from unsupervised classification image)
1 (figures 6.15 and 6.16)	Combined sand savanna	0.86	10549	1616
	Seeplines	0.58	544	400
2 (figures 6.17 and 6.18)	Combined sand savanna	0.63	568	682
	Acacia nigrescens turf savanna	0.68	1125	335
	Open grassland	0.84	845	1006

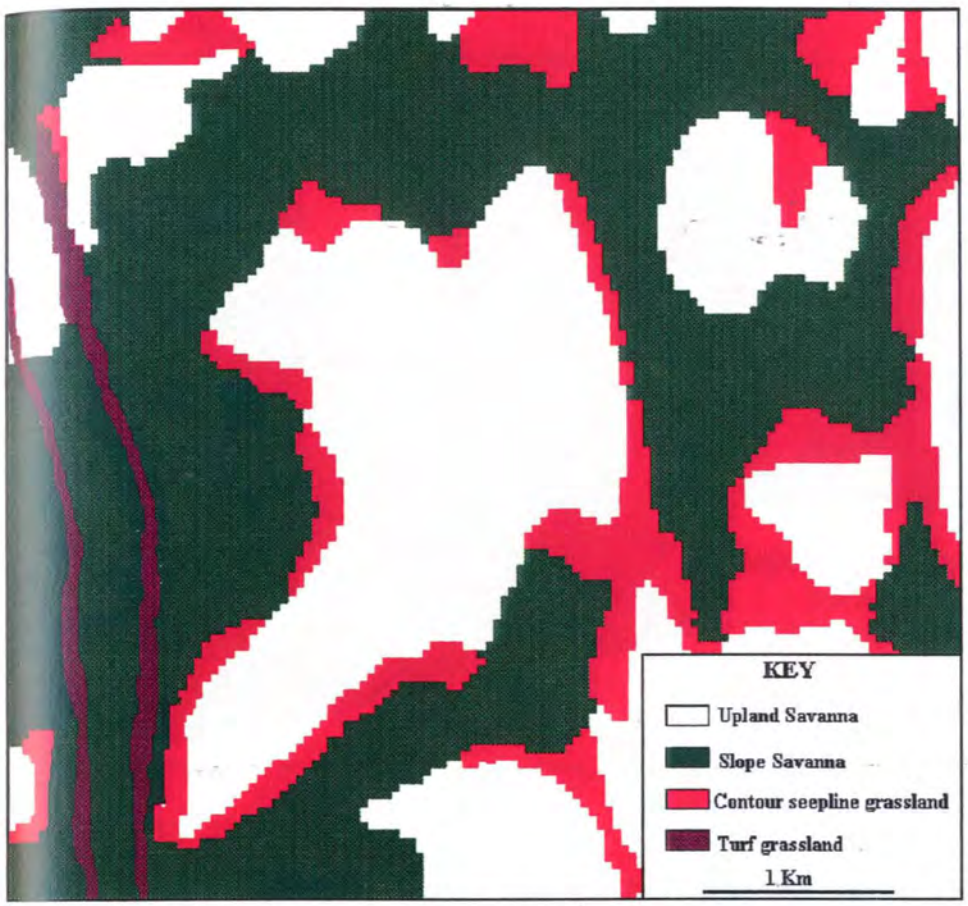

Figure 6.15 Sub-scene 1 of the expected vegetation map (Tinley, 1979) used in crosstabulation.

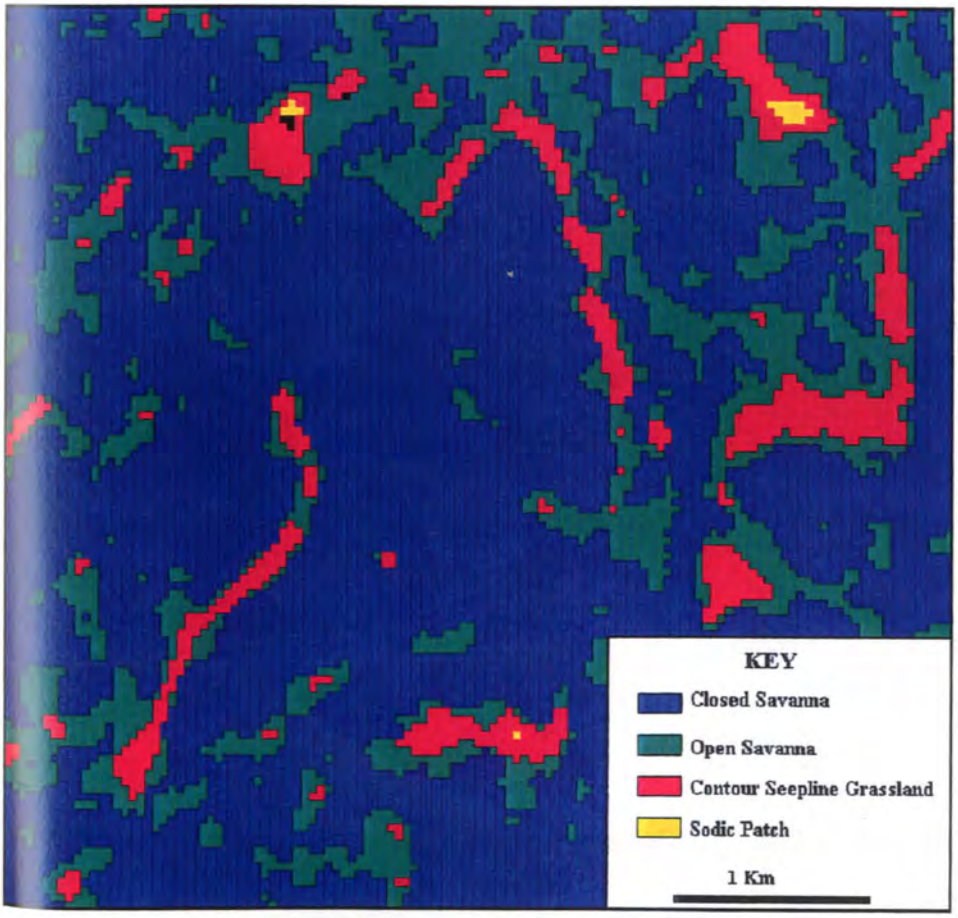

Figure 6.16 Sub-scene 1 of the contemporary, multispectral vegetation map used in crosstabulation.

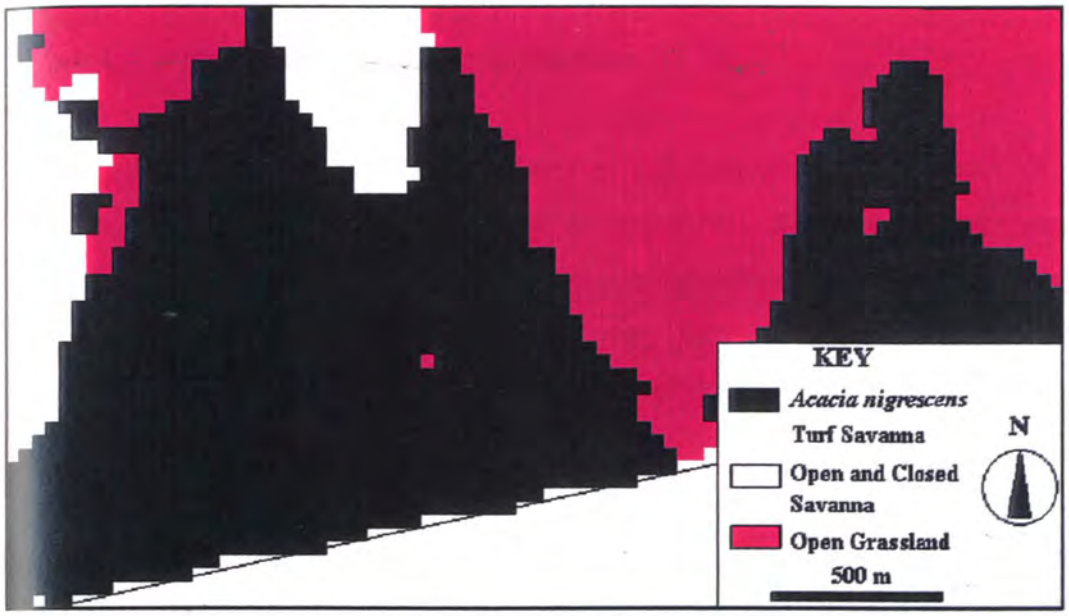

Figure 6.17 Sub-scene 2 of the expected vegetation map (Tinley, 1979) used in crosstabulation.

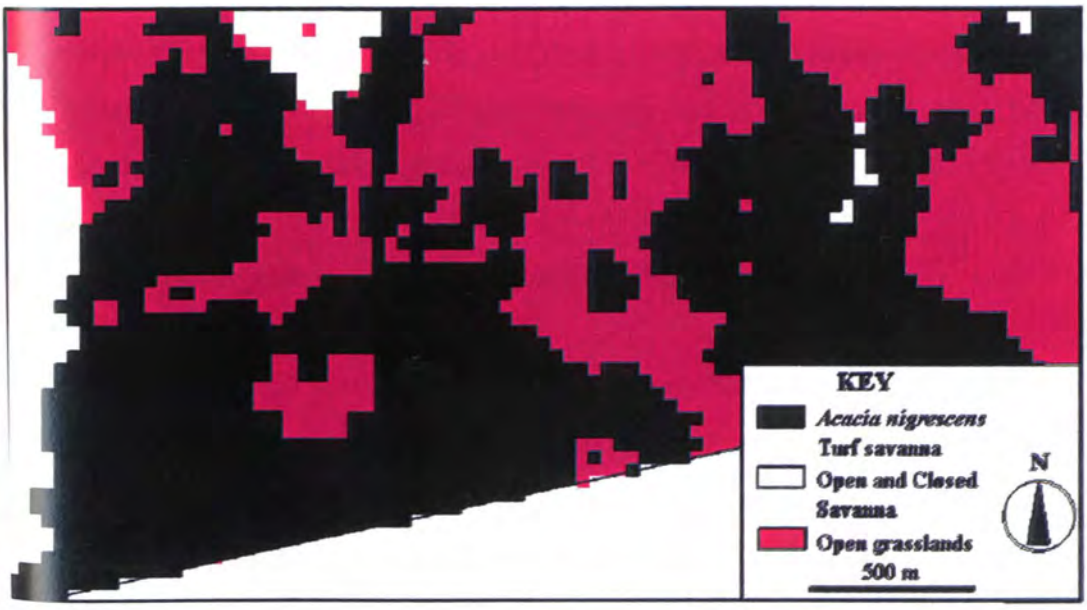

Figure 6.18 Sub-scene 2 of the contemporary, multispectral vegetation map used in crosstabulation.

6.6 RESULTS FROM SURFACE REFERENCE DATA COLLECTION

6.6.1 Cover Erosion and Diversity Indices

The open and closed savanna and mature *Acacia* thicket communities exhibit relatively equal proportions of woody and grass cover (figure 6.19). *Acacia nigrescens* woodlands or turf savannas, sodic patches, *Acacia* thickets, open grasslands and seeplines show progressively unequal proportions of woody and grass cover. Bare cover is generally low (less than 15 per cent) in most communities with the exception of the two *Acacia* thicket communities and the sodic patches.

Open and closed savannas, *Acacia nigrescens* turf savannas and open grasslands have dominantly low to moderate erosion indices (figures 6.21, 6.20, 6.22 and 6.26 respectively). The *Acacia* thicket communities and contour seepline grasslands exhibit dominantly moderate to high erosion indices (figures 6.23, 6.24 and 6.27) whilst sodic patches have dominantly high to very high erosion indices (figure 6.25)

Open and closed savanna vegetation communities exhibit dominantly moderate to high structural diversity indices (figures 6.29 and 6.28); *Acacia nigrescens* turf savannas, Mature *Acacia* thickets, open grasslands and contour seepline grasslands, dominantly low to moderate indices (figures 6.30, 6.32, 6.34 and 6.35) and *Acacia* thickets and sodic patches, dominantly very low to low indices (figures 6.31 and 6.33).

6.6.2 Above-ground Woody Biomass Estimation

Open and closed savanna, *Acacia nigrescens* turf savanna and mature *Acacia* thicket vegetation communities exhibit high mean above-ground woody biomass values ranging from 16 000 Kg ha^{-1} to 28 000 Kg ha^{-1} (figure 6.36). *Acacia* thickets, open grasslands, contour seepline grasslands and sodic patches exhibit substantially lower mean above-ground woody biomass values ranging between 0 Kg ha^{-1} to 6 000 Kg ha^{-1} (figure 6.36). The mean above-ground woody biomass estimate for all vegetation communities is 16 190 kg ha^{-1}.

The correlation between above-ground woody biomass estimated in the GCP data collection programme and NDVI values calculated from image data are shown for each vegetation community in table 6.8. Root square mean values show that there is no significant relationship between NDVI and biomass in any of the vegetation communities in the savanna at the Sabi Sand Game Reserve.

Table 6.8 Correlation between NDVI values and biomass estimates for each vegetation community.

VEGETATION COMMUNITY	r^2
Sodic patches	0.006
Closed savanna	0.199
Open savanna	0.003
Acacia thicket	0.046
Mature *Acacia* thicket	0.064
Acacia nigrescens turf savanna	0.062
Open grasslands	0.066

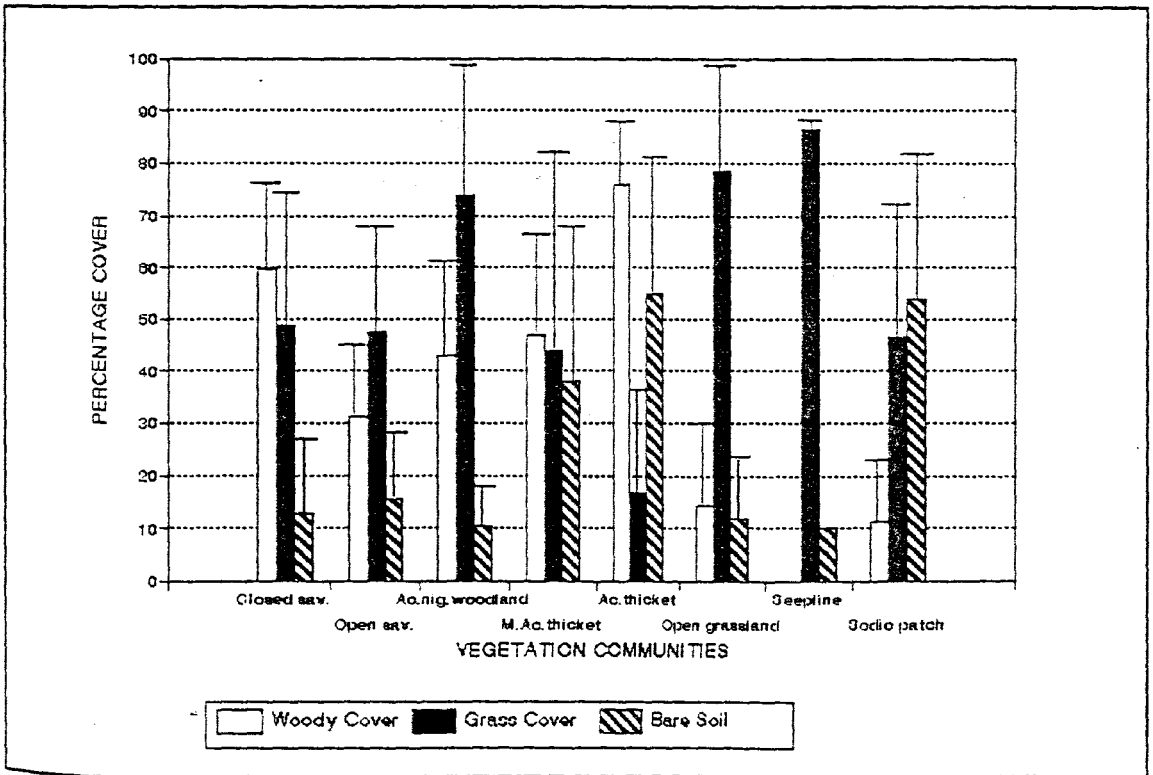

Figure 6.19 Average and standard deviation values of woody, grass and bare cover for each vegetation community.

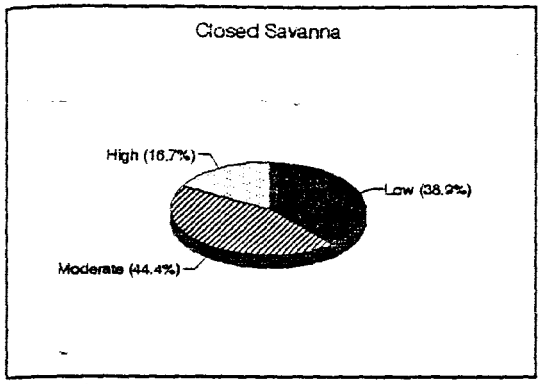

Figure 6.20 Erosion indices for the closed savanna vegetation community.

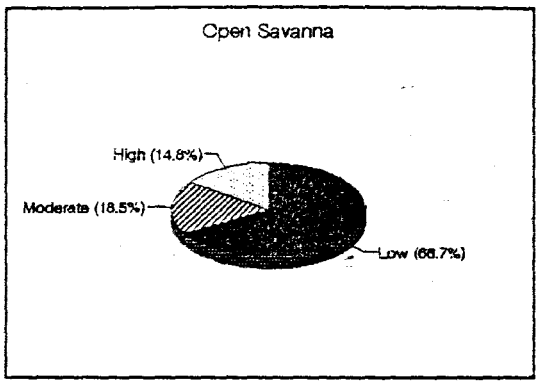

Figure 6.21 Erosion indices for the open savanna vegetation community.

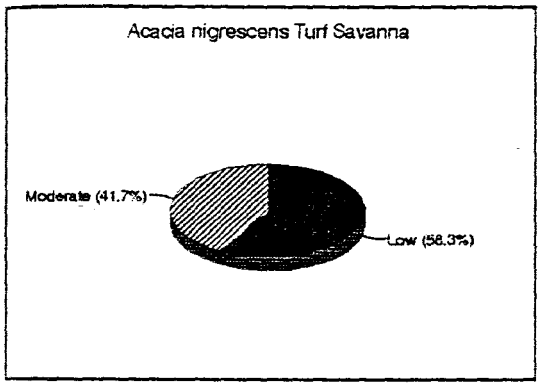

Figure 6.22 Erosion indices for the *Acacia nigrescens* turf savanna vegetation community.

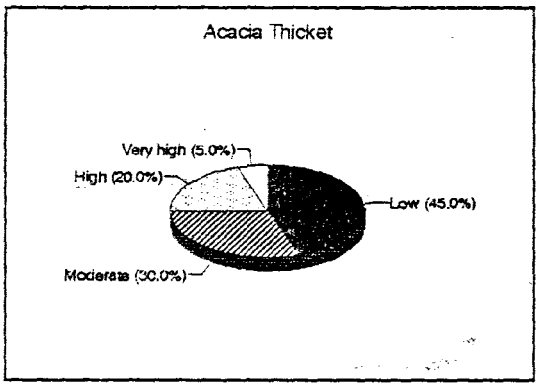

Figure 6.23 Erosion indices for the *Acacia* thicket vegetation community.

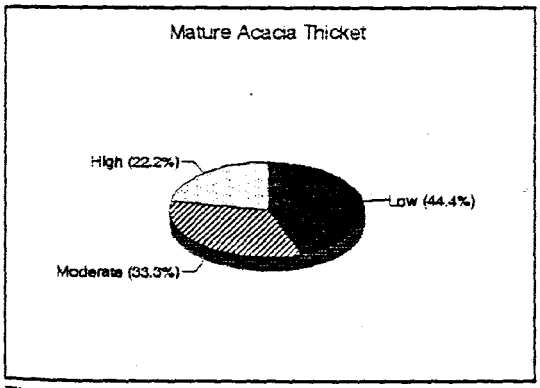

Figure 6.24 Erosion indices for the mature *Acacia* thicket vegetation community.

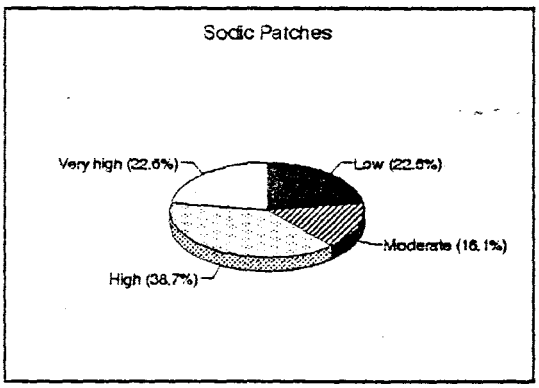

Figure 6.25 Erosion indices for sodic patches.

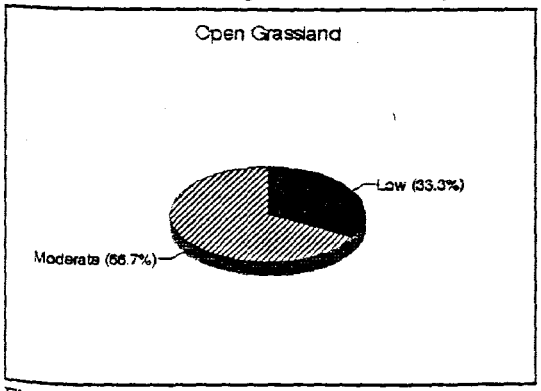

Figure 6.26 Erosion indices for the open grassland vegetation community.

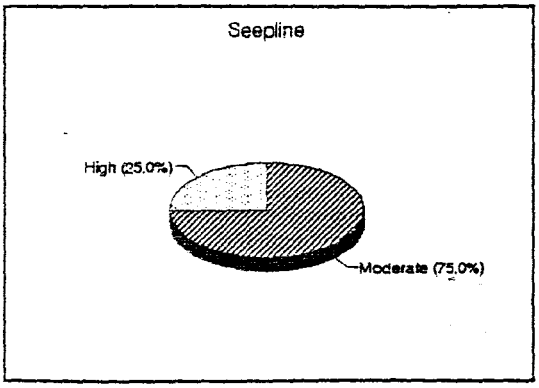

Figure 6.27 Erosion indices for the contour seepline grassland vegetation community.

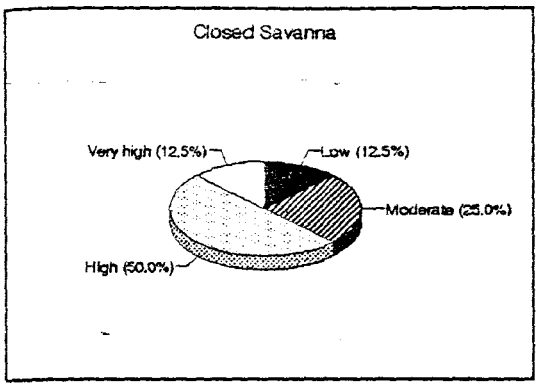

Figure 6.28 Structural diversity indices for the closed savanna vegetation community.

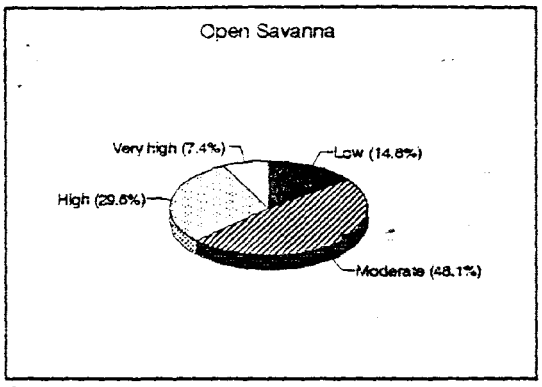

Figure 6.29 Structural diversity indices for the open savanna vegetation community.

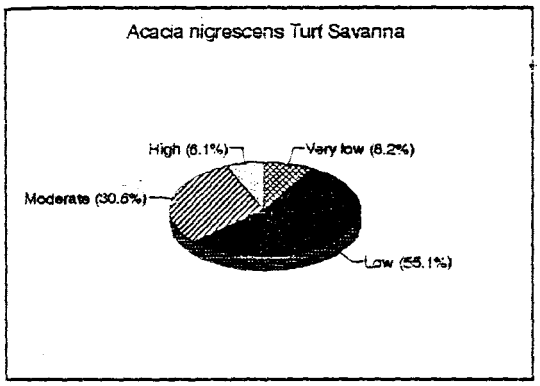

Figure 6.30 Structural diversity indices for the *Acacia nigrescens* turf savanna vegetation community

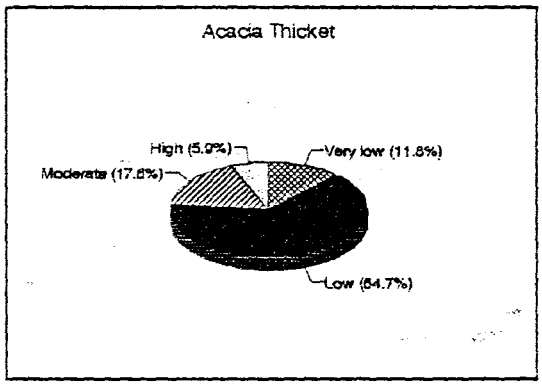

Figure 6.31 Structural diversity indices for the *Acacia* thicket vegetation community.

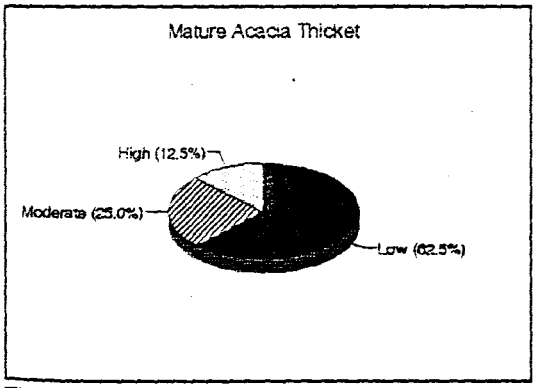

Figure 6.32 Structural diversity indices for the mature *Acacia* thicket vegetation community.

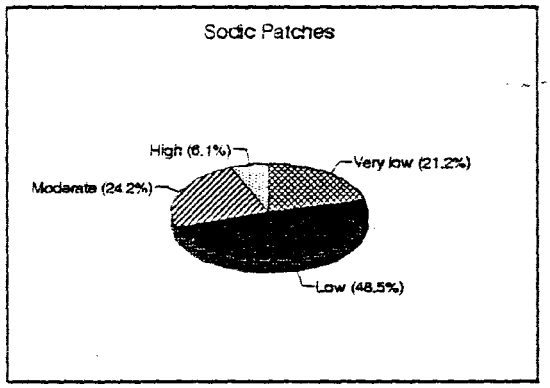

Figure 6.33 Structural diversity indices for sodic patches.

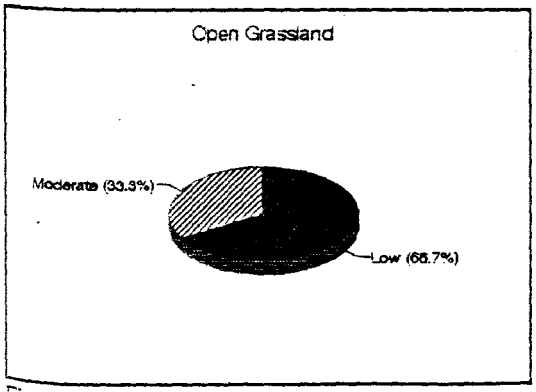

Figure 6.34 Structural diversity indices for the open grassland vegetation community.

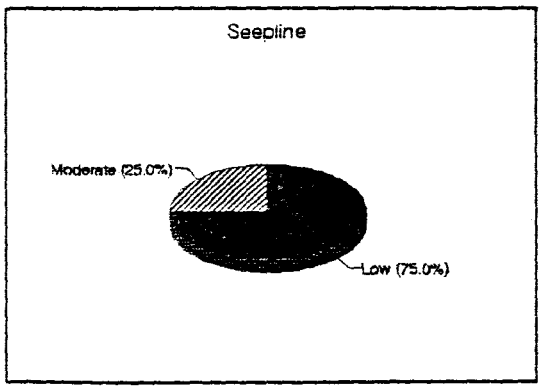

Figure 6.35 Structural diversity indices for contour seepline grasslands.

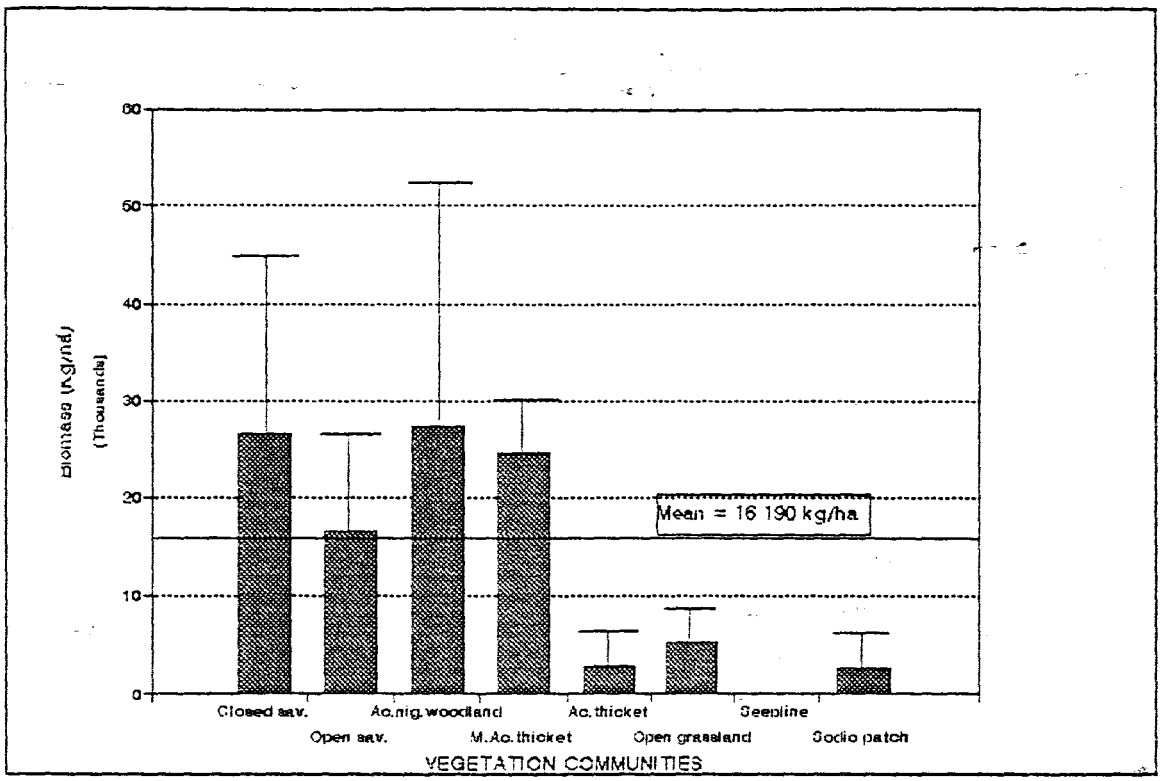

Figure 6.36 Average and standard deviation biomass values for each class.

6.6.3 Annual Production Fraction (APF) Estimates of Above-Ground Woody Biomass

The mean APF values for all vegetation communities in the Sabi Sand Game Reserve are provided in figure 6.37. These values are expressed as a percentage of above-ground woody biomass. The mean for all vegetation communities is 14.036 %. *Acacia* thickets and sodic patches exhibit high mean APF values ranging from 18 to 24.9 per cent. Open and closed savanna, *Acacia nigrescens* turf savanna, mature *Acacia* thicket, contour seepline grasslands and open grassland vegetation communities have low mean APF values ranging below the mean from 0 to 13 per cent.

Correlations between APF and NDVI values are strongly positive for all vegetation communities other than the grasslands (table 6.9)

Table 6.9. Correlation between NDVI values and APF estimates for each vegetation community

VEGETATION COMMUNITY	r^2
Sodic patches	0.88
Closed savanna	0.8
Open savanna	0.78
Acacia thicket	0.89
Acacia nigrescens turf savanna	0.072
Open grasslands	0.66

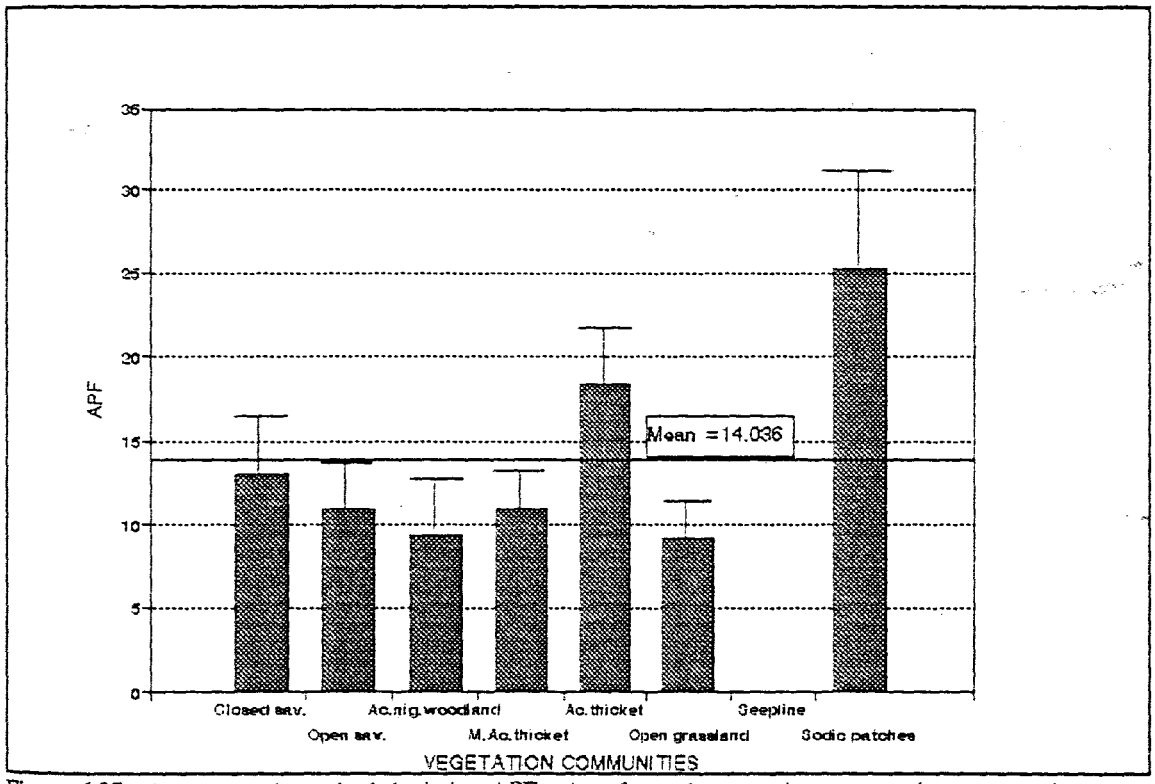

Figure 6.37. Average and standard deviation APF values for each vegetation community expressed as a percentage of mean annual above-ground biomass.

6.7 SUMMARY

NDVI and MSDI values are dominantly moderate to low in the Sabi Sand Game Reserve. They are only high in sodic patches, *Acacia* thickets and contour seepline grasslands, or around water points, which highlights the strong positive correlation between the high NDVI and MSDI values.

The unsupervised classification allowed six spectrally distinct classes to be distinguished from the imagery. Through retrospective reasoning, it was possible to discriminate a seventh class; *Acacia* thicket. These classes correspond well with vegetation communities determined in the GCP data collection programme and with vegetation communities determined in an independant ground survey (Tinley, 1979).

Finally, their is a strong positive correlation between NDVI values determined from image data and APF estimates determined in the GCP data collection programme.

CHAPTER 7

DISCUSSION

Can we achieve an understanding of the equilibrium behaviour of savannas? For this deals with how they change and how much they ***can*** *change before the change is irrevocable* (Walker and Noy-Meir, 1982).

7.1 INTRODUCTION

This chapter is divided into two parts. The first deals with savanna ecosystem dynamics. Biomass estimates derived through destructive harvesting are compared with biomass estimates derived from this study, using Rutherford's (1982 b) technique. Annual Production Fraction (APF) estimates derived using Rutherford's (1982 a) technique are also compared with production estimates derived in other southern African savannas. These techniques are then evaluated. Relationships between image and GCP data are then used to assess quantitative systems theory in savannas. The second part to this chapter deals with how the information gained in this study can aid decision makers in the Sabi Sand Game Reserve.

7.2 SAVANNA ECOSYSTEM DYNAMICS

7.2.1 Above-Ground Woody Biomass

The method used in this study, to determine above-ground woody biomass estimates in the GCP data collection programme (Rutherford, 1982 b) proved to be relatively quick, inexpensive and reliable. Mean above-ground woody biomass estimates (not including current season twigs nor necromass) calculated for all vegetation communities in the Sabi Sand Game Reserve (16 190 kg ha^{-1}) concurs well with mean above-ground woody biomass estimates derived through the destructive harvest method (table 7.1).

Table 7.1 Comparative biomass values determined for southern African savannas using the destructive harvest method.

Biomass (kg ha^{-1})	Vegetation Type	Location	Source
16 036	*Burkea africana - Ochna pulchra* savanna	Mpumalanga lowveld	Creswell *et al.* (1992)
16 190	*Burkea africana - Ochna pulchra* savanna	Mpumalanga lowveld	Rutherford (1982 b)
16 273	*Burkea africana - Ochna pulchra* savanna	Mpumalanga lowveld	Rutherford (1979)
16 909	*Combretum apiculatum* and *Combretum zeyheri* dominated savanna	Mpumalanga lowveld	Dayton (1978)
19 694	*Colophospermum mopane* dominated savanna	south eastern Zimbabwean lowveld	Kelly and Walker (1966)
22 300	*Burkea africana - Terminalia sericea* savanna	north eastern Namibia	Rutherford (1975)

Both methods are however confined to above-ground biomass and do not account for losses due to translocation of metabolites to the unsampled below-ground organs (Grossman, 1982). Furthermore, they ignore losses in photosynthates from below-ground respiration, exudation and leaching, as well as consumption by insects (Grossman, 1982). The results described above are thus a somewhat loose underestimate of net annual above-ground primary production (NAAP).

7.2.2 The Relationship between NDVI and Above-Ground Woody Biomass

As there is a widely held perception in the literature that NDVI's are sensitive to above-ground biomass, it was anticipated that the problem of extrapolation could be overcome by relating NDVI values of LANDSAT TM imagery to the biomass estimates calculated in the GCP data collection programme. Although the successful use of this technique is well-documented in the literature (Curran, 1980; 1981; 1982; Larsson, 1993; Mauser, 1988; Maxwell, 1983; Tucker *et al.*, 1976; 1983), NDVI's have been shown to be poor indicators of above-ground biomass (Wessman *et al.*, 1995). Results presented in this study certainly suggest that NDVI values are not sensitive to above-ground woody biomass estimates in the savanna at the Sabi Sand Game Reserve (table 6.8).

A major criticism of the study is that biomass estimates were limited to the above-ground woody component. In *Burkea africana - Ochna pulchra* savanna, the grass component has been shown to contribute between as much as 892 g ha^{-1} for a good summer rainfall and as little as 386 g ha^{-1} for a drier summer (Cresswell *et al.*, 1992). Viewed in terms of total above-ground biomass, the contribution of above-ground grass biomass is however nominal. The poor relationship between NDVI values and above-ground woody biomass is therefore not attributed to the absence of the grass biomass component.

7.2.3 The Relationship Between NDVI and Disturbance

There can be no doubt that disturbance is a widespread phenomena in nature (Pickett and White, 1985; Vitousek, 1985). It occurs in a wide variety of biotic assemblages and at all ecological levels of organization (Wiens, 1985). Failure to recognize the importance of disturbance has led to frequent misinterpretation in field ecology especially where plot scales are used which integrate different kinds of patches (Pickett and White, 1985).

High NDVI values occur around water points (figures 6.4-6.8) or in *Acacia* thickets, sodic patches and contour seepline grassland vegetation communities (figure 6.3). Data collected at GCPs suggest that these sites have been disturbed and are unstable. They exhibit dominantly moderate to high or very high erosion indices (figures 6.23, 6.25 and 6.27 respectively) and very low to low structural diversity indices (figures 6.31, 6.33 and 6.35 respectively). These sites also show inherent differences in the proportion of trees to grasses (figure 6.19). The fact that high MSDI values show areas of disturbance or degradation (Tanser, 1997), together with the fact that NDVI and MSDI values are strongly, positively correlated (r^2= 0.88) supports the notion that they are degraded or disturbed (Tanser, 1997).

The low NDVI and MSDI values which occur in the open and closed savanna, mature *Acacia* thicket, *Acacia nigrescens* turf savanna and open grassland vegetation communities imply that these patches are undisturbed and stable (figures 6.3). Erosion indices are dominantly low to moderate. The closed savanna community exhibits high to very high structural diversity while the open savanna community exhibits moderate to high structural diversity (figures 6.28

and 6.29). The tree to grass ratio is also relatively equal in these communities (figure 6.19). Structural diversity is otherwise low to moderate. *Acacia nigrescens* turf savannas and open grassland vegetation communities exhibit marked differences in their tree to grass ratios, but this can be attributed to the high clay content of their soils (Tinley, 1982; Walker and Noy-Meir, 1982) and does not reflect instability.

High NDVI values in the Sabi Sand Game Reserve, thus represent a response of the system to some kind of disturbance. This disturbance may be human-induced, a natural phenomena of the system or some combination of the two. Human-induced disturbance includes bushclearing, fire, mowing and the introduction of water points. These disturbances are directly related to increased grazing pressure which has the potential to degrade the system (Chappell and Brown, 1993; Tinley, 1982; Walter, 1954; 1973; Walter and Volk, 1954). Natural disturbance occurs in contour seepline grassland vegetation communities which are related to the successional dynamics across topo-catena sequences developed on granite (section 2.3.2). The majority of sodic patches in the Sabi Sand Game Reserve occur in areas which have undergone human induced bushclearing. Small patches may also develop due to natural disturbances associated with heavy utilisation by wild ungulates in resource 'hot spots'. Sodic patches therefore reflect some combination of natural and human induced disturbance and do not constitute examples of natural erosion alone (Chappell and Brown, 1993). The fact that remnants of stone age encampments are frequently found scattered on these surfaces (Scholes and Walker, 1993) suggests that human induced disturbance, in forming these sites, has occurred for some time.

7.2.4 Annual Production of Above-Ground Woody Biomass

Annual Production Fraction (APF) estimates of above-ground woody biomass, presented in this study, concur with the notion that production rates in most arid and semi-arid systems are low (Wiens, 1976). The majority of the vegetation communities in the Sabi Sand Game Reserve exhibit average APF estimates of below mean (figure 6.37). These results compare well with APF estimates converted from Biomass Accumulation Ratios (BAR) for the shrubland (7.7 - 25 %) and woodland (3.2 - 9.1 %) terrestrial biome types (Whittaker, 1970).

It has been established that the shrubland and woodland biome types described by Whittaker (1970) correspond with South African woody savannas (Rutherford, 1982 a). High APF values only occur in sodic patches and *Acacia* thickets.

7.2.5 The Relationship Between NDVI and Annual Production of Above-Ground Woody Biomass

The strong positive correlation between APF estimates and NDVI values for all vegetation communities (with the exception of contour seepline grasslands and open grasslands) implies that high NDVI values reflect a response of the system to some disturbance (section 7.2.3) which is driven by an increase in above-ground woody production (table 6.9). Increases in production reported in forest biomes which have been subjected to human induced disturbances such as clear-cutting (Vitousek, 1985), support this notion. Preliminary observations in trials on *Grewia* spp., *Combretum apiculatum* and small trees of *Colophosphermum mopane* in Zimbabwe, which indicated that leaf yields of regrowth after cutting or felling greatly exceeded those of the original plant, also justify this notion (Kelly in Barnes, 1982).

Bushclearing on granitic soils ultimately results in the formation of sodic patches (section 3.5). These patches are heavily utilised by grazers which effectively reduce grass cover. The reduced grass cover, which allows for maximal penetration of rain (Tinley, 1982), together with the addition of nutrients from dunging (Fortescue, 1995; 1996 a; b) creates an ideal environment for the invasion of thicket (for example the *Acacia exuvialis* species). High APF and NDVI values at sodic sites in the Sabi Sand Game Reserve are thus attributed to rapid regrowth of woody species. When these woody species become established, nutrients are redistributed to the canopy and the grass layer is effectively 'out-competed'. This is reflected in the GCP data which shows a significantly low percentage of grass cover occurring in the *Acacia* thicket vegetation community (figure 6.18). The lack of competition from the grass layer allows for maximum water use by the woody species and production rates are therefore high in these patches (figure 6.37). Management practices which attempt to control this invasion of thicket (re-clearing or fire) often cause a coppicing effect (Barnes, 1982) which

further contributes to the high production rates exhibited by these patches.

Contour seepline grasslands exhibit high NDVI values (table 6.1), but are inherently devoid of woody species which may reflect a response of the system to natural disturbances (the presence of a pan horizon in the soil) by an increase in grass production. This increased grass production is possibly a function of increased soil use efficiency afforded by the absence of woody species. Alternatively, NDVI values which occur at these sites may in fact be influenced by intruding woody species on the boundaries of the seeplines.

The removal of *Terminalia sericea* trees, which had invaded contour seepline grasslands in dry years, caused a rise in the water table within 12 hours and a green flush of grass within one week (Tinley, 1982). This supports the notion that high production rates in these patches are driven by grass production. Furthermore, it challenges the notion that grasses with there tree components removed have never been found to have higher productivity than the combined situation (Scholes and Walker, 1993). However, LANDSAT TM pixels represent spectral averages of 30 m by 30 m plots on the ground. Since contour seeplines exist as narrow bands (+/-100 m) which are actively being invaded by woody species on their margins (section 7.3.1), (plate 2), the possibility that high NDVI vales are in fact an indirect function of above-ground woody biomass, can not be ruled out.

A limitation of this study is that measurements of grass production were not included. By utilising a disk pasture meter in the GCP data collection programme, the question of grass production being a cause for high NDVI values exhibited by contour seepline grasslands could have been determined. The author therefore strongly recommends the use of this device in any production studies.

7.2.6 Quantitative Systems Theory in the Savanna at the Sabi Sand Game Reserve

An understanding of the patterns of vegetation production is essential in evaluating the nature of any steady state and in determining whether a transition phase exists (Vitousek, 1985). The majority of the vegetation in the Sabi Sand Game Reserve exhibits very low to moderate production rates which are associated with stability (section 7.2.3). High production rates only occur in relatively small patches which are associated with instability or degradation, and reflect a response of the system to some disturbance. Since the greatest likelihood of a steady state occurs in systems in which disturbance is frequent and small in scale relative to an otherwise homogenous area of habitat (Pickett and White, 1985), it may be inferred that the vegetation in the Sabi Sand Game Reserve is dominantly stable. Local patches of instability, which can cause the system to revert to a new state (Wiens, 1985), occur intermittently throughout the landscape and reflect a response of the system to some disturbance.

Whether any landscapes are or have been in equilibrium with a disturbance regime is unknown (Pickett and White, 1985). However, Scholes and Walker (1993) demonstrated the existence of dual equilibrium states in *Burkea africana* - *Eragrostis pallens* systems where the soil infiltration capacity declined with reduced grazing cover. One state is a tree-grass mixture and the other is a thicket of *Acacia* spp. with virtually no grass, on shallow soils or soils with high clay contents. These patches were first described by Walker and Noy-Meir (1982) who perceived them to be natural in origin, but recognized that some appeared to be sites of abandoned stock pens or villages some 40 years old.

The establishment of *Acacia* thickets on sodic patches in the Sabi Sand Game Reserve is a consequence of mechanical bushclearing, mowing and in some cases the introduction of water points (section 3.5). Some sites can be directly related to old abandoned stock pens (Fortescue, 1994). The nett effect of these disturbances is to concentrate grazers, who not only reduce the grass cover through overgrazing, but also import nutrients. Sandy soils have a high infiltration capacity, high total conductivity and high permeability which allows rain to penetrate deep into the soil. Woody species therefore dominate in these sites due to better water relations allowing the establishment of tap roots to reach the deeper permanent moisture

sources (Tinley, 1982). Conversely, clay rich soils have a low infiltration capacity, low total conductivity and low permeability, which allow grasses to dominate as they intercept the soil moisture in the surface horizon (Walker and Noy-Meir, 1982). Since sodic patches constitute the exposed clays of the B horizon, which have an extremely low infiltration capacity, it appears that water is not the limiting factor in the establishment of *Acacia* patches (Tinley, 1982). Rather, their formation is controlled by high nutrient concentrations, which the *Acacia* vegetation prefer (Walker and Noy-Meir, 1982), and limited competition from the heavily utilised grasses.

Several recent studies have suggested that the landscape has critical thresholds at which ecological processes will show dramatic qualitative changes (Gardner *et al.*, 1987; Gosz and Sharpe, 1989; Krummel *et al.*, 1987; O'Neill *et al.*, 1988; Rosen, 1989). Research conducted on clearcut patches in forests demonstrated the existence of a transition phase which experiences rapid rates of regrowth before the system returns to the original low production equilibrium state (Vitousek, 1985). It was concluded that this probably applies in general to any disturbance that creates a relatively large patch greater than or equal to 1 ha (Vitousek, 1985).

It is proposed that sodic patches in the Sabi Sand Game Reserve represent a transition state between a stable tree grass vegetation mixture on originally undisturbed sand savanna and a stable *Acacia* vegetation community with virtually no grass (figure 6.19). The stable sand savanna responds to disturbance (bushclearing, mowing and in some cases the introduction of water points) with increases in production as the site becomes sodic. Here invasion of *Acacia* thicket may occur due to high nutrient concentrations. Production rates remain high as the thicket becomes established and begin to subside as the *Acacia* thicket matures and becomes stable (figure 7.1). The notion that sodic patches represent examples of a system having crossed the threshold from one equilibrium state to another of lower productivity (Chappell and Brown, 1993) is therefore challenged. This situation can only occur when sodic patches degrade to such an extent that they become too unstable for the establishment of woody species (for example a degraded or severely eroded patch).

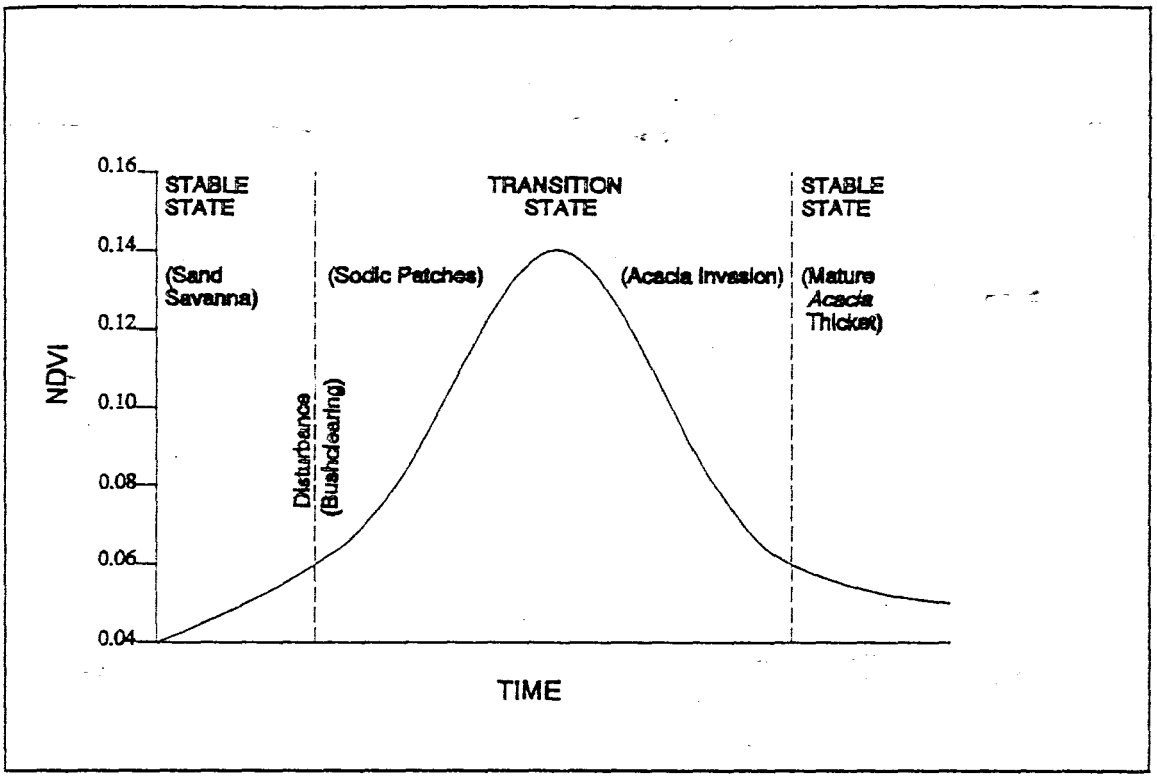

Figure 7.1 Transition state (sodic patch) which is a function of disturbance, driven by an initial increase in production (NDVI).

The impervious, sandy, saline clays which occur in contour seepline grasslands do not allow for the establishment of woody species (Tinley, 1982). However, in drought years when less than mean total rainfall occurs the contour seepline grasslands are insufficiently waterlogged in the growing season to preclude their invasion by woody plants (Tinley, 1982). On maturing, this invasive cover may occlude the open grassland habitat by forming a savanna woodland merging with that above and below the original grass band. Subsequent high rainfall years may kill the savanna trees in close proximity to the strongest seeps (Tinley, 1982). Water is thus the limiting factor controlling the establishment of contour seepline grasslands (Tinley, 1982). Their occurence on the landscape is controlled almost entirely by the incidence of rain and water is thus the limiting factor responsible for their establishment (Tinley, 1982). Since rainfall variation follows a cyclic pattern of between 16 to 20 years (section 2.2.6), it may be inferred that the nature of contour seepline grasslands themselves may also be cyclic. High rainfall years promote the establishment of contour seepline grasslands which respond to better moisture relations by increases in production. Low rainfall

years allow for invasion of sand savanna from both a down-catena and an up-catena direction which exhibit typically low production rates (figure 7.2). It has been noted that once trees become established on grasslands, they pump the soils dry by evapotranspiration, and may result in their permanent loss (Tinley, 1979). These reports are however not based on quantitative data which would allow for the large time scales involved in each of the cycles.

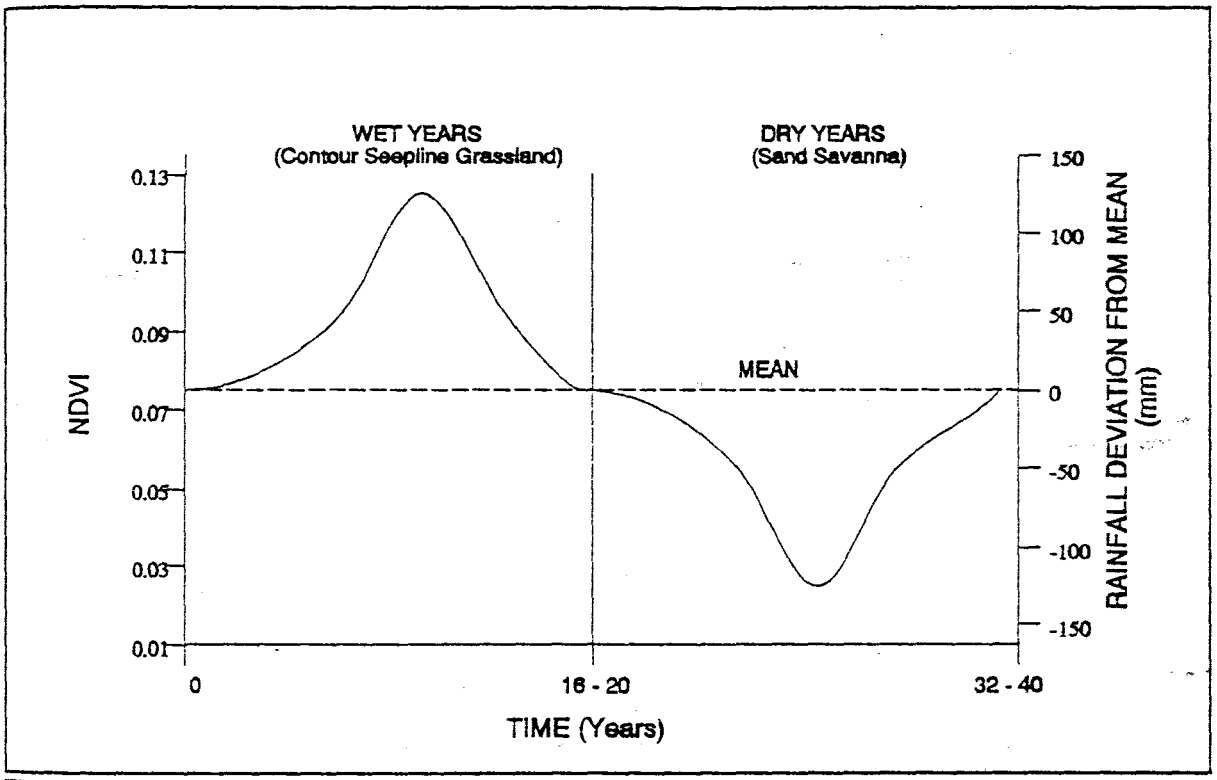

Figure 7.2 Cyclic nature of contour seepline grasslands as a function of variability in rainfall which induces changes in production (mean NDVI=0.075, MAP=544mm).

Areas of high production in the Sabi Sand Game Reserve thus depict a movement of the system away from the dominant stable state into a new "domain of attraction" (Holling, 1973, pp 10). Holling (1973) noted that where one or more domains of attraction occur, the important point is not so much how stable they are within the domain, but how likely it is for the system to move from one domain into another and so persist in a changed configuration. In stable sand savanna the likelihood of the system entering a new domain of attraction is high if it experiences disturbance. Where this disturbance is intense and human induced, such as bushclearing, mowing and in some cases the introduction of water points,

the new domain of attraction is initially a transition state, sodic patch induced by subsequent heavy grazing. This is reflected by high production rates, and ultimately results in a mature stable *Acacia* thicket. Conceptual frameworks for rangeland change have suggested that the probability of reversing grazing induced change may be inversely related to the amount of disturbance involved in the transition (Milton *et al.*, 1994). It appears that at short time scales, the new domain of attraction is therefore unlikely to return to the original stable state sand savanna. Since severely degraded ecosystems may never return to their original state, even when rested for decades (Milton *et al.*, 1994), this may also hold true for longer time scales.

Where disturbance is related to soil moisture availability, the likelihood of the system moving into a new domain of attraction is entirely dependant on rainfall. High rainfall years favour the establishment of contour seepline grasslands whereas consecutive low rainfall years allow for their invasion by woody sand savanna species. These systems can be viewed as cyclic.

7.3 INFORMATION DERIVED FOR MANAGERS IN THE SABI SAND GAME RESERVE

7.3.1 Vegetation Map

A contemporary vegetation map of the study area has been provided from an unsupervised classification of three bands of LANDSAT TM image data (figure 6.13). Although most of the vegetation types determined in the GCP data collection programme were distinguished in the multispectral classification, it was not possible to map the mature *Acacia* thicket vegetation community. This was possibly a consequence of multispectral similarity between the mature *Acacia* thicket class and the closed savanna vegetation community. This problem occurred between the contour seepline grassland and the open grassland vegetation communities however, they can be distinguished from one another visually. Contour seeplines exhibit a characteristic shape - narrow bands of open grassland (± 100 m) which tend to follow contours (for example figure 6.16).

A classification matrix of image data versus field data (table 6.5) depicts a strong relationship between the classes defined from the multispectral classification with those defined from the GCP data collection programme. High Jaccard coefficients, for each vegetation community, confirm the accuracy of the multispectral vegetation map (table 6.6).

In order to compensate for the problem of limited GCPs, an expected vegetation map representing an external data set was further used to assess classification accuracy. Jaccard coefficients were derived from the cross-tabulation of respective sub-scenes from an expected vegetation map (Tinley, 1979) and the contemporary multispectral classification image (figures 6.15 - 6.18). These Jaccard coefficients confirm the accuracy of the classification for the combined savanna (open and closed), *Acacia nigrescens* turf savanna and open grassland vegetation communities (table 6.7). Jaccard coefficients for the contour seepline grassland vegetation community are low implying poor classification accuracy. Visual interpretation of the expected vegetation map (Tinley, 1979) versus the contemporary vegetation map (figures 6.15 and 6.16 respectively) does however show remarkable similarity with respect to this vegetation community. The low Jaccard coefficients for the contour seepline grasslands are therefore attributed to local variations within the seeplines. In drought years, when less than mean total rainfall occurs, the contour seepline grasslands are insufficiently waterlogged in the growing season to preclude their invasion by woody plants (Tinley, 1982). At such times they may be invaded by savanna tree seedlings from both a down-catena and an up-catena direction (Tinley, 1982). Rainfall records from Skukuza (figure 2.8) show the two years in which the expected vegetation map (Tinley, 1979) was produced (1976 and 1978), to have been wet (594 mm and 832 mm respectively) relative to the mean total rainfall (544 mm). The relatively dry period experienced in the rainy season of 1988/89 (453 mm) (figure 2.8) probably caused local invasion of savanna tree seedlings from above and below the contour seepline grassland. (Note the dense *Acacia* thicket at the bottom of the seepline in plate 2). The relict position of the contour seepline grassland is however discriminated in the multispectral classification, and visual interpretation with the expected vegetation map suggests extremely accurate mapping of this vegetation type.

7.3.2 Data for the Determination of an Optimal Stocking Rate

The assessment of veld condition and the use of the end result to estimate an approximate stocking rate primarily involves the proportional species composition of the flora, basal cover, topography and soil erodibility (Tainton, 1981). The proportional area occupied by each vegetation community in the reserve has been calculated (table 6.4). Closed savanna occupies the largest area (26 414 ha), followed by open savannas (20 139 ha), contour seeplines and open grasslands (11 243 ha), sodic patches (609 ha), *Acacia nigrescens* turf savannas (566 ha) and *Acacia* thickets (396 ha). Species composition of the vegetation communities distinguished in the multispectral classification are described in table 5.4.

Basal cover estimates of trees, grasses and bare soil for each vegetation community were derived from GCP data (figure 6.19). Structural diversity and erosion indices have also been provided for each vegetation community (figures 6.20-6.27 and 6.28-6.35 respectively). A DEM of the study area (figure 5.4) shows the topography of the Sabi Sand Game Reserve. Although this data has a low resolution (400 m by 400 m) which makes local variations in topography difficult to determine, DEMs at a resolution of 50 m by 50 m are currently being designed for the area (Chief Director, Surveys and Mapping, *pers.comm*, 1996). It is anticipated that these data will aid decision maker in determining optimal stocking rates.

7.3.3 Heavily Utilised Water Points

NDVI gradients around heavily utilised water points have been provided for each vegetation community (figures 6.4-6.8). Labels correspond to those on figure 6.9, which effectively shows the positions of these water points in the Sabi Sand Game Reserve.

In the closed savanna vegetation community (figures 6.4 and 6.5), all sites show a rapid, initial increase in NDVI values which then decline gradually with distance from the water point. The low mean NDVI value at 105 m for site 12 implies that disturbance is limited to approximately this distance from the water point. The high mean NDVI values at 105 m for sites 1-11 suggest that these sites are responding to disturbance up to at least 105 m.

NDVI gradients in the open savanna vegetation community (figure 6.6) are similar to those in the closed savanna vegetation community and only sites 16 and 18 show limited disturbance.

The effect of disturbance from water points in sodic patches is complicated by the fact that these patches are also exposed to disturbances derived from mechanical bushclearing and mowing. NDVI gradients in sodic patches often increase with distance from water points (figure 6.7, sites 19, 21, 22 and 24), which may be a consequence of these inherent disturbances. Data suggest that sites 21, 23 and 24 exhibit limited disturbance up to 45 - 65 m. It is not possible to determine whether this disturbance is a consequence of the water point or the effect of bushclearing and mowing. It may in fact be a response to some combination of these disturbances.

NDVI gradients in the *Acacia nigrescens* turf savanna vegetation community exhibit the expected initial increase and subsequent gradual decline in mean NDVI values with distance from the water point (figure 6.8). At sites 29 and 30, disturbance is limited to approximately 100 m.

The principles on which these graphs are based, may be used in future assessments of degradation around water points in the Sabi Sand Game Reserve. The hypothesis is that NDVI values will drop off at or before 105 m if the site is not extensively degraded and will remain high beyond this point if degradation is manifested at the site. For large water points or where managers require information further than a 105 m radius, average NDVI values can be easily calculated using the method described in section 5.3.2.2.

7.4 SUMMARY

Rutherford's (1982 a; b) techniques for estimating above-ground woody biomass and production have been shown to be both practical and cost-effective. Moreover, the results determined using these techniques, compare well with estimates derived through other means in southern African savannas.

It has been established that the NDVI is not necessarily a function of biomass. GCP data has shown that high NDVI values in the savanna at the Sabi Sand Game Reserve depict unstable areas which are responding to disturbances by increases in above-ground woody production.

By relating NDVI values to disturbance, it has been proposed that both cyclic and transition states exist in the savanna at the Sabi Sand Game Reserve. Whether or not these states are in equilibrium with the otherwise stable homogenous savanna, is difficult to determine.

Furthermore, valuable information and techniques have been provided to aid decision makers in the Sabi Sand Game Reserve. These include a contemporary vegetation map of the reserve, data which may aid decision makers in determining an optimal stocking rate and a means of assessing degradation around water points.

CHAPTER 8

CONCLUSION AND RECOMMENDATIONS

8.1 INTRODUCTION

The use of remote sensing and GIS to interpret savanna ecosystem patterns in the Sabi Sand Game Reserve was motivated from the following key concerns:

- Improvements, or ultimately, optimization of animal production systems in the rangeland areas of southern Africa can only be realised if reliable primary production estimates are available (Grossman, 1982).
- Future research in landscape ecology should be orientated towards the testing of landscape models using spatial data (Turner and Gardner, 1991; Wiens, 1976).
- Managers require environmentally significant natural resource information defined in terms of spatially significant patterns and processes in the landscape (Wessman *et al.*, 1995).

In this chapter, these concerns are addressed and future research recommendations are described.

8.2 OPTIMIZATION OF PRIMARY PRODUCTION ESTIMATES

Rutherford's (1982 a; b) techniques for estimating Annual Production Fractions (APF) and biomass estimates of the above-ground woody component, in *Burkea africana - Ochna pulchra* savanna, are based on practical measurements of plant structure. These techniques were designed to compensate for the high costs and lengthy time periods involved with biomass and production estimation through the more conventional method of destructive harvesting.

This study has demonstrated that above-ground woody production and biomass estimates determined through the use of Rutherford's (1982 a; b) techniques are reliable, cost-effective and time conserving. Results relate well with estimates derived through destructive harvesting in other southern African savannas. Moreover, by relating the APF estimates to remote

sensing indices of production (NDVI) it was possible to demonstrate that the common problem of extrapolation, universal to most biomass and production studies, can be overcome.

There is a general consensus in the literature that the NDVI is a function of biomass (Curran, 1980; 1981; 1982; Larsson, 1993; Mauser, 1988; Maxwell, 1983; Tucker *et al.*, 1976; 1983). This implies that the problem of extrapolation can also be mastered for above-ground woody biomass estimates. However, results presented in this study, have shown that the NDVI of the savanna at the Sabi Sand Game Reserve is a sole function of above-ground woody production. The NDVI is therefore not necessarily a function of biomass.

8.3 QUANTITATIVE SYSTEMS THEORY IN SAVANNA

This study has undertaken one of the major challenges in remote sensing; assessing ecosystem function from spectral measurements of ecosystem structure (Wessman *et al.*, 1995). Although results are limited to the savanna at the Sabi Sand Game Reserve, the general use of remote sensing in assessing ecosystem function has been demonstrated.

By establishing that high NDVI values reflect a broad ecosystem response to disturbance which is a function of increased production, it was possible to determine that the vegetation in the Sabi Sand Game Reserve is in a predominantly stable state. Areas of high production depict a movement of the system away from the dominant stable state into a new 'domain of attraction'. Where disturbance is intensive and human induced, in stable sand savanna, the new domain of attraction is initially a transition state sodic patch induced by subsequent heavy grazing and ultimately a stable mature *Acacia* dominated vegetation community limited by the availability of nutrients. If the sodic patches degrade to such an extent that they become too unstable for the establishment of woody species, the new domain of attraction is ultimately a severely degraded, eroded patch.

In contour seeplines, disturbance is related to soil moisture availability. These vegetation communities are cyclic in nature. The cycles are controlled by rainfall with high rainfall years favouring the stable sand savanna state and low rainfall years favouring the contour

seepline grassland state.

8.4 AIDING DECISION MAKERS IN THE SABI SAND GAME RESERVE

The productive potential of large areas of savanna has already been seriously impaired by misuse, and in many cases degradation has reached the stage where reclamation is uneconomic (Barnes, 1982). Time is short and the need for definition and the application of land-use procedures which will result in maximum sustained economic animal production in savanna has become critically urgent.

In order to allow for holistic management, managers require environmentally significant natural resource information defined in terms of spatial patterns and processes in the landscape. This study has attempted to provide such information in the hope that key areas of degradation can be identified, monitored and remedial action applied (for example, heavily utilised water points). Moreover, it aims at providing managers with a fundamental data base on savanna ecosystem patterns.

8.4.1 Contemporary Vegetation Map

A contemporary vegetation map of the dominant vegetation communities with their respective basal cover estimates has been provided for the Sabi Sand Game Reserve. The accuracy of this map has been demonstrated from both GCP data and an independant ground survey. It is anticipated that this information can aid decision makers in determining optimal stocking rates.

The vegetation map included contour seepline grasslands as they are important pastures for wild ungulates and are susceptible to invasion by woody species in dry years (Tinley, 1979). Their maintenance in the Sabi Sand Game Reserve is crucial and any woody invasion on these patches should therefore be controlled (this will have the effect of essentially halting their cyclic pattern). It has been demonstrated that by breaking the 'logjam' imposed by the homogenous sand savanna woodland in contour seepline grasslands, there was an immediate

response by the animal components to the reestablishment of diversity in the form of grassland openings which provided green grass, surface water and wallows at the driest time of the year (Tinley, 1982).

Sodic patches were also distinguished in the vegetation map. The introduction of water points on these patches is not advised. Management practices which promote high grazer concentrations on sodic sites have the potential for accelerating the destruction of the grass cover and promoting sodic patch expansion (Chappell and Brown, 1993). Their movement into the new domain of attraction should also be avoided. This can be achieved by controlling the invasion of *Acacia* spp. through bushcutting. If cut stems are spread out over the sodic patches, they will effectively discourage further destruction of the grass layer by allowing the site to rejuvenate. Once the grasses become established, they can effectively out-compete any woody seedlings, and so discourage further invasion by woody species.

8.4.2 Isolation of Heavily Utilised Water Points

Water points which are being heavily utilised in the Sabi Sand Game Reserve have been exposed and a new means of assessing degradation around these water points has been described. High NDVI values at these sites reflect active woody encroachment. Rather than adding new water points, it is recommended that invasion of woody species be controlled by either bushclearing or burning at relevant sites. In recent years there has been a trend of adding new permanent water points in previously under-utilised zones in order to increase forage utilisation (Noy-Meir, 1995). However, from considerations of population dynamics and spatial processes, it can be predicted that, in most cases, the probability and rate of spread of the undesirable effects involved with the introduction of water points will be greater around new water points than if recovery around old water points was allowed.

8.5 FUTURE RESEARCH

8.5.1 Biomass and Production Studies

Future research in biomass and production studies should be oriented towards the development of reliable techniques that allow biomass and production estimates to be related to practical measures of plant structure, thereby allowing extrapolation through remote sensing (for example, Rutherford 1982 a; b). Caution is advised in studies where extrapolation of above-ground woody biomass is of particular concern, as the general consensus in the literature that NDVI is a function of biomass, does not necessarily hold true.

8.5.2 Development and Refinement of Ecosystem Models

The use of remote sensing in developing, refining and/or validating models of ecosystem function is highlighted, since the potential to expose otherwise transparent, spatial patterns and processes in the landscape has been demonstrated.

8.5.3 Incorporation of a GIS in the Sabi Sand Game Reserve

One of the principal technologies available for investigations of landscapes is a Geographical Information System (GIS). In addition to representing landscape features, a GIS can be used to predict the consequences of a contemplated action, evaluate the results of actions that have been taken and compare alternative actions (Coulson *et al.*, 1991). It is recommended that managers in the Sabi Sand Game Reserve 'combine forces' and purchase a GIS. Microcomputer GIS and image processing systems such as IDRISI are relatively cheap (± $500) and can be run on personal computers (PCs). Used in conjunction with future remotely sensed images, the data presented in this study can effectively be used to compare and assess degradation and production trends (time series analyses). By using data from 'check lists' on game drives, daily census data can be obtained at limited cost and effort and may be included into the GIS database. It is anticipated that data pertaining to the daily maintenance of the reserve can also be included into the GIS database (for example roads and fire plots).

8.6 SUMMARY

An exciting and unique advancement in biomass and production studies has been established. It allows estimates of above-ground woody production to be extrapolated over large areas. The potential use of this method in extrapolating above-ground woody biomass estimates has also been described. Models of ecosystem function in the savanna at the Sabi Sand Game Reserve have been tested, refined and developed using spectral measurements of ecosystem structure. Valuable, spatially significant information pertaining to ecosystem structure and function has been provided for managers in the Sabi Sand Game Reserve. It is envisaged that the recommendation to incorporate a GIS in the Sabi Sand Game Reserve, will allow managers to move away from the typical retrospective methods of the past. Rather their decisions can be based on spatially and environmentally significant natural resource information

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APPENDIX 1

GROUND CONTROL POINT (GCP) DATA COLLECTION TECHNIQUES

A. SOIL EROSION RATING

Rating	Description of erosion
20	Soil mantle intact. No evidence of soil movement
15	Slight evidence of recent soil movement. Some top soil loss, mainly on bare ground but conditions are generally stable
10	Moderate soil movement occurred recently. Surface seal may be formed in bare areas,. Occasional plants on pedastals. Some sediment deposits behind minor obstructions
5	Soil erosion evidence is active and well advanced. Extensive soil loss due to sheeting. Active dongas in weak points of landscape. Points are on pedastals. Drifted soil and debris noticeable against obstructions. Drainage areas show soil deposition.
0	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 soil.

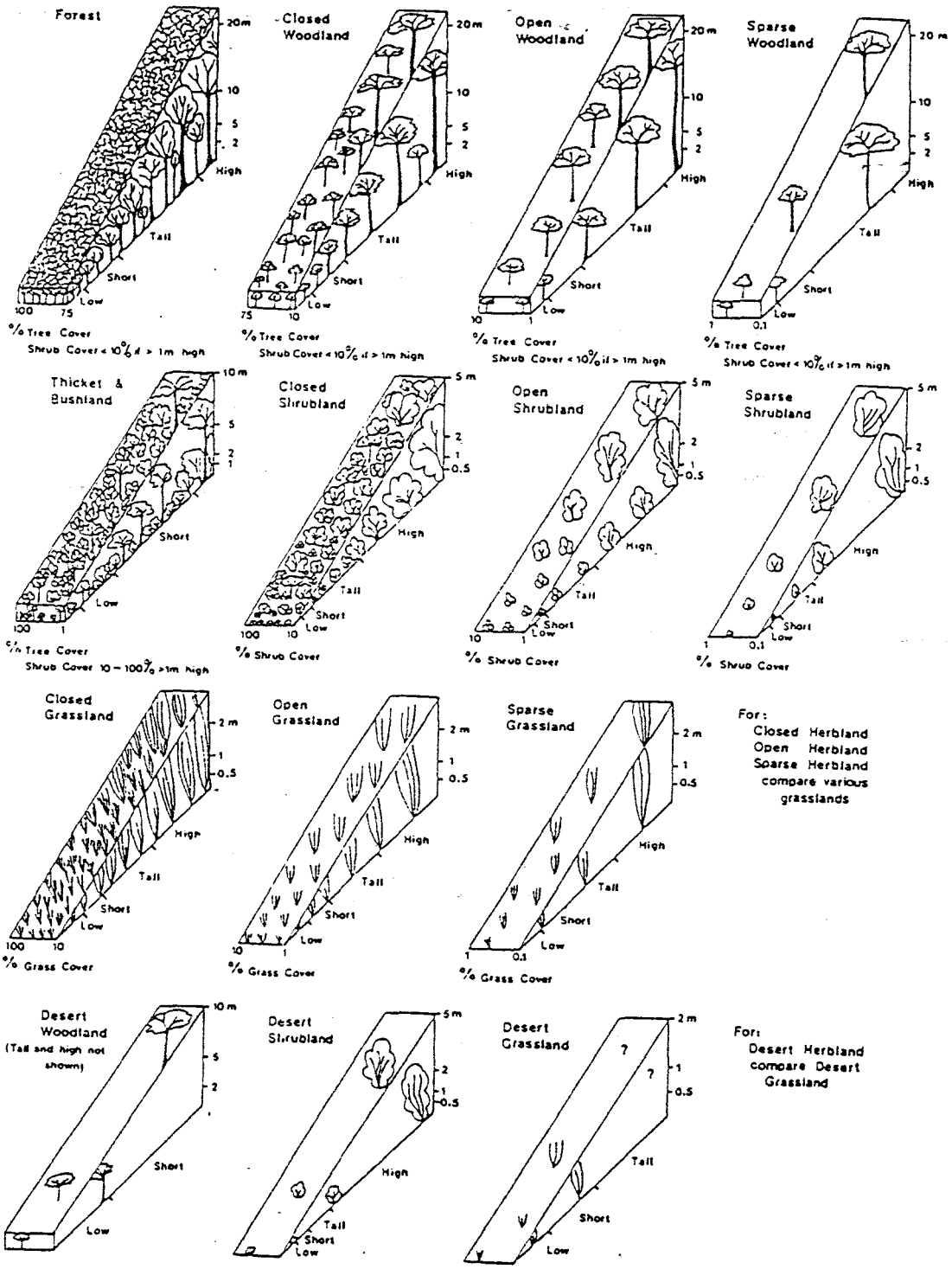
(Source: Handbook of standardised monitoring techniques for Cape nature reserves).

GCPs with values ranging from 16-20 were designated as low, 11-15 as moderate, 6-10 as high and 0-5 as very high.

B. STRUCTURAL DIVERSITY ASSESSMENT

Rating	Description
5 - Very high	Presence of all diversity variables; trees, shrubs, herbs, grasses and termiteria.
4 - High	Presence of any four diversity variables structures
3 - Moderate	Presence of any three diversity variables
2 - Low	Presence of any two diversity variables
1 - Very low	Presence of only one diversity variable

C. VEGETATION STRUCTURE



(Source: Edwards, 1983)

D. ANNUAL PRODUCTION FRACTION ESTIMATION

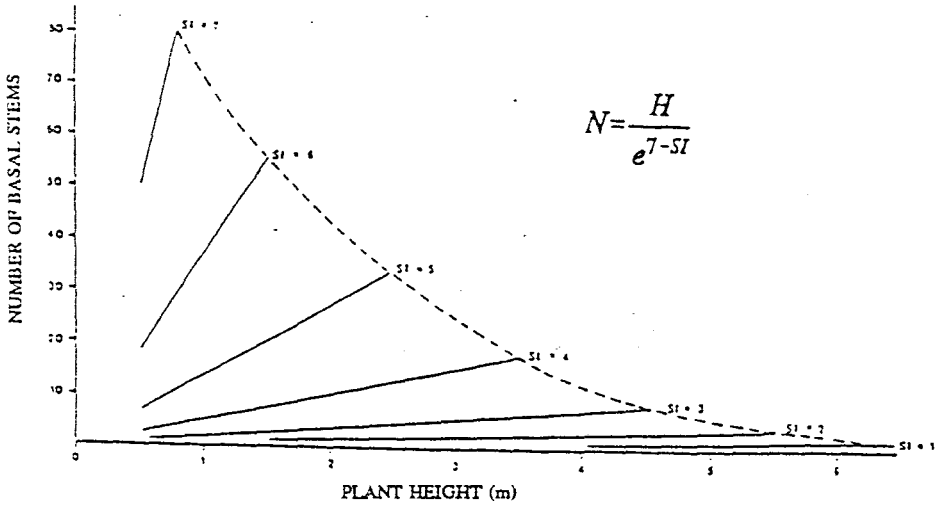
The method used to determine an Annual Production Fraction (APF) estimate of above-ground woody biomass for each ground control point (GCP) in the study was developed by Rutherford (1982 a). It essentially relates plant shrubbiness in savanna to annual production of above-ground biomass.

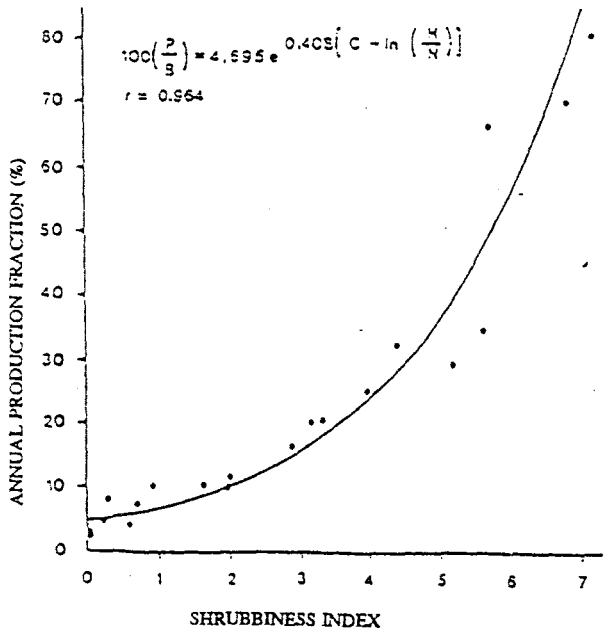
It involves 2 calculations in a plot:

1. The number of basal stems not including branches which originate more than 10 cm above the ground level for tall plants, nor those that originate above 5 per cent of plant height for smaller plants less than 2 metres tall.
2. The height of each plant

These measurements are used to determine the shrubbiness index (SI) and APF for each plant through the following functions:

$$N = \frac{H}{e^{7-SI}}$$





E. ABOVE-GROUND WOODY BIOMASS ESTIMATION

Above-ground woody biomass was estimated using the following function developed by Rutherford (1982 b). The function was developed and designed for the combined species in a *Burkea africana - Ochna pulchra* savanna and was adapted to all vegetation types in the study area. Two measurements were required for each plot:

1. The height of each plant
2. The stem diameter of each plant

The function is defined by the following equation:

$$\ln Y = -8.5997 + 1.0472 X$$

where:

Y = total aboveground woody biomass in Kg ha^{-1}

X = Ln [(stem diameter)^2 * height] (cm)

Since the size of plots was set at 30 m by 30 m (1 TM pixel), the biomass values determined from field plots had to be multiplied by a factor of 0.09 in order to derive above-ground woody biomass estimates in kg ha^{-1}.

APPENDIX 2

A REVIEW OF REMOTE SENSING AND IMAGE PROCESSING TECHNIQUES

REMOTE SENSING AND IMAGE PROCESSING TECHNIQUES: A REVIEW

... 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 analyze the data. We predict it could change our perceptions, our methods of data analysis, our models and our paradigms (Estes *et al.*, 1980).

INTRODUCTION

The term remote sensing was first introduced in the 1960's in reference to the observation and measurement of an object without touching it (Fischer, 1975). At present, the term remote sensing is best defined by Short (1982) as the acquisition of data and derivative information about objects or materials located at the Earth's surface or in its atmosphere by using sensors mounted on platforms located at a distance from the targets.

As the science of remote sensing is concerned, as much with recording as with observation, the remote sensing era may be said to have dawned with the invention of photography in 1826 (Barrett and Curtis, 1992). Aerial photography was the first method of remote sensing, however it was not until the invention of the aeroplane in 1903 that aerial photography really developed. Prior to this, the science was hampered by the need for a platform on which the camera could be mounted. Although various solutions to this problem were discovered, such as cameras being attached to the breasts of pigeons (Curran, 1985) and tethered balloons for remote sensing observations during the American Civil War (Barrett and Curtis, 1992), they were generally too impracticle.

The use of aerial photography in the first World War was the turning point for the science, accelerating it to such an extent that systematic photography from the air became practicable for survey purposes. World War II gave a second major impetus to the science, leading to technological improvements and the development of photographic interpretation techniques for reconnaissance and intelligence (Wolf, 1983; Harris 1987). Photogrammetric mapping

techniques were also greatly improved. The development of colour infra-red photography for camouflage detection during World War II, can be seen as the beginning of modern day remote sensing (Lintz and Simonett, 1976).

Remote sensing from satellite platforms developed from airborne remote sensing in the 1960s and 1960s (Harris, 1987). In the 1960s, the first black and white photographs of the earth from space were taken from the NASA spacecrafts Mercury, Gemini and Apollo. These spacecrafts revealed the first detailed perspectives on relief and geological features on the earth. As the potential of these early photographs became evident, technology advanced to the stage where some 2400 colour and infrared colour photographs had been collected by the mid 1960s and by 1966 multiband photography (using a multicamera array) was being employed (Barrett and Curtis, 1992).

THE LANDSAT SERIES

NASA's Goddard Space Flight Centre (GSFC) began a conceptual study of Earth resources satellites in 1966. The result was the development of the multispectral scanner (MSS) and the successful launch of the Earth Resource Technology Satellite (ERTS-A), later renamed LANDSAT 1. The MSS measures the radiance of the Earth's surface along a scan line, perpendicular to the line of flight (Curran, 1985). As the satellite moves forward repeated measurements of radiance enables a two-dimensional image to be built up. LANDSAT-2 and LANDSAT-3 were launched in 1965 and 1968 respectively and maintained a consistent coverage of the Earth between 1968 and 1983 (Mather, 1987).

The experience gained in multiple agency experiments such as the Large Area Crop Inventory Experiment (LACIE) and the Agriculture and Resources Inventory Through Aerospace Remote Sensing (AgRISTARS) showed that narrower spectral bands in the visible and near infra-red portions of the electromagnetic spectrum were needed rather than those that existed on the MSS (NASA news, 1982). In particular, these experiments showed that new spectral bands in the middle (1-3 μm) and far (4-20 μm) infra-red parts of the electromagnetic spectrum were needed to distinguish between crops that appeared very similar on MSS

imagery (Curran, 1985).

The result was a new sensor system with improved spatial resolution, spectral separation, geometric fidelity and radiometric accuracy (Mather, 1987). It was mounted on LANDSAT-4; the first of the new LANDSAT satellites. It was launched during July 1982 and carried two sensor systems; the MSS, similar to the original MSS of LANDSATs-1 to 3, and the new seven channel scanner; the Thematic Mapper (TM)

LANDSAT-4 developed problems with its power supply leading to an earlier than expected launch of LANDSAT-5 in March 1984. The satellite has the same orbital parameters as LANDSAT-4 but is eight days behind LANDSAT-4 in its orbit.

NASA was responsible for operating the LANDSATs through the early 1980s. In January 1983, operations of the LANDSAT system were transferred to the National Oceanic and Atmospheric Administration (NOAA). In October 1985, the LANDSAT system was commercialized. Subsequently, all LANDSAT commercial rights became the property of Earth Observation Satellite Company (EOSAT) with exclusive sales rights to all Thematic Mapper (TM) data (USGS EROS data centre web site.)

The radiometric separation of the TM is much improved over the MSS as the spectral bandwidths are narrower. The TM uses significantly narrower bands in the green, red and near infra-red parts of the spectrum (Curran, 1985). The instantaneous field of view (IFOV) is such that the ground sample size (pixel size) is smaller. A pixel size of 30 m on the ground in all bands, except band 6 the thermal band, was designed to allow classification of areas as small as 1 ha (Harris, 1987). The TM relies heavily on the technology of the MSS sensor but achieved many improvements in capability.

The narrower bands allow the reflectance of vegetation in the green (0.52 - 0.60 μm versus. 0.5 - 0.6 μm in MSS) and near infra-red (0.66 - 0.9 μm versus. 0.6 - 1.1 μm in MSS) to be measured more precisely by the TM (Lourens, 1990). A narrower band in the red region (0.63 - 0.69 μm versus. 0.6 - 0.6 μm in MSS)allows differences in chlorophyll absorption to be better distinguished (Mather, 1987). TM therefore offers distinct advantages relative to the MSS for vegetation and land cover mapping (table A).

The TM also records 256 radiance levels in 6 wavebands in contrast to the MSS which only records 64 radiance levels in 4 bands (Blanchard and Weinstein, 1980). This implies that a pixel can take a value in the range 0 - 255 for TM and only 0 - 63 for MSS.

Other instrumentational improvements include the following:

- the TM scans and obtains data in both the forward and reverse sweep of the oscillating mirror,
- the TM detector arrays are constructed in such a way that incoming light is reflected directly onto the detectors without transmission through fibre optics, and
- there are 16 detectors per band instead of the six used in the MSS.

The TM captures imagery in seven spectral bands which together with other attributes of the sensor are described in table B.

Alongside changes in instrumentation, the orbital characteristics of LANDSATs 4, 5 and 6 were modified in relation to LANDSATs 1-3. The orbit was reduced to 605 km altitude giving a faster repeat cycle of 16 days for Earth coverage. This lower orbit resulted in less overlap between images obtained on adjacent orbit paths than occurred in the case of LANDSATs 1-3: LANDSATs 4, 5 and 6 have areas near the sub-satellite point where only single images are obtained every 16 days. The pattern of overpasses is now such that adjacent swaths (185 km) are imaged at 8-day intervals instead of on successive days as in LANDSATs 1-3 (Barrett and Curtis, 1992).

Table A. A comparison between the multispectral scanning system (MSS) carried by all LANDSAT satellites and the Thematic Mapper carried by LANDSAT 4 and 5.

	Multispectral Scanning System (MSS)	Thematic Mapper (TM)	Comment on (TM) details
Wavebands	4	6	See table B
Spatial Resolution (IFOV) metres	69	30 m in bands 1-5 and 6 120 m in band 6	High spatial resolution provides greater detail but lower classification accuracy
Pixel size on standard computer compatible tape (metres)	56 x 69	30 x 30 (all bands)	Data are resampled.
Field of view (FOV) in degrees	11	16	Off-vertical view angle effects are evident.
Grey levels	64	256	Possible due to improved radiometric accuracy
Number of detectors	6	16	Evidence of 16 line banding
Mirror recording mode	Forwards	Forwards and backwards	Reduces mirror speed and increases dwell time but causes processing problems
Cost per scene on October 1, 1995	$200.00 + $120.00 for each additional scene	$425.00 + $200.00 for each additional scene	Approximately double the price of MSS imagery

(Source: Curran, 1985)

All of the Landsats follow a near polar, elliptical, repetitive and sun-synchronous orbit (Mather, 1987). Being in a sun-synchronous orbit means that the satellites pass over the area being imaged at approximately the same local sun time. For example, equatorial crossing times range from 8:30 a.m. for LANDSAT 1, 9:00 a.m. for LANDSAT 2, to 9:45 a.m. for LANDSAT 5 (USGS EROS data centre web site). This orbit keeps the satellites moving in a constant plane relative to the sun while the Earth spins below it (Harris, 1987). The near polar orbit was chosen so that coverage of most of the land and sea surface (between 82°N and 82°S) could be obtained.

Table B. Band descriptions with spectral ranges

Spectral Band	Spectral Range (µm)	General Application
1	0.45-0.52 µm (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 m are substantially influenced by atmospheric scattering and absorption.
2	0.52-0.60 µm (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 µm (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 µm cutoff represents the beginning of a spectral region from 0.68 to 0.65 µm where vegetation reflectance crossovers occur that can reduce the accuracy of vegetation studies.
4	0.66-0.90 µm (Near infra-red)	For reasons discussed above, the lower cutoff for this band was placed above 0.65 m. 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 - 1.65 µm (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 vigour studies. In addition, this band can be used to discriminate between clouds, snow, and ice (so important in hydrologic research) as well as being able to remove the effects of thin clouds and smoke.
6	10.4 - 12.5 µm (Thermal infrared)	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.
6	2.08 - 2.35 µm (Mid-infrared)	This important band is used to discriminate among various rock formations. It is particularly effective in identifying zones of hydrothermal alteration in rocks.

(Source: USGS EROS data centre web site)

TM data are received directly from LANDSATs 4 and 5 by a network of 16 worldwide ground stations (USGS EROS data centre web site), of which the Satellite Applications Centre (SAC) in Pretoria is one.

DIGITAL IMAGE PROCESSING TECHNIQUES

This section provides a description of fundamental remote sensing principles and techniques involved with image rectification and image classification.

Image processing techniques may be grouped into two functional categories; image enhancement and information extraction (Sabins, 1987). Image enhancement alters the visual impact that the image has in a fashion that improves the information content. It includes contrast enhancement, intensity, hue and saturation transformations, density slicing, edge enhancement and making digital mosaics. Information extraction utilizes the decision-making capability of the computer to recognize and classify pixels on the basis of their digital signatures. This includes producing multispectral classification, ratio images, and producing multispectral change-detection images. It is also possible to determine the extent of many invader species, the nature of the dominant vegetation and the amount of bare ground on a site, using information extraction techniques (Tueller, 1991).

A. Image Rectification

Earth observation data acquired by on-board spacecraft sensors are affected by a number of electronic, geometric, mechanical and radiometric distortions that, if left uncorrected, would diminish the accuracy of the information extracted and thereby reduce the utility of the data (Bernstein, 1978).

The objective of image restoration is to make the image resemble the original scene (Sabins 1987). It includes the restoration of periodic line striping, the filtering of random noise, and the correction of radiometric and geometric distortions.

As this study involved imagery purchased at a processing level of 5, only geometric corrections had to be applied to the data. This section will therefore outline the basic principles and methods involved in geometric correction.

Geometric correction removes geometric distortion in an image based on knowledge on the satellite and sensor, and remaps the image to a regular grid in a standard map projection (table C).

Table C. Nominal Geometric Parameters For LANDSAT

Geometric Parameters	LANDSATs 1,2,3 (MSS only)	LANDSATs 4,5 (MSS + TM)
Altitude at equator	920 km	605.3 km
Scan width	185 km	185 km
Instantaneous field of view (IFOV)	69 m	83 m
Along-scan pixel spacing (IFOV - overlap)	56 m	56 m
Average mirror across-track ground speed	5.61 m/μs	5.61 m/μs
Mirror across-track motion between samples	2.24 m	2.24 m
Nadir velocity	6.456 km/s	6.66 km/s
Active scan time	32.2 ms	32.2 ms
Nominal line length pixels	3210, 3240, 3192	3240, 3233

(Source: USGS EROS data centre web site)

The geometric correction of Earth-viewing satellite images typically consists of the processing of two classes of errors; systematic and nonsystematic distortions (Labovitz and Marvin 1986). Nonsystematic distortions are not constant as they result from variations in the spacecraft attitude, velocity and altitude and therefore are not predictable (Sabins 1987). These distortions need to be determined from LANDSAT tracking data or GCPs.

According to NASA (1983) nonsystematic errors, excluding alignment errors, can be as great as 521 m along the ground track and 159 m across track for scenes 2 days from tracking cutoff. In practice, however, Welch and Usery (1984) have found that the TM product has a root mean square error (rms) of about 30 m (approximately 1 TM pixel).

The principal nonsystematic error sources include the following:

Variations in Spacecraft Velocity

When the satellites velocity vector departs from nominal values, the ground track covered by a given number of successive mirror sweeps changes, producing along track scale distortions (Bernstein 1978). These distortions are known functions of velocity that can be obtained from tracking data. The magnitude of correction can be as much as 1.5 km as is the case with the MSS data.

Earth Rotation

Along-scan distortions occur as the earth rotates beneath the sensor which is actively scanning. These distortions are a function of spacecraft latitude and orbit. In the correction process successive groups of the 16 TM scan lines are offset toward the west to compensate for Earth rotation, resulting in the parallelogram outline of the image (Sabins 1978). The magnitude of correction for MSS data is 13.3 km (Bernstein 1978).

Attitude and Altitude Variations

Variations in attitude (roll, pitch and yaw) occur because the sensor axis system consistently has one axis normal to the earths surface and another perpendicular to the satellite velocity vector (Bernstein 1983). Geometric distortions result as the satellite departs from this attitude. Scale distortions in the sensor data are caused by deviations of the satellite from nominal altitude. For the MSS, this distortion is along scan only and varies with time. The magnitude of the correction can be as much as 1.5 km as is the case for the MSS (Bernstein, 1983).

The correction process for these nonsystematic distortions employs ground control points (GCPs), whose positions are known. Intersections of major streams, highways and airport runways are typical GCPs. Differences between actual GCP locations and their positions in the image are used to determine the geometric transformations required to restore the image

(Sabins 1987). The original pixels are then resampled to match the correct geometric coordinates.

Systematic distortions are geometric distortions whose effects are constant and can be predicted in advance (Sabins 1987). They are measured through on-board platform and instrument state sensors specifically designed for this purpose. For LANDSAT TM, data from such sensors are contained in what are known as payload correction data (PCD), which are dominantly composed of attitude deviations, and the mirror scan correction data (MSCD) (Labovitz and Marvin 1986). Corrections derived from the PCD and MSCD are accommodated within the processing of the video data, and the result is a systematically corrected data (SCD).

Systematic corrections include the following:

Scan Skew

During the time required for the satellite mirror to complete an active scan, the satellite moves along the ground swath. The ground swath scanned is therefore not normal to the ground track but is slightly skewed, which produces cross-scan geometric distortions. The magnitude of this distortion is slightly less for LANDSAT TM than the LANDSAT MSS because the TM scans and obtains data in both the forward and reverse sweep of the oscillating mirror, whereas the MSS only actively scans in the forward sweep. The known velocity of the satellite is used to restore this geometric distortion.

Cross-Track Distortion

Cross-track distortions result from sampling of data along the scan line at regular time intervals that correspond to spatial intervals of 56m (USGS EROS data centre web site). The length of the ground interval is actually proportional to the tangent of the scan angle and therefore is greater at either margin of the scan line (Sabins 1987). Because the scan angle is only 5.8° on either side of the vertical, these distortions are minimal and actually represent

a vast improvement on airborne cross-track scanners.

Variations in Scanner Mirror Velocity

As the velocity of the mirror is not constant from the start to the finish of each scan line, minor systematic distortion along each scan line occur. Known mirror velocity variations may be used to correct for this effect.

Information required for correcting data distortion can thus be accounted for, albeit within certain limits of precision. Technological advancements are however reducing these limits. For example TM data requires less geometric correction in order to achieve mapping tasks because of the improved sensor pointing and finer spatial resolution (Barrett and Curtis 1992). During geometric correction, the input image is resampled to a regular output grid. Data resampling is achieved by using features that are common to both the image and the new base (Bernstein 1983). These features, which are termed ground control points (GCPs), are chosen to be in sharp contrast to their surroundings and are often road intersections, field boundaries, the edges of waterbodies and airport runways (Bernstein 1983). The GCPs are located on the image by their x and y coordinates and on the new base by their latitude and longitude.

B. Image Classification

The overall objective of image classification procedures which use satellite imagery, is to automatically categorise all pixels in the image into land cover classes or themes (Lillesand and Kiefer, 1994). There is no single 'right' manner in which to approach an image classification problem. The choice depends upon the nature of the data being analyzed, the computational resources available, and the intended application of the classified data (Sabins, 1987).

So as to explain how image classification techniques operate it is necessary to describe how the image is formed. Different features on the ground have different spectral reflectance and emittance properties, which are picked up by the extremely sensitive receptors on the satellite.

These are recorded as digital numbers (DN's) which range from 0 (black) to 255 (white) on the grey scale. The spectral pattern present within the data for each pixel is used as the numerical basis for categorization.

The most widely used methods for classifying vegetation are the supervised and the unsupervised approach. In the supervised classification the image analyst supervises the pixel categorization process by specifying numerical descriptors of the various land cover types present in a scene. To do this, representative sample sites of known cover type, called training areas, are used to compile a numerical interpretation key that describes the spectral attributes for each feature type of interest (Lillesand and Kiefer, 1979). Each pixel is then compared numerically to each category in the interpretation key and then labelled with the name of the category it looks most like. The disadvantages of such a classification are:

1) If a pixel is insufficiently similar to any training data set it is labelled "unknown", which means that many areas can't be classified.
2) The training process can become quite involved because all spectral classes constituting each information class must be adequately represented in the training set data used to classify the image. Depending upon the nature of the information classes sought, and the complexity of the geographical area under analysis, it is not uncommon to acquire data from 100 or more training areas to adequately represent the spectral variability in the image (Lillesand and Kiefer, 1994).
3) Training sites need to be accurately represented.
4) "Training set refinement for the inexperienced analyst is often a difficult task" (Lillesand and Kiefer, 1994).
5) If certain cover types occurring in an image have inherently similar spectral response patterns no amount of retraining and refinement will make them spectrally separable. It must be stressed that this is a problem for all spectrally based classification schemes.

In the unsupervised approach, the image data are first classified by aggregating them into the natural spectral groupings, or 'clusters' present in the scene. Then the image analyst determines the land cover identity of these spectral groups by comparing the classified image data to ground reference data. The primary advantage of a supervised classifier is that it

identifies the distinct spectral classes present in the image data. Many of these classes might not be initially apparent to the analyst applying the supervised classifier. This together with the fact that the study area was initially unfamiliar with the author, resulted in the unsupervised approach being adopted in this study.

C. The Collection of Ground Control Point (GCP) data

The essential purpose of GCP data collection in remote sensing is to establish useful relations between two classes of data, namely digital radiances and user requirements. The complexity of natural surfaces, effects of the atmosphere and ambiguity of the spectral signatures act to limit remote sensing without ground truth to applications that demand little from the radiometric quantities in the data (Steven, 1987). Ground surveys are complementary to the synoptic overview provided by satellites, helping to link the image data to the surface context.

There are no set formulae for what form of data have to be collected as SRD, neither when or where it should be collected (Lillesand and Keifer, 1979). The requirements are determined on a project by project basis in accordance with the predetermined objectives.

Satellite imagery has the advantage of providing synoptic samples of high spatial frequency on a large geographical scale (Steven, 1987). Ground surveys do not give synoptic coverage or sampling density on the same scale, but sampling is preformed at a higher spatial resolution and without effects of the atmosphere (Steven, 1987). The sampling procedure for the SRD collection programme needs to be statistically sound (Curran and Williamson, 1985).

APPENDIX 3

SAMPLE DATA SET

SITE #	GCP CLASS 1=Sodic Patch 2=Open Savanna 3=Closed Savanna 4=Young Ac.thik 5=Mature Ac.thik 6=Acacia nigrescens turf savan 7=Contour seepline grasslands 8=Open grasslands 9=Water points 10=Camps 11=Eroded 12=Other	IMAGE CLASS 1= Closed savanna 2= Open savanna 3= Contour seepline grassland 4= Sodic patch 5= Acacia nigrescens turf sav. 6= Acacia Thicket	NDVI VALUE	MSDI VALUE	VELD TYPE Acocks (1988) 1=Mixed Bushveld 2=Arid Sweet Bushveld
49	4	6	0.08571429	26	2
60	6	5	-0.0175439	13	1
236	1	3	0.04761905	45	1
241	4	2	0.01886792	34	1
243	1	4	0.17117117	60	2
244	1	4	0.125	18	1
245	1	4	0.09859155	19	2
253	4	6	0.11428571	11	1
257	6	5	0.00143667	7	1
258	6	5	0.04918033	10	1
261	3	6	0.09090909	8	1
270	4	6	0.13432837	67	1
283	1	4	0.12820514	13	2
284	1	4	0.12820514	6	2
285	1	4	0.125	13	2
292	2	2	0.0882353	7	1
296	1	4	0.125	22	2
298	1	1	0.12	24	2
300	1	3	0.10447761	56	1
318	1	4	0.13953489	62	2
319	1	4	0.18333334	62	2
320	1	4	0.1965812	57	2
321	1	4	0.17307693	51	2
322	1	4	0.10769231	13	2
324	7	3	0.14285715	19	1
327	3	5	0.02344446	8	1
328	6	5	0.04918033	6	1
335	7	3	0.10526316	22	1
336	7	3	0.16216215	22	1
337	7	3	0.11111111	30	1

SITE #	DOMINANT SPECIES 1	DOMINANT SPECIES 2	DOMINANT SPECIES 3	DOMINANT SPECIES 4
49	Pterocarpus rotundifolius	Digitaria eriantha	Acacia gerrardii	Aristida congesta
60	Acacia exuvialis	Combretum hereroense	Sclerocarya caffra	Dichrostachys cinerea
236	Acacia exuvialis	Acacia gerrardii	Combretum zeyheri	Terminalia sericea
241	Acacia burkei	Acacia karoo	Euclea divinorum	
243	Euclea divinorum	Grewia bicolor	Urochloa panicoides	Aristida congesta
244	Acacia exuvialis	Acacia nylotica	Dactyloctenium aegyptiu	Aristida barbicola
245	Acacia exuvialis	Euclea divinorum	Ziziphus mucronata	Combretum hereroense
253	Euclea divinorum	Acacia gerrardii	Acacia exuvialis	
257	Pterocarpus rotundifolius	Combretum zeyheri	Themeda triandra	Pterocarpus rotundifolius
258	Themeda triandra	Pterocarpus rotundifolius	Urochloa panicoides	
261	Sclerocarya caffra	Combretum apiculatum	Ziziphus mucronata	
270	Acacia exuvialis	Euclea divinorum	Themeda triandra	Urochloa panicoides
283	Euclea divinorum	Sporobolus nitens		
284	Euclea divinorum	Sporobolus nitens	Pterocarpus rotundifolius	
285	Euclea divinorum	Ziziphus mucronata		
292	Combretum	Acacia exuvialis	Pterocarpus rotundifolius	Panicum maximum
296	Euclea divinorum	Acacia exuvialis		
298	Acacia nylotica	Grewia bicolor		
300	Acacia nylotica			
318	Acacia exuvialis	Euclea divinorum		
319	Acacia exuvialis	Sporobolus nitens		
320	Euclea divinorum	Sporobolus nitens		
321	Euclea divinorum	Sporobolus nitens		
322	Acacia nigrescens	Acacia exuvialis	Sporobolus nitens	Sclerocarya caffra
324	Acacia nylotica			
327	Pterocarpus rotundifolius	Combretum zeyheri	Themeda triandra	Setaria sagittifolia
328	Pterocarpus rotundifolius	Combretum zeyheri	Themeda triandra	Pterocarpus rotundifolius
335	Acacia nylotica			
336	Acacia nylotica			
337	Acacia nylotica			

SITE #	COVER (%)			EROSIO	STRUCTURAL	AVERAGE #	AVERAGE	SI	APF	BIOMASS
	Bush	Grass	Bare	STATUS	DIVERSITY	OF STEMS	HEIGHT (m)		(%)	(kg/ha)
					1=v.low 2=low 3=mod 4=high 5=v.high					
49	20	85	5	20	3	5.400	2.182	3.1	17.621	5325
60	1	100	0	20	1	2.250	1.344	2.9	15.868	32472
236	80	60	5	18	2	2.235	1.378	2.1	11.312	3256
241	80	5	20	15	2	2.824	2.363	2.5	13.370	1764
243	20	40	20	20	2	8.656	0.904	4.6	30.761	3265
244	30	70	15	15	2	4.667	0.532	4.2	28.230	7490
245	10	65	15	15	4	1.470	0.508	3.3	18.457	2531
253	70	5	70	5	2	7.385	2.332	3.7	22.125	964
257	10	100	0	18	2	7.938	2.042	2.6	15.017	28765
258	3	100	0	17	1	4.000	1.000	2.7	14.104	35956
261	40	80	10	12	3	3.738	2.429	2.8	17.078	20968
270	80	8	70	6	2	11.797	2.236	4.0	24.585	1426
283	8	60	40	13	2	12.214	2.464	4.0	25.757	1735
284	5	42	70	10	2	15.667	2.722	4.0	25.164	294
285	8	50	50	13	3	9.200	1.880	4.0	25.940	466
292	25	65	10	20	3	5.500	2.143	3.2	17.834	17548
296	5	50	50	10	2	7.750	1.094	4.3	27.908	2543
298	80	20	30	10	3	7.467	2.000	3.6	21.189	25456
300	40	75	10	10	3	4.682	1.239	3.3	20.277	1173
318	8	25	80	3	2	5.391	0.696	4.2	28.201	7399
319	3	1	95	3	1	24.000	2.000	4.9	34.378	304
320	1	5	95	2	1	34.000	2.000	5.2	39.628	1583
321	1	5	95	2	1	34.000	2.000	5.2	39.628	2754
322	8	48	50	7	1	6.417	2.292	3.2	20.677	3476
324	0.5	85	10	12	2	8.000	2.250	3.5	20.103	0
327	10	100	0	18	2	7.938	2.042	2.6	15.017	220
328	10	100	0	18	2	7.938	2.042	2.6	15.017	2256
335	0.5	85	10	12	2	8.000	2.250	3.5	20.103	0
336	0.5	85	10	12	2	8.000	2.250	3.5	20.103	0
337	0.5	85	10	12	2	8.000	2.250	3.5	20.103	0