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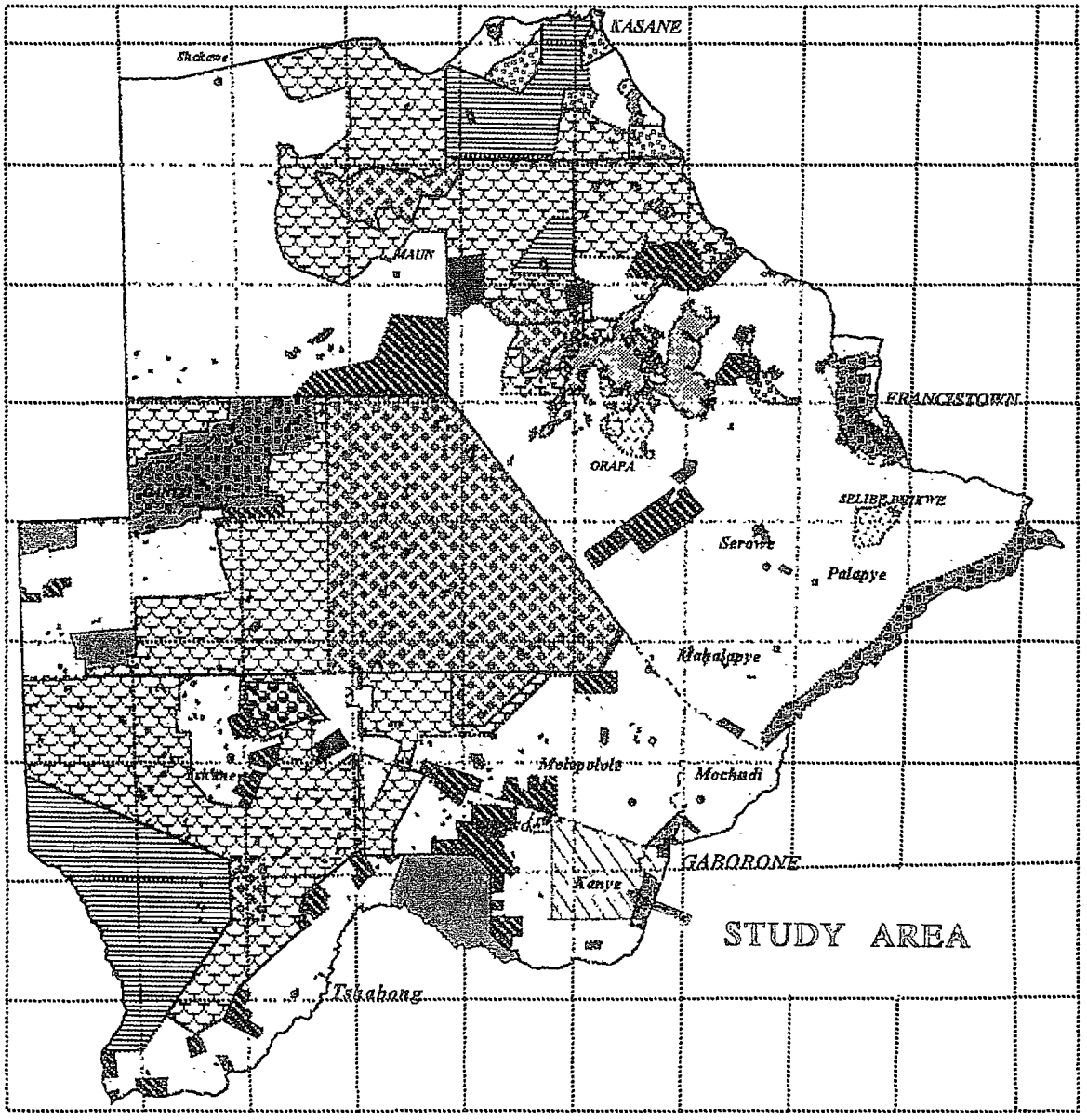
INTEGRATING REMOTE SENSING AND GIS FOR NATURAL RESOURCE MANAGEMENT IN BOTSWANA



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B

FINAL REPORT

Reporting Period: October 1, 1993 - September 30, 1996

Grant No.: PCE-5053-G-00-3044-00

Title: Integrating Remote Sensing and GIS for Natural Resource Management in Botswana

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EXECUTIVE SUMMARY

The primary purpose of this project was to explore the use of remote sensing and geographic information systems technology to analyze and document land use issues for improving long term use of resources in Botswana. The specific objectives were: (1) to collect and analyze baseline resource data which is essential for planning and implementing sound, long-term natural resource development, and (2) to use remote sensing and geographic information systems to document and analyze land use conflicts and resource problems. The activities initiated to address these objectives included the development of a GIS based land use map of the Southern District; the development of a GIS based ecological map; assessment of communal grazing lands; an assessment of soil erosion as affected by soil type and vegetation condition; and an assessment of land use conflicts and their relevance to expected land use conservation practices.

Differentiation of land use classes and surface soil conditions based on selected TM spectral bands is possible according to the results generated from this project. Highly significant relationships among the spectral data, soil physical properties, and soil conditions were obtained. Land use classes were differentiated at an overall accuracy of 66.7% while the soil mapping units were differentiated at an overall accuracy of 88.6%. Prediction of surface soil conditions such as compaction and grazing intensity, and NDVI from the spectral data and surface soil physical properties is possible as indicated by the high R^2 values. Soil compaction was best described by using TM bands 2 and 4, soil structure, texture, and erosion intensity. Percent cover was most successfully predicted using the NDGR index (R^2 = 0.875). Grazing intensity was best described using a combination of TM bands 3 and 4, soil structure, erosion intensity, and vegetation cover (R^2 = 0.769) or by using the NDVI index and TM band 4 (R^2 = 0.771).

Percent vegetation cover is also a good indicator of woody materials/trees that can be used as a source of woodfuel as well as food for browsing livestock. As in most

developing countries, Botswana's population continues to depend on woodfuel as one of their important sources of energy. As part of Botswana's Southern District Development Plan, comprehensive regional land use planning of woodland resources is one of six priority areas of concern. However, the availability of baseline information on the spatial and temporal variation of woodfuels is limited.

The results presented here provide optimision for using Landsat TM data for mapping spatial variation and amount of woodfuel resources. For trees, TM band 2 provided the highest degree of correlation with tree density and as an index of tree biomass. Landsat TM band 3 was the best estimator of shrub density, whereas band 4 was most significant in predicting shrub biomass index values.

The comparison of wet season and dry (residual) vegetation cover was undertaken to provide a basis for rangeland management in contrasting rocky/loamy and sandy semi-arid ecosystems. Comparative indicators of range condition were developed following field data collection, spectral vegetation cover trends using six band TM imagery and classification models. Spectral cover trends mostly showed high pixel values for the mid-infrared (NIR) bands and relatively low values for both near infrared (NIR) and visible bands. Low NIR reflectance is typically indicative of the general low level of green cover, even in the wet season and recognized as vegetative darkening. The proportion of TM band separability for incremental vegetation cover varies seasonally. Spectral separability indices (SSIs) indicate that wet season imagery is inherently more valuable in differentiating increments of vegetation cover than dry season imagery although this is ecosystem (soil type) dependent. Seasonal differences in natural vegetation cover relative to soil background reflectance controls the wavebands used optimally for classification analysis. Using SSI indices, TM3, TM4, and TM7 are recommended inputs for wet season classification and TM3, TM4, and TM5 for dry season classification. While classification results in the medium and low range categories for the hardveld environment are consistent with field work data, dry season inputs are found to exaggerate the amount

of both high density (higher quality) range cover and the amount of bush encroachment. This contrasts with sandveld data sets which show no increase in the amount of high density (higher quality) range cover in the dry season. Hence whereas it may be possible to classify areas of sandy soil and obtain basic data for range management, the high spectral interseasonal variability in rocky/loamy soils is misleading and may lead to the calculation of excessively high (dry season) stocking rates in semi-arid environments.

Overall, these results reinforce the significance of satellite remote sensing for providing a more synoptic view of various rural land use pressures associated with management practices. Such findings provide spatial information in support of the Botswana government's national natural resource conservation efforts.

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INTRODUCTION

Statement of the Problem

The relationship between the environment and development in Botswana has attracted attention for many years (Armtzen and Veenendal, 1986; Arntzen et al., 1988). Three major factors have stimulated this interest. First, the economy of Botswana has a very high dependence on natural resources. Mining, which accounted for 45.2 percent of the Gross Domestic Product (GDP) in 1987/88, has been between 80 and 90 percent of the value of the country's exports for many years (Central Statistics Office, 1989). Although agriculture was only 3.5 percent of the GDP in 1987/88, it is the major source of livelihood for over 80 percent of the country's population. Second, in recent years there has been increased pressure on the country's natural resources with increasing population numbers and a consequently greater demand for production from the land (Republic of Botswana, 1985). Botswana's brittle environment has recently shown signs of strain from these demands (Cooke, 1987). Third, it has been realized that the future of a sustainable development effort will have to depend more on renewable resources and less on mining (Perrings et al., 1988).

Given the current level of development in Botswana, the land provides the most important of all renewable resource alternatives for development. Increased production to raise the contribution of the land and to employ more people is required if the land is to provide any significant solution.

The government has been concerned about issues involving growth, development, and the environment for a number of years. Growing awareness of environmental problems and the desire to achieve sustainable development of the Nation's resources were major motivating factors in undertaking the development of a National Conservation Strategy (BNCS) program. In summary, the BNCS advises a rational utilization of natural resources that accounts not only for current costs of use but also for additional

costs that will ensure the resources that are used will not degenerate but will be maintained for future generations (Perrings et al., 1988).

Objectives

This project used remote sensing and geographic information systems technology to analyze and document land use issues to improve long-term use of Botswana's resources. These technologies can provide low-cost information on the location, amount, and type of resources available for development. In particular, remote sensing and geographic information systems can provide valuable information for mineral exploration, agricultural research, forestry, water management, and land use planning. A major advantage of the use of this technology is that it may lead to more interchange with individual resource managers and ultimately to an integrated and sound resource policy. The specific objectives of the research undertaken were:

a. To collect and analyze baseline resource data which is essential for planning and implementing sound, long-term natural resource development.
b. To use remote sensing and geographic information systems to document and analyze land use conflicts and resource problems.

In order to address these objectives, five research tasks were identified which included: (1) the development of a GIS based land use map of the Southern District; (2) the development of a GIS based ecological map of the Southern District; (3) an assessment of communal grazing lands of the Southern District; (4) an assessment of soil erosion as affected by soil type and vegetative condition; and (5) an assessment of land use conflicts and their relevance to expected land use conservation practices.

Bibliographic Reference Supporting Research

The usefulness of satellite-based remote sensing techniques in assessing natural resources and ecotype mapping is well documented in the literature. Since the initial launch of the Landsat satellite, considerable evidence has shown that remotely-sensed data acquired from aerospace platforms can provide accurate and timely information of natural resources (Hegyi and Quentet, 1980; Barker, 1981; Bartolucci et al., 1983; Barker, 1988) and generating land cover maps on a regional scale (Hill and Megier, 1988; Shimoda et al., 1988; Coleman et al., 1992). Foresters were the first to use remotely-sensed data for applications to forest inventory and damage assessment operations (Heller, 1975). The synoptic view achieved through the use of aerospace remote sensing systems allows regional inventories to be performed, and many researchers have reported the successful use of Landsat multispectral scanner (MSS) data in mapping forest resources (Kirby et al., 1975; Dodge and Bryant, 1976; Fleming and Hoffer, 1977; Kourtz, 1977; Harding and Scott, 1978; Beaubien, 1979; Johnson et al., 1979; Kalensky et al., 1979; Montgomery et al., 1982). Still others have been successful in using Landsat Thematic Mapper (TM) data for mapping general forest types, defining stand age groups, and condition assessment of forest stands (Nelson and Hoffer, 1980; Benson and DeGloria, 1985; MacKenzie, 1986; Hopkins et al., 1988; Coleman et al., 1990a; Coleman et al., 1990b). An application in which considerable integration gains have been achieved is that of change detection. Remote sensing offers greatly enhanced capability to GIS in updating map information on a regular basis. Ehlers et al. (1990) demonstrated that SPOT data could be used in a GIS environment for regional growth analysis and local planning at a scale of 1:24,000. Once incorporated into a GIS, the spatial growth pattern can be readily analyzed (Jadkowski and Ehlers, 1989). Change detection in forestry by means of integration of cartographic and remotely-sensed data has been demonstrated by Goldberg et al. (1985) and Goodenough et al. (1987) using a knowledge-based approach. Recent advancements in satellite remote sensing and GIS technologies have made it possible to

use satellite and ancillary data to differentiate wetland habitats and wildlife openings which are important to forest managers (Jensen et al., 1984; Hodgson et al., 1987). Another application of integration which combines satellite imagery and digital elevation models (DEM) can be used to produce realistic perspective views of the terrain for planning and environmental impact analysis (Gugan, 1988). The last few years have seen increased use of GIS for simple two-dimensional modeling using standard overlay procedures (Berry, 1987). Extension to three-dimensional spatial and dynamic modeling is crucial for application in several disciplines such as marine science, climatology, geology, and soils modeling (Burrough et al., 1988).

The traditional methods of acquiring, storing, and analyzing spatially referenced data are too costly and inflexible in meeting information requirements. Computerized geographic information systems are emerging as the spatial data handling tool of choice for solving complex geographical problems. A well designed GIS allows analysts to process and interrelate many more kinds of data than were previously feasible. Therefore, GIS users have the potential to improve traditional missions, such as data collection, research, assessment, and information delivery (Guptill, 1989). Geographic information systems have been used successfully for various natural resource management and planning projects (Walsh, 1985; Hart et al., 1985; Burrough, 1986; Ripple, 1987).

The integration of such capable data acquisition and analysis technologies is becoming increasingly important for resource management. This progress has been facilitated by a number of recent developments including: (i) software and hardware advances in GISs (Dangermond, 1987; Frank, 1988; Croswell and Clark, 1988); (ii) the availability of high resolution satellite data in digital formats such as SPOT's High Resolution Visible (HRV) and Landsat's Thematic Mapper (TM); and (iii) new developments in automated information extraction, especially the application of image matching techniques for Digital Elevation Model (DEM) generation (Swann et al., 1988).

APPROACH AND METHODOLOGIES

Study Site

The Southern District of Botswana is located in the southeastern portion of the country and covers an area of 26,876 square kilometers. The Southern District has a harsh physical environment and is composed of two major woodland-environmental units: the hardveld and the sandveld. The hardveld region is generally represented by upland areas that are greater than 1200 meters. The region, for the most part is gently, rolling plains with numerous isolated hills and rock outcrops. A majority of the area, except for the rock outcrops and a few hills, is woodland and shrub savanna with varieties of Acacia and Combretum as the dominant species. The sandveld region is represented by areas less than 1200 meters in elevation. This flat savanna region is a mosaic of open green grassland with trees and shrubs. Vegetation varies from Eastern Broadleaved Savanna in the northeast corner to the Southern Broadleaved Savanna in the southeastern corner, with the Kgalagadi Plain Microphyllous Savanna dominate in the arid western half of the district.

The methodology employed in carrying out this research was designed to fit within the Government of Botswana's planning at the local level. Under the current development strategy an effort was made to follow an approach that recognizes the ability to identify needs and problems of development. The government seeks advice through local councils at the district level and strongly supports a democratic "bottom up" philosophy. Within this framework the central administration would lay out overall development strategies which district level administrators would use to help local communities administer their development programs on resource utilization. This approach has many favorable points. Specifically: (1) It utilizes local knowledge in a country where major differences in human and natural resources occur at the local level;

and (2) It facilitates a continuous interest in those programs that give a sense of self-reliance in rural development.

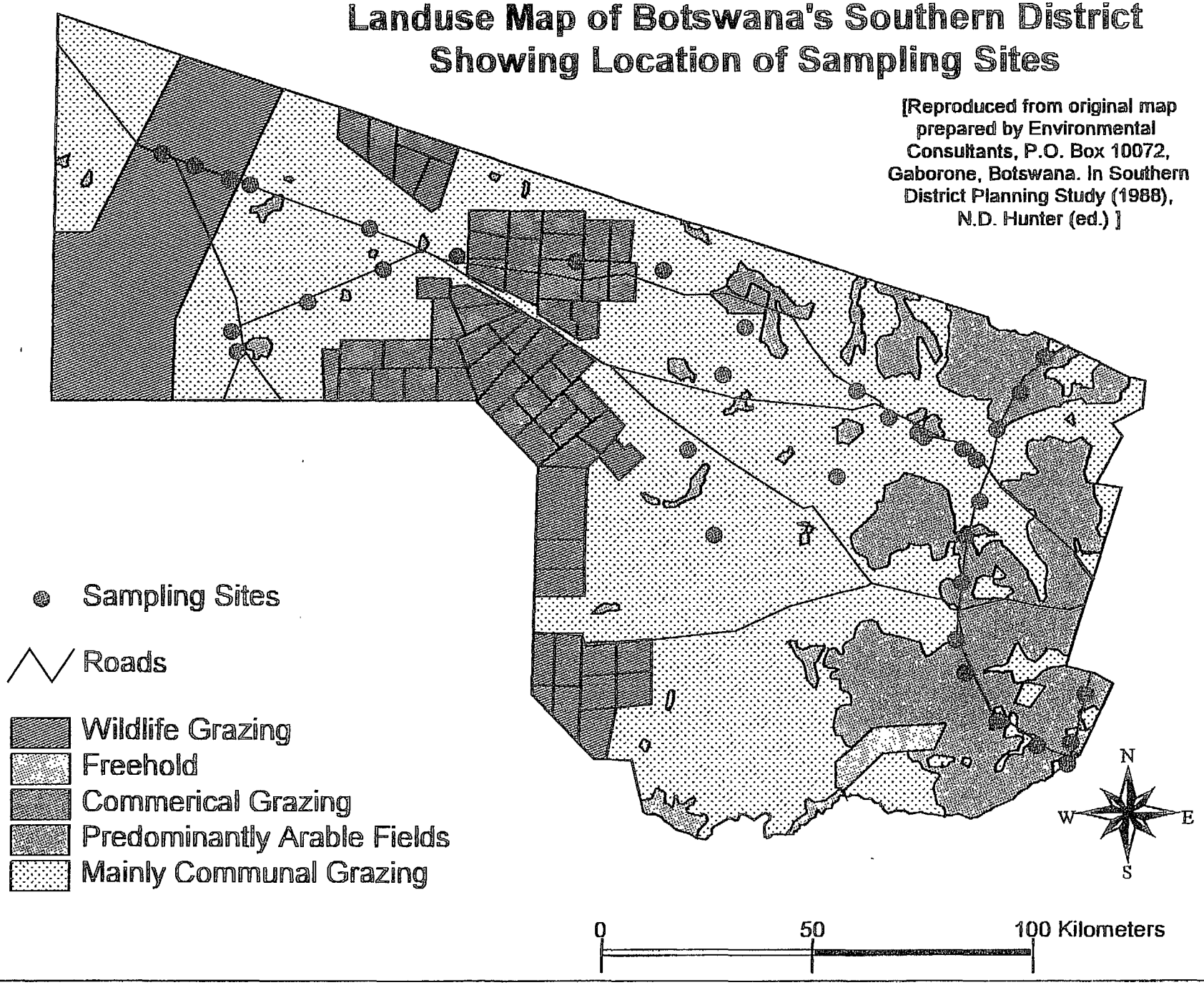
Collection of Ground Referenced Data

Thirty-four sites were selected throughout Botswana's Southern District which provided a broad representation of its diverse land cover (Figure 1). Generally, the sites were sampled along transects through various portions of the District at systematic intervals of 10 to 20 km. However, exact locations of cover change and transitions were noted. Each sampling site represented an area of 900 m^2 and was identified using a global positioning system (GPS) as well as other reference points such as road intersections in the District. In addition, odometer readings and directional headings were noted for each site. Other observation sites from key location points, e.g., villages, mine areas, boreholes, and cattle posts were also documented. At each site, the number and height of trees, brushes/shrubs, and grasses were recorded. Grass density and stem clusters were sampled at the mid-point of each cell-side and at the center of each 30 x 30 m cell using a 50 cm quadrant frame. This was done in order to determine vegetation percentages and densities within the area. The major land use within the area was also recorded. Additionally, the grazing intensity within and around each site was determined and recorded as slight, moderate, severe, and very severe and coded as 1, 2, 3, and 4, respectively for use in the statistical analyses. The assignment of a grazing intensity category at each site was determined based on the amount of visible bare soil, evidence of soil erosion, indications of animal impact through trampling, and grass densities and heights.

Within each sampling cell a 50 cm quadrant frame was randomly dropped at three locations, and the soil structure, texture, color, evidence of erosion, crusting, and compaction were evaluated using local qualitative field techniques and legends used by the Soil Mapping and Advisory Service (Remmelzwaal, 1988; Husken, 1988). In order to use

Figure 1.
Landuse Map of Botswana's Southern District Showing Location of Sampling Sites

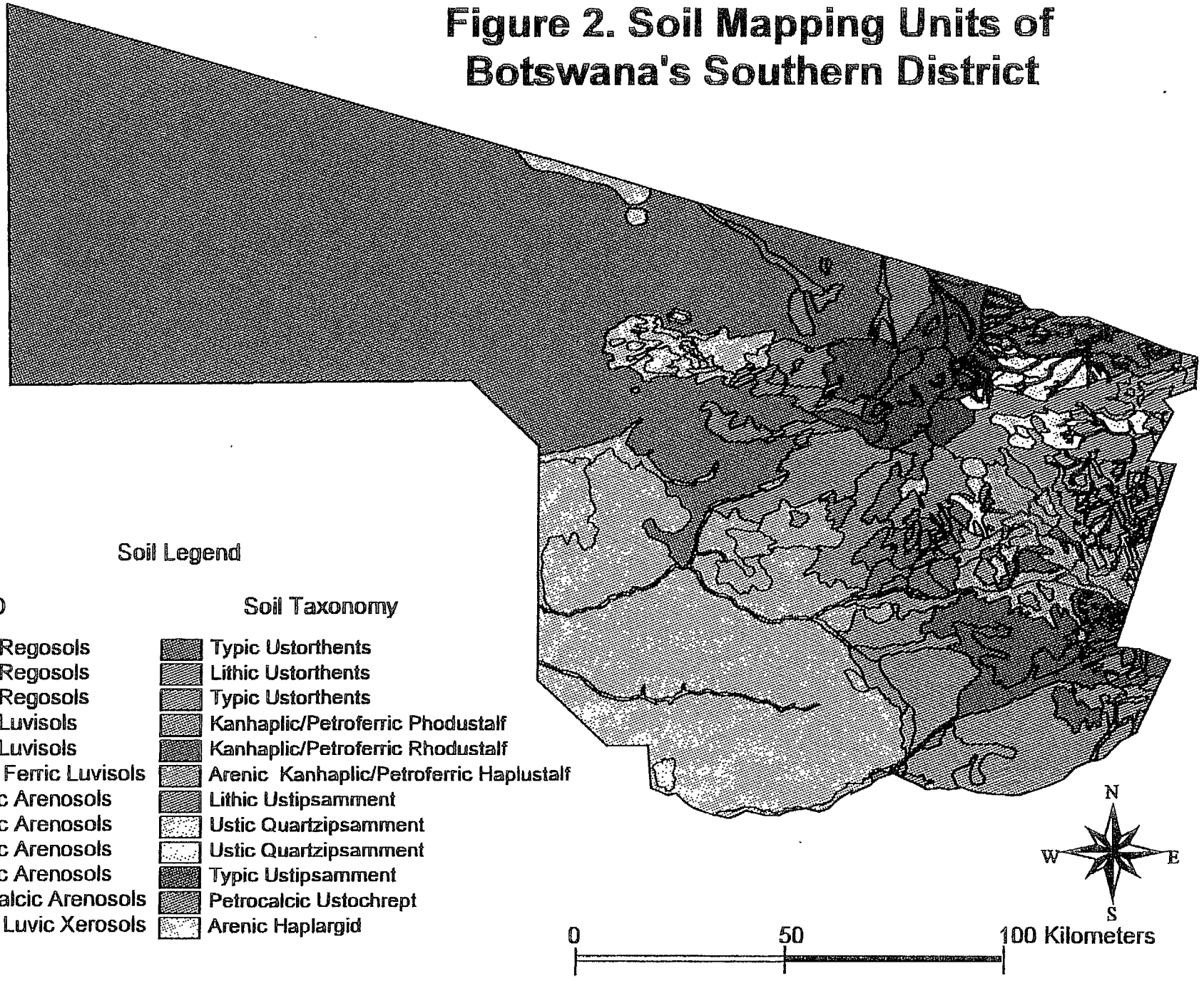
[Reproduced from original map prepared by Environmental Consultants, P.O. Box 10072, Gaborone, Botswana. In Southern District Planning Study (1988), N.D. Hunter (ed.)]



these data in a statistical evaluation for generating prediction equations they were assigned numerical values. Soil structure was recorded as loose/single grain, granular, subangular blocky, or stoney and given a value of 1, 2, 3, or 4, respectively. Soil texture was recorded as sandy/coarse, medium, or clayey/heavy and given a numerical value of 1, 2, or 3, respectively. Sandy/coarse texture corresponded to sand, fine sand, loamy sand, and light sandy loam. Medium soil texture corresponded to heavy sandy loam, loam, clay loam, and silt loam. Clayey/heavy soil texture corresponded to sandy clay loam, sandy clay, and clay. Soil color was recorded as light, medium, and dark and coded as 1, 2, and 3, respectively. Light soil colors corresponded to the Munsel color codes of 2.5YR 3/2, 10YR 5/3, and 2.5Y 3/2. Medium colors corresponded to codes such as 10YR 5/6, 7.5YR 5/6, and 2.5YR 5/8. Dark soil colors corresponded to Munsel codes of 7.5 YR 4/6, 5YR 5/8, and 2.5YR 3/6 or darker.

Soil erosion was characterized as slight, moderate, and severe according to the presence of rills and gullies and the visible reduction in soil material from underneath shrubs and low growing trees to areas not covered by vegetation. An area with a slight rating was given a value of 1, moderate a value of 2, and severe a value of 3. Soil compaction was characterized as none/slight, moderate, and severe and was coded as 1, 2, and 3, respectively. Compaction was estimated based on the number of animal hoof prints present and crusting of the surface soil. No quantitative laboratory measurements were used to determine the actual degree of compaction nor any of the other associated variables. Soil crusting was defined by the degree of cohesiveness of the surface soil particles. Soil crusting was recorded as none/slight, moderate, and severe and coded as 1, 2, and 3, respectively for use in the analyses. The soil mapping unit which corresponded with each sampling site was also recorded from the 1:250,000 soils map of the District (Figure 2).

Figure 2. Soil Mapping Units of Botswana's Southern District



Remote Sensing Imagery

Landsat Thematic Mapper (TM) data of the District were obtained from the Satellite Applications Centre, Pretoria, South Africa. Six TM quarter scenes were required to cover the District. Three of the scenes were recorded on June 23, 1994, two on July 7, 1994 and one on August 1, 1994. TM bands 2, 3, and 4 were preselected for analysis based on past research in Botswana by Ringrose et al. (1991). The areas that corresponded to the field sites were identified from the GPS coordinates that were recorded for each site. The digital numbers (DN) of each of the sampling areas were extracted using the Earth Resource Data Analysis System (ERDAS) Imagine software housed on a Sun SPARC10 computer (ERDAS, 1995). The actual DN values of the georeferenced TM data were used in the analyses. The DN values were used because a previous study conducted by the senior author revealed that there were no advantages gained from converting the DN values to intensity of reflectance values (Coleman et al., 1993).

The satellite data scenes were subjected to standard preprocessing routines for radiometric and geographic corrections and haze removal. A supervised maximum likelihood algorithm was used to classify the satellite data. The training data sets were derived by identifying the land use classes as polygons in each of the satellite scenes. The training data sets were examined statistically to see if the land use classes represented by the polygons were separable and/or contain multiple spectral classes (Benson and DeGloria, 1985).

Additionally, two six band TM scenes were acquired -- one in the wet season (January 7, 1994) and one during the dry season (July 23, 1994) to study seasonal variations in vegetation. These data were georeferenced at source by GIMS (BIL-EXABYTE) to a UTM grid (Zone 35) based on the Clarke 1880 Spheroid commonly used in southern Africa. Field work for this part of the project took place during December-January 1994 (mid wet season) and August-September 1994 (mid dry season)

to coincide with both satellite overpass times. Data collection took place from 67 mostly coincident field sites each entailing three transacts through a 90 m x 90 m area. Field analysis techniques included the recording of continuous species and canopy diameters through the 3 x 90 m transacts, and 50 cm quadrats thrown at 30 m intervals to determine herbaceous (alive/senesced) cover. Soil colour was recorded using the Munsell color notation and the extent of eroded area/senesced of trampling was also recorded. Field data were used to calculate the percentage of woody vegetation cover (WVC), alive herbaceous cover (AHC), and bare soil extent (BS). The WVC and AHC were added to produce the total vegetation cover (TVC) from which a biomass estimate was derived (Field, 1978). In addition the total number of woody cover species per 90 x 90 m square were calculated, and the species richness (a surrogate of species diversity), which is defined as the number of species divided into the total area. A palatability index was also established using published palatability criteria (Hendzel, 1981; Ringrose and Matheson, 1987, 1991a).

Statistical Analyses

Descriptive statistics were computed by the elementary statistics procedures in the Statistical Analysis System (SAS) computer software (SAS Institute, 1994). The DISCRIM procedure in SAS was used to develop discriminant functions to classify each observation into one of the soil mapping units and land use classes. These functions were also employed to compare the ability of the TM spectral data and selected surface soil physical properties in differentiating among soil mapping units and land use classes of the District.

Correlation analyses were used to determine the degree of correlation between TM bands 2, 3, and 4, as well as woody vegetation indices based on a normalized difference vegetation index (NDVI), and a normalized difference green red index (NDGR) with woody vegetation (trees and bush/shrubs) in a subset of the District. NDVI is based on a

ratio transformation, where near infrared (NIR) minus red is ratioed over NIR plus red. This index has had some successful application in Botswana (Farrar et al., 1994). In contrast NDGR is based on a ratio transformation where green minus red is ratioed over green plus red.

Pearson correlation analysis and multiple regression models were used to determine the relative significance of the TM bands with woody vegetation and associated resource potential. Stepwise regression procedures were used to develop the models (Linear equations) to predict surface soil conditions from spectral data and selected soil surface properties.

RESULTS AND DISCUSSION

The five research tasks identified to address the objectives of this project were developed into referred manuscripts and submitted for publication. Copies of these manuscripts which were submitted to peer reviewed journals are given in Appendix A through D. The succeeding paragraphs provide a discussion of the research findings which specifically address our objectives.

Southern District Land Use

Current as well as historic information on land use activitiy in Botswana is critical for resource managers to effectively manage the country's natural resources. Land use planning plays a key role in the decision-making process at all levels of government. Acording to Hunter (1988), it provides a logical framework for the development and coordination of extension services throughout the country.

This activity was conducted in collaboration with individuals of the Land Utilization Division of the Ministry of Agriculture (MOA). The Mebutsane, Jwaneng, Kanya, Goodhope, and Moshupa areas were used to collect detailed reference data of the land use activities along with other observations which were noted at an additional twenty-nine sampling sites along the four transects (Figure 1). We also made use of a questionnaire, Mr, Molelo, a Land Use Officer for the Southern District developed. The questions we attempted to answer were: How or if the land use patterns had changed over time? What were the major factors affecting land use? and Does soil type or the elecological zones control the land use?

Four land use classes were identified within the thirty four sampling sites. They included communal grazing, communal grazing/mixed farming; wildlife management zone, and private/communal grazing (Table 1). The major ecological zones in the Southern District are the hardveld and sandveld. Land use in the eastern hardveld of the Southern

Table 1. Soil taxonomic classifications and land use classification of the sampling sites

No. of Sites	Soil Symbol†	Taxonomic Classification: FAO††	Taxonomic Classification: Soil Taxonomy	Land Use Classification§
9	R	Eutric Regosols	Typic Ustorthents	Communal Grazing
3	R	Eutric Regosols	Typic Ustorthents	Communal Grazing/Mixed Farming
3	R	Eutric Regosols	Typic Ustorthents	Wildlife Management Zone
3	Gba	Ferric Luvisols	Kanhaplic/Petroferric Rhodustalfs	Communal Grazing
2	S1	Ferralic Arenosols	Lithic Ustipsamments	Communal Grazing
2	S5	Ferralic Arenosols	Ustic Quartzipsamments	Communal Grazing
1	S3	Ferralic Arenosol	Ustic Quartzipsamment	Communal Grazing
1	R	Eutric Regosol	Typic Ustorthent	Private/Commercial Grazing
1	KSi2a	Arenic Luvic Xerosol	Arenic Haplargid	Communal Grazing
1	G6a	Ferric Luvisol	Kanhaplic/Petroferric Rhodustalf	Communal Grazing/Mixed Farming
1	G6	Arenic Ferric Luvisol	Kanhaplic/Petroferric Haplustalf	Private/Commercial Grazing
1	G6	Arenic Ferric Luvisol	Arenic Kanhaplic/Petroferric Haplustalf	Communal Grazing/Mixed Farming
1	G4	Ferralic Arenosol	Typic Ustipsamment	Private/Commercial Grazing
1	G4	Ferralic Arenosol	Typic Ustipsamment	Communal Grazing
1	G106	Ferric Luvisols	Kanhaplic/Petroferric Rhodustalf	Communal Grazing
1	Glc	Eutric Regosol	Typic Ustorthent	Communal Grazing
1	Gla	Eutric Regosol	Lithic Ustorthent	Private/Commercial Grazing
1	C3	Petrocalcic Arenosol	Petrocalcic Ustochrept	Communal Grazing/Mixed Farming

† Soil symbols used to identify mapping units in Botswana's Soil Mapping Program.

†† FAO/UNESCO, 1974. Classifications obtained from "General Soil Legend of Botswana", A. Remmelzwaal, 1988 and "The Soils and Land Suitability for Arable Farming of the Jwaneng Area", J. Huesken, 1988.

§Classifications obtained from "Southern District Planning Study", Environmental Consultants, 1988.

District is largely mixed farming, and the landscape is composed of a mixture of arable fields with more or less open grazing areas in between. Because the traditional farming system relies heavily on cattle for draft power, the co-existence of arable land with open grazing is a logical system. Fields are small; most farmers still plant seed by broadcasting; capital investments are low; and implements are simple, the most common being the single plough. A variety of crops are grown. The main cereals are maize and sorghum, with beans and mellons being important secondary crops. In the Barolong Farms area larger scale commercialized activity exists. Overall crop cultivation is characterized by low levels of inputs. Low and variable rainfall amounts together with poor quality soils make crop farming a risky venture.

The central part of the district as well as the area to the west of the wildlife - management area, is dominated by communal grazing. Scattered arable fields are found around some of the villages. The spread of grazing westward into the Kalaharai sandveld has been made possible by borehole drilling to provide water. Water availability has made the establishment of permanent cattle posts feasible. It is a long established principle in Botswana that water rights confer grazing rights in cattle post areas. Although boreholes should be situated at least eight kilometers apart to provide an adequate grazing area for livestock, in some cases they may be closer. Not surprisingly the impact of cattle on vegetation is greatest around these water points but decreases as one moves away from the water source.

To understand the factors which affect land use, one has to evaluate the soil characteristics in the area. Table 1 lists the FAO and Soil Taxonomy classifications of the soil mapping units found in the Southern District. There were six soil mapping units identified using the FAO system which translated to eleven soil mapping units using Soil Taxonomy. The association of the surface soil properties (texture, crusting, erosion intensity, color, and compaction) was measured by generating a correlation matrix, which show highly significant correlations among TM spectral bands, vegetation indices and

conditions, and surface soil physical properties (Table 2). Grazing intensity was significantly adversely affected by soil structure, texture, and color as evident by the r values of -0.432**, -0.404** and -0.323**, respectively. Percent vegetation cover is also affected by these same soil properties at about the same level of intensity. Vegetation cover and grazing intensity is directly related to the land use that the area is subjected to. It has been our observation that the communal grazing areas are the first to exhibit signs of overgrazing which usually result in excellerated erosion and deterioration of the land.

Satellite imagery and vegetation indices that are generated using combinations of the satellite spectral bands can assist in identifying major land use areas as well as assessing surface soil and vegetation conditions. Previous studies in the semi-arid regions of Africa and Australia have reported success in mapping vegetative landscaping using multispectral satellite data (Ringrose et al. 1988; 1989; Ringrose and Matheson 1991a; Matheson and Ringrose 1994a; 1994b; Ringrose et al., 1994; Nellis et al., 1995; Sefe et al., 1996). Data in Table 2 shows that significant relationships exists among the TM spectral bands, vegetation indices and conditions, and the surface soil variables. Discriminant analyses were used to determine the soil and spectral bands that were best in differentiating land use classes. The communal grazing class was the only class that was differentiated at an accuracy of less than 66 percent (Table 3). The commission error, which is a measure of the incorrect assignment of an observation, was fairly high which may imply that the variables used in the discriminant functions did not account for enough of the variability in differentiating the classes or that the classes were too similar in their spectral reflectance and surface soil physical properties. The overall classification accuracy in differentiating among the soil mapping units and land use classes was 88.2% and 67.6%, respectively. These results indicate that the TM DN values and surface soil physical properties can be effectively used to differentiate soil mapping units and major land use classes in Botswana's Southern District.

Table 2. Correlation coefficients (r) of the variables considered for predicting soil parameters (n=102).

Variables †	TM2	TM3	TM4	SST	SCO	STX	SER	SCM	SCT	GI	VEG	NDVI
TM2		O.954**	0.935**	-0.174	-0.499**	-0.229*	-0.174	-0.423**	0.276**	0.132	-0.155	-0.198
TM3			0.969**	-0.358	-0.359**	-0.087	-0.124	-0.391**	0.343**	0.055	-0.078	-0.324**
TM4				-0.044	-0.407**	-0.096	-0.111	-0.348**	0.292**	0.074	-0.121	-0.124
SST					0.538**	0.555**	0.023	-0.211*	-0.027	-0.432**	0.411**	-0.206**
SCO						0.555**	0.015	0.122	-0.059	-0.323**	0.323**	-0.315**
STX							0.111	0.027	-0.086	-0.404**	0.388**	-0.154
SER								-0.078	-0.104	0.003	-0.075	0.149
SCM									0.164	0.131	-0.067	0.092
SCT										0.078	-0.104	-0.377**
GI											-0.868**	0.095
VEG												-0.175
NDVI												

*, ** Denotes significance at the .05 and .01 probability level, respectively.

† TM = Thematic Mapper Spectral bands, SST = Soil Structure, SCO = Soil Color, STX = Soil Texture, SER = Soil Erosion, SCM = Soil Compaction, SCT = Soil Crusting, GI = Grazing Intensity, VEG = Vegetation Percentage, NDVI = Normalized Difference Vegetation Index.

Table 3. Summary of discriminant analysis classification and accuracy assessment for soil mapping units and land use categories

Soil Mapping Units and Symbols	% Total Correct	Classification Results	
		% Commission Error	% Omission Error
Eutric Regosols (R)	91.7	0	8.3
Eutric Regosols (Gla)	66.7	33.3	33.3
Eutric Regosols (Glc)	100	40.0	0
Ferric Luvisols (Gl10b)	100	25.0	0
Ferric Luvisols (Gba)	66.7	0	33.3
Arenic Ferric Luvisols (Gb)	100	14.3	0
Ferralic Arenosols (S1)	66.7	0	33.3
Ferralic Arenosols (S3)	100	33.3	0
Ferralic Arenosols (S5)	100	25.0	0
Ferralic Arenosols (G4)	100	25.0	0
Petrocalcic Arenosols (C3)	66.7	33.3	33.3
Arenic Luvic Xerosols (KSi2a)	100	25.0	0
% Overall Agreement	88.2		
Land Use Categories			
Communal Grazing	49.1	0	50.9
Communal Grazing/Mixed Farming	83.3	52.4	16.7
Private/Commercial Grazing	100	45.5	0
Wildlife Management Zone	100	10.0	0
% Overall Agreement	67.6		

The results of the multivariate analysis used in differentiating among the soil mapping units and land use classes are given in Table 4. The variables which accounted for most of the variability in differentiating both the soil mapping units and land use classes were soil structure, erosion intensity, grazing intensity, soil color, and texture. Soil compaction and TM bands 4 and 2 were also key variables in differentiating the soil mapping units. However, the amount of variability that these variables accounted for in differentiating the soil mapping units and land use classes was quite low according to the average squared canonical correlation (ASCC) values of 0.3570 and 0.3811, respectively. The ASCC values, however, were significant at the 0.0001 probability level. Wilks Lambda which is a measure of how well the groups are separated was also significant at the .0001 probability level.

The importance of being able to differentiate among surface soil types and land use classes using remotely sensed data is in its ability to evaluate large areas not easily accessible under normal conditions. Botswana is a large country that is sparsely populated with approximately two-thirds of its population living in the eastern third of the country. Because of this, one could encounter areas within the country that are somewhat desolate of people and facilities. Such is the case for parts of the Kalahari Desert and the western portion of this study area. Even though the spectral sensors can only penetrate the upper surface of the soil, they do provide valuable information about the surface conditions which can be useful in mapping and monitoring desolate areas.

Southern District Vegetation Indices

Ground truth data of the vegetation conditions were also collected along four transects, three oriented from north to south and one traversing east and west of the Southern District (Figure 1). Results of a correlation analysis of the various satellite spectral bands and indices relative to the best indicators of land cover conditions such as percent vegetative cover and grazing intensity varied considerably based on the satellite

Table 4. Multivariate statistics used in differentiating among soil mapping units and major land use classes in Botswana's Southern District.

STEP	Variable Entered	Number In	Partial R2	F Statistics	Probability F	Wilks† Lambda	Probability Lambda	ASCC††	Probability ASCC
				Soil Mapping Units					
1	Structure	1	0.6219	13.459	0.0001	0.3780	0.0001	0.0565	0.0001
2	Erosion	2	0.6258	13.531	0.0001	0.1415	0.0001	0.1116	0.0001
3	Color	3	0.5451	9.587	0.0001	0.0643	0.0001	0.1594	0.0001
4	Texture	4	0.4284	5.927	0.0001	0.0368	0.0001	0.1961	0.0001
5	Grazing	5	0.4149	5.544	0.0001	0.0215	0.0001	0.2193	0.0001
6	TM4	6	0.3770	4.677	0.0001	0.0134	0.0001	0.2437	0.0001
7	Compaction	7	0.5798	10.537	0.0001	0.0056	0.0001	0.2726	0.0001
8	TW	8	0.4482	6.128	0.0001	0.0031	0.0001	0.2984	0.0001
9	Vegetation	9	0.3025	3.233	0.0011	0.0022	0.0001	0.3208	0.0001
10	NDVI	10	0.2645	2.649	0.0060	0.0016	0.0001	0.3363	0.0001
11	Crusting	11	0.2094	1.926	0.0479	0.0013	0.0001	0.3485	0.0001
12	TM3	12	0.1785	1.560	0.1273	0.0010	0.0001	0.3570	0.0001
				Land Use Classes					
1	Structure	1	0.5115	34.200	0.0001	0.4885	0.0001	0.1705	0.0001
2	Crusting	2	0.2488	10.711	0.0001	0.3670	0.0001	0.2525	0.0001
3	Grazing	3	0.2050	8.250	0.0001	0.2918	0.0001	0.2970	0.0001
4	Texture	4	0.1478	5.491	0.0016	0.2486	0.0001	0.3370	0.0001
5	Color	5	0.1429	5.223	0.0022	0.2131	0.0001	0.3811	0.0001

† Wilks Lambda is close to zero if the groups are well separated.

†† ASCC is averaged squared canonical correlation. It is close to 1 if all groups are well separated.

digital data index used. Shrub measurements in each sample area were not significantly linked to the satellite vegetation index values. For percent cover, the NDGR (normalized difference green red index), provided the highest degree of association with the land cover conditions (R^2 = 0.875) (Figure 3). This contrasted significantly with the NDVI (normalized difference vegetation index), which was a poor indicator of percent cover. The results support the importance of a red and green reflectance combination in explaining cover conditions in this semi-arid to arid environment with considerable sandy soil background and marginal vegetation condition. This is especially highlighted during the dry season of June and July. Both single band TM3 and TM4 values were also good indicators of percent cover (R^2 = 0.704 and 0.716, respectively). The degree of variation between these two bands; however, was insignificant to create an indicator index when integrated into an NDVI. In contrast TM band 2 and band 3 associations were greater in variation as single band indicators. This variation was further highlighted when integrated into the NDGR index.

Woody vegetation is also a very important source of grazing vegetation for domestic animals and wildlife. In comparing individual TM bands 2, 3, and 4 with tree density (number of trees per field sample area), TM band 2 provided the best results (Table 5). Tree density varied from 0 to 150 per 900 m^2 field site. The high R^2 (0.897) suggests the significance of the green wavelengths in measuring woody vegetation during the dry season. Band 3 and band 4 also offered relatively significant association with tree density values. In contrast, NDVI and NDGR indices were significantly less successful in providing an estimate of tree density.

In order to provide a better indicator of relative tree biomass associated with each field site, we multiplied the mean tree height found at the field site with the tree density to generate a ComTree(CT) variable. Tree height varied from less then 1 meter to approximately 8 meters. The results were slightly less significant than the individual tree densities. Again, band 2 and 3 were most highly correlated with the CT variable (0.838

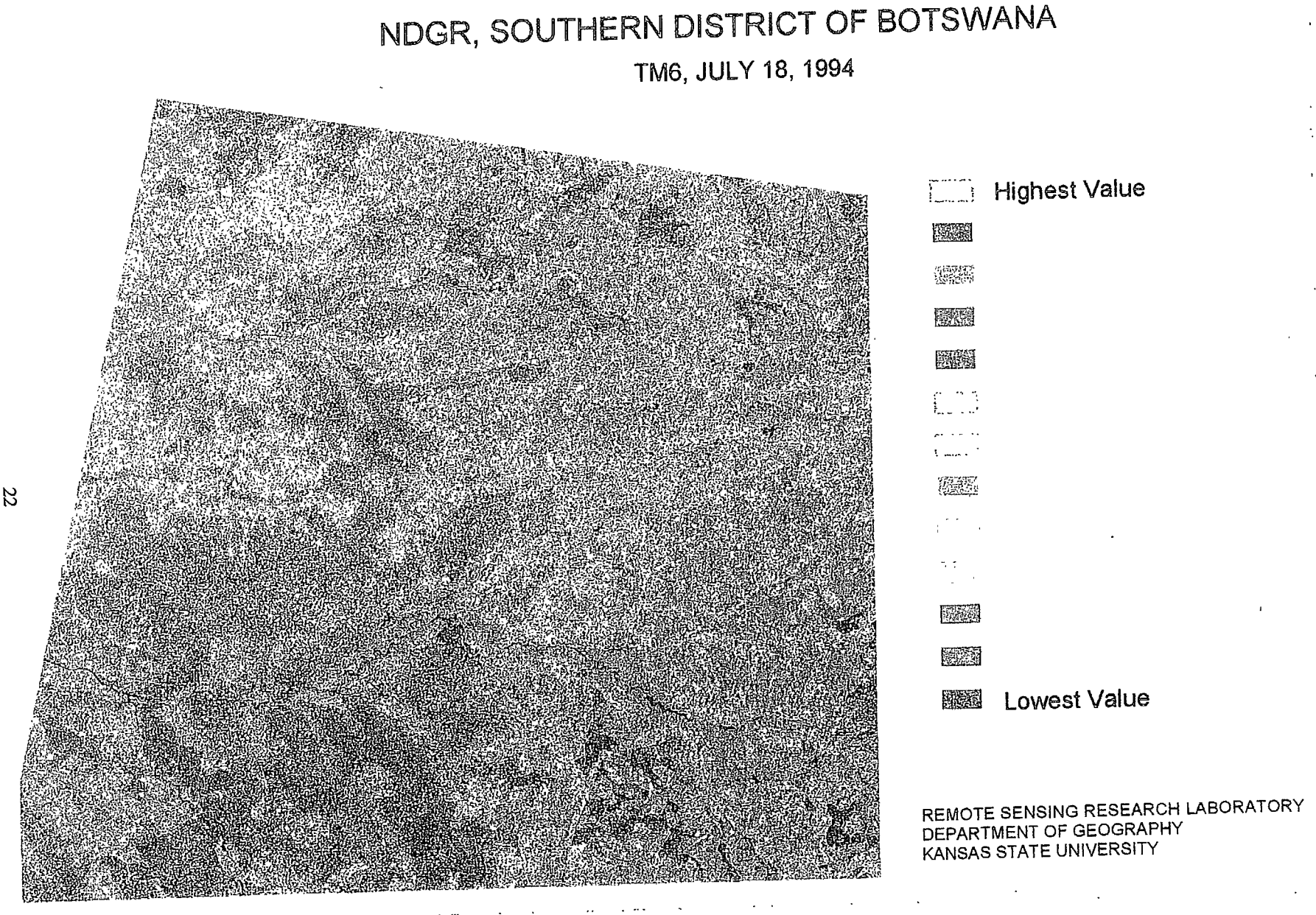


Figure 3. NDGR, Southern District of Botswana

Table 5. Simple regression relationship (R^2) between woody vegetation and Landsat Thematic Mapper data.

	TM2	TM3	TM4	NDVI	NDGR
Tree Density (TD)	0.897	0.841	0.753	0.007	0.413
Com Tree (CT)[a]	0.838	0.810	0.722	0.011	0.485
Shrub Density (SD)	0.501	0.624	0.596	0.011	0.598
Com Shrub (CS)[b]	0.533	0.633	0.777	0.008	0.562

[a]Com Tree is based on multiplying the tree density by the mean tree height.
[b]Com Shrub is based on multiplying the shrub density by mean shrub height.

Table 6. Multiple regression relationship (R^2) between woody vegetation and combinations of Landsat Thematic mapper data

Tree density (TD)	=	71.674 - 2.320*TM2 r^2=0.897
Shrub density (SD)	=	268.977 - 5.508*TM3 r^2=0.624
Com Tree (CT)	=	352.704 - 11.511*TM2 r^2=0.838
Com Shrub (CS)	=	408.882 - 8.467* TME

and 0.810, respectively). The NDVI and NDGR indices were again sufficiently less important predictors of this tree biomass indicator (CT).

Band 3 (red) provided the highest degree of association with shrub density (Table 5). Shrub density varied from 0 to 220 per 900 m^2 field site. Band 4 (near infrared) was the next most significant predictor among the individual bands, with band 2 least important. The more leafy nature of the dry season shrub is a probable explanation for the greater sensitivity of the red and near infrared bands to shrub density variability relative to tree density. The NDGR behaved similar as a predictor of tree density as were bands 3 and 4, while the NDVI was not closely associated with shrub density.

In contrast to ComTree (CT) R^2 values, the ComShrub (CS) R^2 values (based on mean shrub height multiplied by shrub density) enhanced the degree of association with one of the individual TM bands. The enhancement was most significant between ComShrub (CS) and band 4 (R^2 = 0.777). This can possibly be explained where the addition of mean shrub weight in combination with shrub density provides a more accurate measure of leaf canopy and associated near infrared response. Other band and vegetation index combination R^2 values were not altered significantly by linkage with mean shrub height.

Multiple regression approaches did not add any degree of correlation to the simple regression analysis (Table 6). In each test of TD, CT, SD, and CS, individual bands continued to provide the highest degree of correlation with the field data. Grazing intensity, which is a function of a variety of landscape variables, including vegetation condition, soil compaction and animal density ratio with regard to land area, was more difficult to predict with the satellite data. Single TM band 4 data were most closely associated (R^2= 0.620) with intensity followed by TM band 3. Of the combined indices, NDGR was a better predictor than NDVI. The TM band 4 infrared reflectance (0.76 - 0.90 micrometers) evidently explained the combination of grazing land indicators.

Southern District Communal Grazing Lands

Communal lands were traditionally held by the chief on behalf of the people and he allocated to headmen who in turn allocated it to individual households. Each household had automatic rights to the land for their homestead, arable activity, and grazing. Today communal land is administered by Land Boards. In the Southern District nearly all of the land is communal. This land is usually subdivided into tribal territory, the wildlife management areas, and the commercial leasthold areas.

The communal grazing lands are the areas normally affected the most by over grazing, soil compaction, crusting, and erosion. These areas are easily differentiated within satellite imagery because they have a fairly high reflectance of radiative energy when it strikes the earth's surface. Therefore, the implementation of basic image processing techniques could provide land manages valuable information about grazing activities within their Districts.

Estimation of surface soil conditions from TM spectral data and soil physical properties for use in soil and land use mapping is an important potential application of remote sensing in Botswana and other countries. Table 7 shows the results of a stepwise regression analysis for selection of the best combination of variables for predicting selected surface soil conditions. Five to six variables were required to generate an equation that would adequately predict the surface soil condition of interest. By computing all of the possible linear regression equations and considering the amount of variability explained and the bias of the resulting equation, the best subset of variables was selected (Table 8).

Soil compaction was best described using TM bands 2 and 4, soil structure, texture, and erosion intensity. The resulting equation explained 36.7% of the variability with a coefficient of variability (C.V.) of 21.37%. Soil crusting was best described using TM bands 2, 3, and 4, soil texture, and erosion intensity. However, the equation only accounted for 19.9% of the variability. This suggests that there are probably other

Table 7. Summary of stepwise regression for determining the best combination of TM spectral bands and soil properties in predicting surface soil conditions

Soil Condition	Step	Variables Entered	Number In	Model R^2	CP†	F	Probability F
Compaction	1	TM2	1	0.1790	24.18	21.79	0.0001
	2	Structure	2	0.2626	13.74	11.23	0.0011
	3	TM4	3	0.3242	6.57	8.94	0.0035
	4	Erosion	4	0.3635	2.73	5.98	0.0163
	5	Texture	5	0.3674	4.14	0.59	0.4434
Crusting	1	TM3	1	0.1174	5.94	13.30	0.0004
	2	TM2	2	0.1470	4.46	3.43	0.0669
	3	Texture	3	0.1730	3.39	3.08	0.0821
	4	TM4	4	0.1922	3.13	2.31	0.1320
	5	Erosion	5	0.1994	4.28	0.86	0.3553
Grazing Intensity	1	Vegetation	1	0.7531	2.44	304.99	0.0001
	2	Structure	2	0.7599	1.66	2.82	0.0962
	3	Erosion	3	0.7633	2.29	1.39	0.2413
	4	TM4	4	0.7647	3.70	0.60	0.4414
	5	TM3	5	0.7691	3.92	1.82	0.1811
Vegetation Percentage	1	Structure	1	0.1691	6.05	20.35	0.0001
	2	Texture	2	0.2061	3.41	4.62	0.0340
	3	Erosion	3	0.2179	3.94	1.47	0.2279
	4	TM4	4	0.2276	4.73	1.21	0.2731
	5	TM3	5	0.2473	4.25	2.52	0.1155
NDVI	1	TM3	1	0.1050	350.42	11.74	0.0009
	2	TM4	2	0.7020	53.29	198.37	0.0001
	3	Color	3	0.7761	18.18	32.42	0.0001
	4	TM2	4	0.7975	9.46	10.25	0.0018
	5	Erosion	5	0.8105	4.94	6.59	0.0118
	6	Texture	6	0.8121	6.16	0.78	0.3794

† The regression equation is unbiased when the 'Cp' value is equal to or less than the number of variables in the equation.

Table 8. Regression equations generated from TM spectral data and soil physical properties for predicting surface soil conditions

Soil Condition	Regression Equation†	R^2	C.V.(%)††
Compaction	$Y = 2.39 - 0.08X_2 + 0.03X_3 + 0.18X_4 + 0.05X_5 - 0.25X_6$	0.367**	21.37
Crusting	$Y = 1.49 - 0.07X_1 + 0.07X_2 - 0.03X_3 - 0.14X_5 - 0.13X_6$	0.199**	28.48
Grazing Intensity	$Y = 4.55 + 0.03X_2 - 0.04X_3 - 0.12X_4 - 023X_6 - 0.03X_7$	0.769**	16.62
Vegetation	$Y = 34.06 + 1.68X_2 - 2.17X_3 + 9.83X_4 + 12.01X_5 - 10.80X_6$	0.247**	93.89
NDVI	$Y = 23.01 + 8.84X_1 - 25.62X_2 + 21.43X_3 + 5.84X_5 + 26.09X_6 - 20.84X_8$	0.812**	13.29

** Denotes significance at the .01 level

† X_1, X_2, X_3 = TM bands 2, 3 and 4; X_4 = Structure; X_5 = Texture; X_6 = Erosion

X_7 = Vegetation percentage; X_8 = Soil Color

†† Coefficient of variability

variables not used in this study that would better describe soil crusting. The equation was significant, however, at the .01 probability level and unbiased according to the Cp value of 4.28. An unbiased equation (based on the data entered) is indicated by a Cp value that is equal to or less than the number of terms in the resulting regression equation (Mallows, 1973).

Grazing intensity was best described using TM bands 4 and 3, soil structure, erosion intensity, and vegetation percentage. The resulting equation accounted for 76.9% of the variability with a C.V. of 16.62% and Cp value of 3.92. Vegetation percentage was best described using TM bands 3 and 4, soil structure, texture, and erosion intensity. The resulting equation accounted for only 24.7% of the variability and had a high C.V. value of 93.89%. The normalized distance vegetation index (NDVI) was best described using TM bands 2, 3, and 4, soil color, texture, and erosion intensity. The resulting regression equation accounted for 81.2% of the variability with a C.V. value of 13.29%.

These results confirm that the prediction of surface soil conditions such as compaction, crusting, and grazing intensity, using selected TM spectral bands and surface soil physical properties is possible based on the significant R^2 values and low C.V. values that resulted from the data set (Table 8). The results given in Tables 7 show the contribution of each of the variables that form the relationships. The contribution of TM band 3 and TM band 4 in explaining variability in the NDVI relationship was expected; however, the significant contribution of color, texture, and erosion was not. The NDVI index is supposed to be a predictor of biomass or green vegetative cover; however, in this study the percent vegetation cover variable did not significantly contribute to the NDVI relationship. Further, the variables that contributed the most to the relationship for predicting the percentage of vegetation cover were soil structure, texture, and erosion. The TM spectral bands, 3 and 4, made only minor contributions to predicting vegetation cover. These results concur with other studies conducted in the semi-arid areas of Botswana, the Sahel, and Australia, which reported that NDVI was a poor indicator of

vegetation cover (Ringrose and Matheson, 1991a; 1992; Matheson and Ringrose, 1994a; 1994b; Ringrose et al., 1994). These equations are geographically dependent and may not be applicable to other areas. However, equations such as these can be quickly generated for other areas if the TM data is available and the soils' physical properties are known. The prediction of surface soil conditions, such as the ones discussed in this paper, can have an enormous impact on the management practices used to control the wildlife population and grazing of domestic cattle in Botswana's Southern District as well as other parts of the country. The overgrazing problems in Botswana are well documented in many internal publications. It is our hope that the results of this study will be used to help initiate a monitoring program to better manage the country's natural resources.

Soil Erosion and Vegetation Conditions

Soil erosion from both wind and water is a major problem for Botswana. The sandveld region of the Southern District is most susceptible to soil erosion because of the light texture surface soils and the reduced vegetation cover due to the effects of over grazing. Results in Table 2 show that soil erosion has a significant effect on vegetation percentage (0.388**) and grazing intensity (-0.404**). As erosion becomes more severe in an area vegetation cover percentages decrease and grazing intensity also decreases because there is less vegetation available for livestock and wildlife to graze. Data in Table 7 shows that soil erosion is the third most important factor that affects vegetation and grazing intensity in the Southern District. Soil erosion is also an important variable in generating mathematical equations for predicting soil compaction, crusting, grazing intensity, vegetation percentages, and NDVI (Table 7).

An assessment of the degree of soil erosion in an area can be determine from the examination of satellite imagery by generating the NDVI or NDGR indices. Areas of severe erosion will appear as bright spots, high reflectance areas, within the imagery. Results in Table 4 show that the NDVI or NDGR is postively correlated with shrub

density (0596) and com shrub (0.562). These data can be interpreted to mean that high NDGR values reflects dense vegetation and hence, less erosion. This observation is further substantiated with the results from a multiple regression analysis which show that NDGR could accurately predict vegetative cover 87.5% of the time (Percent Cover = 62.735 - 0.34* NDGR, $R^2 = 0.875$) and that the NDVI and TM band 4 could accurately predict grazing intensity 77.1% of the time in the Southern District (Grazing intensity = 9.900 - 0.014* NDVI - 0.117*T4, $R^2 = 0.771$).

Accurate and current information of vegetation conditions is essential for proper rangeland management in contrasting ecosystems as found in Botswana. Significant problems exist worldwide in determining seasonal cover on rangelands in semi-arid areas where expensive (dry season) stocking rates are considered to be a major contributing factor to range degradation (Tothill and Mott, 1985; Timberlake; 1988). Range quality is assumed to have a direct relationship to the amount of vegetation cover or above ground woody plus herbaceous biomass. Studies in semi-arid areas worldwide have shown that whereas, grass cover is important, browse species are critical to sustaining livestock throughout the year (Platou and Tueller, 1988; Matheson and Ringrose, 1994a; 1994b). The amount of brouse is sometimes regarded as "fall-back" pasture, or that which helps sustain livestock through the dry season and drought. It has been reported by Shoshany et al. (1995) that seasonal vegetation cover changes are indicative of soil types. Miller et al. (1991) suggested that seasonal variability was due to leaf reflectance red edge. Ringrose et al. (1994) reported that plant reflectance characteristics vary along climatic gradients (e.g., subtropical, semi-arid, arid transitions) with the most problematic zone in terms of vegetation spectral reflectance being the semi-arid zone.

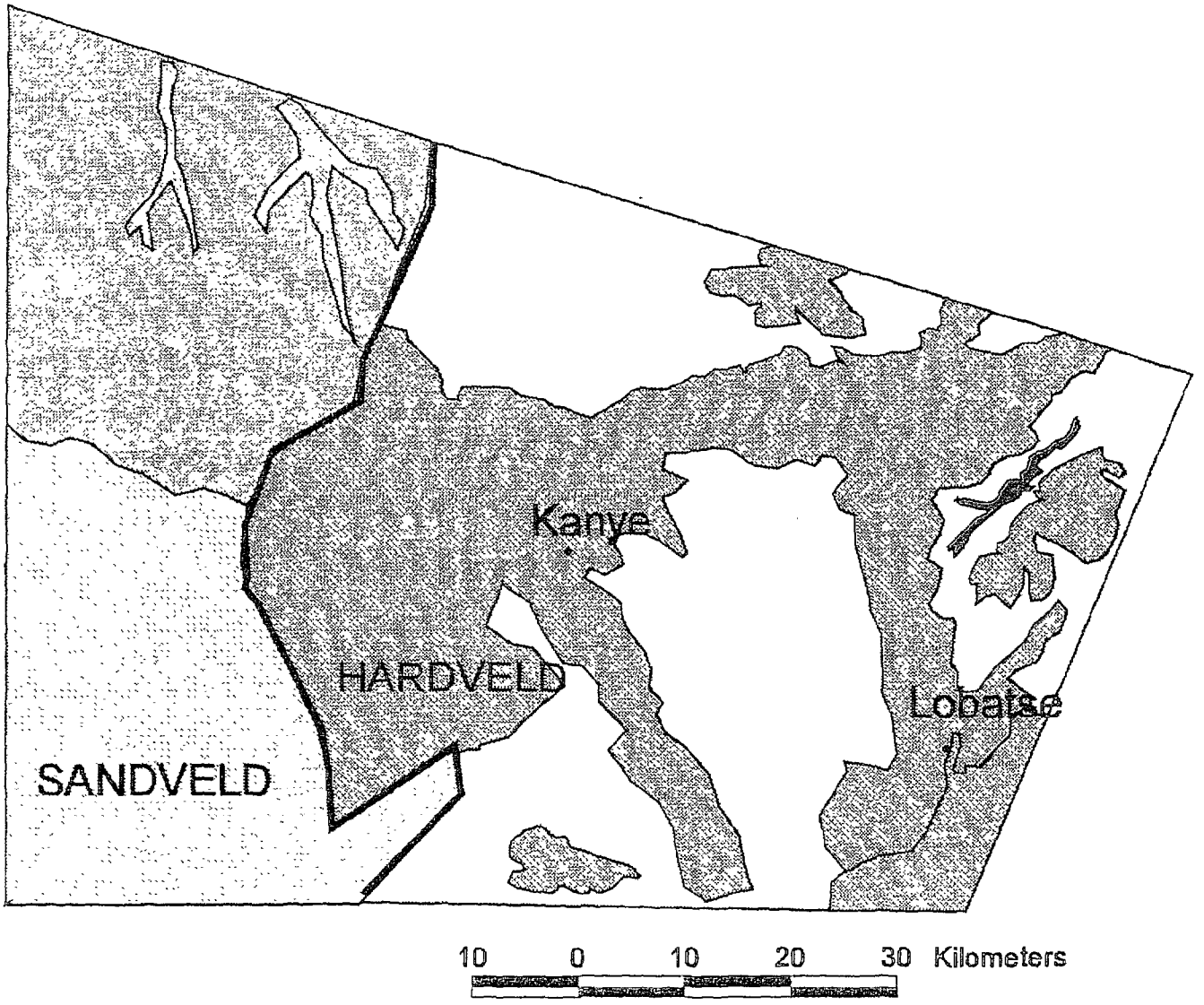
Indicators of range conditions can be assessed by comparing wet season and dry season reflectance characteristics where extensive areas of bare soil or low shrub densities might be regarded as low quality rangeland. It has been reported that the most critical time in terms of positive management and carrying capacity occurs towards the end of the

dry season (Tothill and Mott, 1985), when soil effects are maximized (Ringrose and Matheson, 1991b; Matheson, 1994). Wet and dry season TM data were used to determine differences in seasonal vegetation cover in three rocky/loamy soil areas (hardveld) and three sandy soil areas (sandveld) of the Southern District. The six areas are shown in Figure 4. A description of the ecosystems is given in Table 9. The 1994 wet-dry precipitation data are shown in Figure 5. Statistical data relative to the two sences after geometric and radiometric conections are given in Table 10.

Results from wet season and dry season field surveys are shown as Tables 11 and 12. During the 1994 wet season most of the woody vegetation cover (hence biomass) was fouind on rocky hill tops (Figure 6) with least in the hardveld cultivated valleys. Despite the rains, the alive and dead herbaceous cover values are relatively low for most of the study area and large expenses of bare soil prevail. Total vegetation cover (TVC) and biomass values were much more variable in the hardveld than in the sandveld. In terms of the relative palatability of the bush cover, the most palatable areas were found in the sandveld ecosystems. In terms of relative species richness per unit area both the hardveld and sandveld ecosystems appear comparable. In the dry season, the extent of woody vegetation cover mostly declined due to leaf fall, although certain species remain green throughout. The alive herbaceous cover is negligible and the proportion of dead herbaceous cover and litter increased commensurately. The proportion of total biomass is low with relatively higher amounts on rocky plateau/pediments and in sandveld ecosystems, except in localized areas where wind erosion problems occur (Figure 7).

Ecosystem Spectral Analysis

The range of spectral reflectance values depicting relative vegetation cover for the six ecosystems was assessed for each of the reflective TM bands to determine how spectral response varies seasonally with increasing vegetation cover. This procedure was also undertaken to assess which TM bands might provide the most useful inputs for



Major Ecosystems

- I Cultivated and Grazed Plains
- V Grazed Plateau and Pediments
- VI Grazed Interfluves (A)
- VII Grazed Interfluves (B)
- VIII Cultivated Fossil Valleys
- II Cultivated Valleys

Hardveld-Sandveld Boundary

Figure 4. Outline of the study area showing the major hardveld sandveld division and the sub-division of the constituent ecosystems.

Table 9. Ecosystems and land-uses: Southeastern Botswana

Ecosystem	Name	Erosion Features	Soil type and colour	Land use
I	Hardveld - cultivated plains	Gully, sheetwash and rill erosion	Ferric Luvisol 5YR5/4	Mixed agriculture and grazing
II	Hardveld - cultivated valleys	Gully and sheetwash erosion	Gleyic Luvisol 10YR4/2	Mainly agriculture - crop production
V	Hardveld - rocky hills	Gully and rill erosion	Regosol 5YR5/6	Grazing
VI	Sandveld-multicoloured arenosols	Wind erosion	Petrocalcic Arenosol 5YR6/6	Grazing and arable clearing
VII	Sandveld arenosols and pans	Little erosion	Arenosol 10YR7/3	Grazing - some agriculture
VII	Fossil valleys in sandveld	Some rill and sheetwash erosion	Luvisol 10YR8/4	Grazing - some agriculture

Table 10. Basic spectral data for wet season and dry season imagery

Dry Season	Maximum	Minimum	Mean	Median	Standard Deviation
TM1	189	0	45.4	59	27.2
TM5	255	0	69.4	88	43.4
TM7	253	0	32.0	39	20.7
Wet Season					
TM3	229	0	50.0	61	38.3
TM5	255	0	108.7	140	81.0
TM7	255	0	51.9	62	40.6

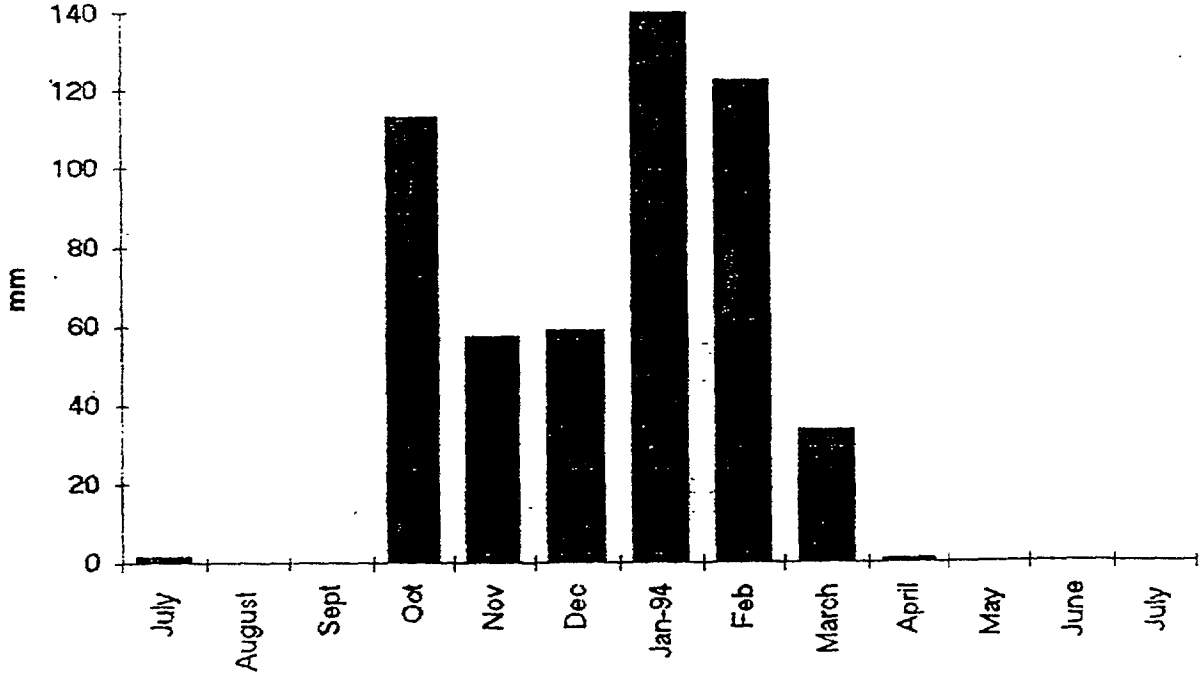


Figure 5. Seasonal distribution of rainfall over southeast Botswana (Gaborone Meteorological Station) showing the average precipitation for wet season during the three months prior to January 1994 and for the dry season prior to July 1994.

Table 11. Vegetation survey results - wet season

Ecosystem	WVC%	AHC %	DHC%	BS%	PAL*	APPROX. BIOMASS**	RICH***
I (n=5)	33.1	2.8	0.7	63.4	1.47	4600	2.05
II (n=3)	15.2	1.8	0.9	82.1	1.52	2700	1.90
V (n=18)	45.7	1.5	1.9	50.9	1.55	5900	2.22
VI (n=10)	26.6	6.1	3.4	63.9	1.64	4200	1.68
VII (N=12)	29.0	2.7	2.3	66.0	1.96	4200	2.29
VIII (n=11)	25.0	3.0	1.6	70.4	1.73	3800	1.80

WVC = Woody Vegetation Cover
AHC = Alive Herbaceous Cover
DHC = Dead Herbaceous Cover
* PAL = Palatability
**Approximate biomass in Kg/Ha
***Rich = Species richness

Table 12. Vegetation survey results -dry season

Ecosystem	WVC	AHC	DHC	BS	PAL*	APPROX. BIOMASS**	RICH***
I (n=5)	19.4	0.0	20.7	59.9	NSD	3400	1.8
II (n=3)	10.5	5.7	15.2	68.6	NSD	2600	1.3
V (n=18)	41.9	0.8	13.5	43.8	NSD	4100	2.0
VI (n=12)	25.3	0.0	22.8	51.9	1.8	14	1.5
VII (N=15)	30.0	0.0	19.3	51.7	1.96	17	2.29
VIII (n=11)	22.9	3.0	15.4	58.7	1.73	13	1.80

NSD = No species data available

WVC = Woody Vegetation Cover
AHC = Alive Herbaceous Cover
DHC = Dead Herbaceous Cover
* PAL = Palatability
**Approximate biomass in Kg/Ha
***Rich = Species richness

Figure 6. Relatively dense woody vegetation cover in hardveld ecosysem V, rocky plateau and pediments north of Kanye.

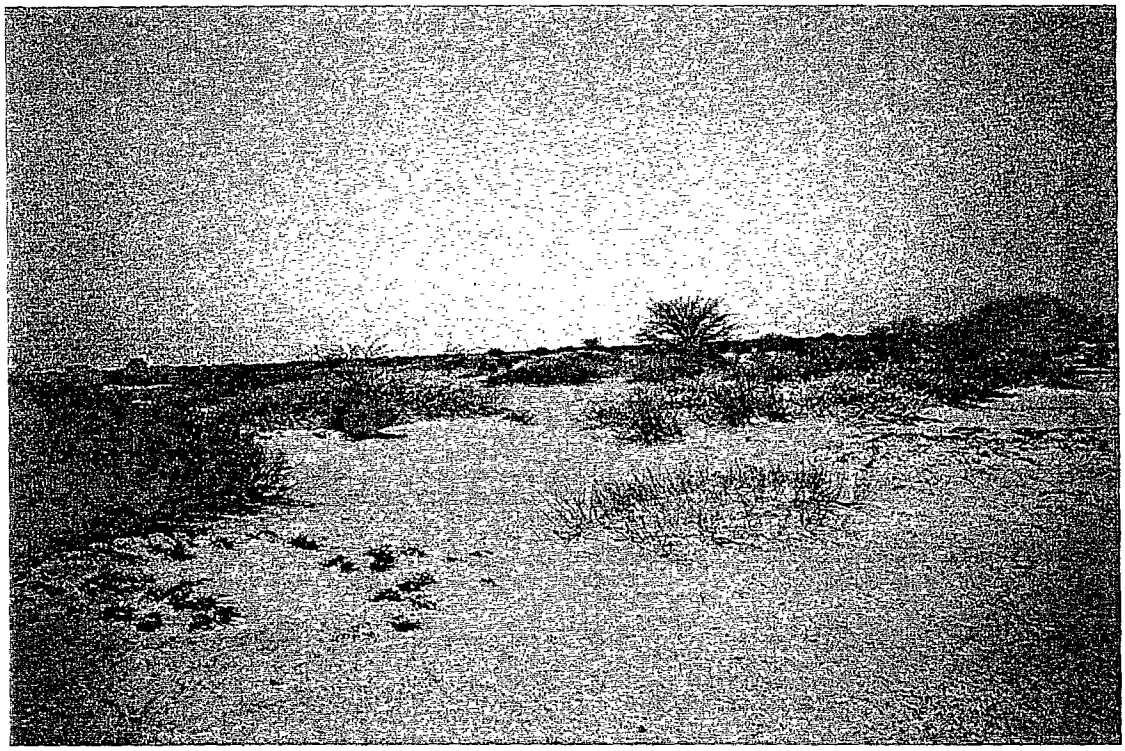
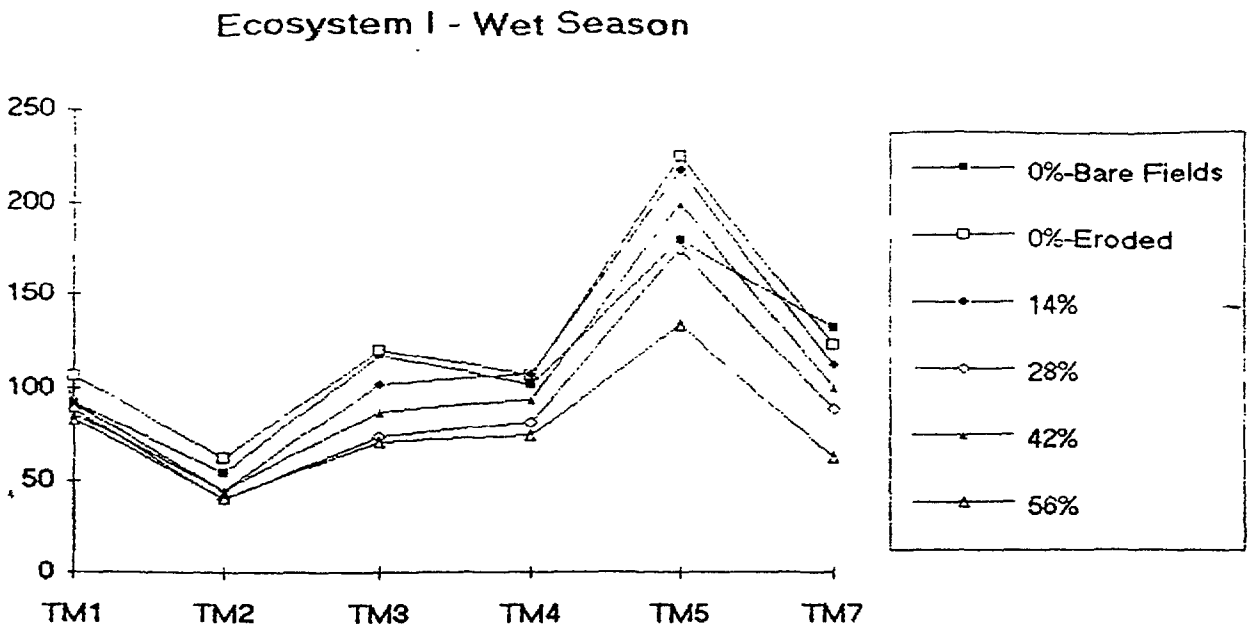


Figure 7. Extensive areas of windblown sand trapped in *Acacia hebeclada*, adjacent to zones transformed as a result of agricultural clearing in sandveld ecosysem VII (taller shrub = 1.5m).

range assessment techniques using the classification approach. Initially nine pixel values were recorded (and subsequently averaged) using the Inquire Cursor Function in ERDAS IMAGINE 8.2 by locating the cursor over known field sites on both wet and dry season imagery. Also recorded were either bare (cultivated or grazed) or eroded soil pixels. These results were developed into spectral sequences of successive increments of vegetation cover in all the ecosystems to facilitate wet/dry season comparison.

The results from the hardveld ecosystems are considered first. Ecosystem I (mainly undulating plains) shows high pixel values for the mid-infrared (MIR) bands and relatively low values for the near infrared and visible bands (Figure 8). This overall pattern is replicated throughout all the ecosystems. The low level of NIR reflectance is indicative of the general low level of green cover, even in the wet season. The plots for ecosystem I show that wet season and dry season trends are generally similar but that most proportional vegetation differentiation takes place in the dry season on mid-infrared bands. For ecosystem II (cultivated valleys) both wet season and dry season curves appear similar but with greater seasonal differentiation in the wet season (Figure 9). In ecosystem V (rocky hills), the series of vegetation increment curves are similar for all TM bands on both the wet and dry season images (Figure 10). In the dry season the pixel value differences for TM1 is relatively high. Generally the dry season curves seem to indicate a greater incremental vegetation cover differentiation over most TM bands than the wet season.

For the sandveld ecosystems, in ecosystem VI (sandveld, darker soils) while both wet and dry season curves are similar, the interband contrast and relative cover increment is more marked in the dry season imagery (Figure 11). In ecosystem VII which has more recently opened fields and more visible incidence of wind erosion, there is more overall contrast in the wet season imagery. This occurs particularly in terms of the wind eroded and ploughed fields relative to the three increments of vegetation cover (Figure 12). However a clearer density increment on all bands was more noticeable on the dry season



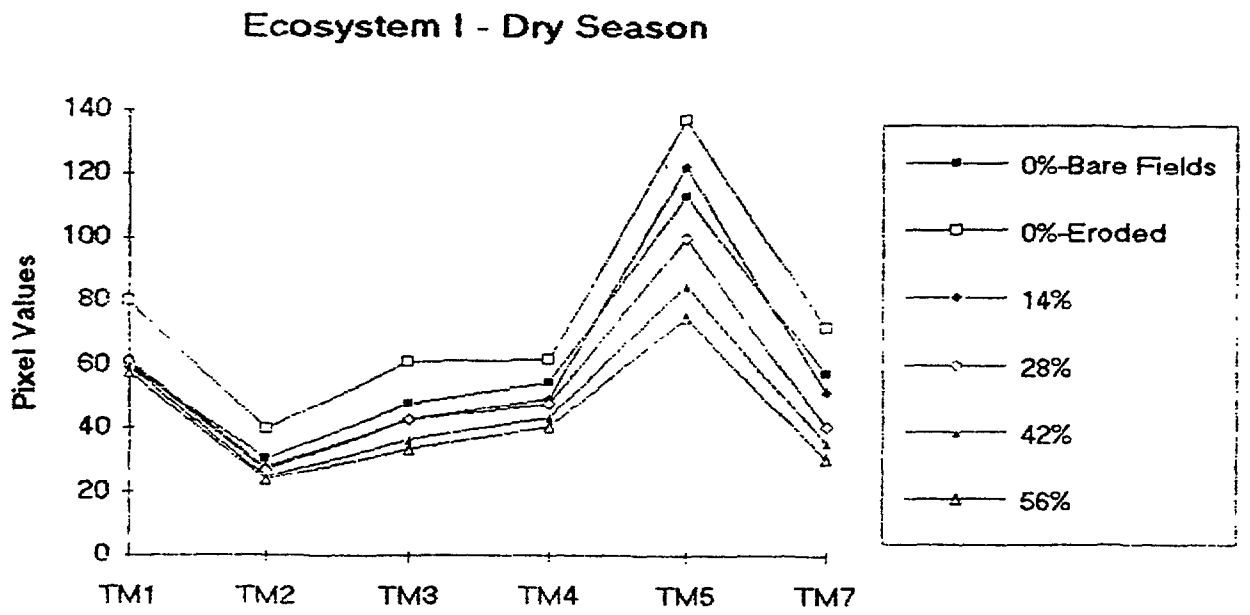
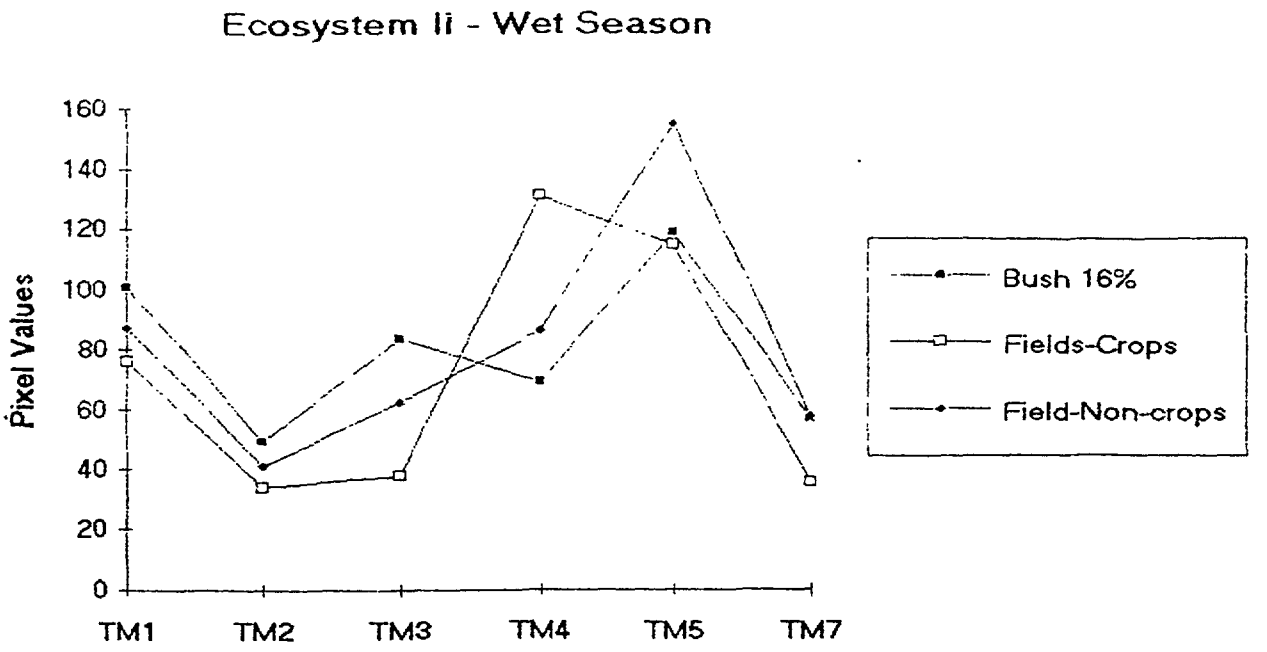


Figure 8. Differences between spectral reflectance curves with increments of vegetation cover for the hardveld plains ecosystems I over the six reflective TM bands.



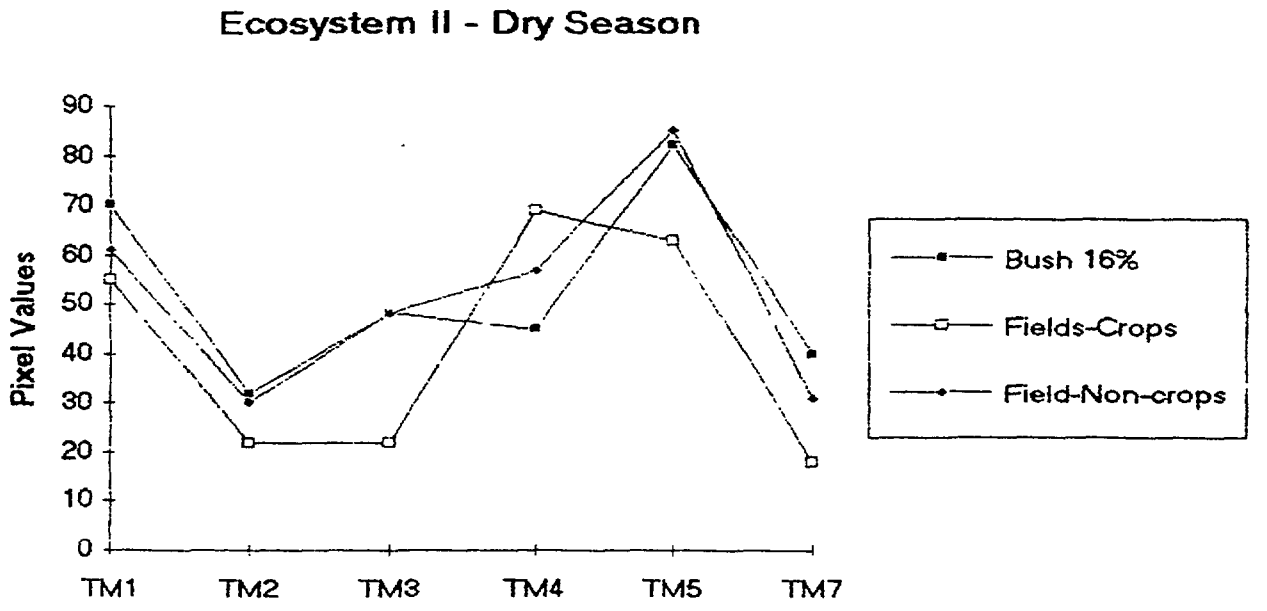
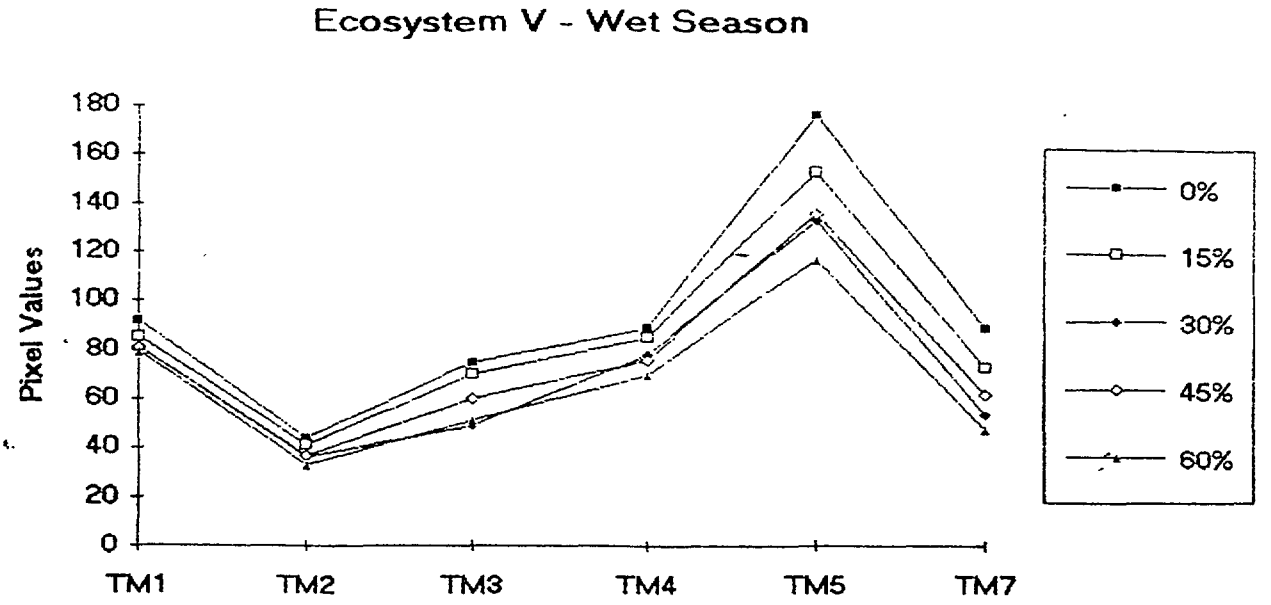


Figure 9. Differences between spectral reflectance curves with increments of vegetation cover for the hardveld cultivated valley ecosystem II over the six reflective TM bands.



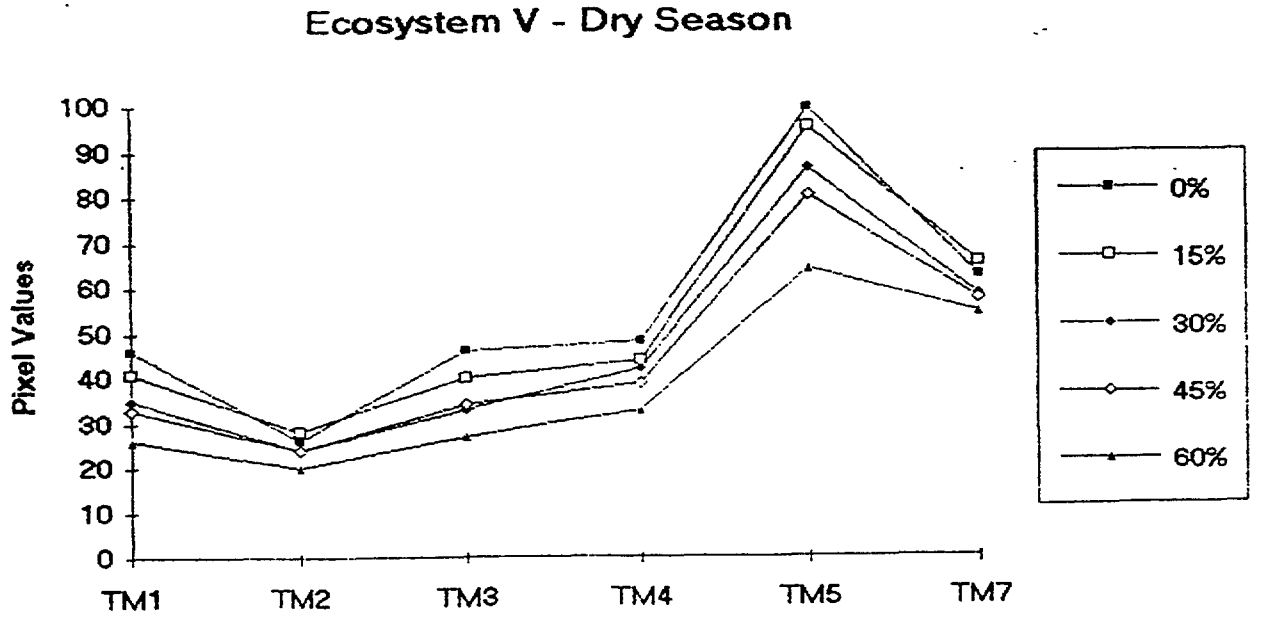
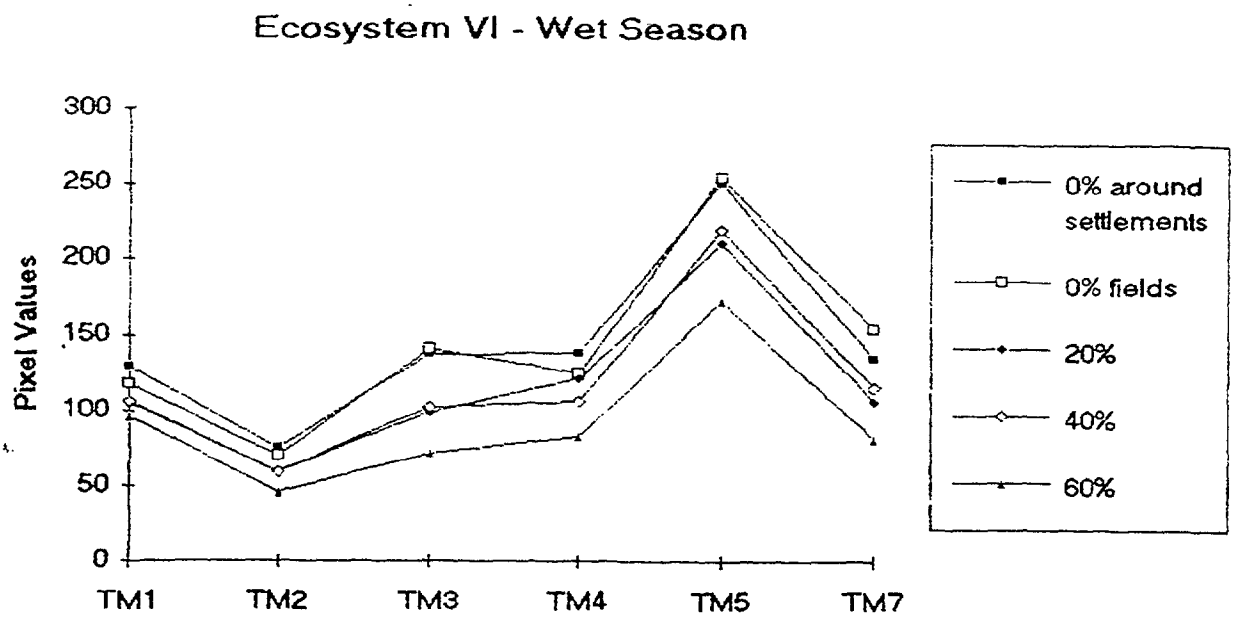


Figure 10. Differences between spectral reflectance curves with increments of vegetation cover for the hardveld plateau/pediments ecosystem V over the six reflective TM bands.



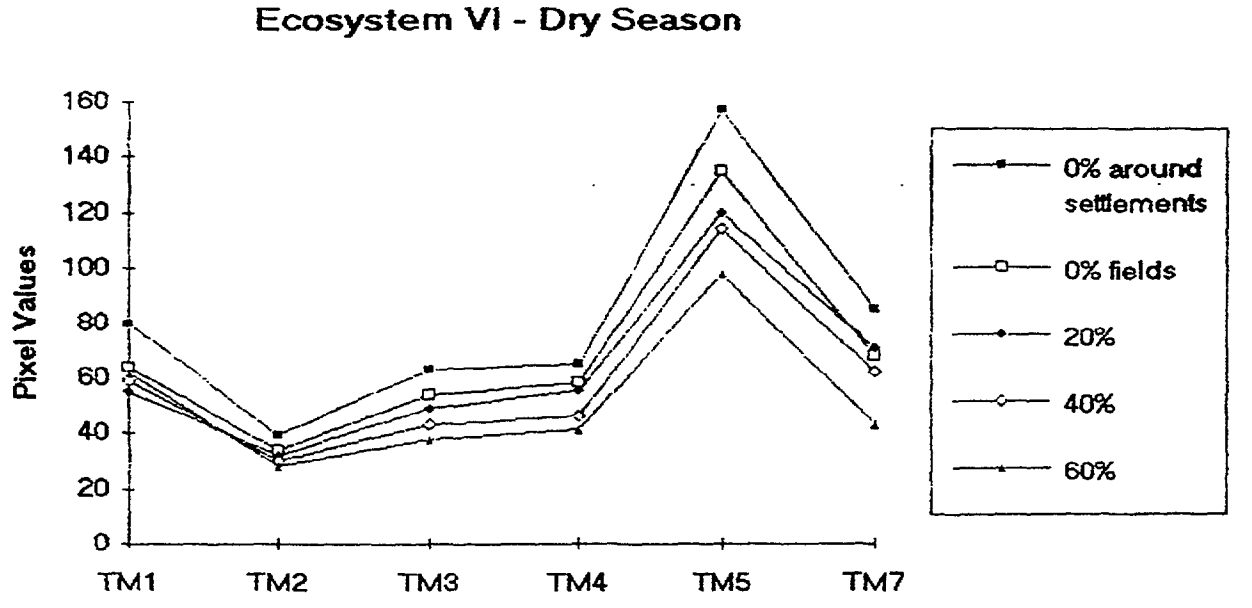
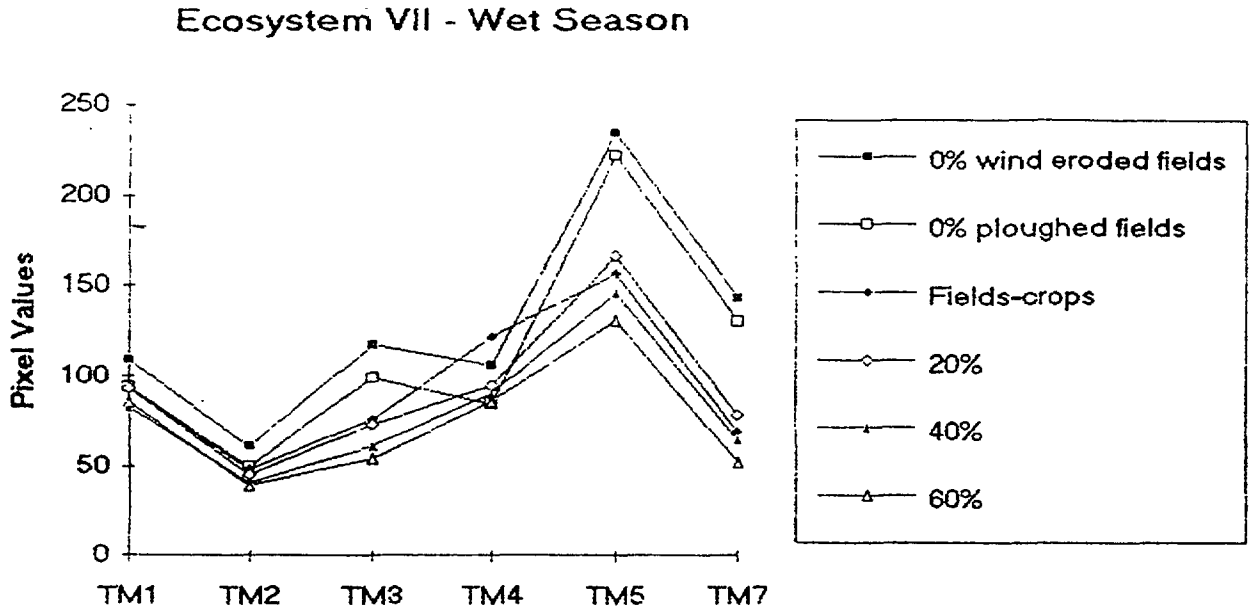


Figure 11. Differences between spectral reflectance curves with increments of vegetation cover for the sandveld darker soil ecosystem VI over the six reflective TM bands.



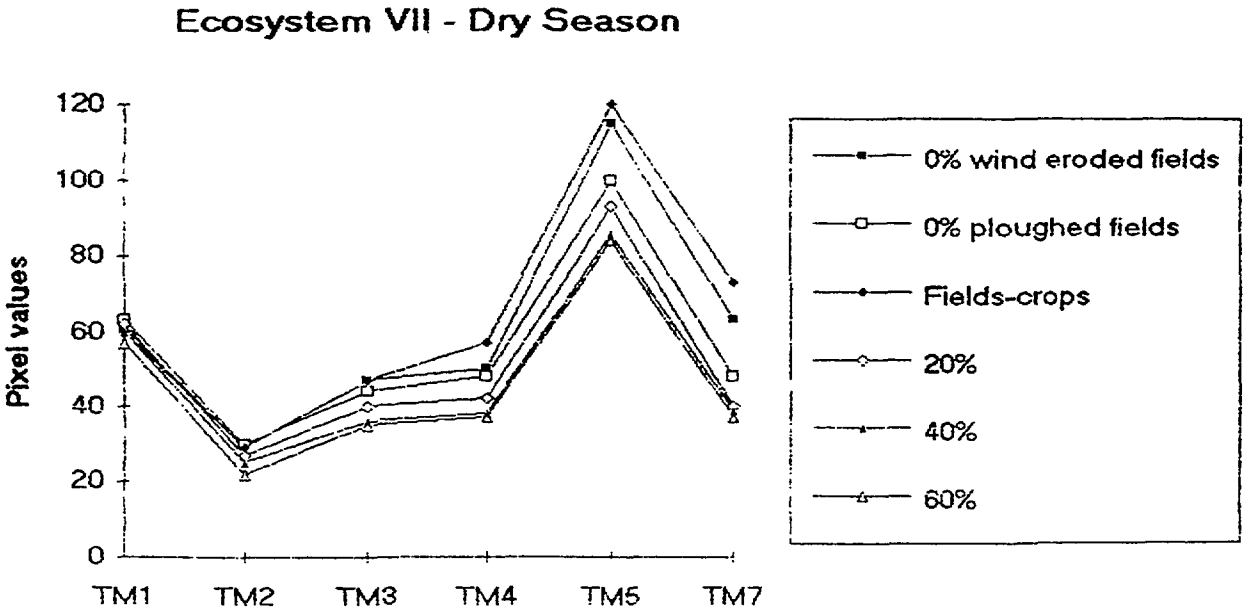
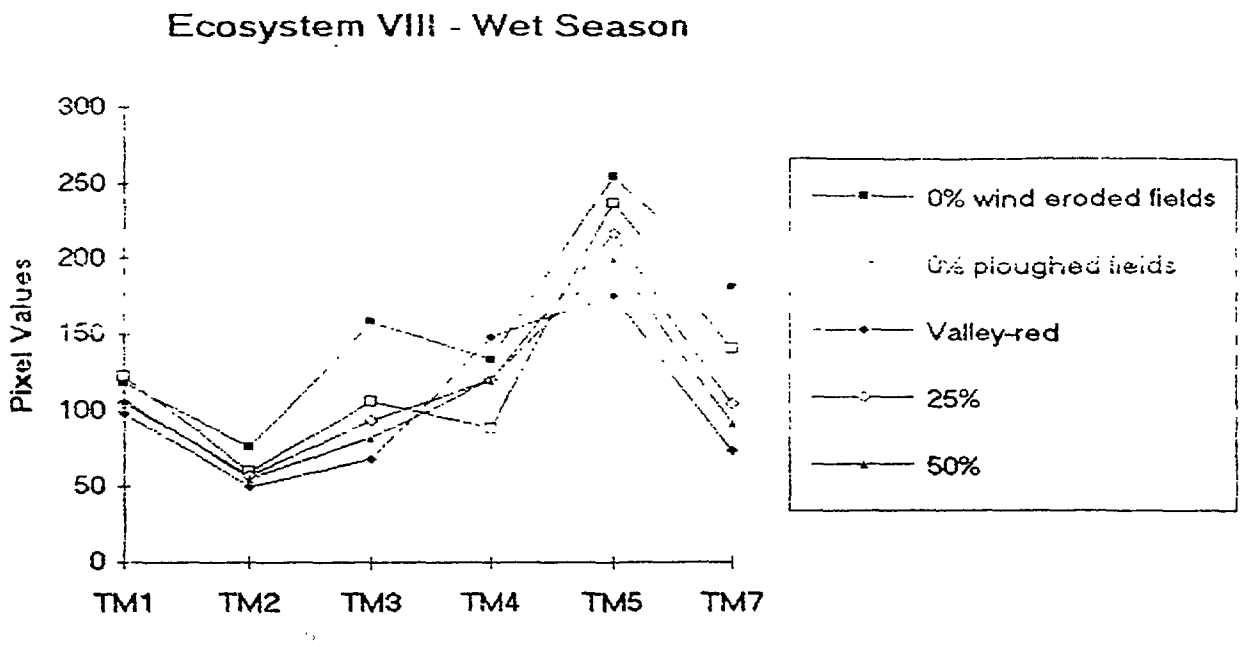


Figure 12. Differences between spectral reflectance curces with increments of vegetation cover for the sandveld lighter soil ecosystem VII over the six reflective TM bands.

imagery. Finally in the case of ecosystem VIII (fossil valleys), there is more band separability in the MIR range in the wet season and more separability in the dry season in the visible portion of the spectrum (Figure 13). Hence the degree of separability varies seasonally and with differences in ecosystems in terms of the TM reflectance wavebands.

Steps were taken to determine which bands and/or band combinations might inherently contain most useful data in terms of separating increments of vegetation cover and thereby predicting range condition. Spectral separability indices (SSIs) were devised based on the relative separability of TM bands in terms of increments of vegetation cover graded from 0-4 where 0 = total overlap (i.e. with a high degree of overlapping of pixel values); 1 = partial overlap; 2 = some separation/some overlap; 3 = total separation, no sequence; 4 = complete separation in sequence (i.e. vegetation cover increments increasing or decreasing in terms of increasing or decreasing pixel values) (Table 13).

The results show SSI values ranging from 0.54 to 0.83 for wet season imagery and from 0.38 to 0.79 and for dry season imagery. For most ecosystems, wet season imagery is inherently clearer in differentiating increments of vegetation cover. This is possibly because of the relatively high density of vegetation cover and clearer differences between plant and soil reflectance values which occur during the wet season. This is enhanced by the minimal extent of darkened (shadowed) vegetation cover relative to highly reflective bare soil (e.g. Ringrose et al., 1989; Otterman, 1996). The reflectance curves from dry season imagery are relatively unpredictable with pixel values possibly influenced by, variable proportions of dormant tree/shrub cover and senesced grass, The extent of vegetation induced (lateral) shadow is also far greater in the dry season. In terms of the relative usefulness (inferred data content) for classification purposes, TM3 (SSI 0.66), TM5 (SSI 0.7) and TM7 (SSI 0.83) were chosen as the most suitable input bands for wet season rangeland evaluation. TM3 (SSI 0.71), TM4 (SSI 0.7) and TM5 (SSI 0.79) were chosen for dry season evaluation (Table 13). With respect to optimal band usage in this part of semi-arid southern Africa, TM3 and TM5 (0.63-0.69 μm and 1.55-1.75 μm)



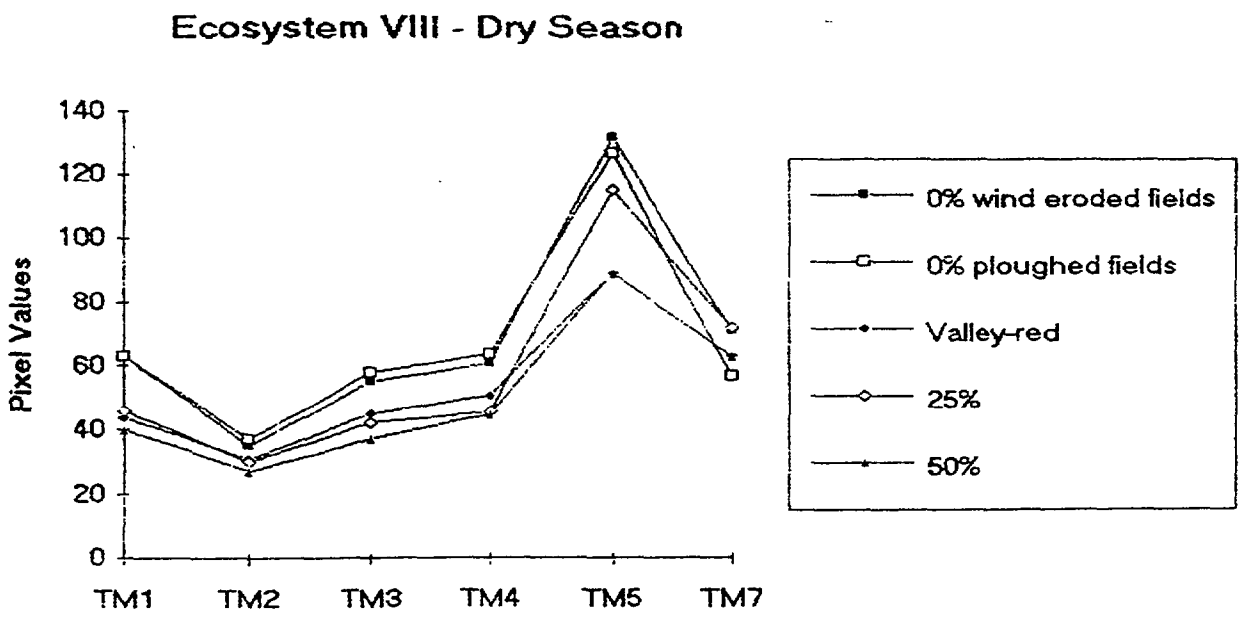


Figure 13. Differences between spectral reflectance curves with increments of vegetation cover for the sandveld fossil valley ecosystem VIII over the six reflective TM bands.

Table 13. Spectral separability indices used to develop bands for use in classification

Ecosystem HARDVELD	TM1	TM2	TM3	TM4	TM5	TM7
I - Wet Season	2	2	3	3	3	3
I - Dry Season	1	1	2	2	3	4
II - Wet Season	4	4	4	4	2	2
II - Dry Season	4	2	2	4	4	4
V - Wet Season	3	3	1	1	3	4
V - Dry Season	4	1	3	3	4	2
Ecosystem SANDVELD						
VI = Wet Season	2	1	2	4	2	3
VI = Dry Season	2	2	4	4	4	2
VII = Wet Season	1	1	2	1	4	4
VII= Dry Season	1	1	2	2	3	1
VIII= Wet Season	1	1	4	0	4	4
VIII= Dry Season	2	2	4	3	1	1
Wet Season Separability	0.54	0.54	0.66	0.54	0.75	0.83
VII = Wet Season Separability	0.58	0.38	0.71	0.75	0.79	0.58

Where 0 is no spectral separability, 1 = minimal separability, 2 = some separability, 3 = separbility but not in sequence of incremental vegetation cover, 4 = separability in sequence of vegetation cover.

appear equally effective, irrespective of seasonal variability. The data from TM4 (0.76-0.90 μm) are particularly valuable in the dry season, presumably because of vegetative darkening in the near infrared part of the spectrum (Ringrose et al., 1989). Interestingly, TM7 (2.08-2.35 μm) contains most useful information for range assessment in the wet season, a factor that may be related to soil/vegetation moisture retention (Elvidge and Portigal, 1990).

Image Classification

The classification was undertaken using the three optimal input bands per season to provide a comparative quantitative assessment of range conditions in hardveld and sandveld ecosystems. Using ERDAS IMAGINE 8.2 two, three band TM images were created for each season by first subsetting the relevant whole scenes into study area subscenes and then further reducing the subscenes into hardveld and sandveld components using AOI (area of interest) tools and the SUBSET function. The separation of hardveld and sandveld components was necessary because of interpretational problems which arise after devising classification schemes across major ecoregion boundaries (Ringrose, et al., 1990). Data content was evaluated specifically for the different seasons. Similar procedures were undertaken on all four subscenes which were classified separately to obtain maximum variability in terms of cover density and hence range condition. Data from field observations, away from the field data collection sites were located on the image areas to predict classes in terms of relative amounts of vegetation cover. This was followed by polygon generation and the development of initial classes covering situations ranging from varying degrees of vegetation cover to land-use types in terms of fields, bare soil areas and degrees of erosion. As far as possible, the training polygons were obtained from the same areas for the wet and dry season cases. Typically 15-20 initial training signatures were generated for the hardveld images which show greater variability in terms of edaphic conditions and land cover types, while 10-15 signatures were developed for

the sandveld. Each of the four preliminary signature files were edited using the edit functions in the signature editor cell array. The consistency of the signatures in terms of statistical distribution curves was assessed using histogram analysis and multimodal signatures were reformulated. Degrees of signature overlap were determined using the contingency matrix and the coinciding and/or overlapping classes were either merged or deleted. Dimensional class distribution plots were displayed as ellipses on feature space diagrams using different channel combinations and overlapping classes were deleted. Additional non-parametric classes were derived directly using feature space plot routines in areas devoid of classes. This was undertaken interactively using linked cursors and the original data set.

Classification routines were undertaken using an initial feature space separation, followed by both overlap and unclassified rules being set to parametric with data separation taking place using the maximum likelihood classification algorithm setting the probabilities for each class at zero (Foody et al., 1992). The initial classification results were assessed using the Jefferies-Matusita signature separability function on one layer per combination. Thresholding was also applied to evaluate the classes in terms of their histogram distribution and respective chi-square values. This technique enabled classes to be more closely defined but also left a large number of unclassified pixels. These pixels were located on the original image using the alarm function and the revised signatures added to the respective signature files. The classification algorithms had to be run through each data set several times before four acceptable classified images were generated. The initial naming/interpretation of the classes was clarified and expanded using the alarm function in conjunction with the raster attribute editor. Following classification the relative accuracy was assessed with reference to the original field data sites.

The results of the classification process for the hardveld ecosystems are shown in Tables 14 and 15 (and Figures 14 and 15) and for the sandveld ecosystems in Tables 16 and 17 (and Figures 16 and 17). A total of sixteen classes, identifying mainly differing

Table 14. Results of classification in the wet season, Hardveld

Ecosystem	RRC*	Area (Ha)	Interpretation and Percentage Accuracy
I	-	22607	Bare fields - some erosion (77%)
I/V	L-B	63009	Moderate bush encroached vegetaton cover on pediments/plains (81%)
I	-	9866	Cultivated fields (89%)
I/V	L-B	15083	Dense bush encroached vegetation cover on pediments/plains (85%)
V	M	38095	Moderate broadleaf and herbaceous vegetaton cover on plateau (73%)
I	L-S	153804	Bare soil and eroded area (79%)
V	-	5335	Hill shadow and gorges/water (87%)
I	M	25598	Moderate dense broadleaf and herbaceous riparian/plains vegetation cover (84%)
I	L-S	46975	Moderate sparse shrubby vegetation cover on plains - some erosion (69%)
I/II	-	13227	Partially vegetated fields/fields with crops (78%)
I/II/V	H	13602	Very dense broadleaf and herbaceous vegetation cover on plains/plateau and clay valleys (87%)
V	L-B	40897	Moderate bush encroached vegetation cover on pediments/plains (84%)
V	L-S	11443	Sparse shrub vegetation on near surface bedrock (73%)
II	M	6464	Moderate broadleaf and herbaceous vegetation on near surface bedrock (72%)
I	-	1879	Pans - highly reflective soils (93%)
II	-	22083	Partially vegetated/cultivate fields (65%)

* = Relative Range Condition

Table 15. Results of Classification in the Dry Season, Hardveld

Ecosystem	RRC*	Area (Ha)	Interpretation and Percentage Accuracy
I	-	423	Partially vegetated fields (81%)
I	-	702	Bare fields - some erosion (73%)
I/V	L-B	44486	Moderate bush encroached vegetation cover on pediments/plains (64%)
II	-	82	Surface water (100%)
II/I	-	1490	Bare fields (95%)
V	M	28320	Moderate broadleaf and herbaceous vegetation cover on plateau (74%)
V	H	34352	Dense broadleaf and herbaceous vegetation cover on plateau (62%)
I/V	L-B	65312	Dense bush encroachment vegetaton cover on pediments/plains (59%)
V	-	964	Hill shadow and gorges (100%)
I/V	L-B	60973	Moderate bush encroached vegetation cover on pediments/plains (71%)
I	M	25165	Moderate dense broadleaf and herbaceous riparian/plains vegetation cover (75%)
V	L-S	22790	Sparse shrub vegetation on near surface bedrock (65%)
II	M	159	Moderate broadleaf and herbaceous vegetation on near surface bedrock (68%)
I	-	1805	Pans - highly reflective soils (73%)
I/II/V	H	19895	Dense broadleaf and herbaceous vegetation cover on plains/plateau and clay valleys (64%)
I	L-S	48546	Moderate-sparse shrub vegetation cover on plains - some erosion (72%)

* = Relative Range Condition

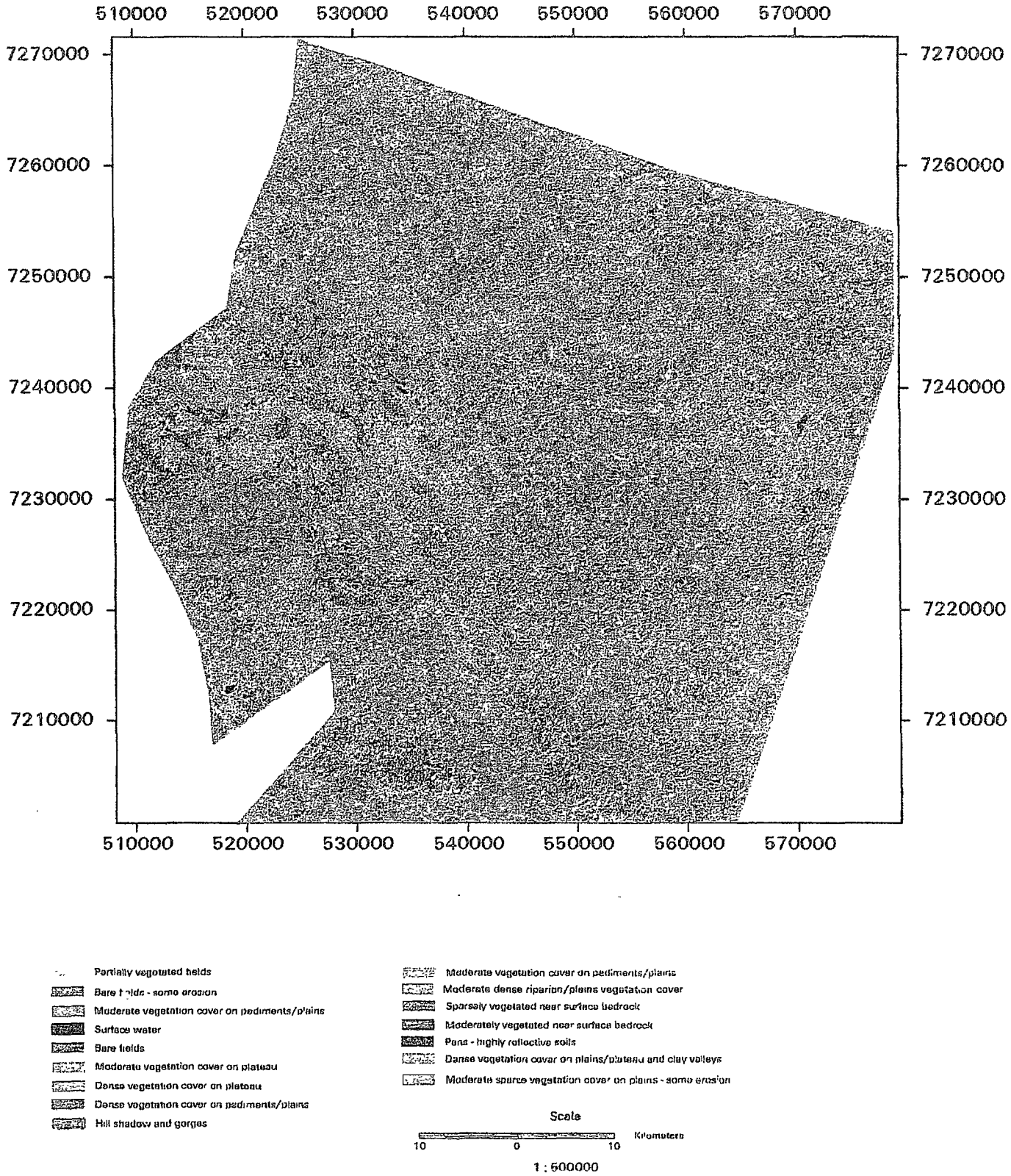


Figure 14. Map showing the spatial extent of vegetation density/land-use classes for the hardveld ecosystems during the 1994 wet season.

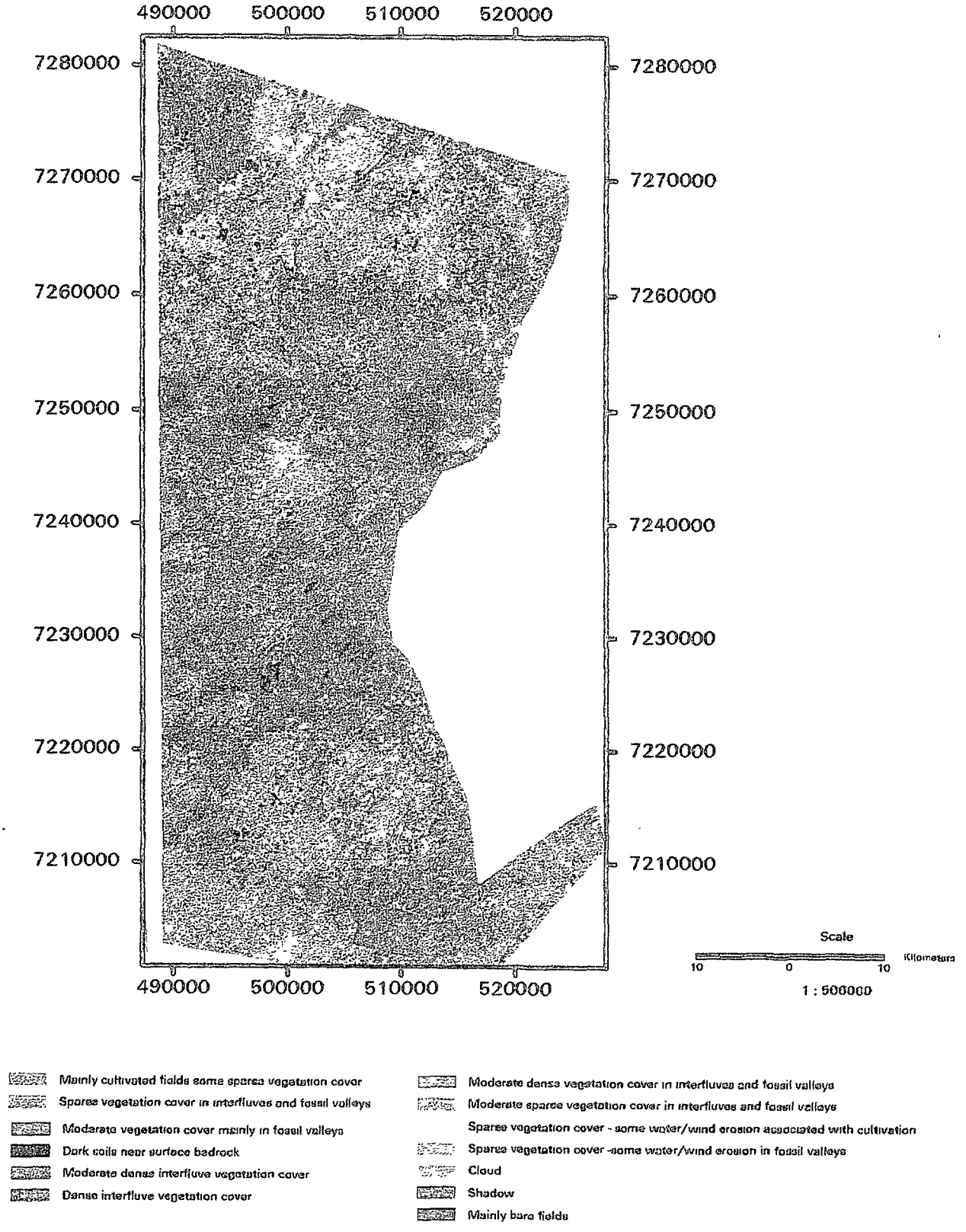


Figure 15. Map showing the spatial extent of vegetation density/land-use classes for the sandveld ecosystems during the 1994 wet season.

Table 16. Results of Classification in the Wet Season, Sandveld

Ecosystem	RRC*	Area (Ha)	Interpretation and Percentage Accuracy
VI/VII	-	7609	Mainly cultivated fields some sparse vegetation cover (88%)
VI/VII/VIII	L-S	15089	Sparse shrub vegetation cover in interfluves and fossil valleys (82%)
VIII	M	5609	Moderate broadleaf and herbaceous vegetation cover mainly in fossil valleys (65%)
VII	L-S	1241	Dark soils - shrub cover on near surface bedrock (71%)
VI/VII	M	14499	Moderate dense broadleaf and herbaceous interfluve vegetation cover (85%)
VI/VII	H	4147	Dense broadleaf and herbaceous interfluve vegetation cover (84%)
VI/VII/VIII	M	49161	Moderate dense broadleaf and herbaceous vegetation cover in interfluves and fossil valleys (90%)
VI/VII/VIII	L-S	44259	Moderate sparse shrub vegetation cover in interfluves and fossil valleys (69%)
VIII	-	7625	Sparse vegetation cover some water/wind erosion associated with cultivation (73%)
VIII	L-S	6570	Sparse shrub vegetation cover some water wind erosion in fossil valleys (75%)
VII/VIII	-	2303	Mainly bare fields (84%)

* = Relative Range Condition

Table 17. Results of Classification in the Dry Season, Sandveld

Ecosystem	RRC*	Area (Ha)	Interpretation and Percentage Accuracy
VI/VII	-	9613	Mainly bare fields some sparse vegetation cover (89%)
VIII	L-S	16357	Sparse shrub vegetation cover-some wind/water erosion associated with cultivation (70%)
VII	L-S	176	Pans and light coloured soils (64%)
VII	-	1605	Dark soils - shrub cover on near surface bedrock (83%)
VI/VII	M	28612	Moderate dense broadleaf and herbaceous interfluve vegetation cover (83%)
VI/VII	L-S	30587	Sparse shrub interfluve vegetation cover (85%)
VI/VII/VIII	S	53609	Moderate sparse broadleaf and herbaceous vegetation cover in inerfluves and fossil valleys (72%)
VI/VII/VIII	M	16053	Moderate dense broadleaf and herbaceous vegetation cover in interfluves and fossil valleys (84%)
VIII	S	2209	Sparse shrub vegetation cover some wind/water erosion in fossil valleys (78%)

*Relative Range Condition

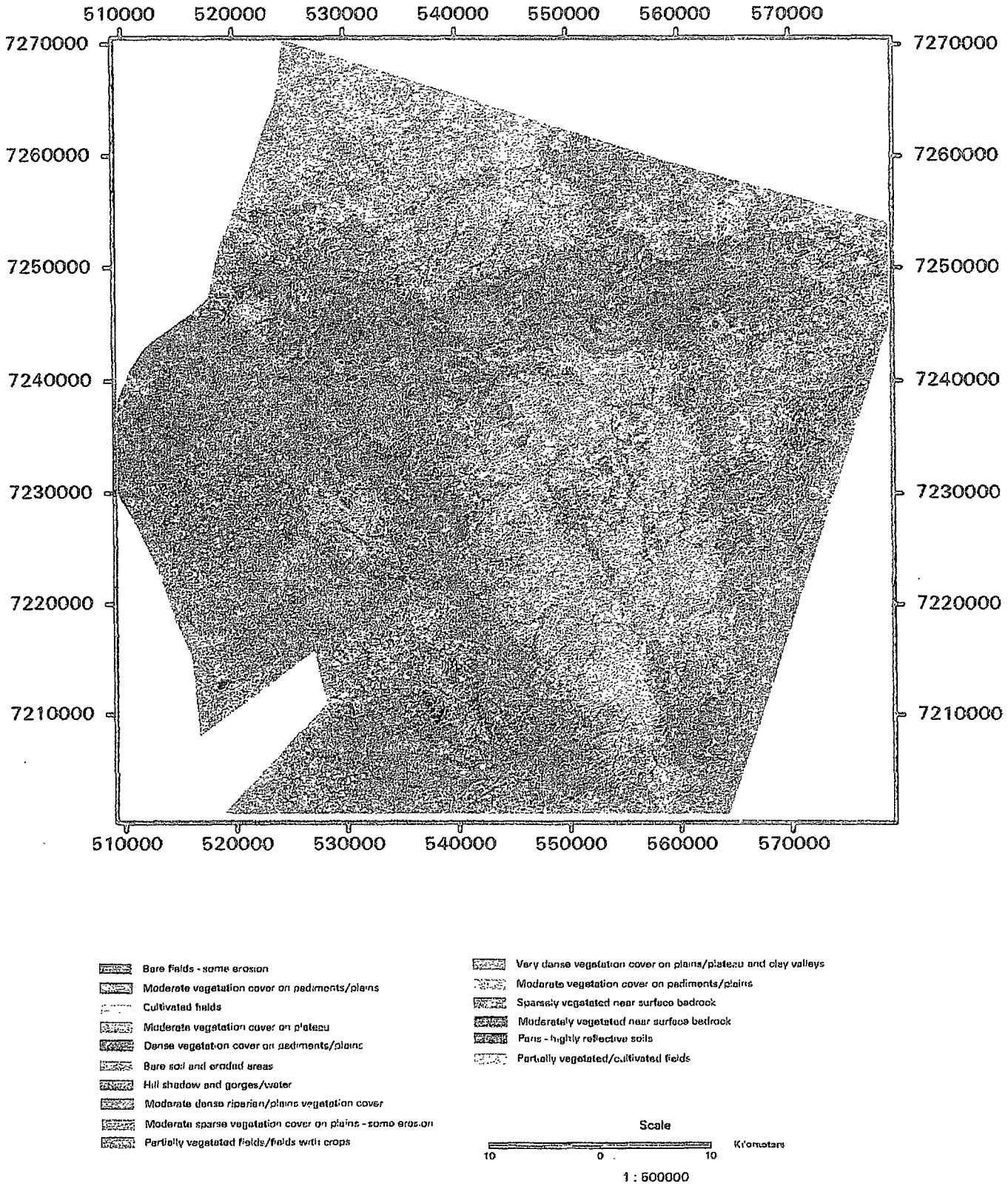
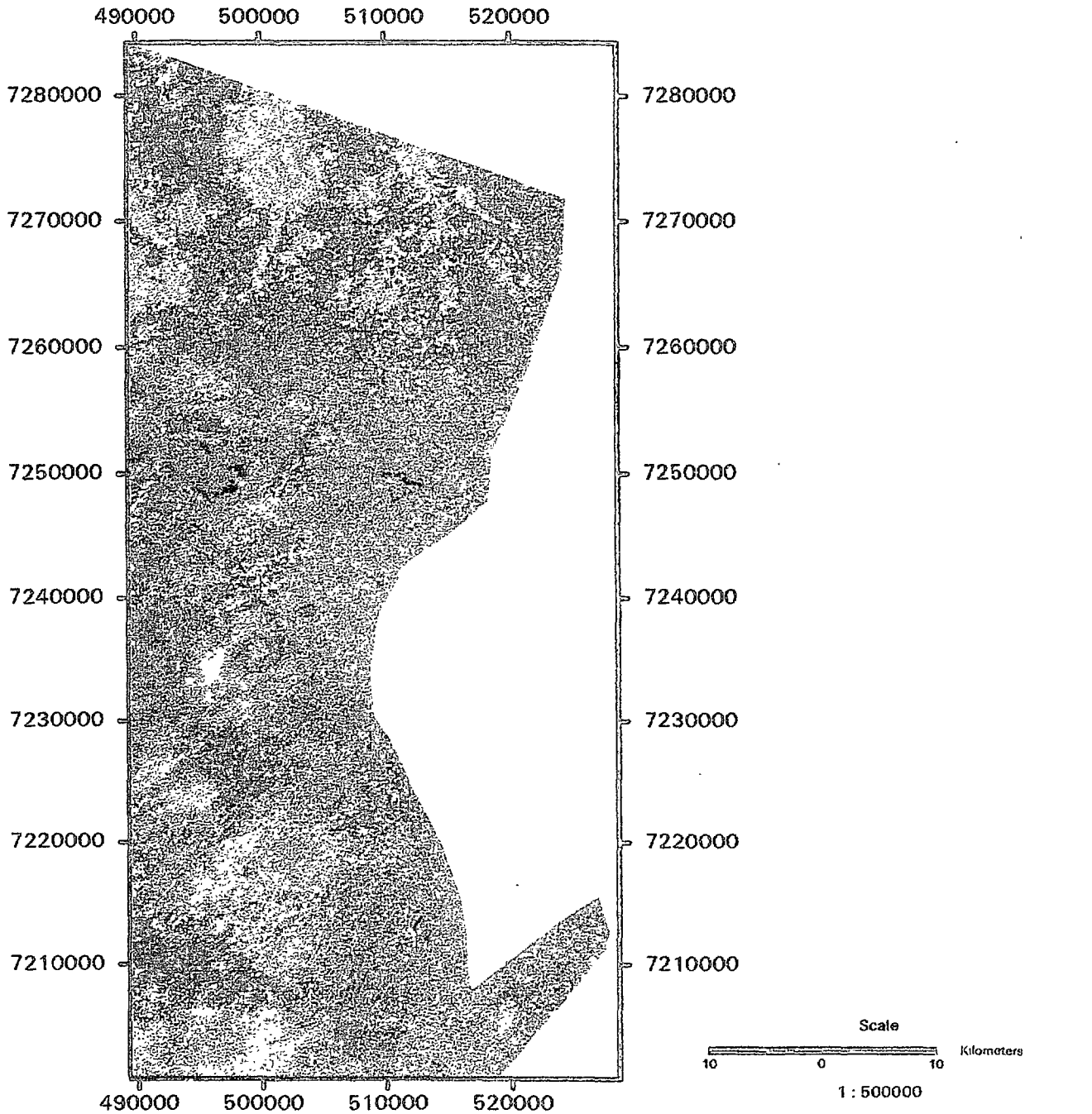


Figure 16. Map showing the spatial extent of vegetation density/land-use classes for the hardveld ecosystems during the 1994 dry season.



Mainly bare fields some sparse vegetation cover

Sparse vegetation cover -some wind/water erosion associated with cultivation

Pans and light coloured soils

Dark soils near surface bedrock

Moderate dense interfluve vegetation cover

Sparse interfluve vegetation cover

Moderate-sparse vegetation cover in interfluves and fossil valleys

Moderate-dense vegetation cover - in interfluves and fossil valleys

Sparse vegetation cover some wind/water erosion in fossil valleys

Figure 17. Map showing the spatial extent of vegetation density/land-use classes for the sandveld ecosystems during the 1994 dry season.

densities and types of vegetation cover were found to be spectrally distinct for the hardveld ecosystems whereas fewer classes were isolated for the sandveld. In terms of hardveld seasonal class comparability, moderate and dense vegetation cover types were merged for both pediments and plains (ecosystems 11 and V) during both seasons (Tables 16 and 17). This is probably because these classes depicted mainly darkened *Acacia spp.* cover, much of which is highly indicative of bush encroached areas, and which mask the inherently different soils reflectance values. In the dry season it was possible to differentiate dense vegetation cover specifically on the plateau (V). Moderate vegetation cover on the plateau was differentiated for both seasons (Tables 16 and 17). For both the hardveld and sandveld, for both seasons it was possible to isolate spectrally moderate dense riparian/plains cover, moderate sparse plains cover with erosion features, and sparse to moderately vegetated near surface bedrock. Mostly the hardveld wet season vegetation (rangeland) classes have a classification accuracy of between 73% and 89% which is higher than the dry season classes which have an accuracy of between 64% and 75% (e.g. Varjo, 1996).

In order to determine the extent to which the maximum likiihood classification model could adequately define classes useful in terms of range assessment, a range categorization system was applied to the resulting classes. Areas of known high density broadleaf (forage) and herbaceous cover were allocated into a high rangeland quality class. Areas of moderate vegetation cover, comprising mainly broadleaf (forage) and herbaceous cover were ascribed a medium category. The low quality rangeland was divided into two categories based on whether the category comprised mainly bush encroached areas or whether this included mainly low shrubby vegetation cover with eroded areas (Ringrose et al., 1996). Initially, a range category rating was accorded to each hardveld class and the relevant class areas were summarized on Table 18. For the medium range categories, the results are reasonably consistent with vegetation type changes as indicated from the field data set. As expected, much more area was seen to be eroded in the wet season than the

Table 18. Estimated area (km^2) under different rangeland categories by hardveld ecosystem for the wet and dry season, 1995/6.

	IH	IM	ILB	ILS	IIH	IIM	IILB	IILS	VH	VM	VLB	VLS
WS	60	275	400	640	60	80	-	-	61	395	810	120
DS	170	320	920	560	50	-	90	-	410	170	220	95

WS = Wet Season
DS = Dry Season
I, II, V = Hardveld Ecosystems

Rangeland Condition Categories
H = High
M = Medium
LB = Low - Bush encroached
LS = Low = Bare soil with eroded areas

Table 19. Estimated area (km^2) under different rangeland categories by sandveld ecosystem for the wet and dry season, 1995/6.

	VIH	VIM	VILS	VIIH	VIIM	VIILS	VIIIH	VIIIM	VIIILS
WS	70	249	271	120	169	283	-	72	292
DS		269	323		269	341	-	-	321

WS = Wet Season
DS = Dry Season
VI, VII, VIII = Sandveld Ecosystems

Rangeland Condition Categories
H = High
M = Medium
LS = Low = Bare soil with eroded areas

dry season. However problems arose in the higher and lower quality range categories. Unaccountably, a far larger area of dense vegetation cover was obtained for the dry season data than for the wet season. The bush encroached areas also appear to have expanded from the wet season to the dry season in the plains ecosystem which is inconsistent with observations. However, in the case of the rocky plateau/pediment ecosystem, the extent of bush encroachment remained similar for both seasons. The dry season imagery particularly in the plains ecosystem therefore appears to exaggerate the amount of both high density (higher quality) range cover and the amount of bush encroached area. This is possibly due to the enlarged areas of darkening (mainly caused by extended plant shadow) particularly over the darker soil background prevalent in the hardveld.

For the sandveld class interpretations, a high degree of comparability was noted between the seasons with seven of the nine (dry season) and nine (wet season) classes being coincident (Tables 16 and 17). Small areas of cloud and shadow in the sandveld ecosystems (wet season) were omitted from subsequent analysis. In terms of the relative interpretation of wet season and dry season classes, one class, 'sparsely vegetated interfluves' was only identified in the dry season. In the wet season, two classes 'moderate vegetation cover mainly in the fossil valleys' and 'dense interfluve vegetation cover' were uniquely spectrally separable. The classification accuracy of the sandveld range vegetation classes is slightly higher than that achieved for the hardveld being between 69-90% for the wet season and 64-85% for the dry season.

In order to determine the extent to which this classification technique could adequately define sandveld classes useful in terms of range assessment, a range categorization system, similar to that used for the hardveld, was applied to the results (Tables 16 and 17). The range category data were summarized for each ecosystem and the results given on Table 19. The results show that in the wet season, for the two interfluve ecosystems (VII and VIII) a proportion of the range is readily divided between the high, medium and low categories, consistent with vegetation cover types indicated

from the field data set. In terms of soil eroded areas, since these are mainly wind blown soils, as expected much more area was seen to be eroded in the dry season than the wet season. Interestingly fewer problems arose with the sandveld assessment, relative to the hardveld assessment. In the sandveld data set when separate classification signature files are used, the exaggeration of the amount of high density (higher quality) range found in the hardveld results, was not apparent. The direct effects of vegetative darkening noticeable on loamy hardveld soils appears relatively ineffective when sandy soils are classified. While this is probably related to differences in soil reflectance of significance here is the smaller size of the trees shrubs in the drier sandveld which produce a minimal amount of lateral shadow, even in the dry season.

Land Use Conflicts

Botswana is a fairly vast country; however, because of its climatic setting which limits the amount of area inhabited by its population to about one-third of its total area, there are numerous conflicts for the use of land. Many of these conflicts deals with urban issues, domestic grazing, and wildlife as well as protection of the environment. The government of Botswana is very concerned about these issues and developed a National Conservation Strategy to address them. The ability to monitor policies effectively has been limited by the lack of timely information on accurate land-cover and natural resources for planning and monitoring land use changes. The use of the earth monitoring satellites such as Landsat and the advances in interpreting these data afford individuals tools to better implement the policies.

Dissemination of Results

The results of this project have been presented at a number of conferences in the United States and Southern Africa. Also, to this date, four manuscripts have been submitted to refereed journals for publication consideration, which included the Remote

Sensing of Environment and the Journal of Geocarto International. Copies of these manuscripts are given in Appendix A through D. One additional manuscript will be submitted by September 30, 1996; however a draft copy was not available at the time this final report was printed.

Presentations of research results generated from this project were made at the 87th Annual Meetings of the American Society of Agronomy and Soil Science Society of America in St. Louis, MO, 29 October - 3 November 1995 and the 1996 Annual Meetings of the Associaton of American Geographers in April at Charlotte, NC. An abstract from each of these presentations was published in the conference abstracts and proceedings. A listing of the manuscripts and abstract publications is given in Table 20.

Table 20. Listing of manuscripts submitted, abstracts published and presentations of research results

Manuscripts Submitted:

Coleman, T. L., M. Nkambwe, S. Ringrose, M. D. Nellis, and C. E. Bussing. 1996. Correlation of Soil Attributres with spectrally-derived land use classes. (Submitted to Remote Sensing of Environment.)

Nellis, M. D., C. E. Bussing, T. L. Coleman, M. Nkambwe, and S. Ringrose. 1996. Spectral and Spatial Dimensions of rural land use systems in the southern District of Botswana. (Submitted to Geocarta International.)

Nellis, M. D., C. E. Bussing, T. L. Coleman, M. Nkambwe and S. Ringrose. 1996. Landsat TM vegetation indices for meaning woodfuel resources in the Southern District, Botswana. (Submitted to Geocarta International.)

Ringrose, S., S. M. Nkambwe, T. L. Coleman, M.D. Nellis, and C. E. Bussing. 1996. The use of Thematic Mapper imagery in predicting seasonal cover and inferred range conditions in contrasting semi-arid ecosystems. (Submitted to Remote Sensing of Environment.)

Abstract Published:

Coleman, T. L., M. Nkambwe, S. Ringrose, M. D. Nellis, and C. E. Bussing. 1995. Correlation of soil attributes with spectrally-derived land use classes of south central Botswana. p. 276. *In* Agron. Abstr. American Society of Agronomy, Madison, WI.

Nellis, M. D., C. E. Bussing, T. L. Coleman, M. Nkambwe, and S. Ringrose. 1996. Spectral and spatial dimensions of rural land use systems in the southern district of Botswana. AAG Abst., Association of American Geographers, Charlotte, NC.

Presentations:

Coleman, T. L., M. Nkambwe, S. Ringrose, M. D. Nellis, and C. E. Bussing. 1995. Correlation of soil attributes with spectrally-derived land use classes of south central Botswana. 87th Annual Meetings America Society of Agronomy, 29 October - 3 November 1995, St. Louis, MO. American Society of Agronomy, Madison, WI.

Nellis, M. D., C. E. Bussing, T. L. Coleman, M, Nkambwe, and S. Ringrose. 1996. Spectral and spatial dimensions of rural land use systems in the southern district of Botswana. Association of American Geographers Annual Meetings. April 1996, Charlotte, NC. Sponsored by the Association of American Geographers.

CONCLUSIONS

One of the limiting factors in the rural land management of Botswana's resources is lack of accurate information on land conditions that can be related back to different land management practices. The results of this project offer some prospect of providing synoptic indices of percent cover, grazing intensitiy, and surface soil conditions in the semi-arid portions of Botswana's Southern District.

Differentiation of land use classes and surface soil conditions based on selected TM spectral bands is possible according to the results presented in this report. Although the amount of variability that the variables accounted for in the analyses was low, the resulting discriminant functions and equations presented were found to be significant based on the statistical tests used. Highly significant relationships among the spectral data, soil physical properties and surface soil conditions were obtained. Land use classes were differentiated at an accuracy of 66.7% while the soil mapping units were different were differentiated at an overall accuracy of 88.6%. Prediction of surface soil conditions such as compaction and grazing intensity, and NDVI from the spectral data and surface soil physical properties was highly significant as indicated by the high R^2 values. Soil compaction was best described using TM bands 2 and 4, soil structure, texture, and erosion intensity. Percent cover was most successfully predicted using an NDGR index ($R^2 = 0.875$). Grazing intensity was best described using a combination of TM bands 3 and 4, soil structure, erosion intensity, and vegetation cover ($R^2 = 0.769$) or by using the NDVI index and TM band 4 ($R^2 = 0.771$).

Percent vegetation cover is also a good indicator of woody materials/trees that can be used as a source of woodfuel as well as food for browsing livestock. As in most developing countries, Botswana's population continues to depend on woodfuel as one of their important sources of energy. As part of Botswana's Southern District Development Plan, comprehensive regional land use planning of woodland resources is

one of six priority areas of concern. However, the availability of baseline information on the spatial and temporal variation of woodfuels is limited.

The results presented here provide optimision for using Landsat TM data for mapping spatial variation and amount of woodfuel resources. For trees, TM band 2 provided the highest degree of correlation with tree density and as an index of tree biomass. Landsat TM band 3 was the best estimator of shrub density, whereas band 4 was most significant in predicting shrub biomass index values.

Comparison of wet season and dry season imagery for six ecosystems in the Botswana hardveld and sandveld were also accomplished using TM data sets. Field work results indicated that in the 1994 wet season most of the total vegetation cover (TVC) was found on the hardveld plateau/pediments ecosystem and least in the plains ecosystem. The sandveld had a lower TVC, but cover was generally more consistent over the sandveld ecosystems. In terms of species richness (diversity), the two ecoregions are comparable. In the 1994 dry season, the TVC appears to have declined probably due to the semi-deciduous nature of the tree/shrub cover and the depletion/senescence of grasses. The dead herbaceous cover and litter components are relatively high in both the hardveld and sandveld during the dry season.

Spectral reflectance curves were developed for increments of vegetation cover based on field locations for the six TM reflective bands. The reflectance curves were graded to assess the relative separation attainable per increment of total vegetation cover per waveband. The results for both hardveld and sandveld ecosystems show high pixel values for the mid-infrared (MIR) bands and relatively low values for the near infrared and visible bands. Low NIR reflectance is indicative of the minimal green cover, even in the wet season. Spectral separability indices (SSIs) were devised to determine the relative distinctivness of TM-bands in terms of increments of vegetation cover. The SSI results for wet season imagery range from 0.54 to 0.83 and for dry season imagery from 0.38 to 0.79. These data indicate that for most ecosystems, wet season imagery is inherently

more valuable in differentiating increments of vegetation cover than dry season imagery. This is likely because the higher density of vegetation cover creates clearer differences between plant and soil reflectance values particularly for darkened (shadowed) vegetation cover (Ringrose et al., 1989). The reflectance curves from dry season imagery are relatively unpredictable with the reflectance values possibly influenced by relatively high (and variable) proportions of dormant tree/shrub cover and senesced grass in addition to laterally extensive shadows.

Seasonal differences in natural vegetation growth relative to soil background reflectance, control which wavebands are used optimally. As a result of SSI analysis, TM3 and TM5 (0.63-0.6 μm and 1.55-1.75 μm) were proven to be equally useful, irrespective of seasonal variability. The data from TM4 (0.76-0.90 μm) were particularly valuable in the dry season. This demonstrates the NIR vegetative darkening effect or the infrared paradox, (Ringrose et al., 1989, Otterman, 1996). Data from TM7 (2.08-2.35 μm) contain most useful information for range assessment in the wet season, a factor that may be related to soil/vegetation moisture retention (Elvidge and Portigal, 1990).

Hence for classification purposes, TM3 (SSI 0.66), TM5 (SSI 0.7) and TM7 (SSI 0.83) were chosen as the most suitable input bands for wet season rangeland evaluation. TM3 (SSI 0.71), TM4 (SSI 0.7) and TM5 (SSI 0.79) were chosen for dry season evaluation. Each sub-scene was classified separately to obtain the maximum variability in terms of cover density and hence range condition. A total of sixteen classes, identifying mainly differing densities of vegetation cover were found to be spectrally distinct for the hardveld ecosystems whereas fewer classes were isolated for the sandveld. Whereas every attempt was made to ensure comparability of the results, slightly different classes eventuated for wet season and dry season conditions reflecting the seasonally varying nature of the vegetation cover. Classification accuracy for the wet season ranged from 73% to 89% for the hardveld and 69% to 90% for the sandveld. Dry season accuracies ranged from 64 to 75% for the hardveld and 64 to 85% for the sandveld.

To determine the extent to which the classification method could adequately define classes useful in terms of range assessment, a range categorization system was applied to depict areas of high, medium and low range quality. While results in the medium and low categories for the hardveld were consistent with field data, problems arose as areas of dense vegetation cover and bush encroachment for the dry season data were exaggerated, particularly in the plains ecosystem. In the sandveld data set the same exaggeration of the amount of both high density (higher quality) range cover found in the hardveld data was not apparent. Hence the direct effects of darkening (shadow) noticeable on hardveld imagery appear relatively ineffective when sandveld areas are classified. This may be a function of tree/shrub structure, generally much taller, shady trees are found in the hardveld than the sandveld. Hence whereas it may be possible to analyze sandy open savanna ecosystems and obtain basic data for stocking rates from the interseasonal variability of wet season and dry season data, data from rocky or loamy tree savanna ecosystems tend to be less conclusive. In these latter areas, the extent of dense darkened vegetation and bush encroached vegetation cover are overstated especially in the dry season which is when stocking rates would need to be calculated.

Overall, these results reinforce the significance of satellite remote sensing for providing a more synoptic view of various rural land use pressures associated with management practices. Such findings provide spatial information in support of the Botswana government's national natural resource conservation efforts.

ACKNOWLEDGMENTS

The authors wish to acknowledge the support of the United States Agency for International Development (USAID) personnel in Washington, DC (Mr. David Rakes and Dr. Kenneth LuePhang) and the Botswana Mission (Mr. Robert McColaugh and Mr. Paul Bartel). Acknowledgment is also extended to the Government of Botswana personnel who have provided support for our efforts during the life of this project. These collaborators are too numerous to name individually; we trust that all who assisted us will accept this broad acknowledgment as our sincere appreciation of all of your support. The authors are also appreciative for the support provided by the University of Botswana, Department of Environmental Science personnel (Professor Silitshena, Department Head) and Mr. Thomas Matthew, Assistant Bursar of the University. Acknowledgment is also extended to the staff of the Alabama Center for Applications of Remote Sensing (ACARS) Laboratory, the Center for Hydrology, Soil Climatology, and Remote Sensing (HSCaRS) and the Geography Department at Kansas State University for their assistance in data analyses. A special thank you is extended to Ms. Joyce Mapanyane of the Ministry of Local Government and Lands for the front cover drawing of the Country of Botswana.

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APPENDIX A

CORRELATION OF SOIL ATTRIBUTES WITH SPECTRALLY-DERIVED LAND USE CLASSES

CORRELATION OF SOIL ATTRIBUTES WITH SPECTRALLY-DERIVED LAND USE CLASSES

by

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ABSTRACT

The primary objective of this study was to investigate relationships among soil spectral properties and selected soil physical properties used in differentiating soil mapping units and land use classes in south central Botswana, Africa. Thirty-four sites were selected along multiple transects which dissect Botswana's Southern District. This resulted in one hundred and two samplings units. The surface soil parameters investigated were structure, color, texture, degree of erosion, crusting, and compaction. Additionally, grazing intensity, vegetation percentage, and the normalized difference vegetation index (NDVI) were used in the analyses. Spectral data were extracted from six three-band Landsat Thematic Mapper (TM) quarter scenes (TM bands 2, 3, and 4) recorded June 23, July 7, and August 1, 1994. Land use classes of each quarter scene were determined using an unsupervised classification routine of the Earth Resource Analysis System (ERDAS) Imagine Software and verified using ground reference data.

Significant correlations were found among the spectral data, surface soil physical properties and surface soil conditions investigated in this study; however, the amount of variability explained was low. Seven of the soil mapping units and two land use classes were accurately differentiated at levels of 100%. The communal grazing land use class was the only class differentiated at a level less than 66%. The

overall classification accuracy for differentiating the soil mapping units and land use classes was 88.2% and 67.6%, respectively. Prediction equations for estimating surface soil conditions such as compaction, crusting, and grazing intensity were successfully generated from the spectral data and surface soil physical properties. The equations for surface soil compaction and grazing intensity accounted for 36.7% and 76.9% respectively, of the variability in the data. Significant relationships were also found among NDVI, vegetation percentage, and the surface soil properties investigated. The relationship for estimating NDVI was strongly influenced by the TM spectral bands, surface soil color, erosion, and texture. The predicition equation accounted for 81.2% of the variability in the data.

List of Keywords: Soil properties, variability, spectral, spectra, radiance, land cover

INTRODUCTION

Current as well as historic information on land use activity in Botswana is critical for resource managers to effectively manage the country's natural resources. Land use planning plays a key role in the decision-making process at all levels of government. According to Hunter (1988) it provides a logical framework for the development and coordination of extension services throughout the country. It rationalizes the provisions of infrastructure and social services and the structuring of areas under rural development programs. It provides a framework of collecting and assessing resource data and should help to reconcile institutional boundaries.

Studies have shown that remotely-sensed data from satellites can be used to generate land cover maps on a regional scale (e.g. Hill and Megier, 1988; Shimoda et al., 1988; Coleman et al., 1992). Satellite remotely-sensed data as a source for generating land use maps offers a unique advantage over the more traditional aerial photographic means of generating land use maps. Satellites afford land use managers an opportunity to utilize computer image processing techniques and repetitive coverage of an area to assess temporal changes in a quantitative manner. However, there are also inherent problems associated with the use of computers to generate land use classes from satellite imagery. These problems are associated with pixels that have two or more land cover classes within their boundaries. In an attempt

to alleviate these problems Lucas et al. (1990) integrated topographic data from a geographic information system (GIS) to improve the classification accuracy of an object classification. They defined an object as an area where only one land cover type was expected. The results of the per pixel classification were used per object to determine the land cover type of that object. The object classification improved the overall accuracy of two agricultural regions by 12 and 20 percent. Gong and Howarth (1990) used a structural information band to increase the classification accuracy by 10.5 percent compared to a conventional maximum-likelihood classification. Cushnie (1987) used a pre-classification filtering method and median, mean and other low-pass filters to improve his classification accuracy by almost 20 percent. Others have used techniques of integrating satellite image data with cartographic data to improve classification accuracies (e.g. Goldberg et al., 1985; Goodenough et al., 1987; Jensen et al., 1984; Hodgson et al., 1987; Gugan, 1988; Zhou, 1989; Walsh et al., 1990; Ross et al., 1991). Still others have used two-and three-dimensional modeling techniques to assist in defining spectral classes (Berry, 1987; Burrough et al., 1988; Coleman, 1992).

Traditional means of using aerial photointerpretative techniques to produce land use maps have been very successful. However, the success of these efforts are dependent upon the quality of prints available for the study. A land use map of Botswana's Southern District was successfully prepared at a scale of 1:250,000 using

photographs collected in 1982 by Environmental Consultants of Gaborone, Botswana [Southern District Planning Study, 1988. N. H. Hunter (ed)]. The major land use classes identified were communal mixed farming, communal grazing, commercial grazing, wildlife management zones, residential, and industrial.

Soil mapping in Botswana is based on main units of parent material groupings which show a strong relationship with both soils and landscape (Remmelzwaal, 1988). The main system of classification used is the 1974 Food and Agriculture Organization (FAO) Legend of the Soil Map of the World (FAO/UNESCO, 1974) which is correlated with Soil Taxonomy (Soil Survey Staff, 1994) and the Revised Legend of the Soil Map of the World (FAO, 1988).

Several studies have shown that satellite spectral reflectance data can be effectively used to differentiate soils and soil properties in North America (e.g. Cipra et al., 1980; Latz et al., 1984; Coleman and Montgomery, 1987; Henderson et al., 1989; Agbu et al., 1990; Coleman et al., 1993) and Southern Africa (Ringrose et al., 1988; 1989). Multispectral satellite data have been effectively used for mapping vegetative landscapes of temperate regions (e.g. Horvath et al., 1984; Thompson et al., 1984; Lee et al., 1988; Coleman et al., 1990; Coleman et al., 1992) and the semi-arid regions of Africa and Australia (e.g. Ringrose and Matheson, 1991a; 1992; Matheson and Ringrose, 1994a; 1994b; Ringrose, et al., 1994; Nellis et al., 1995). Significant correlations among surface soil attributes, such as texture, color, moisture, and

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organic matter content, and multispectral reflectance data have been found for both temperate, semi-arid, and the African Sahel regions (e.g. Ringrose and Matheson, 1987; 1991b; Coleman et al., 1993; Coleman and Tadesse, 1995).

The objectives of this study were to (i) determine if soil mapping units and land use classes of Botswana's Southern District can be differentiated using Landsat Thematic Mapper (TM) spectral data and (ii) identify the spectral band combinations and soil properties that could be used to estimate soil compaction, crusting, and grazing intensity in the area.

MATERIALS AND METHODS

Thirty-four sites were selected throughout Botswana's Southern District which provided a broad representation of its diverse land cover (Figure 1). Generally the sites were sampled along transects through various portions of the District at systematic intervals of 10 to 20 km. However, exact locations of cover change and transitions were noted. Each sampling site represented an area of 900 m^2 and was identified using a global positioning system (GPS) as well as other reference points such as road intersections in the District. In addition, odometer readings and directional headings were noted for each site. Other observation sites from key location points, e.g., villages, mine areas, boreholes, and cattle posts were also documented. At each site, the

number and height of trees, brushes/shrubs, and grasses were recorded. Grass density and stem clusters were sampled at the mid-point of each cell-side and at the center of each 30 x 30 m cell using a 50 cm quadrant frame. This was done in order to determine vegetation percentages and densities within the area. The major land use within the area was also recorded. Additionally, the grazing intensity within and around each site was determined and recorded as slight, moderate, severe, and very severe and coded as 1, 2, 3, and 4 respectively for use in the statistical analyses. The assignment of a grazing intensity category at each site was determined based on the amount of visible bare soil, evidence of soil erosion, indications of animal impact through trampling, and grass densities and heights.

Within each sampling cell a 50 cm quadrant frame was randomly dropped at three locations, and the soil structure, texture, color, evidence of erosion, crusting, and compaction were evaluated using local qualitative field techniques and legends used by the Soil Mapping and Advisory Service (Remmelzwaal, 1988; Husken, 1988). In order to use these data in a statistical evaluation for generating prediction equations they were assigned numerical values. Soil structure was recorded as loose/single grain, granular, subangular blocky, or stoney and given a value of 1, 2, 3, or 4, respectively. Soil texture was recorded as sandy/coarse, medium, or clayey/heavy and given a numerical value of 1, 2 or 3, respectively. Sandy/coarse texture corresponded to sand, fine sand, loamy sand and light sandy loam.

Medium soil texture corresponded to heavy sandy loam, loam, clay loam, and silt loam. Clayey/heavy soils texture corresponded to sandy clay loam, sandy clay, and clay. Soil color was recorded as light, medium, and dark and coded as 1, 2, and 3, respectively. Light soil colors corresponded to the Munsel color codes of 2.5YR 3/2, 10YR 5/3 and 2.5Y 3/2. Medium colors corresponded to codes such as 10YR 5/6, 7.5YR 5/6, and 2.5YR 5/8. Dark soil colors corresponded to Munsel codes of 7.5 YR 4/6, 5YR 5/8 and 2.5YR 3/6 or darker.

Soil erosion was characterized as slight, moderate, and severe according to the presence of rills and gullies and the visible reduction in soil material from underneath shrubs and low growing trees to areas not covered by vegetation. An area with a slight rating was given a value of 1, moderate a value of 2, and severe a value of 3. Soil compaction was characterized as none/slight, moderate, and severe and was coded as 1, 2, and 3, respectively. Compaction was determined based on the number of animal hoof prints present and crusting of the surface soil. No quantitative laboratory measurements were used to determine the actual degree of compaction or any of the other associated variables. Soil crusting was defined by the degree of cohesiveness of the surface soil particles. Soil crusting was recorded as none/slight, moderate, and severe and coded as 1, 2, and 3, respectively for use in the analyses. The soil mapping unit which corresponded with each sampling site was also recorded from the 1:250,000 soils map of the District (Figure 2).

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Landsat Thematic Mapper (TM) data of the District were obtained from the Satellite Applications Centre, Pretoria, South Africa. Six TM quarter scenes were required to cover the District. Three of the scenes were recorded on June 23, 1994, two on July 7, 1994 and one on August 1, 1994. Based on previous work carried out by Dr. Ringrose and Dr. Nkambwe in the area, only TM bands 2, 3, and 4 were purchased and used in the analyses. The areas that corresponded to the field sites were identified from the GPS coordinates that were recorded for each site. The digital numbers (DN) of each of the sampling areas were extracted using the Earth Resource Data Analysis System (ERDAS) Imagine software housed on a Sun SPARC10 computer (ERDAS, 1995). The actual DN values of the georeferenced TM data were used in the analyses. The DN values were used because a previous study conducted by the senior author revealed that there were no advantages gained from converting the DN values to intensity of reflectance values (Coleman et al., 1993).

Descriptive statistics were computed by the elementary statistics procedures in the Statistical Analysis System (SAS) computer software (SAS Institute, 1994). The DISCRIM procedure in SAS was used to develop discriminant functions to classify each observation into one of the soil mapping units and land use classes. These functions were also employed to compare the ability of the TM spectral data and selected surface soil physical properties in differentiating among soil mapping units and land use classes of the District. In the DISCRIM procedure,

distance functions between the observation and the centroid of each population were calculated, and each observation was placed in the class from which it had the smallest generalized squared distance, assuming that each class has a multivariate normal distribution. The classification criterion was based on either the individual within-group covariance matrix or the pooled covariance matrix, taking into account the prior probabilities of the groups. The Chi-Square test was used to determine the covariance matrices that was used in the discriminant functions. Stepwise regression procedures were used to develop the models (linear equations) to predict surface soil conditions using spectral data and selected soil surface properties.

RESULTS AND DISCUSSION

Discriminant Classification of Soils and Land Use

The soil taxonomic and land use classifications of each of the sampling sites are given in Table 1. There were six soil mapping units identified using the FAO soil classification system which translated to eleven mapping units using Soil Taxonomy (Soil Survey Staff, 1994). Four land use classes were included in the thirty-four sampling sites. The association of the variables was measured by generating a coefficient of correlation matrix, which showed highly significant correlations among the TM spectral data and surface soil physical properties observed (Table 2). The homogeneity test of the within-group covariance matrices for differentiating the soil mapping units

was found to be not significant at the 0.100 probability level; therefore, the pooled covariance matrix was used in the discriminant function. The within-covariance matrices were used in the discriminant functions generated from the variables used to differentiate the land use classes because the Chi-square value of 1669.5 was significant at the 0.0001 probability level. The soil mapping units and land use classes used in this study were differentiated at a high level of accuracy using the discriminant functions generated from the covariant matrices (Table 3). Seven of the soil mapping units and two of the land use classes were accurately differentiated (100%). The communal grazing land use class was the only class that was differentiated at an accuracy of less than 66 percent (Table 3). The commission error, which is a measure of the incorrect assignment of an observation, was fairly high which may imply that the variables used in the discriminant functions did not account for enough of the variability in differentiating the classes or that the classes were too similar in their spectral reflectance and surface soil physical properties. The overall classification accuracy in differentiating among the soil mapping units and land use classes was 88.2% and 67.6%, respectively. These results indicate that the TM DN values and surface soil physical properties can be effectively used to differentiate soil mapping units and major land use classes in Botswana's Southern District.

The results of the multivariate analysis used in differentiating among the soil mapping units and land use classes are given in Table 4.

The variables which accounted for most of the variability in differentiating both the soil mapping units and land use classes were soil structure, erosion intensity, grazing intensity, soil color and texture. Soil compaction and TM bands 4 and 2 were also key variables in differentiating the soil mapping units. However, the amount of variability that these variables accounted for in differentiating the soil mapping units and land use classes was quite low according to the average squared canonical correlation (ASCC) values of 0.3570 and 0.3811, respectively. The ASCC values, however, were significant at the 0.0001 probability level. Wilks Lambda which is a measure of how well the groups are separated was also significant at the .0001 probability level.

The importance of being able to differentiate among surface soil types and land use classes using remotely sensed data is in its ability to evaluate large areas not easily accessible under normal conditions. Botswana is a large country that is sparsely populated with approximately two-thirds of its population living in the eastern third of the country. Because of this, one could encounter areas within the country that are somewhat desolate of people and facilities. Such is the case for parts of the Kalahari Desert and the western portion of this study area. Even though the spectral sensors can only penetrate the upper surface of the soil, they do provide valuable information about the surface conditions which can be useful in mapping and monitoring desolate areas.

Prediction of Surface Soil Conditions

Estimation of surface soil conditions from TM spectral data and soil physical properties for use in soil and land use mapping is an important potential application of remote sensing in Botswana and other countries. Table 5 shows the results of a stepwise regression analysis for selection of the best combination of variables for predicting selected surface soil conditions. Five to six variables were required to generate an equation that would adequately predict the surface soil condition of interest. By computing all of the possible linear regression equations and considering the amount of variability explained and the bias of the resulting equation, the best subset of variables was selected (Table 6).

Soil compaction was best described using TM bands 2 and 4, soil structure, texture, and erosion intensity. The resulting equation explained 36.7% of the variability with a coefficient of variability (C.V.) of 21.37%. Soil crusting was best described using TM bands 2, 3, and 4, soil texture and erosion intensity. However, the equation only accounted for 19.9% of the variability. This suggests that there are probably other variables not used in this study that would better describe soil crusting. The equation was significant, however, at the .01 probability level and unbiased according to the Cp value of 4.28. An unbiased equation (based on the data entered) is indicated by a Cp value that is equal to or less than the number of terms in the resulting regression equation (Mallows, 1973).

Grazing intensity was best described using TM bands 4 and 3, soil structure, erosion intensity, and vegetation percentage. The resulting equation accounted for 76.9% of the variability with a C.V. of 16.62% and Cp value of 3.92. Vegetation percentage was best described using TM bands 3 and 4, soil structure, texture, and erosion intensity. The resulting equation accounted for only 24.7% of the variability and had a high C.V. value of 93.89%. The normalized distance vegetation index (NDVI) was best described using TM bands 2, 3, and 4, soil color, texture, and erosion intensity. The resulting regression equation accounted for 81.2% of the variability with a C.V. value of 13.29%.

These results confirm that the prediction of surface soil conditions such as compaction, crusting, and grazing intensity, using selected TM spectral bands and surface soil physical properties is possible based on the significant R^2 values and low C.V. values that resulted from the data set (Table 6). The results given in Tables 5 and 6 show the contribution of each of the variables that form the relationships. The contribution of TM3 and TM4 in explaining variability in the NDVI relationship was expected; however, the significant contribution of color, texture, and erosion was not. The NDVI index is supposed to be a predictor of biomass or green vegetative cover; however, in this study the percent vegetation cover variable did not significantly contribute to the NDVI relationship. Further, the variables that contributed the most to the relationship for predicting the precentage of vegetation cover were soil structure,

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texture, and erosion. The spectral bands, TM3 and TM4, made only minor contributions to predicting vegetation cover. These results concur with other studies conducted in the semi-arid areas of Botswana, the Sahel, and Australia, which reported that NDVI was a poor indicator of vegetation cover (Ringrose and Matheson, 1991a; 1992; Matheson and Ringrose, 1994a; 1994b; Ringrose et al., 1994). These equations are geographically dependent and may not be applicable to other areas. However, equations such as these can be quickly generated for other areas if the TM data is available and the soils' physical properties are known. The prediction of surface soil conditions, such as the ones discussed in this paper, can have an enormous impact on the management practices used to control the wildlife population and grazing of domestic cattle in Botswana's Southern District as well as other parts of the country. The overgrazing problems in Botswana are well documented in many internal publications. It is our hope that the results of this study will be used to help initiate a monitoring program to better manage the country's natural resources.

SUMMARY AND CONCLUSIONS

Discriminant classification of soil mapping units and land use classes based on selected TM spectral bands and surface soil physical properties is possible according to the results presented. Although the amount of variability that the variables accounted for in the analyses was low, the resulting discriminant functions and equations presented were found to be significant based on all the statistical tests used. Highly significant relationships among the spectral data, soil physical properties and surface soil conditions were obtained. Soil mapping units were differentiated at an overall accuracy of 88.6% while the land use classes were differentiated at an accuracy of 66.7%. Prediction of surface soil conditions such as compaction and grazing intensity, and NDVI from the spectral data and surface soil physical properties was highly significant as shown by the high R^2 values. Soil compaction was best described using TM bands 2 and 4, soil structure, texture, and erosion intensity. Grazing intensity was best described using TM bands 3 and 4, soil structure, erosion intensity and vegetation percentage. NDVI was best described using TM bands 2, 3 and 4, soil color, texture, and erosion intensity. Further study of the coding technique used to convert the soil physical properties into numerical values for use in the analysis is encouraged as well as the investigation of other soil variables to better define and describe the relationships presented.

ACKNOWLEDGMENTS

The authors wish to acknowledge the support of the United States Agency for International Development (USAID) personnel in Washington, DC (Mr. David Rakes) and the Botswana Mission (Mr. Robert McColaugh and Mr. Paul Bartel). Acknowledgment is also extended to the Government of Botswana personnel who have provided support for our efforts during the life of this project. These collaborators are too numerous to name individually; we trust that all who assisted us will accept this broad acknowledgment as our sincere appreciation of all of your support. The authors are also appreciative for the support provided by the University of Botswana, Department of Environmental Science personnel (Professor Silitshena, Department Head) and Mr. Thomas Matthew, Assistant Bursar of the University. Acknowledgment is also extended to the staff of the Alabama Center for Applications of Remote Sensing (ACARS) Laboratory and the Geography Department at Kansas State University for their assistance in data analyses.

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LIST OF FIGURES

Figure 1. Land use map of Botswana's Southern District showing location of sampling sites. [Reproduced from original map prepared by Environmental Consultants, P.O. Box 10072, Gaborone, Botswana. *In* Southern District Planning Study (1988), N. D. Hunter (ed.)].

Figure 2. Soil mapping units of Botswana's Southern District.

Figure 1.
Landuse Map of Botswana's Southern District Showing Location of Sampling Sites

[Reproduced from original map prepared by Environmental Consultants, P.O. Box 10072, Gaborone, Botswana. In Southern District Planning Study (1988), N.D. Hunter (ed.)]

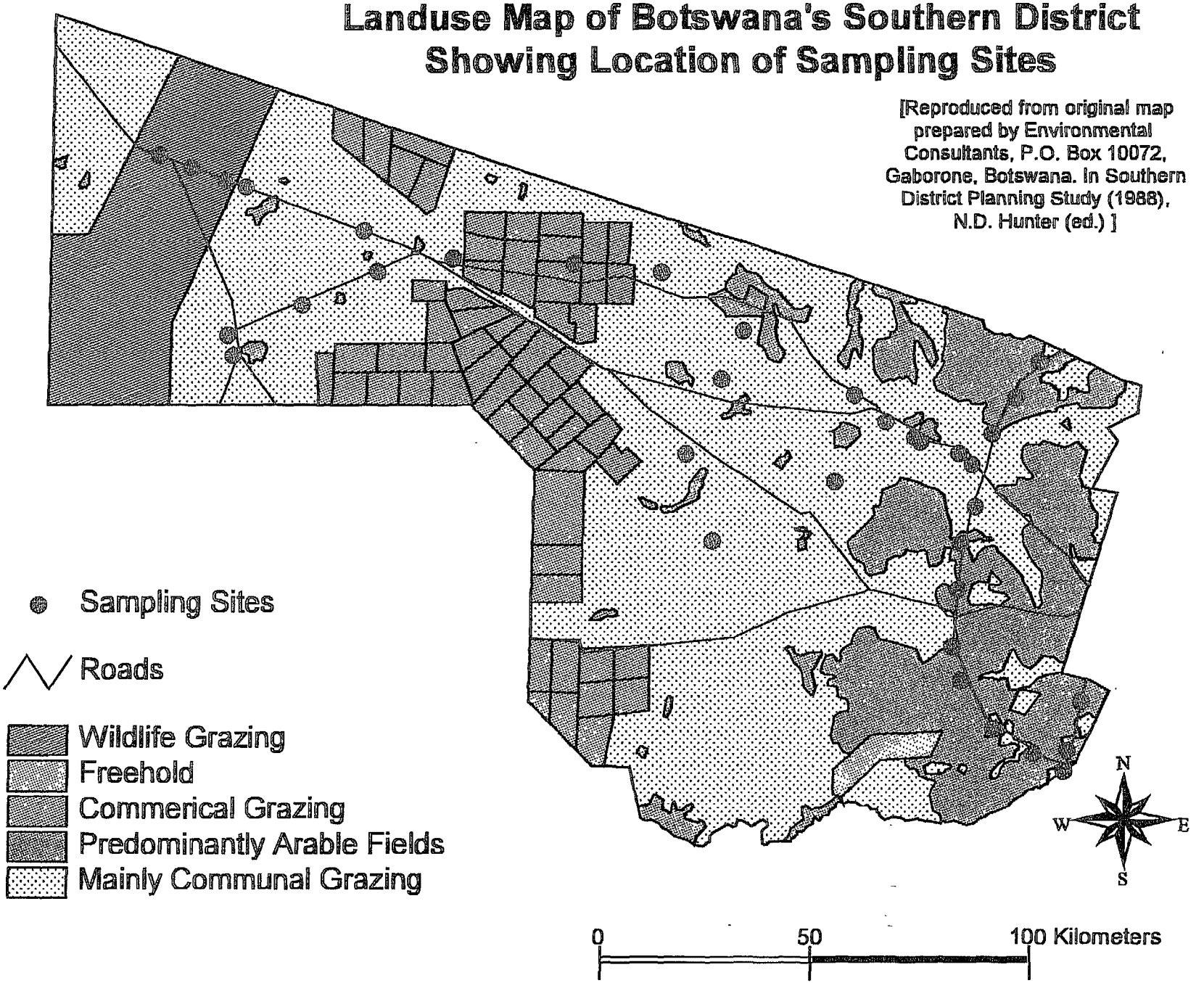

Figure 2. Soil Mapping Units of Botswana's Southern District

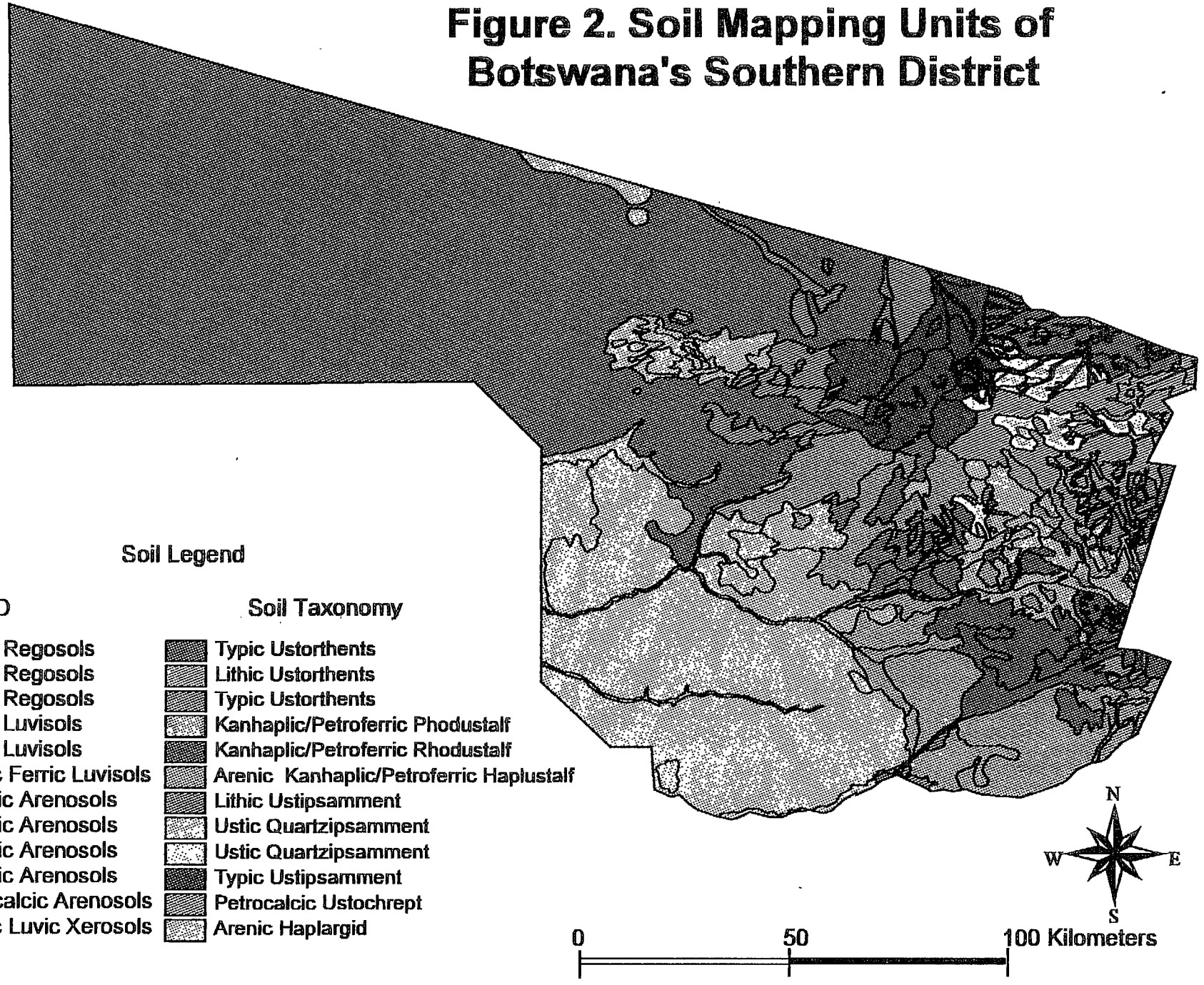

Table 1. Soil taxonomic classifications and land use classification of the sampling sites.

No. of Sites	Soil Symbol†	Taxonomic Classification: FAO††	Taxonomic Classification: Soil Taxonomy	Land Use Classification§
9	R	Eutric Regosols	Typic Ustorthents	Communal Grazing
3	R	Eutric Regosols	Typic Ustorthents	Communal Grazing/Mixed Farming
3	R	Eutric Regosols	Typic Ustorthents	Wildlife Management Zone
3	Gba	Ferric Luvisols	Kanhaplic/Petroferric Rhodustalfs	Communal Grazing
2	S1	Ferralic Arenosols	Lithic Ustipsamments	Communal Grazing
2	S5	Ferralic Arenosols	Ustic Quartzipsamments	Communal Grazing
1	S3	Ferralic Arenosol	Ustic Quartzipsamment	Communal Grazing
1	R	Eutric Regosol	Typic Ustorthent	Private/Commercial Grazing
1	KSi2a	Arenic Luvic Xerosol	Arenic Haplargid	Communal Grazing
1	G6a	Ferric Luvisol	Kanhaplic/Petroferric Rhodustalf	Communal Grazing/Mixed Farming
1	G6	Arenic Ferric Luvisol	Kanhaplic/Petroferric Haplustalf	Private/Commercial Grazing
1	G6	Arenic Ferric Luvisol	Arenic Kanhaplic/Petroferric Haplustalf	Communal Grazing/Mixed Farming
1	G4	Ferralic Arenosol	Typic Ustipsamment	Private/Commercial Grazing
1	G4	Ferralic Arenosol	Typic Ustipsamment	Communal Grazing
1	G106	Ferric Luvisols	Kanhaplic/Petroferric Rhodustalf	Communal Grazing
1	Glc	Eutric Regosol	Typic Ustorthent	Communal Grazing
1	Gla	Eutric Regosol	Lithic Ustorthent	Private/Commercial Grazing
1	C3	Petrocalcic Arenosol	Petrocalcic Ustochrept	Communal Grazing/Mixed Farming

† Soil symbols used to identify mapping units in Botswana's Soil Mapping Program.

†† FAO/UNESCO, 1974. Classifications obtained from "General Soil Legend of Botswana", A. Remmelzwaal, 1988 and "The Soils and Land Suitability for Arable Farming of the Jwaneng Area", J. Huesken, 1988.

§Classifications obtained from "Southern District Planning Study", Environmental Consultants, 1988.

Table 2. Correlation coefficients (r) of the variables considered for predicting soil parameters (n=102).

Variables †	TM2	TM3	TM4	SST	SCO	STX	SER	SCM	SCT	GI	VEG	NDVI
TM2		O.954**	0.935**	-0.174	-0.499**	-0.229*	-0.174	-0.423**	0.276**	0.132	-0.155	-0.198
TM3			0.969**	-0.358	-0.359**	-0.087	-0.124	-0.391**	0.343**	0.055	-0.078	-0.324**
TM4				-0.044	-0.407**	-0.096	-0.111	-0.348**	0.292**	0.074	-0.121	-0.124
SST					0.538**	0.555**	0.023	-0.211*	-0.027	-0.432**	0.411**	-0.206**
SCO						0.555**	0.015	0.122	-0.059	-0.323**	0.323**	-0.315**
STX							0.111	0.027	-0.086	-0.404**	0.388**	-0.154
SER								-0.078	-0.104	0.003	-0.075	0.149
SCM									0.164	0.131	-0.067	0.092
SCT										0.078	-0.104	-0.377**
GI											-0.868**	0.095
VEG												-0.175
NDVI												

*, ** Denotes significance at the .05 and .01 probability level, respectively.

† TM = Thematic Mapper Spectral bands, SST = Soil Structure, SCO = Soil Color, STX = Soil Texture, SER = Soil Erosion, SCM = Soil Compaction, SCT = Soil Crusting, GI = Grazing Intensity, VEG = Vegetation Percentage, NDVI = Normalized Difference Vegetation Index.

Table 3. Summary of discriminant analysis classification and accuracy assessment for soil mapping units and land use categories.

Soil Mapping Units and Symbols	Classification Results		
	% Total Correct	% Commission Error	% Omission Error
Eutric Regosols (R)	91.7	0	8.3
Eutric Regosols (Gla)	66.7	33.3	33.3
Eutric Regosols (Glc)	100	40.0	0
Ferric Luvisols (Gl10b)	100	25.0	0
Ferric Luvisols (Gba)	66.7	0	33.3
Arenic Ferric Luvisols (Gb)	100	14.3	0
Ferralic Arenosols (S1)	66.7	0	33.3
Ferralic Arenosols (S3)	100	33.3	0
Ferralic Arenosols (S5)	100	25.0	0
Ferralic Arenosols (G4)	100	25.0	0
Petrocalcic Arenosols (C3)	66.7	33.3	33.3
Arenic Luvic Xerosols (KSi2a)	100	25.0	0
% Overall Agreement	88.2		
Land Use Categories			
Communal Grazing	49.1	0	50.9
Communal Grazing/Mixed Farming	83.3	52.4	16.7
Private/Commercial Grazing	100	45.5	0
Wildlife Management Zone	100	10.0	0
% Overall Agreement	67.6		

Table 4. Multivariate statistics used in differentiating among soil mapping units and major land use classes in Botswana's Southern district.

STEP	Variable Entered	Number In	Partial R^2	F Statistics	Probability F	Wilks† Lambda	Probability Lambda	ASCC††	Probability ASCC
				Soil Mapping Units					
1	Structure	1	0.6219	13.459	0.0001	0.3780	0.0001	0.0565	0.0001
2	Erosion	2	0.6258	13.531	0.0001	0.1415	0.0001	0.1116	0.0001
3	Color	3	0.5451	9.587	0.0001	0.0643	0.0001	0.1594	0.0001
4	Texture	4	0.4284	5.927	0.0001	0.0368	0.0001	0.1961	0.0001
5	Grazing	5	0.4149	5.544	0.0001	0.0215	0.0001	0.2193	0.0001
6	TM4	6	0.3770	4.677	0.0001	0.0134	0.0001	0.2437	0.0001
7	Compaction	7	0.5798	10.537	0.0001	0.0056	0.0001	0.2726	0.0001
8	TM2	8	0.4482	6.128	0.0001	0.0031	0.0001	0.2984	0.0001
9	Vegetation	9	0.3025	3.233	0.0011	0.0022	0.0001	0.3208	0.0001
10	NDVI	10	0.2645	2.649	0.0060	0.0016	0.0001	0.3363	0.0001
11	Crusting	11	0.2094	1.926	0.0479	0.0013	0.0001	0.3485	0.0001
12	TM3	12	0.1785	1.560	0.1273	0.0010	0.0001	0.3570	0.0001
				Land Use Classes					
1	Structure	1	0.5115	34.200	0.0001	0.4885	0.0001	0.1705	0.0001
2	Crusting	2	0.2488	10.711	0.0001	0.3670	0.0001	0.2525	0.0001
3	Grazing	3	0.2050	8.250	0.0001	0.2918	0.0001	0.2970	0.0001
4	Texture	4	0.1478	5.491	0.0016	0.2486	0.0001	0.3370	0.0001
5	Color	5	0.1429	5.223	0.0022	0.2131	0.0001	0.3811	0.0001

† Wilks Lambda is close to zero if the groups are well separated.

†† ASCC is averaged squared canonical correlation. It is close to 1 if all groups are well separated.

Table 5. Summary of stepwise regression for determining the best combination of TM spectral bands and soil properties in predicting surface soil conditions.

Soil Condition	Step	Variables Entered	Number In	Model R^2	CP†	F	Probability F
Compaction	1	TM2	1	0.1790	24.18	21.79	0.0001
	2	Structure	2	0.2626	13.74	11.23	0.0011
	3	TM4	3	0.3242	6.57	8.94	0.0035
	4	Erosion	4	0.3635	2.73	5.98	0.0163
	5	Texture	5	0.3674	4.14	0.59	0.4434
Crusting	1	TM3	1	0.1174	5.94	13.30	0.0004
	2	TM2	2	0.1470	4.46	3.43	0.0669
	3	Texture	3	0.1730	3.39	3.08	0.0821
	4	TM4	4	0.1922	3.13	2.31	0.1320
	5	Erosion	5	0.1994	4.28	0.86	0.3553
Grazing Intensity	1	Vegetation	1	0.7531	2.44	304.99	0.0001
	2	Structure	2	0.7599	1.66	2.82	0.0962
	3	Erosion	3	0.7633	2.29	1.39	0.2413
	4	TM4	4	0.7647	3.70	0.60	0.4414
	5	TM3	5	0.7691	3.92	1.82	0.1811
Vegetation Percentage	1	Structure	1	0.1691	6.05	20.35	0.0001
	2	Texture	2	0.2061	3.41	4.62	0.0340
	3	Erosion	3	0.2179	3.94	1.47	0.2279
	4	TM4	4	0.2276	4.73	1.21	0.2731
	5	TM3	5	0.2473	4.25	2.52	0.1155
NDVI	1	TM3	1	0.1050	350.42	11.74	0.0009
	2	TM4	2	0.7020	53.29	198.37	0.0001
	3	Color	3	0.7761	18.18	32.42	0.0001
	4	TM2	4	0.7975	9.46	10.25	0.0018
	5	Erosion	5	0.8105	4.94	6.59	0.0118
	6	Texture	6	0.8121	6.16	0.78	0.3794

† The regression equation is unbiased when the 'Cp' value is equal to or less than the number of variables in the equation.

Table 6. Regression equations generated from TM spectral data and soil physical properties for predicting surface soil conditions.

Soil Condition	Regression Equation†	R^2	C.V.(%)††
Compaction	$Y = 2.39 - 0.08X_2 + 0.03X_3 + 0.18X_4 + 0.05X_5 - 0.25X_6$	0.367**	21.37
Crusting	$Y = 1.49 - 0.07X_1 + 0.07X_2 - 0.03X_3 - 0.14X_5 - 0.13X_6$	0.199**	28.48
Grazing Intensity	$Y = 4.55 + 0.03X_2 - 0.04X_3 - 0.12X_4 - 023X_6 - 0.03X_7$	0.769**	16.62
Vegetation	$Y = 34.06 + 1.68X_2 - 2.17X_3 + 9.83X_4 + 12.01X_5 - 10.80X_6$	0.247**	93.89
NDVI	$Y = 23.01 + 8.84X_1 - 25.62X_2 + 21.43X_3 + 5.84X_5 + 26.09X_6 - 20.84X_8$	0.812**	13.29

** Denotes significance at the .01 level

† X_1, X_2, X_3 = TM bands 2, 3 and 4; X_4 = Structure; X_5 = Texture; X_6 = Erosion

X_7 = Vegetation percentage; X_8 = Soil Color

†† Coefficient of variability

APPENDIX B

SPECTRAL AND SPATIAL DIMENSIONS OF RURAL LAND USE SYSTEMS IN THE SOUTHERN DISTRICT OF BOTSWANA

Spectral and Spatial Dimensions of Rural Land Use Systems in the Southern District of Botswana

by

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Abstract

Few countries depend more on natural vegetation resources to sustain the livelihood of a largely rural population than Botswana. The use of land for livestock grazing is crucial to the economic sustainability of this semi-arid/arid country. Range-fed beef is also important as an export item and thus a significant source of foreign exchange. The development of a National Conservation Strategy has provided a policy framework to address rural land use issues. The ability to monitor policy effectiveness is limited by the lack of timely resource information on the relationship between the land's carrying capacity and cattle stocking rates. This study uses Landsat thematic mapper (TM) digital data for the Southern District, Botswana to analyze variations of grazing intensity. Southern District represents an area of transition between the hardveld of eastern Botswana and the sandveld of the Kalahari. Thirty-four sites representing communal grazing, mixed farming, private-commercial grazing, and wildlife management were analyzed at ground level and georectified to Landsat TM grazing indices using global positioning system (GPS) precision readings. Pearson Correlation and multiple regression analysis of selected land cover variables in relation to the Landsat TM data found that land use degradation was best described using an NDGR index and TM band 4.

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Introduction

The Government of Botswana is concerned about environmental resource issues and the development of a National Conservation Strategy has provided a policy framework to address these issues. The ability to monitor policy effectiveness has been limited by a lack of timely information on accurate land-cover and natural resources for planning and monitoring land-use changes. Because of recent technical developments, data collection and analysis for planning and management purposes can readily be achieved with satellite remote sensing and geographic information technologies.

The agricultural share of the gross domestic product in Botswana has declined dramatically since independence; however, two out of three Batswana still live in rural areas and the agricultural sector remains important as a source of employment, income, and food. In addition, the cattle industry continues to be a major contributor to exports. The use and management of environmental resources is therefore of critical importance for most Batswana.

The pattern of a more or less balanced resource use has changed radically in this century. Rapid growth of human population has inexorably led to a significant increase in the use of environmental resources. Towns and villages have expanded rapidly in size creating demand for wood for heating and cooking. More land has been brought into agricultural production and poor quality soils have become progressively degraded. Increased livestock numbers have created a greater demand on grazing resources. The expansion

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of transportation networks and the ability to drill deep boreholes have made it possible to expand onto marginal grazing land. These human changes have created an unrelenting pressure on fragile environments and led to an altering of the character and content of ecosystems throughout much of Botswana.

This study in Southern District will provide baseline information on the relationship between the carrying capacity and cattle stocking rates. Related to rural land, in this study, Landsat thematic mapper (TM) digital data of Southern District, Botswana was used to analyze variations of grazing intensity (Figure 1).

Physiography

The Southern District has a harsh physical environment. In general terms the District is composed of two major physiographic units: the hardveld and the sandveld.

The hardveld is confined to the eastern third of the district where old, hard igneous and sedimentary rocks are exposed. The hardveld region is generally represented by the upland areas (greater than 1200 meters) of the District (Figure 2). For the most part the region is a gently rolling plain with numerous isolated hills and rock outcrops. The medium to fine textured soils of varying depth that have developed in this area are the most fertile and combined with an annual rainfall of 500-550 mm are adequate for cultivation. Most of the area, except for the rock outcrops and few hills, is woodland and shrub savanna with varieties of Acacia and Combretum as the dominant species. Land use is predominantly mixed farming with both livestock and arable agriculture present (Environmental Consultants, 1988).

The remaining two-thirds of the district is sandveld (in areas generally less than 1200 meters elevation). The terrain in the east is nearly flat to undulating but in the west is more undulating and hummocky. A few dry river valleys and numerous pans are also present. The Kalahari beds of the sandveld generally consist of fine grained sands that overlie variably consolidated sands, sandstones, clay, calcrete, and silcrete. Soils are typically of a medium to coarse texture and grey and brown in color. In pans fine textured clay soils are present and in some cases saline and alkaline soils are found. Rainfall decreases

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across the district to about 300 mm in the west. Almost all the rainfall, which is highly variable in time and space, occurs as localized showers and thunderstorms during the summer months from November to March. Drought, often lasting several years is a recurring hazard. This flat savanna is a mosaic of open green grassland with trees and shrubs. Most of which are Acacia species. For the most part the sandveld is not suitable for cultivation and is generally used for grazing of livestock and wildlife.

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Tenure and Rural Land Use

There is a close relationship between land use and land tenure. Land use describes the purpose to which land is put while land tenure is concerned with how land is or can be held.

In Botswana, land is held by three major tenure types - state land, freehold land, and communal or customary land (Southern District Council, 1989). As the term implies, state land is held by the government and can be used in any way the government decides including the conversion to other forms of tenure. Nationally, about 25% of all land fits into this category and is devoted primarily to national parks, game, and forest reserves. In Southern District only 1.2% of land is state controlled; however, it contains the Jwaneng Diamond area, perhaps the most valuable piece of real estate in all of Botswana (Figure 3).

Freehold land, the second type of tenure, involves exclusive ownership. Nationally, approximately 5% of the land area is in this category. In Southern District about 0.1% of land is of this type; consequently, it is of limited significance.

In communal tenure, the third type, the land was traditionally held by the chief on behalf of the people, and he allocated land to headmen who in turn allocated it to individual households. Each household had automatic rights to the land for their homestead, arable activity and grazing. Today communal land is administered by land boards. In Southern

District nearly all of the land is communal. This land can be subdivided into tribal territory, the wildlife management area, and the commercial leasehold areas.

Land use in the eastern hardveld of the Southern District is largely mixed farming, and the landscape is composed of a mixture of arable fields with more or less open grazing areas in between. Because traditional farming system relies heavily on cattle for draft power, the co-existence of arable land with open grazing is a logical system. Fields are small; most farmers still plant seed by broadcasting; capital investments are low; and implements are simple, the most common being the single plough. A variety of crops are grown. The main cereals are maize and sorghum, with beans and mellons being important secondary crops. In the Barolong Farms larger scale commercialized activity exists. Overall crop cultivation is characterized by low levels of inputs. Low and variable rainfall amounts together with poor quality soils make crop farming a risky venture.

The central part of the district, as well as the area to the west of the wildlife management area, is dominated by communal grazing. Scattered arable fields are found around some of the villages. The spread of grazing westward into the Kalaharai sandveld has been made possible by borehole drilling to provide water. Water availability has made the establishment of permanent cattle posts feasible. It is a long established principle in Botswana that water rights confer grazing rights in cattle post areas. Although boreholes should be situated at least eight kilometers apart to provide an adequate grazing area for livestock, in some cases they may be closer. Not surprisingly the impact of cattle on

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vegetation is greatest around these water points but decreases as one moves away from the water sources.

Commercial grazing under leasehold is found in some of the Tribal Grazing Land Policy blocks within the District. Because of variation in natural resource endowment, stocking rates and management practices, the kind and intensity of use is highly variable.

As was mentioned earlier, the Southern District represents an area of transition between the hardveld of eastern Botswana and the sandveld of the Kalahari. For this study, thirty-four sites, representing communal grazing, mixed farming, private-commercial grazing, and wildlife management zones were analyzed at ground level, land georectified to Landsat TM data sets using global positioning system (GPS) precision readings, then linked to grazing indices.

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Methodology

Field Analysis

In order to link ground level observations with Landsat TM (thematic mapper) satellite digital data, a variety of information related to land cover, field condition, and physical resource parameters was recorded at an extensive network of sites throughout Botswana's Southern District. Sites were sampled along transects bisecting the District's diverse physiography and land use management systems. Landcover and condition samples were recorded at 10 to 20 km intervals (depending on landscape diversity) along each of the transects. In addition, thirty-four detailed field sites, representing samples of major land use change, were selected; each of an area 900 m^2 (Figure 1). Both transect detailed sample site locations were noted using a global positioning system (GPS).

Also identified in the field analysis were locations of villages, mine areas, boreholes, and cattle posts along the transects. At each of the detailed field sites, the number and height of trees, brush/shrubs, and grasses were recorded. Grass density, height, and stem clusters were sampled at the mid-point of each grid cell side, and at the end of each 900m^2 cell using a 50cm quadrant frame. These measures of grass characteristics provided some index of grass density. In addition, major land use category (e.g. commercial grazing, wildlife management area, or mixed farming); grazing intensity (slight, moderate, severe, and very severe); and indications of soil erosion or compaction (associated with grazing activity) were noted.

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Satellite Image Analysis

Landsat TM digital data of the Southern District were obtained from the Satellite Applications Center, Pretoria, South Africa. Six TM quarter scenes were required to cover the District. Three of the scenes were recorded on June 23, 1994; two on July 7, 1994, and one on August 1, 1994. The dates were selected to closely correspond to dates of the ground level observations and to maximize the quality of cloud-free coverage over the region.

The general study area was clipped from each of the images to form six District subscenes. These were registered to ground topographic maps published in 1989 by the Botswana Department of Survey and Lands, Gaborone, Botswana, using ground control points and a second-order transformation which achieved a total RMS error of 0.33 pixels. The subscene was then transformed to a Universal Transverse Mercator (UTM) projection using a nearest neighbor resampling algorithm.

In order to test the research questions associated with this paper, an analysis was performed to see the degree of correlation between TM bands 2, 3, and 4, as well as vegetation indices based on a normalized difference vegetation index (NDVI), and a normalized difference green red index (NDGR) with rural land cover condition in a subset of the District. TM bands 2, 3, and 4 were preselected for analysis based on past research in Botswana by Ringrose et al. (1991) and Sefe et al. (1996). NDVI is based on a ratio transformation, where near infrared (NIR) minus Red is ratioed over NIR plus Red. In

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contrast NDGR is based on a ratio transformation where green minus red is ratioed over green plus red.

Through a PEARSON correlation analysis and development of a multiple regression model, we then were able to detail the relative significance of the TM bands and vegetation indices with land cover condition associated with resource management.

Discussion

Table 1 provides the results of the correlation analysis of the various satellite measures relative to the two best indicators of land cover condition (percent cover and grazing intensity). The R^2 value for percent cover and grazing intensity varied considerably based on the satellite digital index used. Shrub measurements in each sample area were not significantly linked to the satellite vegetation index values.

For percent cover, the NDGR (normalized difference green red index), provided the highest degree of association with the land cover conditions (0.875) (Figure 4). This contrasted significantly with the NDVI (normalized difference vegetation index), which was a poor indicator of percent cover. The results support the importance of a red and green reflectance combination in explaining cover conditions in this semi-arid to arid environment with considerable sandy soil background and marginal vegetation condition. This is especially highlighted during the dry season of June and July. Both single band TM3 and TM4 values were also good indicators of percent cover. The degree of variation between these two bands, though, was insignificant to create an indicator index when integrated into an NDVI. In contrast, the TM2 and TM3 associations were greater in variation as single band indicators. This variation was further highlighted when integrated into the NDGR index.

Grazing intensity, which is a function of a variety of landscape variables, including vegetation condition, soil compaction and animal density ratio with regard to land area,

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was more difficult to predict with the satellite data. Single TM band 4 data were most closely associated (R^2=0.620) with intensity followed by TM band 3. Of the combined indices, NDGR was a better predictor than NDVI. The TM band 4 infrared reflectance (0.76-0.90 micrometers) evidently explained the combination of grazing land indicators.

Multiple regression models were then generated for explaining percent cover and grazing intensity (Table 2). Percent cover as an indicator of land condition was a more successfully explanation (R^2=0.875) than was the grazing intensity model. Again, the complexity of the variables used to derive the grazing intensity classification resulted in less success in explaining the intensity category using the satellite digital data input.

Conclusions

One of the limiting factors in the rural land management of Botswana's resources is lack of accurate information on land condition that can be related back to different land management practices. These results offer some prospect for providing synoptic indices of percent cover and grazing intensity in the semi-arid and arid portions of Botswana's Southern District.

Percent cover was most successfully predicted using an NDGR index that was based on a significant variation between TM bands 3 and 2 as associated with this landscape parameter. In contrast, grazing intensity, which is based on a combination of land use conditions, was more difficult to predict. TM band 4, however, was most useful in explaining grazing intensity. The magnitude of TM band 4 ability to explain grazing intensity in this setting, however, was still marginal.

Percent cover over various rural land use systems was most successfully modeled using multiple regressive (including NDGR) relative to measured landscape parameters. In contrast, grazing intensity was modeled at a more modest correlation using TM band 4.

Overall, results reinforce the significance of satellite remote sensing for providing a more synoptic view of various rural land use pressures associated with management practices. Such findings provide spatial information in support of the Botswana government's national natural resource conservation efforts.

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Table 1. Correlation coefficient comparing percent vegetative cover and grazing intensity to Landsat TM bands and indices.

	R^2	
	Percent Cover	Grazing Intensity
TM2	0.450	0.345
TM3	0.704	0.524
TM4	0.716	0.620
NDVI	0.119	0.356
NDGR	0.875	0.523

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Table 2. Multiple regression models for percent cover and grazing intensity.

Percent Cover = 62.735 - 0.34 * NDGR $R^2 = 0.875$
Grazing Intensity = 9.900 - 0.014 * NDVI - 0.117 * TM4 $R^2 = 0.771$

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ACKNOWLEDGMENTS

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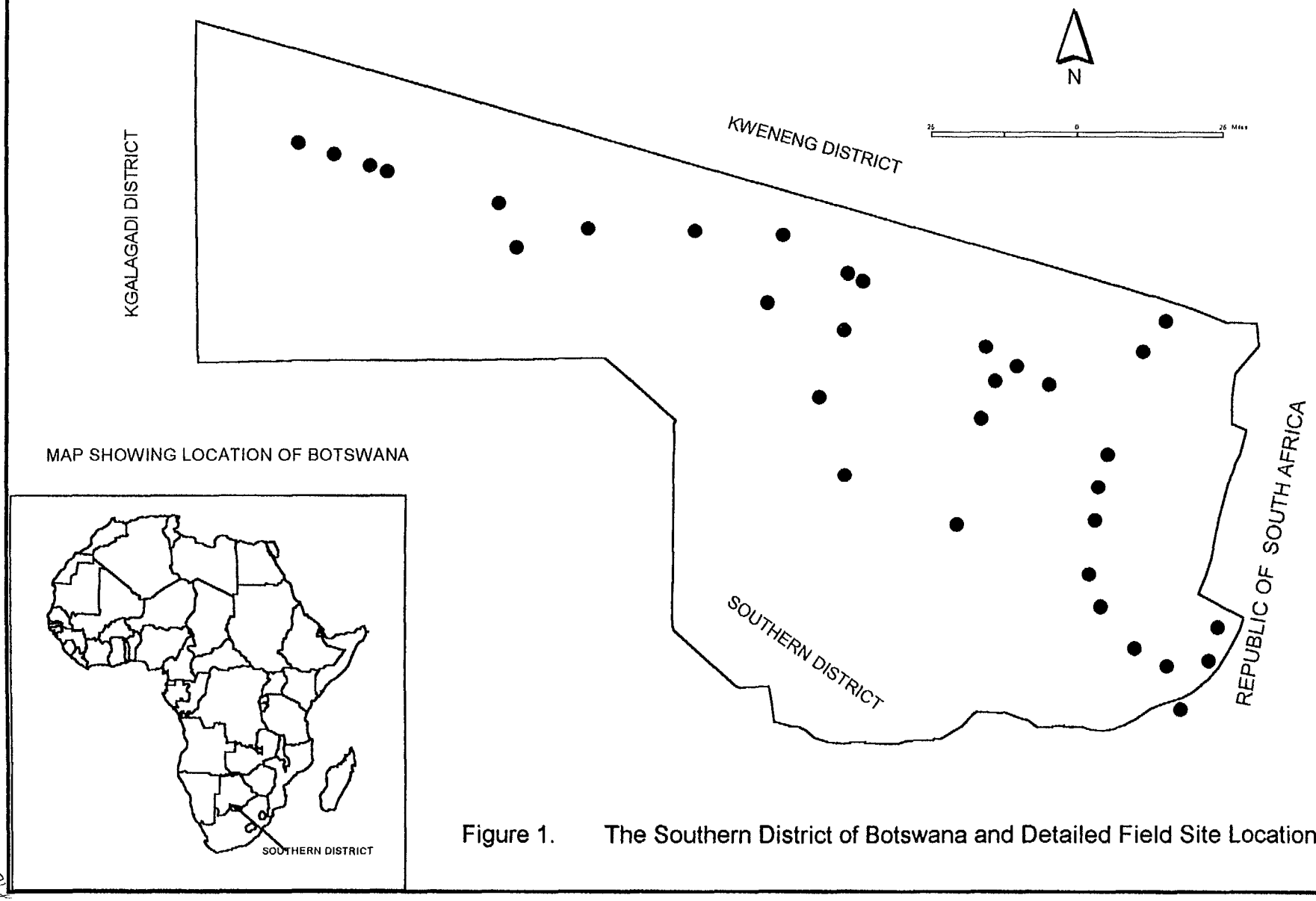
SOUTHERN DISTRICT OF BOTSWANA FIELD SITES



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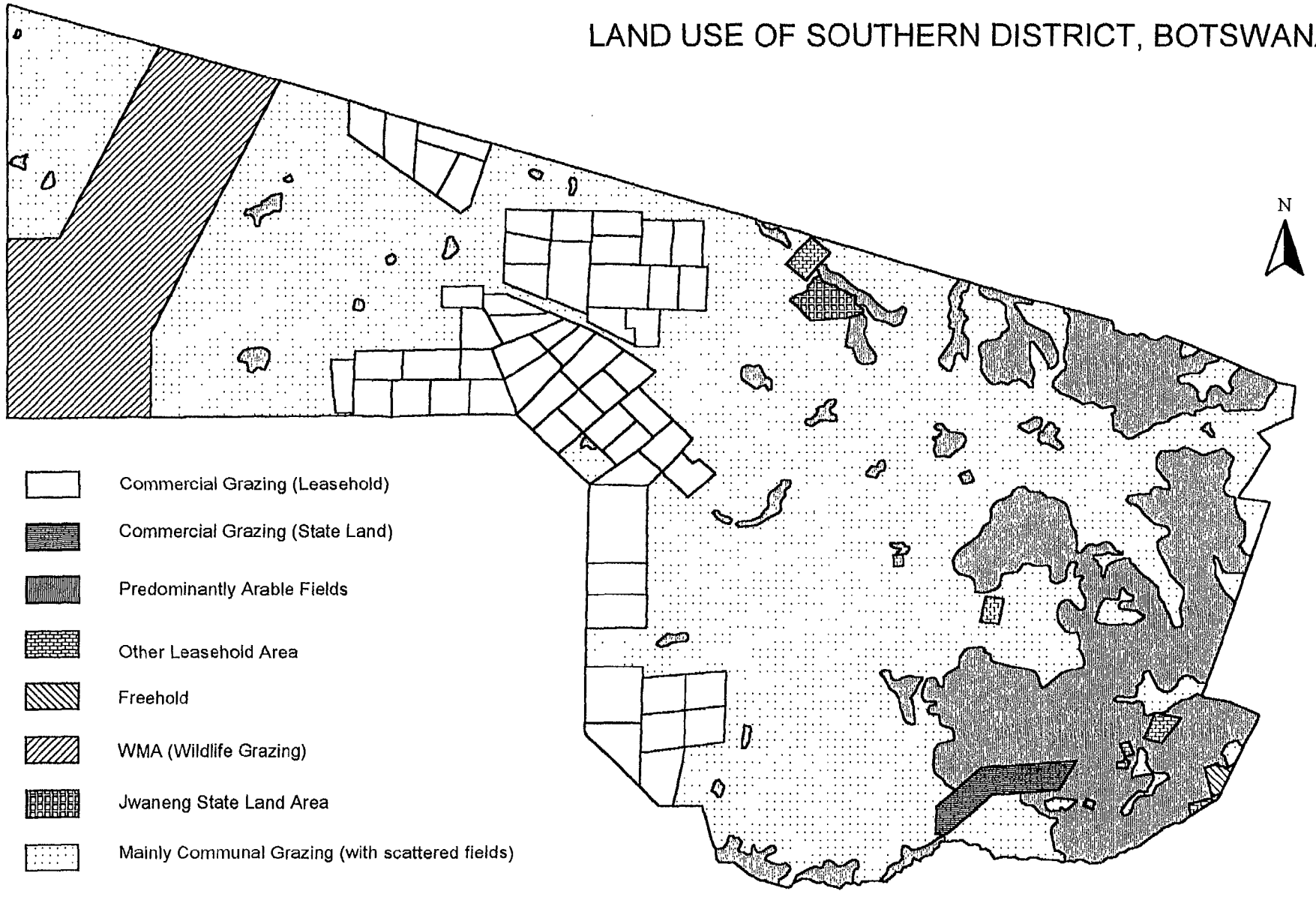

Source: Southern District Land Use Plan(1986)

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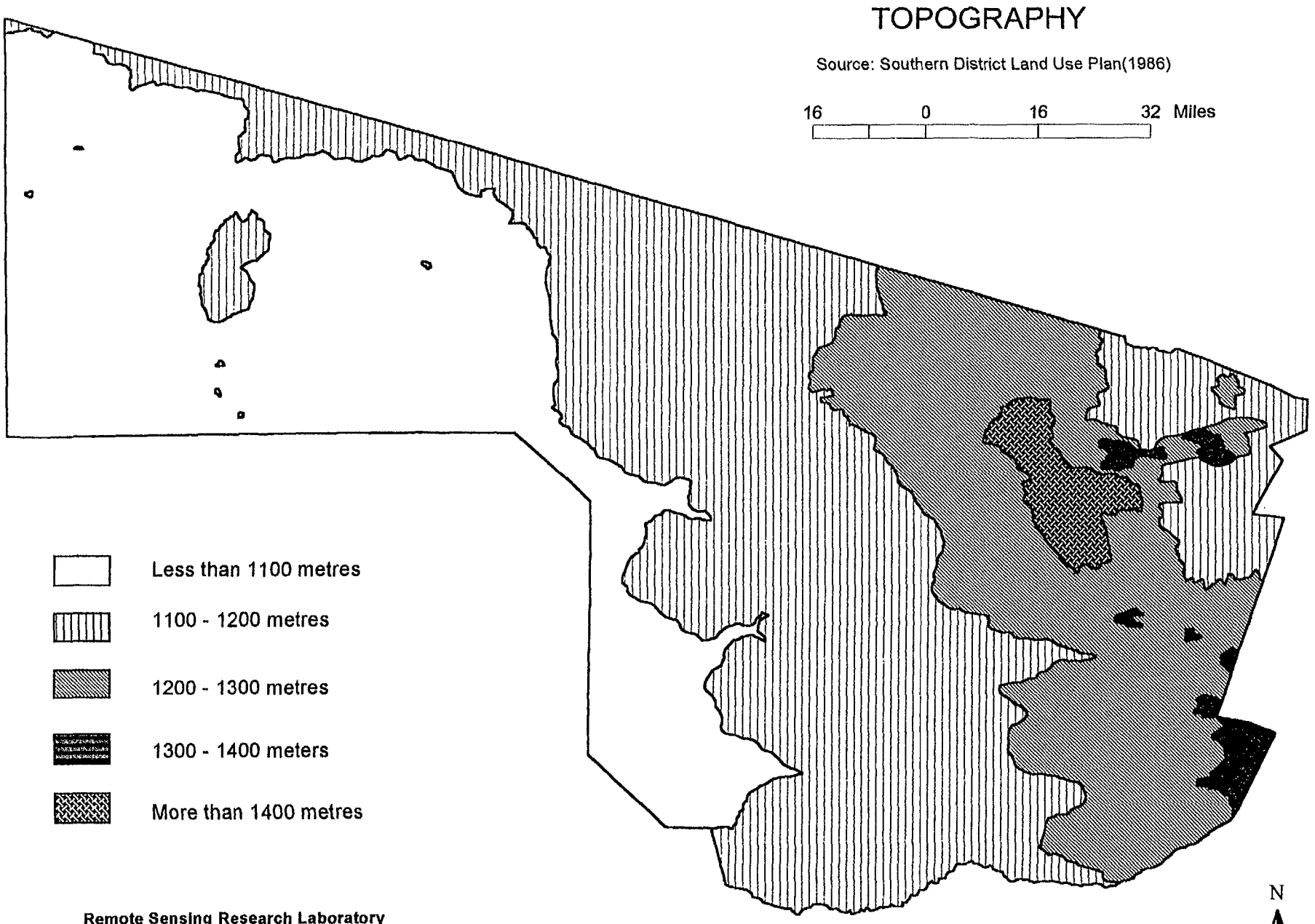
Remote Sensing Research Laboratory
Kansas State University

Figure 3. Major land management areas in the Southern District, Botswana.

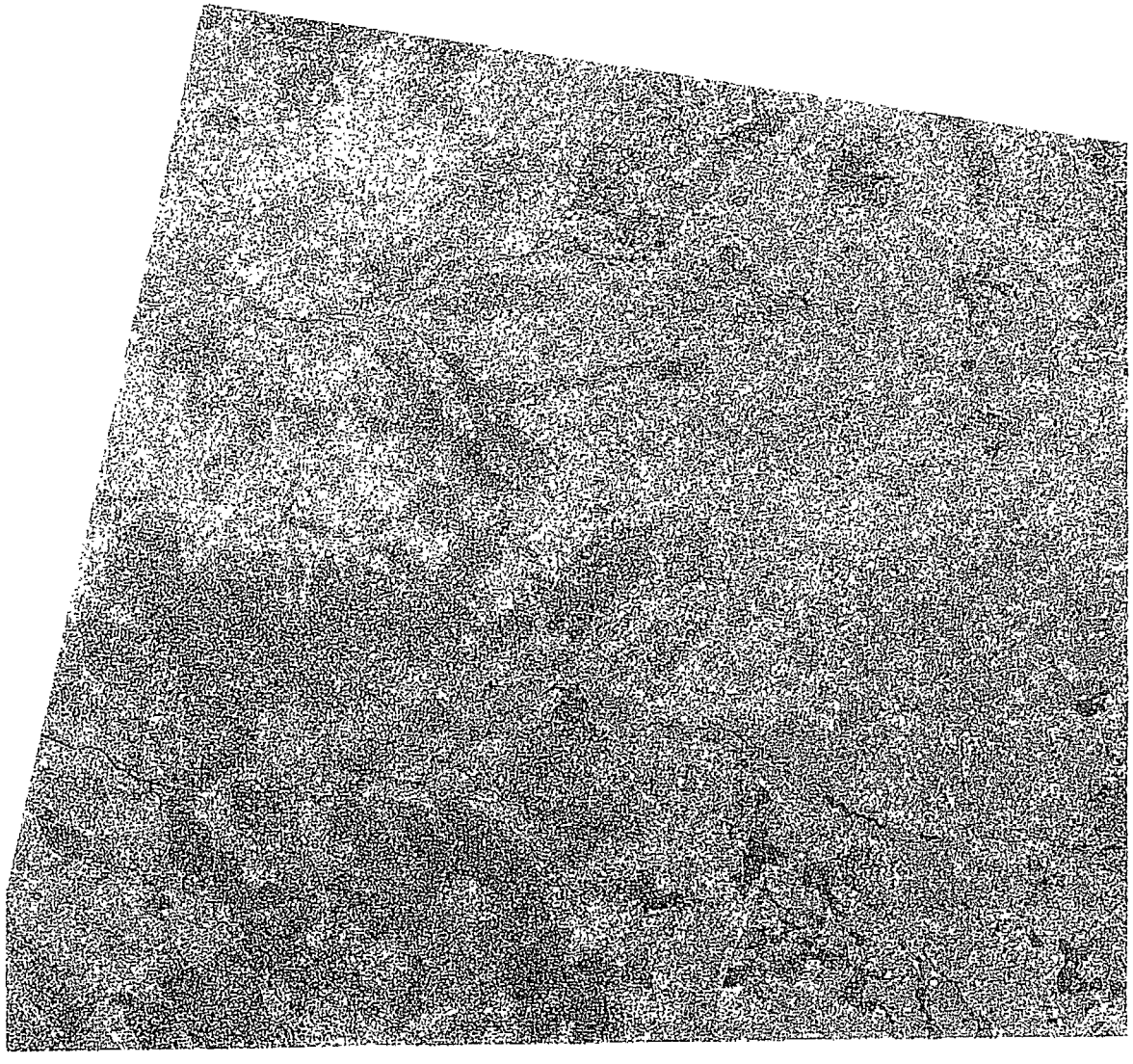


Remote Sensing Research Laboratory
Department of Geography
Kansas State University

Figure 2. Topographic Regions within the Southern District, Botswana.

NDGR, SOUTHERN DISTRICT OF BOTSWANA

TM6, JULY 18, 1994



Highest Value

Lowest Value

REMOTE SENSING RESEARCH LABORATORY
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KANSAS STATE UNIVERSITY

Figure 4. A NDGR (Normalized Difference Green Red) Index of a portion of Botswana's Southern District.

APPENDIX C

LANDSAT TM VEGETATION INDICES FOR MEASURING WOODFUEL RESOURCES IN THE SOUTHERN DISTRICT, BOTSWANA

Landsat TM Vegetation Indices for Measuring Woodfuel Resources In the Southern District, Botswana

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Tom L. Coleman
Alabama A & M University

Musisi Nkambwe and Susan Ringrose
University of Botswana

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Introduction

In many areas forests and associated woodlands are being depleted for woodfuel faster than they are being replenished. Almost seventy percent of the people in the less developed countries rely on biomass as their primary fuel for heating and cooking (Miller, 1994). About fifty percent comes from wood or charcoal, thirty three percent from crop residues, and seventeen percent from dung. Each year the energy provided by biomass is about equal to that from oil supplied by OPEC nations. The United Nations Food and Agriculture Organization projects a woodfuel crisis by the end of this century for 3 billion people in seventy seven less developed countries (Miller, 1994).

In Botswana, woodfuel remains the most important energy source for the rural population and is also widely used by urban households. In fact, wood accounts for over half of net energy supply in Botswana (Botswana Ministry of Finance and Development Planning, 1991).

Since woodfuel is mainly collected by the consumers themselves, no formal market for woodfuel exists and only limited quantitative data is available. In past studies by the Government of Botswana, the supply of woodfuel has been estimated using climatic and biological factors which are difficult to establish precisely. Information that does exist suggests that the present wood supply in rural areas is still sufficient to satisfy traditional household

demands in the majority of areas. However, around larger villages and urban centers, woodfuel demand is already exceeding supply. These problems are further exacerbated by increasing non-traditional wood users (for various commercial uses).

In light of these woodfuel resource concerns, policy and management strategy effectiveness is dependent of the availability of relatively high quality estimates of woodfuel areas and dynamics. In this study, we develop a research approach that yields promising results for utilizing Landsat TM digital indices for estimating the spatial and quantitative magnitude of woodfuel resources in the Southern District of Botswana (Figure 1).

The Study Area and Dominant Woody Vegetation

The Southern District of Botswana is located in the southeast portion of the Country. The District has an area of 26,876 square kilometers. The Southern District has a harsh physical environment. In general terms the District is composed of two major woodland-environmental units: the hardveld and the sandveld.

The hardveld is confined to the eastern third of the district where old, hard igneous and sedimentary rocks are exposed. The hardveld region is generally represented by the upland areas that are greater than 1200 meters.

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District. For the most part the region is a gently rolling plain with numerous isolated hills and rock outcrops. A majority of the area, except for the rock outcrops and few hills, is woodland and shrub savanna with varieties of Acacia and Combretum as the dominant species. Specific ecological vegetation zones, however, are quite varied. The Southern Microphyllous Savanna, Terminalla Sericea Tree and Shrub Savanna, RhusLepiodictya Tree Savanna, and Rhus Lancea and Acacia Karroo Tree Savanna are dominant vegetation zones. *Arcacia Erioloba, Acacia Hebeciada, Acacia Leuderitzil,* and *Grewia Flava* are in the Southern Microphyllous Savanna (southern part of the hardveld). *Terminalla Sericea* and *Acacia Fleckil* are found in the Terminalla Sericea Tree and Schrub Savanna (north/northeast within the hardveld). *Rhus Leptodictya* and *Acacia Karroo* species are found in the Rhus Leptodictya Tree Savanna (east central portion of the hardveld), while dominant species in the Rhus Lancea and Acacia Karroo Tree Savanna are *Rhus Lancea* and *Acacia Karroo* (West Central portion of the hardveld).

In rock outcrop and steep hill areas of the hardveld the dominant specie is *Croton Gratissimus*, of part of the Croton Gratissimuss Hill Woodland ecological zone (Figure 2).

Within the hardveld, the medium to fine textured soils of varying depth that have developed in this area are the most fertile and combined with an annual

rainfall of 500-550 mm they are adequate for cultivation. Land use is predominantly mixed farming with both livestock and arable agriculture present (Environmental Consultants, 1988).

The remaining two-thirds of the district is sandveld (in areas generally less than 1200 meters elevation). In the sandveld, rainfall decreases across the district to about 300 mm in the west. Almost all the rainfall, which is highly variable in time and space, occurs as localized showers and thunderstorms during the summer months from November to March. Drought, often lasting several years, is a recurring hazard.

This flat savanna region is a mosaic of open green grassland with trees and shrubs (Figure 3). Vegetation varies from Eastern Broadleaved Savanna in the northeast corner of the sandveld to Southern Broadleaved Savanna in the southeast corner of the sandveld, with the Kgalagadi Plain Microphyllous Savanna dominate in the more arid western half of the district (and the eastern two-thirds of the sandveld). In the Eastern Broadleaved Savanna the dominate species are *Burhea Africana, Ochna Pulchra, Terminalia Sericea, Acacia Fleckil,* and *Bauhinia Petersiana.* The Southern Broadleaved Savanna is dominated by *Terminalea Sericea* and *Aacacia Fleckil. Acacia Erioloba* and *Acacia Leuderitzil* are the dominant species in the Kgalagudi Plain Microphyllous Savanna.

The terrain in the eastern sandveld is nearly flat to undulating but in the west is more undulating and hummocky. A few dry river valleys and numerous pans are also present. The Kalahari beds of the sandveld generally consist of fine grained sands that overlie variably consolidated sands, sandstones, clay, calcrete, and silcrete. Soils are typically of a medium coarse texture and grey and brown in color. In pans fine textured clay soils are present and in some cases saline and alkaline soils are found.

For the most part the sandveld is not suitable for cultivation and is generally used for grazing of livestock and wildlife.

As part of the Southern District Development Plan, 1989-1995 (Southern District Council, 1989) one of six areas needing addressed by comprehensive regional land use planning is woodland management. More specially, the plan calls for an inventory and monitoring of woodland resources as a source of energy. This research paper provides a synoptic approach for mapping spatial dimensions of the woodland resource in a portion of Botswana.

Methods

Field Analysis

In order to link ground level observations with Landsat TM (thematic mapper) satellite digital data, a variety of information related to woody vegetation and

field condition was recorded at an extensive network of sites throughout Botswana's Southern District. Sites were sampled along transects bisecting the District's diverse physiography and vegetation ecosystems. Landcover and condition samples were recorded at 10 to 20 km intervals (depending on landscape diversity) along each of the transects. In addition, thirty-four detailed field sites, representing samples of major woody vegetation, were selected; each of an area 900 m^2 (Figure 1). Both transect detailed sample site locations were noted using a global positioning system (GPS).

At each of the detailed field sites, the number and height of trees and brush/shrubs were recorded. These measures of woodfuel characteristics provided some index of woody vegetation resource potential.

Satellite Image Analysis

Landsat TM digital data of the Southern District were obtained from the Satellite Applications Center, Pretoria, South Africa. Six TM quarter scenes were required to cover the District. Three of the scenes were recorded on June 23, 1994; two on July 7, 1994, and one on August 1, 1994. The dates were selected to closely correspond to dates of the ground level observations and to maximize the quality of cloud-free coverage over the region.

The general study area was clipped from each of the images to form six

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In order to test the research question associated with this paper, an analysis was performed to see the degree of correlation between TM bands 2, 3, and 4, as well as woody vegetation indices based on a normalized difference vegetation index (NDVI), and a normalized difference green red index (NDGR) with woody vegetation (trees and bush/shrubs) in a subset of the District. TM bands 2, 3, and 4 were preselected for analysis based on past research in Botswana by Ringrose et al. (1991) and Sefe et al. (1996). NDVI is based on a ratio transformation, where near infrared (NIR) minus Red is ratioed over NIR plus Red, and has had some successful application in Botswana (Farrar etal., 1994). In contrast NDGR is based on a ratio transformation where green minus red is ratioed over green plus red.

Through a PEARSON correlation analysis and development of a multiple regression model, we then were able to detail the relative significance of the TM bands with woody vegetation and associated resource potential.

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Discussion

In comparing individual TM bands 2, 3, and 4 with tree density (number of trees per field sample area), Landsat TM band 2 provided the best results (Table 1). Tree density varied from 0 to 150 per 900m² field site. The high level of R-squared (0.897) suggests the significance of the green wavelengths in measuring woody vegetation during the dry season. Landsat TM band 3 and TM band 4 also offered relatively significant association with tree density values. In contrast, NDVI and NDGR indices were significantly less successful in providing an estimate of tree density.

In order to provide a better indicator of relative tree biomass associated with each field site, we multiplied the mean tree height in the field site with the tree density to generate a ComTree(CT) variable. Tree height varied from less than 1 meter to approximately 8 meters. The results, though, were slightly less significant. Again, Landsat TM band 2 and 3 were most highly correlated with the CT variable (0.838 and 0.810, respectivity). The NDVI and NDGR indices were again significantly less important predictors of this tree biomass indicator (CT).

Landsat TM band 3 (red) provided the highest degree of association with shrub density (Table 1). Shrub density varied from 0 to 220 per 900m² field

site. Landsat TM band 4 (near infrared) was the next most significant predictor among the individual bands, with Landsat TM band 2 least important. The more leafy nature of the dry season shrub is a probable explanation for the greater sensitivity of the red and near -infrared bands to shrub density variability relative to tree density. The NDGR was similar as a predictor of tree density as were TM bands 3 and 4, while the NDVI was not closely associated with shrub density.

In Contrast to ComTree (CT) R-squared values, the ComShrub (CS) R-squared values (based on mean shrub height multiplied by shrub density) enhanced the degree of association with one of the individual Landsat TM bands. The enhancement was most significant between ComShrub (CS) and Landsat TM band 4 (0.777 R-squared). This can possibly be explained where the addition of mean shrub height in combination with shrub density provides a more accurate measure of leaf canopy and associated near infrared response. Other band and vegetation index combination R-squared values were not altered significantly by linkage with mean shrub height.

Multiple regression approaches did not add any degree of correlation to the simple regression analysis (Table 2). In each test of TD, CT, SD, and CS, individual bands continued to provide the highest degree of correlation with the field data.

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Conclusions

As in most developing countries, Botswana's population continues to depend on woodfuel as one of their important sources of energy. And as part of Botswana's Southern District Development Plan, comprehensive regional land use planning of woodland resources is one of six priority areas of concern. Yet the availability of baseline information on the spatial and temporal variation of woodfuels is limited

The results of this study provide optimision for using Landsat Thematic mapper data for mapping spatial variation and amount of woodfuel resources. For trees, Landsat TM band 2 provided the highest degree of correlation with tree density and as an index of tree biomass. Landsat TM band 3 was the best estimator of shrub density, whereas Landsat band 4 was most significant in predicting shrub biomass index values.

The results also suggest the limitations, at least, in this study, of using vegetation indices based on band combinations for predicting dry season woodfuel conditions. Although the NDGR index provided some degree of association with the woody vegetation, the NDVI values were not successful measures.

Future resource policy planning associated with woodfuel depletion will

require information that can be facilitated through the use of satellite data. Operationalizing such satellite approaches at the regional level of planning seems like the most appropriate use of this technology for enhancing opportunities for resource sustainability in Botswana.

Acknowledgments

The authors wish to acknowledge the support of the United States Agency for International Development (USAID) personnel in Washington, DC (Mr. David Rakes) and the Botswana Mission (Mr. Robert McColaugh with Mr. Paul Bartel). Acknowledgement is also extended to the Government of Botswana personnel who have provided support for our efforts during the life of this project. These individuals are too numerous to name individually, we trust that all who assisted us will accept this broad acknowledgment as our sincere appreciation of all of your support. The authors are also appreciative for the support provided by the University of Botswana, Department of Environmental Science personnel (Professor Silitshena, Department Head). Acknowledgment is also extended to the staff of the Geography Department (in particular Chi Zhenhuan) at Kansas State University for their assistance in data analyses, and the Alabama Center for Applications of Remote Sensing (ACARS) Laboratory at Alabama A&M University, Normal, Alabama.

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Table 1. Simple regression relationship (R^2) between woody vegetation and Landsat Thematic Mapper data.

	TM2	TM3	TM4	NDVI	NDGR
Tree Density (TD)	0.897	0.841	0.753	0.007	0.413
Com Tree (CT)[a]	0.838	0.810	0.722	0.011	0.465
Shrub Density(SD)	0.501	0.624	0.596	0.011	0.598
Com Shrub (CS)[b]	0.533	0.633	0.777	0.008	0.562

[a] Com Tree is based on multiplying the tree density by the mean tree height.
[b] Com Shrub is based on multiplying the shrub density by mean shrub height.

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Table 2. Multiple regression relationship (R^2) between woody vegetation and combinations of Landsat Thematic mapper data.

Tree density (TD)	= 71.674 - 2.320* TM2 $r^2 = 0.897$
Shrub density(SD)	= 268.977 - 5.508* TM3 $r^2 = 0.624$
Com Tree (CT)	= 352.704 - 11.511* TM2 $r^2 = 0.838$
Com Shrub (CS)	= 408.882 - 8.467* TM3 $r^2 = 0.633$

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Figure 3. A Portion of the Savanna Vegetation in the More Arid Sandveld Portions of The Southern District.

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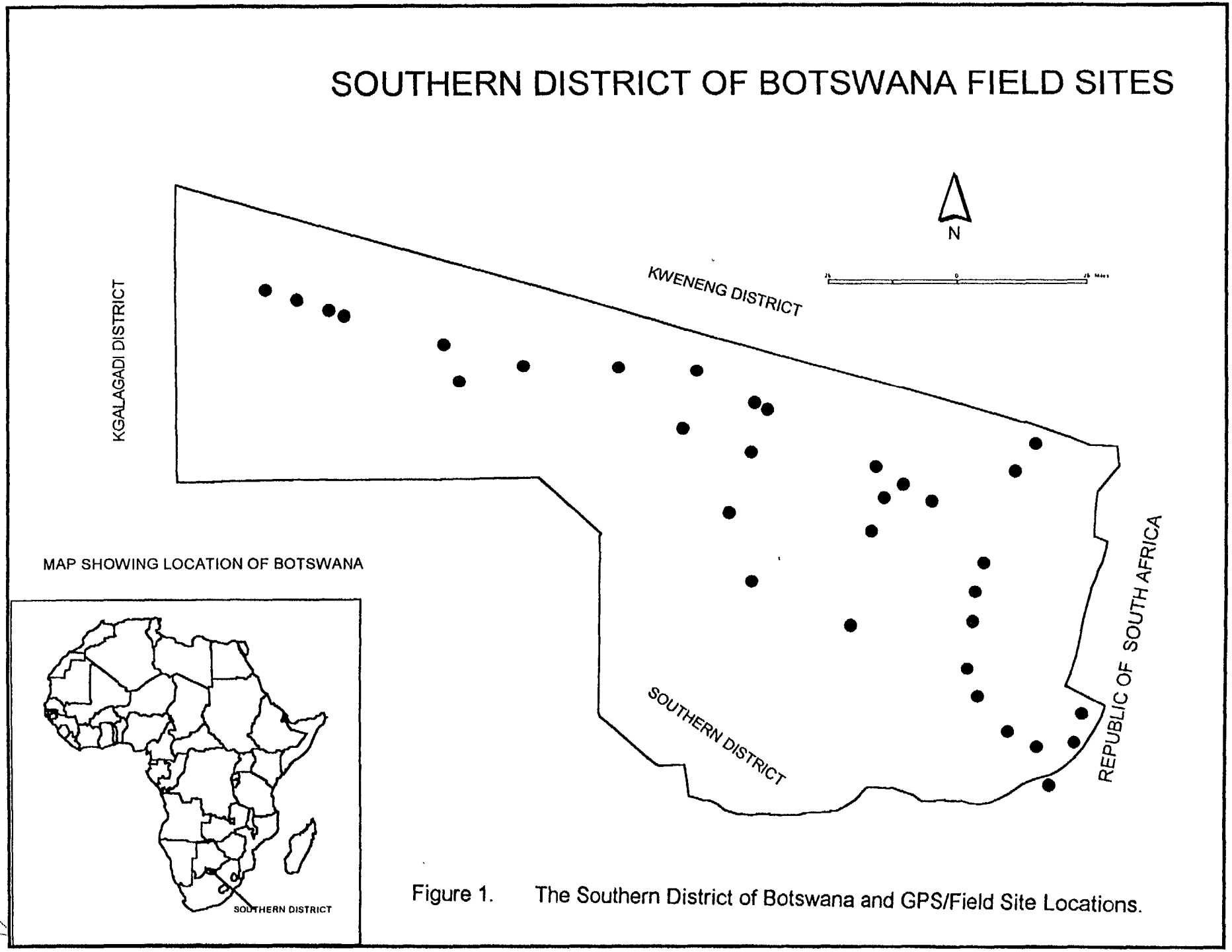

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APPENDIX D

THE USE OF THEMATIC MAPPER IMAGERY IN PREDICTING SEASONAL COVER AND INFERRED RANGE CONDITION IN CONTRASTING SEMI-ARID ECOSYSTEMS

The use of Thematic Mapper imagery in predicting seasonal cover and inferred range condition in contrasting semi-arid ecosystems

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Abstract

The comparison of wet season and dry (residual) vegetation cover was undertaken to provide a basis for rangeland management in contrasting rocky/loamy and sandy semi-arid ecosystems. Comparative indicators of range condition were developed following field data collection, spectral vegetation cover trends using six band Thematic Mapper imagery and classification models. Spectral cover trends mostly showed high pixel values for the mid-infrared (MIR) bands and relatively low values for both near-infrared (NIR) and visible bands. Low NIR reflectance is typically indicative of the general low level of green cover, even in the wet season and recognised as vegetative darkening. The proportion of TM band separability for incremental vegetation cover varies seasonally. Spectral separability indexes (SSIs) indicate that wet season imagery is inherently more valuable in differentiating increments of vegetation cover than dry season imagery although this is ecosystem (soil type) dependant. Seasonal differences in natural vegetation cover relative to soil background reflectance controls the wavebands used optimally for classification analysis. Using SSI indexes, TM3, TM5 and TM7 are recommended inputs for wet season classification and TM3, TM4 and TM5 for dry season classification. While classification results in the medium and low range categories for the hardveld environment are consistent with field work data, dry season inputs are found to exaggerate the amount of both high density (higher quality) range cover and the amount of bush encroachment. This contrasts with sandveld data sets which show no increase in the amount of high density (higher quality) range cover in the dry season. Hence whereas it may be possible to classifiy areas of sandy soil and obtain basic data for range management, the high spectral interseasonal variability in rocky/loamy soils is misleading and may lead to the calculation of excessively high (dry season) stocking rates in semi-arid environments.

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Introduction

Problems in determining seasonal cover on rangelands are significant world-wide, particularly in semi-arid areas where excessive (dry season) stocking rates are considered to be a major contributing factor to range degradation (Tothill and Mott, 1985; Timberlake, 1988). Stocking rates on Botswana rangelands for instance are assumed to be particularly high (Field, 1978) but their estimates stem from an absence of detailed vegetation cover maps and in particular information showing the extent to which vegetation cover or biomass can vary seasonally. Work on rangeland applications in semi-arid zones have been undertaken by a number of authors using Landsat Multispectral Scanner (MSS) data, (e.g. Pickup and Foran, 1987; Graetz *et al.*, 1988). Because of pixel (resolution) size (30 x 30 m), considerably more data can potentially be obtained per unit area on Landsat TM (relative to Landsat MSS) (e.g. Fiorella and Ripple, 1993; Ghitter *et al*, 1995). Problems involved in the use of NOAA derived indexes, especially the Normalised Difference Vegetation Index (NDVI) for range (and general vegetation cover) assessment in semi-arid areas have been discussed elsewhere (Nicolson and Farrar, 1984; Ringrose *et al.*, 1989).

Range quality is assumed to have a direct relationship to the amount of vegetation cover or above ground woody plus herbaceous biomass. Work in semi-arid areas worldwide indicates that whereas grass cover is important, the range can only sustain livestock year long where critical numbers of browse species are present (Platou and Tueller, 1988; Matheson and Ringrose, 1994a, 1994b). The amount of browse is sometimes regarded as "fall-back" pasture, or that which helps sustain livestock through dry season or drought. Grass cover is relatively ephemeral and to a large extent will regenerate over bare soil areas after rains. Browse cover is however a relatively permanent feature of the range unless removed by fire or for fuelwood, fencing or construction use. Work by Shoshany *et al.*, (1995) indicated that seasonal vegetation cover changes are indicative of soil types whereas Miller *et al.*, (1991) discussed seasonal variability in terms of leaf reflectance red edge characteristics. Part of the problem in semi-arid environments lies in the low proportion of effective photosynthetically active radiation, a factor which may not be overcome with the higher resolution of TM imagery (e.g. Rampha, 1996). Overall plant reflectance characterisitcs are known to vary along climatic gradients (e.g. sub-tropical,semi-arid,arid transitions) with the most problematical zone in terms of vegetation spectral reflectance being the semi-

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arid zone (Ringrose *et al.*, 1994). Indicators of range condition can be assessed by comparing wet season and dry season reflectance characterisitcs where extensive areas of bare soil or low shrub densities might be regarded as low quality rangeland. In fact the most critical time in terms of pasture management and carrying capacity occurs towards the end of the dry season (Tothill and Mott, 1985), when soil effects are maximised (e.g. Ringrose and Matheson, 1991b; Matheson, 1994). As a result, very little work has concentrated on inter-seasonal variability in semi-arid areas although the approach has been shown to work successfully in other spectrally variable environments (e.g. Schriever and Congalton, 1995).

This study uses six (reflective) band TM satellite data, field work, band separation techniques and classification analysis to determine differences in seasonal vegetation cover in three rocky/loamy soil areas (called the hardveld ecosystems) and three sandy soil areas (called the sandveld ecosystems) of semi-arid southern Botswana. The purpose of the work is firstly to determine the extent to which the six reflective TM bands can separate out increments of vegetation cover in hardveld and sandveld ecosystems in the wet season and dry season. A second objective is to assess which bands/band combinations may contain most information with respect to vegetation cover differentiation seasonally and in the different ecosystems. A third objective is to determine whether the optimal band combinations can be used to develop classified image models which can then be evaluated in terms of range condition. Initially these data are used to determine the validity of interseasonal comparisons which might later be applied to the calculation of stocking rates.

Semi-Arid Rangelands

Semi-arid rangelands which normally support cattle in addition to smallstock (sheep and goats) occupy 17% of the world's surface area in all continents (Timberlake, 1988). They provide a significant proportion of the GNP in a number of developing countries, such as Botswana (4% in 1995) where beef exports are presently in effect subsidised by the European Union. In Botswana rangelands are divided in terms of their use (communally held herds - village based), cattle post (borehole based) or freehold/government leased ranch. Normally only the last category is fenced and under some kind of formal pasture management. In cattle posts and communal situations pasture management is variably

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applied and the lack of an overall organisational structure has contributed locally to range degradation (Ringrose *et al.*, 1996). This lack of management is partly predicated on the absence of a suitable data base from which optimal stocking rates may be determined.

In common with other semi-arid areas, Botswana comprises hardveld ecosystems (rocky and loamy soils) and sandveld ecosystems (sandy soils with silty fossil valleys), the so-called Kalahari desert. Hardveld areas include low lying, undulating plains and valleys which are relatively highly populated. Farming activities entail mixed cultivation and cattle and smallstock grazing which extend from the outskirts of towns and villages. The landscape is mostly a mosaic of fields and abandoned fields interspersed by grazing bush and the occasional water source. Increasingly the rocky upland areas (plateau and pediments) are being used for livestock/smallstock grazing as grazing on the adjacent plains becomes depleted (Ringrose and Matheson, 1996). Soil erosion problems are becoming increasingly significant in the hardveld, especially adjacent to ephemeral streams and downslope from adjacent plateau/pediment. These contrast with sandveld areas which have no surface water and are relatively less densely populated, but whose villages are expanding partly as a result of large scale bush clearing aimed at stimulating crop production. Originally agricultural activity was centred on or near the finer soils of the fossil valleys which presently provide groundwater sources for both people and livestock.

Study Area

The study area covers about 5 600 square kilometres in southeast Botswana which is irregular in shape but which extends from about 24 degrees 30 minutes to 25 degrees 30 minutes south, through 24 degrees 30 minutes to 25 degrees 80 minutes east (Figure 1). This comprises about 3520km^2 of hardveld and 1580km^2 of sandveld (Figure 2) with a description of the ecosystems given as Table 1. Included to the east are communal grazing lands of the Southern or South East Districts and freehold fenced (farm) areas south of Gaborone and around Lobatse. The area is considered critical to Botswana and is experiencing rapid population growth (Central Statistics Office, 1992). Rainfall in the hardveld averages between 500-550mm per year and decreases in the adjacent sandveld to 450-500mm per year. The 1994 wet-dry precipitation data are shown on Figure 3.

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The imagery used comprises two six band TM scenes from the Satellite Applications Centre, Pretoria. The thermal band was excluded. Statistical data relative to the two scene areas after geometric and radiometric corrections are given as Table 2. The two scenes were acquired on 94 01 07 (wet season) and 94 07 20 (dry season). The data were georeferenced at source by GIMS (BIL-EXABYTE) to a UTM grid (Zone 35), based on the Clarke 1880 Spheroid commonly used in southern Africa.

Field Data Collection

Field work took place during December-January 1994 (mid wet season) and August-September 1994 (mid dry season) to co-incide with both satellite overpass times. Data collection took place from 67 mostly co-incident field sites each entailing three transects through a 90 m x 90 m area. Field analysis techniques included the recording of continuous species and canopy diameters through the 3*90m transects, and 50cm quadrats thrown at 30m intervals to determine herbaceous (alive/senesced) cover. Soil colour was recorded using the Munsell Color notation and extent of eroded area/degree of trampling was also recorded. Field data were used to calculate the percentage of woody vegetation cover (WVC), alive herbaceous cover (AHC) and bare soil extent (BS). The WVC and AHC were added to produce the total vegetation cover (TVC) from which a biomass estimate was derived (Field, 1978). In addition the total number of woody cover species per 90*90m square were calculated, and the species richness (a surrogate of species diversity), which is defined as the number of species divided in to the total area. A palatability index was also established using published palatability criteria (Hendzel, 1981; Ringrose and Matheson, 1987, 1991a).

Results - Data Analysis

Results from wet season and dry season field surveys are shown as Tables 3 and 4. Table 2 shows that during the 1994 wet season most of the woody vegetation cover (hence biomass) is found on rocky hill tops (Figure 4) with least in the hardveld cultivated valleys. Despite the rains, the alive and dead herbaceous cover values are relatively low for most of the study area and large expenses of bare soil prevail (Figure 5). Total Vegetation Cover (TVC) and biomass values are much more variable in the hardveld than in the sandveld. In terms of the relative palatability of the bush cover, the most palatable

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areas are found in the sandveld ecosystems. In terms of relative species richness per unit area, both the hardveld and sandveld ecosystems appear comparable. In the dry season, the extent of woody vegetation cover mostly declined due to leaf fall, although certain species remain green throughout. The alive herbaceous cover is negligible and the proportion of dead herbaceous cover and litter increased commensurately. The proportion of total biomass is low with relatively higher amounts on rocky plateau/pediments and in sandveld ecosystems, except in localised areas where wind erosion problems occur (Figure 6).

Results - Ecosystem Spectral Analysis

The range of spectral reflectance values depicting relative vegetation cover for the six ecosystems was assessed for each of the reflective TM bands to determine how spectral response varies seasonally with increasing vegetation cover. This procedure was also undertaken to assess which TM bands might provide the most useful inputs for range assessment techniques using the classification approach. Initially nine pixel values were recorded (and subsequently averaged) using the Inquire Cursor Function in ERDAS IMAGINE 8.2 by locating the cursor over known field sites on both wet and dry season imagery. Also recorded were either bare (cultivated or grazed) or eroded soil pixels. These results were developed into spectral sequences of successive increments of vegetation cover in all the ecosystems to facilitate wet/dry season comparison.

The results from the hardveld ecosystems are considered first. Ecosystem I (mainly undulating plains) shows high pixel values for the mid-infrared (MIR) bands and relatively low values for the near infrared and visible bands (Figure 7). This overall pattern is replicated throughout all the ecosystems. The low level of NIR reflectance is indicative of the general low level of green cover, even in the wet season. The plots for ecosystem I show that wet season and dry season trends are generally similar but that most proportional vegetation differentiation takes place in the dry season on mid-infrared bands. For ecosystem II (cultivated valleys) both wet season and dry season curves appear similar but with greater seasonal differentiation in the wet season (Figure 8). In ecosystem V (rocky hills), the series of vegetation increment curves are similar for all TM bands on both the wet and dry season images (Figure 9). In the

dry season the pixel value differences for TM1 is relatively high. Generally the dry season curves seem to indicate a greater incremental vegetation cover differentiation over on most TM bands than the wet season.

For the sandveld ecosystems, in ecosystem VI (sandveld, darker soils) while both wet and dry season curves are similar, the interband contrast and relative cover increment is more marked in the dry season imagery (Figure 10). In ecosystem VII which has more recently opened fields and more visible incidence of wind erosion, there is more overall contrast in the wet season imagery. This occurs particularly in terms of the wind eroded and ploughed fields relative to the three increments of vegetation cover (Figure 11). However a clearer density increment on all bands was more noticeable on the dry season imagery. Finally in the case of ecosystem VIII (fossil valleys), there is more band separability in the MIR range in the wet season and more separability in the dry season in the visible portion of the spectrum (Figure 12). Hence the degree of separability varies seasonally and with differences in ecosystems in terms of the TM reflectance wavebands.

Steps were taken to determine which bands and/or band combinations might inherently contain most useful data in terms of separating out increments of vegetation cover thereby predicting range condition. Spectral separability indexes (SSIs) were devised based on the relative separability of TM bands in terms of increments of vegetation cover graded from 0-4 where 0 = total overlap (i.e. with a high degree of overlapping of pixel values); 1 = partial overlap; 2 = some separation/some overlap; 3 = total separation, no sequence; 4 = complete separation in sequence (i.e. vegetation cover increments increasing or decreasing in terms of increasing or decreasing pixel values) (Table 5). The results show SSI values ranging from 0.54 to 0.83 for wet season imagery and from 0.38 to 0.79 and for dry season imagery. For most ecosystems, wet season imagery is inherently clearer in differentiating increments of vegetation cover. This is possibly because of the relatively high density of vegetation cover and clearer differences between plant and soil reflectance values which occur during the wet season. This is enhanced by the minimal extent of darkened (shadowed) vegetation cover relative to highly reflective bare soil (e.g. Ringrose *et al.*, 1989; Otterman, 1996). The reflectance curves from dry season imagery are relatively

unpredictable with pixel values possibly influenced by variable proportions of dormant tree/shrub cover and senesced grass. The extent of vegetation induced (lateral) shadow is also far greater in the dry season.

In terms of the relative usefulness (inferred data content) for classification purposes, TM3 (SSI 0.66), TM5 (SSI 0.7) and TM7 (SSI 0.83) were chosen as the most suitable input bands for wet season rangeland evaluation. TM3 (SSI 0.71), TM4 (SSI 0.7) and TM5 (SSI 0.79) were chosen for dry season evaluation (Table 5). With respect to optimal band usage in this part of semi-arid southern Africa, TM3 and TM5 (0.63-0.69um and 1.55-1.75um) appear equally effective, irrespective of seasonal variability. The data on TM4 (0.76-0.90um) are particularly valuable in the dry season, presumably because of vegetative darkening in the near infrared part of the spectrum,(Ringrose *et al.*, 1989). Interestingly, TM7 (2.08-2.35um) contains most useful information for range assessment in the wet season, a factor maybe related to soil/vegetation moisture retention (Elvidge and Portigal, 1990).

Results - Image Classification

Image classification was undertaken using the three optimal input bands per season to provide a comparative quantitative assessment of range conditions in hardveld and sandveld ecosystems. Using ERDAS IMAGINE 8.2 two, three band TM images were created for each season by first subsetting the relevant whole scenes into study area subscenes and then further reducing the subscenes into hardveld and sandveld components using AOI (area of interest) tools and the SUBSET function. The separation of hardveld and sandveld components was necessary because of interpretational problems which arise after devising classification schemes across major ecoregion boundaries (Ringrose, *et al.*, 1990). Data content was evaluated specifically for the different seasons. Similar procedures were undertaken on all four sub-scenes which were classified separately to obtain maximum variability in terms of cover density and hence range condition. Data from field observations, away from the field data collection sites were located on the image areas to predict classes in terms of relative amounts of vegetation cover. This was followed by polygon generation and the development of initial classes covering situations ranging from varying degrees of vegetation cover to land-use types in terms of fields, bare soil areas and degrees of

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erosion. As far as possible, the training polygons were obtained from the same areas for the wet and dry season cases. Typically 15-20 initial training signatures were generated for the hardveld images which show greater variability in terms of edaphic conditions and land cover types, while 10-15 signatures were developed for the sandveld. Each of the four preliminary signature files were edited using the edit functions in the signature editor cell array. The consistency of the signatures in terms of statistical distribution curves was assessed using histogram analysis and multimodal signatures were reformulated. Degrees of signature overlap were determined using the contingency matrix and the co-inciding and/or overlapping classes were either merged or deleted. Dimensional class distribution plots were displayed as ellipses on feature space diagrams using different channel combinations and overlapping classes were deleted. Additional non-parametric classes were derived directly using feature space plot routines in areas devoid of classes. This was undertaken interactively using linked cursors and the original data set.

Classification routines were undertaken using an initial feature space separation, followed by both overlap and unclassified rules being set to parametric with data separation taking place using the maximum likelihood classification algorithm setting the probabilities for each class at zero (c.f. Foody *et al.*, 1992). The initial classification results were assessed using the Jefferies-Matusita signature separability function on one layer per combinations. Thresholding was also applied to evaluate the classes in terms of their histogram distribution and respective chi-square values. This technique enabled classes to be more closely defined but also left a large number of unclassified pixels. These pixels were located on the original image using the alarm function and the revised signatures added to the respective signature files. The classification algorithms had to be run through each data set several times before four acceptable classified images were generated. The initial naming/interpretation of the classes was clarified and expanded using the alarm function in conjunction with the raster attribute editor. Following classification the relative was accuracy was assessed with reference to the original field data sites.

The results of the classification process for the hardveld ecosystems are shown in Tables 6 and 7 (and Figure 13 and 14) and for the sandveld ecosystems in Tables 9 and 10 (and Figures 15 and 16). A total of sixteen classes, identifying mainly differing densities and types of vegetation cover were found to be

spectrally distinct for the hardveld ecosystems whereas fewer classes were isolated for the sandveld. In terms of hardveld seasonal class comparability, moderate and dense vegetation cover types were merged for both pediments and plains (ecosystems II and V) during both seasons (Tables 6 and 7). This is probably because these classes depicted mainly darkened *Acacia spp.* cover, much of which is highly indicative of bush encroached areas, and which mask the inherently different soils reflectance values. In the dry season it was possible to differentiate dense vegetation cover specifically on the plateau (V). Moderate vegetation cover on the plateau was differentiated for both seasons (Tables 9 and 10). For both the hardveld and sandveld, for both seasons it was possible to isolate spectrally moderate dense riparian/plains cover, moderate sparse plains cover with erosion features and sparse to moderately vegetated near surface bedrock. Mostly the hardveld wet season vegetation (rangeland) classes have a classification accuracy of between 73% and 89% which is higher than the dry season classes which have an accuracy of between 64% and 75% (e.g. Varjo, 1996).

In order to determine the extent to which the maximum liklihood classification model could adequately define classes useful in terms of range assessment, a range categorisation system was applied to the resulting classes. Areas of known high density broadleaf (forage) and herbaceous cover were allocated into a high rangeland quality class. Areas of moderate vegetation cover, comprising mainly broadleaf (forage) and herbaceous cover were ascribed a medium category. The low quality rangeland was divided into two categories based on whether the category comprised mainly bush encroached areas or whether this included mainly low shrubby vegetation cover with eroded areas (c.f. Ringrose *et al.*, 1996).

Initially a range category rating was accorded to each hardveld class and the relevant class areas were summarised on Table 8. For the medium range categories, the results are reasonably consistent with vegetation type changes as indicated from the field data set. As expected, much more area was seen to be eroded in the wet season than the dry season. However problems arose in the higher and lower quality range categories. Unaccountably, a far larger area of dense vegetation cover was obtained for the dry season data than for the wet season. The bush encroached areas also appear to have expanded from the wet season to the dry season in the plains ecosystem which is inconsistant with observations. However,

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in the case of the rocky plateau/pediment ecosystem, the extent of bush encroachment remained similar for both seasons. The dry season imagery particularly in the plains ecosystem therefore appears to exaggerate the amount of both high density (higher quality) range cover and the amount of bush encroached area. This is possibly due to the enlarged areas of darkening (mainly caused by extended plant shadow) particularly over the darker soil background prevalent in the hardveld.

For the sandveld class interpretations, a high degree of comparability was noted between the seasons with seven of the nine (dry season) and nine (wet season) classes being co-incident (Tables 9 and 10). Small areas of cloud and shadow in the sandveld ecosystems (wet season) were omitted from subsequent analysis. In terms of the relative interpretation of wet season and dry season classes, one class, 'sparsely vegetated interfluves' was only identified in the dry season. In the wet season, two classes 'moderate vegetation cover mainly in the fossil valleys' and 'dense interfluve vegetation cover' were uniquely spectrally separable. The classification accuracy of the sandveld range vegetation classes is slightly higher than that achieved for the hardveld being between 69-90% for the wet season and 64-85% for the dry season.

In order to determine the extent to which this classification technique could adequately define sandveld classes useful in terms of range assessment, a range categorisation system, similar to that used for the hardveld, was applied to the results (Tables 9 and 10). The range category data were summarised for each ecosystem and the results given on Table 11. The results show that in the wet season, for the two interfluve ecosystems (VII and VIII) a proportion of the range is readily divided between the high, medium and low categories, consistent with vegetation cover types indicated from the field data set. In terms of soil eroded areas, since these are mainly wind blown soils, as expected much more area was seen to be eroded in the dry season than the wet season. Interestingly fewer problems arise with the sandveld assessment, relative to the hardveld assessment. In the sandveld data set when separate classification signature files are used, the exaggeration of the amount of high density (higher quality) range found in the hardveld results, was not apparent. The direct effects of vegetative darkening noticeable on loamy hardveld soils appears relatively ineffective when sandy soils are classified. While this is probably related

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to differences in soil reflectance of significance here is the smaller size of the trees/shrubs in the drier sandveld which produce a minimal amount of lateral shadow, even in the dry season.

Conclusions

Work in semi-arid areas worldwide has indicated that whereas grass cover is important, the range can only be regarded as being able to sustain livestock year long where critical numbers of browse species are present in addition to senesced grass cover. In the present work, comparative indicators of range condition are assessed by field data collection, the development of vegetation cover trends on Thematic Mapper bands and as a result of image classification. TM data sets were used in the comparison of wet season and dry season imagery for six ecosystems in the Botswana hardveld and sandveld. Field work results indicated that in the 1994 wet season most of the total vegetation cover (TVC) was found on the hardveld plateau/pediments ecosystem and least in the plains ecosystem. The sandveld has a lower TVC, but cover is generally more consistent over the sandveld ecosystems. In terms of species richness (diversity), the two ecoregions are comparable. In the 1994 dry season, the TVC appears to have declined probably due to the semi-deciduous nature of the tree/shrub cover and the depletion/senescence of grasses. The dead herbaceous cover and litter components are relatively high in both the hardveld and sandveld during the dry season.

Spectral reflectance curves were developed for increments of vegetation cover based on field locations for the six TM reflective bands. The reflectance curves were graded to assess the relative separation attainable per increment of total vegetation cover per waveband. The results for both hardveld and sandveld ecosystems show high pixel values for the mid-infrared (MIR) bands and relatively low values for the near infrared and visible bands. Low NIR reflectance is indicative of the minimal green cover, even in the wet season. Spectral separability indexes (SSIs) were devised to determine the relative distinctivness of TM bands in terms of increments of vegetation cover. The SSI results for wet season imagery range from 0.54 to 0.83 and for dry season imagery from 0.38 to 0.79. These data indicate that for most ecosystems, wet season imagery is inherently more valuable in differentiating increments of vegetation cover than dry season imagery. This is likely because the higher density of vegetation cover

creates clearer differences between plant and soil reflectance values particularly for darkened (shadowed) vegetation cover (e.g. Ringrose *et al.*, 1989). The reflectance curves from dry season imagery are relatively unpredictable with the reflectance values possibly influenced by relatively high (and variable) proportions of dormant tree/shrub cover and senesced grass in addition to laterally extensive shadow.

Seasonal differences in natural vegetation growth relative to soil background reflectance, control which wavebands are used optimally. As a result of SSI analysis, TM3 and TM5 (0.63-0.69um and 1.55-1.75um) were proved to be equally useful, irrespective of seasonal variability. The data on TM4 (0.76-0.90um) were particularly valuable in the dry season. This demonstrates the NIR vegetative darkening effect or the infrared paradox, (Ringrose *et al.*, 1989, Otterman, 1996). Data on TM7 (2.08-2.35um) contain most useful information for range assessment in the wet season, a factor maybe related to soil/vegetation moisture retention (Elvidge and Portigal, 1990).

Hence for classification purposes, TM3 (SSI 0.66), TM5 (SSI 0.7) and TM7 (SSI 0.83) were chosen as the most suitable input bands for wet season rangeland evaluation. TM3 (SSI 0.71), TM4 (SSI 0.7) and TM5 (SSI 0.79) were chosen for dry season evaluation. Each sub-scene was classified separately to obtain the maximum variability in terms of cover density and hence range condition. A total of sixteen classes, identifying mainly differing densities of vegetation cover were found to be spectrally distinct for the hardveld ecosystems whereas fewer classes were isolated for the sandveld. Whereas every attempt was made to ensure comparability of the results, slightly different classes eventuated for wet season and dry season conditions reflecting the seasonally varying nature of the vegetation cover. Classification accuracy for the wet season ranged from 73% to 89% for the hardveld and 69% to 90% for the sandveld. Dry season accuracies ranged from 64-75% for the hardveld and 64-85% for the sandveld. To determine the extent to which the classification method could adequately define classes useful in terms of range assessment, a range categorisation system was applied to depict areas of high, medium and low range quality. While results in the medium and low categories for the hardveld were consistent with field data, problems arose as areas of dense vegetation cover and bush encroachment for the dry season data were exaggerated, particularly in the plains ecosystem. In the sandveld data set the same exaggeration of the

amount of both high density (higher quality) range cover found in the hardveld data was not apparent. Hence the direct effects of darkening (shadow) noticeable on hardveld imagery appear relatively ineffective when sandveld areas are classified. This may be a function of tree/shrub structure as generally much taller, shady trees are found in the hardveld, than the sandveld. Hence whereas it may be possible to analyse sandy open savanna ecosystems and obtain basic data for stocking rates from the interseasonal variability of wet season and dry season data, data from rocky or loamy tree savanna ecosystems tend to be less conclusive. In these latter areas, the extent of dense darkened vegetation and bush encroached vegetation cover are overstated especially in the dry season which is when stocking rates would need to be calculated.

Acknowledgments

Funding for this work was provided by USAID under contract. Wilma Matheson is thanked for providing field work support and for working on the vegetation calculations. Cornelius Vanderpost contributed to the development of the final classified maps. Joyce Mapanyane is also thanked for providing Figure 1.

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Table 1: Ecosystems and Land-Uses: Southeastern Botswana

Ecosystem	Name	Erosion Features	Soil type and colour	Land use
I	Hardveld - cultivated plains	Gully, sheetwash and rill erosion	Ferric Luvisol 5YR5/4	Mixed agriculture and grazing
II	Hardveld - cultivated valleys	Gully and sheetwash erosion	Gleyic Luvisol 10YR4/2	Mainly agriculture - crop production
V	Hardveld - rocky hills	Gully and rill erosion	Regosol 5YR5/6	Grazing
VI	Sandveld-multicoloured arenosols	Wind erosion	Petrocalcic Arenosol 5YR6/6	Grazing and arable clearing
VII	Sandveld arenosols and pans	Little erosion	Arenosol 10YR7/3	Grazing - some agriculture
VIII	Fossil valleys in sandveld	Some rill and sheetwash erosion	Luvisol 10YR8/4	Grazing - some agriculture

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Table 2: Basic Spectral Data for wet season and dry season imagery

Dry Season	Maximum	Minimum	Mean	Median	Standard Deviation
TM1	189	0	45.4	59	27.2
TM5	255	0	69.4	88	43.4
TM7	253	0	32.0	39	20.7
Wet Season					
TM3	229	0	50.0	61	38.3
TM5	255	0	108.7	140	81.0
TM7	255	0	51.9	62	40.6

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Table 3: Vegetation Survey Results - Wet Season

Ecosystem	WVC%	AHC%	DHC%	BS%	PAL*	APPROX BIOMASS**	RICH***
I (n=5)	33.1	2.8	0.7	63.4	1.47	4600	2.05
II (n=3)	15.2	1.8	0.9	82.1	1.52	2700	1.90
V (n=18)	45.7	1.5	1.9	50.9	1.55	5900	2.22
VI (n=10)	26.6	6.1	3.4	63.9	1.64	4200	1.68
VII (n=12)	29.0	2.7	2.3	66.0	1.96	4200	2.29
VIII (n=11)	25.0	3.0	1.6	70.4	1.73	3800	1.80

WVC = Woody Vegetation Cover
AHC = Alive Herbaceous Cover
DHC = Dead Herbaceous Cover
* PAL = Palatability
** Approximate biomass in Kg/Ha
*** RICH = Species richness

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Table 4: Vegetation Survey Results - Dry Season

Ecosystem	WVC	AHC	DHC	BS	PAL*	APPROX BIOMASS**	RICH***
I (n=8)	19.4	0.0	20.7	59.9	NSD	3400	1.8
II (n=5)	10.5	5.7	15.2	68.6	NSD	2600	1.3
V (n=18)	41.9	0.8	13.5	43.8	NSD	4100	2.0
VI (n=12)	25.3	0.0	22.8	51.9	1.8	14	1.5
VII (n=15)	30.0	0.0	19.3	51.7	1.96	17	2.29
VIII (n=11)	22.9	3.0	15.4	58.7	1.73	13	1.80

NSD = No species data available

WVC = Woody Vegetation Cover
AHC = Alive Herbaceous Cover
DHC = Dead Herbaceous Cover
* PAL = Palatability
** Approximate biomass in Kg/Ha
*** RICH = Species richness

Table 5: Spectral Sepability Indexes used to develop bands for use in classification

Ecosystem HARDVELD	TM1	TM2	TM3	TM4	TM5	TM7
I-Wet Season	2	2	3	3	3	3
I-Dry Season	1	1	2	2	3	4
II-Wet Season	4	4	4	4	2	2
II-Dry Season	4	2	2	4	4	4
V-Wet Season	3	3	1	1	3	4
V-Dry Season	4	1	3	3	4	2
Ecosystem SANDVELD						
VI-Wet Season	2	1	2	4	2	3
VI-Dry Season	2	2	4	4	4	2
VII-Wet Season	1	1	2	1	4	4
VII-Dry Season	1	1	2	2	3	1
VIII-Wet Season	1	1	4	0	4	4
VIII-Dry Season	2	2	4	3	1	1
Wet Season Separability	0.54	0.54	0.66	0.54	0.75	0.83
Dry Season Separability	0.58	0.38	0.71	0.75	0.79	0.58

Where 0 is no spectral separability, 1 = minimal separability, 2 = some separability, 3 = separability but not in sequence of incremental vegetation cover, 4 = separability in sequence of vegetation cover

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Table 6: Results of Classification in the Wet Season, Hardveld

Ecosystem	RRC *	Area (Ha)	Interpretation and Percentage Accuracy
I	-	22607	Bare fields - some erosion (77%)
I/V	L-B	63009	Moderate bush encroached vegetation cover on pediments/plains (81%)
I	-	9866	Cultivated fields (89%)
I/V	L-B	15083	Dense bush encroached vegetation cover on pediments/plains (85%)
V	M	38095	Moderate broadleaf and herbaceous vegetation cover on plateau (73%)
I	L-S	15804	Bare soil and eroded areas (79%)
V	-	5335	Hill shadow and gorges/water (87%)
I	M	25598	Moderate dense broadleaf and herbaceous riparian/plains vegetation cover (84%)
I	L-S	46975	Moderate sparse shrubby vegetation cover on plains - some erosion (69%)
I/II	-	13227	Partially vegetated fields/fields with crops (78%)
I/II/V	H	13602	Very dense broadleaf and herbaceous vegetation cover on plains/plateau and clay valleys (87%)
V	L-B	40897	Moderate bush encroached vegetation cover on pediments/plains (84%)
V	L-S	11443	Sparse shrub vegetation on near surface bedrock (73%)
II	M	6464	Moderate broadleaf and herbaceous vegetation on near surface bedrock (72%)
I	_	1879	Pans - highly reflective soils (93%)
II	_	22083	Partially vegetated/cultivated fields (65%)

* = Relative Range Condition

Table 7: Results of Classification in the Dry Season, Hardveld

Ecosystem	RRC *	Area (Ha)	Interpretation and Percentage Accuracy
I	-	423	Partially vegetated fields (81%)
I	-	702	Bare fields -some erosion (73%)
I/V	L-B	44486	Moderate bush encroached vegetation cover on pediments/plains (64%)
II	-	82	Surface water (100%)
II/I	-	1490	Bare fields (95%)
V	M	28320	Moderate broadleaf and herbaceous vegetation cover on plateau (74%)
V	H	34352	Dense broadleaf and herbaceous vegetation cover on plateau (62%)
I/V	L-B	65312	Dense bush encroached vegetation cover on pediments/plains (59%)
V	-	964	Hill shadow and gorges (100%)
I/V	L-B	60973	Moderate bush encroached vegetation cover on pediments/plains (71%)
I	M	25165	Moderate dense broadleaf and herbaceous riparian/plains vegetation cover (75%)
V	L-S	22790	Sparse shrub vegetation on near surface bedrock (65%)
II	M	159	Moderate broadleaf and herbaceous vegetation on near surface bedrock (68%)
I	-	1805	Pans - highly reflective soils (73%)
I/II/V	H	19895	Dense broadleaf and herbaceous vegetation cover on plains/plateau and clay valleys (64%)
I	L-S	48546	Moderate-sparse shrub vegetation cover on plains - some erosion (72%)

* = Relative Range Condition

Table 8: Estimated area (km2) under different rangeland categories by hardveld ecosystem for the wet and dry season, 1995/6

	IH	IM	ILB	ILS	IIH	IIM	IILB	IILS	VH	VM	VLB	VLS
WS	60	275	400	640	60	80	-	-	61	395	810	120
DS	170	320	920	560	50	-	90	-	410	170	220	95

WS = Wet Season
DS = Dry Season
I, II, V = Hardveld Ecosystems

Rangeland Condition Categories
H = High
M = Medium
LB = Low - Bush encroached
LS = Low - Bare soil with eroded areas

Table 9: Results of Classification in the Wet Season, Sandveld

Ecosystem	RRC *	Area (Ha)	Interpretation and Percentage Accuracy
VI/VII	-	7609	Mainly cultivated fields some sparse vegetation cover (88%)
VI/VII/VIII	L-S	15089	Sparse shrub vegetation cover in interfluves and fossil valleys (82%)
VIII	M	5609	Moderate broadleaf and herbaceous vegetation cover mainly in fossil valleys (65%)
VII	L-S	1241	Dark soils - shrub cover on near surface bedrock (71%)
VI/VII	M	14499	Moderate dense broadleaf and herbaceous interfluve vegetation cover (85%)
VI/VII	H	4147	Dense broadleaf and herbaceous interfluve vegetation cover (84%)
VI/VII/VIII	M	49161	Moderate dense broadleaf and herbaceous vegetation cover in interfluves and fossil valleys (90%)
VI/VII/VIII	L-S	44259	Moderate sparse shrub vegetation cover in interfluves and fossil valleys (69%)
VIII	-	7625	Sparse vegetation cover some water/wind erosion associated with cultivation (73%)
VIII	L-S	6570	Sparse shrub vegetation cover some water wind erosion in fossil valleys (75%)
VII/VIII	-	2303	Mainly bare fields (84%)

* Relative Range Condition

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Table 10: Results of Classification in the Dry Season, Sandveld

Ecosystem	RRC *	Area (Ha)	Interpretation and Percentage Accuracy
VI/VII	-	9613	Mainly bare fields some sparse vegetation cover (89%)
VIII	L-S	16357	Sparse shrub vegetation cover-some wind/water erosion associated with cultivation (70%)
VII	L-S	176	Pans and light coloured soils (64%)
VII	-	1605	Dark soils, shrub cover on near surface bedrock (70%)
VI/VII	M	28612	Moderate dense broadleaf and herbaceous interfluve vegetation cover (83%)
VI/VII	L-S	30587	Sparse shrub interfluve vegetation cover (85%)
VI/VII/VIII	S	53609	Moderate-sparse broadleaf and herbaceous vegetation cover in interfluves and fossil valleys (72%)
VI/VII/VIII	M	16053	Moderate-dense broadleaf and herbaceous vegetation cover in interfluves and fossil valleys (84%)
VIII	S	2209	Sparse shrub vegetation cover some wind/water erosion in fossil valleys (78%)

* Relative Range Condition

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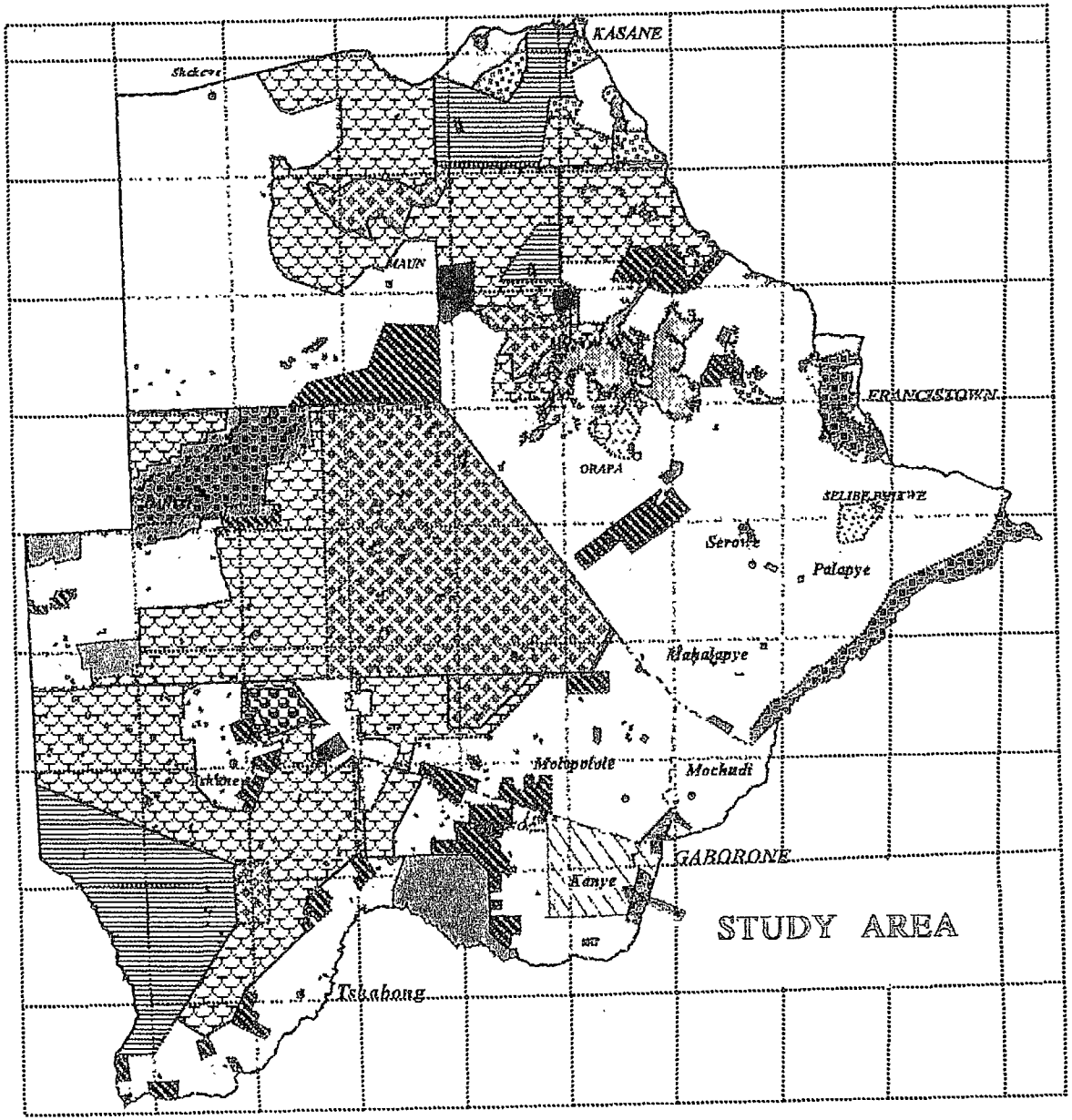
Table 11: Estimated area (km2) under different rangeland categories by sandveld ecosystem for the wet and dry season, 1995/6

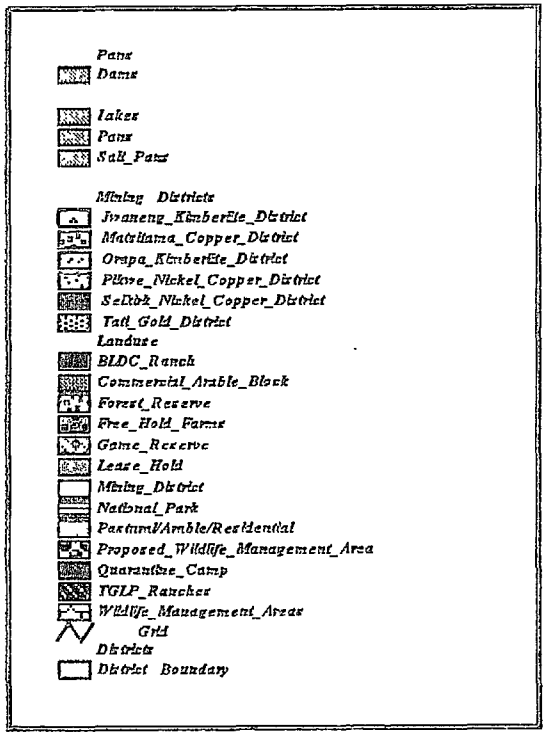
	VIH	VIM	VILS	VIIH	VIIM	VIILS	VIIIH	VIIIM	VIIILS
WS	70	249	271	120	169	283	-	72	292
DS		269	323		269	341	-	-	321

WS = Wet Season
DS = Dry Season
VI, VII, VIII = Sandveld Ecosystems

Rangeland Condition Categories
H = High
M = Medium
LS = Low - Bare soil with eroded areas

BOTSWANA NATIONAL LAND USE MAP

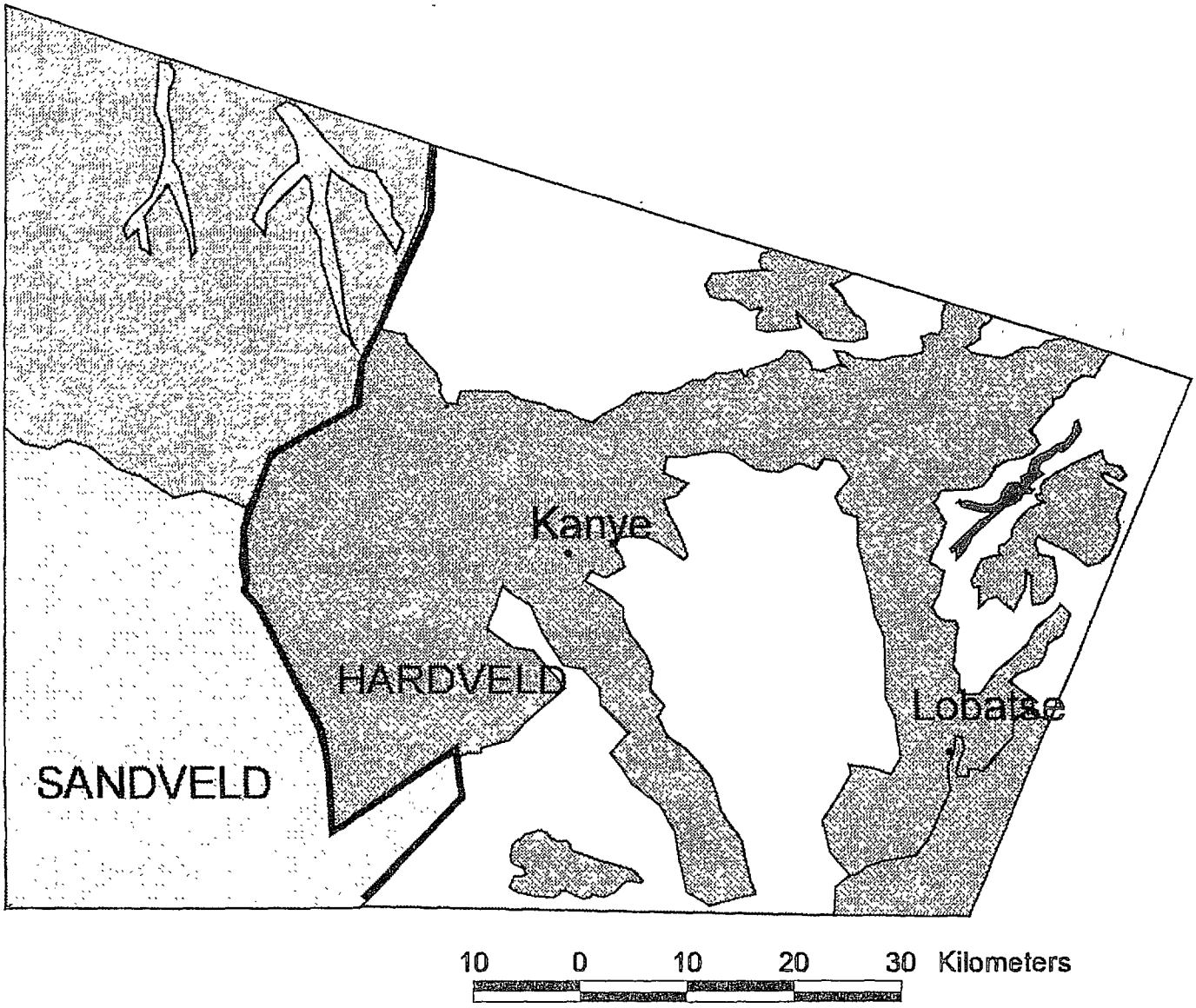




SOURCE - Landuse Map 1988, Scale 1:1 500 000
Ministry of Local Government Lands and Housing and
1975 Geological Survey Map of
Mineral Occurrences of Eastern Botswana.

GIS - Natural Resource Database For Botswana 1995 by J G Kgathwane.

Figure 1. Location of the study area in southeast Botswana, showing the degree of typicalness in terms of land-use across Botswana.



Major Ecosystems

- I Cultivated and Grazed Plains
- V Grazed Plateau and Pediments
- VI Grazed Interfluves (A)
- VII Grazed Interfluves (B)
- VIII Cultivated Fossil Valleys
- II Cultivated Valleys

Hardveld-Sandveld Boundary

Figure 2. Outline of the study area showing the major hardveld sandveld division and the sub-division of the constituent ecosystems.

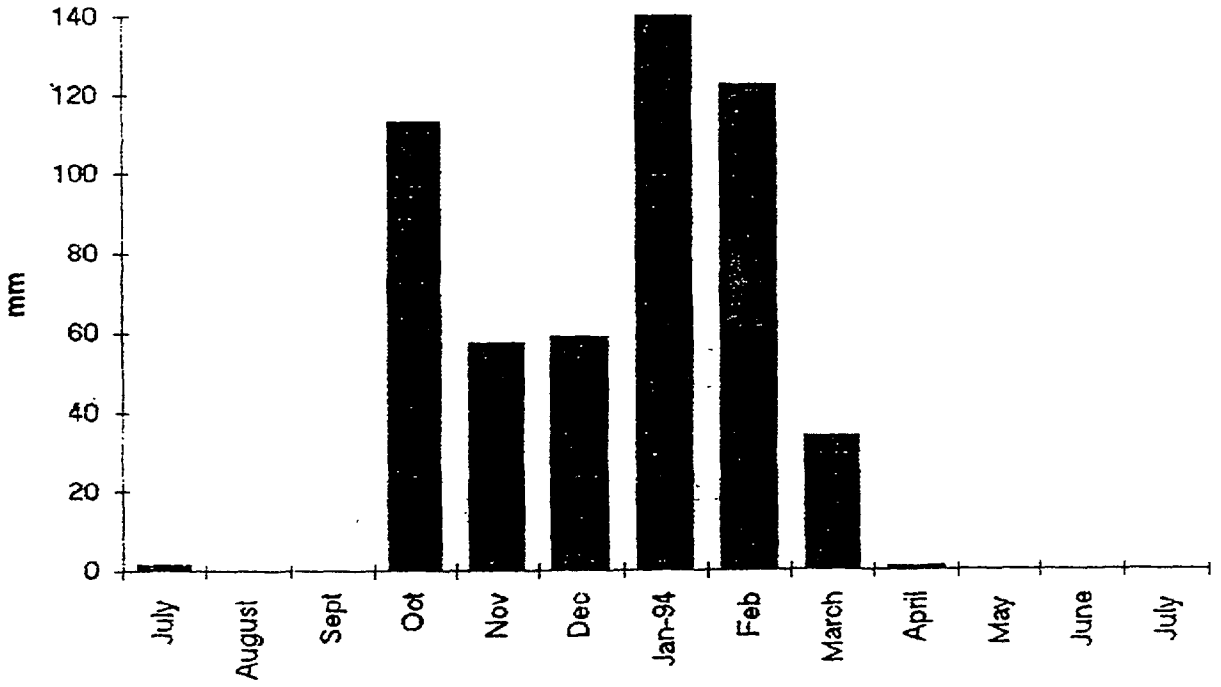


Figure 3. Seasonal distribution of rainfall over southeast Botswana (Gaborone Meteorological Station) showing the average precipitation for wet season during the three months prior to January 1994 and for the dry season prior to July 1994.

Figure 4. Relatively dense woody vegetation cover in hardveld ecosystem V, rocky plateau and pediments north of Kanye.

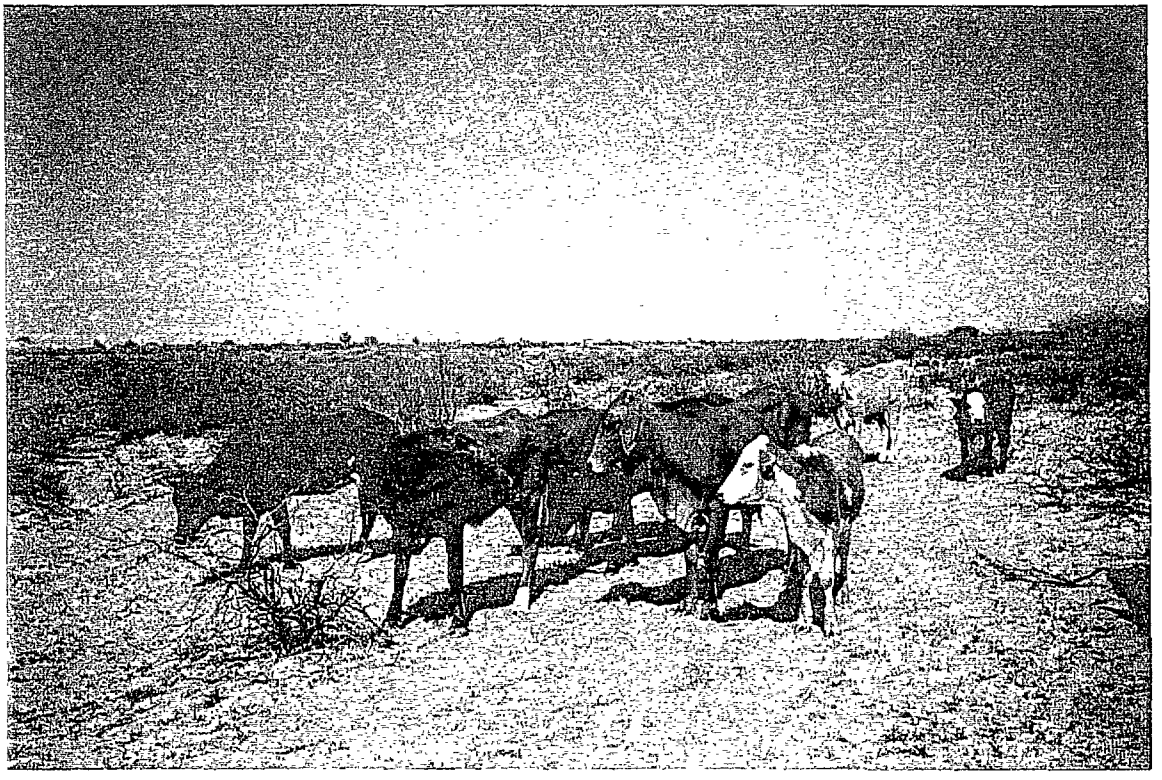


Figure 5. Extensive areas of bare soil prevalent during the 1994 wet season in the hardveld plains ecosystem I southeast of Kanye.

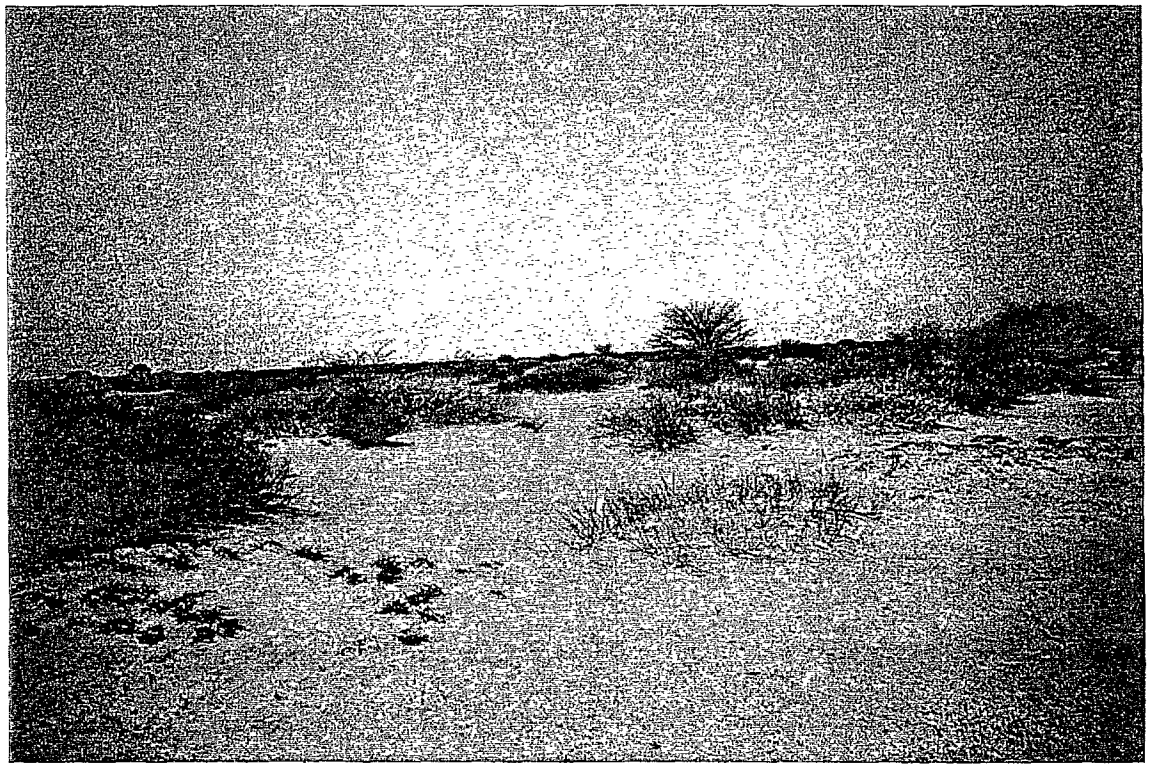
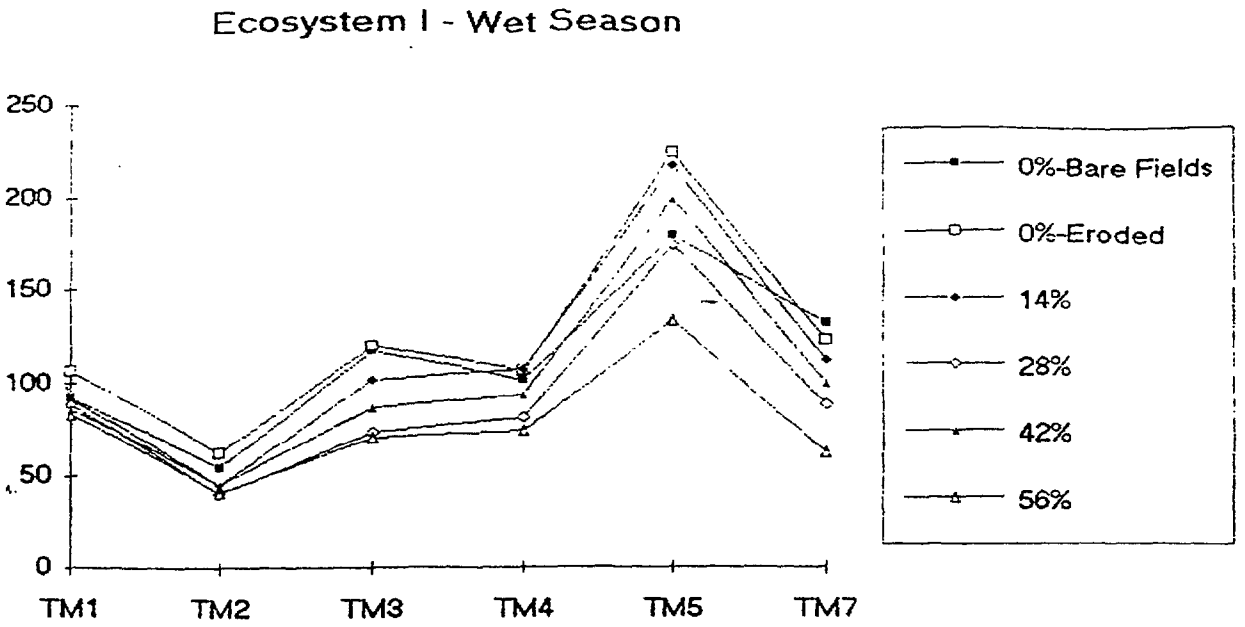


Figure 6. Extensive areas of windblown sand trapped in *Acacia hebeclada*, adjacent to zones transformed as a result of agricultural clearing in sandveld ecosystem VII (taller shrub ≐ 1.5m).



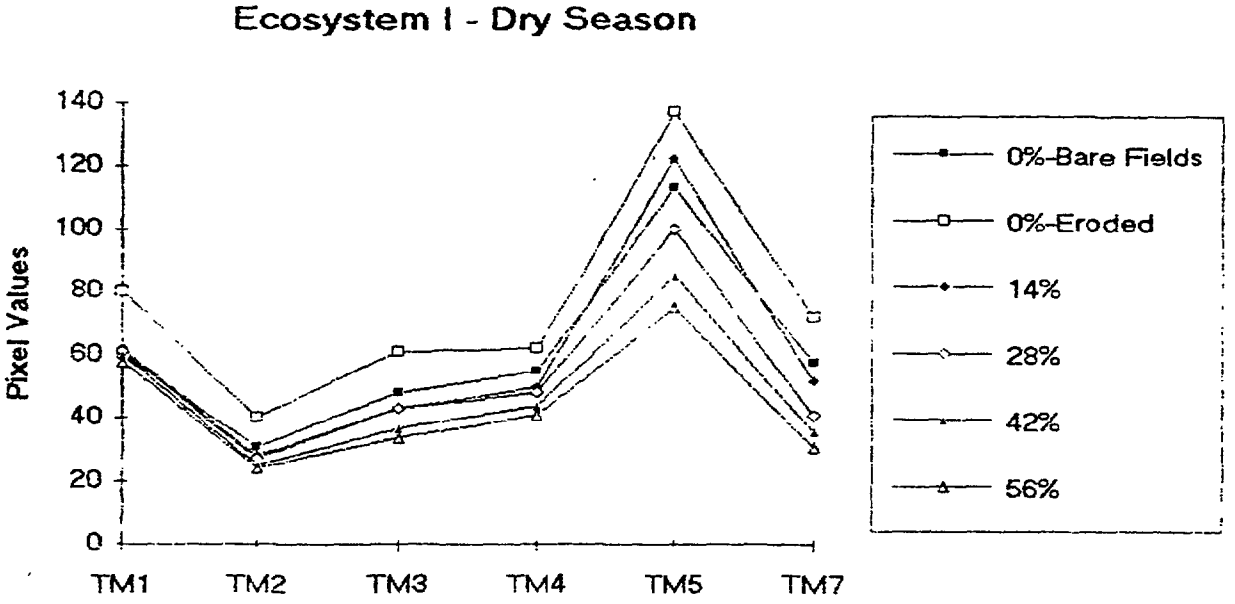
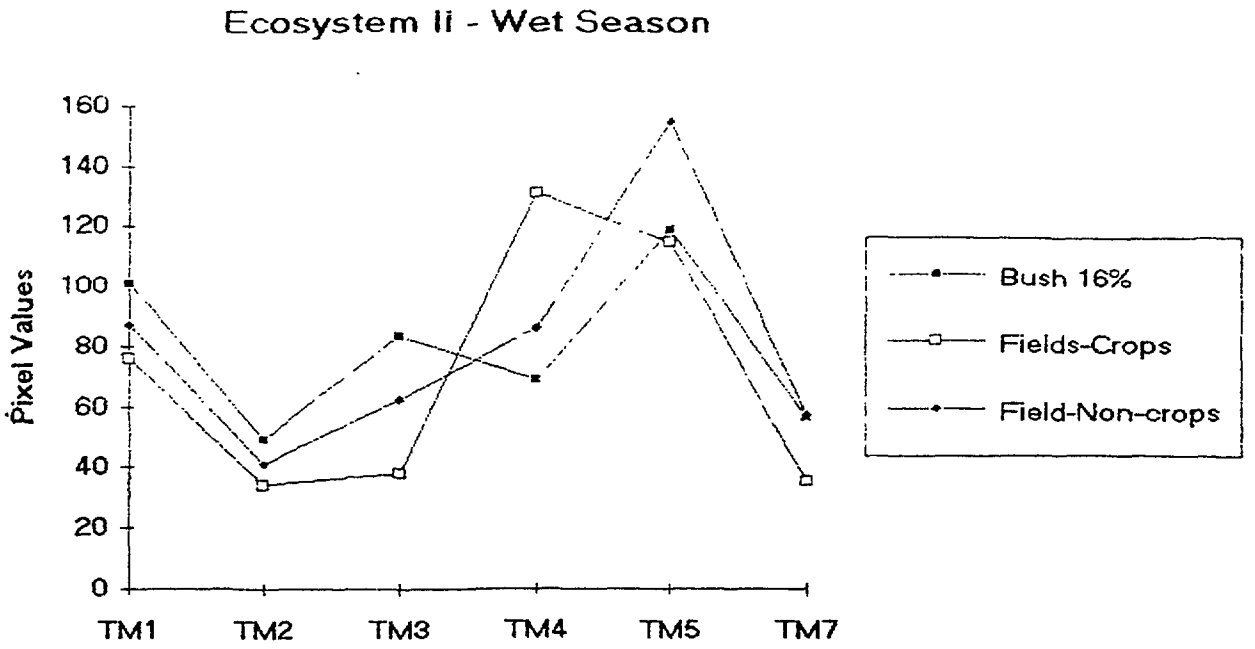


Figure 7. Differences between spectral reflectance curves with increments of vegetation cover for the hardveld plains ecosystem (I) over the six reflective TM bands.



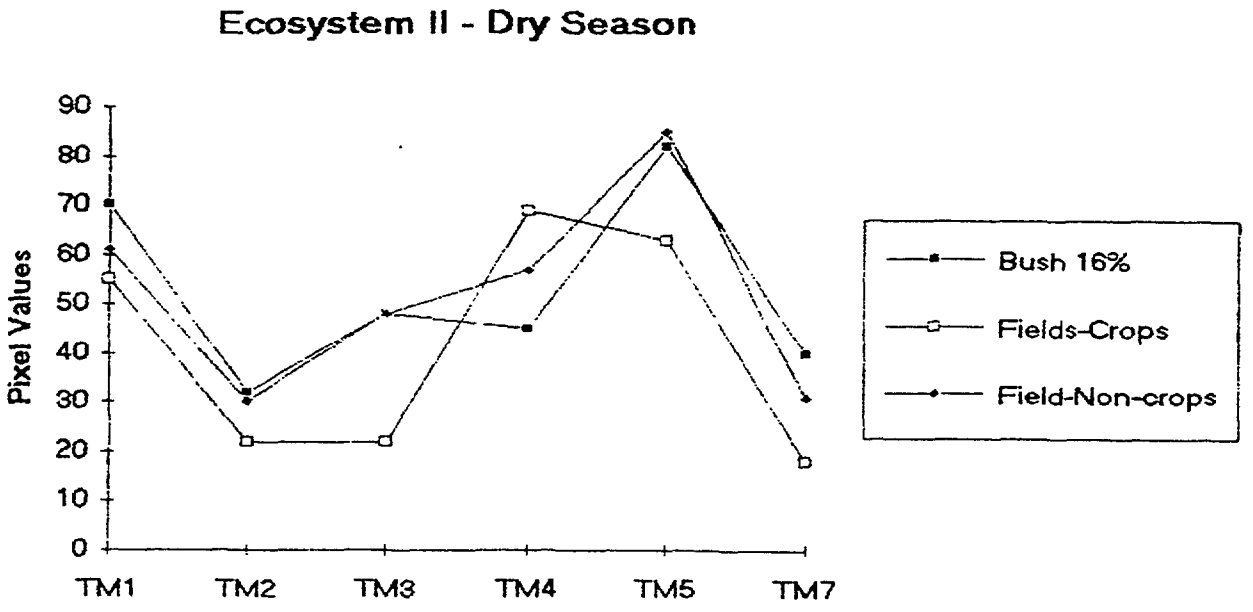
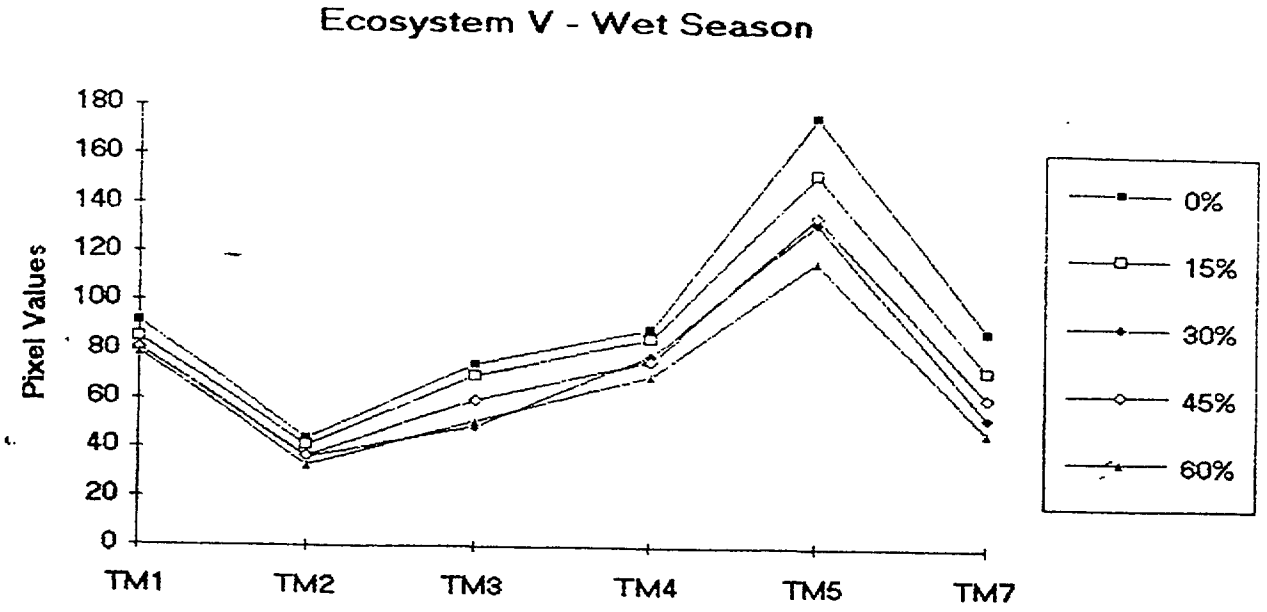


Figure 8. Differences between spectral reflectance curves with increments of vegetation cover for the hardveld cultivated valley ecosystem (II) over the six reflective TM bands.



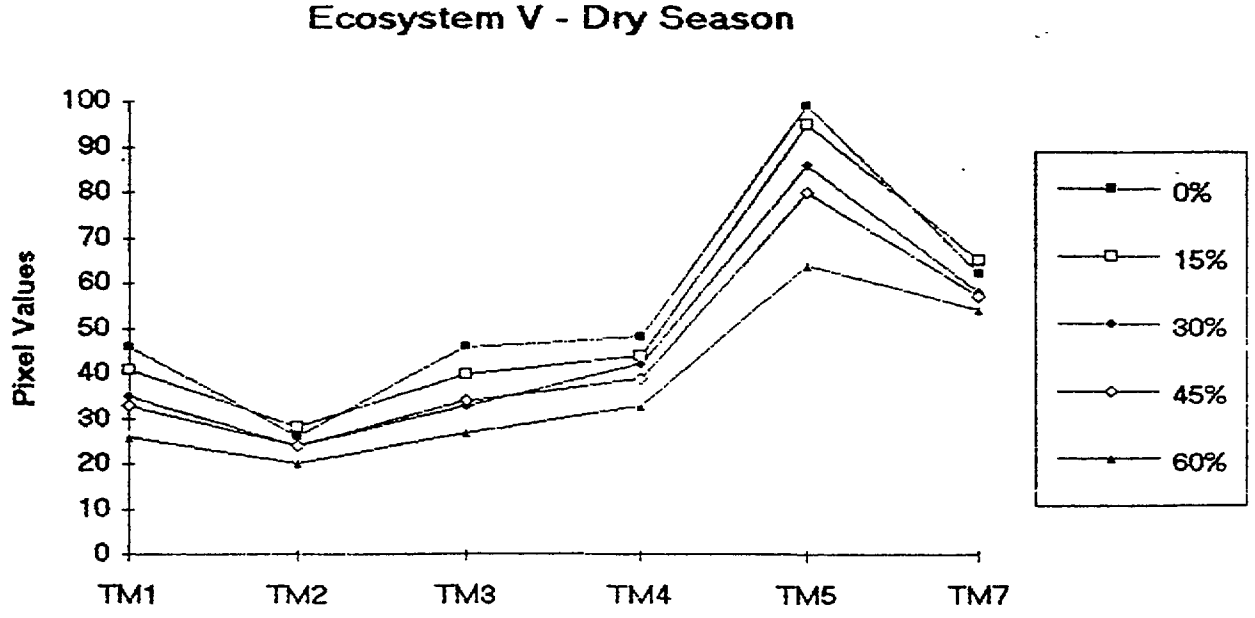
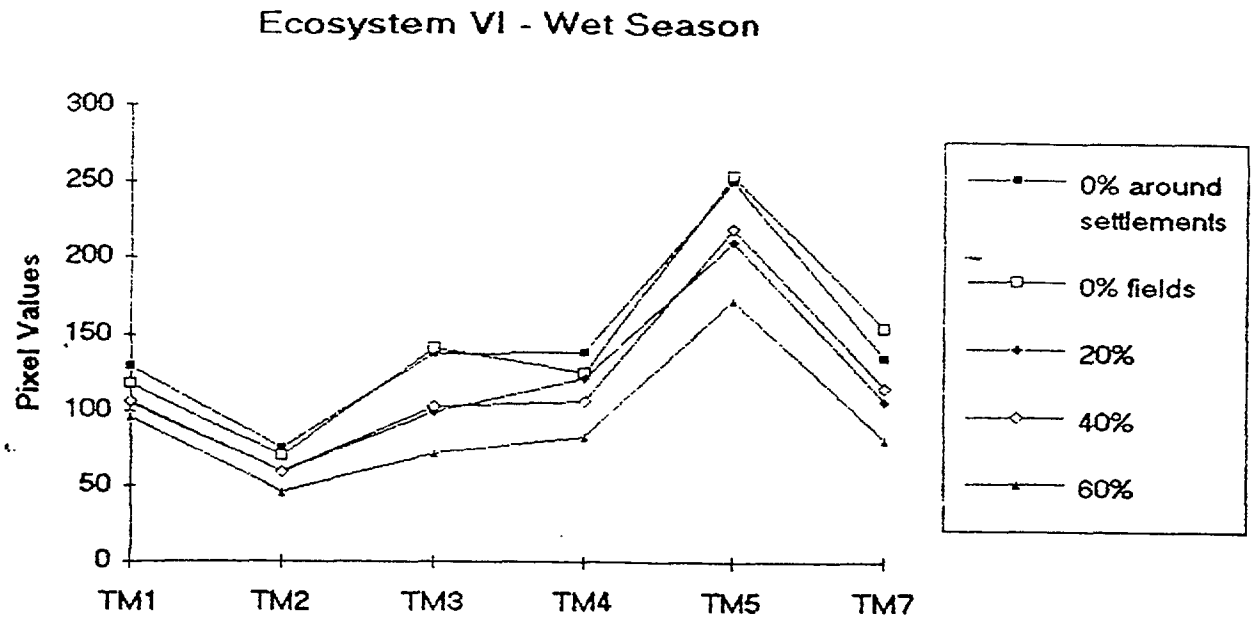


Figure 9. Differences between spectral reflectance curves with increments of vegetation cover for the hardveld plateau/pediments ecosystem (V) over the six reflective TM bands.



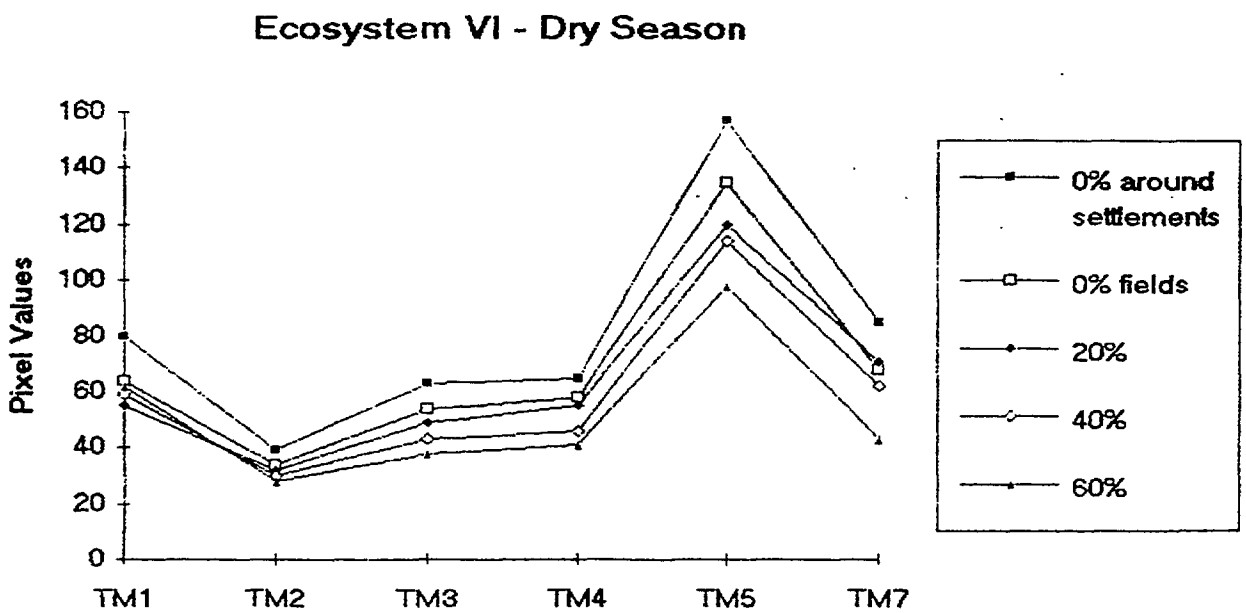
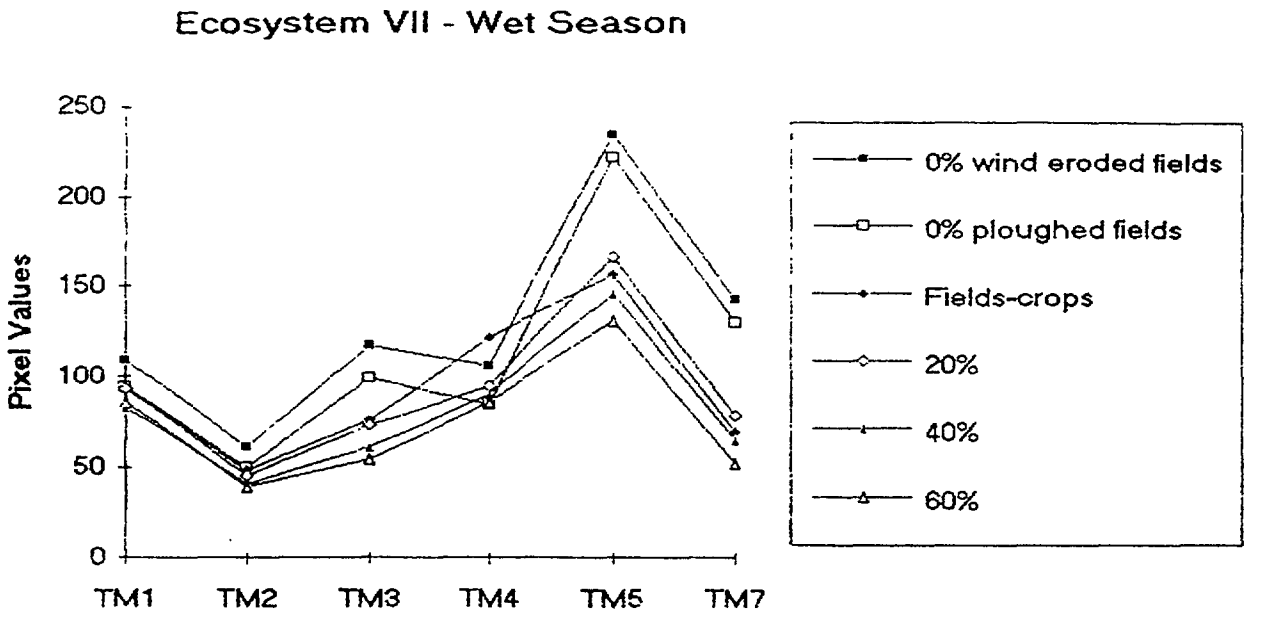


Figure 10. Differences between spectral reflectance curves with increments of vegetation cover for the sandveld darker soil ecosystem (VI) over the six reflective TM bands.



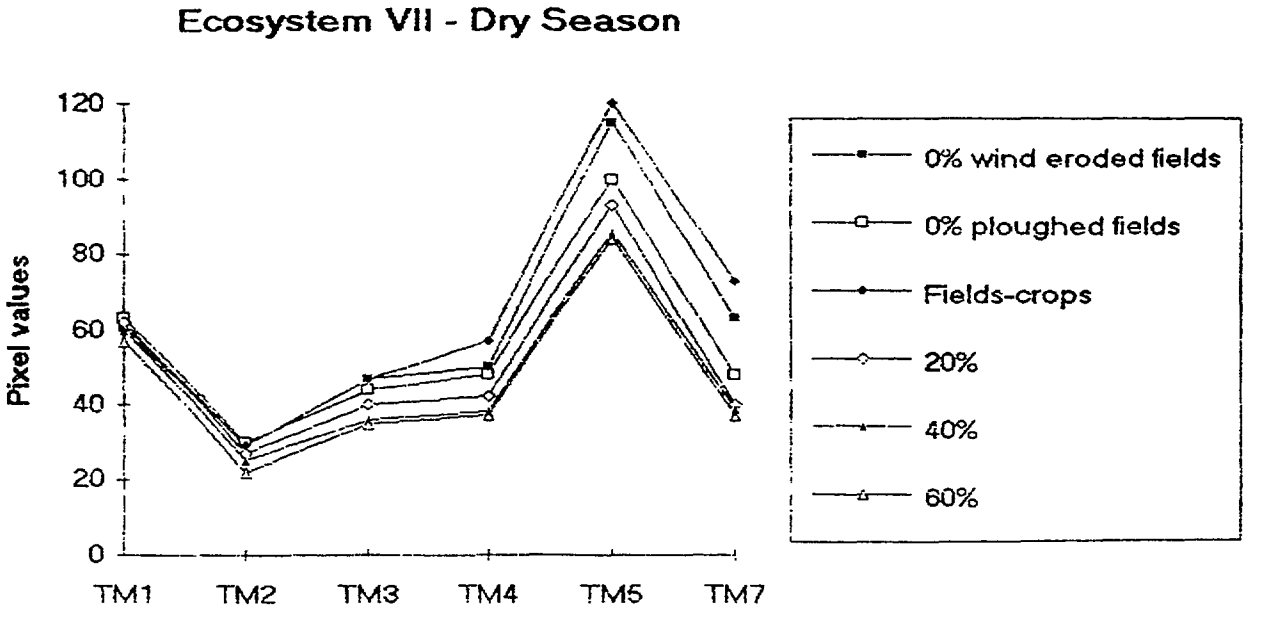
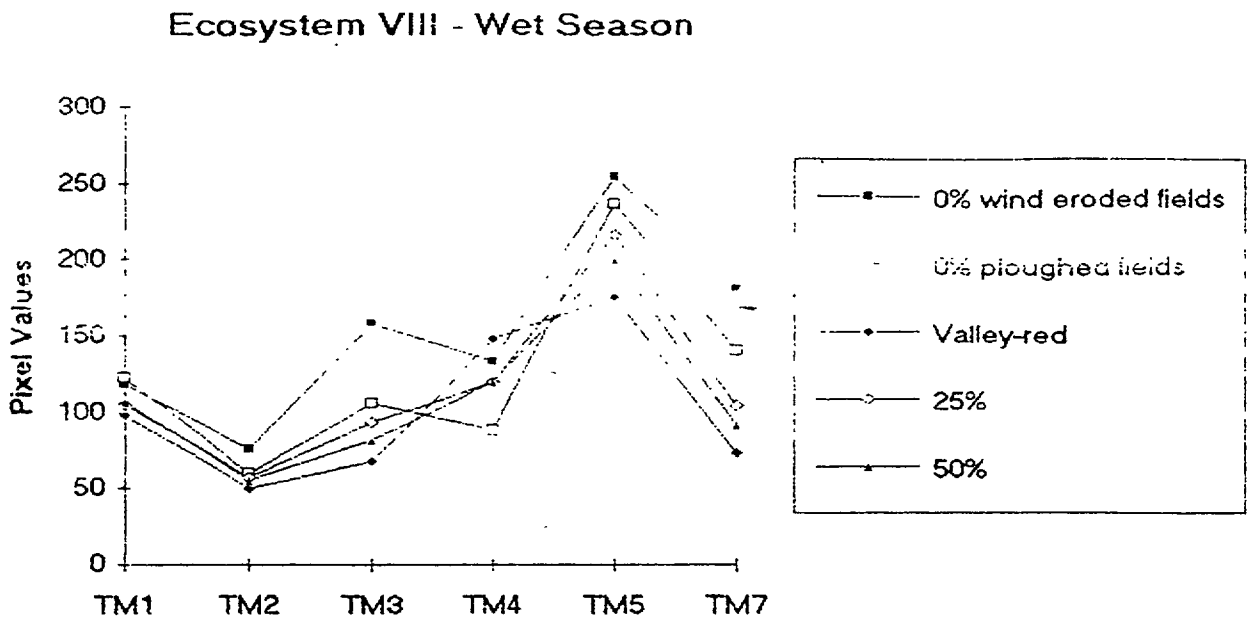


Figure 11. Differences between spectral reflectance curves with increments of vegetation cover for the sandveld lighter soil ecosystem (VII) over the six reflective TM bands.



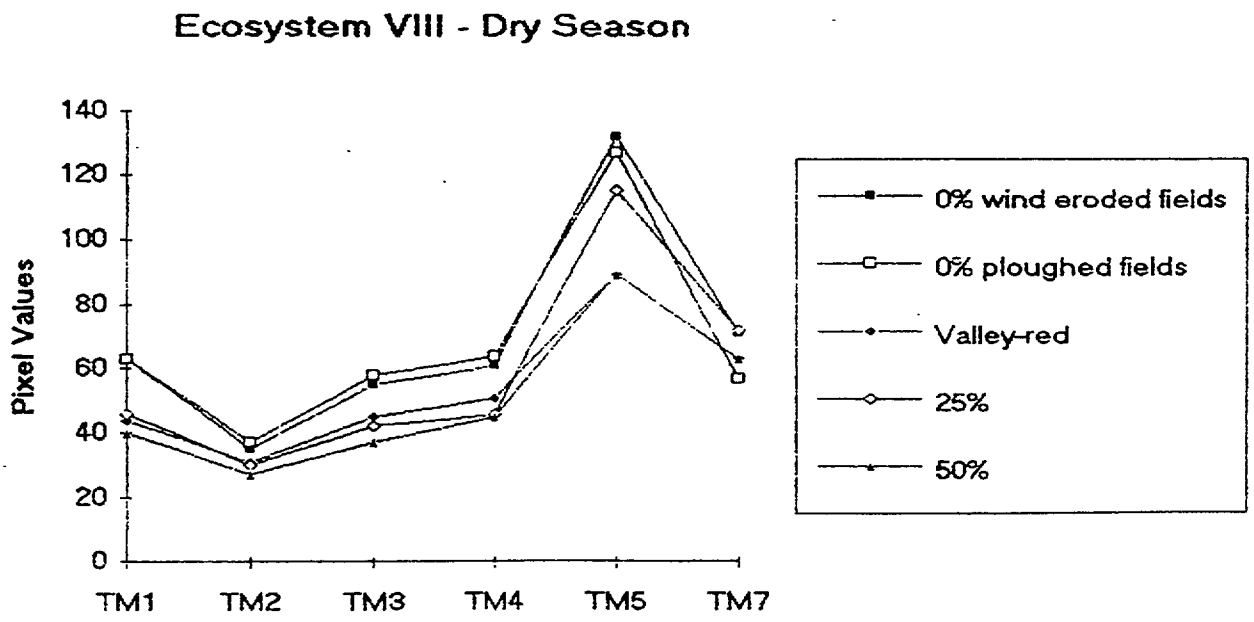
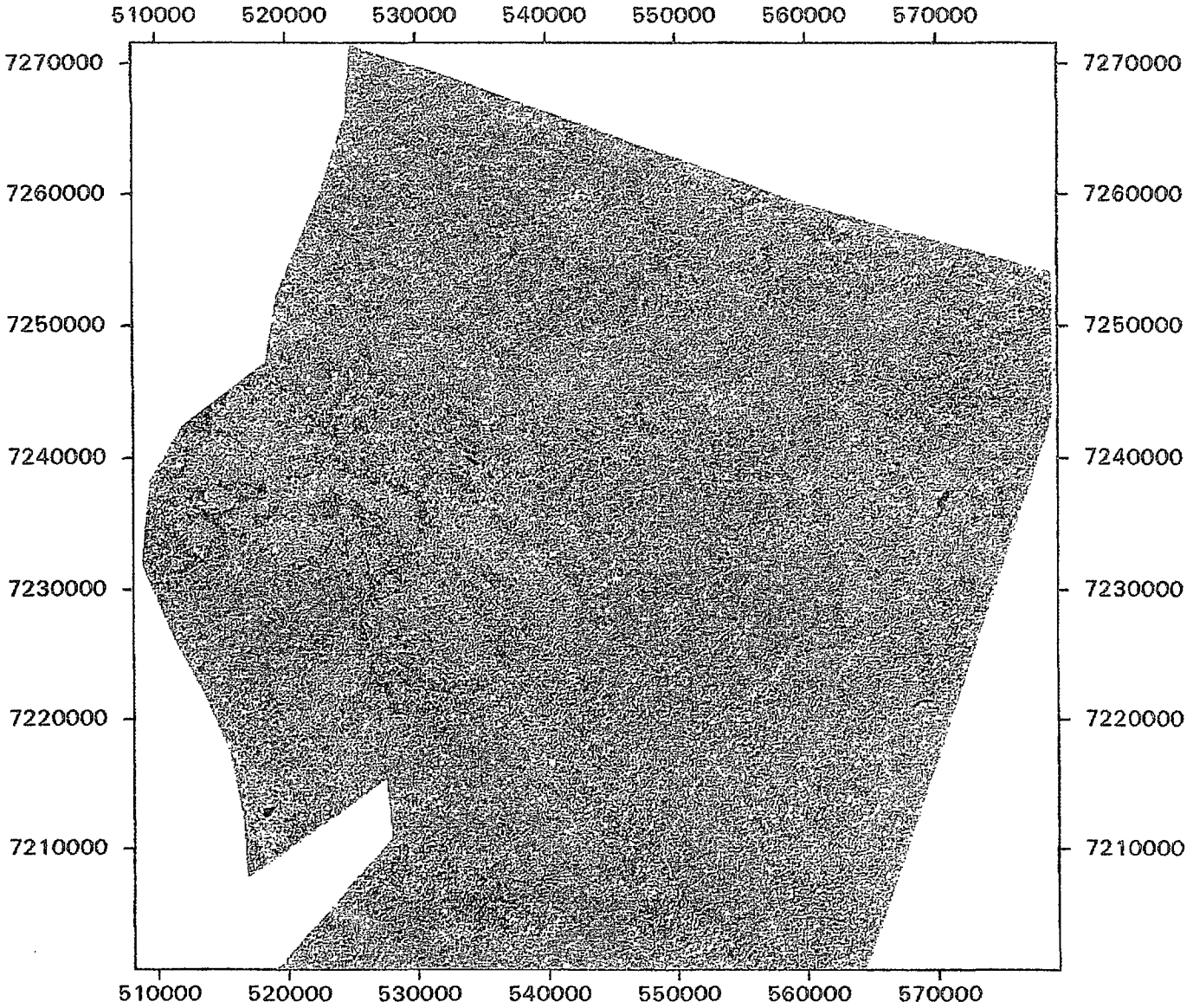


Figure 12. Differences between spectral reflectance curves with increments of vegetation cover for the sandveld fossil valley ecosystem (VIII) over the six reflective TM bands.



Partially vegetated fields
Bare fields - some erosion
Moderate vegetation cover on pediments/plains
Surface water
Bare fields
Moderate vegetation cover on plateau
Dense vegetation cover on plateau
Dense vegetation cover on pediments/plains
Hill shadow and gorges
Moderate vegetation cover on pediments/plains
Moderate dense riparian/plains vegetation cover
Sparsely vegetated near surface bedrock
Moderately vegetated near surface bedrock
Pans - highly reflective soils
Dense vegetation cover on plains/plateau and clay valleys
Moderate sparse vegetation cover on plains - some erosion

Scale

10 0 10 Kilometers

1 : 600000

Figure 13. Map showing the spatial extent of vegetation density/land-use classes for the hardveld ecosystems during the 1994 wet season.

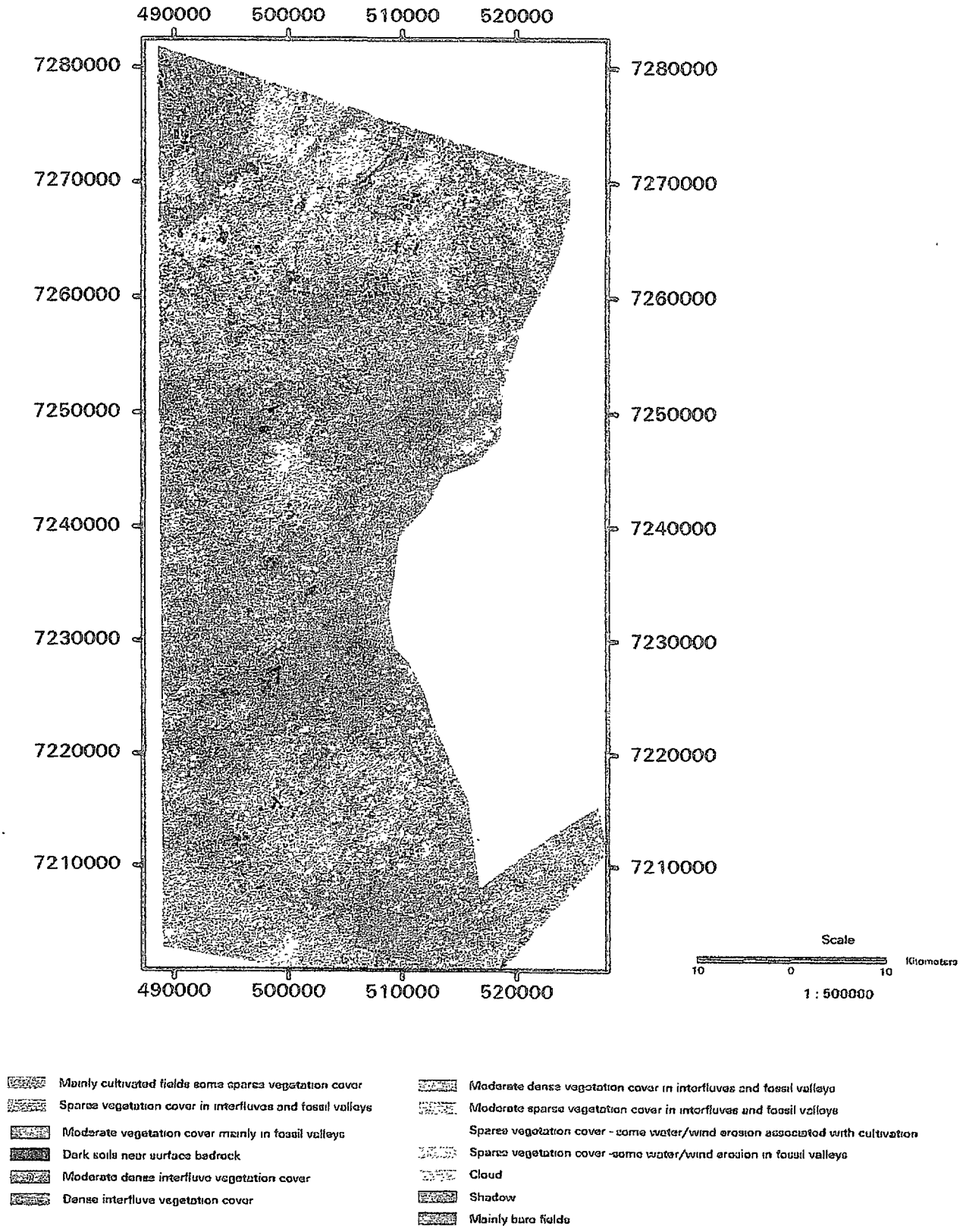


Figure 14. Map showing the spatial extent of vegetation density/land-use classes for the sandveld ecosystems during the 1994 wet season.

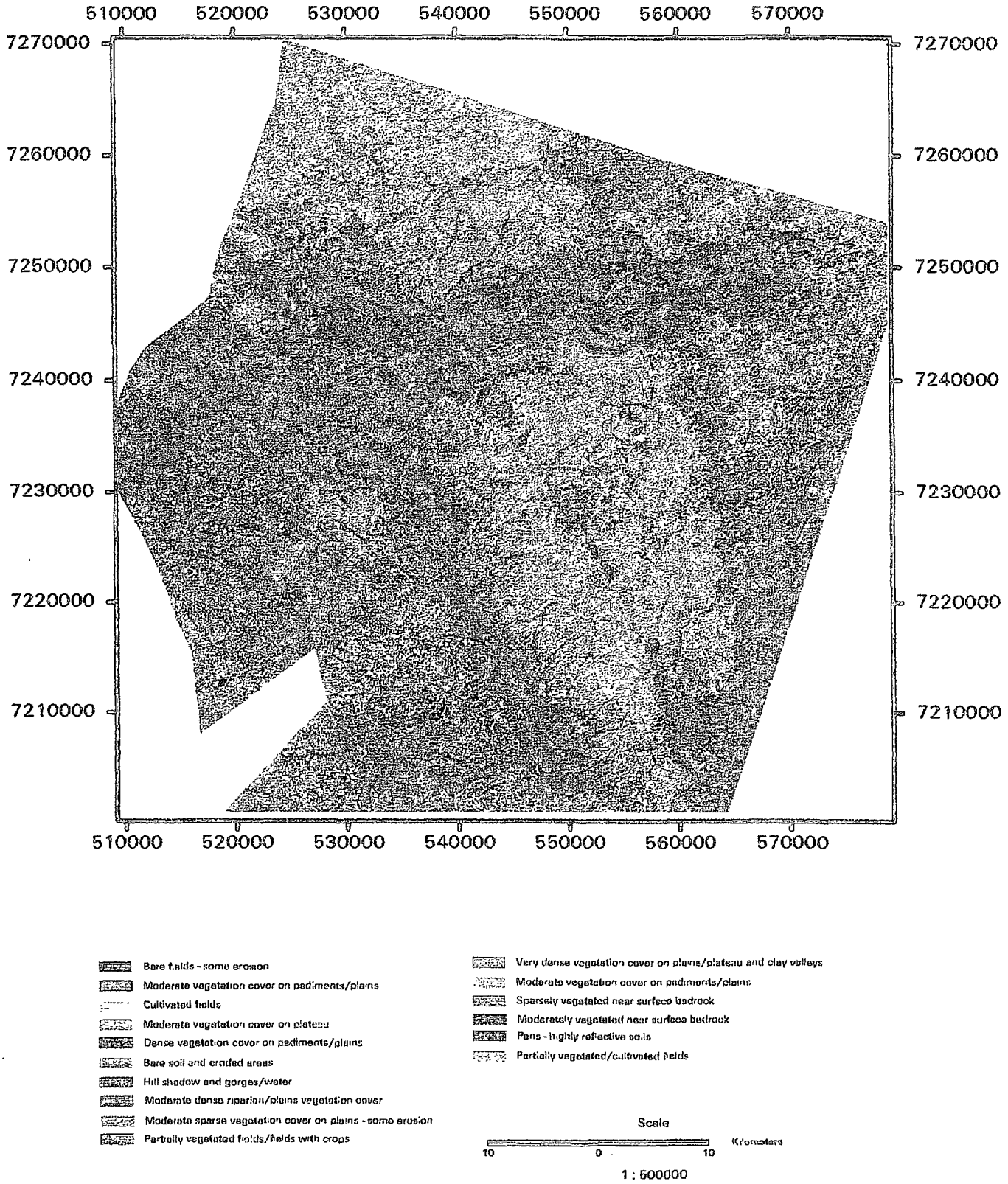
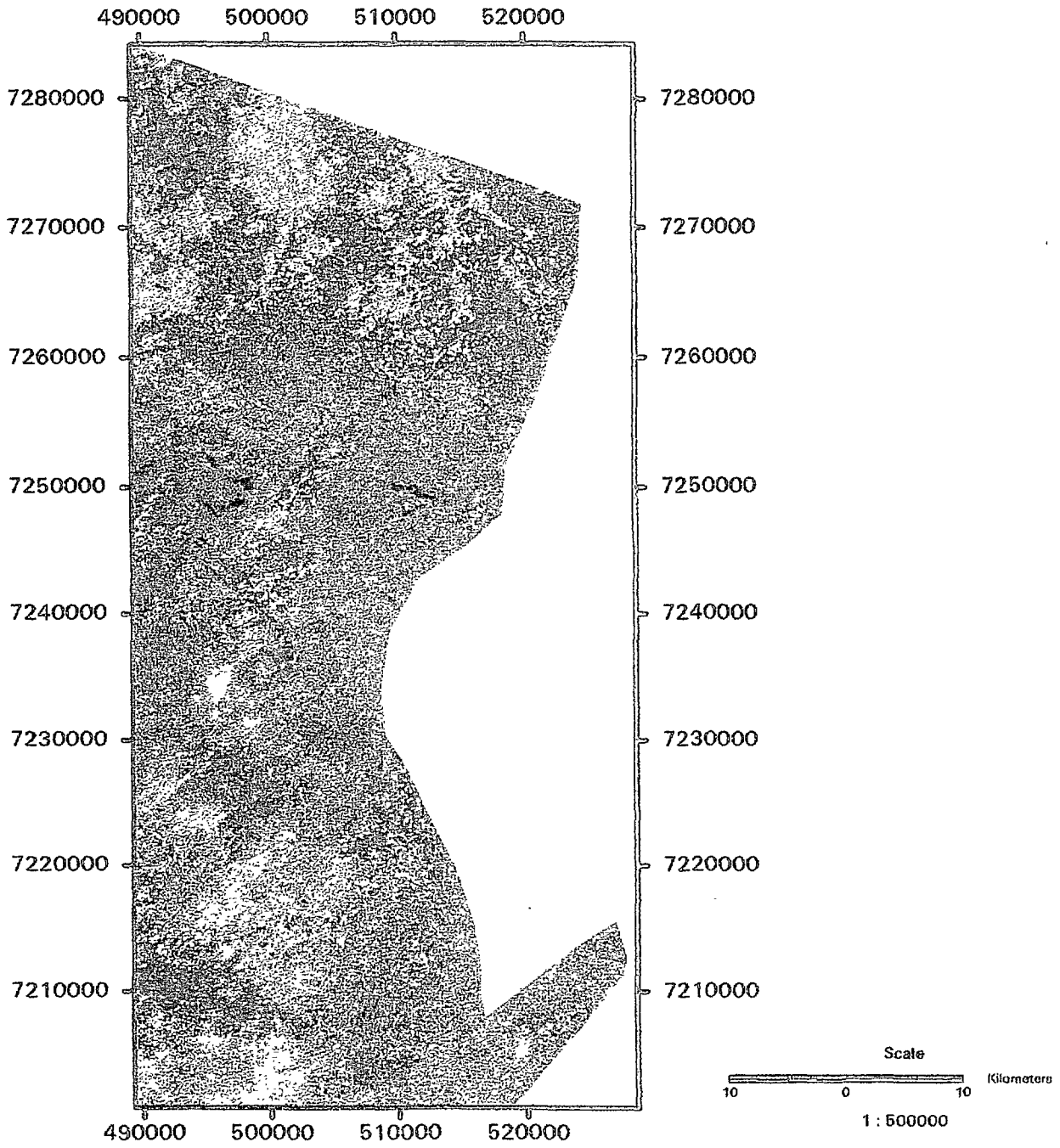


Figure 15. Map showing the spatial extent of vegetation density/land-use classes for the hardveld ecosystems during the 1994 dry season.



Mainly bare fields some sparse vegetation cover

Sparse vegetation cover -some wind/water erosion associated with cultivation

Pans and light coloured soils

Dark soils near surface bedrock

Moderate dense interfluve vegetation cover

Sparse interfluve vegetation cover

Moderate-sparse vegetation cover in interfluves and fossil valleys

Moderate-dense vegetation cover - in interfluves and fossil valleys

Sparse vegetation cover some wind/water erosion in fossil valleys

Figure 16. Map showing the spatial extent of vegetation density/land-use classes for the sandveld ecosystems during the 1994 dry season.