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Use of image processing and GIS techniques to determine the extent and possible causes of land management/fenceline induced degradation problems in the Okavango area, northern Botswana

S. RINGROSE,‡ C. VANDERPOST‡ and W. MATHESON†

‡Department of Environmental Science, University of Botswana, Gaborone, Botswana

†Westwood International School, P.O. Box 2446, Gaborone, Botswana

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Abstract. Attention worldwide has been focused on the need to assess the appropriateness of land management strategies especially where these occur near sensitive areas of wildlife habitat. This work considers the use of mainly Thematic Mapper data in providing an assessment of the relative impact of different land management strategies on the natural vegetation cover in part of the sensitive Okavango area in Botswana. Supervised classification (maximum likelihood) techniques when used on six-band TM imagery showed that differential degradation was prevalent in land management areas, especially where these are separated by fencelines with an overall accuracy 72 per cent. Marginally more degradation is evident in a controlled hunting area adjacent to the Game Reserve, relative to a communal grazing area. Band transform analyses indicate that distinctive changes in cover type and density frequently take place over boundaries or fencelines separating land management areas. Some degradation in the controlled hunting area appears related to the influence of faultlines on the distribution of soil, hence plant community types. In other cases the pattern of degradation is distributed randomly between the Game Reserve and the cordon fence. Reasons for this unusual distribution pattern may lie in the restriction of movement of migratory wildlife species southwards by the cordon fence separating communal grazing from hunting land uses. A more appropriate management strategy may lie in the prediction of wildlife movements, prior to the erection of cordon fences.

1. Introduction

Considerable attention has been focused on the use of satellite imagery and GIS analysis techniques, and their role in providing data to help resolve resource conflicts, in the Third World and elsewhere (Hellden 1991, Breininger *et al.* 1991). These include assisting in the resolution of land-use related environmental problems which tend to focus on degradation issues currently widespread across Africa. Data derived from satellite imagery has been used in this context to show the extent of human induced degradation as opposed to that driven by droughts or seasonal effects (Otterman 1974, Ringrose *et al.* 1990, Ringrose and Matheson 1992, ~~Steininger 1996~~). High resolution imagery has shown that the effects of degradation in southern Africa tend to be either localized expanding bare soil areas away from discrete locations or are manifested as areas of woody weed formation (bush encroachment) (e.g., Perkins and Thomas 1993, Ringrose *et al.* 1996).

Throughout southern Africa problems arise from human and livestock population pressure and general development activities which include increasing demands for

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arable land, tourism pressure and water usage. These activities are particularly acute in areas of communal grazing which now contain very little wildlife and which are subject increasingly to various forms of degradation (Sefe *et al.* 1996). Whereas it is assumed that savanna characteristics are related to specific determinants (Rutherford 1983, Scholes and Walker 1993) little research has been undertaken on the relative involvement of herbivory (livestock and wildlife) and human veldproduct use (e.g., Vanderpost 1995) in the context of land degradation (Ringrose *et al.* 1996).

Little specific work has been undertaken using Landsat Thematic Mapper data, in combination with GIS techniques to ascertain major savanna determinants in the context of natural resource depletion (~~Matheson and Ringrose~~ 1991, Chavez and MacKinnon 1994). Increasing importance is attached to mapping aspects of vegetation cover using Thematic Mapper data although this has mainly taken place in wetter climates (Fiorella and Ripple 1993, Franklin 1995, Ghitter *et al.* 1995). Other studies have concentrated on the use of multi-spectral scanner data in relation to species content and vegetation structure (Matheson 1994) and how these change over time (Lee and Marsh 1995). Increasing emphasis is being placed on the use of Geographic Information Systems (GIS) to develop an improved understanding of complex vegetation-human inter-relationships in a spatial context. Mapped data derived from satellite imagery are often used as inputs to a GIS database (Ghosh 1993, O'Neill *et al.* 1993, Hastings and Di 1994, Ringrose *et al.* 1996).

The aims of the present work are to assess the viability of classification techniques as a basis for mapping vegetation cover and hence degrees of degradation, using Thematic Mapper imagery. The second part involves relating the extent and distribution of degraded areas to different land management strategies in part of the Okavango area using GIS techniques. Thirdly, an assessment is made of image processing results to determine vegetation cover changes in land management areas and across boundaries to ascertain whether boundary controls have a bearing on relative degradation.

2. Study area and satellite imagery

The southern Okavango area lies to the north-east of Maun, mainly in the Kalahari sandveld portion of north-central Botswana, administratively in Ngamiland District (figure 1). The area is located towards the south-eastern margin of the environmentally sensitive Okavango Delta between 19° 50′ and 20° 00′ S and 23° 50′ and 24° 00′ E. Four major (and not entirely mutually exclusive) land management systems are currently prevalent (figure 2). These include the National Park – Game Reserve area (part of Moremi Game Reserve which comprises 12·6 per cent of the area), the controlled hunting and tourism area (Wildlife Management Area, 37·3 per cent of the area), the communal grazing system which includes cattle posts (47·6 per cent of the area) and the cultivated area, which occurs close to settlements, for instance Shorobe (2·6 per cent of the area).

Irrespective of the needs of migratory animals and in an attempt to stem the outbreak of diseases, the major land management areas are mainly separated by cordon fences. While the Moremi Game Reserve in the north-east is not fenced thereby facilitating transitional land-uses, the main cordon fence (constructed in 1982) which runs northeastwards through the study area is a major land-use divide (figure 2). Some of the area to the south of the fence is under cultivated agriculture (molapo farms in the intermittently flooded Okavango distributary channels) or dryland farming. The remainder comprise communal rangelands which support

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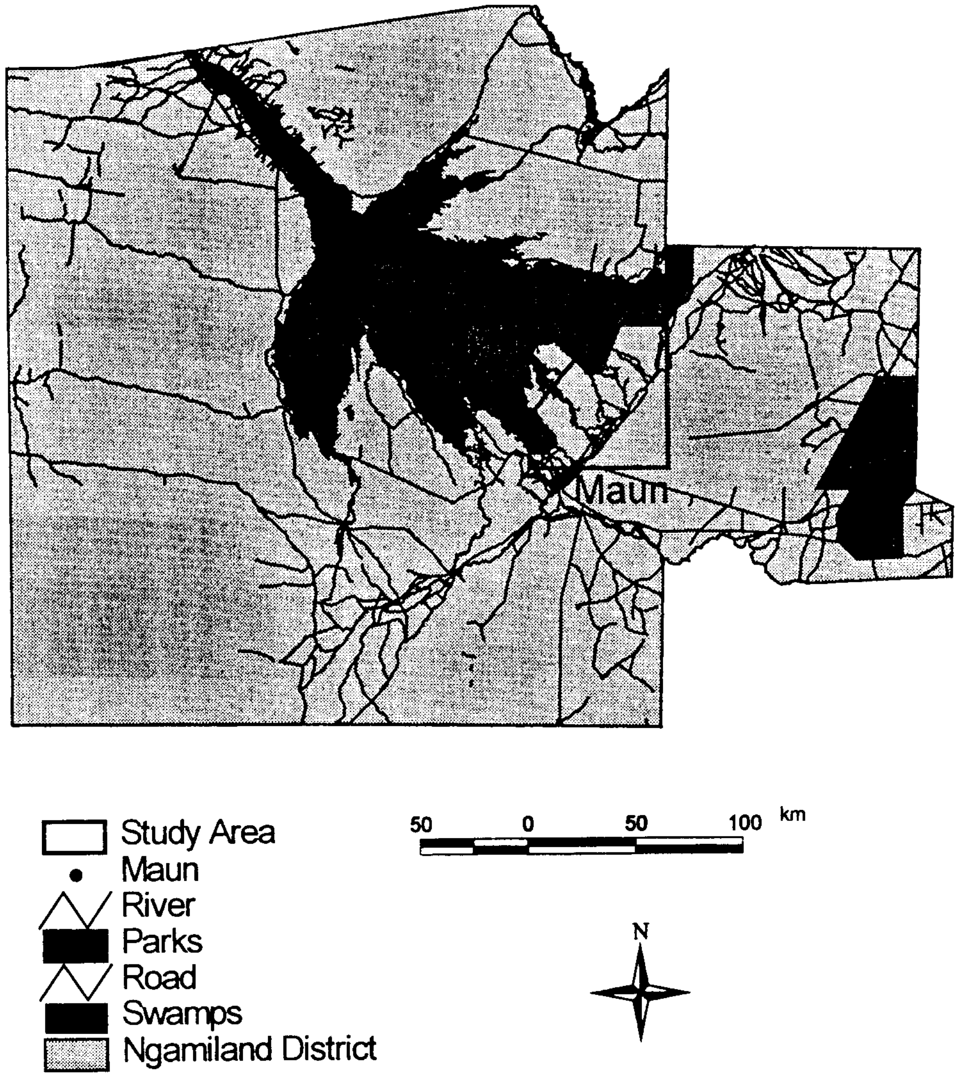

Figure 1. Location of study area in the distal Okavango delta, Ngamiland District, north-western Botswana.

livestock herding. Expansive herding, frequent fires and anthropogenic activity have a cumulative effect on the nature of the vegetation cover over time.

Both in arable and rangeland areas, people have modified the vegetation cover by removing especially woodland species during agricultural clearing, fuelwood collection and construction purposes. The effects of heavy grazing which decreases both the cover density and biodiversity of the area are found typically in the vicinity of settlements and cattle posts. These degraded areas tend to form concentric circles of vegetation depletion (mainly bare soil) followed by a wider zone of woody weed formation (Ringrose *et al.* 1996). North of the cordon fence, wildlife in the form of large herbivores and predators prevail both in the controlled hunting area and Game Reserve. A particular concern stems from the role played by wildlife in land radation.×

degradation

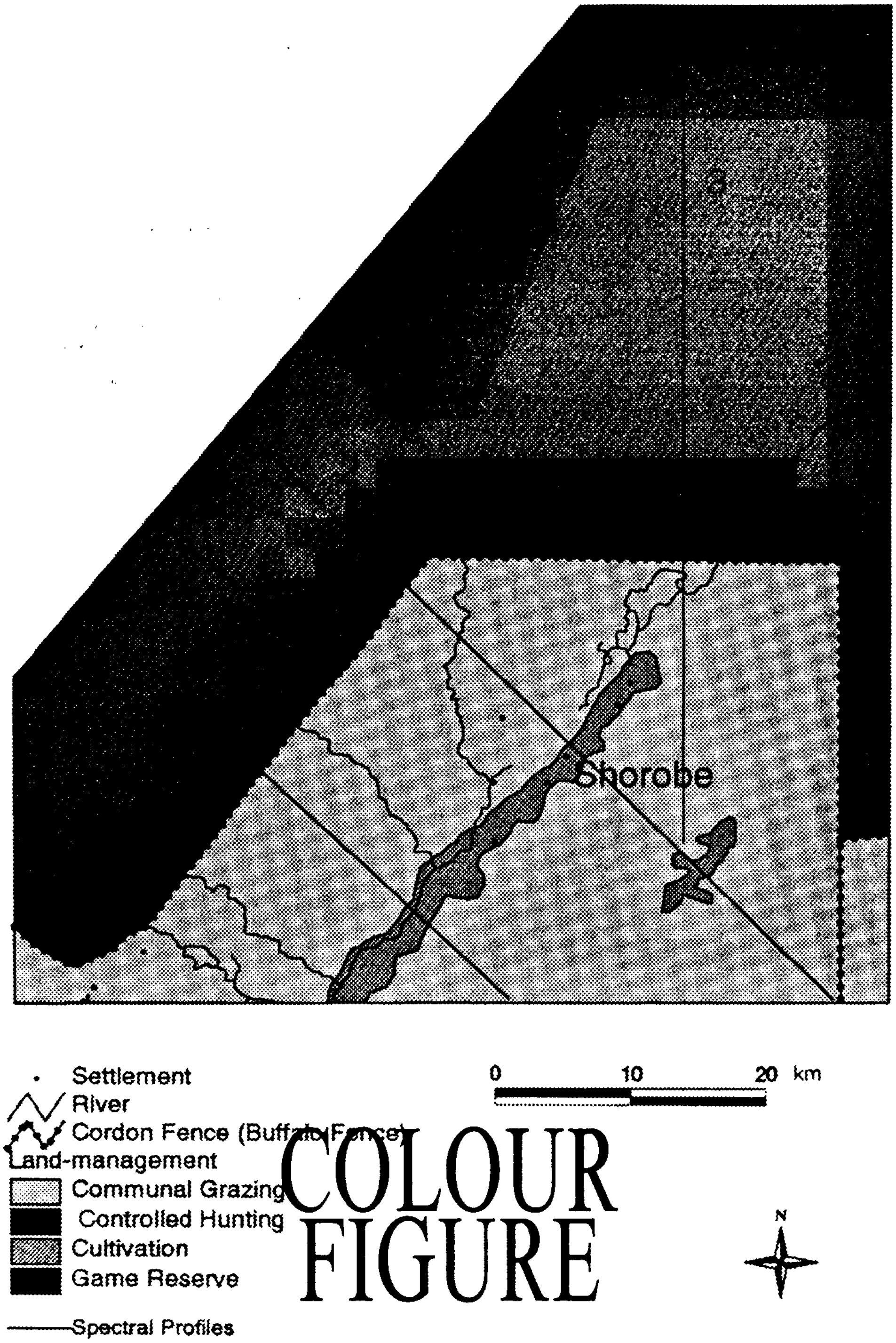

Figure 2. Main land management units in Okavango study area.

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Being part of the natural environment wildlife are not normally considered to contribute to degradation. However, problems arise from the restrictive nature of habitats in National Parks and Game Reserves and the needs of especially migratory species to move over wide areas in search of additional forage and water (Crowe 1996).

The southern Okavango is covered by part of one Thematic Mapper scene (177/074) and was obtained from Satellite Applications Centre, Pretoria, South Africa. The seven-band imagery was geometrically corrected to the UTM grid (Zone 34) at source. Cloud-free data were acquired on 20 August 1995 comprising 2601 × 2978 pixels. The imagery date was chosen to take advantage of peak flow through the Okavango distributaries. August also corresponds to the time of early fruiting or flowering among certain species in the various Okavango ecosystems. This occurs irrespective of the onset of rains in response to seasonal temperature changes. The TM data have an effective ground resolution (after resampling following geometric correction) of 25 m.

The Okavango distributaries which have changed their courses in recent geological times, present a complex environment within which a distinctive terminology has evolved to describe the various ecosystems (e.g., Ringrose *et al.* 1988, McCarthy and Ellery 1993, McCarthy *et al.* 1993, Ellery *et al.* 1995). After displaying several three-band combinations indications of a high degree of complexity was evident in terms of silty channels and floodplains juxtaposed with drier sandy tongues and islands (figure 3). However, in terms of internal homogeneity there is relatively little variability (as expressed in terms of pixel reflectance) within major land cover categories. For instance the floodplain soil–vegetation complexes are characteristically highly reflective in the mid-infrared (MIR). The greener mophane (*Colophospernum mopane*) woodlands on the drier sandveld have a higher near-infrared (NIR) reflectance while mixed Acacia woodlands are depicted by a darkening effect over bright sandy soils (Ringrose *et al.* 1988, 1989). Boundaries between major cover types are frequently sharp, with only occasional transitional ecotones. Preliminary data analyses show that many of the TM bands for the study area are highly correlated leading to data redundancy. The least correlated band is TM6 which was incorporated into the analysis after resampling. The least correlated reflective bands are TM3 and TM4 (table 1).

3. Field work and soils data

Field work was conducted during August 1995 at the time of image acquisition. After general reconnaissance, sample sites were established to facilitate direct association between vegetative cover and multi-spectral reflectance characteristics. This technique has been used frequently in Botswana, the Sahel and Australia and is described in the literature (e.g., Ringrose and Matheson 1992, Matheson and Ringrose 1994 a, 1994 b). A series of 64 sites were selected and field measurements taken to represent the main plant community types and density variations. Each site was located using a Magellan NAV7000AX Global Positioning System to ±50 m. Table 2 lists the main species associations found during the field work exercise with contributions from background data sources (Palgrave 1981, MLGLH 1989, Roodt 1995).

Additional work was undertaken using 1:250 000 soil maps (Soil Mapping and Advisory Services 1990) to determine the relationship between soil factors and the occurrence of degradation. Soil data are available in digital format from the Botswana Ministry of Agriculture. These required boundary merging and attribute editing as

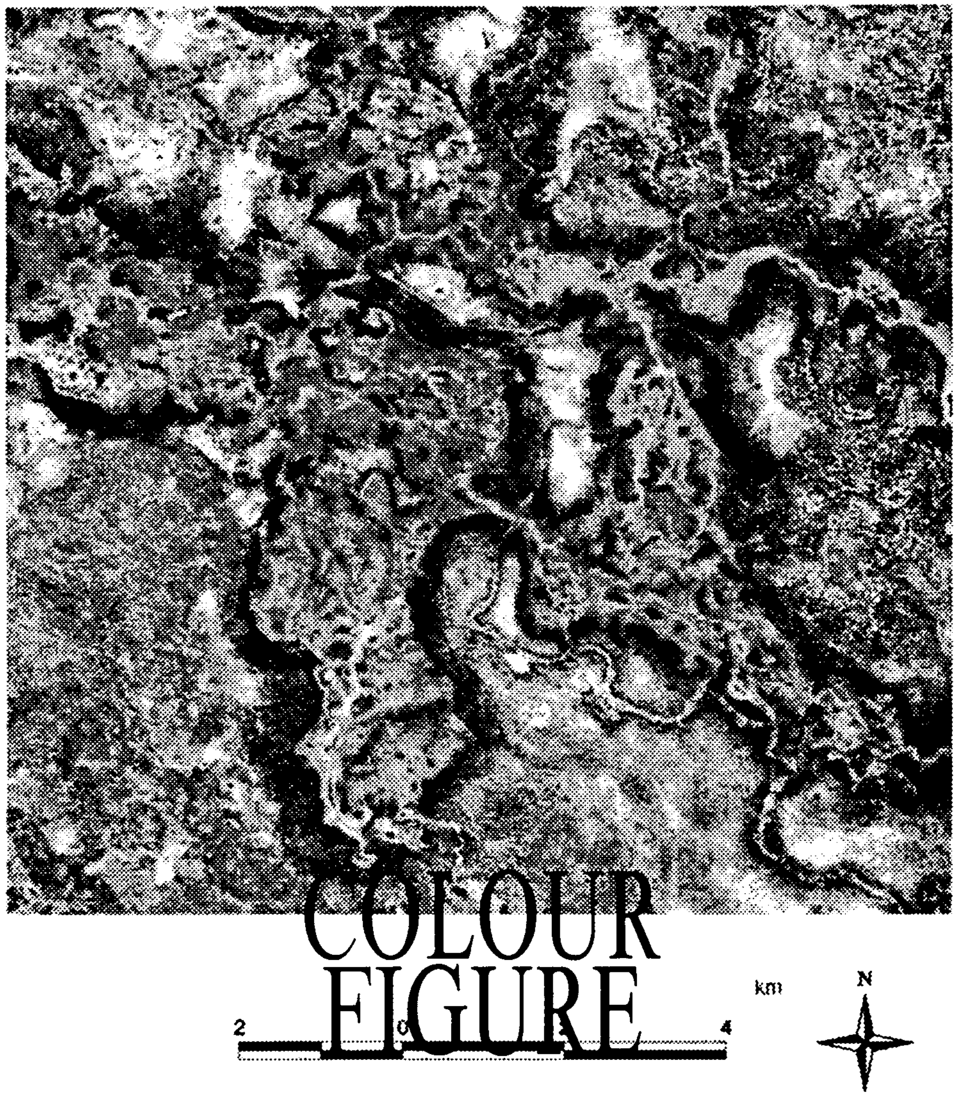

Figure 3. Part of the Okavango area showing floodplains (TM5-pink), dense mophane, (TM4-green) and darkened vegetation on highly reflective arenosols (TM3-grey).

Table 1. Correlation between bands for field site data ($n = 594$).

	TM1	TM2	TM3	TM4	TM5	TM6	TM7
TM1	—	0·91	0·96	0·87	0·95	0·31	0·90
TM2		—	0·94	0·81	0·91	0·32	0·90
TM3			—	0·87	0·95	0·31	0·93
TM4				—	0·82	0·26	0·80
TM5					—	0·44	0·99
TM6						—	0·44
TM7							—

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Table 2. General species associations from field work and ancillary data—Okavango area.

Mophane woodland (dry)
1. Mixed mophane
2. Monospecific mophane
3. Shrub mophane
4. Marginal calcrete zone

Acacia woodland (dry)
5. *Acacia erioloba* woodland
6. *Acacia tortilis* woodland

Sandveld (dry)
7. *Terminalia sericea* woodland
8. Mixed sandveld woodland
9. Disturbed woodland–shrubland

Marginal floodplain woodland (islands) (wet or seasonally wet)
10. *Acacia nigrescens* marginal woodland
11. *Hyphaene petersiana* marginal woodland

Marginal floodplain woodland-islands (seasonally wet)
12. *Combretum imberbe* marginal woodland

Localized depression woodlands
13. *Terminalia prunioides* (Boteti) woodland

Floodplain areas (dry and seasonally wet)
14. Bare soil—sparse grass cover
15. *Vernonia* spp. and/or grasses
16. Shrub-covered

Channel areas
17. Permanent/seasonal swamp vegetation cover and associated seasonally wet channels

part of the present work. The main soil types are depicted on table 3 and figure 4. GIS analyses techniques were applied to assess the land management categories in terms of prevalent soils types to determine their relative distribution (table 4). Some similarity was established between the Game Reserve area and the communal grazing area in terms of dominant soil type (Calcaric Cambisol) and secondary soil type (Haplic Luvisol) although differences occur in the tertiary soil type. The controlled hunting and cultivated areas also showed broad similarities as they comprise mainly Ferralic Arenosols with Haplic Calcisols being of secondary or tertiary importance. Relatively more Haplic Luvisols are found in the controlled hunting area. Soil distribution changes along the two north-east trending faultlines and the surface expression of the more westerly faultline was found to correspond to the north-east trending cordon fence (figure 2).

4. Statistical analyses of spectral data

Image processing was undertaken using ERDAS IMAGINE 8·2 running on a SPARC10 workstation. Relationships between major vegetation characteristics (in terms of relative density of woody cover, alive and dead herbaceous cover, litter and bare soil) and spectral data were explored. This was to determine which bands or band transformations may be useful for vegetation cover and/or degraded feature recognition within land management categories. Pixel data from the original seven bands were taken from field site locations on the image using the Inquire Cursor Function. The results were transferred into the statistical package SPSS and subject

Table 3. Description of main soils in the Maun area (from Soil Mapping and Advisory Services Project, 1990).

Soil type (FAO classification)	Soil description
Calcaric Cambisol	Moderate deep to very deep, imperfectly to moderately well drained dark greyish-brown to brown sandy loam to sandy clay
Haplic Luvisol	Deep to very deep, imperfectly to moderately well drained, dark greyish-brown to black sandy loam
Gleyic Luvisol	Deep to very deep, poorly to imperfectly drained dark grey to greyish-brown sandy clay loam to clay
Ferralic Arenosol	Deep to very deep, poorly to imperfectly drained, dark grey to greyish-brown sand
Haplic Calcisol	Shallow to moderately deep to imperfectly drained very dark greyish-brown to brown sandy loam to sandy clay
Arenosol/Gleysol Complex	Deep to very deep, poorly to imperfectly drained dark grey to greyish-brown sand to clay
Vertic Cambisol	Deep to very deep, imperfectly drained greyish-brown sandy clay loam to clay
Eutric Fluvisol	Very deep, very poorly to imperfectly drained black to dark greyish-brown sandy loam to clay
Gleysol/Arenosol Complex	Deep to very deep, poorly to imperfectly drained dark grey to greyish-brown clay to sand
Calcaric Luvisol	Deep to very deep, imperfectly to moderately well drained, dark greyish-brown to black sand to loamy sand over sandy loam

to regression and correlation analyses. Soil chroma and value data (Munsell Notation) were added to help infer soil type and/or condition (e.g., Ringrose *et al.* 1989). In an attempt to improve the degree of correlation between vegetation cover and spectral data, the latter were reformulated into Vegetation Indexes (VIs) and Principal Components transformations (PCA). Normally the standard VIs are predicated on relationships between bands detecting NIR scatter (e.g., TM4) relative to those detecting chlorophyll absorbance (e.g., TM3) although occasionally the green band is used (e.g., TM2) (Jensen 1986, Ringrose *et al.* 1994). These are manipulated into indexes such as the Normalised Difference Vegetation Index (NDVI) or its Transformed equivalent (TNDVI). Additional nonstandard indexes (table 7) were developed to make further use of vegetation data in TM5 or TM7. All vegetation index and PCA values were added to the field site results spreadsheet for analysis relative to known vegetation characteristics to determine their efficacy.

5. Image processing – classification

Because of the nature of the terrain and the fine resolution of the 25 m pixel-based imagery, a so-called 'hard' classification technique was applied to the Okavango imagery (cf. Foody 1996). This technique assumes that the dataset are normally distributed and that most pixels are relatively homogeneous (i.e., not significantly mixed) in terms of their reflectance values for a given cover type (§2). A 'soft' technique involving neural networks and mixture modelling was not used here as the aim was to produce a broad cover/plant community map, where the mapped units represent the extent (or density) of relatively mono-specific communities such as *C. mophane*, *A. nigrescens*/*C. imberbe* or *A. erioloba* using fine pixel resolution

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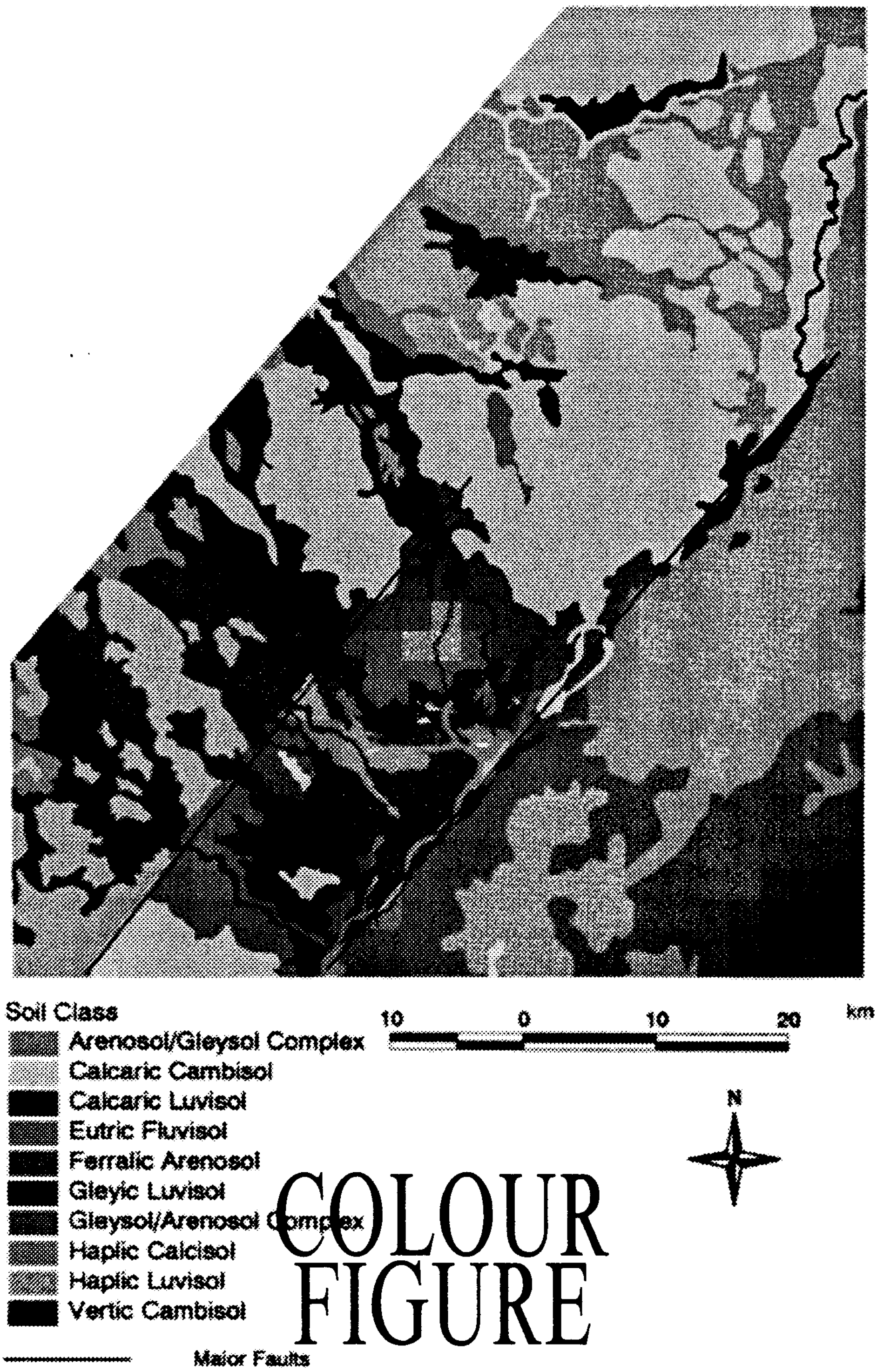

Figure 4. Distribution of the main soil types according to the FAO classification (Soil mapping and Advisory Services Project, 1990).

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Table 4. Relative frequency (percentage) of main soil types by land management class.

Soil type (FAO classification)	Game Reserve	Controlled hunting	Communal grazing	Cultivation
Calcaric Cambisol	40·1	8·6	38·3	1·7
Haplic Luvisol	23·1	17·8	14·8	1·3
Gleyic Luvisol	3·5	4·6	1·2	0·1
Ferralic Arenosol	0·00	34·4	1·6	58·3
Haplic Calcisol	2·8	10·4	5·0	18·8
Arenosol/Gleysol Complex	15·3	1·9	10·5	0·0
Vertic Cambisol	8·8	11·8	14·4	12·3
Eutric Fluvisol	3·1	2·9	2·3	7·2
Gleysol/Arenosol Complex	0·0	5·7	0·5	0·1
Calcaric Luvisol	3·3	2·0	11·4	0·2

data (25 m). Whereas some transitional ecotonal changes do occur, it appeared unlikely that an improvement to the dominant plant community-density map could be achieved by mixture modelling as this would result in additional transitional classes being created. The intention here is to develop an overview of the main plant communities and the relative extent of bare soil within them, so as to formulate classes which can be later used as indicators of relative degradation in specific land management areas.

Supervised classification was applied to the Okavango image using TM bands 2–7. TM1 was excluded because of its high degree of correlation especially with other visible bands. TM6 was included because of the need to clearly differentiate land- and water-based communities as problems had previously arisen when only reflective bands were used (Ringrose *et al.* 1988) because classification was intended to provide broad distribution information of the main plant community types and cover density, which have not previously been mapped at medium scales. Training sites for pattern recognition were developed in 6-dimension (TM) space from a number of locations known to represent typical vegetation-degradation conditions in the field. Once these locations were identified and enlarged, polygons were created interactively using area of interest (AOI) tools in a magnified viewer to ensure pixel homogeneity. Signature statistics were evaluated using standard procedures, including feature space plots, thresholding and the use of the alarm function (ERDAS Inc. 1991). The signature statistics were revised until a reasonable degree of separability of the resultant ellipses was apparent throughout the available feature space. The alarm function was used interactively to locate areas defined by training site pixel statistics on the original image. Hence a check was made to determine the reliability of the initial signatures in terms of overall image reflectance values.

Following the training exercise, a series of parametric signatures were generated based on the statistical parameters (e.g., mean vector and covariance matrix) of pixels in the training cluster. Classification was based on the maximum likelihood decision rule which was applied after first passing the data through feature space ellipse separation procedures. The basic algorithm assumes equal probabilities for all classes and that input bands are normally distributed. Most variability in terms of class reflectance characteristics was apparent in the mean values of TM5 and TM7 (figures

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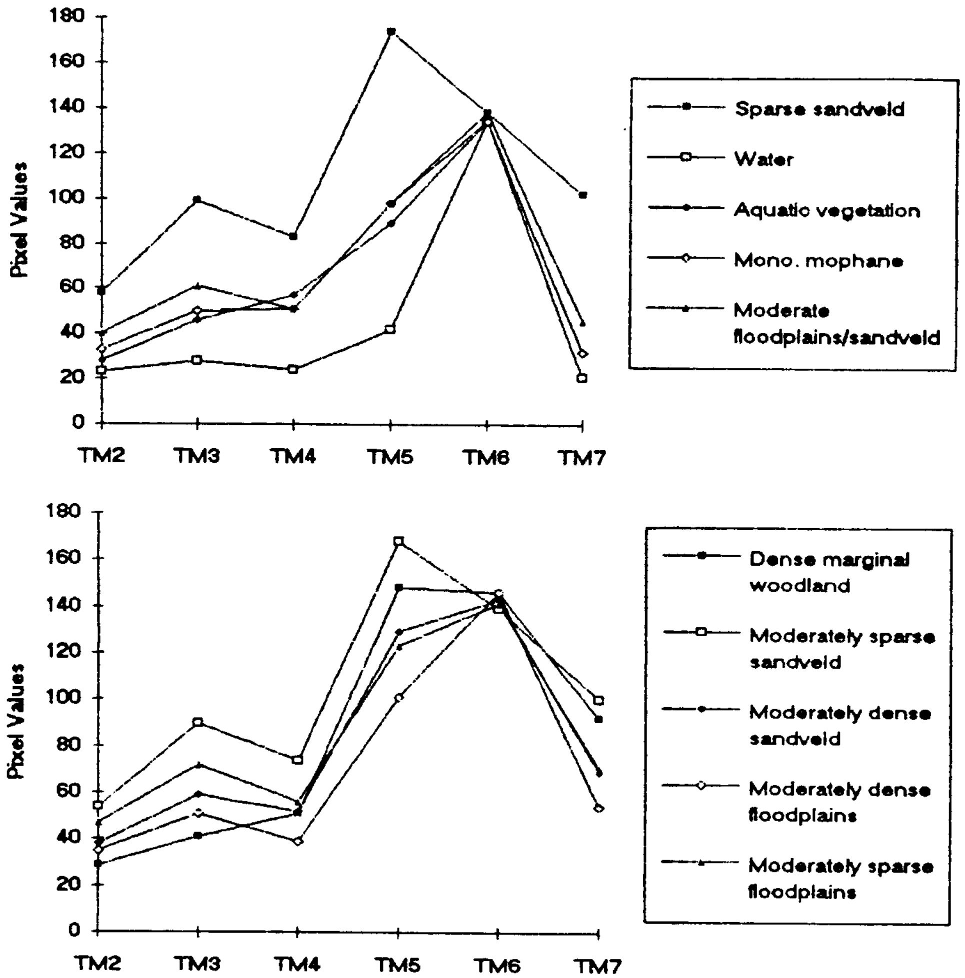

Figure 5. Mean spectral values of vegetation type Classes 1–10.

5 and 6). For most classes the average reflectance of TM4 is lower than that of TM3 or TM2 suggesting the prevalence of vegetation darkening in this semi-arid environment (Matheson 1994). However aquatic vegetation, dense/very dense marginal woodland categories (on figure 5) along with *T. sericea*/*A. erioloba* woodlands (on figure 6) all show relatively high NIR values.

Once classified, the data were smoothed using neighbourhood modal analysis through a majority 7 × 7 filter. The classified image was transferred to ARC/GRID and polygonized using a weed tolerance of 250 m to minimize the vertices. The smaller (less than 1 ha) islands were removed using the RESELECT function. The resulting map shows 20 different plant community/density classes (table 5 and figure 7). In the following descriptions, the terms dense refer to woodland/shrubland cover in excess of 45 per cent moderately dense = 25–45 per cent woodland/shrubland; moderate = 15–25 per cent woodland/shrubland; moderately sparse = 5–15 per cent mainly shrubland and sparse = less than 5 per cent usually shrubland.

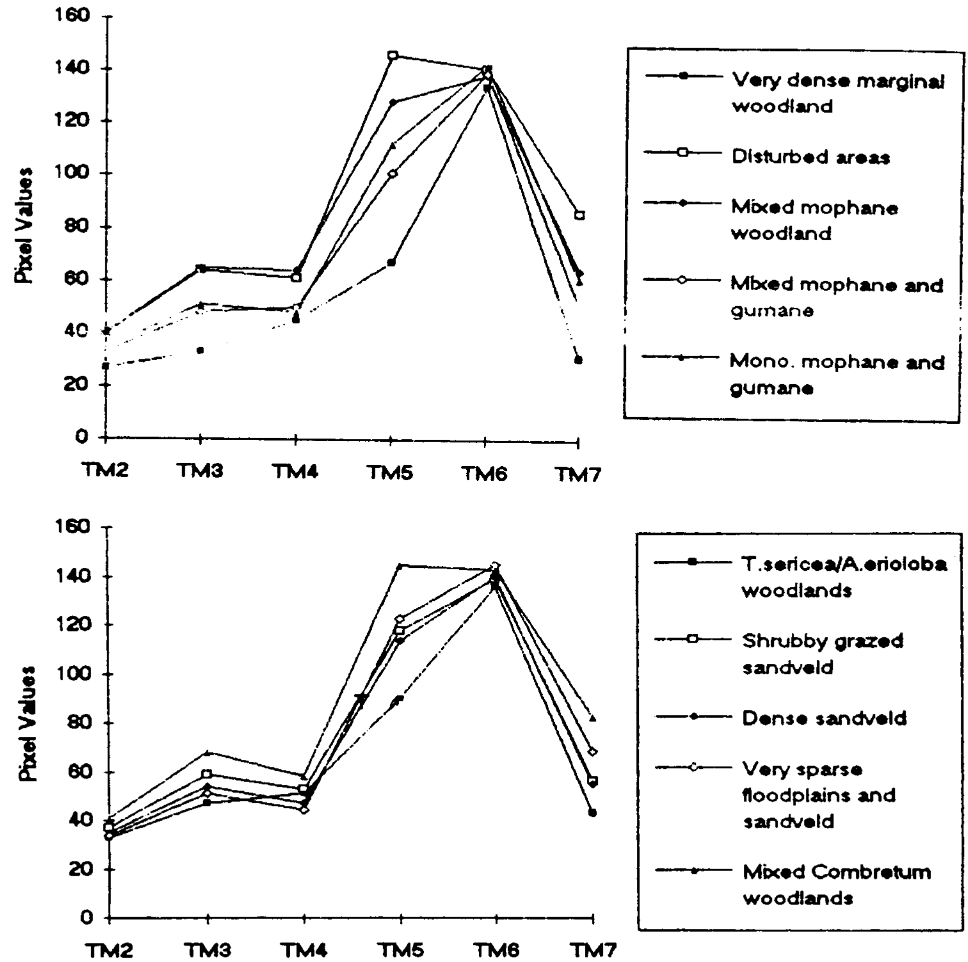

Figure 6. Mean spectral values of vegetation type Classes 11–20.

6. Statistical analyses

Statistical analyses were carried out to determine which bands or band transformations could be used to predict the amount of vegetation cover and therefore provide some concrete evidence for degraded areas. Single band data show that the highest correlations in relation to woody vegetation cover are found in TM2, TM3 and TM5 (table 6). The correlation coefficients show negative relationships for all bands including the thermal band. These relationships are typical of a dry season image in Botswana even though some green cover persists for instance in the ubiquitous mophane woodlands. The statistical results imply that despite mid-August being the time of maximum river flow, vegetative regrowth is minimal. The soil value (intensity) and chroma (contrast) terms of the Munsell colour notation do not significantly influence reflectance relationships in the study area and therefore are not considered further.

The results of correlation analysis for the Vegetation Indexes and Principal Components images suggest that additional information can be obtained beyond that ascribed to the individual bands (table 7). The TM4–TM3, LOGTM4–TM3,

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Table 5. Results of classification analysis and interpretation of classes in terms of major plant communities as derived from TM imagery.

Class	Area (ha)	Interpretation of vegetation class type
1	635	Very sparsely vegetated sandveld woodland/shrubland—*T. sericea, Z. mucronata, Albizia anthelmintica, Burkea africana, Lonchocarpus nelsii, G. flava*
2	5378	Open water and aquatic vegetation—*Miscanthus junceus, Cyperus articulatus, Schoenoplectus corymobosus* and *Phragmites australis*
3	320	Actively growing green aquatic vegetation *Miscanthus junceus, Cyperus articulatus, Schoenoplectus corymobosus* and *Phragmites australis*
4	24 023	Monospecific stands of *Colophospherrnum mopane* ± *Boscia mossambicensis, A. erioloba, G. flava, C. hereroense*
5	30 218	Moderately vegetated floodplains and sandveld—*Burkea africana, Lonchocarpus nelsii, G. flava, A. hebeclada, A. erioloba, C. collinum, A. erubescens, C. hereroense, Rhigozum brevispinosum*
6	20 325	Dense marginal and depression woodlands—*A. nigrescens, Garcinia livingstonei, Loncocarpus capassa, Combretum imberbe, H. petersiana, Croton mossambicensis, C. megalobotrys, Ficus thonningii, Berchemia discolor, Kigelia africana, Euclea divinorum*
7	11 250	Moderate to sparsely vegetated sandveld areas—*Burkea africana, Lonchocarpus nelsii, G. flava, A. hebeclada, A. erioloba, C. collinum, A. erubescens, C. hereroense, Rhigozum brevispinosum*
8	66 301	Moderately dense sandveld areas—*Burkea africana, Lonchocarpus nelsii, G. flava, A. hebeclada, A. erioloba, C. collinum, A. erubescens, C. hereroense, Rhigozum brevispinosum, Rhus tenuinervis, Adansonia digitata, Cadaba termitaria*
9	11 623	Floodplain channels or wallows with medium to dense vegetation cover woody weeds—*Vernonia* spp., *Panicum maximum, A. fleckii, Cadaba termitaria, A. mellifera, A. erioloba, Vernonia* spp.
10	11 506	Floodplain channels or wallows with medium to sparse cover—woody weeds *Vernonia* spp., *Panicum maximum, A. fleckii*
11	914	Very dense marginal woodland—*A. nigrescens, Garcinia livingstonei, Loncocarpus capassa, Combretum imberbe, H. petersiana, C. mossambicensis, Croton mossambicensis, C. megalobotrys, Ficus thonningii, Berchemia discolor, Kigelia africana, Euclea divinorum*
12	18 585	Anthropogenically and naturally disturbed areas—*A. tortilis, A. erubescens, A. fleckii, G. flavescens, A. leuderitzii, A. mellifera, Bauhinia petersiana, Dichrostachys cinerea, Tephrosia sericea*
13	32 220	Mixed mophane woodland—*C. mophane, Ximenia americana, X. caffra, Commiphora africana, A. erioloba, L. nelsii, T. sericea, Grewia flava, G. flavescens, Boscia albitrunca*
14	62 147	Mixed mophane woodland with some areas of gumane mophane—*C. mophane, G. flavescens, Catophractes alexandri, Bauhinia petersiana, A. tortilis, Dichrostachys cinerea*
15	53 096	Monospecific mophane woodland with areas of gumane mophane in depressions—*C. mophane, G. flavescens, Catophractes alexandri, Bauhinia petersiana, A. tortilis, Dichrostachys cinerea*
16	7223	Moderately densely vegetated *T. sericea* and *A. erioloba* woodland/shrubland—*A. erioloba, T. sericea, C. molle, L. nelsii, Grewia flava, Combretum collinum, A. erubescens, C. hereroense, R. brevispinosum, Rhus tenuinervis*
17	2287	Excessively graced shrubby sandveld—*A. tortilis, A. erubescens, A. fleckii, G. flavescens, A. leuderitzii, A. mellifera, Bauhinia petersiana, Dichrostachys cinerea, Tephrosia sericea*

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Table 5. (*continued*)

Class	Area (ha)	Interpretation of vegetation class type
18	3962	Densely vegetated sandveld—*A. erioloba, A. nigrescens, A. leuderitzii, Combretum imberbe, Maytenus senegalensis, Ziziphus mucronata, B. albitrunca, B. mossambicensis, A. ataxacantha, Rhus retinervis*
19	9275	Very sparsely vegetated areas including sandveld and some channels/islands and areas damaged by fires—*Panicum maximum*
20	13 153	Mixed moderately dense *Terminalia—Combretum* woodland—*T. sericea, Z. mucronata, Albizia anthelmintica, Burkea africana, Lonchocarpus nelsii, G. flava, A. hebeclada, A. erioloba, C. collinum, A. erubescens*

NDVI, TNDVI and LOGTNDVI relationships provide some significant correlation coefficients with green woody vegetation cover which are marginally higher than those found on individual TM bands. Of particular interest are the negative NDVI type relationships which suggest that the higher the NDVI value, the lower the woody and/or total green vegetation cover. This is the opposite of that predicted in the literature (e.g., Jensen 1986, Prince and Astle 1988). Few of the indexes are useful in detecting green (alive) herbaceous cover although some association was found in relationships between TM5 and TM7 and as a result of Principal Components analysis. Images resulting from the most highly correlated indexes were later used to assess relative degradation across land management boundaries.

7. Classification and GIS results

Classification analysis resulted in the development of a vegetation community map which showed that the north-eastern part of the study area was dominated by mophane woodland, the central part comprised a large proportion of moderate-dense sandveld vegetation types while the south-western part comprises mainly floodplain vegetation and anthropogenically disturbed areas (figures 8 and 9). While most of the vegetation classes found in the field were identified spectrally, problems arose particularly in terms of species/community associations. For instance, the *Terminalia* and *Combretum* woodlands were also not spectrally separable and so had to be combined. Because of similarities in soil reflectance in certain areas, the extensive drier floodplains could not be distinguished from some of the sandveld areas (mainly arenosols). However, the 20 classes obtained using 'hard' classification techniques proved functional in terms of differentiating main community types and their relative densities and provided four sub-categories for the relatively ubiquitous *C. mopane* (figure 9). The classification process also clearly showed relative cover densities such that heavily grazed shrubby areas or areas with predominantly woody weeds could be differentiated from classes containing mainly broad-leaved species, for example *Combretum* spp./*Croton* spp. and *T. sericea*/*A. erioloba*. Classification accuracy was difficult to achieve because the only feasible independent source of data were variable panchromatic aerial photographs dated 20 August 1991 at 1:50 000. However tenuous, the results of accuracy assessment are shown on table 8. The accuracies range from 43·8 per cent for class 5 to 93·8 per cent for class 3 with an overall classification accuracy of 72·4 per cent.

Spatial analysis techniques were used to superimpose land management categories

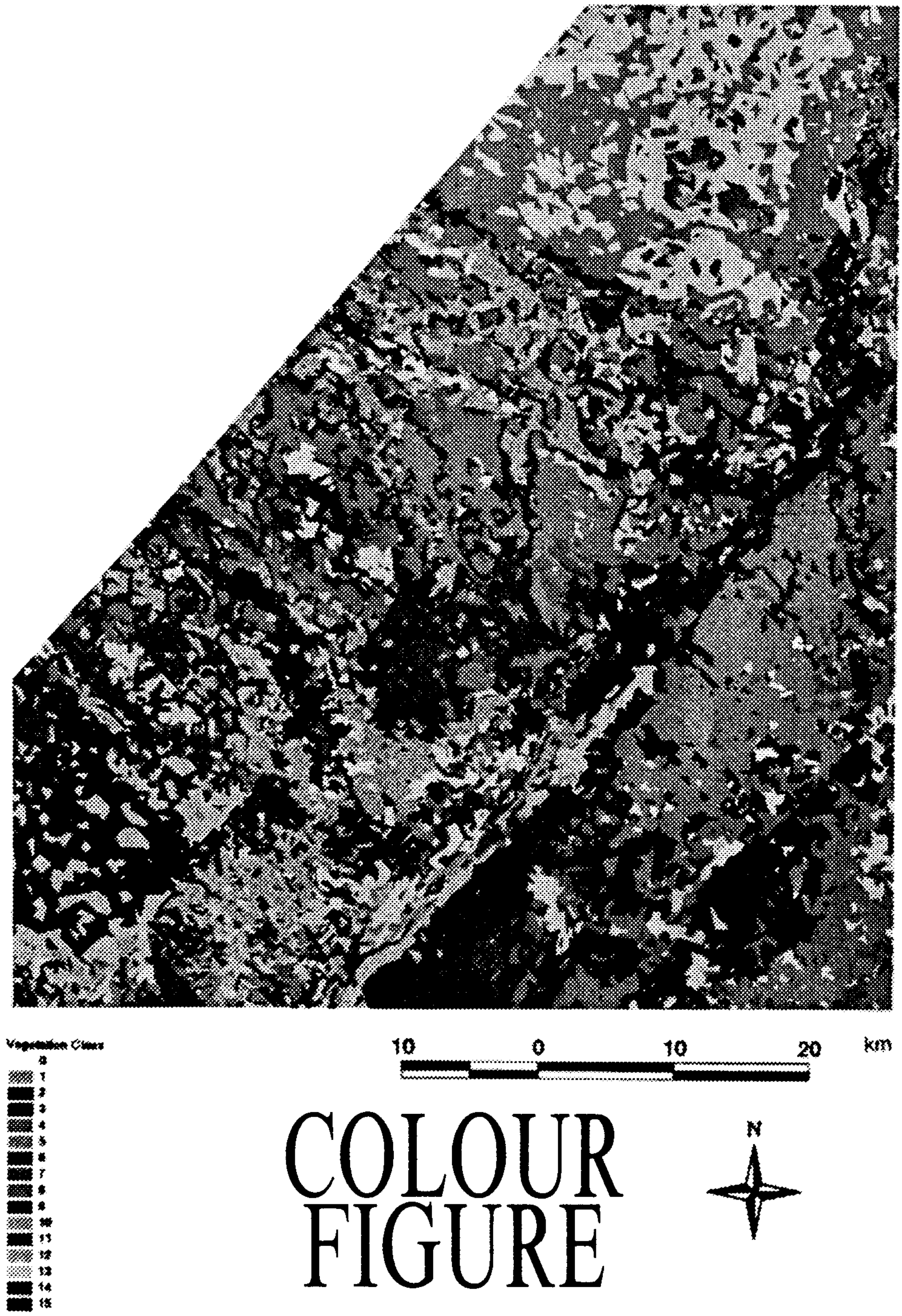

Figure 7. Distribution of vegetation types by spectral classification.

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Table 6. Correlation coefficients for the main vegetation–soils characteristics in relation to TM reflectance values (P = probability function).

TM band	WVC	AHC	DHC	BS	Soil value	Soil chroma
TM1	−0·33	−0·26	−0·09	0·58	0·06	−0·21
	P=0·004	P=0·19	P=0·226	P=0·000	P=0·311	P=0·050
TM2	−0·36	−0·25	−0·07	0·61	0·12	−0·06
	P=0·001	P=0·023	P=0·290	P=0·000	P=0·172	P=0·314
TM3	−0·36	−0·24	−0·04	0·59	0·17	−0·09
	P=0·001	P=0·027	P=0·388	P=0·000	P=0·086	P=0·233
TM4	−0·35	−0·22	0·17	0·53	0·23	−0·09
	P=0·002	P=0·039	P=0·085	P=0·000	P=0·033	P=0·231
TM5	−0·33	−0·30	0·00	0·60	0·16	−0·01
	P=0·003	P=0·007	P=0·486	P=0·000	P=0·096	P=0·464
TM6	−0·01	−0·32	−0·19	0·42	−0·06	0·08
	P=0·134	P=0·005	P=0·067	P=0·00	P=0·326	P=0·276
TM7	−0·32	−0·29	−0·02	0·57	0·13	−0·2
	P=0·05	P=0·009	P=0·444	P=0·000	P=0·149	P=0·424

WVC = woody vegetation cover; AHC = alive herbaceous cover (mainly grasses); DHC = dead herbaceous cover (including litter); BS = bare soil.

on the vegetation community/density map and the resulting distribution assessed (table 9). The Game Reserve was found to comprise mainly monospecific mophane (as 28 per cent of Class 4) and mixed mophane woodland (29 per cent of Class 13). The controlled hunting area encompassed three main vegetation types including moderately dense sandveld (20 per cent – Class 8), mixed mophane woodland (21 per cent – Class 14) and monospecific mophane with small shrubby gumane (23 per cent – Class 15). The communal grazing area comprised two main vegetation types, moderately dense sandveld (18 per cent – Class 8) and mixed mophane woodland (17 per cent – Class 14). Similarities were found to exist between the controlled hunting and communal grazing areas in terms of general vegetation cover content, despite the fencelines and changes along the faultlines. Some vegetation boundaries are clearly related to the northeastward trending faultlines. The westerly faultline in particular appears to control sediment deposition and therefore the soil type distribution and resultant vegetation response. Hence the geographic coincidence of faultline and cordon fence tends to emphasize vegetation change on either side of the fenceline. The cultivated area(s) are also distributed linearly along parallel faultlines and are mainly classified as being anthropogenically disturbed (35 per cent – Class 12).

To provide a more concise assessment of the relative extent of range degradation, the vegetation type classes were reassigned in ARC/INFO to range quality classes (table 9). Classes with a relatively low density cover were assigned to low quality–bare soil categories. These included areas which were known to be heavily grazed or in which extensive fire or elephant damage has occurred. Those with a high proportion of woody weeds were reassigned to low quality–woody weed categories and the remaining classes were reassigned to medium or high quality rangeland categories. This assignment depended on known species content and cover density, hence relative browse availability.

To determine whether a direct relationship exists between soil type and relative range quality, these two coverages were overlain in ARC/INFO (table 10). The results show that the distribution of Calcaric Cambisols, Haplic Luvisols, Vertic

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Table 7. Correlation of Vegetation Indexes and their log equivalents with field site data (where $P >$ or $= 0{\cdot}001$) ($n = 64$).

Transform	WVC	AHC	BS	TVC
TM4 − TM2	N/S	N/S	N/S	N/S
LOGTM4 − TM2	N/S	N/S	N/S	−0·41 $P=0{\cdot}000$
TM4 − TM3	−0·41 $P=0{\cdot}000$	N/S	0·52 $P=0{\cdot}000$	−0·53 $P=0{\cdot}000$
LOGTM4 − TM3	−0·32 $P=0{\cdot}000$	N/S	N/S	N/S
TM4 + TM3	N/S	N/S	N/S	N/S
LOGTM4 + TM3	N/S	N/S	N/S	N/S
NDVI	−0·39 $P=0{\cdot}001$	N/S	0·52 $P=0{\cdot}000$	−0·52 $P=0{\cdot}000$
TNDVI	−0·44 $P=0{\cdot}000$	N/S	0·56 $P=0{\cdot}000$	−0·57 $P=0{\cdot}000$
LOGTNDVI	−0·43 $P=0{\cdot}000$	N/S	0·55 $P=0{\cdot}000$	−0·56 $P=0{\cdot}000$
TM5/TM7	N/S	0·43 $P=0{\cdot}000$	−0·51 $P=0{\cdot}000$	0·50 $P=0{\cdot}000$
LOGTM5/TM7	N/S	0·39 $P=0{\cdot}001$	−0·51 $P=0{\cdot}000$	0·50 $P=0{\cdot}000$
TM5 − TM7	N/S	N/S	−0·59 $P=0{\cdot}000$	−0·59 $P=0{\cdot}000$
TM5 + TM7	N/S	N/S	−0·60 $P=0{\cdot}000$	−0·60 $P=0{\cdot}000$
PC1	N/S	−0·33 $P=0{\cdot}001$	N/S	N/S
PC2	N/S	N/S	N/S	N/S
LOGPC1	N/S	−0·39 $P=0{\cdot}001$	N/S	N/S
LOGPC2	N/S	−0·36 $P=0{\cdot}001$	N/S	N/S

WVC = woody vegetation cover; AHC = alive herbaceous cover (mainly grasses); DHC = dead herbaceous cover (including litter); BS = bare soil; N/S = relationship not signficant.

Cambisols and Ferralic Arenosols is relatively consistent, irrespective of the land management category. However Haplic Calcisols, the mixed Arenosol/Gleysol complex and Calcaric Luvisols support a particularly high proportion of shrub-dominated woody weeds (and fewer taller tree types) while the Arenosol/Gleysol complex is characterized by a high proportion of bare soil. Hence it appears that certain soil types may be predisposed to woody weed growth while others may preferentially give rise to more bare soil. This is valid in the case of floodplain soils which occur mostly in the controlled hunting area particularly on the north-western side of the cordon fence.

The association of rangeland quality relative to land management class data indicate that most of the Game Reserve consists of medium-high quality range, as the mophane species provide reasonable forage for herbivores ~~(table 10 and figure 11)~~. figure 10 table 11 The communal grazing and controlled hunting areas both show a relatively high proportion of low quality (degraded) range on the basis of both of woody weed encroachment and the extent of bare soil. Although the difference is small, the

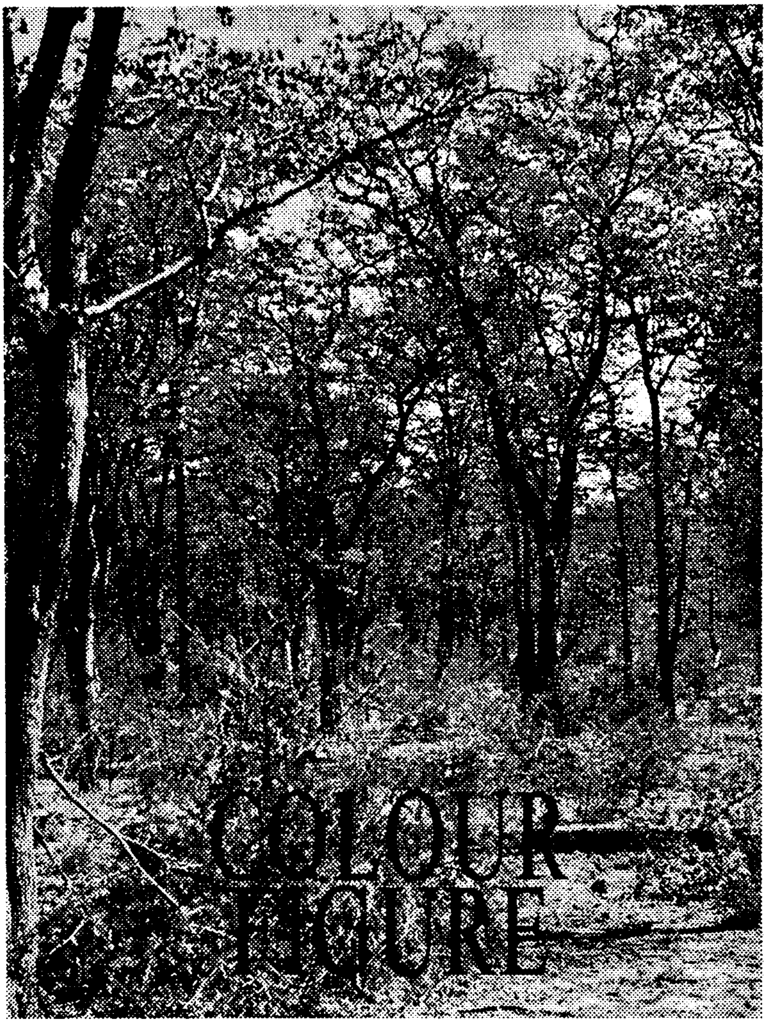

Figure 8. Monospecific mophane woodland—Class 4 (average tree height=4·5 m).

controlled hunting area (40·8 per cent) has more degraded land than the communal grazing area (32·5 per cent). The cultivated areas characteristically show a high proportion of bare soil particularly as cleared and abandoned fields.

A pattern begins to emerge. Firstly, because of faultline controls on vegetation types along the north-east trending cordon fence, much of the degraded area is found on the controlled hunting side of the fence. Secondly, not all of the degraded area is found directly along the fencelines but tends to be scattered in a zone between the Game Reserve and the main Okavango distributaries. Degradation in the controlled hunting area is unlikely to result from human induced change so may result from wildlife migration out of the Game Reserve through the controlled hunting areas mainly south and southwestwards towards available (or fenced off) water in the Okavango distributary systems. Prevalent degradation in the communal areas is usually ascribed to heavy grazing around villages and boreholes in addition to tree felling for general construction purposes.

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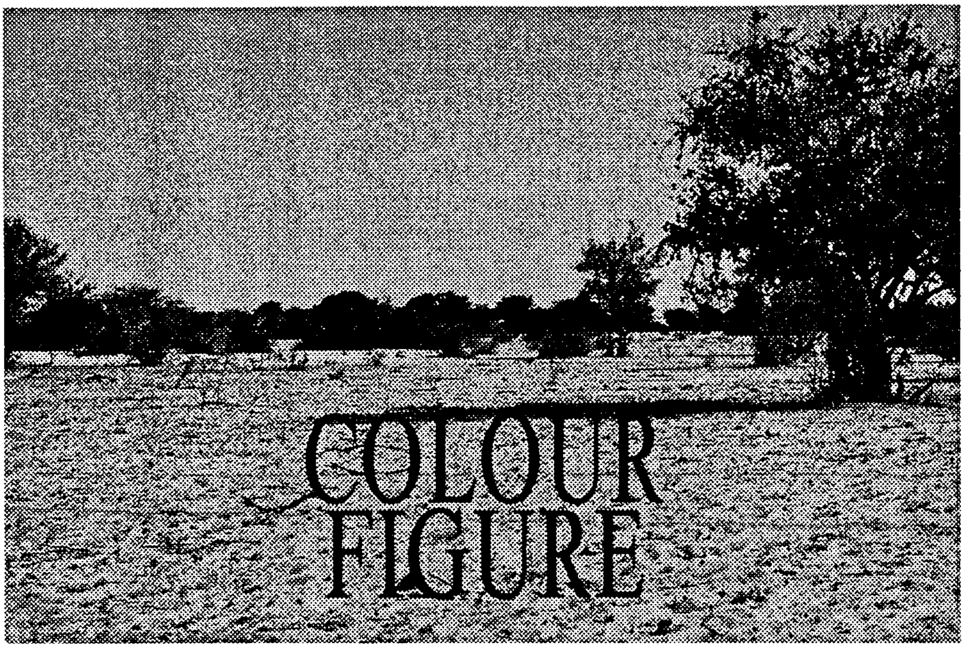

Figure 9. Bare soil in the anthropogenically disturbed areas—Class 12.

Table 8. Tentative classification accuracy assessment using 1991 aerial photography (horizontal axis = data derived from imagery vertical axis = data derived from aerial photographs).

	1	2	3	5	6	7	8	9	1	11	1	1	1	19
1	22										2		3	
2		19										1		
3		1	15											
5	3			7			4	2						
6					13				1			3		
7	4			3		18	2							
8					2		22							
9				1		3		1						
10								4	1		2			
11							1			5				
12	2										1	3	2	
17			1				4					1	3	
18										2		4	1	
19								2					3	12

Assessment Class 1 = 81·5%, Class 2 = 90·5%, Class 3 = 93·8%, Class 5 = 43·8%, Class 6 = 76·5%, Class 7 = 66·7%, Class 8 = 88%, Class 9 = 78·9%, Class 10 = 66·7%, Class 11 = 55·6%, Class 12 = 58·8%, Class 17 = 70·4%, Class 18 = 71·4%, Class 19 = 70·6%. Average = 72·4%.

Classes 13, 14, 15, 16 and 20 omitted because no species data available from alternative sources.

8. Results – fencelines

Information on relative boundary impacts, especially where these may normalize soil effects, may be obtained by band transform analysis. Spectral profiles of band transformations were drawn orthogonal to the boundaries between land management

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Table 9. Percentages of the vegetation classes occurring in the land management categories and class reassignments.

Vegetation class	Game Reserve	Controlled hunting	Communal grazing	Cultivation
1. Bare soil–Low	0·07	0·01	0·24	0
2. Unclassified	0·06	0·44	2·64	2·27
3. Unclassified	0·22	0·11	0·07	0
4. High	27·91	0·59	5·1	0
5. Medium	10·01	9·79	6·16	10·02
6. High	3·87	3·98	6·09	3·53
7. Bare soil–Low	2·13	2·74	2·91	0·01
8. Woody weeds–Low	10·06	20·5	17·58	7·16
9. Woody weeds–Low	0·09	0·15	6·46	0
10. Bare soil–Low	0·14	0·95	5·24	0·24
11. High	0·03	0·17	0·12	2·08
12. Bare soil–Low	2·71	3·93	4·22	34·86
13. Medium	28·53	1·68	9·05	0
14. Medium	4·57	21·18	17·48	14·81
15. High	1·66	23·4	8·8	18·89
16. Medium	2·83	0·06	2·97	0
17. Bare soil–Low	0·56	0·32	0·58	0
18. High	0·12	1·57	0·72	0
19. Bare soil–Low	2·61	3·84	0·68	6·08
20. Medium	1·77	4·51	2·82	0·01

Bare soils/woody weeds description infers this condition prevails within the class in addition to other vegetative conditions (see table 7).

High, Medium, Low refers to rangeland quality with Low classes signifying evidence of range degradation.

Table 10. Relative frequency (percentage) of main soils by range quality.

Soil type (FAO classification)	High	Medium	Low-woody weeds	Low-bare soil
Calcaric Cambisol	17·27	35·42	22·04	29·40
Haplic Luvisol	20·31	15·92	18·94	10·54
Gleyic Luvisol	4·60	3·03	0·26	2·42
Ferralic Arenosol	20·23	16·22	11·31	10·13
Haplic Calcisol	6·45	3·97	14·59	6·47
Arenosol/Gleysol Complex	15·3	1·9	10·5	0·0
Vertic Cambisol	16·03	11·42	9·92	13·64
Eutric Fluvisol	2·56	2·63	1·54	4·09
Gleysol/Arenosol Complex	2·70	2·75	0·48	3·20
Calcaric Luvisol	4·92	2·59	10·69	7·18

categories (figures 2 and 11) using the three most significant transform-field data associations (TNDVI, TM5/7 and TM5+7) (table 7). The range of the rescaled images and linear regression relationships of the three transforms in terms of differing aspects of vegetation cover are shown in table 12.

Whereas the TNDVI values show a predominantly negative relationship, various anomalies appear when the image is displayed. Bare soils and settlement areas appear as darker grey tones whereas actively growing aquatic or riparian vegetation appeared as lighter tones. The TNDVI profiles show relatively low values in the

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Table 11. Percentage of range quality relative to the land management categories.

Range quality	Game reserve	Communal grazing	Controlled hunting	Cultivation
Unclassified	0·33	0·63	2·78	2·31
High	33·59	29·72	20·83	24·5
Medium	44·87	37·17	35·51	24·85
Low-woody weeds	10·15	20·65	24·04	7·16
Low-bare soil	11·05	11·84	16·84	41·19

Game Reserve followed by intermediate values in the controlled hunting area, thereby inferring a decrease in vegetation cover over the boundary. This changes at the cordon fence to widely fluctuating values (mixed cover) through the communal grazing area and lower values (higher cover) through the cultivated area (figure 12).

On the TM5/TM7 image, bare soils and settlement areas appear in lighter grey tones whereas actively growing vegetation types appear very dark. Vegetation on the floodplains and in the sandveld also appears in lighter tones. The TM5/TM7 profiles show an increase in herbaceous cover as the profile passes southwards from the Game Reserve into the controlled hunting area with increasing variability in cover with distance south. The amount of herbaceous cover decreases at the cordon fence into the communal grazing area then increases again with distance south (figure 13). The TM5 + TM7 image which reflects total vegetation cover, shows bare soil and settlement areas in lighter grey tones whereas many of the vegetation types appear dark. Profiles from the TM5 + TM7 image indicate a relatively high TVC in the Game Reserve with lower total cover through more fluctuating cycles as the profile passes southwards into the controlled hunting area. A marked increase in total cover is apparent when the profile passes the north-east trending cordon fence. However no major change is noted as the profile passes the east–west cordon fence into the communal grazing area (figure 14).

The transforms and related profiles tend to show distinctive changes in vegetation cover types at the land management boundaries. Less difference is noted using the results from TNDVI transforms and more clear distinctions are apparent when relationships involving the MIR bands are applied. The TM5/TM7 transform infers that a greater portion of herbaceous cover is available in the controlled hunting area, relative to the communal grazing area. However, the TNDVI and TM5 + TM7 transforms both suggest that while the Game Reserve area has a moderate woody or total vegetation cover, this changes to sparser cover in the controlled hunting area and increases again in the communal grazing area. Whereas to some extent this change may be due to geological factors (such as faultlines) the evidence with respect to browse suggests that herbivore activity north and west of the cordon fences is having a more profound effect on the range than the effect of livestock/smallstock to the south and east of the cordon fences. The relatively heavy browsing may be due to the restriction of wildlife migration routes at the cordon fence which may cause heavy seasonal browsing pressure in the controlled hunting area (L. Patterson, personal communication) and concommitant degradation in this part of the Okavango system.

9. Conclusions

The relative impact of different land management strategies on the natural vegetation cover is causing increasing concern in Botswana and other parts of Africa.

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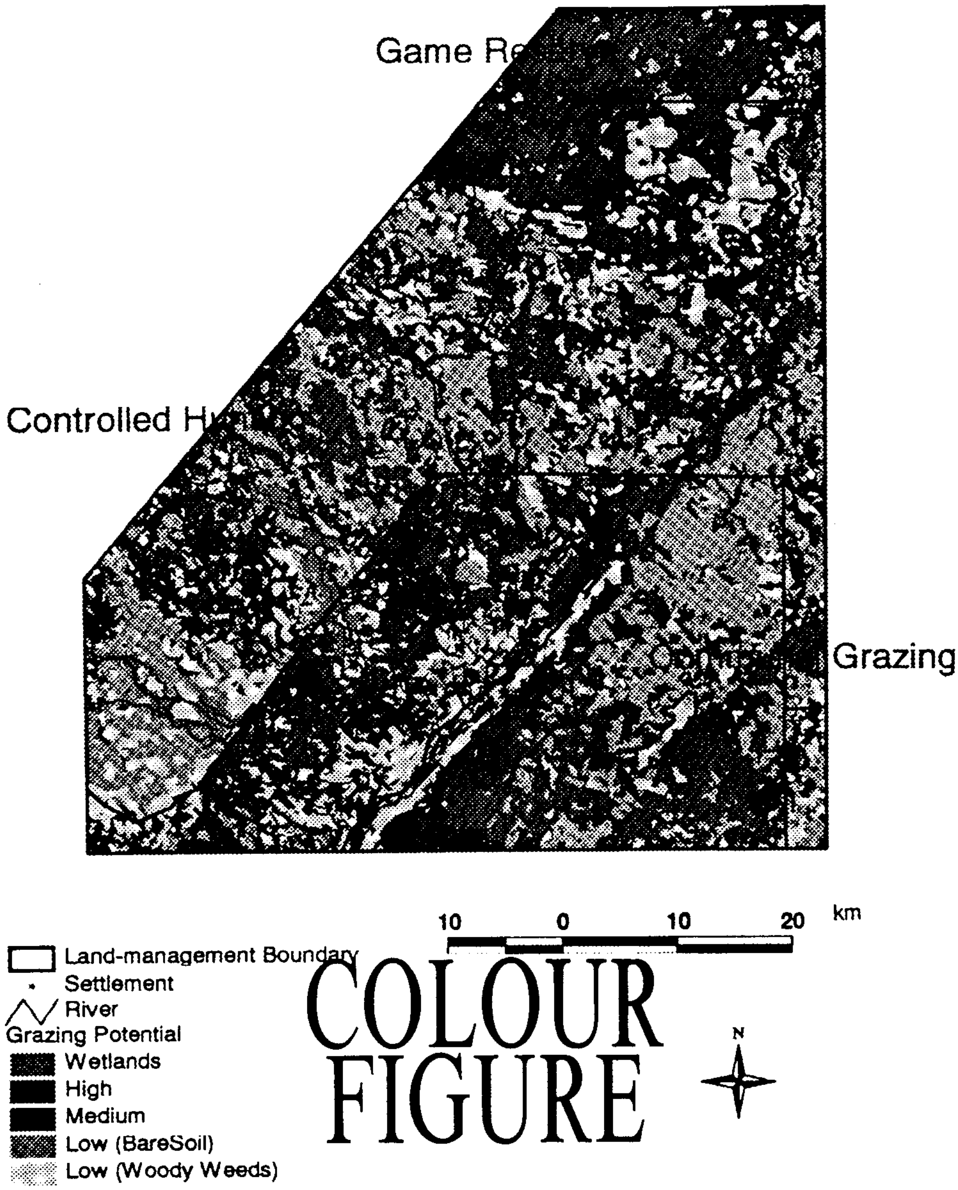

Figure 10. Quality of rangeland in relation to land management categories.

Image processing and GIS techniques were able to show that land management strategies, especially where these are separated by fencelines, have some effect in terms of overall range quality in a sensitive part of the Okavango region in northern Botswana. The study area comprised part of a Game Reserve in addition to controlled hunting, communal grazing and cultivated areas. Six-band Thematic Mapper imagery from the late dry season was used to map vegetation cover. Two techniques, supervised classification and profile analysis, were applied to assess cover changes both

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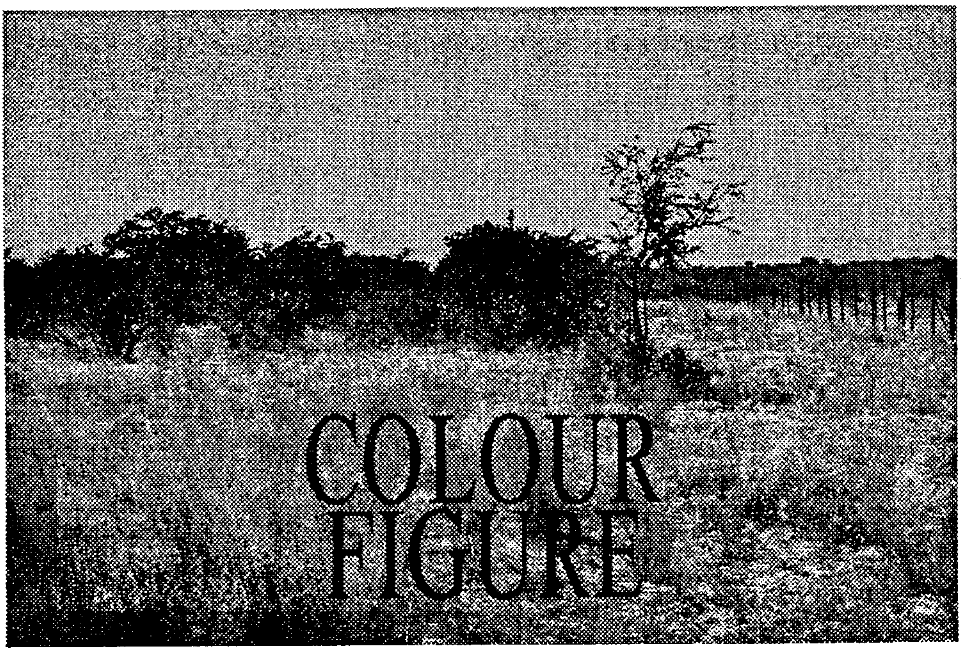

Figure 11. *Terminalia sericea* woodland adjacent to cordon fence in the south-eastern part of the study area.

Table 12. Regression relationships of three most highly correlated band transforms in terms of vegetation characteristics.

Range of band values	Linear regression relationship	r2	S.E.
0·2–0·9	TNDVI = 0·65 + 63·1·WVC	−0·44	27·7
(−85)–(+100)	TM5/7 = 2·94 + 2·95·AHC	+0·43	13·4
0–365	TM5 + 7 = 42·78 + 5·47·TVC	−0·6	56·2

across and within the land management areas to assess the degree of degradation and change as this may relate to land management practices.

Supervised classification undertaken on the basis of field work data, resulted in twenty classes being generated which, while not entirely species specific, formed a general basis for vegetation community mapping and cover density determination. The classes were later re-evaluated in terms of range quality. Low quality range was subdivided into two categories. Firstly, classes with very little vegetation cover were described as bare soil and secondly, those with a high proportion of bush encroachment were described as woody weeds. Classes with a medium-high browse content were described as medium or high quality range respectively. Comparison with land management category boundaries indicates that a fractionally larger extent of bare soil and woody weed classes (8 per cent) prevailed in the controlled hunting area, relative to the communal grazing area. In terms of spatial distribution, some of these low range quality areas were related to the influence of faultlines on soil type and hence on vegetation cover. In other cases the low range quality areas were widely

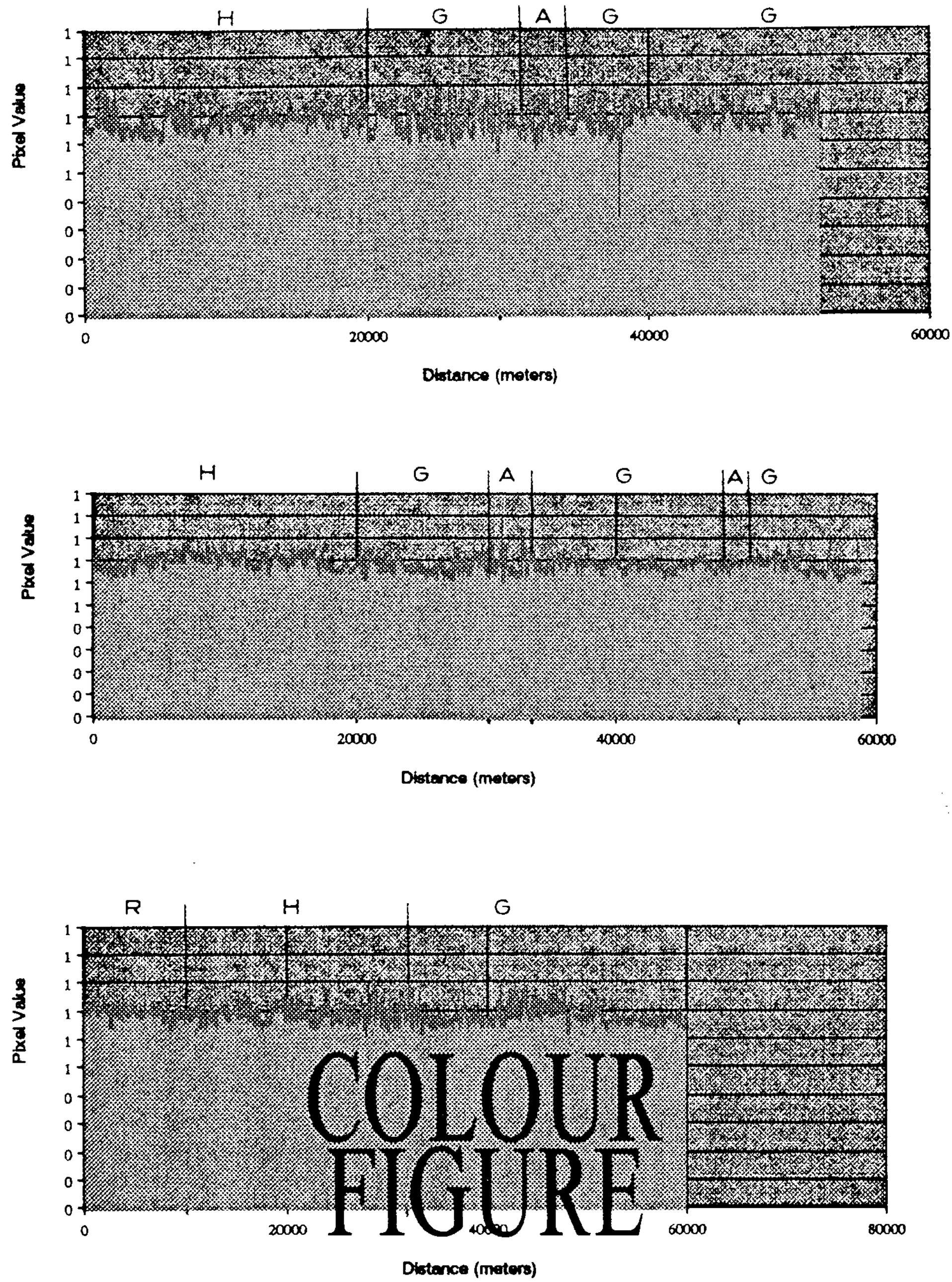

Figure 12. Spatial profile showing changes in TNDVI values across the main land management categories (for profile location and extent see figure 2)—H = controlled hunting, G = communal grazing, R = Game reserve, A = agricultural area.

distributed throughout the controlled hunting area, between the Game Reserve and the cordon fence.

Regression analyses showed that TNDVI data were negatively correlated with woody vegetation cover, TM5/TM7 positively correlated with herbaceous cover and

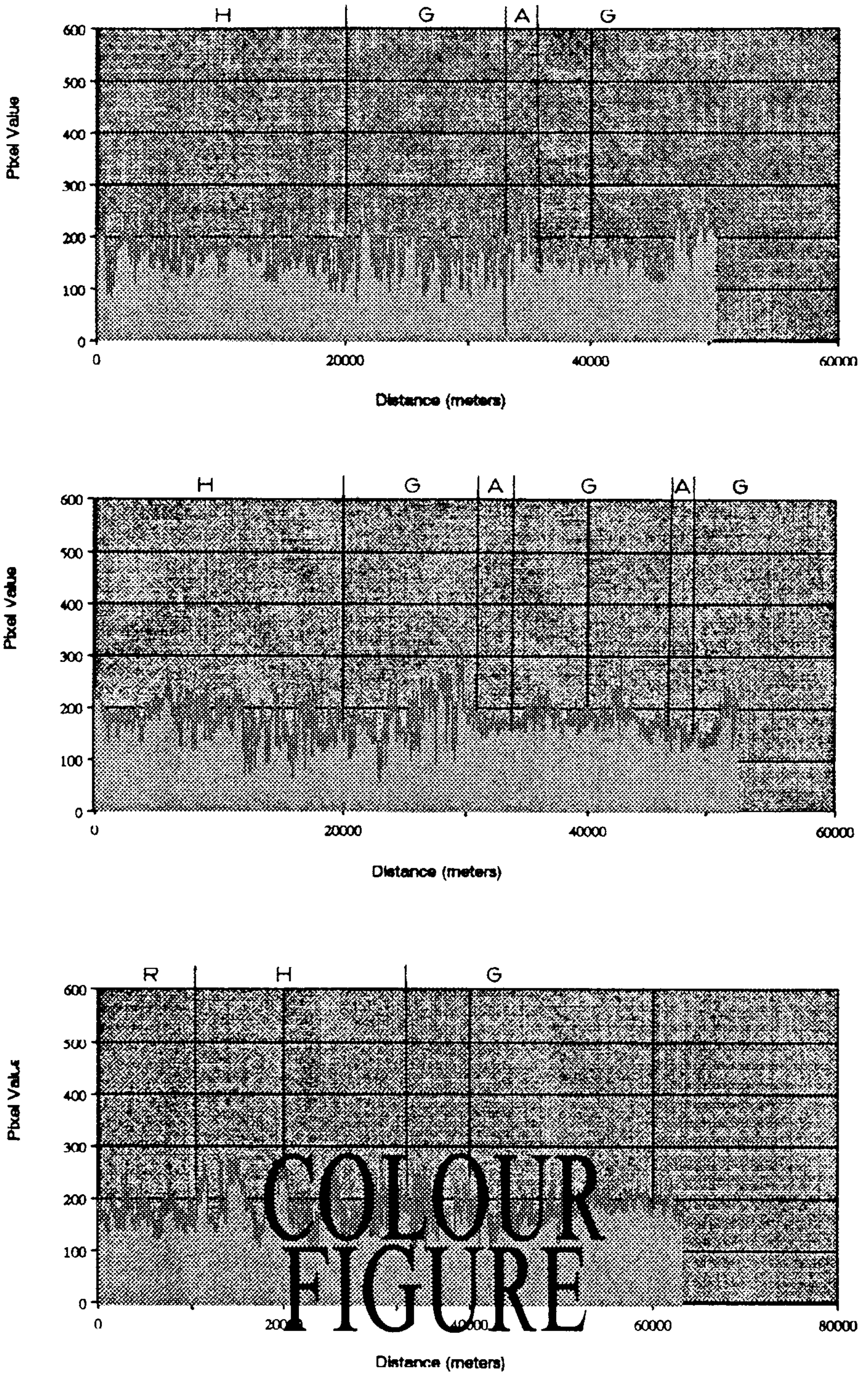

Figure 13. Spatial profile showing changes in TM5/TM7 values across the main land management categories (for profile location and extent see figure 2)—H = controlled hunting, G = communal grazing, R = Game Reserve, A = agricultural area.

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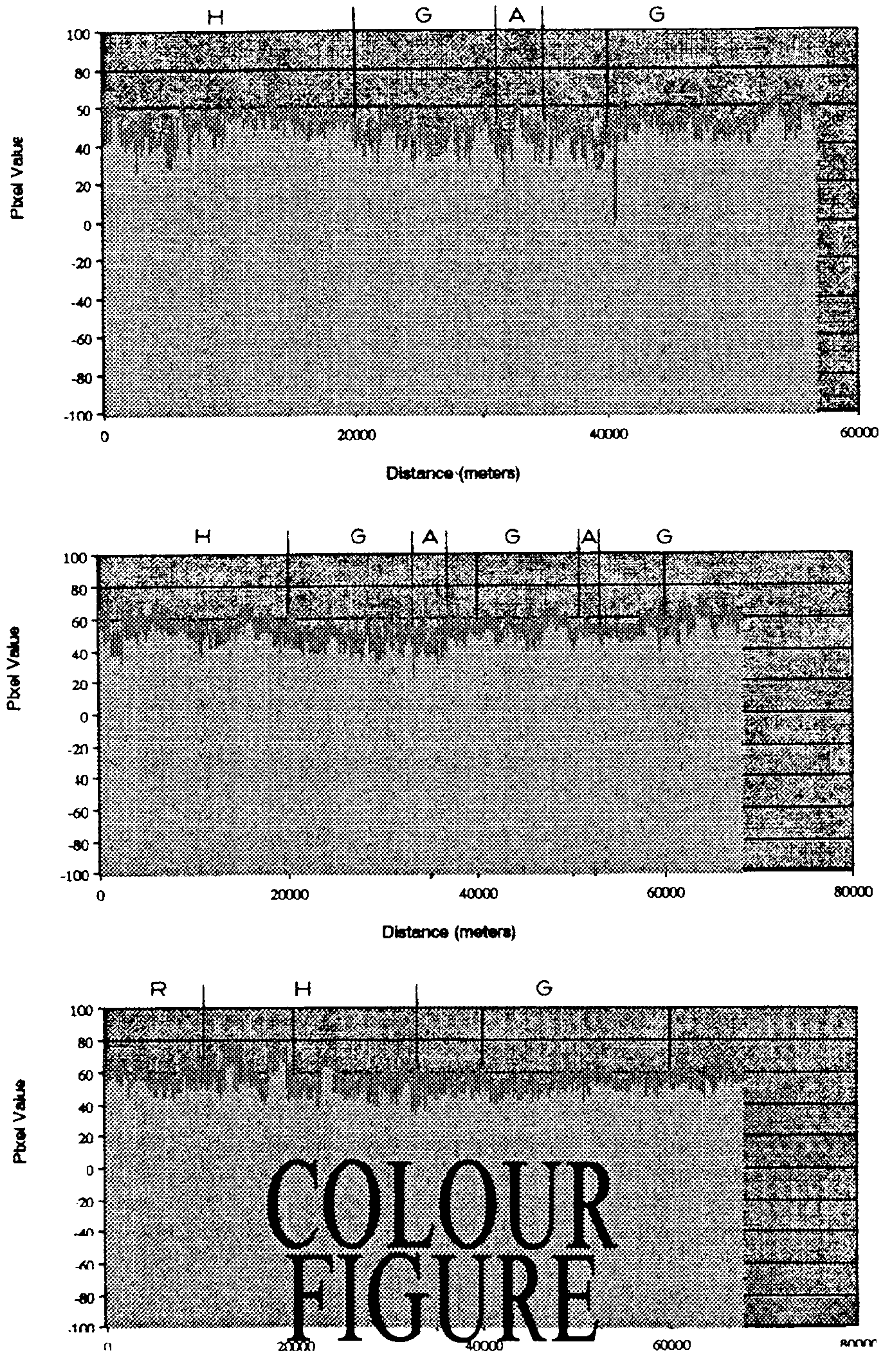

Figure 14. Spatial profile showing changes in TM5/TM7 values across the main land management categories (for profile location and extent see figure 2)—H = controlled hunting, G = communal grazing, R = Game Reserve, A = agricultural area.

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TM5 + TM7 negatively correlated with total vegetation cover. Spatial profiles of MIR transform data drawn orthogonal to land management boundaries provided most useful information. The profile data mostly indicate that the Game Reserve comprises a relatively high tree density cover, while the controlled hunting area has relatively low woody cover compared to the communal grazing area. The changes from higher to lower cover are frequently detected at land management boundaries. The relatively high degree of degradation in the controlled hunting area, away from the faultlines, is partially explained in terms of migrating wildlife whose passage is restricted by the cordon fences.

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