Assessment of vegetation indexes useful for browse (forage) prediction in semi-arid rangelands

N. MOLEELE†, S. RINGROSE‡, W. ARNBERG§, B. LUNDEN§ and
C. VANDERPOST†¶

†Department of Environmental Sciences, University of Botswana, P/Bag 0022,
Gaborone, Botswana
‡Directorate of Research and Development, University of Botswana,
P/Bag 0022, Gaborone, Botswana
§Department of Physical Geography, Stockholm University,
S-106 91 Stockholm, Sweden

Abstract. Considerable significance is placed on the mapping and monitoring of degraded areas in semi-arid regions of the world, including Botswana. Degraded areas include those suffering from bush encroachment, believed to result from heavy cattle grazing over a number of years. However, certain bush encroachment species have been found to be relatively nutrient-rich. The present work considers the extent to which a series of quantified layers through mainly bush encroachment canopies can be identified using conventional and newly derived vegetation indexes and transforms based on Thematic Mapper (TM) imagery. Field work involved the stratification of green biomass into firstly the herbaceous cover layer; secondly the 0.3–1.5 m browse layer; then the 1.5–2.5 m browse layer; and finally the >2.5 m browse layer. Biomass measurements from these layers were statistically associated with conventional vegetation indexes and transforms such as the Normalized Difference Vegetation Index (NDVI), brightness and greenness values, and relatively newly derived darkening indexes involving the mid-infrared bands. When green biomass and transformed pixel data were averaged per classified vegetation unit, weak negative correlations emerged between grass biomass and the transformed pixel data and no significant correlations developed with the woody biomass (browse) layers. However, when point data were used in the analyses, results showed that most indexes and the brightness transform were significantly correlated with the lower browse layer. Only the darkening indexes and brightness function were sensitive to the browse layers individually and the browse plus grass layers. This work shows the limitations of conventional indexes such as the NDVI in terms of browse and herbaceous layer assessment. New indexes for forage assessment based on relationships between the mid-infrared bands, such as those found in the new MODIS TERRA platform, are urgently required for semi-arid areas.

1. Introduction

Encroachment of woody species in sites under pressure from human activity has been interpreted as land degradation in Botswana and an aspect of environmental change (Van Vegten 1981, 1983, Ringrose et al. 1996a, 1997a). Degraded areas are recognized globally and manifest as, for instance, soil erosion, declines in species palatability and increases in soil salinity (e.g. Scoones 1995). Less frequently recognized are the positive relationships between encroacher woody plant species and cattle pressure (Ringrose et al. 1996a, Moleele and Perkins 1998). However, some of the encroaching woody plant species have been found to be more important in cattle diet than non-encroachers during certain months of the year (Moleele 1998). Hence bush encroachment may not necessarily form part of range degradation and steps should be taken to incorporate some bush encroachment species into 'carrying capacity' assessments within the context of sustainable development.

Estimation of availability and abundance of woody browse species in semi-arid rangelands is time-consuming when using conventional survey methods (Pickup 1989, Moleele 1994). These methods require numerous sample points to represent highly diverse savanna landscapes. The end result may be a limited number of points that are incorrectly interpolated or extrapolated to represent the whole landscape. The alternative is to use remotely sensed data and carefully selected sampling sites. Data, which can be obtained from satellite images, include vegetation indexes whose values may be related to total green vegetation cover or grass biomass (e.g. Graetz and Gentle 1982, Jackson 1983, Musick 1984, Jensen 1986, Huete and Warwick 1990, Matheson and Ringrose 1994a). Whereas remotely sensed data have the advantage of covering the whole landscape and allowing for detailed spectral analysis (e.g. Pickup and Chewings 1994), limitations include an absence of community mapping or species characteristics, unless fully integrated with field derived data (e.g. Ringrose et al. 1996a, 1997b).

Existing models of vegetation indexes were mainly developed for deciduous forest or agricultural applications (e.g. Jackson 1983, Jensen 1986). These tend to be characterized by less heterogeneous vegetation canopies than those typically found in semi-arid areas. Drier areas contain a wide variety of different vegetation complexes including a number of different woody species with different canopy closure and under-storey contributions over a variety of soils (e.g. Skarpe 1990, 1991). These areas therefore comprise a high degree of variation in leaf optical and structural properties (e.g. Shultis 1991, Sellars et al. 1992, Nemani et al. 1993). Land-use practices are also diverse and differ spatially (Ringrose and Dube 1988). These characteristics pose problems in the spectral discrimination of vegetation classes, particularly with regard to forage estimates in semi-arid areas (Ringrose and Matheson, 1987, 1991, Matheson and Ringrose 1994a,b). Attempts are here made to overcome these problems by vertically separating out the herbaceous and browse fractions and stratifying the browse into spatially homogeneous vegetation layers. An assessment is then made of the extent to which these layers may be estimated by spectrally derived indexes and transforms. Specific objectives of this work are to determine the spectral separability of browse fractions in bush-encroached semi-arid rangeland and to determine whether green browse biomass can be quantified using conventional and newly derived vegetation indexes and transforms from Landsat Thematic Mapper (TM) data. The overall aim is to develop specifically useful indexes for browse assessment in semi-arid rangelands.

2. Study area

The study area, which is approximately 600 km^2, is situated around the village of Olifants Drift, Kgatleng District, in south-east Botswana (figure 1). The area is

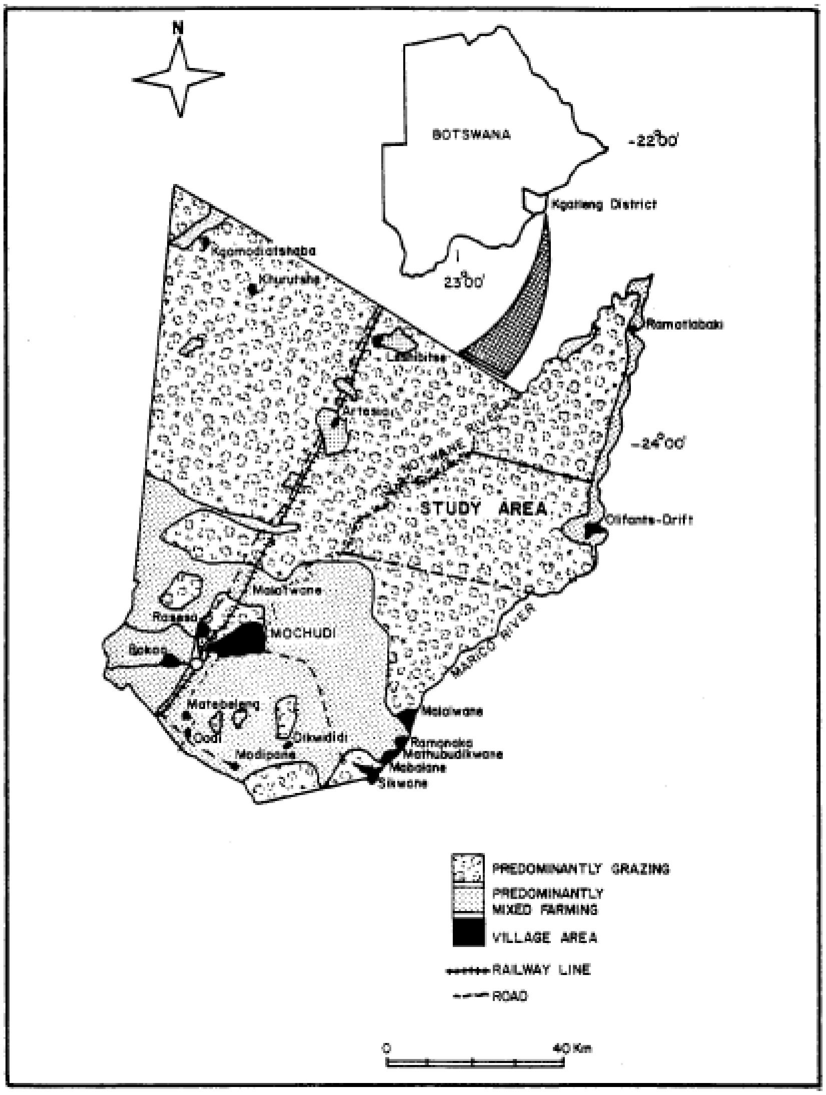

Figure 1. Location and land-use of Olifants Drift in Kgatleng District, south-east Botswana (Allen 1996).

communally owned and predominantly used for cattle grazing, although arable farming is slowly intruding from nearby villages. The original vegetation types are divided into three main groupings based on topography and soils characteristics (table 1). The area has a long history of grazing, a high cattle density and is recognized as being heavily bush encroached (e.g. Cooke 1981, Ministry of

Table 1. Major original vegetation groupings, their species associations and soil types for the Olifants Drift area (Soil Mapping and Advisory Services Project 1991).

Major vegetation grouping	Woody and herbaceous species associations	Soil description
Transition sandveld–hardveld	Terminalia sericea, Ziziphus mucronata, Acacia erubescens, Acacia tortilis, Boscia albitrunca, Acacia mellifera	mostly deep sandy soils (arenosols) interspersed with patches of sandy loam
Hardveld	Peltophorum africanum, Acacia tortilis, Terminalia sericea, Acacia karroo, Ziziphus mucronata, Combretum apiculatum, Acacia nigrescens	loamy-clay soils (mostly luvisols) intermittently poorly drained
Recent alluvium	Acacia tortilis, Cynodon dactylon, Cenchrus ciliaris, Combretum imberbe, Combretum erythrophyllum, Lonchocarpus capassa, Terminalia prunoides	alluvial deposits (luvisols and vertisols) deep poorly drained

Agriculture 1993, Tolsma et al. 1987, Ringrose et al. 1997a, Moleele and Perkins, 1998). The mean annual rainfall is 388 mm, which occurs during the wet season, October to March. Each wet season month receives at least an average of 50 mm rainfall, hence the herbaceous layer persists throughout the wet season (O'Connor 1991, Abel 1993). During the dry season cattle are known to graze on senesced grass and to browse leaves from the woody cover to around 2.5 m.

3. Vegetation unit mapping

A quarter scene (172/077) Landsat TM image was obtained in the six optical bands from Satellite Applications Centre, Mikomtek, South Africa. The Landsat TM data had standard radiometric and geometric corrections (processing level 8) applied at source (SAC 1991). Vegetation unit information was taken from colour infrared (CIR) photography flown along a strip (7 km × 38 km) within the study area (figure 2). Previous work has shown that the spatial stratification (at large scales) of bush encroached areas in terms of biomass measurements for carrying capacity estimates can be achieved using CIR photography (Moleele and Arnberg 1997). Since the CIR photographs covered only 10% of the entire study area, classified Landsat TM data were required to extrapolate the baseline vegetation units.

Initial analysis of the six optical bands took place to determine their relative separability in terms of the 20 mapped units (e.g. Ringrose et al. 1990, 1999). Results showed that few of the vegetation units have a high near-infrared (NIR) component (figures 3–6). Vegetation units 6, 7, 9 and 17 are mostly separable in the NIR and mid-infrared (MIR) bands whereas other units mainly composed of broad-leaved species are more potentially separable using the chlorophyll absorbance band (units 16, 20 and 8). This suggests the prevalence of vegetation darkening which has been previously documented in Botswana (Ringrose and Matheson, 1987, 1991, Ringrose et al. 1997a,b) and elsewhere in the world (Otterman 1981, Brown et al. 1983, Tueller et al. 1984, Chavez and MacKinnon 1994, Matheson and Ringrose 1994b). A few classes (e.g. units 6, 7 and 9) showed relatively high TM4 (NIR) values (no darkening).

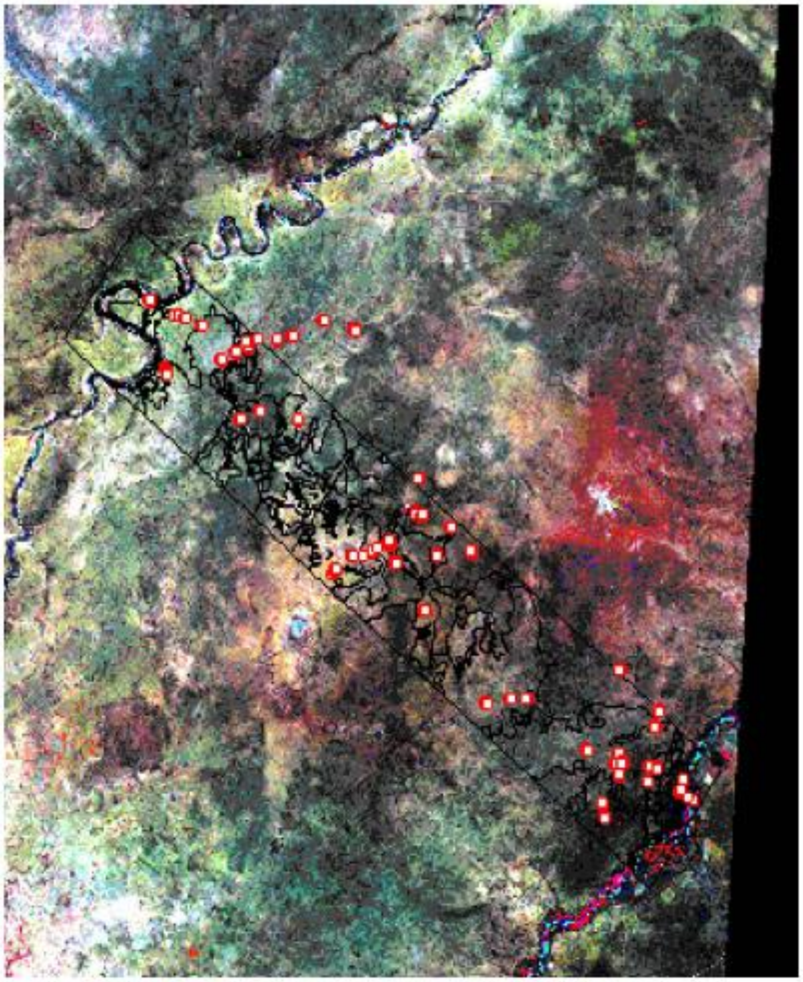

Figure 2. Mapped vegetation units derived from CIR photography superimposed on Landsat TM imagery (2, 3, 4:BGR). Red dots are sample sites used in single point analysis.

Classification analysis was used to expand the map derived from CIR photographs across the TM image. Hence training areas for classification purposes were located from co-incident sites on the CIR photographs. A conventional supervised classification using the Maximum Likelihood method was performed based on the relative homogeneity of the vegetation structure (cf. Foody 1996, Ringrose et al. 1997b). Classification analysis of the Landsat TM image showed that the study area was dominated by Terminalia sericea woodland and the 'mixture of scattered thorny shrubs' units, each covering 13% and 12% of the study area, respectively (table 2). The accuracies for vegetation units within the classified image ranged from 33% for

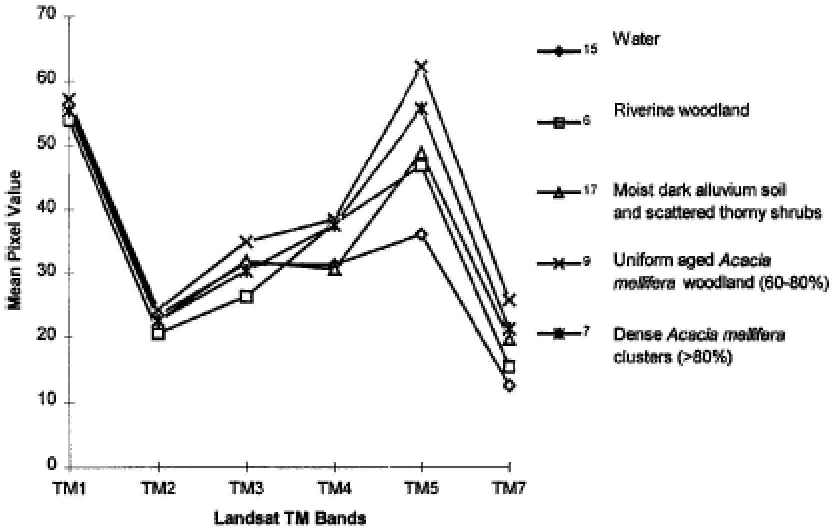

Figure 3. Mean pixel values of vegetation units 6, 7, 9, 15 and 17.

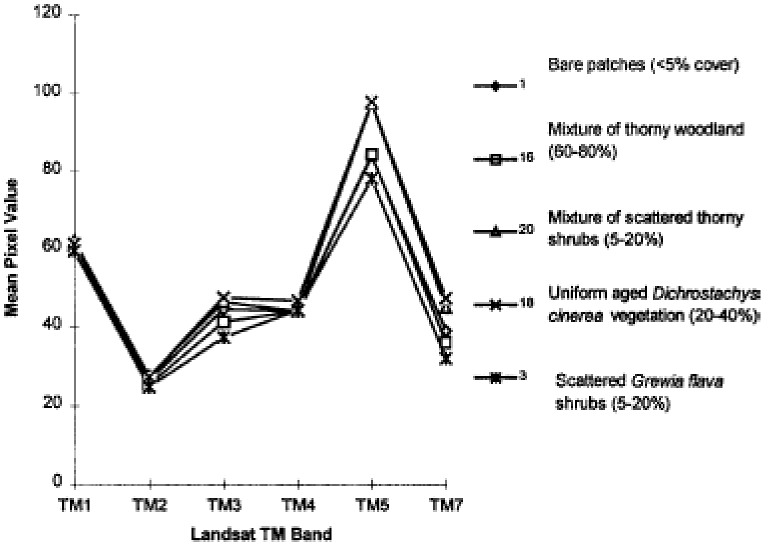

Figure 4. Mean pixel values of vegetation units 1, 3, 16, 18, and 20.

class 9 to 98% for class 16, with an overall average classification accuracy of 63.5% (table 5). The units from the classified imagery proved functional in terms of differentiating main community types and their relative green biomass contribution over extensive areas.

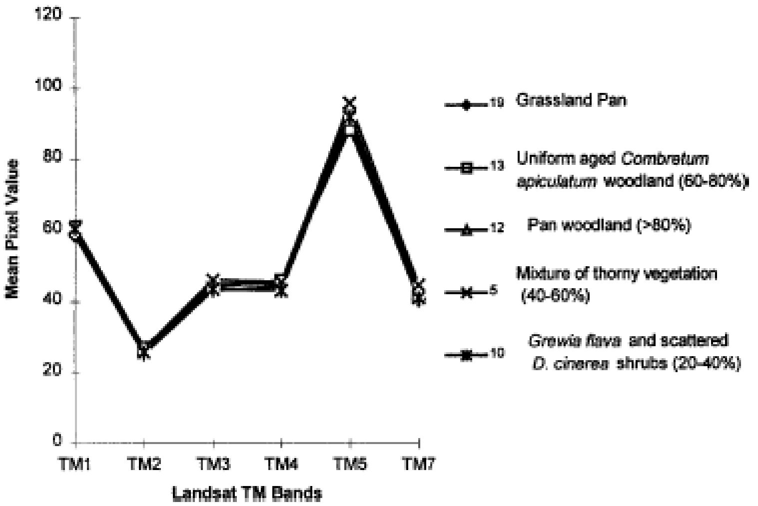

Figure 5. Mean pixel values of vegetation units 5, 10, 12, 13 and 19.

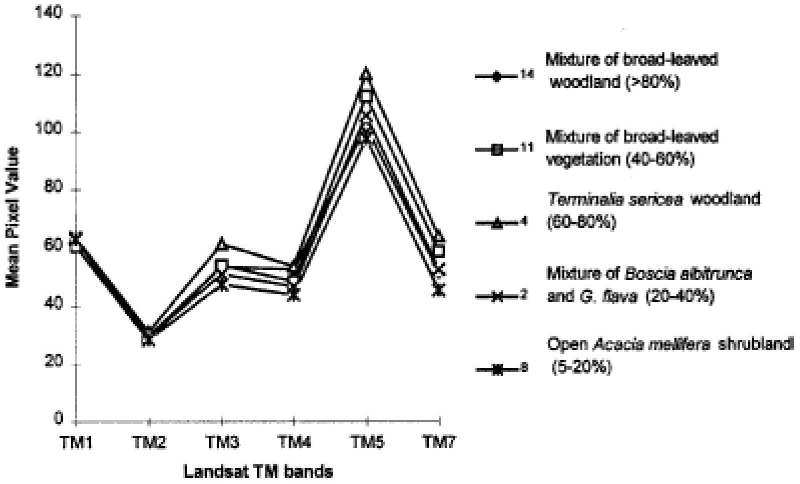

Figure 6. Mean pixel values of vegetation units 2, 4, 8, 11 and 14.

4. Field methodology and biomass assessment

Fieldwork was carried out in March to April 1996 and 1997. This coincided seasonally with CIR photography acquisition (April 1995) and is slightly earlier than the nearest cloud-free Landsat TM image (May 1993). The three years of image acquisition (1993, 1995 and 1997) had good wet seasons with rainfalls above the annual average of 388 mm. Hence, fieldwork results are used as a surrogate for ground conditions during both the CIR and TM overpasses. The assumption here adopted was that the quantity of green vegetation present determines the pixel value

Table 2. Description of mapped vegetation units, respective woody plant species, their relative frequency per height strata and average green biomass derived from ground measurements.

No.	Vegetation unit	Area (%)	Dominant species composition	Species frequency			Average green biomass (kg ha^{-1})
				0.3–1.5 m	1.5–2.5 m	> 2.5 m	
1	Bare patches (< 5% cover)	3.31	Acacia tortilis	0.75	0.25	0	3.32
			Dichrostachys cinerea	0.75	0.25	0	4.85
2	Mixture of scattered Boscia alibitrunca and Grewia flava shrubs	5.26	Boscia albitrunca	0.0322	0.352	0.616	266.90
			Grewia flava	1	0	0	205.42
			Commiphora glandulosa	1	0	0	8.83
3	Scattered Grewia flava shrubs	5.49	Acacia tortilis	0.667	0.333	0	89.23
			Grewia flava	1	0	0	96.23
			Commiphora glandulosa	1	0	0	9.52
			Boscia albitrunca	0.18	0.82	0	4.63
			Dichrostachys cinerea	0.75	0.25	0	88.43
4	Terminalia sericea woodland (60–80%)	12.75	Acacia senegal	0.129	0.227	0.644	167.95
			Terminalia sericea	0.369	0.442	0.19	1006.88
			Grewia flava	1	0	0	53.24
			Rhus lancea	1	0	0	98.31
			Grewia flavescens	0.9	0.1	0	334.80
5	Mixture of thorny vegetation (40–60%)	5.81	Acacia tortilis	0.257	0.743	0	116.36
			Acacia erubescens	0.667	0.333	0	322.47
			Dichrostachys cinerea	0.323	0.603	0.0737	152.08
			Grewia flava	0.69	0.31	0	47.53
			Commiphora glandulosa	1	0	0	5.56
6	Riverine woodland	0.47	Ziziphus mucronata	0.35	0.35	0.3	4543.15
			Combretum erythrophyllum	0.2	0.3	0.5	9611.95
			Diospyros lycioides	1	0	0	72.99
7	Acacia mellifera clusters (> 80%)	0.20	Acacia mellifera	0.185	0.556	0.259	1489.30
			Grewia flava	1	0	0	45.52
			Boscia albitrunca	0.206	0.794	0	3.58
			Acacia tortilis	0.0909	0.455	0.455	82.66
8	Scattered Acacia mellifera shrubs	6.40	Acacia mellifera	0.4	0.6	0	238.34
			Grewia flava	1	0	0	130.02
9	Uniform aged Acacia mellifera woodland (60–80%)	0.28	Acacia mellifera	0.138	0.666	0.196	3776.48
			Grewia flava	0.111	0.444	0.444	479.23
			Boscia albitrunca	0.313	0.375	0.313	6.26
			Acacia tortilis	1	0	0	21.49
10	Scattered Grewia flava and Dicrostachys cinerea shrubs	2.14	Dichrostachys cinerea	1	0	0	138.80
			Grewia flava	0.721	0.279	0	312.27
			Grewia bicolor	0.745	0.255	0	187.11
			Commiphora glandulosa	1	0	0	8.51
11	Mixture of broad-leaved vegetation (40–60%)	8.00	Terminalia sericea	0.302	0.199	0.5	1267.84
			Commiphora apiculatum	0.3	0.2	0.5	1799.78
			Combretum zehyeri	0.16	0.21	0.65	1241.18
			Ochna pulchra	0	0.312	0.682	479.45
			Dichrostachys cinerea	0.25	0.5	0.25	162.03
			Acacia senegal	0.352	0.463	0.185	43.27
			Sclerocarya birrea	0	0.188	0.812	1428.21

Table 2. (Continued).

12	Pan/depression woodland (> 80%)	5.40	Zziphus mucronata	0.294	0.294	0.412	219.11
			Combretum imberbe	0	0.5	0.5	15.88
			Grewia flava	1	0	0	18.81
			Dichrostachys cinerea	0.2	0.6	0.2	1811.46
			Acacia mellifera	0.105	0.368	0.526	12 561.17
			Acacia tortilis	0.167	0.5	0.333	9977.72
			Rhus lancea	1	0	0	57.59
			Maytenus senegalensis	0.667	0.233	0.1	262.38
13	Uniform aged Combretum apiculatum woodland (60–80%)	2.83	Combretum apiculatum	0.213	0.277	0.51	2553.71
			Grewia flava	1	0	0	29.63
			Dichrostachys cinerea	1	0	0	119.55
			Commiphora glandulosa	1	0	0	11.4
			Grewia bicolor	1	0	0	246.28
14	Mixture of broad-leaved woodland (> 80%)	5.88	Terminalia sericea	0.369	0.232	0.399	506.69
			Combretum apiculatum	0.267	0.333	0.4	19 342.85
			Ochna pulchra	0.0909	0.455	0.455	1799.02
			Combretum zeyheri	0.333	0.333	0.333	1682.80
			Dichrostachys cinerea	0.323	0.538	0.14	17.72
			Unidentified shrub	0.605	0.363	0.0315	46.70
			Sclerecarya birrea	0	0.5	0.5	1453.43
15	Water	0.04	—	0	0	0	0
16	Mixture of thorny woodland (60–80%)	8.48	Acacia tortilis	0.255	0.225	0.49	438.94
			Acacia erubescens	0.241	0.33	0.439	1509.37
			Dichrostachys cinerea	0.417	0.331	0.252	427.59
			Grewia flava	0.75	0.25	0	111.3
			Acacia erioloba	0.5	0.5	0	76.28
			Acacia senegal	0.07	0.515	0.415	143.93
			Acacia mellifera	0.148	0.37	0.482	982.01
			Commiphora glandulosa	1	0	0	6.99
			Acacia luederitzii	0.23	0.32	0.45	973.36
			Acacia robusta	0.17	0.2	0.63	4975.96
17	Moist dark alluvium soils with scattered thorny shrubs	0.26	Acacia tortilis	1	0	0	2.41
			Dichrostachys cinerea	1	0	0	1.09
			Acacia karroo	1	0	0	0.60
			Acacia mellifera	1	0	0	1.16
18	Uniform aged Dicrostachys cinerea vegetation (20–40%)	5.91	Dichrostachys cinerea	0.25	0.75	0	123.78
			Grewia flava	1	0	0	2.83
			Acacia tortilis	1	0	0	5.41
19	Grassland pan	3.67		0	0	0	0
20	Mixture of scattered thorny shrubs	11.60	Acacia tortilis	0.5	0.5	0	88.26
			Acacia erubescens	1	0	0	98.00
			Dichrostachys cinerea	0.443	0.278	0.278	166.27
			Grewia flava	1	0	0	39.92
			Commiphora glandulosa	1	0	0	4.5
			Boscia albitrunca	1	0	0	27.97

of a particular vegetation unit, and that the background soil values are relatively uniform (cf. Ringrose et al. 1989, Huete and Warwick 1990, Ringrose et al. 1999).

The measurement of green biomass for forage availability is normally regarded as a function of bush height, although there is no accepted standard (Rutherford 1979, Abel et al. 1987, Van Heist 1991). Green leaf layers within each of the mapped units were measured in four strata. These are the herbaceous (grass) cover layer; the lower 0.3–1.5 m browse layer; the intermediate 1.5–2.5 m browse layer; and finally the > 2.5 m browse layer. Normally the herbaceous layer, the 0.3–1.5 m and 1.5–2.5 m browse layers are readily accessible to cattle and the higher layer (> 2.5 m) is used with difficulty and contributes significantly, in terms of dropped pods and leaves. Measurements of green leaf contents per strata were undertaken in 10 field sites randomly selected in each vegetation unit, giving a total of 190 sites. The data collected included standard measurements of grass biomass from 0.5 m quadrats. The oven-dried weight was converted to green grass biomass (kilograms of grass per hectare). Green browse (woody) biomass was measured in 112.5 m^2 plots. This was achieved by sample counting then estimating the number of green leaves within each strata per species (table 2). Average dry weight of leaves of each species was determined and used to calculate the amount of green biomass (kg ha^{-1}) per unit and per strata (table 3). The 'grassland pan' (unit 19) has the highest grass biomass (4218 kg ha^{-1}). The broad-leaved woodland, pan/depression woodland and riverine woodland have the highest green browse biomass values of 24 926, 24 924 and 14 228 kg ha^{-1}, respectively. While this varies with each vegetation unit, the total browse biomass is greater than the total grass biomass by a factor of three (table 4). The relative importance of the thorny woody and broad-leaved encroacher species in the browse biomass is almost the same at 46 439 and 47 154 kg ha^{-1}, respectively. More than 90% of the total green browse biomass (84 537.83 kg ha^{-1}) is from woody species potentially edible by cattle (table 4).

5. Thematic Mapper transform and correlation analysis

Further processing of the six-band TM imagery involved the development of vegetation indexes, band transforms including the perpendicular vegetation index and principal components analysis (e.g. Matheson 1994, Ringrose et al. 1997b). Standard vegetation indices include the Normalized Difference Vegetation Index

Table 3. Vegetation units and biomass contributions of the different vegetation strata.

Vegetation unit	Grass biomass (kg ha^{-1})	Total browse biomass (kg ha^{-1})	Browse biomass in the >2.5 m layer (kg ha^{-1})	Browse biomass in the 1.5–2.5 m layer (kg ha^{-1})	Browse biomass in the 0.3–1.5 m layer (kg ha^{-1})
1	15	3.9	0	1.8	2.1
2	1800	81.2	164.4	93.9	222.8
3	2985	298.7	0	143.0	225.7
4	1500	1880.8	490.4	516.2	845.7
5	1875	742.8	11.2	300.3	332.5
6	1365	14 228.1	6168.9	4473.7	3585.5
7	805	1668.9	423.3	868.5	329.3
8	2004	371.8	0	143.0	225.4
9	1200	4315.1	955.1	2730.4	597.8
10	2630	646.6	0	134.8	511.9
11	805	6225.4	3861.3	1387.6	1172.9
12	1009	24 924.1	10 423.1	10 836.4	3664.6
13	1280	3021.1	1302.4	707.4	950.8
14	1100	24 925.9	10 048.7	8690.7	6109.8
15 (water)	0	0	0	0	0
16	1660	9691.9	5091.5	2546.6	2007
17	10	5.3	0	0	5.3
18	1560	132.0	0	92.8	39.2
19	4218	0	0	0	0
20	3160	442.1	46.3	90.4	288.2

Table 4. Total biomass contribution of different vegetation components.

Vegetation groups	Biomass (kg ha^{-1})
Total grass biomass	30 981.00
Total green from thorny and broad-leaved vegetation	93 592.83
Thorny vegetation green material	46 438.66
Broad-leaved vegetation green material	47 154.17
Green material from potential edible woody species (by cattle)	84 537.83
Green material from inedible woody species (by cattle)	9055.00

Values were obtained by summing up the relevant species in table 2. Species utilized by cattle are after Moleele (1998) while thorny and broad-leaved are after Van Vegten (1981) and Moleele and Perkins (1998).

(NDVI) and its transformed equivalent; the TNDVI (Jensen 1986). Problems are known to arise in the interpretation of the NDVI over semi-arid terrain due to the lack of effective NIR radiance, especially when single date imagery is used (e.g. Ringrose et al. 1989, Matheson and Ringrose 1994a). Hence a range of indexes and transformations were applied to the study area to provide a means of detecting the accessible browse layers. These included the development of brightness and greenness measures from the 'tasselled cap' linear transformation (e.g. Jensen 1986), and specific newly devised mid-infrared transforms, TM5/TM7, TM5− TM7 and TM5+ TM7. These were applied in an attempt to enhance the darkening characteristics of the vegetation units (Ringrose et al. 1996b).

The classified map was initially used as a template from which to extract average pixel values from the 20 mapped units. Biomass values for the grass cover and different browse layers were also averaged within the mapped vegetation units. An attempt was made to determine whether the vegetation units within the classified image had different pixel value characteristics and whether such characteristics could be rationalized in terms of the amounts of green vegetation cover present in each unit. The IMSTAT program was used to obtain a single average pixel value for each of the 20 units (Syren 1994). Within these units, vegetation indexes and transforms were calculated (along with their log equivalents) per vegetation unit. The two datasets were run through correlation analysis in SPSS. Initially there was little significant correlation found between the seven mean indices/transform values and their log equivalents, and the measured biomass variables. Although the correlation coefficients were not high, PC3 was correlated ($r = 0.53$ at the 99% significance level) to the log of total green browse biomass plus grass biomass. The grass biomass alone was negatively correlated ($r = -0.44$ at the 97% significance level) with the darkening index TM5+ TM7.

The averaging of field variables and indexes per vegetation unit was regarded as the major cause of the absence of correlation. Hence further analyses were undertaken specifically using the location of field sites. Fifty-six field points were therefore accurately located by GPS co-ordinates within the mapped vegetation units. Ten pixel values for each of the transforms/indexes were averaged from the image at the site location. For each of the 56 sampling points located on the Landsat TM, the more promising vegetation indexes or transforms were again calculated. These were again subjected to correlation analysis with field-derived data (table 6).

Results showed that biomass in the three browse layers had strong negative correlations mainly with the brightness transform and the two darkening indexes

Table 5. Classification accuracy assessment of the Landsat TM Imagery using the 1996 CIR photographs as ground control points. Values are pixel numbers from the training areas drawn on the Landsat TM false colour composite.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	(%) Accuracy
1	142						7					3		10		26	5	2			72.6
2		388			204																66
3			259							10		7	10	50		50		50		36	55
4				454	78			146								1		1		3	68.3
5			70	2	106																60
6						49									43						53.3
7							42		11							10					66.7
8	5				4			192								9	15	40		65	58.2
9									21							41	2				32.8
10										262		1		6		43		2			83.5
11											150	2		96							60.5
12							25					143		38		51		9			53.6
13										24		2	372			270				1	55.6
14							3							489		289		7		13	61
15															38						100
16							1					32	6	1		156				1	97.5
17															24		20				45.5
18										53		3		5		14		88		24	47
19	23						5					15		39		174	52		215		41
20										6		1				10	4	42		736	92.1

Average accuracy= 63.5%.

Horizontal axis= data derived from CIR photography, vertical axis= data derived from TM imagery.

Table 6. Correlation coefficients of vegetation indices and transforms with field-derived green grass and browse values for point-sampled data within mapped vegetation units (n= 56).

	1	2	3	4	5	6
Greenness	0.04 p= 0.38	− 0.22 p= 0.05	− 0.01 p= 0.49	− 0.10 p= 0.22	0.08 p= 0.28	− 0.10 p= 0.23
Brightness	− 0.63 p= 0.00	− 0.42 p= 0.00	− 0.49 p= 0.00	− 0.56 p= 0.00	− 0.10 p= 0.22	− 0.56 p= 0.00
NDVI	0.52 p= 0.00	0.15 p= 0.14	0.33 p= 0.01	0.33 p= 0.01	0.07 p= 0.31	0.33 p= 0.01
PVI	0.31 p= 0.01	0.03 p= 0.42	0.23 p= 0.05	0.18 p= 0.10	0.10 p= 0.22	0.18 p= 0.10
TM5/TM7	0.54 p= 0.00	0.27 p= 0.03	0.39 p= 0.00	0.41 p= 0.00	0.07 p= 0.30	0.42 p= 0.00
TM5+ TM7	− 0.63 p= 0.00	− 0.42 p= 0.00	− 0.50 p= 0.00	− 0.56 p= 0.00	− 0.07 p= 0.30	− 0.56 p= 0.00
TM5 − TM7	− 0.72 p= 0.00	− 0.47 p= 0.00	− 0.50 p= 0.00	− 0.60 p= 0.00	0.06 p= 0.34	− 0.60 p= 0.00

1, Green browse biomass in the 0.3–1.5 m layer; 2, green browse biomass in the 1.5–2.5 m layer; 3, green browse biomass in the >2.5 m layer; 4, total green browse in the three layers; 5, green grass biomass; 6, total green browse biomass plus grass biomass.

TM5+ TM7 and TM5− TM7. The NDVI is most highly correlated with the lower browse layer and none of the other layers. Whereas the NDVI is not correlated with the total green biomass there are relatively high correlations between the total green biomass and all three of the darkening indexes and the brightness function. The darkening indexes therefore appear able to differentiate between green browse biomass in the three layers, total browse and total browse plus grass biomass. The fact that darkening is so prevalent in the landscape is emphasized by the fact that the brightness transform is also potentially useful in differentiating between the browse layers. However, the lowest correlation coefficients for all the indexes and transforms are found for the grass layer alone.

Further analyses were undertaken on the most significant correlations to develop predictive regression equations based on biomass–vegetation index relationships (table 7). These results reinforce the relative strength of subtractive and additive relationships involving the mid-infrared band in developing predictions not only for the lower most accessible browse layer but also for all three browse layers, taken together. All four strata (the browse and grass layers) are relatively difficult to predict but some estimate of green biomass availability may be obtained from TM5− TM7 and the Brightness function. A further significant point here is that the MODIS sensor within the NASA EOS constellation is designed to upgrade the use of NOAA-AVHRR imagery, hence the use of the NDVI, world-wide. It appears that data from the MODIS sensor, which includes a number of bandwidths in the mid-infrared, could be transformed into a more relevant index than the NDVI for semi-arid rangeland discrimination.

6. Summary and conclusions

This work was undertaken as a result of considerable significance being placed on the mapping and monitoring of degradation in semi-arid areas. Degraded areas in Botswana are normally believed to include those suffering from bush encroachment, which is now spatially extensive and believed to result from heavy cattle grazing. Certain bush encroachment species have been found to be relatively nutrient-rich and therefore the determination of green biomass within such species is significant for forage (hence carrying capacity) estimates. Hence the present work considered the extent to which a series of quantified layers through fine- and broad-leaved bush encroachment canopies in addition to the grass layer can be identified using conventional and newly derived vegetation indexes and transforms based on TM imagery.

Field results showed that the total browse biomass is greater than the total grass biomass by a factor of three, and that the relative importance of thorny and broad-leaved encroacher species in the browse biomass is almost the same. More than 90%

Table 7. Linear regression relationships of the darkening indexes and transforms in terms of measured browse biomass layers.

Linear regression relationship	Regression coefficient	Standard error
$\text{Biomass}_{(0.3\text{–}1.5\,\text{m strata})} = 163\,807.9 - 2946.6 \times \text{TM5} - \text{TM7}$	−0.52	19 118.0
$\text{Biomass}_{(0.3\text{–}1.5\,\text{m strata})} = 100\,113.8 - 597.6 \times \text{TM5} + \text{TM7}$	−0.40	21 181.8
$\text{Biomass}_{(\text{three browse strata})} = 612\,136.5 - 10914.7 \times \text{TM5} - \text{TM7}$	−0.37	95 507.0
$\text{Biomass}_{(\text{all four strata})} = 610\,407.2 - 10\,925.9 \times \text{TM5} - \text{TM7}$	−0.36	95 759.5
$\text{Biomass}_{(\text{all four strata})} = 519\,863.6 - 3459.0 \times \text{Brightness}$	−0.31	99 826.4

of the total green browse biomass is from woody species and is potentially accessible and edible to cattle. Biomass measurements within four quantified layers were correlated against conventional vegetation indexes and transforms such as the NDVI, brightness and greenness values, and relatively newly derived darkening indexes involving associations between the mid-infrared bands. Generalized results from mapped vegetation units showed few significant correlations with woody biomass. Results from point data within the vegetation units showed that most indexes (NDVI and darkening indexes) and the brightness transform could be used to discriminate the spatially extensive 0.3–1.5 m browse layer. However, only the darkening indexes and brightness function could separate out all the canopy layers individually and the total green biomass in terms of grass and woody components. None of the indexes or transforms could be used to reliably detect the grass layer. Hence while conventional indexes such as the NDVI may be used as a first approximation for browse estimates, stronger correlations (hence more potentially accurate estimates of total forage) can be derived from relationships involving the mid-infrared bands (TM5 and TM7). Consideration should therefore be given to the use of these bands in developing more accurate assessments of vegetation cover, hence potential forage in semi-arid areas. This may be achieved in the future through the use of the EOS, MODIS dataset which has a number of mid-infrared bands that could be transformed for forage estimates (MODIS 1998).

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