The Development and Causes of Range Degradation Features in Southeast Botswana Using Multi-Temporal Landsat MSS Imagery

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ABSTRACT: Multi-temporal Landsat imagery spanning 15 years was acquired to assess changes in range condition during non-drought and drought periods in the hardveld of southeast Botswana. Maximum likelihood classification was applied with different class signatures describing land-use/land-cover areas for the 1984 base year. These signatures were applied to data from 1972, 1982, 1986, and 1987. The natural vegetation rangeland comprised extensive darkened areas, including dense green trees and shrubs forming bush encroachment and less dense areas of moderate to sparse vegetation. Also included were areas of actively growing tree and shrub vegetation and herbaceous cover. In addition to the changes in the range brought about naturally during periods of rainfall and drought, field work (during drought) indicated that for most classes the species diversity and quality of browse also decreased. The main vegetation classes were combined into Severity of Degradation Indicators (SDIs) and correlated against such variables as human and livestock populations and rainfall to determine whether changes were naturally occurring or man-induced. The main conclusions were that livestock contributed to range degradation during both periods of good rains and periods of drought and that, for sustainable production, reductions in herd sizes were needed.

INTRODUCTION

RANGE DEGRADATION in Botswana has been considered by a number of authors (e.g., Van Vegten, 1980; Bhalotra, 1985; Cooke, 1983, 1985; Arntzen and Veenendaal, 1988), and can generally be resolved into problems resulting from high cattle stocking rates (above carrying capacity) on rangelands or increased human and smallstock (sheep, goat, and donkey) pressure concomitant with development along routeways and nodes throughout the country. The present study involved the use of Landsat MSS imagery to provide an assessment of change over a 15-year period from 1972 to 1987, to assess whether changes in the range occurred naturally over drought periods and periods of good rainfall, or whether some changes were due to anthropomorphic influences. The time limit fell within accepted United Nations guidelines for the assessment of range degradation or desertification (e.g., Reining, 1978).

The range in Botswana comprised natural vegetation cover of broadleaf and *Acacia* tree and shrub savanna, with a mixed species herbaceous layer developed during periods of above average rainfall (i.e., greater than 500mm per year) (Weare and Yalala, 1971). During drought the herbaceous layer is largely absent due to continued grazing. Tyson (1978) has indicted that in southeast Botswana rainfall trends have followed a sigmoidal pattern with a length of 15 to 20 years. In six out of every 10 years the seasonal rainfall was found to be lower than the mean.

BACKGROUND

A bibliography aimed at research in remote sensing towards desertification monitoring is available for the period until 1981 (Walker and Robinove, 1981) while a consideration of range assessment techniques is available in Carnegie *et al.* (1983). Graetz *et al.* (1983) established a Landsat database for rangeland assessment in southern Australia. Indicators of range quality included the development of "cover" from areas with low reflectance in the MSS 5 and MSS 7 bands. The "cover" index is similar to the darkening effect, described as a positive way of assessing the availability of forage in semi-arid range in drought affected savanna woodland environments (Ringrose and Matheson, 1987; Ringrose *et al.*, in press). In their work in the southwest United States, Warren and Hutchinson (1984) indicated that the direction of vegetation change could be established from multi-date imagery taken at times when the grass and/or shrubs were at maximum greenness. Musick (1984) tried different indicators for range assessment monitoring and opted for change in "brightness" index on standardized Landsat scenes. Otterman (1981) and Robinove (1983) noted sharp increases in albedo on Landsat MSS imagery due to (observed) anthropogenic effects. Darkening referred to an increase in land quality, while a brightened landscape denoted a possible decline in land quality. Darkening, however, can include a number of variables. Wilson and Tueller (1987) assumed shadow and litter were major components of darkening in Nevada range sites while Ringrose *et al.* (in press) reported that, while shadow and dark soil were the most important contributors to overall darkening, green leaves also provided a critical contribution.

The main objectives of the present work using Landsat MSS imagery are as follows:

- To develop spectral classes for 1984 hardveld land-use/land-cover features which can be used to indicate changes in range condition during drought and non-drought periods;
- To determine, from field work, whether changes were naturally occurring or due to man-induced influences;

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- To categorize range classes and to correlate these with rainfall and anthropomorphic parameters to determine the causes of range degradation; and
- To develop recommendations aimed at improving range management for sustainable production in Botswana.

THE STUDY AREA

The location of the study area is shown in Figure 1. The area occupied a small portion of southeast Botswana approximately 12,000km square, and was initially subdivided into two distinct ecological macro areas referred to as hardveld and sandveld (Ringrose and Matheson, 1987). The hardveld, considered in the present paper, is an area of loamy soil with an average rainfall of about 520 mm per year supporting relatively intensive agricultural activity in the form of crop production, cattle, and smallstock rearing. The carrying capacity of the range varied from 13 to 20 ha/LSU under "average" conditions in the more productive areas to 47 to 100 ha/LSU in more remote uplands (Field, 1977). Woody vegetation is also used for construction and as firewood. Exceptional areas included commercial ranches and less accessible rocky uplands in which woody vegetation density levels were maintained. This area was chosen because human and livestock pressures were dominant in the southeast around Gaborone as development in Botswana escalated in the 1970s and 1980s. Heavy demands were applied to the range resources especially during the 1980's drought.

METHODS

Image Acquisition

Landsat MSS imagery was acquired to cover the period of good rainfall (average 700 mm/year: 1972 to 1982) and the drought period (average 300 mm/year: 1982 to 1987) as shown in Table 1. An attempt was made to ensure that the data sets were as comparable as possible with respect to seasonality. The rains in Botswana usually extended from late September to March. The foliage and herbaceous cover responded to the first rains (in species sequence), increasing temperature, and lengthening daylight hours. The range was fully green by January, after which the herbaceous layer began to decline and different species showed leaf senescence, dependent on rain duration. January was chosen as the time when the vegetation was fully green and representing maximum growth. This was approximated by December imagery in 1972 and early March imagery in 1986. This was considered valid as December 1972 represented a phase of active vegetation regrowth in the recovery period following the 1960's drought. During the year 1986 late rains brought on a later greening of the study area. The only data available from 1987 was in September because of localized rains and cloudy conditions during the 1986–87 wet season. This date was considered representative of the last stages of drought in southeast Botswana and the end of vegetation dormancy.

Table 1. Landsat MSS Imagery and Data Used to Convert Digital Numbers to Reflectance Values

Date and Scene Identification	Sun Elevation (Degrees)	Earth-Sun Distance (AUs)	Band	L_{min}	L_{max}	E_{sun}	Haze
1972-12-29	54	0.98335	4	0	24.8	185.2	21
10159-			5	0	20.0	158.4	14
07415			7	0	15.3	90.4	0
1982-01-14	48.82	0.98353	4	0.8	26.3	185.6	23
22549-			5	0.6	17.6	155.9	12
07281			7	0.4	13.0	90.6	3
1982-01-14	48.71	0.98358	4	0.8	26.3	185.6	30
22550-			5	0.6	17.6	155.9	28
07340			7	0.4	13.0	90.6	29
1984-01-20	51.22	0.98393	4	0.2	23.0	183.1	26
40553-			5	0.4	18.0	159.3	18
07422			7	0.3	13.3	87.8	10
1986-03-06	44.9	0.99221	4	0.4	24.0	184.9	33
50735-			5	0.3	17.0	159.5	15
07403			7	0.2	12.7	87.0	9
1987-09-01	39.58	1.00925	4	0.4	24.0	184.9	37
51279-			5	0.3	17.0	159.5	25
07405			7	0.2	12.7	87.0	13

Field Work

Field work data were collected within one month of the 1984 overpass. Every effort was made to obtain January to March imagery in 1987, and routine field work took place during this period. As only September 1987 imagery could be obtained, the same sites were field checked again during August and September. The species composition and proportional vegetation

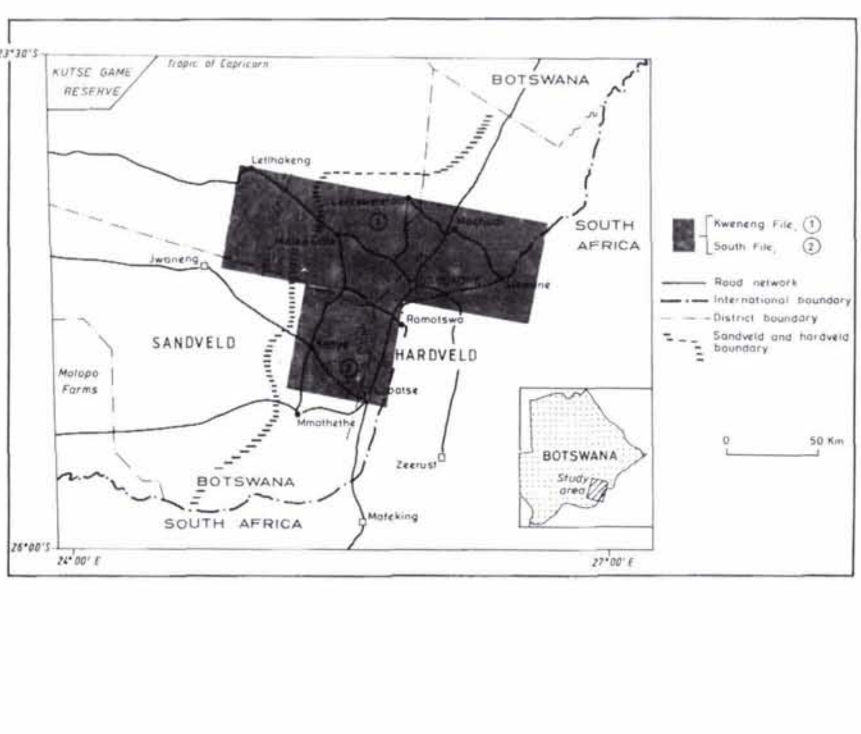

Fig. 1. Dimensions and location of the study area in Botswana.

cover were essentially similar. One major change was that a much higher degree of senescence was prevalent in September 1987. Quantitative field techniques included transect measurements, as described in Ringrose and Matheson (1987). Data collected in the field included measurements of tree and shrub species cover (normally considered as browse), alive and dead herbaceous cover, litter plus dead wood, soil type and color, and erosion features. Detailed measurements were taken on 81 specific sites, 53 of which were used as a basis for training areas in classification procedures. The entire area was covered by road transects with detail on conditions recorded and mapped annually over the period 1984, 1985, 1986, and 1987. The same 81 sites were returned to, wherever possible. Difficulties in finding the exact location arose as the markers had in many cases been removed. However, the authors' familiarity with the area made it possible to locate 85 percent of the areas accurately.

Data Corrections

Computer analysis of the data involved the identification of sub-scene areas intended for analysis. The region was sub-divided into two rectangular areas and the data, on MSS bands 4, 5 and 7, were stored in files referred to as "Kweneng" and "South" (Figure 1). This caused a minor reduction in the study area. January 1984 data were used as the base year. The data were precision corrected to the Universal Transverse Mercator (UTM) map projection using ground control points (GCP) scaled from 1:50 000-scale map sheets. The root-mean-square (RMS) error in location was 100 metres. Resampling was nearest neighbor and the output pixel size was 57 by 57 m. All other data (1972, 1982, 1986, and 1987) were registered to the 1984 image using homologous ground detail in each pair of images. The maximum RMS error in registration was 1.2 pixels.

The data were dehazed and calibrated to reflectance measure in the range 0 to 255. The formulae for conversion to radiance and reflectance measure were taken from Markham and Barker (1986), Robinove (1982), and Nelson (1985). These formulae incorporating the hazed offsets were reduced to a multiplicative factor (gain) and an additive factor (offset) (Table 1). The calculations for reductions of the formulae and haze bias to sample gains and offsets are given below:

$$\text{Radiance } (L) = (DN - H)\,\frac{L_{max} - L_{min}}{D_{max}} + L_{min} \qquad (1)$$

where DN = the pixel digital number from Computer Compatible Tape (CCT);
H = Haze offset in DN (from histograms of data);
L_{min} = Spectral Radiance at $DN = 0$ (from tables in Markham and Barker (1968));
L_{max} = Spectral Radiance at $DN = D_{max}$; and
D_{max} = Maximum DN recorded on CCT.

Spectral radiance at sensor aperture is given in $mW.cm^{-2}.ster^{-1}.\mu m^{-1}$

$$\text{Reflectance} = \frac{255.L.\pi.d^2}{E_{sun}.\sin a} \qquad (2)$$

where L = Radiance in $mW.cm^{-2}.ster^{-1}.\mu m^{-1}$ from Equation 1;
d = Earth-sun distance in astronomical units from the *Astronomical Almanac* (different years);
E_{sun} = Mean solar exoatmospheric irradiance in $mW.cm^{-2}.ster^{-1}.\mu m^{-1}$ (from tables in Markham and Barker (1986));
a = Solar elevation angle in degrees (CCT header); and
255 = Multiplicative constant to bring unitless reflectance measure (0–1) to the range 0 to 255.

$$\text{Let } P = \frac{255.\pi.d^2}{E_{sun}.\sin a} \qquad (3)$$

$$\text{Let } Q = \frac{L_{max} - L_{min}}{D_{max}} \qquad (4)$$

Now, substituting Equation 3 into Equation 2 gives
Reflectance = P.Radiance
and substituting Equation 4 into Equation 1 gives
Reflectance = $P.[Q.\,(DN - H) + L_{min}]$
= $(P.Q)DN + P.[L_{min} - (Q.H)]$
Thus, the Multiplicative factor = $P.Q$.
and the Additive factor = $P.[L_{min} - (Q.H)]$

The Earth-sun distances for the relevant dates in 1984 and 1987 were obtained from the *Astronomical Almanac*. The 1972 and 1982 images were calculated from formulae taken from Duffet-Smith (1979) and from Notes and Formulae on the Sun (C24) in the *Astronomical Almanac* (1987). The solar elevation angle was taken from the Landsat computer compatible tape (CCT) header information and checked for shift due to registration by formulae from Duffet-Smith (1979). Physical values used in dark area subtraction were taken from Robinove (1982). The 53 field location points were identified on the 1984 control image. The means of a 3- by 3-pixel window centered on each point in all 12 channels of 1972, 1982, 1984, and 1986 data were extracted. These values were used in class interpretation.

Classification and Grid Development

Supervised training was carried out on the 1984 base year data using training sites. Each training area was 512 by 512 pixels or 29.2 km square in extent. EASI-PACE software allowed investigation of both image and feature space relative to field work sites. Key areas were demarcated in image space and corresponding areas highlighted in a two-dimensional scatterplot of MSS 5 against MSS 7. The reverse process revealed image locations of gaps in feature space. Both files, Kweneng and South, were classified with a maximum likelihood classifier using the signatures separately unless less than 5 percent of the available pixels occurred in the null category. The same classification procedure was then applied to the remaining area. Sixteen classes with 8.2 percent null classes were obtained for the hardveld data. The same classification means and probabilities were used for the remaining multi-temporal data sets with a consequent decrease in classification accuracy away from the 1984 base year. A complete grid pattern of 100 by 109 pixels (5.7 by 6.2 km) was superimposed over both Kweneng and South files for each year. The classification results were generated for each grid square to facilitate multiple regression analyses.

Classification Accuracy

Techniques for establishing classification accuracy over time were applied using standard procedures (e.g., Story and Congalton, 1986). The results of classification accuracy are shown on Table 2. The accuracy of each individual class was assessed using contingency tables. The classified data were validated by comparing the class results with a previously stratified map superimposed with a comparable grid and derived from a combination of field work and background supplementary data. The classification accuracy by individual classes is shown on Table 2 which shows overall accuracy values ranging from 89 percent to 95 percent.

Ancillary Data Collection

Four additional independent data sets were obtained. Rainfall data were acquired from the Department of Meteorological

TABLE 2. ACCURACY ASSESSMENT FOR HARDVELD, SHOWING DEGREE OF ASSOCIATION (AS PERCENT ACCURACY) BETWEEN CLASSIFIED AREAS AND COMPARABLE AREAS CHECKED ON THE GROUND OR BY ANCILLARY DATA

Classified Areas	1972	1982	1984	1986	1987
1	83	91	100	87	81
2	100	75	80	78	72
3	67	54	73	73	65
4	91	100	83	71	91
5	100	95	100	80	81
6	82	80	71	73	80
7	90	100	100	95	70
8	87	97	100	97	95
9	100	100	100	99	90
10	99	98	100	100	100
11	100	89	100	100	100
12	90	100	100	93	89
13	89	90	100	57	77
14	94	83	100	84	89
15	100	100	100	96	82
16	64	83	82	78	75
Overall Accuracy %	90	90	93	85	84

Services for five stations throughout the study area. This was antecedent to the satellite overpass for 1972, 1982, 1984, 1986, and 1987. The data were distributed throughout the grid squares to equidistant points between stations for multiple regression analyses. Data on population distributions and changes over time were obtained from 1971 census estimates (given in the 1981 census) for major villages, and generalized throughout the grid squares for the remaining population (Central Statistics Office, 1981a, 1981b). Data for the different Enumeration Areas (EAs) for the 1981 census were applied directly to the grid squares. This was facilitated by 1:250 000-scale EA maps produced by the Department of Town and Regional Planning (D. Greenhow, unpublished). A consultants report (Aquatech Environmental Consultants, 1988, unpublished) provided population estimates for 1986 which covered most of the grid squares in the South file. Data on cattle and smallstock populations were collected each year by the Ministry of Agriculture (Botswana Agricultural Statistics, 1978, 1982, 1984, 1986, 1987) for each agricultural district. In each case the area of an agricultural district was estimated and the proportion of livestock was determined per grid square.

RESULTS

RANGE SPECTRAL CHARACTERISTICS

Spectral aspects of drought adaptation in relation to different soil types (as represented by soil color) are reported elsewhere (Ringrose *et al.*, in press). Basically, drought adapted vegetation showed as dark tones on visible bands and is at its darkest in areas of dense, impenetrable *Acacia* bush. This is regarded as a "desertification" phenomenon referred to as bush encroachment. Where dense *Acacia* foliage overlies dark soil, the combined spectral response was very similar to that of sediment laden water (Ringrose *et al.*, 1988). Less extreme darkening occurred when vegetation consisted predominantly of open structured plants which were drought adapted in the sense that they consisted of relatively few leaves with a high proportion of inter-leaf shadow. This effect was exacerbated by the high sun-angle over the Tropic of Capricorn during the summer (wet) months.

Green leaves provided a significant contribution to the darkening effect both in terms of canopy development and due to a drought adaptive cell structure which reduced NIR (near infrared) scatter. Drought adaptive components in a plant were emphasized by the unusually highly reflective soil which, under drought conditions, was exposed by continuous grazing. Drought adapted vegetation was also referred to as single story (Type 1) vegetation and has a low NIR reflectance while dense, green well-watered vegetation was referred to as multi-story (Type 3) vegetation. Type 2 vegetation cover contained components of each during a period of transition. The significance of darkening indicating moderate-sparse or even sparse drought-adapted vegetation lay in the fact that forage was available from such areas (when validated by fieldwork) during drought conditions. Field observations showed that many drought adapted animals (springbok, gemsbok, etc.) were able to browse on drought adapted vegetation. Goats (and some sheep) also ate away at stands of *Acacia* species while cattle browse on such broadleaf species as *Combretum*, *Boscia*, and *Grewia*.

CLASSIFICATION INTERPRETATION

Results of the interpretation of spectral classes in terms of land-use and land-cover categories are given in Table 3. The location of the classes in feature space and class ellipses with clusters at a statistical separability of 95 percent are shown as Figure 2. Classes 2 and 15 comprised areas of dense, well watered vegetation (Type 3). Areas of class 2 consisted of broadleaf species adjacent to ephemeral streams in areas of groundwater discharge. Here, multi-story trees and shrubs formed a dense canopy cover which had high NIR reflectance, despite the lack of herbaceous cover (Figure 3). Class 15 consisted of dense herbaceous growth with intermittent shrubs or sub-mature crops growing in response to localized rains. These areas also had a high NIR reflectance. Class 13 had a relatively low NIR reflectance and consisted mostly of dense *Acacia mellifera* and/or *Acacia tortillis*. These trees were characterized by open canopy structure and microphyllous leaves (Type 1). This class, an extreme form of bush encroachment, proved extremely difficult to penetrate on the ground. Estimates showed green woody vegetation densities of around 80 percent with no alive herbaceous cover.

Most of the remaining land-use/land-cover classes lay on the diagonal of Figure 2, which shows an increase in NIR and red reflectance with increasing amounts of exposed soil. Classes 6 and 16 had over 70 percent exposed soil and moderately sparse to sparse vegetation (Type 1). Class 16 had a high proportion of sand introduced through sheetwash. Classes 9, 11, and 12 represented different mixtures of broadleaf and *Acacia* species on different soil color types (Figure 4). They comprised Type 2 vegetation in an area subject to fuelwood cutting and land clearing for agriculture. They had in common evidence of sparse alive herbaceous cover. Classes 3 and 10 consisted of dense and moderate-dense drought adapted mainly *Acacia* vegetation (Type 1). These classes were similar to class 13 except that bush encroachment was less advanced and some broadleaf species were prevalent (Figure 5). Both classes 3 and 10 contained areas of erosion and dead vegetation which became increasingly apparent as the drought progressed. The remaining vegetation classes—4, 8, and 14—consisted of drought adapted broadleaf and *Acacia* species with some evidence of erosional phenomena and little or no alive herbaceous cover (Figure 6). Fuelwood cutting and land clearing for agriculture was prevalent especially in Class 4.

CHANGE DATA

The total areas within each class and the extent to which these changed over time are shown in Table 4. Tables 5 and 6 represent a listing of species in order of dominance for each class visited in the field and Tables 7 and 8 show the soil color, proportion of browse species, and details of the ground cover. A comparison

TABLE 3. INTERPRETATION OF SPECTRAL CLASSES RESULTING FROM HARDVELD MAXIMUM LIKELIHOOD CLASSIFICATION (1983-1984)

Class Number	Interpretation
1	Open water bodies with relatively high sediment content.
2	Dense vegetation fed by ephemeral streams and areas of ground-water discharge. These form mixed woodland with tree plus shrub cover. May include crops and rainfed vegetation in non-drought periods.
3	Moderate-dense, drought adapted, dominantly broadleaf vegetation, including areas of commercial ranching and hills. Includes some areas of bush encroachment where *Acacia* spp. are locally dominant.
4	Moderate-sparse drought adapted vegetation of mixed broadleaf and *Acacia* spp., on dominantly red-brown soils showing some evidence of sheetwash and gulleying.
5	New urban and rural development containing concrete structures.
6	Moderate-sparse, drought adapted vegetation over some areas undergoing erosion (mostly sheetwash) on red-yellow soils.
7	New concrete of airport runway.
8	Moderate-sparse, drought adapted vegetation of mixed broadleaf and *Acacia* spp., on dominantly red-yellow soils which show some evidence of erosion. Includes areas cleared for cultivation.
9	Moderate-sparse, drought adapted vegetation of mixed broadleaf and *Acacia* spp., on dominantly red-yellow soils which show some evidence of erosion. Includes minor areas of vegetation regrowth as crops or in herbaceous layer.
10	Dense, drought adapted dominantly broadleaf and *Acacia* spp., includes areas of dead vegetation. Similar to 3, but with higher proportion of *Acacia* spp., and therefore more indicative of bush encroachment.
11	Moderate-sparse drought adapted dominantly broadleaf vegetation on brown-red soils with evidence of herbaceous regrowth.
12	Moderate-sparse drought adapted vegetation of dominant broadleaf species showing evidence of herbaceous regrowth on dominantly red-brown soils.
13	Dense areas of bush encroachment (dominantly *Acacia* spp.) on dark grey soils with some evidence of erosion. Includes areas of dead vegetation.
14	Moderate-sparse drought adapted dominantly broadleaf vegetation on red-brown soils.
15	Dense well watered vegetation of grasses, weeds, or shrubs mainly peripheral to water sources. Includes sub-mature crops and renewed growth of herbaceous vegetation.
16	Sparse drought adapted vegetated areas with extensive sheetwash erosion containing a high proportion of sand.

Dense = 65% or more vegetation cover.
Moderate – Dense = 50% – 65% vegetation cover.
Moderate = 30% – 50% vegetation cover.
Moderate – Sparse = 25% – 30% vegetation cover.
Sparse = 10% – 25% vegetation cover.
Very Sparse = 10% or less vegetation cover.

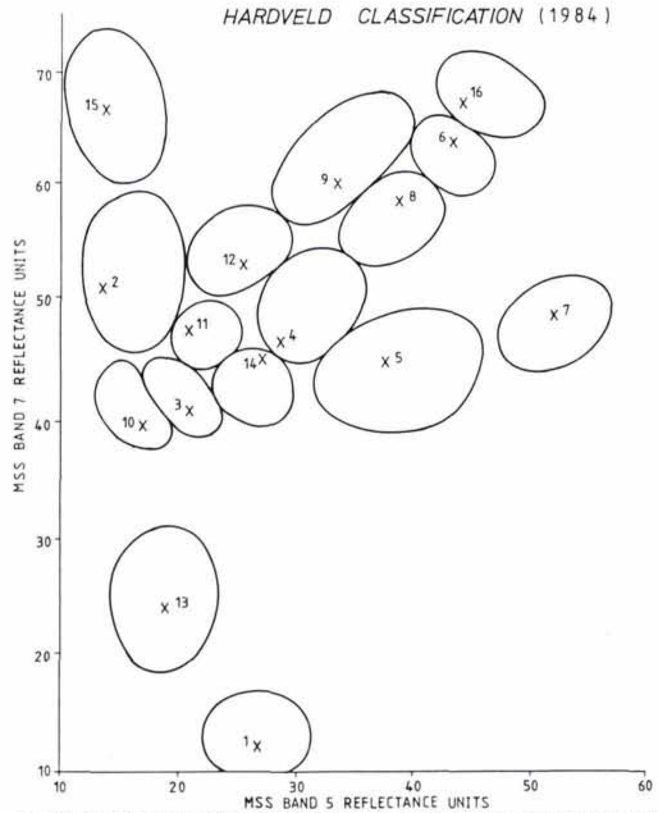

FIG. 2. Distribution of hardveld spectral classes in Landsat MSS bands 5 and 7 feature space, 1984.

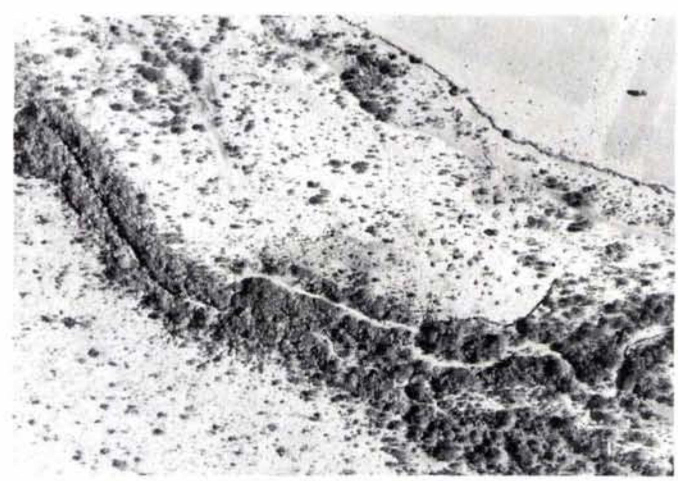

FIG. 3. Dense multi-story vegetation (Type 3) fed by the Metsimothalba river, south of Molepolole, Class 2. The dense vegetation is surrounded by cultivated fields and areas of Class 6, moderate-sparse drought adapted vegetation, (Type 1). SCALE 1:25000

between the tables indicates the main changes which have taken place between the 1983/84 field season and the 1986/87 field season. The areas of classes 2 and 15 increased from 1972 onward as the green foliage responded to the rains. Conversely, the area decreased as dry conditions became prevalent. Field results showed that the amount of deadwood increased in class 2 during the drought. The overall species diversity also decreased with *Terminalia sericea*, an intermediate browse species, becoming more dominant. Areas containing some herbaceous cover in 1984 were diminished by 1987. The proportion of good browse was reduced slightly and the amount of woody vegetation was reduced.

In class 13, the area under very dense bush encroachment showed similar trends to those found in classes 3 and 10. These areas began being relatively small during 1972 and increased slightly during the wet period up to 1982. An extensive increase in the area (especially in class 3) took place during the drought until 1987. On the ground, class 3 showed a marked decline in species diversity, a trend not seen in class 10 where *Dichrostachys*

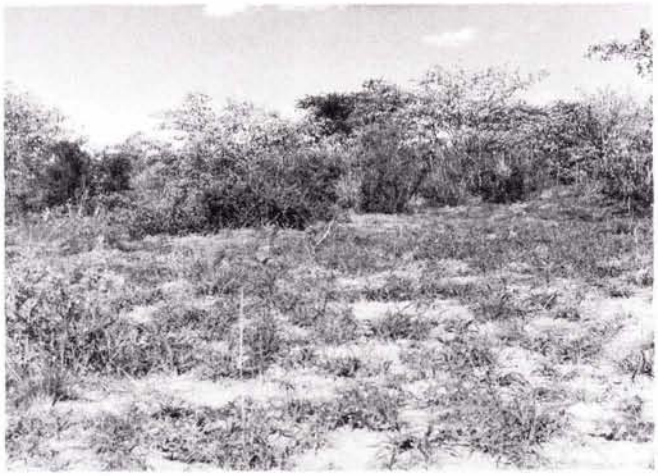

FIG. 4. Moderate-sparse drought adapted vegetation of dominant broadleaf species showing evidence of herbaceous regrowth on dominantly red-brown soils, (Type 1)

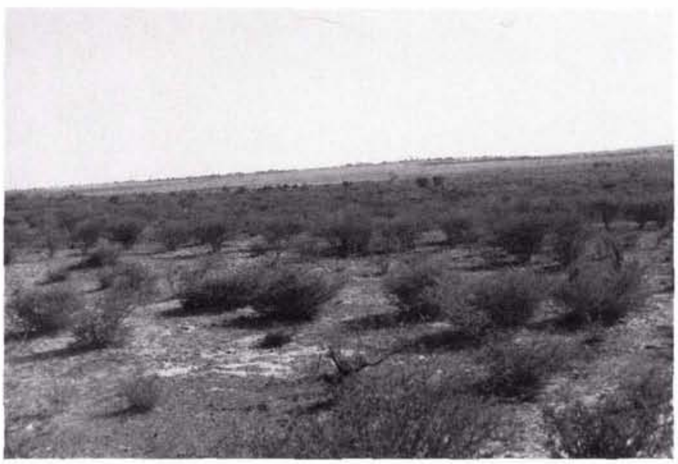

FIG. 5. Area of Class 3 bush encroachment, showing dominant *Acacia* shrub vegetation.

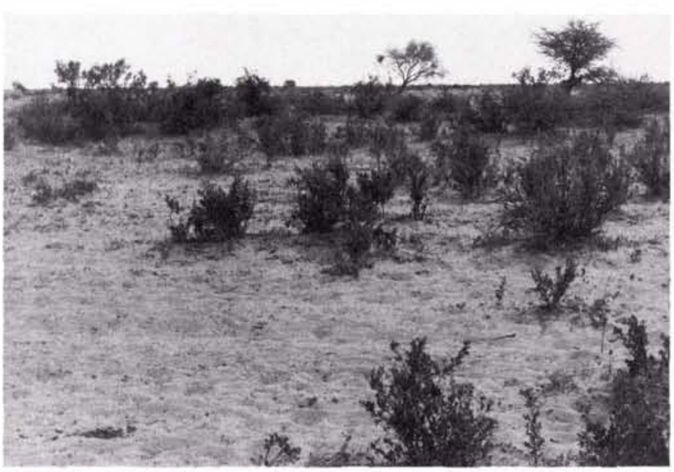

FIG. 6. Class 14:Moderate-sparse drought adapted dominantly broadleaf vegetation on red-brown soil.

cineria (a shrub indicative of overgrazing) became more dominant. Class 3 showed no change in the proportion of browse although the overall proportion of woody species cover declined. Class 10 showed a decline in good browse species and woody vegetation cover. Due to localized rains, class 10 had a much higher proportion of herbaceous cover in 1986/87 than in 1983/84.

TABLE 4. TOTAL AREAS OF CLASSES IN HARDVELD (IN KM SQUARED) AND CHANGES THROUGH TIME

Class	1972	1982	1984	1986	1987
1	0.0	0.5	2.5	0.2	0.1
2	539.2	1050.9	356.9	237.0	1.3
3	64.8	290.5	246.4	797.5	2185.5
4	391.4	496.8	110.6	2154.9	2222.0
5	3.8	28.0	46.0	52.2	1.7
6	326.8	91.4	241.6	54.8	0.0
7	0.5	0.8	0.9	7.4	0.0
8	384.5	293.1	1135.1	371.1	12.8
9	1479.5	750.6	1870.7	192.4	10.7
10	95.4	104.3	838.9	892.0	811.1
11	437.7	1307.4	1151.7	511.7	49.8
12	1386.7	2532.0	1332.5	691.9	92.8
13	17.8	42.0	1833.0	107.8	411.6
14	340.1	700.0	1200.3	1291.8	2465.9
15	75.1	221.7	24.7	26.1	12.6
16	1981.0	184.1	355.4	88.1	0.0
Area Error	3222.9	2653.1	0.0	3270.3	2469.3
Total Area	10747.2	10747.2	10747.2	10747.2	10747.2

Classes 6 and 16 denoted extremes in terms of reflectance on the red and NIR bands. These represented extensive areas of sparse to moderate-sparse vegetation at the end of the 1960s drought which declined as more vegetation was added during the rains, up to 1982. No particular trend was noted through the drought years. During these latter years, Class 16 had a high herbaceous content due to localized rains. From 1984 to 1987 the woody species diversity in both class areas declined with *Grewia flava*, a good browse species, becoming more dominant. The woody cover percent was maintained on the ground in these class areas as the proportion of good browse declined.

Classes 9, 11, and 12, which represented moderate-sparse mixtures of *Acacia* and broadleaf species, mostly increased during the period of good rains and decreased during the drought. All classes suffered a decrease in species diversity with, in the case of class 9, *Terminalia sericea* becoming more dominant as drought progressed. In the case of classes 11 and 12, *Dichrostachys cineria*, indicative of overgrazing, became more dominant. In class 9 the proportion of woody species decreased. None of the classes showed a marked decrease in the proportion of good browse over the three years. Class 12 areas generally had a higher than average alive herbaceous cover and also about 20 percent woody vegetation cover in 1984. This class was regarded as an indicator of relatively strong herbaceous cover change. Classes 4, 8, and 14 represented moderate to sparse vegetation with mixtures of broadleaf and *Acacia* cover. Except in the case of class 14, very little change in the proportion of vegetation cover took place during the wet period. The area of classes 4 and 14 increased considerably during the drought, whereas the area of class 8 appeared to decrease. Classes 4 and 8 suffered a reduction in species diversity. All three classes showed a marked decrease in the woody species percent and a minor decrease in the proportion of good browse.

SEVERITY OF DEGRADATION INDICATORS

It appeared plausible that other characteristics, such as the rapid removal of green herbaceous cover at the onset of drought,

TABLE 5. VEGETATION IN HARDVELD CLASSES (1983-1984) LISTED IN ORDER OF SPECIES DOMINANCE

Class	Perennial Plants	Herbaceous Plants
2	Acacia karroo, Maerua spp, Grewia bicolor, Terminalia sericea, Grewia flava.	Asparagus spp.
3	Croton grassisimus, Diospyros lyciodes, A. tortilis, Grewia flava, Euclea undulata, A. mellifera, Grewia bicolor, Terminalia sericea, Aloe spp.	Indigofera spp. Asparagus spp. Elephantorrhiza spp.
4	Pelphotorum africanum, A. tortilis, Grewia flava, Dichrostachys cinerea, A. tenuispina, A. mellifera, Euclea undulata, A. karroo, Terminalia sericea, A. robusta.	Asparagus spp. Indigofera spp. Elephantorrhiza spp.
6	A. tortilis, Terminalia sericea, Maytenus spp., Diospyros lyciodes, Dichrostachys cinerea, Euclea undulata, Boscia spp., A. nilotica, Lycium austrinum, Grewia flava, Grewia bicolor, Ziziphus mucronata, Aloe spp.	Asparagus spp.
8	A. tortilis, Terminalia sericea, A. mellifera, Euclea undulata, A. nilotica, A. karroo, A. erubescens, Dichrostachys cinerea, Lycium austrinum, Grewia flava.	Elephantorrhiza spp. Indigofera spp.
9	Euclea undulata, A. tortilis, Tarchonanthus camphoratus, Grewia flava, A. hebeclada, Rhigozum brevispinosum, Terminalia sericea, A. nilotica, Dichrostachys cinerea, Aloe spp.	Asparagus spp.
10	A. tortilis, Grewia flava, A. tenuispina, Combretum apiculatum, Lycium austrinum, Aloe spp.	Asparagus spp.
11	A. mellifera, A. tortilis, Grewia flava, A. erubescens, Dichrostachys cinerea, Combretum molle, Terminalia sericea, Euclea undulata.	–
12	A. tortilis, Dichrostachys cinerea, A. fleckii, Grewia flava, A. hebeclada, Grewia bicolor, Terminalia sericea, A. erubescens, Lycium austrinum, Aloe spp.	Elephantorrhiza spp.
14	A. tortilis, Grewia flava, A. mellifera, Euclea undulata, Aloe spp.	Asparagus spp.
15	Combretum molle, A. mellifera, Grewia bicolor.	Anthephora spp. Anstida spp. Juncus spp. Agrostis spp.
16	A. tortilis, A. nebrownii, A. mellifera, Diospyros spp., Aloe spp.	Asparagus spp.

TABLE 6. VEGETATION IN HARDVELD CLASSES (1986-1987) LISTED IN ORDER OF SPECIES DOMINANCE

Class	Perennial Plants	Herbaceous Plants
2	Dead vegetation, Terminalia sericea, Croton gratissimus, Grewia flava.	–
3	Combretum apiculatum, Acacia erubescens, Vitex zeyheri, Croton gratissimus.	Asparagus spp.
4	A. tortilis, Grewia flava.	Asparagus spp.
6	Grewia flava, Dichrostachys cinerea, A. karroo.	Asparagus spp.
8	Grewia flava, A. mellifera.	Asparagus spp. Indigofera spp.
9	Terminalia sericea, Grewia flava, Aloe spp.	–
10	Dichrostachys cinerea, Croton gratissimus, Combretum apiculatum, Lycium austrinum, Euclea undulata, A. tenuispina, A. robusta, Aloe spp.	–
11	Dichrostachys cinerea, Ziziphus mucronata, Euclea undulata, A. tortilis, Grewia flava, Combretum apiculatum, Terminalia sericea.	Asparagus spp.
12	Dichrostachys cinerea, A. erubescens.	Indigofera spp.
14	A. mellifera, A. tortilis, Euclea undulata, Combretum apiculatum, A. erubescens.	Asparagus spp.
16	Grewia flava, A. tortilis, Aloe spp.	–

may be due as much to intensive cattle and smallstock grazing as to natural climatic cycles. Similarly, the decrease of mixed woody vegetation cover may be due to natural die-off or to wood removal by villagers. Severity of Degradation Indicators were needed to provide a summary of significant class changes which then could be correlated with rainfall and man-induced factors to determine the principal causes of range degradation. Class data indicative of broad vegetation changes through time were synthesized into SDIs as follows:

- Changes in the amount of dense, green, multi-story cover vegetation (from classes 2 and 15) = SDI 1. This area contained good quality browse and/or herbaceous cover. This indicator was considered responsive to extensive rains of long duration (more than three months).
- Changes in area of drought adapted bush, especially in the form of bush encroachment, in addition to changes in the area of dead trees and erosional phenomena (from classes 3 and 10) = SDI 2. This indicator was particularly responsive to long term overgrazing.
- Changes in the area of mixed moderate-sparse vegetation resulting from fuelwood cutting, clearing land for agriculture, and other developments on red-brown soil (class 4) = SDI 3 and on red-yellow soil (classes 8 and 9) = SDI 4. These areas indicated the general range condition in terms of the darkening effect.
- Changes in the area of green, herbaceous vegetation cover, class 12 = SDI 5. This area shows the contrast between darkened vegetation and localized, short term rainfall events.

MULTIPLE REGRESSION ANALYSES

SDIs 1 through 5 were run against different ancillary data sets. Results of the analyses are shown in Table 9 for Kweneng file and Table 10 for South file. Variables equated with more than 5 percent significance (i.e., less than 95 percent confidence) were omitted (SPSSX, 1986).

SDI 1, which denoted changes in area of dense, green multi-story vegetation, was positively related to population distribution in 1971, rainfall in 1982 and 1986, and cattle data in 1987. Localized increases in rainfall in 1982 and 1986 were understandably accompanied by increases in SDI 1. In 1987 the number of cattle increased, probably because of the renewed availability of browse and grass in 1986.

SDI 2 was correlated with the largest number of variables. In the Kweneng grid squares, SDI 2 was negatively correlated with rainfall in 1972. This suggested that as rainfall increased the areas of bush encroachment, dead trees, and/or erosional features decreased. In the early stages of drought these areas were positively correlated with rainfall. A second negative correlation with rainfall took place in 1986 which was a slightly wetter year. Throughout most of the dry years, SDI 2 was positively related to smallstock and negatively related to cattle data. Therefore, during the drought years, increases in the number of smallstock were accompanied by increases in bush encroachment, dead trees, and/or erosional features. Simultaneously, the number of cattle decreased as a result of drought. In the South area a positive relationship existed between SDI 2 and cattle numbers.

TABLE 7. DATA ON HARDVELD CLASSES DERIVED FROM FIELD WORK: 1983-1984 WET SEASON

Class	Dominant Soil Color	$\bar{X}$ B : M	*Browse species % woody cover G.	I.	P.	Ground cover (percent) WV	AHC	DHC	BS	N
2	5YR 5/4 Reddish-brown	9 : 5	44	8	48	71.1	1.33	2.48	25.3	4
3	7.5YR 6/6 Reddish-yellow	12 : 5	35	6	59	55.6	1.0	3.9	39.9	5
4	5YR 5/6 Yellowish-red	3 : 2	34	4	61	25.9	0.8	3.1	70.9	7
6	5YR 6/6 Reddish-yellow	5 : 3	38	0	62	21.7	2.4	1.0	76.0	7
8	7.5YR 6/6 Reddish-yellow	5 : 3	36	7	57	28.7	0.6	2.2	70.0	5
9	5YR 6/6 Reddish-yellow	1 : 1	33	8	58	21.6	2.7	1.0	76.0	5
10	5YR 5/6 Yellowish-red	3 : 2	63	4	33	72.3	2.6	1.3	24.9	3
11	5YR 5/6 Yellowish-red	9 : 5	33	0	66	28.5	3.4	2.4	66.9	5
12	5YR 4/4 Reddish-brown	7 : 4	31	8	61	20.3	5.6	1.8	73.2	5
14	5YR 5/8 Yellowish-red	9 : 5	33	0	66	27.7	0.0	1.0	71.3	3
16	5YR 6/6 Reddish-yellow	3 : 3	44	2	54	17.2	0.4	3.1	79.5	4

B = Broadleaf species
M = Microphyllous species
WV = Woody Vegetation

P = Poor, I = Intermediate, G = Good } Browse species

AHC = Alive herbaceous cover
DHC = Dead herbaceous cover
BS = Bare Soil
AHC = Alive herbaceous cover
N = Number of samples

*after Hendzel, 1981

TABLE 8. DATA ON HARDVELD CLASSES DERIVED FROM FIELD WORK: 1986-1987 WET SEASON.

Class	$\bar{X}$ B : M	Browse species % woody cover G.	I.	P.	Ground cover percent WV%	AHC%	DHC%	BS%	N
2	7 : 4	40	15	45	51.7	1.2	7.0	40.1	4
3	9 : 4	39	0	61	33.2	6.0	7.4	53.4	5
4	3 : 2	23	0	77	26.0	16.7	7.7	45.7	7
6	1 : 1	31	8	62	21.7	0.6	7.6	71.9	7
8	7 : 5	34	7	59	44.0	8.7	5.0	43.0	5
9	1 : 1	25	8	67	13.2	7.7	8.1	71.1	5
10	9 : 5	39	2	59	37.9	16.8	8.9	36.4	3
11	9 : 4	48	2	50	37.0	4.1	4.1	49.1	5
12	1 : 1	29	4	67	38.3	16.7	7.7	37.3	5
14	3 : 2	40	0	60	33.0	1.0	3.6	62.4	3
16	3 : 2	25	0	75	15.4	19.8	9.2	56.0	4

B = Broadleaf species
M = Microphyllous species
WV = Woody Vegetation

P = Poor, I = Intermediate, G = Good } Browse species

AHC = Alive herbaceous cover
DHC = Dead herbaceous cover
BS = Bare Soil
AHC = Alive herbaceous cover
N = Number of samples

*after Hendzel, 1981

Hence, larger cattle numbers may have contributed to increases in bush encroachment, dead trees, and/or erosional phenomena.

SDIs 3 and 4 represented areas of moderate-sparse vegetation cover. During the rains these SDIs were positively related to smallstock distributions but during the earlier stages of drought a negative relationship existed. As the drought progressed, negative relationships between cattle and smallstock data became more apparent. This suggested that all the livestock were browsing areas of moderate-sparse vegetation cover during the drought. SDI 5, which included the area of sparse, green herbaceous cover, was most positively correlated with smallstock distribution, but also positively correlated with cattle and rainfall. Cattle and smallstock were concentrated in areas of herbaceous cover. As rain increased in 1986, SDI 5 areas decreased. This suggested that, although additional herbaceous cover was available, livestock consumption at this time was in excess of herbaceous cover production.

CHANGE ANALYSIS

An attempt was made to quantify the changes which occurred for the different SDIs with respect to changes in the controlling variables. The two periods analyzed using change techniques

TABLE 9. RESULTS OF MULTIPLE REGRESSION ANALYSIS, HARDVELD KWENENG.

Relationship	Significance (f)
SDI 1 1972 = 96.4 + 0.037. POP71	0.0002
SDI 1 1986 = 13.11 + 0.377. RAIN 86	0.0184
SDI 1 1987 = 0.23 + 3.818E − 04. CATTLE	0.0004
SDI 2 1972 = 364.933 − 2.506. RAIN 72	0.0038
SDI 2 1982 = −126.569 + 1.064. RAIN 82	0.0007
+ 0.026. CATTLE 82	0.0058
− 0.14. POP81	0.0379
SDI 2 1984 = 70.488 + 1.3225.S STOCK	0.0074
−0.118. CATTLE 84	0.0403
SDI 2 1986 = 533.54 − 1.416. RAIN 86	0.0028
+ 0.353.S STOCK 86	0.0035
SDI 2 1987 = 473.576 + 1.639. S STOCK 87	0.0000
− 0.204. CATTLE 87	0.0010
SDI 3 1984 = 22.996 + 0.071. S STOCK	0.0052
SDI 3 1987 = 916.905 − 0.425. S STOCK	0.0012
SDI 4 1972 = 76.253 + 1.411. CATTLE 78	0.0000
SDI 4 1982 = 485.22 − 0.473.S STOCK	0.0030
SDI 4 1984 = 1214.793 − 0.084. CATTLE 84	0.0086
SDI 4 1986 = 289.024 − 0.034. CATTLE 86	0.0044
SDI 5 1972 = 111.958 + 2.4545. S STOCK	0.0183
SDI 5 1986 = 8.936 + 1.495. RAIN 86	0.0001
SDI 5 1987 = 17.849 + 0.021. CATTLE 87	0.0000
+ 0.099. S STOCK	0.0004

TABLE 10. RESULTS OF MULTIPLE REGRESSION ANALYSIS, HARDVELD SOUTH

Relationship	Significance (f)
SDI 1 1982 = −126.025 + 2.709. RAIN 82	0.0004
SDI 2 1972 = 170.840 − 0.662. S STOCK 78	0.0008
SDI 2 1982 = 66.961 + 0.014. CATTLE 82	0.0004
SDI 2 1984 = 361.096 + 0.097. CATTLE 84	0.0000
SDI 2 1987 = 974.534 + 0.095. CATTLE 87	0.0010
SDI 3 1972 = 311.729 − 1.174. CATTLE 78	0.0001
+ 1.5625.S.STOCK 78	0.0012
SDI 3 1982 = 403.014 − 1.186. RAIN 82	0.0000
SDI 3 1986 = −3614.369 + 15.057. RAIN 86	0.0001
+ 1.520.S.STOCK	0.0003
SDI 3 1987 = 1276.538 − 0.693. S STOCK 87	0.0000
SDI 4 1972 = 253.818 + 2.476. S STOCK 78	0.0070
SDI 4 1982 = 423.618 − 0.036. CATTLE 82	0.0014
SDI 4 1984 = 1327.082 − 0.926. S STOCK 84	0.0001
SDI 4 1987 = 15.212 − 0.011. S STOCK 87	0.0171
SDI 5 1984 = 499.642 − 0.226.S STOCK	0.0222
SDI 5 1986 = 1347.787 − 4.407. RAIN 86	0.0090
SDI 5 1987 = 30.016 − 0.018. S STOCK	0.0074

were the period of rains (1972 through 1982) and the period of drought (1984 through 1986). The year 1987 was excluded because of the absence of population data. The results for both Kweneng and South areas are shown on Tables 11 and 12. The increase in rainfall over time accompanied increases in bush encroachment, moderate-sparse vegetation, and green healthy vegetation. During this time numbers of smallstock were declining while cattle numbers were on the increase.

During the drought, decreases in SDI 1 were negatively related to cattle decreases and positively related to rainfall. This inferred that declines in actively growing, green woody vegetation paralleled localized increases in cattle and generally low rainfall. But in 1986 following a slight increase in rain, because cattle

TABLE 11. RESULTS OF MULTIPLE REGRESSION ANALYSIS FOR CHANGE VARIABLES, HARDVELD KWENENG.

Relationship	Significance (f)
Change 1972-1982	
Δ SDI 2 = −1.115 + 0.791. Δ RAIN	0.0033
Δ SDI 3 = 21.976 + 0.034. Δ POP	0.0350
−0.563. Δ S STOCK	0.0015
Δ SDI 4 = −358.45 + 2.080. Δ RAIN	0.0009
+ 0.649. Δ CATTLE	0.0000
− 8.730. Δ S STOCK	0.0000
Δ SDI 5 = 507.646 − 0.597. Δ S STOCK	0.0250
Change 1984-1986	
Δ SDI 1 = −87.456 − 0.449. Δ CATTLE	0.0370
+ 0.812. Δ RAIN	0.0086
Δ SDI 2 = 122.439 − 1.033. Δ RAIN	0.0001
Δ SDI 3 = 716.900 − 1.141. Δ CATTLE	0.0037
Δ SDI 4 = −762.640 + 2.075. Δ CATTLE	0.0000

TABLE 12. RESULTS OF MULTIPLE REGRESSION ANALYSIS FOR CHANGE VARIABLES, HARDVELD SOUTH.

Relationship	Significance (f)
Change 1972-1982	
Δ SDI 1 = −188.900 + 3.660. Δ RAIN	0.0003
Δ SDI 3 = 163.1 − 1.064. Δ RAIN	0.0003
Δ SDI 4 = −269.9 − 0.557. Δ S STOCK	0.0070
Δ SDI 5 = 438.7 − 0.564. Δ S STOCK	0.0070
Change 1984-1986	
Δ SDI 3 = 95.907 + 7.828. Δ S STOCK	0.0000
−0.868. Δ CATTLE	0.0000

numbers were low this allowed some regeneration of green, woody vegetation. In terms of SDI 2, increases in bush encroachment, dead trees, and eroded areas took place as rainfall decreased. In the Kweneng area increases in SDI 3 (moderate-sparse vegetation on red-brown soils) took place as cattle numbers generally decreased. The reverse was true of SDI 4, because decreases in moderate-sparse vegetation on yellow-red soil took place as cattle numbers decreased. In South area decreases in SDI 3 were related to increases in smallstock. This suggested that, while cattle do browse, smallstock were mainly responsible for browse consumption.

CONCLUSIONS

Maximum likelihood classification for the hardveld area in southeast Botswana resulted in 16 land-use/land-cover classes being developed for the 1984 base year. The same class signatures were applied to corrected Landsat MSS data for earlier years (1972 through 1982) covering a period of good rains and extended until 1987 until the end of the drought period. Accuracy of classified data decreased away from the 1984 base year. The results confirmed that the natural vegetation which comprised the range consisted largely of drought-adapted trees and shrubs during 1984 in which the presence of green foliage could be detected through the darkening effect. These areas were subdivided into very dark areas of bush encroachment (which also included dead trees and erosional features) and lighter areas of moderate-sparse vegetation with virtually no herbaceous cover. Also within the range were darkened areas with some herbaceous cover and areas of actively growing green vegetation.

During the period of rains, the areas of actively growing green vegetation and herbaceous cover increased, as did the areas of bush encroachment. During the drought the areas of moderate-sparse vegetation (darkened areas) increased considerably, bush encroachment areas intensified and increased slightly, while areas of actively growing green vegetation decreased. On the ground, different classes showed decreases in woody species cover, decreases in species diversity, and decreases in the availability of good browse.

Hence, natural vegetation changes which might be regarded as being cyclical, depending on periods of rainfall and drought, also included changes which appeared to be dependent on continuous grazing and/or human factors. Therefore, characteristics of the main bush types, resolved into Severity of Degradation Indicators (SDIs), were run against the main controlling variables considered as numbers of the human population, cattle, and smallstock in addition to rainfall. Generally the results showed that

- Increases in bush encroachment areas during drought years appeared to be mainly due to smallstock browsing although, to a lesser extent, cattle were also implicated.
- Mostly cattle numbers decreased during the early drought as areas of drought adapted vegetation increased. This indicated that through vegetation, cattle were more affected by lack of rainfall than smallstock because they were less adaptive feeders.
- Actively growing green vegetation only increased after cattle numbers declined after the onset of drought conditions.
- During drought the decreased area of moderate-sparse vegetation was related to increases in smallstock, rather than decreases in cattle.

The results generally showed that superimposed over cyclic periods of drought and good rains, which caused fundamental changes to the natural range vegetation, were man-induced influences which caused range degradation. The impacts were less related to population density as such, and more related to the density and distribution of cattle and smallstock herds. Range management recommendations for sustainable production therefore include the need to

- Reduce (or redistribute) the numbers of cattle during especially wet periods of short duration to allow the range to regenerate fully; and
- Reduce the numbers of smallstock entirely, but especially during drought periods. If particularly this last recommendation is not considered, large areas of southeast Botswana will become denuded of vegetation and eventually unable to support present production levels.

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