Satellite based long-term assessment of rangeland condition in semi-arid areas: An example from Botswana

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ABSTRACT

A methodology was devised for comparison of generalised range condition over time, irrespective of the nature of original imagery used. It was applied for range condition change mapping throughout Botswana through 1984–2000. Results showed that range degradation was most widespread during the 1980s drought when 25% of the country was affected, decreased to 6.5% in 1994 and increased to 9.8% in 2000. This suggests that these semi-arid rangelands are fairly resilient and can withstand "normal" droughts even under conditions of heavy grazing pressure. However, degradation that persists during normal or above average rainfall years is related to increasing livestock and other pressures on rangelands and may represent areas with severe range recovery problems. This application meets some requirements of a semi-arid developing country looking to improve range condition monitoring over relatively remote areas.

1. Introduction

This work considers the use of Landsat imagery in determining long-term potential range degradation over natural rangelands in semi-arid Botswana. Degradation and desertification are global environmental problems affecting inhabitants of semi-arid lands (Dregne, 2002; Geist, 2004). Under semi-arid conditions of naturally variable rainfall, increased human activity tends to over-stress land and vegetation resources leading to degradation, salinisation, and erosion (Geist and Lambin, 2004; Hellden, 1991) particularly in Africa where about 20 million pastoralists depend on natural grazing lands for their subsistence (Reynolds et al., 2003; Thomas, 1997). Range degradation has been a problem in Botswana from before independence in 1966 while features associated with desertification, such as deflation hollows and (small) sand-dunes, are widely recognised during droughts (Parsons and Crowder, 1988).

Degradation can be defined as areas undergoing reduced biological productivity as a result of human induced or climatic factors (United Nations, 1992). However, vegetation productivity cannot always be accurately quantified with satellite imagery over vegetated semi-arid areas because of what has been called the vegetation darkening and shadow effect (Dougill et al., 1999; Otterman, 1974; Ringrose et al., 1989). This results in the underestimation of low near infrared-reflective vegetation, which often consists of drought adapted plants, shrubs and trees (Ringrose et al., 1989) and thus, potentially, leads to overestimation of degradation. This risk was particularly high when this work in Botswana started during the early 1980s when the best available satellite imagery consisted of hard-copy prints of Landsat-MSS imagery. Later improvements as for example in MODIS imagery generated vegetation indices (such as NDVI or EVI datasets) were still a long way in coming (Huete et al., 2002). A surrogate degradation indicator was therefore required to mitigate this problem and, additionally, to compensate for image quality differences over the entire study period, while maintaining comparability. In this work, that indicator is the prevalence of highly reflective bare soil areas as visible for instance around settlements and livestock watering points. This corresponds to Tainton's (1999) primary depopulation phase of range degradation as identified for South Africa. Mapping of bare soil (or very sparsely vegetated areas) is regarded as feasible in semi-arid zones with 200–600 mm rainfall and indicative of range degradation (Dube, 1998; Munyati and Makgale, 2009). In our analysis, allowance was made (where possible) for naturally occurring bare soil areas such as e.g. salt-pans. Most human induced bare soil areas begin as small patches which either become green after rains or continue in their bare soil state and thereby

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may be regarded as degraded. Hence a technique is required to identify the degraded state and track its status over decades. Range condition in this work is intended as being relative to the degraded (bare soil) state and hence through time might be moderately or highly improved.

In semi-arid areas livestock not only graze but also browse trees and shrubs, enabling them to maintain condition during a 'normal' dry season (Moleele et al., 2001). Hence any evidence of vegetation cover, including shrubs, is symptomatic of improved range condition in the form of forage availability. Such critical range condition indicators are fairly subtle and not always measured through normalized difference vegetation index (NDVI) data from the Advanced Very High Resolution Radiometer (AVHRR) satellite (Zhang et al., 2003) or similar vegetation indices that tend to underestimate the less vibrant but browse-important grey–green leaves on savanna bushes and trees (Dougill et al., 1999). They are therefore best visualised using relatively high resolution Landsat type imagery (Ringrose and Matheson, 1995).

Regular nation-wide satellite based rangeland monitoring is important to an average sized developing nation like Botswana (580 000 km^2) where issues related to the United Nations Convention to Combat Desertification (http://www.unccd.int) are important. However, in the 1980s and early 1990s this was too large a surface to be covered frequently because of cost involved and image processing and ground-truthing fieldwork required. Hence, a compromise was required.

This paper looks at challenges involved in mapping range degradation in Botswana and develops a methodology for assessing range condition change over the years 1984–2000. This period involved substantial technological changes and rapid population and infrastructure growth (Vanderpost et al., 2007) in combination with increasingly complex climatic variability (Hulme et al., 1996), making comparative imagery interpretation problematical but increasingly necessary. The intent of this paper is to:

1. Develop a methodology to recognise degraded patches in semi-arid vegetation types.
2. Demonstrate its use for range condition change mapping throughout Botswana through 1984–2000.
3. Discuss how persistent range degradation relates to human induced as opposed to natural factors.

2. Methodology

2.1. *Image interpretation*

Landsat images for the three time periods 1984/85, 1994/95 and 2000/01 were used for the study. Range degradation (indicated by bare soil or very sparse vegetation) can only be readily recognised relative to well-vegetated surroundings and hence imagery obtained during the wet season (October–April) is ideal. Concerning the years used, 1984/85 occurred during a drought cycle and 1994/95 during a wet cycle although the actual year was relatively dry. The 2000/01 season was wet and followed on a very wet previous season (http://www.weather.info.bw).

When this work started in the 1980s, digital remote sensing in Botswana was in its infancy so a manual approach was initially employed. A range condition map at 1:1 000 000 scale was constructed using visual interpretation techniques and intermittent fieldwork in the southern part of the country. Wet season 1984/85 (November 1984–March 1985) Multispectral Scanner (MSS) satellite imagery with a pixel resolution of 80 m was interpreted, using 35 individual hard-copy images of the near infrared (0.7–1.1 μm) band. As this was a drought year, patches of dense vegetation tended to show up as darker areas while bare soil areas were more highly reflective (Ringrose et al., 1997). These were visually identified and manually traced onto an acetate overlay. In order to obtain a simple quantitative indicator, the country was divided into quarter degree units (QDU) measuring 0.5 by 0.5° (approximately 50 × 50 km). Range condition measurement was effected by superimposing a 1 × 1 cm (10 × 10 km) minigrid over each QDU sequentially. As this was a purely manual/visual exercise based on hard-copy image prints, a conservative approach was required. For that reason it was decided for each QDU to count minisquares only in terms of showing/not showing 50% or more bare soil. This 50% cut-off point, while being somewhat arbitrary, was practical in terms of visually examining the 1 × 1 cm cells and helped to avoid misleading accuracy not justified by image quality and image spatial accuracy. This also helped to avoid over-estimating bare soil due to pixel saturation, a known MSS problem (Matheson and Ringrose, 1994), while areas with 50% or more bare soil were considered to be decidedly vulnerable to wind and water erosion (Tainton, 1999). Thus, percentage estimates of bare soil condition were made for each QDU based on the proportion of minisquares showing 50% or more bare soil reflectance.

For 1994/5 (September 1994–March 1995), 40 colour composite digital wet season images covering Botswana were obtained as two mosaics corresponding to Botswana's UTM zones 34 and 35. These Landsat Thematic Mapper images with a pixel resolution of 30 m had three bands: TM3 (0.63–0.60 μm), TM4 (0.76–0.90 μm) and TM5 (1.55–1.75 μm), corresponding to the visible red, near infrared and mid infrared parts of the spectrum. Visual interpretation of (unclassified) imagery was done as for 1984/5, except that it took place on-screen and not on prints. To maintain comparability with 1984/85, the same minigrid counting method to obtain QDU bare soil values was used. In addition, supervised digital image classification was performed as reported in Ringrose et al. (1997) and Ringrose et al. (2002), taking into account available fieldwork information (see Section 2.3 below). The results provided useful validation of the visual interpretation as there was close correspondence between the two sets of results (Ringrose et al., 1997).

While the intention was to next assess 2004/05, budget constraints limited fieldwork and 2005 image acquisition to previously identified hot-spot areas (north-east, western-Kweneng, western-Ngamiland). Results thereof were used for national range degradation classification based on freely available 2000/01 imagery consisting of six digital colour composites from the Geo-Cover dataset (http://www.earthsat.com). Each comprised three Landsat ETM + bands, i.e. Band 2 (visible green light), Band 4 (near infrared light) and Band 7 (mid infrared light) with pixels of 14.25 m. As for 1994/5, the image-mosaics were visually inspected for bare soil and subjected to supervised classification as a means of confirmation. The system of recording by QDUs based on a superimposed minigrid was employed to ensure comparability with previous years. Hence, techniques of interpretation, even when evaluated against machine generated classes, were visual in effect and so are regarded as comparable to interpretation undertaken for 1984/5 and 1994/5, especially as this was brought about by the same researchers.

2.2. *Standardized range condition mapping and change detection*

A major challenge was to provide comparable standardized quantitative measures of 'range condition' over the study years especially because data inputs involved both hard copy and digital image products. The procedure was based on visual assessment of bare soil proportions by minigrid cells of 10 × 10 km, using hard-copy imagery (1984/85) or (unclassified) digital imagery (1994/95 and 2000/01), which was then generalised to QDU level, partly to compensate for the estimated geographic location error margin of +/−1 km (especially for the 1984/85 imagery).

A digital polygon layer of QDUs covering Botswana was constructed using ArcInfo GIS software. Percentage degradation recorded through the minigrid method was entered as polygon attributes for each QDU for each year and grouped through standard GIS classification procedures into 6 range condition classes based on natural breaks in the statistical data distribution. The 'best' class consists of QDUs without any minisquares with over 50% bare soil with the next best class made up of QDUs with one such minisquare. The latter class can be regarded as being minimally affected by degradation and as more or less 'normal' for semi-arid conditions. It is labelled 'average' in Fig. 1. The 'worst' class resulting from the grouping consisted of QDUs with 10 or more (>40%) minisquares with over 50% bare soil, presenting a severe erosion risk and reduced recovery potential (Tainton, 1999). Intermediate classes resulting from the natural breaks were considered to be on a gradual scale of increasing degradation. Classes were adjusted to a best-fit-all situation by comparing data distributions for the three different years. After incorporating fieldwork results (see Section 2.3), the resulting classification (based on proportion of minigrid cells per QDU showing 50% or more bare soil reflectance) is shown in Fig. 1. A generalised geographic pattern, based on mean degradation values for Botswana's administrative districts, was derived from this information and the result portrayed in Fig. 2.

With each QDU assigned a range condition value for the 3 years, change analysis relied on spreadsheet techniques to calculate the difference between years. Results were added as polygon attributes and were subsequently used to produce 1984/5 to 1994/5 and 1994/5 to 2000/1 change maps. After overlaying a classified land-use layer from the national land-use map (DSM, 2001), the zone function of Arcview spatial analyst was used with land-use as the zone-layer to obtain range condition values for major national land-use classes. Livestock distribution data from the Department of Wildlife and National Parks' regular aerial surveys, which were available for 1994 and 2003 (but not for 1984), were used to examine degradation in relation to grazing pressure.

2.3. *Field work*

Fieldwork was undertaken in support of image interpretation by the same team using the same techniques (Ringrose and Matheson, 1995). Fieldwork was undertaken mainly in southern Botswana during the mid 1980s, throughout Botswana during the 1994/95 wet season and during mid 2005 for selected hot-spot areas. Sample sites were located to characterise naturally vegetated areas and those subject to human pressure. Data collection entailed pacing three transects through 90 m × 90 m sample plots. Continuous recording and height estimation of tree/shrub species was undertaken and species identified using Palgrave (1981). Three 50 cm × 50 cm quadrats were placed randomly by throwing the quadrat within a 6 m belt along the transect. Alive herbaceous cover (AHC), dead herbaceous cover (DHC), litter and bare soil percentages were estimated within each of the three quadrats. Notes were added on structure, clearing size, extent of trampling and erosional or depositional features and on arable and former arable areas to assess extent of cultivation and erosion. This field data was used to verify bare soil estimates. For the later years this was done by overlaying the fieldwork sites on the image and comparing the visual interpretation with fieldwork data.

3. Results and implications

3.1. *Satellite imagery interpretation*

The 1984/85 range degradation map was developed to support drought relief activities by the Botswana Interministerial Drought Committee. Manual image interpretation and associated fieldwork showed that large areas of Botswana had bare soil and so were potentially suffering from poor range condition (Fig. 1). This was related to three years of drought and heavy grazing pressure by livestock, which led to rapid depletion of grassland and, later, to heavy livestock mortality. Areas near the Okavango Delta and the Boteti River were worst affected. In south-western Botswana some apparent degradation was the result of extensive veld-fires. 61.2% of QDUs were classified as exhibiting poor to extremely poor range quality (Table 1), while the actual land area sustaining some

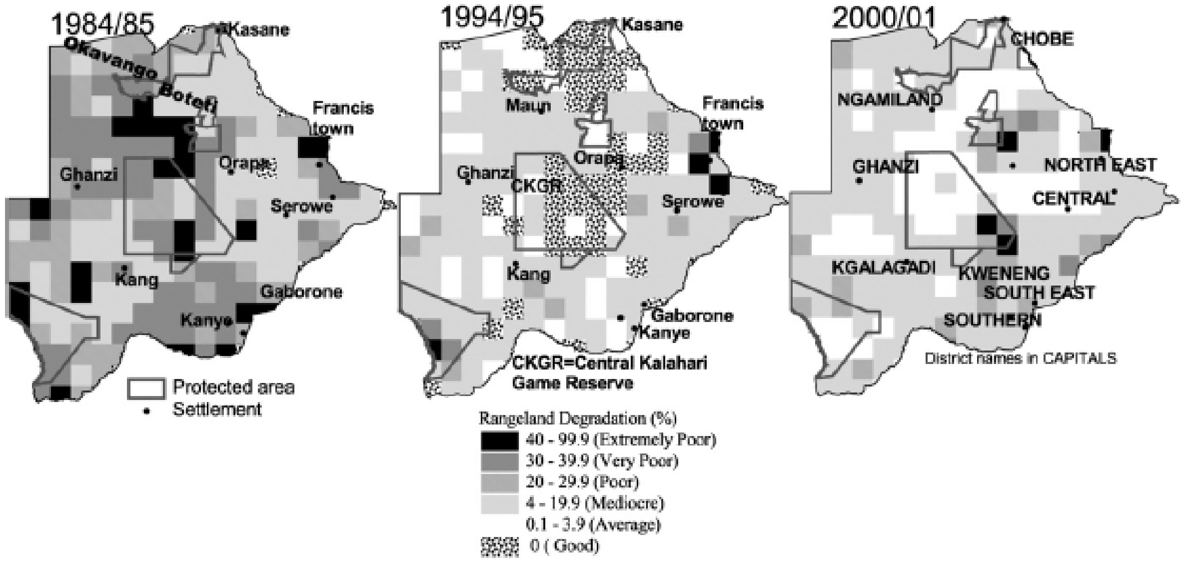
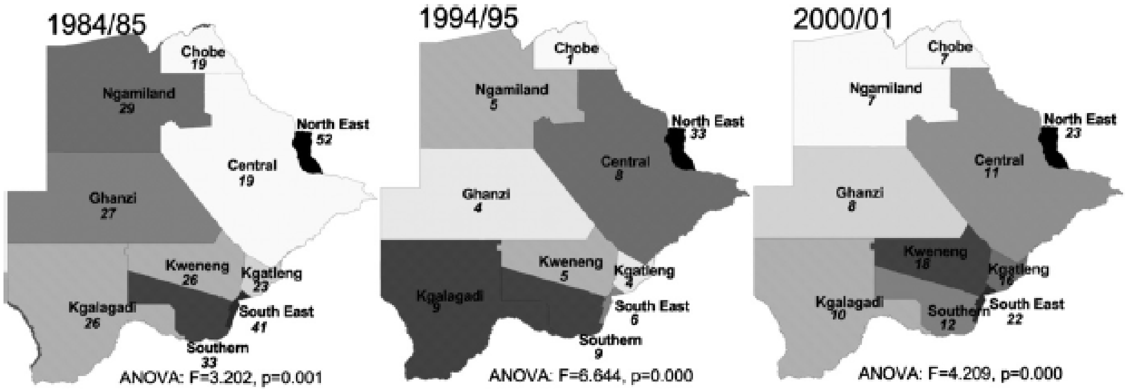


Fig. 1. Range condition/degradation Botswana 1984/85, 1994/95 and 2000/01.



Bostwana administrative districts arranged by degradation level from highest (black) to lowest (white) for 1984/85, 1994/95 and 2000/01 (%value printed under district name).

Fig. 2.

Table 1
Trends in rangeland degradation categories: Botswana, 1984–2000.

Degradation category	Range condition	% QDUs 1984/85	% QDUs 1994/95	%QDUs 2000/01
0% degradation	Good	1.0	20.9	0.0
0.1–4% degradation	Average	0.0	16.5	27.1
4–20% degradation	Mediocre	37.0	55.5	60.1
20–30% degradation	Poor	22.0	4.1	9.0
30–40% degradation	Very poor	30.0	1.5	2.1
40% & over degradation	Extremely poor	10.0	1.5	1.7
Total		100	100	100

QDU = Quarter degree units (0.5 × 0.5°).

form of potential degradation during the 1980s drought period was estimated at about 25% of the country.

The 1994/5 interpretation showed that a much smaller area remained as degraded rangeland compared to 1984. Worst affected areas (Fig. 1) occurred in the north-east near Francistown and appeared to result from extensive soil erosion along major rivers. In the south-west, bare soil areas were, once again, related to fires. Areas near the Okavango and the Boteti also continued to show extensive degradation. Interestingly, most protected areas (National Parks and Game Reserves) showed limited degradation, while non-protected areas showed more extensive if somewhat localised degradation. This infers that protected areas have higher resilience and are better able to regenerate after drought, although the decline in wildlife during the 1980s drought was likely a contributing factor (Crowe, 1995). Such vegetative regeneration to pre-drought levels is not always the case for areas outside parks. For this 1994/5 post-drought period, the total area sustaining some form of range degradation was estimated at about 6.5% of the country. Of QDUs 7.1% were classified as poor to extremely poor range quality (Table 1). As anticipated, the overall situation was one of generally improved range condition as normal rainfall conditions had returned prior to 1994/95.

The 2000/1 analysis showed that about 9.8% of the country was experiencing potential range degradation (Fig. 1). 12.8% of QDUs were classified as poor to extremely poor range quality (Table 1) with the worst areas in the south-east (including western-Kweneng) and in the north-east and adjacent central district between Francistown and Orapa with additional pockets in the south-west (Figs. 1 and 2). It also showed that even during a period of good rains mediocre range conditions remained prevalent over two thirds of the country. Although a quarter of Botswana experienced average to good range condition, no areas qualified for the label 'good'.

3.2. *Change in rangeland condition*

Comparison of 1984/5 and 1994/5 using simple subtraction of the respective bare soil values recorded as QDU attributes led to

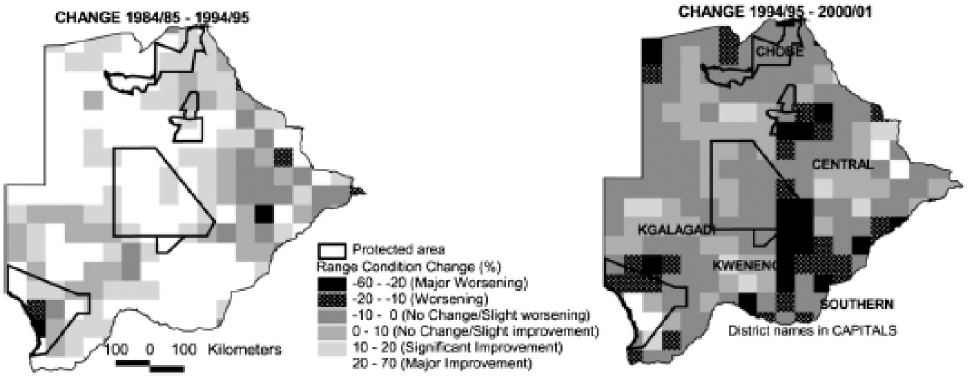


Fig. 3. Range condition/degradation change, Botswana 1984/85 to 1994/95 and 1994/95 to 2000/01.

Table 2
Mean degradation (%) by land-use category, Botswana 1984/85, 1994/95 and 2000/01.

Land-use category	% of country	Mean degradation%		
		1984/85	1994/95	2000/01
Protected areas (parks and reserves)	18.7	27.6	4.9	9.4
Pastoral/arable/residential	44.7	25.0	7.6	10.9
Wildlife management areas	24.1	22.3	4.3	7.6
Ranches	10.5	30.6	10.1	11.1
Other	2.0	28.1	6.9	11.4

ANOVA 1984/85: $F = 3.202$, $p = 0.356$; ANOVA 1994/95: $F = 12.433$, $p = 0.000$; ANOVA 2000/01: $F = 3.450$, $p = 0.008$.

development of the 1984–94 change map which depicts range condition change per QDU since the 1980s drought (Fig. 3). Change over this period was expected to be positive as years of good rains followed the drought. However, certain parts of Botswana experienced negative change and degraded areas increased despite good rains. This occurred particularly in eastern Botswana in catchments of larger rivers which flooded extensively over the two years before 1994/5 causing extensive soil erosion. Other areas showed no change or minor positive change indicating little or no post-drought recovery. Examples include Chobe district, much of Central district and large portions of south-western Botswana. These areas are known to have experienced clear felling of natural tree and shrub cover for agriculture, leading to increased wind erosion, for instance in western-Kweneng and Southern district (Fig. 2).

Comparison of the 1994/5 and 2000/01 maps (Fig. 3) showed that improvement of range condition mostly occurred in the country's centre and north-east, areas that were seriously degraded during the 1980s drought. Following severe livestock mortality toward the end of the drought, slow recovery of livestock numbers may have permitted a slow but sustained level of range regeneration. Western-Kweneng and the Kgalagadi area also registered improved conditions. However, most of the country experienced mild negative change implied by a slight worsening of range conditions, in spite of relatively good rains. This modest range recovery may be an indication of grazing and other pressures on natural rangelands hovering around carrying capacity level (Geist, 2004). Although cattle numbers stabilised in most regions, there was considerable increase in smallstock numbers during the 1990s (Ministry of Agriculture, 1999) especially near cattle posts and dispersed villages which, coupled with inevitably variable rains, limited improvements in range conditions.

Table 1 summarises range condition trends for 1984–2000. The data confirm rangeland resilience to climatic variation. Regions with poor range condition during droughts as in the 1980s recovered during post-drought periods of good rains. However, during episodes of average rainfall and increasing stocking rates, there is a tendency for the range to decline and revert to mediocre or relatively poor condition, as in 2000/01.

The geographic pattern of range condition change is summarised in Fig. 2 which shows the mean degradation values by administrative district for the three study years. Districts are arranged from highest (=black) to lowest (=white) degradation level for each year. This pattern reveals that for each year, the small densely populated North-East district had the highest degradation level with the similarly fairly densely populated south-eastern Southern and South-East districts also fairly high. Nearby Kgatleng and Kweneng ditricts, which are also rather densely populated, show relatively worsening conditions over the 1984–2001 time span, in spite of conditions of improved rainfall.

3.3. *Results in relation to land-use*

Land-use reflects human impacts and management interventions on the natural environment and can be expected to exert a major influence on degradation. In Botswana, reserves and national parks represent the highest level of environmental protection. Wildlife management areas are subject to variably regulated resource exploitation, but in most cases hunting restrictions apply and many are livestock free, while population density tends to be low. Most of the rest of rural Botswana is under communal tenure devoted to rural settlements with pastoral and arable activities. A small proportion of the rural areas is under privately managed ranches.

Using a digital version of the Botswana national land-use map (DSM, 2001), overlay analysis was performed on the three degradation maps to identify patterns of range degradation in relation to land-use (Table 2). Of the major land-use categories, 'ranches' recorded the highest degradation proportion in all 3 years. Wildlife management areas, which are mostly livestock free and tend to

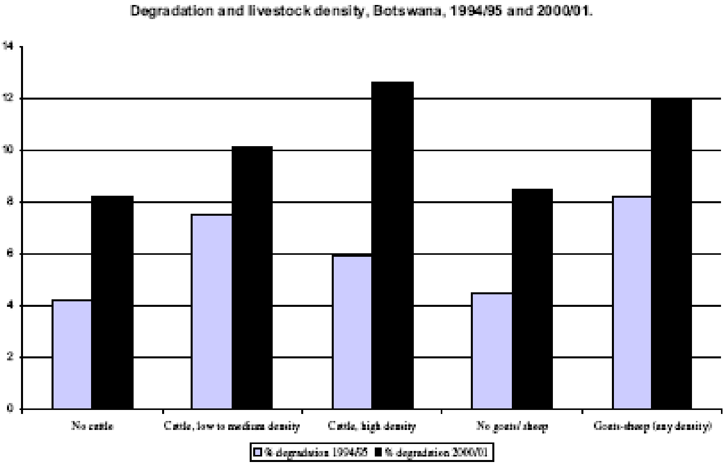


Fig. 4. Degradation and livestock density, Botswana, 1994/95 and 2000/01.

have low wildlife density, recorded lowest degradation in all years, followed by protected areas, except in 1984/85 when drought conditions affected wildlife and livestock areas almost equally. Pastoral/Arable/Residential areas exhibited fairly high degradation levels as expected on account of their locally high population density and, particularly, their high livestock densities (Table 2). Analysis of variance values are printed with Table 2, indicating that differences between land-use categories were significant in 1994/95 and 2000/01, but not in 1984/85, possibly on account of the generally high degradation levels across the entire country.

Land-use related degradation differences are to an extent confirmed by livestock distribution data from the Department of Wildlife and National Parks' regular aerial surveys which were available for 1994 and 2003 (for use with the 2000/01 map) although not for 1984/85. For both years, regions where the cattle count amounted to zero (i.e. no cattle) exhibited lower range degradation levels compared to regions where cattle were counted. For 2000/01 there is a clear increase of degradation from regions with medium/low cattle density to regions with high cattle density. This is not true for 1994. A similar relationship is evident between degradation levels and the distribution of smallstock (Fig. 4).

4. Conclusion and discussion

A methodology was devised for comparison of generalised range condition over time, irrespective of the nature of original imagery used. This facilitated mapping of degraded areas over the period 1984–2000, over drought and non-drought conditions and through changes in technology and image quality. This meets some requirements of a semi-arid developing country looking to improve range management over relatively remote areas. The technique has limitations not least being the gaps between coverage years and hence lack of continuity in terms of rangeland change. Also, the intermittent coverage of field sites prohibited calculation of accuracy measures with respect to the image interpretation. Nevertheless, the technique is potentially applicable to all developing semi-arid lands and can be replicated to facilitate long-term range condition mapping with limited technological usage.

Results of the comparison between individual degradation maps shows large temporal variations strongly associated with rainfall conditions as was found in the Sahel (Herrmann et al., 2005). Degradation was most widespread during the 1980s drought when 25% of the country was affected, decreased to 6.5% in 1994 and increased to 9.8% in 2000. This suggests that these semi-arid rangelands are fairly resilient and can withstand “normal” droughts even under conditions of heavy grazing pressure. However, degradation that persists during normal rainfall years appears related to increasing livestock and other pressures on rangelands and may represent areas with severe recovery problems. There could be a trend towards a slow increase of this component given that between 1994 and 2000 most areas experienced mild negative change in spite of improved rainfall. This could indicate that grazing and other pressures on natural rangelands are hovering around the carrying capacity level. This is supported by the fact that protected areas showed a more significant recovery than non-protected areas.

Analysis of relationships between range condition and land-use identified highest levels of range degradation in ranches and communal areas devoted to pastoral, arable and residential use with lower levels prevailing in wildlife management areas and in National Parks and Game Reserves. However, protected areas are affected by greater fire frequency probably because of higher fuel loads. Evidence suggests that current livestock densities may not under the circumstances be sustainable as, again, was found in the Sahel (Herrmann et al., 2005).

This assessment of range conditions is significant in that it implies that a future drought or series of dry years may have rather immediate effects upon range condition as a natural vegetation buffer is not available. It is also clear from change analysis that individual areas experience considerable swings in range condition, depending on for instance variable regional rainfall, fire occurrences and, possibly, intensity levels of livestock grazing (Ringrose et al., 2002).

As recent images show limited continued range improvement despite better rainfall, the issue arises whether this is a low point on a parabolic trend or the beginning of a decline brought about by population/infrastructure expansion exacerbated by construction of fences and ranches and related development activities. As this is happening under scenarios of climate change which predict a temperature increase with possible shifts of Botswana's main vegetation belts (Hulme et al., 1996) it is important to plan for adequate drought coping strategies. A drought early warning system is in place (http://www.sadc.int/dmc/) and can be a first step toward a range of interventions aimed at mitigation of drought effects upon the livestock industry and people's livelihoods. Climatically the ability to predict El Nino events such as the one of the mid 1980s should enable semi-arid developing nations to take timely stock of their rangeland usage, even when in most countries populations are increasing and natural rangelands diminishing, while flexibility to move livestock to better grazing areas in times of drought is restricted by fences and other boundaries. Broad national land-use planning for improved rangeland management is thus important, while the need for continued and more detailed monitoring of range conditions is also evident.

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References

Crowe, D., 1995. Status of selected wildlife resources in Botswana and recommendations for conservation actions. In: The Present Status of Wildlife and Its Future in Botswana. Kalahari Conservation Society and Chobe Wildlife Trust, Gaborone The Proceedings of a Symposium/Workshop.

Dougill, A.J., Thomas, D.S.G., Heathwaite, A.L., 1999. Environmental change in the Kalahari: integrated land degradation studies for nonequilibrium dryland environments. Annals of the Association of American Geographers 89 (3), 420–442.

Dregne, H., 2002. Land degradation in the drylands. Arid Land Research and Management 16, 99–132.

DSM, 2001. Botswana National Atlas, 2001. Department of Surveys and Mapping, Botswana.

Dube, O.P., 1998. Monitoring vegetation cover over diverse landscape types in semi-arid south-eastern Botswana. Geocarto International 13 (2), 43–51.

Geist, H.J., 2004. The Causes and Progression of Desertification Burlington (VT), Ashgate.

Geist, H.J., Lambin, E.F., 2004. Dynamic causal patterns of desertification. Bioscience 54 (9), 817–829.

Hellden, U., 1991. Desertification – time for an assessment. Ambio 20, 372–381.

Herrmann, S.M., Anyamba, A., Tucker, C.J., 2005. Recent trends in vegetation dynamics in the African Sahel and their relationship to climate. Global Environmental Change Part A 15 (4), 394–404.

Huete, A., Didan, K., Miura, T., Rodriguez, E.P., Gao, X., Ferreira, L.G., 2002. Overview of the radiometric and biophysical performance of the MODIS vegetation indices. Remote Sensing of Environment 83, 195–213.

Hulme, M., Arntzen, J., Downing, T., Leemans, R., Malcolm, J., Reynard, N., Ringrose, S., Rogers, D., 1996. Climate change and southern Africa: an exploration of some potential impacts and implications in the SADC region. In: Hulme, M. (Ed.). WWF International Report Co-ordinated by Climate Research Unit, Norwich, UK.

Matheson, W., Ringrose, S., 1994. Assessment of degradation features and their development into the post-drought period in the west-central Sahel, using landsat MSS. Journal of Arid Environments 26, 181–199.

Ministry of Agriculture, 1999. Botswana Agricultural Statistics, Planning and Statistics. Botswana, Gaborone.

Moleele, N., Ringrose, S., Arnberg, W., Lunden, B., Vanderpost, C., 2001. Assessment of vegetation indexes useful for browse (forage) prediction in semi-arid rangelands. International Journal of Remote Sensing 22 (5), 741–756.

Munyati, C., Makgale, D., 2009. Multitemporal landsat TM imagery analysis for mapping and quantifying degraded rangeland in the Bahurutshe communal grazing lands, South Africa'. International Journal of Remote Sensing 30 (14), 3649–3668.

Otterman, J., 1974. Baring high albedo soils by overgrazing, a hypothesized desertification mechanism. Science 186, 531–533.

Palgrave, K.C., 1981. Trees of Southern Africa. C.Struik Publishers, Cape Town. 959.

Parsons, N., Crowder, M., 1988. In: Rey, Sir Charles: Monarch of All I Survey Bechuanaland Diaries, 1929–1937. The Botswana Society, Gaborone, Botswana, p. 282.

Reynolds, J.F., Stafford Smith, D.M., Lambin, E., June 2003. Aridnet: seeking novel approaches to desertification and land degradation. Global Change Newsletter 54.

Ringrose, S., Matheson, W., Mogosti, B., Tempest, F., 1989. Nature of the darkening effect in drought affected savanna woodland environments relative to soil reflectance in landsat and spot wavebands. Remote Sensing of Environment 25, 519–524.

Ringrose, S., Matheson, W., 1995. An update on the use of remotely sensed data for range monitoring in south-east Botswana, 1984–1994. Botswana Notes and Records 27, 257–270.

Ringrose, S., Vanderpost, C., Kwerepe, R., Mulalu, M., 1997. Comparison of Range Degradation in Botswana Using Satellite Imagery: Stage 1; Visual Analysis of Range Conditions from 1984/5 to 1994/5; Stage 2 Digital Analysis of Range Conditions in 1994/5, An ODA commissioned project for the Botswana Ministry of Agriculture, p. 38.

Ringrose, S., Chipanshi, A.C., Matheson, W., Chanda, R., Motoma, L., Magole, I., Jellema, A., 2002. Climate- and human-induced woody vegetation changes in Botswana and their implications for human adaptation. Environmental Management 30 (1), 98–109.

Tainton, N.M., 1999. Veldt Management in South Africa. University of Natal Press, Pietermaritzburg, South Africa.

Thomas, D.S.G., 1997. Science and the desertification debate. Journal of Arid Environments 37, 599–608.

United Nations, 1992. Managing Fragile Ecosystems: Combating Desertification and Drought, Chapter 12 of Agenda 21. New York. p. 12.

Vanderpost, C., Ringrose, S., Kgathi, D., Matheson, W., 2007. The nature and possible causes of land cover change (1984–1996) along a rainfall gradient in south-eastern Botswana. Geocarto International 22 (3), 161–183.

Zhang, X., Friedl, M.A., Schaaf, C.B., Strahler, A.H., Hodges, J.C.F., Gao, F., Reed, B.C., Huete, A., 2003. Monitoring vegetation phenology using MODIS. Remote Sensing of Environment 84, 471–475.

Web references

Website of: United Nations Convention to Combat Desertification. http://www.unccd.int (accessed 01.03.10).

Official website of the Botswana Department of Meteorological Services. http://www.weather.info.bw (accessed 15.01.10).

Website of Earth Satellite corporation. http://www.earthsat.com (accessed 10.12.09).

Website of: Southern African Development Community Drought Monitoring Centre. http://www.sadc.int/dmc/ (accessed 17.02.10).