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An assessment of land degradation in the Save catchment of Zimbabwe

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The lack of reliable baseline information on land degradation is a hindrance towards its monitoring and mitigation. Of particular interest is the identification of areas susceptible to degradation. In this study, remote sensing and GIS technologies were applied to detect and map susceptibility to land degradation in Buhera district, in Save catchment, Zimbabwe. Data used included Landsat TM and ETM imagery for 1992 and 2002, agro-ecological zones, vegetation cover and population density. The study identified five preliminary categories of degradation susceptibility ranging from very high to low.

Key words: *Save catchment, land degradation, remote sensing, baseline data, NDVI, GIS*

Introduction

Political, economic and environmental factors have interacted in complex ways to bring about the current state of land degradation in the communal areas of Zimbabwe (Whitlow 1988; Stocking 1996). Previous studies on this phenomenon have indicated widespread degradation and soil erosion in the country, particularly in the communal areas, primarily attributed to farming methods, livestock practices as well as historical factors. This paper presents research on production of baseline information on geographical patterns of susceptibility to land degradation in the Save catchment, Zimbabwe. Baseline information is essential for stakeholders to monitor, control and manage land degradation. The absence of such relevant and reliable catchment-wide baseline information, necessary for assessing the severity and extent of degradation, has made its monitoring difficult.

Understanding and monitoring land degradation

Land degradation is a major factor in the progressive deterioration of African livelihoods and economies (Eswaran *et al.* 2001). The Dahlem Report (Reynolds and Stafford Smith 2001) suggests that land degradation is caused by a complex combination of socioeconomic and biophysical factors. These interact and exert influences that vary in space and time, resulting in reduced biological productivity of land (Barrow 1991; Dregne 1998). Population increase, poverty and overgrazing are often cited as major causes of degradation, particularly in sub-Saharan Africa (Booth *et al.* 1994; Chapman and Mather 1995; Young 1998; Reynolds and Stafford Smith 2001). Inequitable land distribution and societal/cultural conflicts have exacerbated the problem (Whitlow 1988; Moyo *et al.* 1991; Booth *et al.* 1994). Climate change, in arid and semi-arid eco-regions, especially the reduction in total precipitation during crucial growing seasons or even slight shifts in the seasonal distribution of rainfall, may contribute to land degradation, by reducing vegetation cover and thus increasing soil erosion (Reynolds and Stafford Smith 2001).

The complexities of the dynamics involved in the onset and progression of land degradation complicate its assessment. Young (1998) observes the lack of techniques to assess the extent and severity of land degradation. This lack of baseline data makes monitoring difficult and hinders policy formulation to manage the problem (Barrow 1991; Young 1998).

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Nonetheless recently developed remote sensing techniques and geographic information systems have been employed to bridge this gap (Prince 2002; Eastman 2003; Lillesand *et al.* 2004). Remotely sensed data can be integrated into a GIS, which provides a platform for storage, retrieval and updating of large datasets for analysis and presentation. The measurement of spatially continuous variables linked to land degradation and the spatial scale of land degradation can be done using remote sensing (Prince 2002). Further, the availability of time series data allows for monitoring of land cover change (Lillesand *et al.* 2004). In particular, remote sensing facilitates the assessment of vegetation, soil and water, which are three essential biophysical components of land degradation (Barrow 1991; Lambin and Strahler 1994; Reynolds and Stafford Smith 2001; Lillesand *et al.* 2004).

While acknowledging limitations of techniques used, this study demonstrates in part the effectiveness of GIS and remote sensing as tools for the production of baseline data for assessment and monitoring of land degradation in the Save catchment.

Monitoring land degradation using remote sensing

Vegetation cover, in particular the change in species composition of vegetation, is often used as an indicator for susceptibility to degradation as well as its severity (Barrow 1991; de Vreede 2001; Lambin and Ehrlich 1996; Prince 2002; Scoones 1992). However, Tucker *et al.* (1991) have argued that in arid and semi-arid regions, such as the Sahel and the Sahara, which are influenced by short-term drought, vegetation cover is not a good indicator of long-term dynamics of degradation. In contrast, a study conducted by Lambin and Ehrlich (1996), on land cover changes in sub-Saharan Africa from 1982 to 1991, showed vegetation as a good indicator of vegetation dynamics and degradation in many countries in the region including the arid and semi-arid regions.

The distinct reflectance spectrum of vegetation, low in the red and high in the infra-red, has been exploited in a large number of spectral indices, as a remote sensing-based technique (Prince 1998; Reynolds and Stafford Smith 2001). The Normalized Difference Vegetation Index (NDVI), a spectral vegetation index which measures soil and vegetation moisture (Singh 1989; Lyon *et al.* 1998), has been widely used for environmental change monitoring (Young 1998; Eastman 2003; Lillesand *et al.* 2004). The index can be used to identify areas showing distressed or degraded vegetation, leading to identification of possible degraded areas (Barrow 1991; Booth *et al.* 1994). Alternatively, the Soil Adjusted Vegetation Index (SAVI) measures soil status, particularly soil colour, moisture, texture and presence of organic matter, which influences the spectral reflectance of vegetation thus influencing calculated vegetation indices (Huete *et al.* 1985). The SAVI has been highly recommended for monitoring vegetation in semi-arid and arid regions with sparse vegetation cover and little rainfall as well as monitoring landscapes with different soil backgrounds (Huete *et al.* 1985; Huete 1988). Whilst not produced for monitoring land degradation, spectral indices have been successfully applied in such studies.

While there has been a wide application of spectral indices in the assessment of ecological processes such as land degradation, Asner and Lobell (2000) allude to the difficulties of measuring indicators such as the spatial extent of vegetation and bare soils using remote sensing techniques. This has been attributed to the scale at which these variations occur. Of particular interest is the fact that spatial and temporal variation in greenness can be measured through the NDVI. However, the greenness does not separate the effects of changing vegetation conditions relative to vegetation cover (Asner and Lobell 2000). This is particularly relevant in the arid and semi-arid ecosystems which, due to limited vegetation cover, have limited spectral information, insufficient spatial resolution and the influence of soil brightness, all of which hinder improved mapping in these eco-regions (Asner and Heidebrecht 2005).

Measuring the decline of vegetation productivity through Net Primary Production (NPP) is another remote sensed based method used to assess degradation. NPP measures the accumulation of biomass over time (Prince 2002). Based on the carbon cycle, NPP measures soil nutrients. While it has been noted that desertification normally reduces NPP (Asner and Heidebrecht 2005) and reductions in NPP below a certain range may indicate degradation (Prince 1998 2002), Huenneke *et al.* (2002) have argued that the structural pattern and biological material of vegetation types changes, while the NPP does not. While NPP alone is directly related to rainfall, Rain Use Efficiency (RUE), calculated as a ratio of NPP and rainfall over a five-year period, provides a useful index of degradation (Reynolds and Stafford Smith 2001).

Change detection

Image differencing of NDVI, which entails a pairwise comparison of spectral reflectance values, is a

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commonly used technique for change detection (Singh 1989; Lyon *et al.* 1998; Sohl 1999). Although considered simplistic, simple differencing has yielded comparatively good results when compared with more complex methodologies (Singh 1989). However, one of the limitations of this method is the process of deciding the level of suitability or the minimum size of sites needed for the final selection, which is termed thresholding. This process is used to ascertain the upper and lower limits of normal variation, to identify positive, negative and no change areas (Singh 1989; Eastman and McKendry 1991; Linderman *et al.* 1998). Since there is no automated method for this process, thresholding is rather dependent on the analyst (Sohl 1999; Eastman 2003). Sensitivity of the procedure to geo-registration is another limitation (Singh 1989). Sohl (1999) cautions that image differencing should not be solely relied upon for change analysis.

Change vector analysis (CVA) is another commonly used technique for monitoring land use change, deforestation and land degradation. Change vector analysis measures spatial patterns of change to characterize the magnitude and direction in spectral space from a first to a second date. The technique has been widely used in environmental change studies in various African countries, including Zambia and Malawi (Lambin and Strahler 1994; Eastman 2003).

Various change detection methods have been proposed and two basic approaches have been identified, namely comparative analysis of independently produced classifications, and simultaneous analysis of multi-temporal data (Singh 1989; Lambin and Strahler 1994). This study uses both approaches to assess land cover change in the Save catchment.

Study site and background

Degradation studies in Zimbabwe have indicated estimated soil loss due to sheet erosion to be as much as 50 tonnes/ha (Elwell 1987). Whitlow and Campbell (1989) estimated that 25 per cent of the communal areas were severely eroded compared to 2 per cent in the commercial areas. Whitlow (1988) found that soil erosion was prevalent in all agro-ecological zones, but more pronounced in zones III, IV and V, with zones IV and V characterized by unreliable rainfall and poor soils. The agro-ecological zones as defined by Vincent and Thomas (1960) are based on seasonal rainfall, quantity and reliability, and on soil types. Zone I is classified as the most productive with highest rainfall and deep fertile soils and zone V as the least agriculturally productive with very little rainfall and poor soils. Land degradation is prevalent, particularly in the communal lands, where an estimated 80 per cent of degraded land in the country was prevalent (Scoones 1992). Despite the assumed contribution of overgrazing and livestock overstocking to degradation, studies by Scoones (1992) in the communal lands indicated that the erosion patterns at the time were not concentrated in key grazing areas and degraded areas did not affect livestock production.

The Save catchment in Zimbabwe, which is constituted primarily of agro-ecological zones III, IV and V and is predominantly communal, comprises two major river systems – the Runde and the Save (see Figure 1). Three tenure systems exist within the catchment: communal areas, resettlement schemes and freeholds for small to medium scale commercial farming. Of the total catchment area in 1982, 39 per cent was under communal tenure, inhabited by 44 per cent of the communal population of Zimbabwe, which consisted mainly of subsistence or peasant farmers. With a then estimated population density of 40 to 70 persons per km^2, population growth has been cited as a factor contributing to the deterioration of the environment in the catchment (Eschweiler 1992).[1]

The catchment is of national importance to the agricultural development of the country, with large areas of economically important irrigation schemes (Eschweiler 1992). Most of its over 8.4 million hectares of land falls within agro-ecological regions IV and V, which are characterized by unreliable rainfall and poor quality soils. As in most communal areas in the country, human and animal populations exceed carrying capacity (Whitlow 1988; Scoones 1992). Nonetheless, in the more resilient savannah ecosystems, separation of the natural versus the man-made influences has been difficult, given that vegetation change and soil erosion are part of the ecosystem changes (Scoones 1992). Moreover, evidence of adverse impacts of land degradation on cattle production was lacking and the indicators measured, such as vegetation change and soil erosion, could not support the widely held contention that communal areas in Zimbabwe are severely degraded (Scoones 1992). This paper will continue to use the term ‘degradation’, but the authors are cognizant of cautions such as those raised by Scoones as to its use.

Land degradation in the catchment is widespread and severe, especially in communal areas, which are characterized by devegetated landscapes, poor

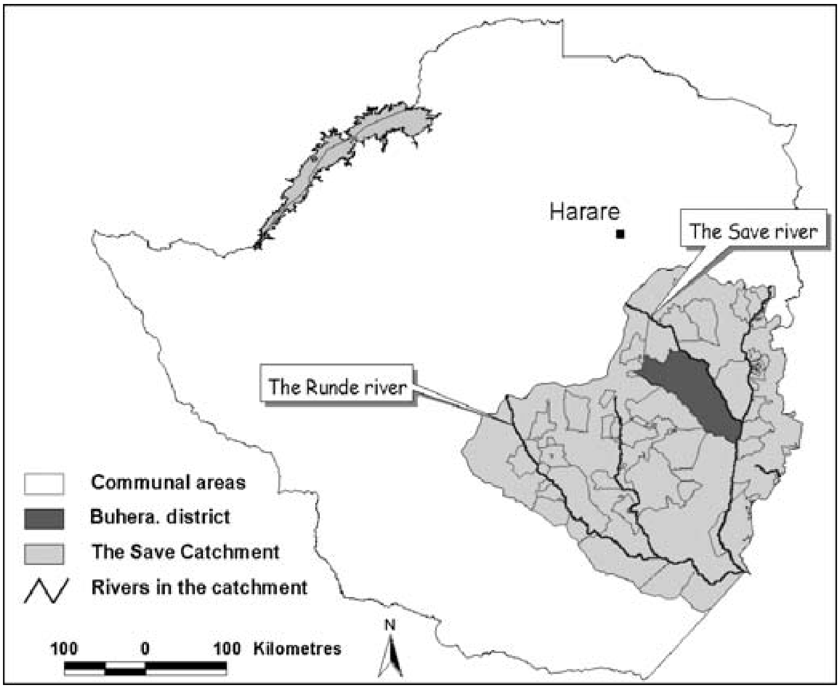

Figure 1 Location and extent of the Save catchment in Zimbabwe[2]

quality pasture and soil infertility. Degradation is mostly manifest as gullies that render large tracts of land virtually unusable, threatening water supply and quality (Booth *et al.* 1994). While gullies are an assumed indicator of severe erosion or degradation, Stocking (1996) argues that gullies are only a symptom of a degraded catchment not the cause, and their sediment contribution is minimal.

The severity of land degradation in the catchment has, however, attracted the attention of more than 15 organizations, including government departments, local community groups, non-governmental organizations, the private sector and research organizations (Eschweiler 1992; IUCN-ROSA 1996). Despite registering significant success in initiating interventions to mitigate degradation, these organizations have not performed to expectation. Minimal coordination and a piecemeal approach to implementation resulted in duplication of effort, inefficiency and competition among the stakeholders. The mitigation methods used by the organizations did not take into account the diversity of land tenure systems within the catchment, thus affecting the success of some projects (IUCN-ROSA 1996).

The uncoordinated response to the degradation problem is symptomatic of a weak basis upon which policies and actions for managing natural resources in the catchment are premised. The problems include a lack of reliable information indicating the severity of and susceptibility to degradation across the catchment; weak institutional frameworks that perpetuate uncoordinated responses for monitoring and impact assessment; and a lack of suitable interventions appropriate for the catchment. The availability of reliable baseline information influences the other two problematic areas. It is therefore essential for such information to be in place as an initial requirement towards addressing the problem of uncoordinated responses to the land degradation problem in the catchment. This does not, however, imply that the development of this information should proceed in isolation of initiatives towards addressing the other elements.

The study area

The study was based in Buhera, a district most representative of the Save catchment in terms of climate, land use and population density (see Figure 2).

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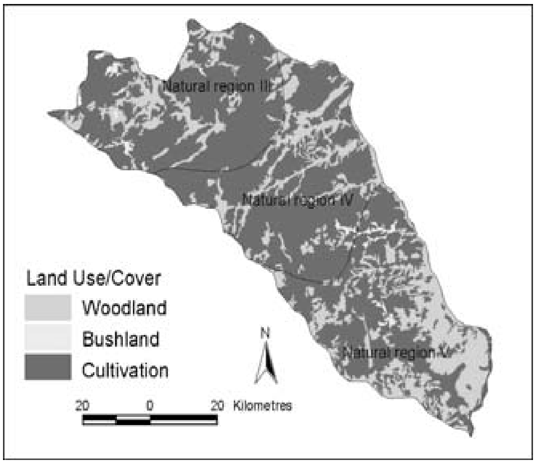

Figure 2 Main land uses/cover in Buhera district (in 1992)[3]

It is entirely under communal land tenure and subject to a combination of several factors that accelerate degradation. Figure 2 provides an indication of the seriousness of land pressure for cultivation.

Buhera district falls under three agro-ecological zones, III, IV and V. As stated earlier, zones IV and V are characterized by unreliable rainfall and poor soils. Zone I is classified as the most productive, with highest rainfall and deep fertile soils, and zone V as the least agriculturally productive, with very little rainfall and poor soils. According to 1992 data, 70.7 per cent of the total area in Buhera district was under cultivation, while only 27.7 per cent was under woodland (see Figure 2). There are indications that woodland has continued to be cleared to expand agricultural activities. The lack of baseline data prior to 1992 has made monitoring of degradation prior to that date difficult.

Methods used

A conceptual framework for assessing severity and susceptibility of land degradation was developed for this study, based on assessment of changes in vegetation cover, manifestation of degradation and biophysical characteristics such as climate, soils and topography. Figure 3 highlights elements of the conceptual model and Table 1 lists the data elements that were used to assess susceptibility to land degradation.

Image processing

Buhera straddles three Landsat satellite scenes, namely 169/74, 169/73 and 168/74. Two sets of the three Landsat TM and ETM scenes for the years 1992 and 2002 were georeferenced using image to image rectification with SPOT images projected in UTM (Zone 36S) and referenced onto the WGS84 ellipsoid. An average of 12 ground control points per image

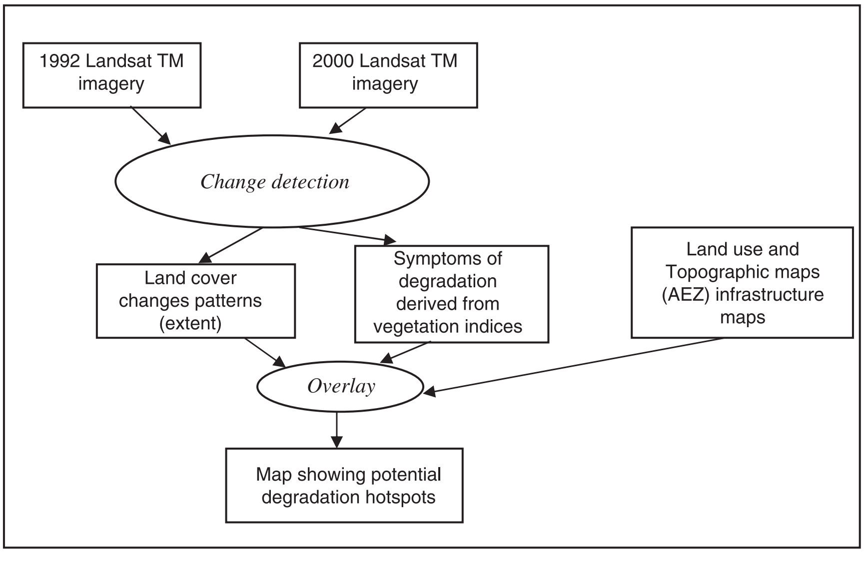

Figure 3 Flow diagram showing assessment of severity of degradation in the Save catchment

Table 1 Data elements used to assess susceptibility to land degradation

Susceptibility
Extent of loss of vegetation cover
Indications of manifestation of degradation
Land use and population
Landscape characteristics
Climate (rainfall) and soils (AEZ)

were used, with a residual error of approximately 2.1 metres. The three scenes were mosaiced and an image enclosing Buhera district was extracted, upon which subsequent image processing was undertaken. Two bands, 3 and 4, were used for change detection analysis. Band 3 (Red) is absorbed by chlorophyll, assisting in vegetation differentiation and the reflectance of Band 4 (Near Infra Red) helps to determine vegetation types, particularly biomass (Lillesand *et al.* 2004).

Vegetation change analysis

Two NDVI images were used to identify areas of change between the two dates 1992 and 2002. NDVI, expressed as a ratio between measured reflexivity in the red and the infra-red bands is calculated as NDVI = (NIR − R)/(NIR + R), where NIR in TM imagery is near infra-red band 4 and R is red band 3. The advantage of using NDVI is that it not only identifies the areas of change but also assesses the state of vegetation. However, it is important to note that non green vegetation (not in leaf) will not give a high NDVI and thus may not be measured.

To identify the spatial patterns of change, simple image differencing was done on the NDVI images. Thresholding, to ascertain the upper and lower limits of variation beyond which true change is considered to have occurred, was performed using the RECLASS command in IDRISI™. Threshold values, based on the standard deviation and the mean, were derived from a histogram of each image and a standard deviation of 2 was used. The reclassed image depicted areas in three categories, positive (more vegetation), negative (less vegetation) and no-change areas, over the ten years.

The second comparative method adopted for change analysis was CVA, which analyses each pixel value in multi-band data, using two bands from different years. The resulting image highlights the direction (expressed as an angle) and magnitude of change (Singh 1989). If used with the red and infra-red bands (as in the NDVI process), the CVA direction of change highlight areas of vegetation growth or reduction (Sohl 1999). The accuracy of results is highly dependent on the availability of anniversary date data.

Limitations of the chosen methodologies

Many remote sensing based methods have limitations associated with the different environments, the analytical methods and the scales of application (Reynolds and Stafford Smith 2001). This study encountered limitations on all these fronts. A notable limitation was access to anniversary data. 1992, being a drought year, was not ideal to serve as a baseline for monitoring, which is ordinarily based on a normal year (Lambin and Ehrlich 1996).

Results

A comparison of the NDVI images reveals that in 1992, higher NDVI values (from 0.11 to 0.73) indicate areas with healthy vegetation mainly in the woodland land-cover class despite 1992 being a drought year. The other different colour tones identified, with lower NDVI values (from –0.38 to –0.51) indicate high moisture, given the low NDVI reflectance of moisture and also given the similarity of the tones to water bodies. These are low-lying areas, characterized by riverine vegetation. In contrast, 2002 shows a general reduction in NDVI values (from 0.25 to 0.63), indicating a possible reduction in healthy vegetation across the district, but the area to the north of the district falling under woodland class shows high NDVI values (from 0.60 to 0.75). Tones indicating moisture patterns, as identified in 1992, have completely disappeared in 2002, except for the water body with an NDVI value of –0.63.

Change analysis using NDVI

Simple differencing and reclassification of NDVI images produced an image highlighting areas of positive, negative and no change, as shown in Figure 4. The difference image clearly highlighted three hotspots of negative change that would constitute priority areas for intervention and further detailed investigation.

Change vector analysis (CVA)

The CVA process produced two images showing the direction and magnitude of change. In Figure 5, the larger directions of change, ranging from 246.51 to

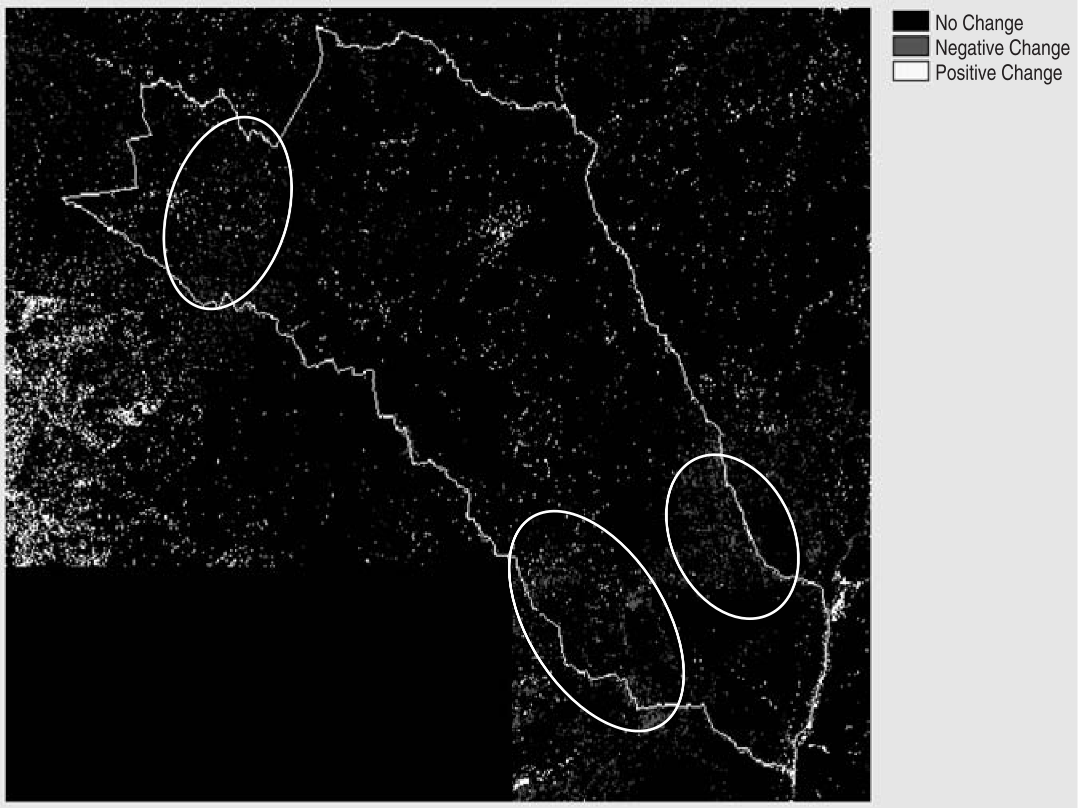

Figure 4 A reclassed image generated by differencing the NDVI images

359.01 (degrees), are prevalent in the hotspot areas identified by the NDVI image differencing. This implies a reduction in vegetation cover in these areas. The smaller directions of change could indicate that little or no change in vegetation growth has occurred. The image also shows a general reduction in vegetation across the whole image. The results are compatible with the image showing magnitude of change, even though the degree of change was moderate (between 132 and 170), given that the highest magnitude of change would be 303. Areas of high magnitude of change correspond to areas of high direction of change.

The results of the change vector analysis and the NDVI image differencing identified three corresponding areas of vegetation reduction or hotspots. These areas are considered to be at greatest risk of degradation.

Ancillary data

Areas that had experienced greatest change, possible vegetation stress and likely degradation, or where degradation is likely to occur, were identified above. To analyse for susceptibility to land degradation, additional data such as agro-ecological zones (soils and climate) and existing data on vegetation cover were used. Vegetation cover and type is a good indicator of soil conditions and thus can be used in conjunction with agro-ecological zones data to identify fragile areas.

The negative change image (Figure 4) was digitized to delineate the different degradation classes, high, moderate and low. It should be noted that this layer is somewhat subjective as it depended on the judgement of the analyst. The negative change map and two other maps, agro-ecological zones and vegetation cover, were rasterized to allow for analysis in a GIS (Figure 6).

The degradation map and the agro-ecological zones were analysed using cross tabulation. The resultant map, showing patterns of land degradation in the three agro-ecological zones, was further analysed using cross tabulation again, with a vegetation map to

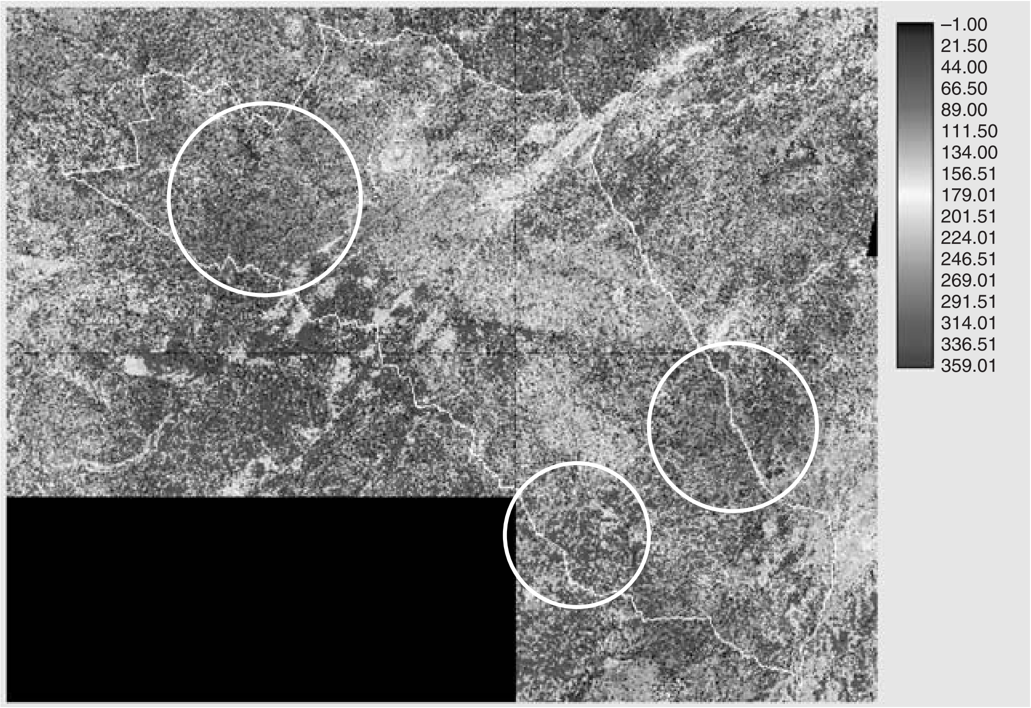

Figure 5 CVA image showing direction of change

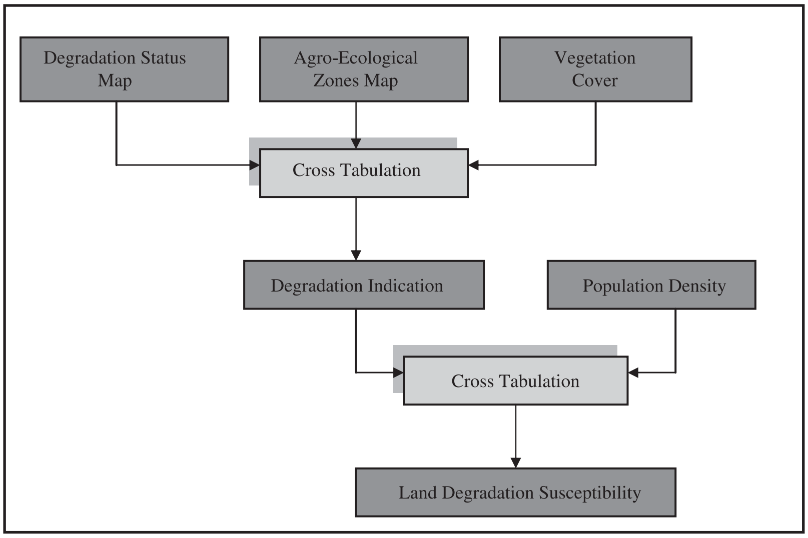

Figure 6 Description of GIS analysis procedure

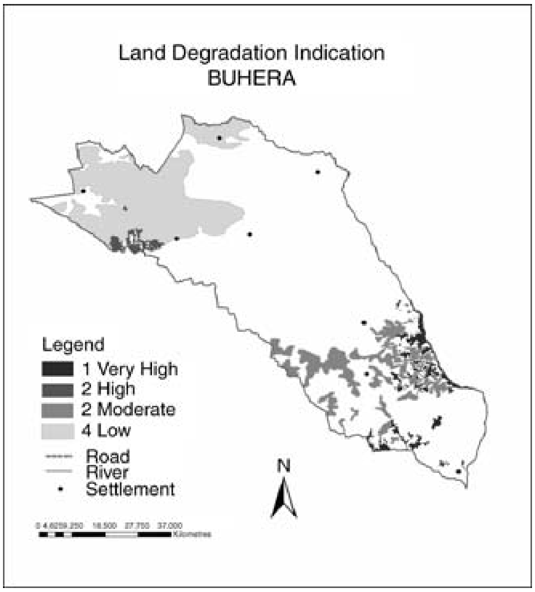

Figure 7 Land degradation indication map

Table 2 Illustration of how severity classes were derived

	AE zone		
Severity	**3**	**4**	**5**
Severity High AE zone	woodland		woodland
Moderate			Any vegetation
Low			

characterize the vegetation cover in the degradation hotspots. The resultant map from the three layers (Figure 7) indicated the following classes:

1 Very High Susceptibility – areas of high risk in the degradation map, falling under agro-ecological zone 5 (extensive farming and regarded as arid) and under woodland in the vegetation map.
2 High Susceptibility – areas of high risk in the degradation map, falling under agro-ecological zone 3 (semi-intensive farming) and under woodland in the vegetation map.
3 Moderate Susceptibility – areas of moderate risk on the degradation map, falling under agro-ecological zone 5 (extensive farming and regarded as arid) and under any vegetation or land class type, including bushland and cultivation.
4 Low Susceptibility – these are areas of moderate risk in the degradation map, falling under any agro-ecological zone, mainly zone IV (semi-extensive farming and semi-arid) and any vegetation or land class type.

Table 2 demonstrates how the four classes are coded in the shades of grey depending on severity. Susceptibility to degradation required investigation of other factors such as population pressure, an assumed contributor of land degradation. A map which classifies population density by ward was used. The lowest density was recorded as being 22.07 and the highest 80.00.

A visual comparison of Figure 7 and the population density map produced the following results:

- Areas of very high indication of degradation were wards with the lowest population density of 22.07–24.00 and 24.01–35.00.
- Areas of high indication to degradation were identified in wards of moderate population density of 45.01–50.
- Areas of moderate to low indication were identified in low and moderate to high population density of 24.01–35 and up to 60.00.

The six categories of population density were regrouped into three classes: high, moderate and low, for analysis with the land degradation indication data. Using cross tabulation, a map representing areas susceptible to degradation was produced (Figure 8). The following findings were made and are coded depending on susceptibility.

Zone 1 (the darkest grey) represents areas of very high susceptibility, with high indication (from Figure 6) despite being in low population areas, and high population in any class of indication (except no change areas). Zone 2 represents high susceptibility areas with high to moderate degradation indication but with medium population density. Zone 3 represents moderate susceptibility areas, with moderate to low indication and medium population density. Zone 4 (white) was classified as low susceptibility areas, with no indication and mainly under cultivation as well as in any agro-ecological zone. These areas are not a priority but should nonetheless be targeted for suitable interventions.

Figure 8 shows that most areas of very high susceptibility (Zone 1) were located along the major rivers and their tributaries in both the northern and southern parts of the district. This clearing could be attributed to expansion of agricultural activities by the

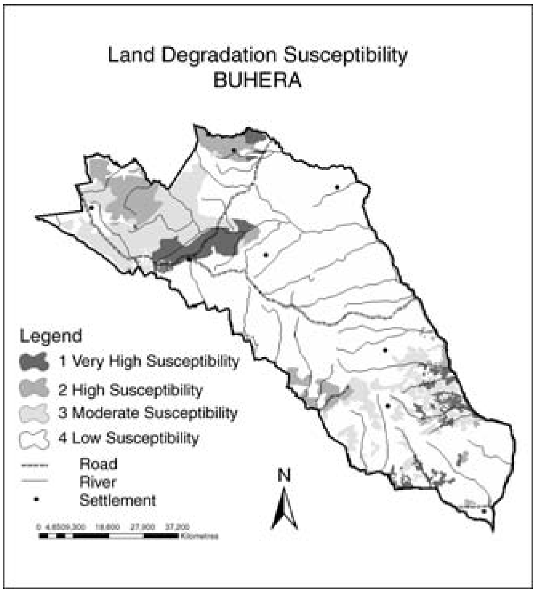

Figure 8 Rivers indicated in black line and highways in double black broken line

smallholder farmers in these areas. In the northern part of the district, some areas of high susceptibility were located along the major highway, suggesting either firewood trading or deforestation for curio businesses. All these possible suggestions would need to be substantiated through further studies.

Discussion

The lack of information about the severity and susceptibility of land degradation can be partly addressed through utilization of technologies such as remote sensing and GIS. Although all the data required for undertaking the necessary analysis is not readily available, enough data exists to potentially improve the basis for decisions aimed at addressing the land degradation problems in the catchment.

The data produced, showing geographical patterns of severity and susceptibility to land degradation, can be utilized for decisionmaking by identifying the wards where susceptibility is greatest. The method used for identifying patterns of vegetation change between 1992 and 2002, change vector analysis and image differencing of the NDVI images, highlighted areas of greatest change where degradation is likely (degradation hot spots) and where interventions for mitigation of degradation should be targeted. The process further assisted in identifying land degradation hot spots that may require urgent attention, namely areas showing possible vegetation stress and vegetation cover loss, as a possible manifestation of land degradation. GIS analysis enabled comparison of the identified areas with topographic and vegetation data to identify the fragile areas. It is important to note that spatial and temporal scales should taken into consideration, since the time scale over which measurements are made is critical for detecting long-term trends of degradation against the short-term variations (Scoones 1992). This data is not, however, conclusive as additional data is required to justify the areas chosen.

Techniques used in this study are by no means exhaustive, given the debates on the suitability of vegetation as an indicator for susceptibility to land degradation, as well as the use of NDVI versus SAVI or NPP for assessment of degradation in arid and semi-arid areas such as Buhera. In addition, lack of access to the most recent data on land tenure, influenced by the ongoing land reform programme in the country, also hindered further analysis of the possible dynamics and drivers of change in the district. Specific biophysical data, such as a detailed vegetation map showing vegetation types or species as well as a detailed soil map of the area, were problematic to obtain.

Conclusion

The study has demonstrated that the problem of lack of information about the severity and susceptibility of land degradation can be partly addressed by harnessing technologies such as remote sensing and GIS. The data produced provides an indication of priority areas (degradation hot spots), where interventions to prevent further change and where practices for mitigating the associated degradation should be targeted. The generated data may be useful for environmental organizations, government and local communities in mainstreaming land degradation interventions and improved coordination of its mitigation. Information produced would also be used to target where further studies should be undertaken to gain a detailed understanding of the dynamics of degradation and the mitigation measures appropriate for these areas, particularly given the findings showing population density as less of a factor than might be assumed.

Acknowledgements

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Notes

1 According to Prince (1998), 1992 census data showed that out of a total population of 11.4 million, 98.8 per cent were black and of this 51.4 per cent still resided in the communal areas.

2 Map compiled by author from VegRIS data (Forestry Commission) and Surveyor General Topographic Data.

3 Map compiled by author from VegRIS data (Forestry Commission) and Surveyor General Topographic Data.

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