academicJournals

Vol. 7(7), pp. 603-610, July 2013
DOI:10.5897/AJEST11.275
ISSN 1996-0786 © 2013 Academic Journals
http://www.academicjournals.org/AJEST

African Journal of Environmental Science and Technology

Full Length Research Paper

Ecosystem recovery analysis of mine tailings at Mhangura copper mine through normalised difference vegetation index

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Accepted 10 July, 2013

Remote sensing techniques are increasingly being employed in monitoring environmental change. Vegetation indices such as normalised difference vegetation index (NDVI), are useful in estimating primary production, an important component of ecosystem function. The success of rehabilitation on mine tailings may be indirectly assessed through NDVI changes. Mine tailings at Mhangura copper mine, Zimbabwe, have not been monitored since their rehabilitation following the mine closure in 2000. The present study indirectly assesses primary productivity over the tailings dams as a way of establishing the extent of ecosystem recovery. NDVI images were obtained from the United States geological survey (USGS), global visualisation viewer (GloVis) website. These were processed using the Integrated Land and Water Information System (ILWIS) Version 3.3 GIS software. Two-way ANOVA showed significant differences in NDVI between the sites ($p < 0.05$). Actual NDVI trends over the years could not be established. NDVI values over the dams were also significantly different from those in adjacent natural Acacia woodland. These observations were supported by principal components and hierarchical cluster analyses. The NDVI analysis thus showed a good establishment of grass on the dams with poor tree cover when compared with the Acacia woodland. This suggests a positive movement towards recovery. However, factors preventing tree establishment need to be investigated.

Keywords: Ecosystem development, normalised difference vegetation index (NDVI), remote sensing, tailings rehabilitation.

INTRODUCTION

The increasing scale of human induced environmental disturbance has necessitated the use of remote sensing techniques in monitoring environmental change (Kerr and Ostrovsky, 2003). Vegetation indices based on differing spectral reflectance in the red and near infrared bands have recently been widely used in assessing vegetation productivity from canopy to global scale (Gamon et al., 1995). Normalised difference vegetation index (NDVI) has proved to be a useful tool in estimating net primary productivity (NPP), a major component of ecosystem

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Abbreviations: NDVI, Normalised difference vegetation index; **USGS,** United States Geological Survey; **GloVis,** global visualisation viewer; **ILWIS,** integrated land and water information system; **GIS,** geographic information systems.

function (Kerr and Ostrovsky, 2003). This is mainly due to its linear relationship with absorbed photosynthetic active radiation (APAR) which then provides a “theoretical connection” between NDVI and net primary production (NPP) (Paruelo et al., 1997). NDVI remains the most commonly employed and studied vegetation index (Kerr and Ostrovsky, 2003), and can be represented by the following equation:

$$NDVI = (RNIR - RRED)/(RNIR + RRED)$$

Where, RNIR and RRED designate reflectance in the near infrared and red bands, respectively (Gamon et al., 2005).

Mine tailings rehabilitation usually starts when a mine is still operational. Much of the monitoring is done during this operational period as mines are required to provide evidence of stability before making a case for closure (Haagner et al., 2008). In Zimbabwe, once a mine is closed, miners are exonerated from any legal liability concerning their mining activities. Thus, there is usually no follow up on long term ecosystem recovery once vegetation cover establishes on the tailings dams. The Zimbabwe Environmental Management Act [Act 13 of 2002 Chapter 20:27] explicitly calls for the restoration of biota and ecological processes on mine tailings dams. Hence, rehabilitation of mine tailings becomes a major step towards land restoration. The Society for Ecological Restoration International (SER) defines ecosystem restoration as “the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed with respect to its health, integrity and sustainability” (SER, 2004). This, therefore, entails the need to establish a self sustaining ecosystem (Aronson et al., 2003; SER, 2004).

The primary objective of the present study was to track the environmental restoration course of the rehabilitated Mhangura Copper Mine through an assessment of primary productivity on mine tailings dams using NDVI as a proxy. Primary productivity acts as a surrogate for ecosystem development at a given period (Raich et al., 1997). When expressed as a ratio of community respiration, primary production can serve as an excellent indicator of ecosystem maturity (Odum, 1969). The use of remote sensing techniques for mapping and planning mine waste disposal sites is gathering impetus as evidenced by their application across southern Africa (Limpitlaw, 2006) and Australia (Lau et al., 2008; Ong et al., 2002). Remote sensing techniques are also increasingly applied in re-vegetation monitoring in China (Wei et al., 2009). Thus, changes in primary productivity on the slimes dumps was assessed by the use of NDVI as an indicator of productivity in order to establish trends in ecosystem development. It was hypothesised that any change in primary production (NDVI), especially an increase towards reference site values over time, indicates an increase in ecosystem functionality.

MATERIALS AND METHODS

Study area

Mhangura Copper Mine lies approximately 186 km northwest of the city of Harare. It is located in the Mashonaland West Province of Zimbabwe, at approximately 16° 53' S and 30° 09' E (Figure 1). The mine area is surrounded by farmland that is mainly used for maize crop cultivation and, to a lesser extent, livestock grazing. Mhangura lies in Natural (Agro-climatic) Region II (Vincent and Thomas, 1960) that is characterised by high rainfall (750 to 1000 mm year^{-1}), and intensive farming. This includes a dry, cool season from May to September when very little rain falls. The wet season is usually characterized by heavy rainfall from November to March. Geologically, Mhangura lies in the largest, old stratabound copper occurrences within the Proterozoic metasediments of the Lomagundi basin. The mine’s original size was estimated to contain some 60 metric tons of copper deposit, at 1.2% Cu, with 15 to 20 ppm silver. There are minor occurrences of gold, platinum and palladium.

Stratification

The study focused on rehabilitated slimes dams (Dams 4, 5 and 6) within the Miriam Shaft Complex. Though they were constructed separately, Dams 4 and 5 coalesce, such that they appear to be a single landform. Hence, for simplicity, in the present study, Dams 4 and 5 were referred to as Dam 5. This particular slimes dam is older, having been constructed in the early 1970’s, whereas Dam 6 was constructed in the early 80’s. The substrate on the dams is homogenous for all sites, although a cladding of organic matter in the form of domestic waste was also used. Sites were initially stratified according to dam number, which is related to dam age, thus resulting in a pseudo-chronosequence. If succession was taking place on the dams, it was assumed that different vegetation types would be observed based on the different ages of the dumps. Aspects provided a second criterion for stratification. Sampling sites were located on the North, South, East and West sides of the dumps (Figure 2). Such stratification bore significance on the naming of the study sites. There was delineation between sampling sites and units. The whole side of a dam was considered as a sampling unit in which several sites were delineated, e.g. D5N-01, D5N-02 and D5N-03 were different sampling sites within sampling unit D5N (northern slope of Dam 5). Stratified random sampling techniques were employed for the delineation with the aid of Google Earth® software. In each case, sampling sites were named in accordance with the slimes dam number first, followed by the aspect and the transect number. Thus, D5N-02 would be the second transect/site surveyed on the northern side of Dam 5.

Reference sites

An acacia woodland lying to the north of and adjacent to Dam 8 was used as a reference site, representing a natural functional ecosystem (Figure 2). Reference sites are supposed to occur in similar biotic zones, in close proximity to the rehabilitated site, and exposed to similar natural disturbances (SER, 2004). Though the site was flat, and did not have similar topography as the slimes dams, it served in providing the biogeochemical potential for rehabilitation. It was also important to compare the rehabilitated sites with a site representing a dysfunctional ecosystem. For this purpose, the top of Dam 7 (also flat) was used (Figure 2). The dam

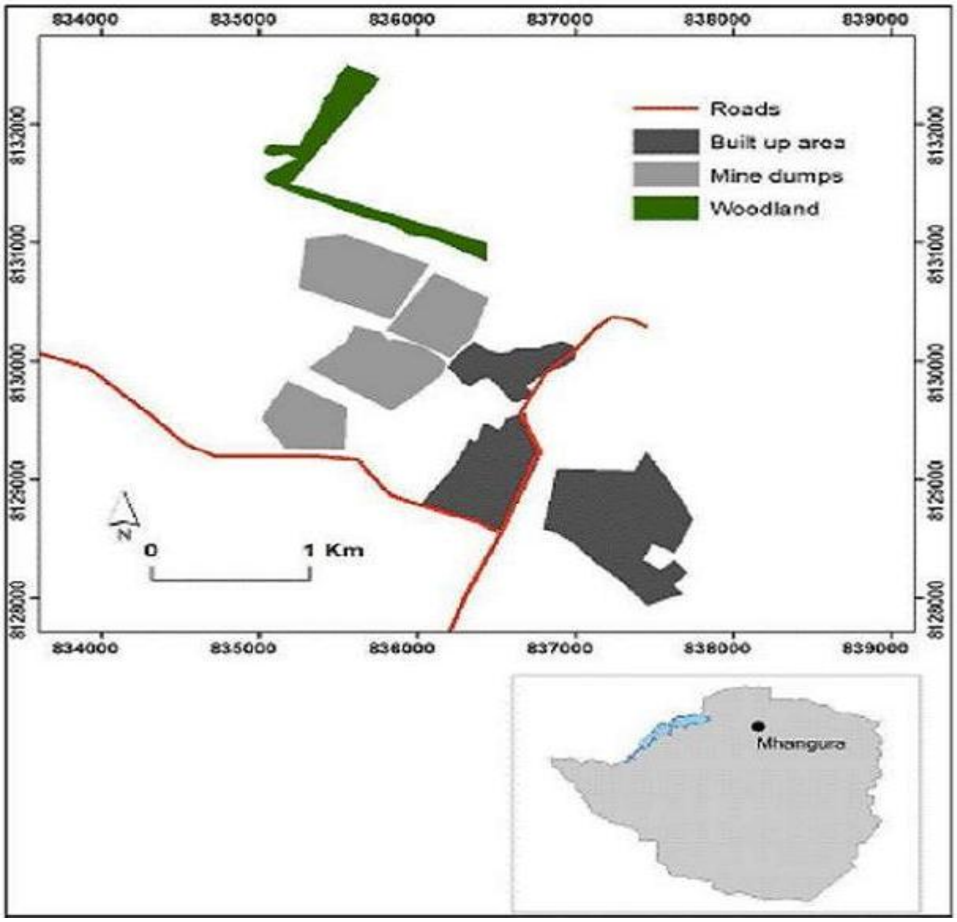

Figure 1. Map of Mhangura Mine showing the location of mine dumps (slimes dams).

was constructed in the late 1980's as an infill between Dams 3 and 5. The mine closed before the dam was fully rehabilitated.

Randomisation

Sampling points were randomly selected on each side of a dump and in the reference sites with the aid of Google Earth® satellite imagery software. The points demarcated positions of sampling sites. Coordinates of each point were recorded and then located in the field using a hand held Global Positioning System (GPS).

Data acquisition and image processing

NDVI data were collected with the assistance of staff of the Department of Geography and Environmental Sciences, University of Zimbabwe. NDVI images were downloaded from the United States Geological Survey (USGS), Global Visualisation Viewer (GloVis) website (www.glovis.usgs.gov). Images from the following dates were available from the USGS archives, and were thus used to show changes over the years: 06 May 1990, 22 September 1994, 30 September 2000 and 05 May 2010. In Zimbabwe, the months of September and May occur within the dry season. This avoids any differences in NDVI which is attributed to differences in season. The images were processed using the Integrated Land and Water Information System (ILWIS) Version 3.3 GIS software which employed map-value function to extract NDVI values from sample locations.

Classification of NDVI values

The classification of NDVI values was carried out according Kriegler et al. (1969) and Weier and Herring (2011). Calculations of NDVI for a given pixel always result in a number that ranges from minus one (-1) to plus one (+1); however, no green leaves gives a value close to zero. A zero means no vegetation and close to +1 (0.8 - 0.9) indicates the highest possible density of green leaves. Very low values of NDVI (0.1 and below) correspond to barren areas of rock, sand or snow. Moderate values represent shrub and grassland (0.2 to 0.3), while high values indicate temperate and tropical rainforests (0.6 to 0.8).

Statistical analysis

Available NDVI data were not sufficient for a full time series analysis. There was still need, however, to assess the existence of any significant changes over the years, and to establish whether any differences existed in terms of NDVI between slimes dams and reference sites. A two-way ANOVA was, therefore, carried out on the data set using the MS Excel Data Analysis package (Windows 2007). The observations were the different sites and the variables

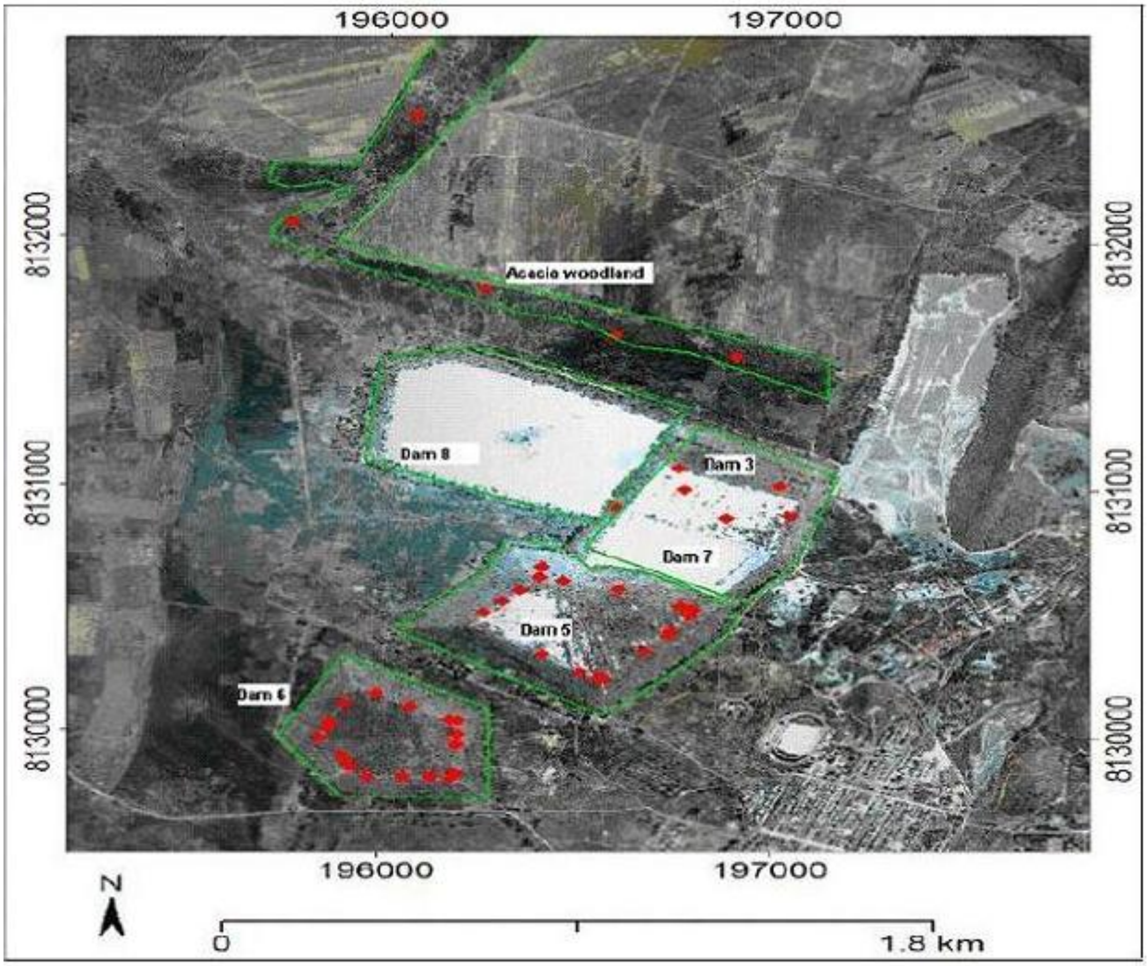

Figure 2. A Google Earth® satellite image showing sampling sites (red dots) on the slimes dams and in the Acacia woodland reference site.

were the NDVI values. To establish whether there were any relationships among the sites in terms of NDVI changes over the years (1990, 1994, 2000 and 2010), a principal components analysis (PCA) was carried out on the data set using program package PAST (Hammer et al., 2001). To further explore the relationships between the sites, a Hierarchical Cluster Analysis (HCA) was carried out on the data set using program package STATISTICA (StatSoft, 1995).

RESULTS

NDVI imagery

Vegetation index images are useful in tracking progress of dump rehabilitation (Limpitlaw, 2006). Thus, NDVI images were used for monitoring vegetation changes on slimes dams at Mhangura Copper Mine. The green shade on the images represents green vegetation. The white-bluish shade represents the bare tailings. Black areas represent burnt vegetation. Figure 3 shows vegetation development on the slimes dams over the years from 1990 to 2010. Dams 6 and 5 showed a considerable amount of greenness by 2010.

NDVI values

Dam 5

There are 4 sets of data corresponding to 16 location points, that is, a total of 64 data points. Among them only one value is more than 0.3 (D5W02 - 1990); there are six other values (2 in 1990; 0 in 1994; 1 in 2000; and 3 in 2010) ranging between (0.2 and 0.3) representing shrub and grassland.

Dam 6

There are 4 sets of data corresponding to 18 location points, that is, a total of 72 data points. Among them only one value is more than 0.3 in 2010 (D6E04) while there

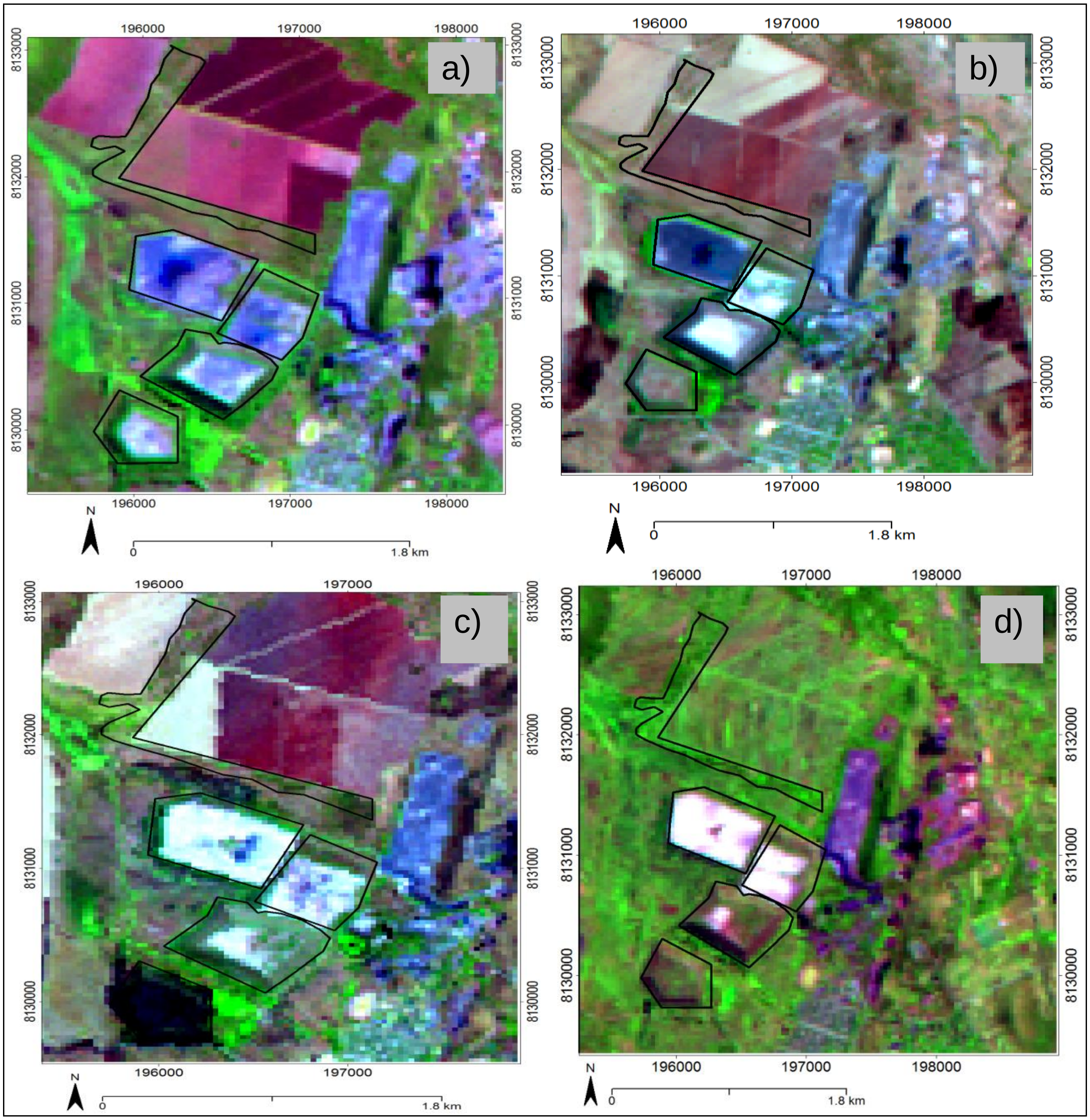

Figure 3. Colour composite Landsat satellite images covering the Mhangura area for the years 1990, 1994, 2000 and 2010 (a, b, c and d, respectively). Also refer to Figure 2.

were 7 values greater than 0.3 in 1990 (D6W02, D6W03, D6W04, D6NW01, D6NW02, D6N01 and D6N02); there are 15 other values (2 in 1990; 0 in 1994; 2 in 2000; and 11 in 2010) ranging between (0.2 and 0.3) representing shrub and grassland.

Dam 7

There are 4 sets of data corresponding to 4 location points, that is, a total of 16 data points. Among them only one value is more than 0.3 (D701 - 2010); there are 2 other values (D701 - 1994; D704 - 2010) ranging between (0.2-0.3) representing shrub and grassland.

Acacia woodland

There are 4 sets of data corresponding to 6 location points, that is, a total of 24 data points. Among them, there are 6 values greater than 0.5 (AW01 - 06 for 2010) representing dense woodland. There are 4 values between 0.2 and 0.3 representing shrub and grassland, 2

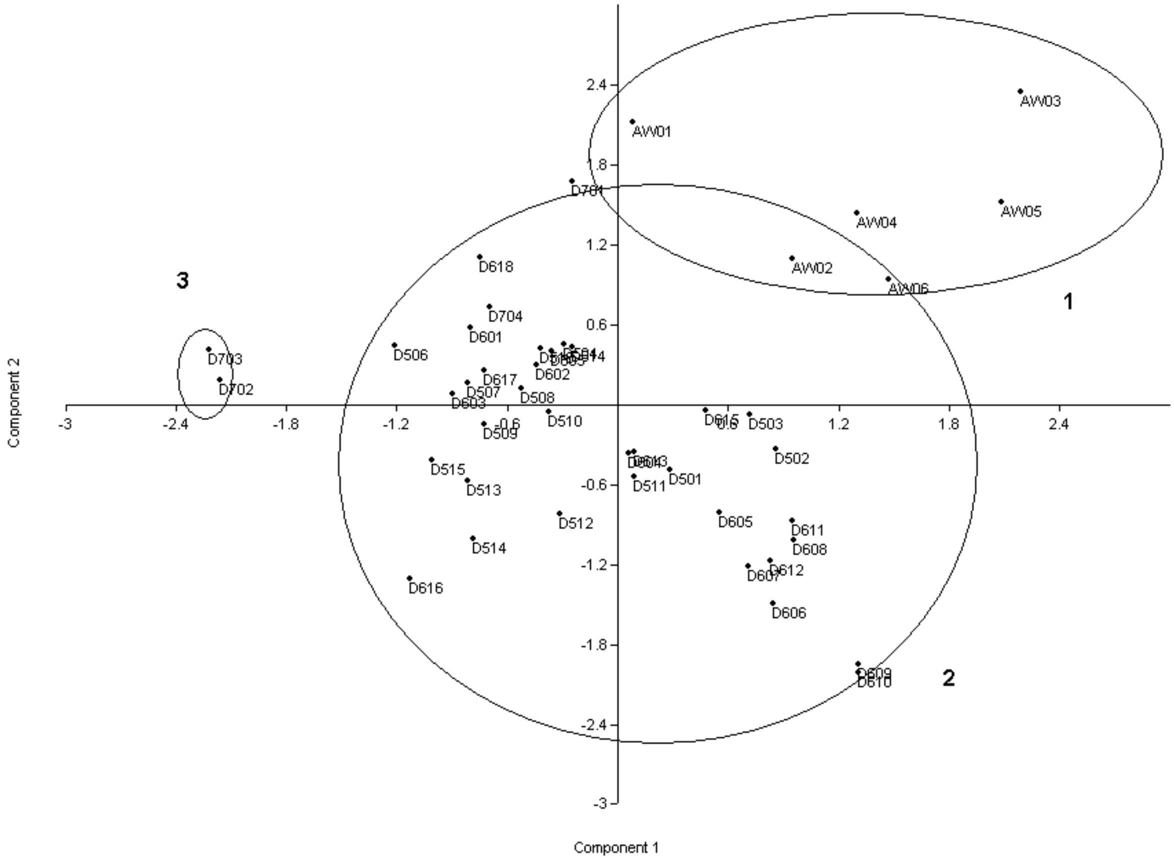

Figure 4. Principal components analysis (PCA) of the NDVI data. The numbers indicate clusters of related sites.

of them occurring in 1990 and the others in 2000. All values for 1994 were less than 0.1 with 1 being negative, representing a bare area.

Statistical analysis

A two-way ANOVA on the data set revealed significant differences between years and sites ($p < 0.05$). The trend implied by these differences, however, could not be established. To further investigate whether there were any differences among the sites in terms of NDVI changes over years 1990, 1994, 2000 and 2010, a principal components analysis (PCA) was carried out on the data set. With an eigenvalue of 0.065093, Component 1 explained 45.271% of the variance, and with an eigenvalue of 0.0402642, Component 2 explained 28.003% of the variance. Together, these two components accounted for 73.274% of the variance.

The PCA (Figure 4) produced three clusters of related sites. The Acacia woodland sites grouped on their own, separate from the slimes dams' sites. Two sites from Dam 7, that is, D703 and D704, also produced a separate cluster. This shows that although the dam sites (Dams 5 and 6) had vegetation cover, their NDVI levels were different from those of the Acacia woodland. Sampled sites of Dam 7 that formed a third cluster (Cluster 3) had no vegetation cover. To further illustrate the differences between the sites, a Hierarchical Cluster Analysis (HCA) was carried out on the data set (Figure 5).

In contrast to the PCA, the HCA produced four clusters. These were: Acacia woodland, Dam 5, Dam 6 and Dam 7. The HCA also had the Acacia woodland clustered furthest from the other sites. It was followed by Dam 7. Although Dams 5 and 6 were different from each other, they lay closer to each other and away from the other sites. Site D616, though exhibiting some difference from the other Dam 6 sites, it was considered to be a sub-cluster of Cluster 1.

DISCUSSION

A visual interpretation of the images in Figure 3 shows that by 2010, the green cover on top of Dam 5 and 6 was extensive (plate d) except for a bare patch on the left corner of Dam 5 (see Figure 2 for dam labels). Other plates show considerable bareness especially 1990 and 1994. The low values recorded in 1994 are attributed to

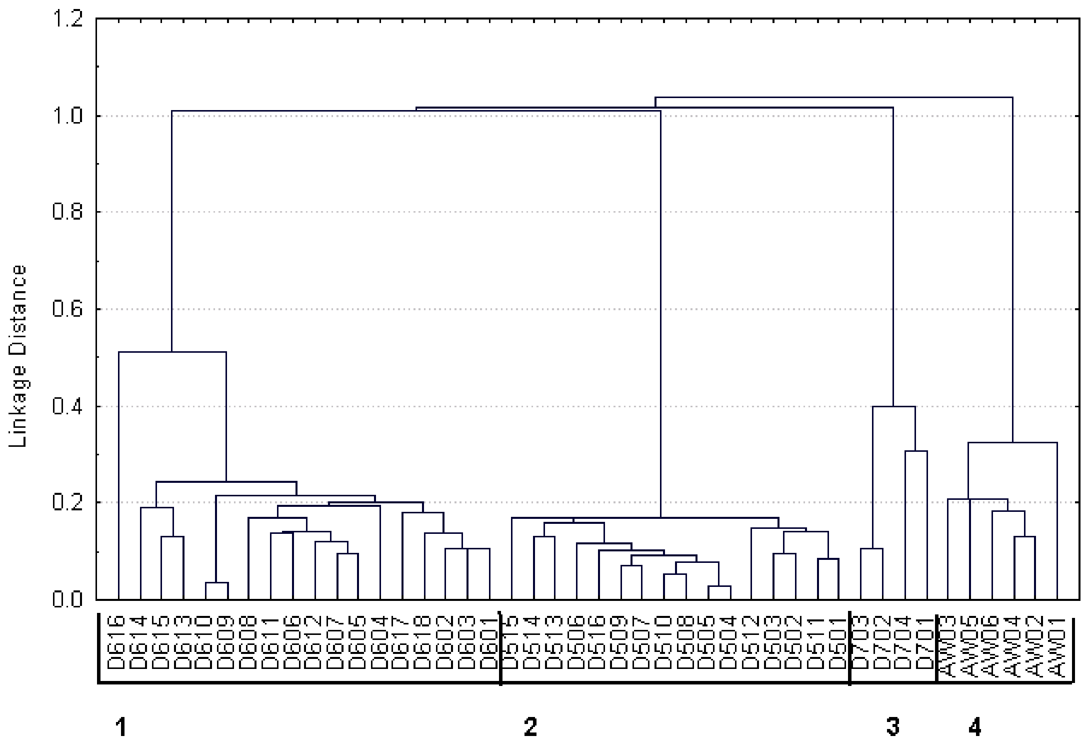

Figure 5. A Hierarchical cluster analysis of the NDVI data. Numbers indicate clusters of related sites.

the 1992 drought that resulted in the death of some plant species as reported by Northard and Figg (1992). A time series analysis which could elucidate the actual trend in NDVI between 1990 and 2010 was, however, not carried out. NDVI images obtainable from Landsat archives (www.glovis.usgs.gov) were only available for a few selected years and months. Other years had images that were not interpretable due to obscurity caused by cloud cover.

The statistical analyses, however, indicate that in terms of NDVI, the slimes dams are still different from the natural Acacia woodland. This is attributed to the differences in tree cover that produced higher NDVI values for the Acacia woodland. There was no significant difference between Dams 5 and 6, although by 2010, Dam 6 recorded more sites with higher NDVI values. Both dams contain sparse tree vegetation and are mostly covered with grass. Dam 7 is devoid of any vegetation as shown by the negative NDVI values and its apparent difference from the rest of the sites. However, it should be noted that a small data set was available for Dam 7 and Acacia woodlands reference sites affecting statistical robustness. Nevertheless, Raich et al. (1997) suggested that primary production of an ecosystem could act as a surrogate for ecosystem development trends over time. Thus, it is evident that grass cover has sufficiently developed over the slimes dams. The same cannot be said for trees and shrubs which are sparsely distributed and very few.

Conclusions

NDVI trends through 1990 to 2010 could not be established. However, it could be established that the levels of NDVI between the tailings dams and Acacia woodland are significantly different. By 2010, there was a considerable grass cover on the slimes dams with a poor tree cover. There is a need to investigate further, the factors preventing the establishment of trees on the tailings dams. Human-induced disturbances such as fire and wood harvesting are possible factors. The establishment of grass on the tailings dams points to ecosystem recovery to a significant extent.

ACKNOWLEDGEMENTS

Much thanks to Dr. A. Murwira and Mr G. Mutowo, Department of Geography, University of Zimbabwe for help with the NDVI image acquisition and analysis. Heartfelt gratitude also goes to the anonymous reviewers for their insightful comments and suggestions.

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