GIS-BASED ASSESSMENT FOR ENVIRONMENTAL MANAGEMENT IN THE ZAMBIAN COPPERBELT

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ABSTRACT

Environmental assessments of mines have become a common feature of best practice. When applied to mature mining areas, such assessments do not necessarily place mines in the context of a changing environment. This may result in drivers of environmental change being overlooked, with significant implications for mine management. Assessing large mining areas using remotely sensed data and geographic information systems helps to provide this environmental contextualisation for the mining site. Using mines in the Zambian Copperbelt, the findings of mine site investigations are compared with environmental changes occurring on a larger scale. Issues identified at mine-site scale are not obvious at a regional scale and incorporation of both is required for medium term planning.

1 INTRODUCTION

Many mining environmental impact assessments and environmental management programmes focus on the mine site and its immediate surroundings. While these assessments commonly take into account the downstream catchment area and/or the downwind area, they are seldom conducted at a scale suitable for assessing impacts. Consequently, significant changes occurring over large areas around the mine site may not be detected. This leads to management programmes structured around perceived priorities which may not address long term environmental sustainability.

Regional environmental assessments are useful in assessing the environment around mature mining areas. The results of this approach are shown for part of the Zambian Copperbelt.

2 THE MINES OF THE ZAMBIAN COPPERBELT

The Zambian Copperbelt lies approximately 300 km due north of the capital, Lusaka, along the Zambezi/Congo watershed which forms the border with the Democratic Republic of Congo. The Copperbelt mining area is about 120 km long and 50 km wide, stretching from Konkola in the Northwest to Luanshya in the south east.

Deposits in the Copperbelt were discovered by modern prospectors around the turn of the last century but most were not exploited on a large scale until the 1930s. The area of interest analysed in this paper (AOI) covers the

Zambian Copperbelt, excluding Ndola and the former Luanshya Division of ZCCM. It lies between 12° 12′ 40″ and 12° 59′ 16″ south and between 27° 42′ 50″ and 28° 32′ 44″ east.

Figure 1 – Location of the Copperbelt

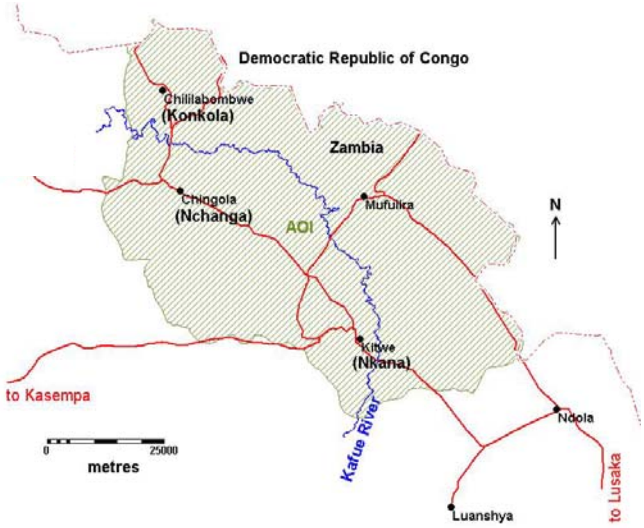


Figure 2 – Towns in the AOI (mines indicated in parenthesis)

2.1 Historical Development

Within the AOI, the first claims were pegged at Chambishi, just north of Kitwe, in 1903 (Mendelsohn, 1961). Shortly after this, the Nkana deposit was discovered in 1910, followed by further discoveries at Nkana, Mufulira and Kirila Bombwe in 1923 and 1924. Large-scale mining operations and metallurgical plants were commissioned between 1929 and 1932 at Nkana and Mufulira, followed closely by Nchanga and later by Konkola (at Kirila Bombwe) in 1957. Kirila Bombwe is now the site of the town of Chililabombwe. These operations were managed privately until after Zambia gained independence in 1964. They were nationalised by the government of Kenneth Kaunda in 1969. In 1982, the nationalised mines were amalgamated into Zambia Consolidated Copper Mines (ZCCM), forming the second largest copper mining operation in the world after Chile’s Codelco (Dolley and Coakley, 1996). ZCCM was privatised at the close of the last decade after protracted negotiations. This brought about reinvestment in the Copperbelt by multinational companies and coincided with improvements in the level of environmental management required under Zambian Law.

2.2 Mining Pollution in the Copperbelt

To comply with regulations and international practice, ZCCM and, later, private investors, undertook mine site environmental assessments. These assessments reported significant environmental contamination around mines (Steffen Robertson and Kirsten, 1997; African Mining Consultants, unpublished). These reports include references to high levels of TDS, sulphate, copper, cobalt, iron, aluminium, nickel, TSS, pH in effluent waters, high levels of copper, cobalt, sulphur and sulphate in stream sediments, widespread contamination of soils and localised groundwater contamination. Older tailings impoundments were found to be susceptible to erosion, resulting in high concentrations of suspended solids in local rivers.

Mine site investigations have therefore shown that there is significant environmental contamination due to mining and mineral processing operations. What is the significance of this for the environment and the community? Is this contamination significantly reducing community livelihoods? Is mining a direct threat to environmental sustainability? To answer these questions and to place the environmental costs of mining in context, it is necessary to examine changes beyond the boundaries of the mining leases and to measure changes in the region.

A portion of the Kafue River catchment extending downstream from the Konkola mine to below Kitwe was selected for analysis. This area includes Konkola, Nchanga, Mufulira, Nkana, Chambishi and Chibuluma all recently privatised.

3 GIS/RS APPROACH

Remotely sensed (RS) data can be used to rapidly and inexpensively assess a large area – the AOI covers 445,160 ha, 1.2% of Zambia's Copperbelt Province. Unlike surface data, RS data does not depend on the existence of a well-funded civil infrastructure (Barrett and Curtis, 1995). Satellite images from the Landsat series of satellites are used in this investigation. Since 1972 these satellites have provided repetitive, synoptic, global coverage of high-resolution multi-spectral imagery (Lillesand and Kiefer, 1994). The earlier Landsat missions (Landsats 1, 2 and 3) were equipped with Multi-Spectral Scanners (MSS). Later missions carried a sensor with greater spatial and spectral resolution: the Thematic Mapper (TM). The characteristics of the TM bands were selected to maximize their capabilities for detecting and monitoring different types of earth resources. The availability and cost of these data make them ideal for environmental impact assessments in developing countries.

Landsat data sets from 1972, 1984, 1998 and 2000 were available for this study. Earlier spatial data sets consist of a set of six topographic maps published between 1959 and 1967 by the Northern Rhodesian (later Zambian) Surveyor General. The maps are based on various aerial photgraphic missions flown between 1947 and 1959. The older set covers the urban areas, excluding Chingola (this sheet was not available). A newer map set consists of six maps, including the Chingola sheet but excluding the Lulamba Headwaters area south of Chingola. These maps, with the exception of the Kitwe sheet, are based on aerial photographic missions flown in 1968. They were published between 1971 and 1972. The Kitwe sheet was published in 1986 and is based on aerial photography acquired in 1984. Aerial photographs used in this assessment are as follows:

- 1968 – panchromatic, nominal scale 1:30,000,
- 1984 – panchromatic, nominal scale 1:20,000,
- 1990 – panchromatic, nominal scale 1:25,000, and,
- 2000 – false colour infrared, nominal scale 1:10,000.

To facilitate analysis, these data sets were imported into ILWIS, a geographic information system (GIS) with image processing capabilities. Use of a GIS permits comparison between disparate data formats.

These datasets were cropped to exclude areas not falling within the AOI and georeferenced using the UTM 35l coordinate system and 25 m pixels. After applying the modified dark object subtraction technique described by Chavez (1988) to reduce the effect of atmospheric haze on the images, the benefits of haze correction were found to be slight. Non-corrected data was therefore used in the analysis.

Several methods of image enhancement were tested. The best results were obtained by applying the Tasselled Cap (TC) transform, first described by Kauth and Thomas in 1976. This transform is based on the principal that combining multiple satellite data bands into a lesser number of features reduces the overall data volume and enhances the processor's ability to extract particular types of scene class information (Crist, *et al*., 1986). This transform provides linear combinations of the original Landsat bands which respond to particular physical scene class characteristics. 95% or more of the total data variability is captured in scenes dominated by vegetation and soils using half of the original number of channels (Crist, *et al*., 1986).

For more information on the wavelengths in which the Landsat series of satellites record radiation from the earth's surface, see the text by Lillesand and Kiefer (1994).

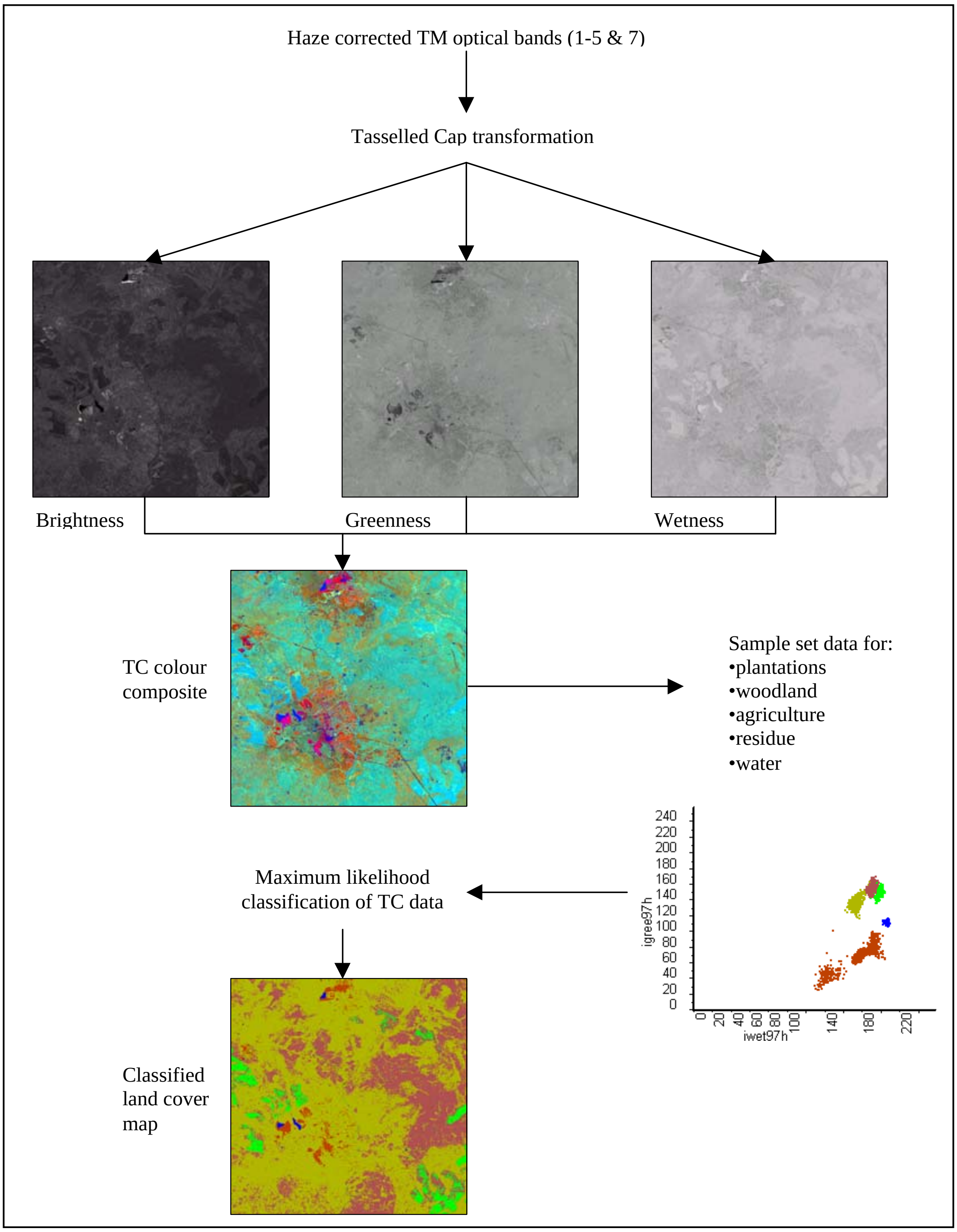


Figure 3 – Full data processing to generate land cover images. A portion of the AOI, centred on the city of Kitwe, is shown. In subsequent runs, haze correction was not applied.

In the TC transform, vegetation and soil data in the six reflective bands of TM occupy three dimensions. The three features corresponding to these dimensions are termed Brightness, Greenness and Wetness. Brightness is a weighted sum of all six bands and is a measure of overall reflectance. Greenness is a contrast between NIR and visible reflectance and measures the presence and density of green vegetation. Wetness is a contrast between short-wave infrared (SWIR) and visible/near infrared (VNIR) and provides a measure of soil moisture content, vegetation density and other scene characteristics (Crist, *et al*., 1986). Wetness also improves delineation between emerging and developing vegetation and vegetation that is senescing. The equivalent TC dimensions occupied by MSS data are termed Soil Brightness, Greenness and Yellow Stuff.

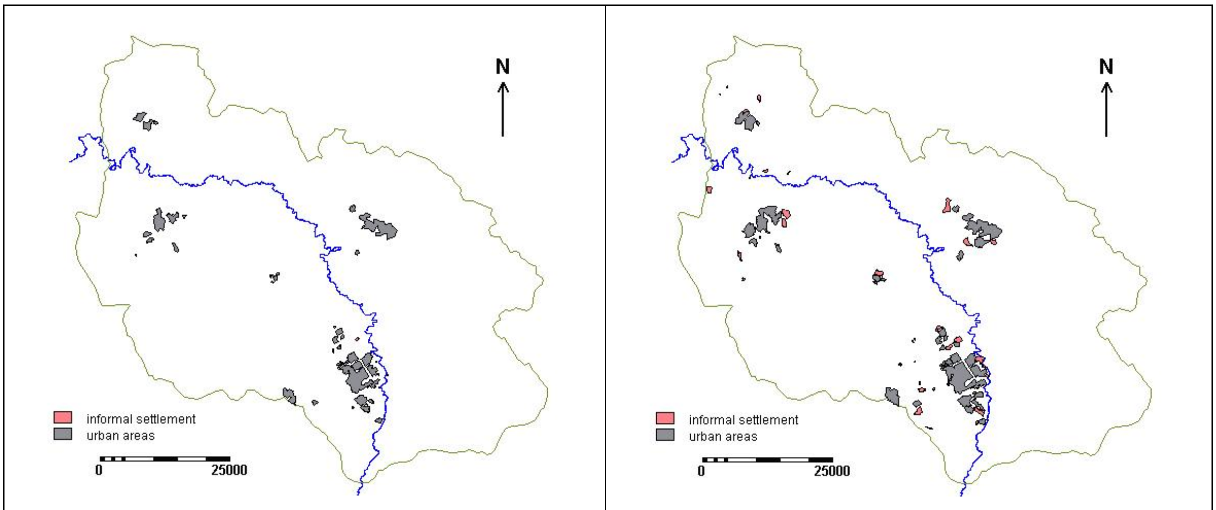
The TC transformation produces features which can be compared between scenes and sensors (Crist, *et al*., 1986), thereby facilitating change detection. The application of TC transformations to the TM and MSS data sets yielded good results.

To quantify changes in area of land uses, a false colour composite (FCC) was generated, as shown in figure 3, using the three TC channels. Land use changes were plotted by tracing the outlines of land use areas identified on these FCCs for each year that data was available and corroborating the land use category by referring to aerial photography and topographic maps.

This method works well for the mixed spectral responses and recognisable patterns associated with anthropogenic surfaces. More homogenous, larger areas, such as tracts of woodland and agricultural areas are more efficiently assessed using supervised classification. To assess land cover classes, representative areas were identified in the TC FCC. A maximum likelihood classifier was then applied to the TC data for the entire AOI, thereby recoding each pixel according to its TC values.

Land use classes are:
- urban settlement – formal, urban areas with recognisable street pattern,
- informal settlement – high density area consisting of informally built dwellings,
- plant, shafts and other disturbed land – mine surface infrastructure and patches of land that have been cleared/contaminated/used for industrial purposes,
- mine residue deposits – mine waste, including overburden dumps, waste rock dumps and tailings impoundments, and,
- mine excavations – open pits.

The land cover classes are:
- Miombo Woodland – the natural climax vegetation in the region,
- agricultural and deforested areas – typically areas used for small-scale agriculture, but other clearings are included in this category,
- forest plantations – exotic plantations of pine and eucalyptus,
- water bodies, and,
- disturbed areas – hard, reflective surfaces, including mine waste deposits and urban areas (less specific than the category above and included in this analysis to reduce the number of non-classified pixels).



Settlement areas in 1972 (note: MSS data is too coarse to detect many informal settlements and so this class is under-estimated for this year)

Settlement areas in 2000

Figure 4 – Settlement areas delineated by on-screen digitising of the FCCs. In 1972, settlement areas covered 7,550 ha, approximately 1.7% of the AOI. By 2000, these areas covered 12,455 ha or 2.8% of the AOI surface area.

4 RESULTS

4.1 Land use categories

All land use categories mapped showed significant changes over the period of investigation. Mining land uses generally increased in a linear fashion (e.g. mine residue) or tended towards an asymptote (e.g. excavations).

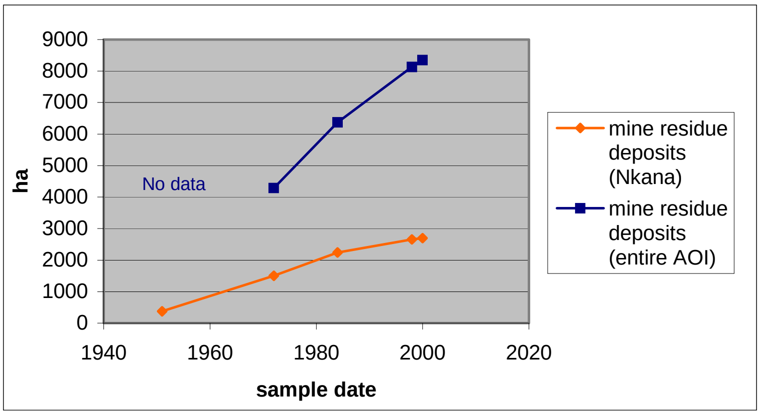


Figure 5 – Changes in area occupied by mine residue deposits. No old map data was available for Chingola at time of writing. The full data set was only available for Nkana, hence the separate plot for Nkana.

By the close of the last decade, residue deposits covered 1.95 times as much land as in 1972, increasing from 4,289 ha to 8,350 ha.

After 1989, no increase in area of surface excavations is detected at Nkana, due to exhaustion of near-surface reserves. Increases in excavation areas at other sites are not apparent, but this may be in part due to the difficulty of separating mine waste from excavations in the high reflectance areas around open pits. No reduction in area is observed and it may therefore be assumed that no effective rehabilitation of open pits has occurred during the period investigated.

In 1972, excavations in the AOI covered 220 ha. This increased by a factor of 4.3 to 953 ha in 2000. The largest excavations and the greatest growth in excavations occur at Nchanga where the Nchanga Open pit has provided the bulk of the ore production.

Human settlements change in a less predictable manner than mine infrastructure and therefore more care is needed in classifying areas on satellite images.

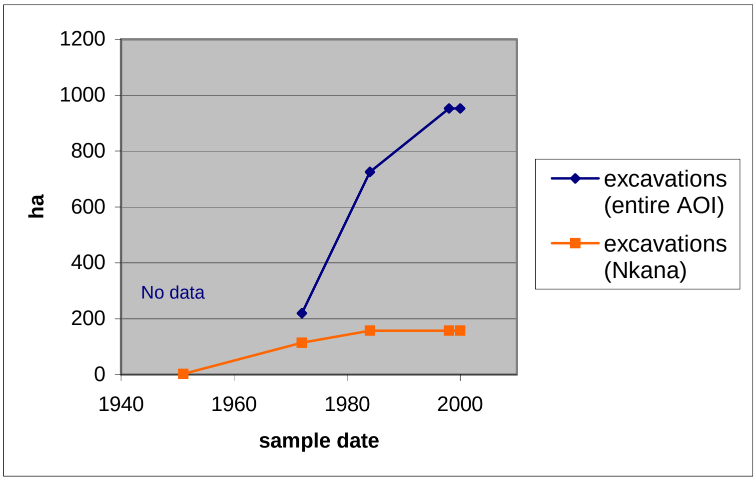


Figure 6 – Increase in area of mine excavations at Nkana (including Chambishi) compared with the entire AOI. The effect of the Nchanga Open Pit is clearly visible.

Settlement areas, especially informal areas, are very difficult to delineate accurately. For Kitwe, comprehensive aerial photograph sets were available while none were available for other areas, such as Chambishi. Consequently, classifications in Kitwe have a higher level of confidence than elsewhere.

Concentrated informal settlements have high building density, small buildings and the absence of street patterns observable on Landsat images. TC transformations were not used to map this land use category as it was found that generating colour composites from original MSS and TM bands (TM bands 4,5 and 1; MSS bands 7,6 and 5) were more useful. Over the period of investigation there has been a 16.3-fold increase in the area occupied by these settlements. This increase must be presented with a caveat as the 1972 MSS image is too coarse to reliably detect informal settlements and therefore some settlements may not have been identified.

Urban areas have similar spectral characteristics to concentrated informal settlements, but exhibit higher spectral variation (possibly due to the presence of gardens and parks). Regular street patterns are observable in these areas.

Informal settlers are vulnerable to water pollution and land degradation by mining as they rely on direct exploitation of these resources. In turn they degrade both land and water by over-exploitation and lack of sanitation. Formal urban areas now cover 1.4 times as much land as in the early 1970s.

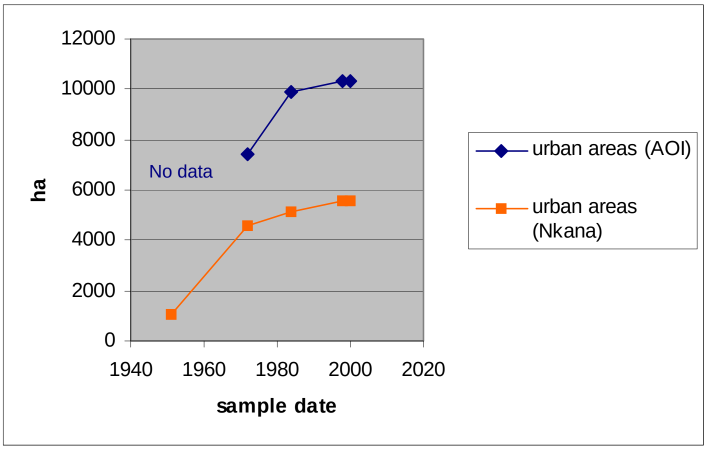


Figure 7 – Change in urban settlements over time.

4.2 Land Cover Categories

From the set of maps presented in figure 8, it is apparent that the area used for agriculture has been increasing at the expense of natural vegetation cover typified by Miombo woodland. Agricultural areas have been expanding concentrically from the mining towns on the Copperbelt. In 1972, Miombo woodland was evenly distributed across the AOI, accounting for 56% of total land cover. By 2000, Miombo accounted for 31% with patches increasingly broken up and only occurring in the peripheral areas of the AOI. It is impossible to attribute these changes to one economic activity as there is a link between agriculture and woodland clearing to supply wood to the mines. It is apparent, however, that a dramatic increase in informal agriculture has occurred and that this has implications for the woodland ecosystem.

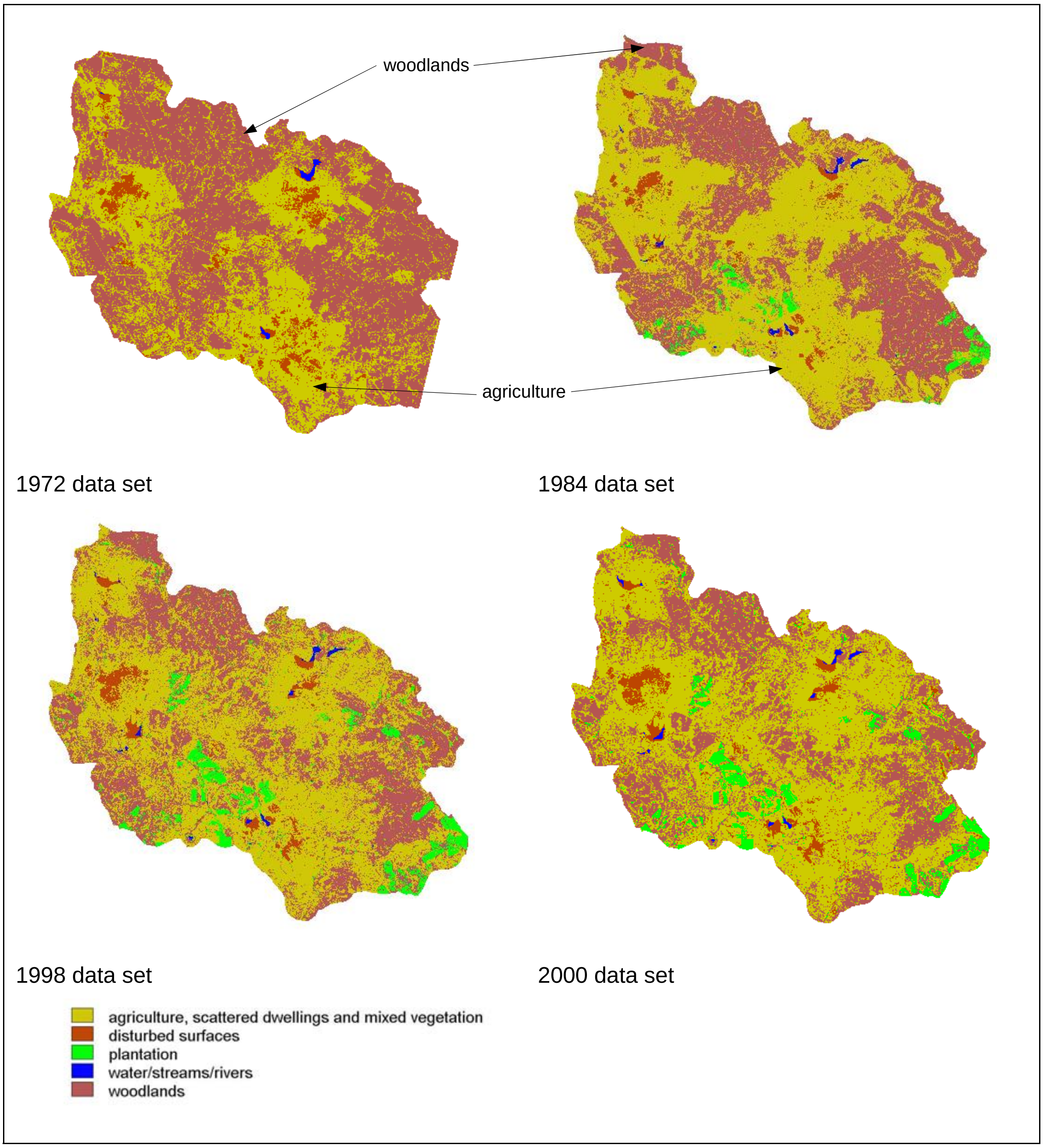


Figure 8 – Classified maps resulting from the application of a maximum likelihood algorithm, to the three TC components for each of the data sets. The northern and eastern boundaries of the 1972 land cover map are

truncated by the boundaries of the MSS data set. This has been accounted for by using land cover percentages to compare cover between years.

Changes at a scale greater than individual mine sites are occurring in the region, and environmental management of mines should take this into account if adequate protection of the environment is to be achieved.

On the FCC, agricultural areas appear as light blue-green areas of high variation characterised by mixed pixels largely corresponding to known occurrences of peasant farming, small settlements and deforested land. The towns in the Copperbelt have acted as settlement nuclei from which agricultural activities have radiated.

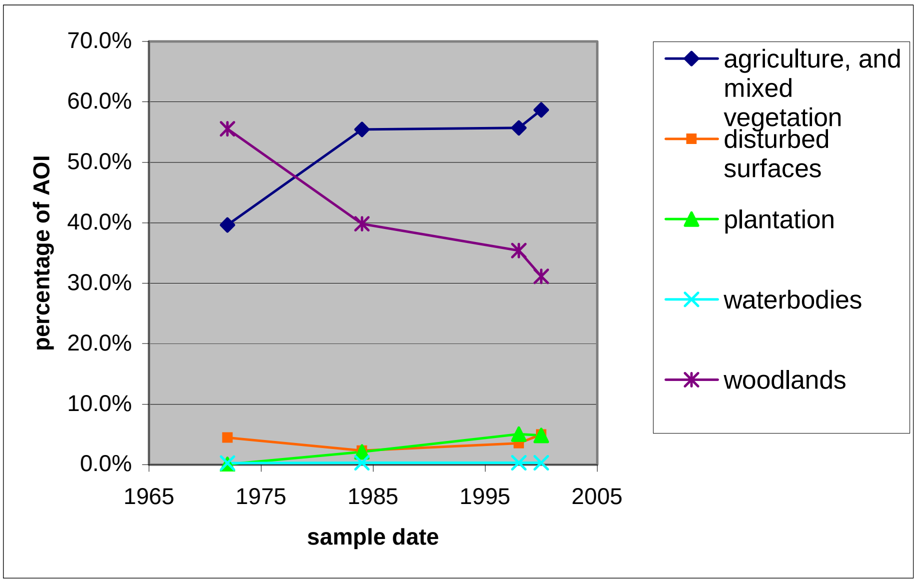


Figure 9 – Changes in major land cover classes identified in classified TC images.

In the forty-year period investigated here, the zone of deforestation around the mining towns has increased dramatically. Natural land cover near the Copperbelt cities has largely been converted into sparsely vegetated (high reflectance) agricultural areas. With the high intensity rainfall events common here and the poor nutrient levels in the latteritic soils, permanent land degradation is likely.

Within Kitwe, most mining-related land uses increased significantly in the 1970's and early 80's during, and shortly after, the good years for the copper industry. Since the decline of world commodity prices, mining infrastructure has ceased growing in area. The same trend occurs in other urban areas in the Copperbelt. Population growth has not stabilised, however, as seen in the increasing extent of informal settlements. With little funding available for urban development and service provision, increasing numbers of people live without sanitation or access to clean water. This, combined with the presence of mine pollution, has led to an unacceptable impact on the community.

Simple techniques applied to RS data have highlighted land use and land cover trends in areas surrounding the Copperbelt mines and within the Copperbelt cities that threaten the long-term sustainability of human habitation in the area.

5 CONCLUSION

Analysis of changes in land use and land cover around the Copperbelt mines shows no clear correlation between growth of mining infrastructure and large-scale changes in the environment. This suggests that, while the direct impacts of mining are substantial and significant, they are not the only impacts that require attention. The assessment conducted indicates that informal agricultural practices and deforestation affect a large area. This affected area has continued to expand, despite a slow down in mining activity. These changes in land cover are in essence a secondary or indirect impact of the mining operations and will continue to increase in magnitude with increasing levels of unemployment and increasing population. If the creation of wealth through mining is to be sustained over the projected life of the Copperbelt mines, approximately thirty years, then mine management will have to play an active role in managing these impacts.

6 REFERENCES

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