Patch analysis of Landsat Datasets for Assessment of Environmental Change in the Zambian Copperbelt

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***Abstract*— A gradual decline in formal economic activity in the Zambian Copperbelt has resulted in increasing levels of poverty. The impacts of poverty on the environment have been mapped using Landsat MSS, ETM and ETM+ images. Changes in the environment have been traced over a period of nearly thirty years and have been assessed by patch analysis. This approach has shown that landscape patches in the Copperbelt are becoming increasingly complex in shape and smaller in size. The natural land cover, miombo woodland, is increasingly fragmented, posing a threat to biodiversity and the well-being of local communities.**

Keywords- miombo woodland; remote sensing; Zambia; Copperbelt; environmental impact

I. THE ZAMBIAN COPPERBELT

A substantial copper mining and processing complex has developed in Zambia, where the 800 km long Lufilian Arc bends southward into the country from the Democratic Republic of Congo. These copper-bearing sedimentary strata were discovered in the early 1900s. Within thirty years, mining towns had been established and rapid urbanisation was taking place. A little more than a decade after Zambia's independence from Britain in 1964, copper prices slumped, leading to a dramatic downturn in the fortunes of the Zambian Copperbelt. Attempts at restructuring the state-run mining company, Zambia Consolidated Copper Mines (ZCCM), and its eventual privatisation, have not halted the rapidly rising levels of poverty.

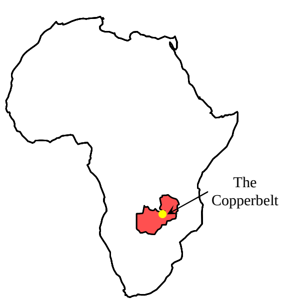

Figure 1. The location of Zambia and the Copperbelt.

Increasing numbers of people in the Copperbelt, both employed and unemployed, are taking up subsistence agriculture as a means of survival. This has had profound impacts on the environment, primarily through the clearing of woodland with its associated impacts on soil fertility and water quality. This paper examines the changes in land cover in the most intensively mined and populated part of the Copperbelt[1].

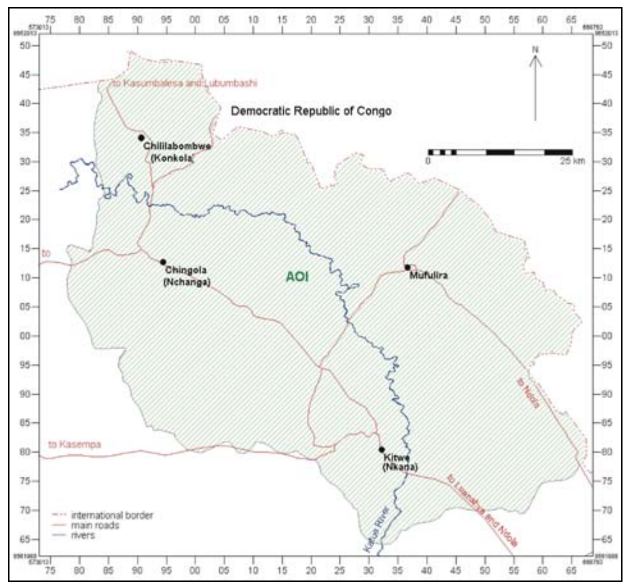

Figure 2. Major towns in the area of interest (AOI) (mines indicated in parenthesis). The Universal Transverse Mercator (UTM) coordinate system is used for all maps of the AOI (zone 35L with the Clarke 1880 spheroid).

II. ENVIRONMENTAL CHANGE DETECTION USING LANDSAT DATASETS

Assessment of remotely sensed (RS) data indicates that small-scale agriculture and mining are the principal drivers of environmental change in the AOI. Historically, mining has

[1] this part of the Copperbelt, shown in Figure 2, is referred to as the area of interest (AOI) in this paper.

been dominant, but with increasing poverty and population pressure, peasant agriculture is now the most significant land use and is likely to drive land cover changes in future. Current mine waste deposits are likely to have a substantial impact on receiving waters and catchments for years to come. For these reasons, mine waste deposits and peasant agriculture are key indicators of anthropogenic landscape change. Over the 28 years for which satellite RS data are available, land cover in the AOI has changed considerably, as shown in Figure 3.

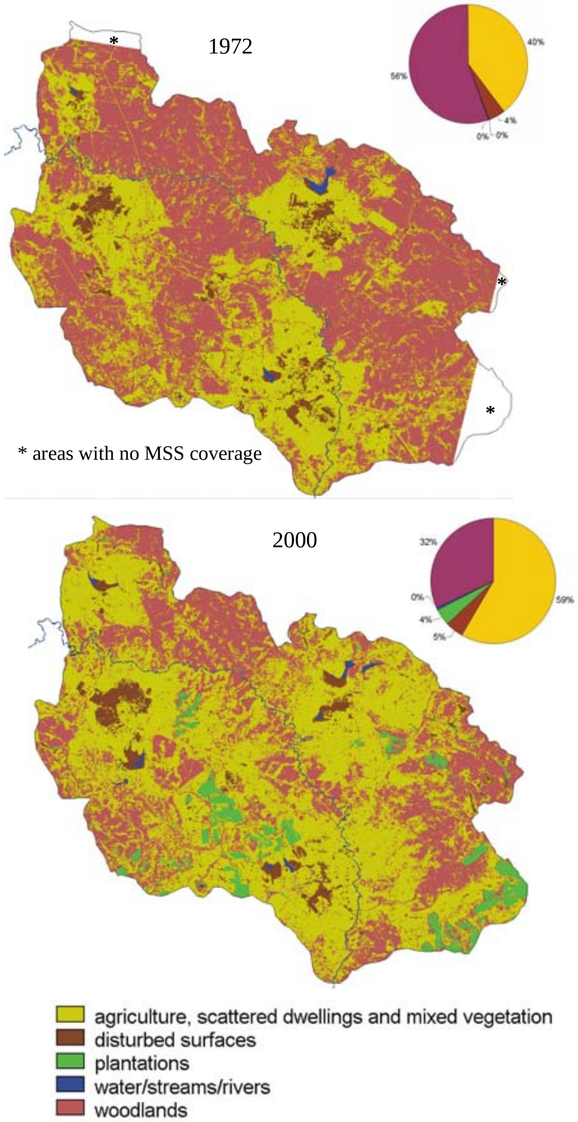

Figure 3. Classified maps of the AOI resulting from the application of a maximum likelihood algorithm, to the three tasselled cap components for each of the data sets. The 1972 land cover map is truncated by the northern and eastern boundaries of the MSS data set. This has been accounted for by using land cover percentages to compare cover between years. These areas are classified as woodland in the 1984 dataset (not shown here), and the 1972 land cover analysis probably underestimates this class as a consequence.

Conversion of woodland to agricultural land has been the principal driver of change in landscape patterns in the AOI. These pattern dynamics, over time and space, are important for ecological processes and wildlife habitats [1], and therefore mapping of change in vegetation assemblages is necessary.

The application of tasselled cap (TC) transformations to the Landsat thematic mapper (TM) and Landsat multispectral scanner (MSS) data sets yielded satisfactory results. A colour composite generated using three TC components[2] discriminated well between various land cover classes. A maximum likelihood classifier applied to the TC transformed data provided the best classification result.

From the land cover maps of the AOI shown in Figure 3, it is apparent that the area used for agriculture has been increasing at the expense of miombo woodland. Agricultural areas have been expanding concentrically from the mining towns in the Copperbelt. In 1972, woodland was relatively evenly distributed across the AOI, accounting for at least 56 percent of total land cover. By 2000, woodland accounted for 32 percent, with patches increasingly broken up and largely confined to the peripheral areas of the AOI. The woodlands are increasingly fragmented and exploited for economic purposes.

A. Agriculture

Agricultural areas in the AOI consist of peasant fields, small settlements and deforested land. The 1972 MSS image was used to digitise spreading centres of deforestation and from this it is apparent that towns in the Copperbelt have acted as nuclei from which agricultural activities have radiated.

Subsistence farming in the AOI is largely based on a traditional slash-and-burn system, known as chitemene. This form of agriculture is environmentally sustainable when the population density is less than four people per square kilometre [3]. In Copperbelt Province, more than one million people (1990 census) live in an area of just over 30,000 square kilometres. There are thus 37 people for each square kilometre in the province. This has important implications for the sustainability of agricultural production in the AOI and is likely to result in increasing levels of environmental degradation.

B. Forestry

Much of the Copperbelt Province's 543,647 ha of designated forest reserve was created to provide wood for the copper industry. Retired miners were permitted to cut timber in the forest reserves soon after their proclamation. Once the trees had been felled, these individuals turned to agriculture. By 1998 thousands of settlers were illegally occupying forest land [4]. This widespread and apparently permanent destruction of forest land may affect water availability downstream, as clearing reduces the amount of water infiltrating the soil and lowers the water table. Progressive deforestation has also allowed for the development of large exotic softwood plantations [5].

Miombo woodlands recover well after cutting due to effective vegetative reproduction and large numbers of existing suppressed seedlings [6]. The establishment of cropland,

[2] these are wetness, greenness and brightness, see [2].

which prevents the regeneration of forest species [7], is thus an important stage in the deforestation process.

C. Timber use

Much of the miombo woodland in the Copperbelt is being converted to grassland through several interlinked activities:

- fuel harvesting – wood is the largest single energy source in Zambia [8] and continues to be the only energy available to most households,
- other harvesting – large quantities of wood are used in mining for construction and underground support, and
- clearing of woodland to allow for agricultural practices such as slash-and-burn/ash fertilisation agriculture.

III. PATCH ANALYSIS: LANDSCAPE PATTERNS AS INDICATORS OF ECOSYSTEM HEALTH

While the increase in agricultural area at the expense of woodlands is important, the distribution, shape and connectedness of the remaining woodland patches are critical factors for the preservation of woodland species. The spatial arrangement of land cover types plays an important role in determining the level of interaction between and within ecosystems. Changes in spatial configuration therefore have implications for ecosystems.

Analysis of spatial pattern is a central feature of landscape ecology as regional patterns often determine and constrain ecological conditions at a smaller scale [9]. The patch concept in landscape ecology is a useful way of addressing the question of the significance of change in the AOI. Landscape patterns can be quantified by calculating metrics such as the number of patches (polygons of one contiguous land cover) and patch size [1]. Analysis of these metrics provides insight into changes in ecosystem health [10].

A. Landscape metrics

Assessment of ecosystems in mining areas has been successfully conducted by applying the patch concept. Some of the metrics applied by reference [10] have been calculated for the AOI and are presented below.

Landscapes consist of patches, corridors and the matrix which surrounds them [11]. The matrix is the most extensive and connected landscape element type and thus plays the predominant role in landscape dynamics. Humans generally increase landscape heterogeneity by modifying rhythms of natural disturbance, leading to distinctive patterns of change.

The Landscape Shape Index (LSI) is the sum of all patch perimeters divided by the perimeter of the circle with a surface area corresponding to the surface area of the patches. LSI increases with overall complexity of patch shapes. In the AOI, the LSI decreased from 128 to 104 between 1972 and 1984 (see Figure 4). This coincided with the agglomeration of previously scattered peasant fields and the establishment of large monoculture stands of exotic softwoods. The LSI then increased to 154 in 1998 as remaining patches of woodland became increasingly fragmented. The LSI decreased to 151 in 2000, possibly through further agglomeration of agricultural plots.

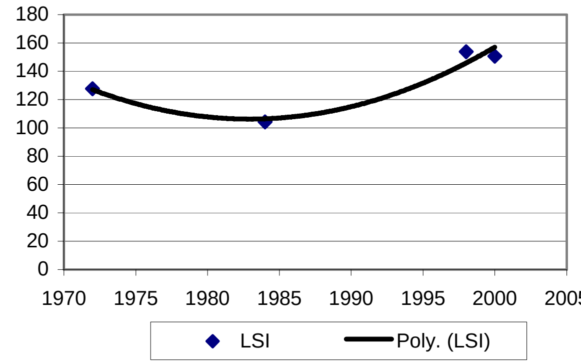

Figure 4. LSI statistics for all land cover classes in the AOI for each year studied (with a polynomial trend line fitted).

The LSI for agricultural patches controls the overall LSI in the AOI. In the AOI, large tracts of woodland existed in 1972. These large patches have been broken up by human activities, increasing the number of patches as well as the perimeter/interior ratio for woodland patches. As patches of remaining woodland become progressively smaller, habitat for woodland species diminishes, reducing species diversity and population sizes. Over the entire period of study, patch shape complexity has increased due to human-induced fragmentation. In the woodland land cover class, the LSI increased from 73 in 1972 to 103 in 2000.

Mean Patch Size (MPS) is calculated by dividing the AOI surface area by the number of patches within it, or, alternatively, by dividing the total land area for a particular class by its number of patches. Over the period of study, the MPS decreased in the AOI, thus fragmentation of the landscape has occurred (see Figure 5). Woodland exhibits a dramatic change in MPS – from 47 ha in 1972 down to 13 ha in 2000, with a minimum of 11 ha in 1998. Agricultural MPS increases from 17 ha in 1972 to 33 ha in 2000.

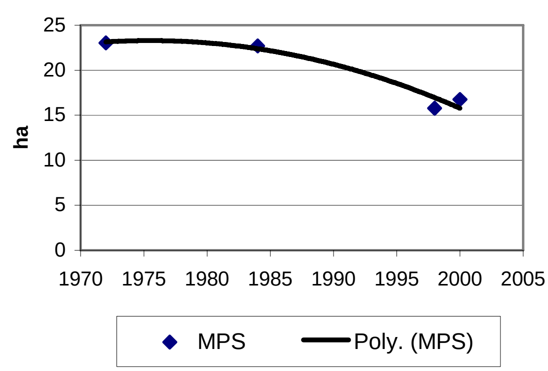

Figure 5. MPS statistics for all land cover classes in the AOI for each year studied (with a polynomial trend line fitted).

In total, the number of patches (NP) in the AOI increased during the period of study. This trend is clearly evident in Figure 6. There is some variation between classes, however.

Woodland patches showed the steepest rate of increase, nearly doubling from 5,183 in 1972 to 10,846 28 years later. This reinforces the notion of increasing fragmentation of woodland habitats presented above. Over the same period, the number of individual agricultural patches decreased from 10,402 to 7,969 as patches expanded outwards, merging with their neighbours.

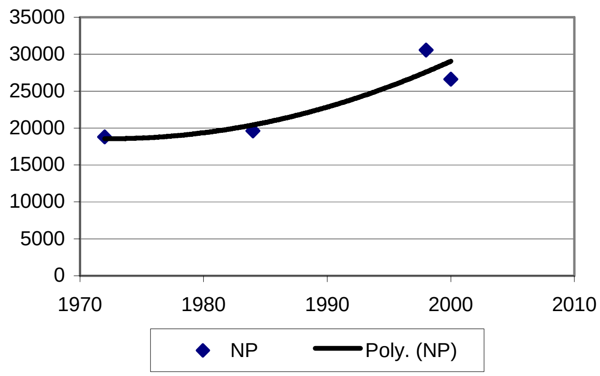

Figure 6. NP statistics for all land cover classes in the AOI for each year studied (with a polynomial trend line fitted).

The Largest Patch Index (LPI) is the proportion of the AOI covered by the largest patch. The LPI statistic for the entire AOI, shown in Figure 7, increased over the study period. This superficially implies decreasing fragmentation. On closer examination, the statistic shows increasing agglomeration of agricultural patches with concomitant fragmentation of woodland patches. In all four scenes assessed, the largest patch in the AOI was agricultural land.

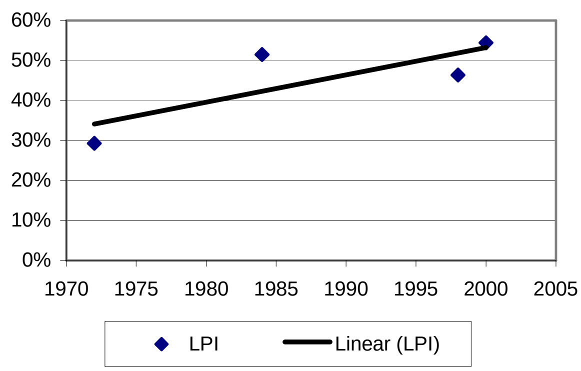

Figure 7. LPI statistics for all land cover classes in the AOI for each year studied (with a linear trend line fitted).

IV. IMPLICATIONS OF CHANGES

In the AOI, the LSI has increased over the period of study and thus the overall complexity (fragmentation) of the landscape has increased. This implies sustained disturbance of the land surface. When undisturbed, horizontal landscape structure tends to increasing homogeneity. Patches are formed by natural disturbances and uneven occurrence of natural resources, such as soil depth [11]. Large patches are important for species diversity, as certain species are adapted to the interior conditions of patches. Division of a landscape into many smaller patches decreases this interior habitat and increases edge habitat. Patch size affects biomass, production and nutrient storage per unit area, species composition and diversity. Patch shape is important as a result of the area to circumference ratio and its consequences for edge effect [11].

Human patterning of a landscape can affect the spread of disturbance or boundary phenomena in general, animal movements, run-off and erosion [11]. With cutting of timber, the structural integrity of the woodland declines, eventually leading to disjointed fragments of various sizes isolated by non-woodland matrix [12]. This reduces the number of woodland species. The simple and cost effective monitoring approach applied in this paper clearly shows that increasing dependence on survivalist activities, such as slash-and-burn agriculture, is eroding the renewable natural resource base of the Copperbelt. In the long-term, this may drastically reduce the sustainability of high density human settlement

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