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Deforestation in Mwanza District, Malawi, from 1981 to 1992, as determined from Landsat MSS imagery

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Abstract

Malawi is critically short of fuelwood, the primary energy source for its poverty-stricken populace. Deforestation from 1981 to 1992 in Mwanza District in southern Malawi was assessed using Normalized Difference Vegetation Index (NDVI) values calculated from multi-temporal Landsat Multispectral Scanner (MSS) images. A control site, where vegetation change was assumed to be minimal, was used to account for the large effect of phenology on NDVI variability between images, and to reveal more subtle differences indicative of changes in percentage woody canopy cover. The average annual deforestation rate was estimated to be 1.8% in Mwanza District between 1981 and 1992.

Keywords: AVHRR; Deforestation; Landsat MSS; Malawi; Mozambique; NDVI

Introduction

Human pressures on natural vegetation can exceed its regenerative capacity, leading to degradation (Ringrose, Vanderpost & Matheson, 1996), particularly in developing countries (Allen & Barnes, 1985), many of which occur in southern

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Africa. Deforestation and forest degradation are becoming locally common features wherever burgeoning human populations cause fuelwood demands to exceed supplies (Millington, Townshend, Kennedy, Saull, Prince & Madams, 1989). The Southern African Development Coordination Conference (SADCC) determined that fuelwood supply and demand varies markedly between Mozambique and Malawi, the two countries involved in this study. Woody biomass resources are plentiful in Mozambique but scarce in much more densely populated Malawi (Millington et al., 1989).

The SADCC biomass assessment was based on Normalized Difference Vegetation Index (NDVI) values derived from solar irradiance measured by the Advanced Very High Resolution Radiometer (AVHRR) on board meteorological satellites operated by the US National Oceanic and Atmospheric Administration (NOAA). Green vegetation both absorbs red light strongly and reflects near-infrared light strongly, giving it the highest NDVI values of any common land cover type. The proven sensitivity of NDVI to green vegetation has stimulated a whole field of research focused on large-scale measurement and monitoring of vegetation using satellite data (e.g. Justice, Townshend, Holben & Tucker, 1985; Tucker, Townshend & Goff, 1985; Tucker, Fung, Keeling & Gammon, 1986; Prince, 1991; Myneni, Keeling, Tucker, Asrar & Nemani, 1997).

The broad spatial extent (2700 km) and high temporal resolution (daily) of AVHRR images make them useful for monitoring regional vegetation phenology (Justice & Hiernaux, 1986; Townshend & Justice, 1986). Landsat MSS images are more applicable to studies of vegetation structure, given their higher spatial resolution (80 m) relative to AVHRR data (>1.1 km). Furthermore, the broad temporal coverage (1972–93) and spatial extent (185 × 185 km) of MSS images make them suitable for measuring vegetation change at landscape to regional scales. Landsat MSS data have been used to assess vegetation cover (Prince & Astle, 1986) and vegetation change (Ringrose & Matheson 1987, 1992; Ringrose, Matheson, Tempest & Boyle, 1990) in African savannas.

The open-canopy woodland savanna occurring in this study area is highly seasonal. The presence of green herbaceous material at the time of satellite data acquisition complicates extraction of woody canopy cover parameters from Landsat MSS data (McCloy & Hall, 1991). Herbaceous material senesces in the early dry season, however, leaving the woody overstory as the only green component of the canopy. In the present study, NDVI was used as an indicator of woody canopy cover. It was hypothesized that by selecting Landsat MSS images acquired in approximately the same season (late autumn), when only the woody overstory is green, NDVI could be applied to estimate woody canopy cover change. The goal was to quantify and map deforestation patterns by analysing Landsat MSS NDVI data within a GIS framework. The study area (Mwanza District, Malawi) was selected based on the availability of 1981, 1987 and 1992 MSS images acquired in the autumn.

The analysis used AVHRR imagery to characterize the temporal pattern of vegetation phenology and MSS imagery to map spatial patterns in woody cover and woody cover change. The AVHRR image analysis was necessary to develop and defend the strategy for removing the influence of phenology on NDVI values derived from MSS imagery.

Malawi's deforestation problem

Malawi is divided into three administrative regions (Fig. 1). Like Mozambique, the Northern Region has high biomass reserves, but the more populous Central and Southern regions have acute shortages of fuelwood and building poles due to severe deforestation (Millington et al., 1989). The Southern Region contains one-third of the total land area yet nearly half the total population (House & Zimalirana, 1992), at a density of 162 persons km^{-2} (Bunderson & Hayes, 1995). Population growth rate is an alarming 3.3% per annum (National Statistical Office, 1988), contributing to environmental degradation and persistent poverty (House & Zimalirana, 1992; Kalipeni, 1992).

Demand for woody biomass exceeds supply in the Central and Southern regions

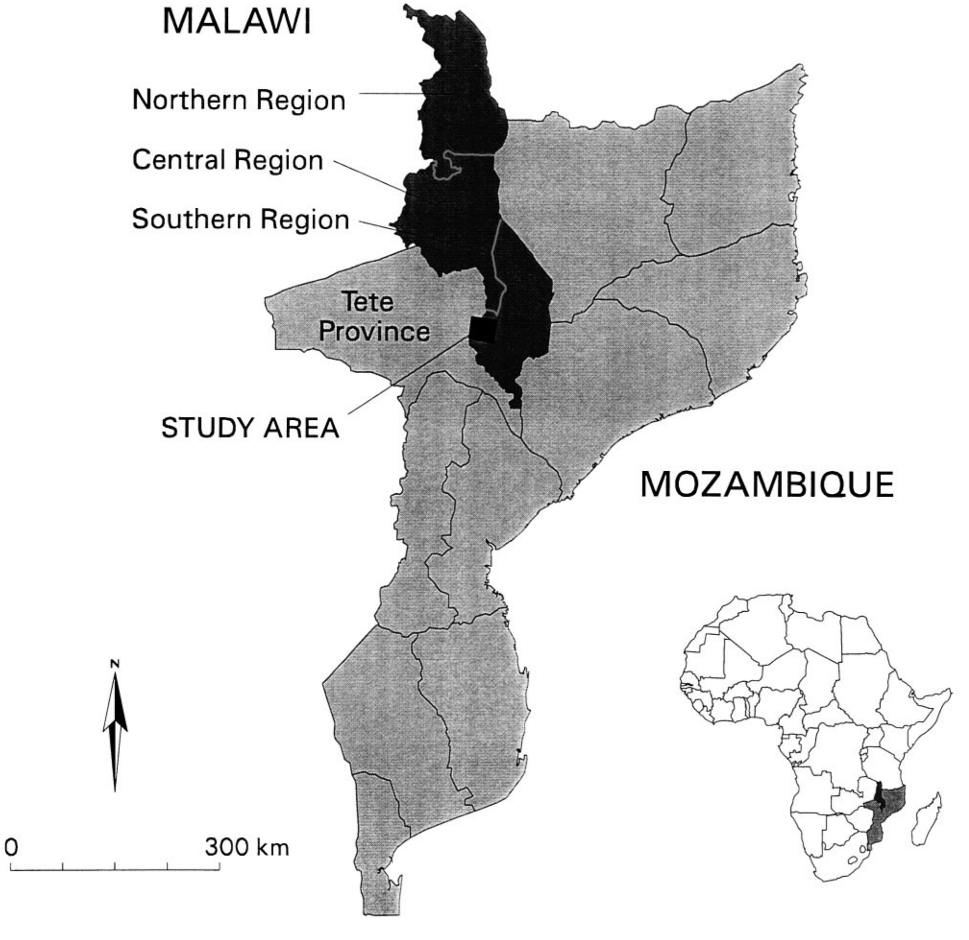


Fig. 1. Study area location, and regional and provincial boundaries in Malawi and Mozambique, respectively.

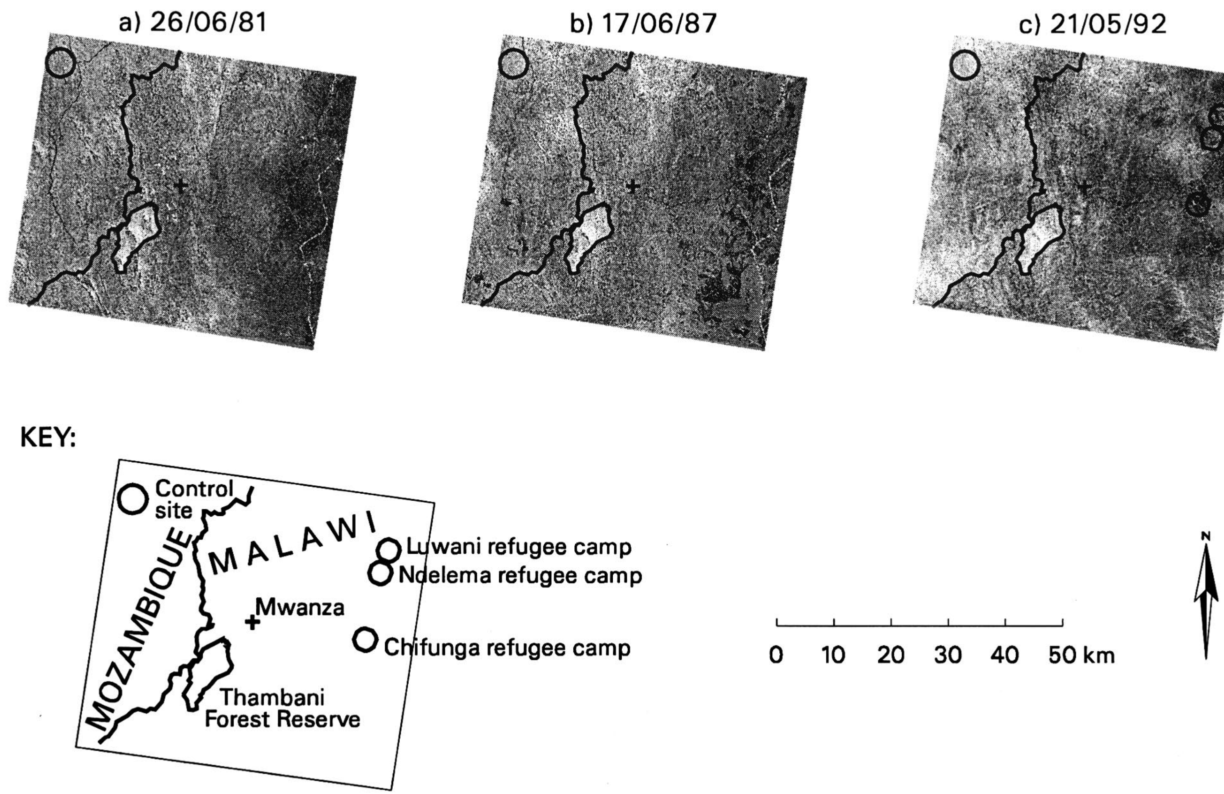


Fig. 2. Spatial patterns in woody cover across the study area, as indicated by Landsat MSS NDVI values on (a) 26 June 1981; (b) 17 June 1987, and (c) 21 May 1992. Note that while the brightness in a given area (such as the control site) may differ between images, this is a function of the image display and not necessarily indicative of actual NDVI differences. Administrative boundaries and other features have been overlaid to aid interpretation.

(Munslow, Katerere, Ferf and O'Keefe, 1988). Moyo, O'Keefe and Sill (1993) projected that by 1995 wood consumption (11.7×10^6 m^3) would have exceeded production (5.3×10^6 m^3) by 6.4×10^6 m^3. In 1988, the Malawi Office of the President and Cabinet estimated total forest cover to be declining by 3.5% annually. Between 1972 and 1990, total forest cover declined by 41%, an annual average loss of 2.3% (Bunderson & Hayes, 1995). Malawi may have lost 24% of its forest area during the 1990s alone (Lele & Stone, 1989). At this rate, Kalipeni (1992) warned that the country could be laid completely bare in less than 12 years. Fuelwood shortages are so severe in some areas that even mango trees, which provide an important source of food, are being removed (Munslow et al., 1988; Gore, 1992).

Fewer than 1% of Malawian consumers are connected to electricity (Gore, 1992); consequently, fuelwood supplies 90% of the country's energy requirement (Moyo et al., 1993). Private tobacco estates consume 23% of the wood energy for curing tobacco, Malawi's most lucrative cash crop (Munslow et al., 1988). In the Central and Southern regions, most remaining woody biomass resources exist in areas where public access is restricted: game reserves, forest reserves, plantations, and traditional clan graveyards. The most critical fuelwood shortages exist along the Mozambican border and have been blamed on the influx of Mozambican refugees (Millington et al., 1989).

Study area

Physical environment

Fig. 2 illustrates raw NDVI values at three dates across the 2,663-km^2 study area, which is centred over the town of Mwanza (15°61′S, 34°52′E). Mwanza is the capital of Mwanza District, which occupies almost three-quarters of the study area. The remaining quarter to the west is located in Moatize District in Tete Province of Mozambique. The international border follows the watershed divide; climate, soils, topography and potential vegetation are essentially the same on both sides. A portion of Mozambique was included in the study area because the NDVI analysis strategy depended on the use of a 'control' site where deforestation was assumed to be minimal.

Rainfall is distinctly seasonal, beginning in late spring (November) and ending in early autumn (April), with high interannual variability (see Fig. 4a). Between 1980 and 1996, mean annual rainfall ranged from 1042 to 1269 mm at the three recording stations located within the study area, at elevations ranging from 670 to 870 m (Department of Meteorological Services, Blantyre). Elevation in the study area ranges from a minimum of 213 m in the Shire River Valley in the southeastern corner to a maximum of 1453 m at the peak of Thambani Mountain within Thambani Forest Reserve. The highly weathered soils are ferruginous lithosols derived from gneiss (Agnew & Stubbs, 1972: 32–39).

Natural vegetation throughout most of the study area is classified as seasonal, open-canopy *miombo* (savanna) woodland. Trees in the *miombo* woodland, dominated by *Julbernalia globiflora* and *Brachystegia* spp., exhibit a striking pre-rains flush (Agnew & Stubbs, 1972; Fuller, 1994). The higher elevations in Thambani Forest Reserve and at the northern extreme of the Mozambique/Malawi border are classified as evergreen/semi-deciduous forest and woodland (Millington et al., 1989). Vegetation below 500 m elevation in the much flatter Shire River Valley includes an overstory of *Adansonia digitata* (baobab), *Pseudocadia* and *Sterculia* spp. and understory thickets of *Pterocarpus antonesii*, *Fagara* spp., *Grewia* spp. and *Commiphora* spp., among others; these thickets have probably been induced by humans through cultivation (Agnew & Stubbs, 1972). Population density and agricultural land use generally increase with decreasing altitude, while tree densities are greater at higher elevations.

Demography

Mozambique was decimated by a 17-year civil war ending in 1994, which caused a massive exodus of refugees into neighbouring countries, including Malawi, to which a million refugees had fled by 1992. The fact that Southern Malawi extends into Mozambique like a peninsula contributed to dramatic refugee influxes into Malawi's Southern Region, further straining already scarce resources (Kalipeni, 1992). Several small refugee camps had sprung up along the border by 1988. These eventually contained a total of about 16 000 refugees. Three much larger refugee camps developed further east (see Fig. 2). Most refugees at Chifunga camp came by foot via the main border crossing west of Mwanza, while refugees at the Luwani and Ndelema camps were trucked there from overflowing refugee camps south of the study area. Eventually, 150 000 refugees occupied Mwanza district, effectively doubling the human population (Fig. 3). Relative to Malawi, Mozambique is underpopulated; population density in Tete province of Mozambique was <10 km^{-2} in 1986 (King, 1987), while it was 53 km^{-2} in Mwanza District in 1987 (National Statistical Office, 1988).

Methods

Satellite image processing

AVHRR monthly NDVI composites were processed in global area coverage (GAC) format (GIMMS, NASA Goddard Space Flight Center (GSFC), Greenbelt, Maryland, USA) for the period January 1982 to October 1992 with EASI/PACE Version 5.1 software (PCI, Ontario, Canada). The NDVI is calculated from AVHRR channels 1 (red) and 2 (near-infrared) according to the following formula:

$$NDVI_{AVHRR} = (band\ 2 - band\ 1)/(band\ 2 + band\ 1) \quad (1)$$

The spatial resolution of GAC data is 4.4 km at nadir. Pixels from the study area were extracted from the regional NDVI composites. Sequential NDVI values for six

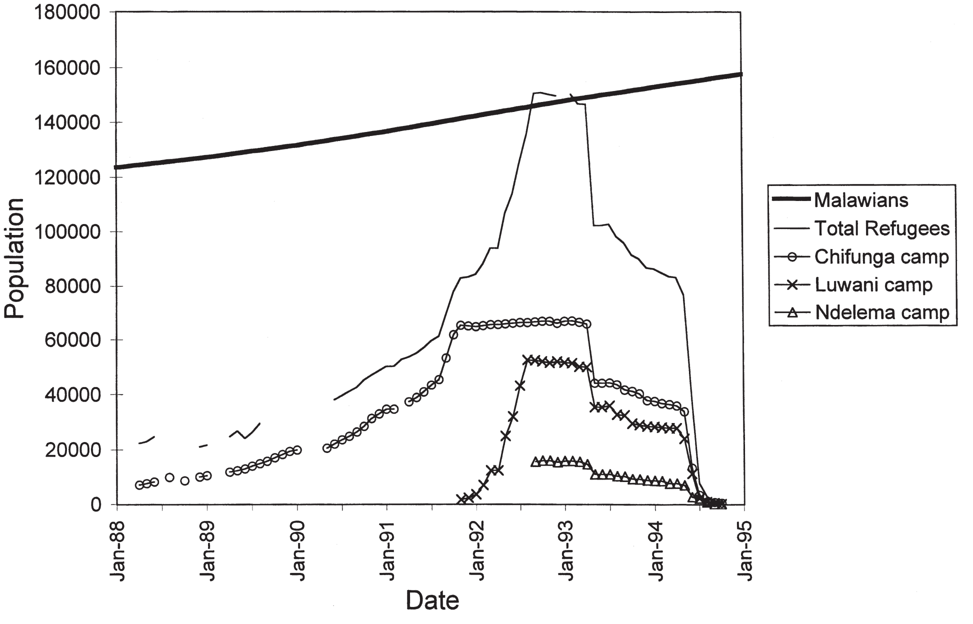


Fig. 3. Malawian and Mozambican populations in Mwanza District, 1988–95, showing the steady increase in the Malawian population along with the sudden influx of Mozambican refugees, primarily at three large refugee camps. *Sources*: Malawian figures from projections from *Malawi Statistical Yearbook*, 1988; Mozambican figures from situational reports, Office of Disaster Preparedness, Relief and Rehabilitation, Lilongwe.

pixels over predominantly agriculture land and six pixels over predominantly *miombo* woodland were isolated for comparison.

Four Landsat MSS images (EROS Data Center, Sioux Falls, South Dakota, USA) were processed with ENVI Version 2.8 software (RSI, Boulder, Colorado, USA). The relevant characteristics of the imagery are detailed in Table 1. The 1992 image was rectified to 1:50 000 topographic maps (Department of Surveys, Blantyre, Malawi) after establishing 15 ground control points with a cumulative root mean square (RMS) error of <0.5 pixel. A first-order polynomial warping function with nearest-neighbour radiometric resampling was used. The 1981 and two 1987 scenes were registered to the rectified 1992 base image after establishing 16 ground control

Table 1
Characteristics of the Landsat MSS imagery used in this study

Image date	Satellite	Image quality
26 June 1981	Landsat 2	Band 1 striped
13 March 1987	Landsat 5	Good, but ~10% cloud cover
17 June 1987	Landsat 5	Band 1 striped; Band 3 absent
21 May 1992	Landsat 4	Good

points with a cumulative RMS error of <0.5 pixel in each case. Again, first-order polynomial transformations with nearest neighbour radiometric resampling were applied.

The georegistered images were corrected for atmospheric path radiance by subtracting band minimum values from within the darkest topographic shadows. Next, the images were calibrated to correct for different sun elevation angles and sensor gain/offset constants, and to convert radiance values into reflectance values. Image preprocessing was completed by subsetting the study area from the northeast corner of the coregistered images, since most of the area in the full scenes was in Mozambique, where field data were unavailable.

As indicated in Table 1, bands 2 (red) and 4 (near infrared) were the only high-quality bands common to all four scenes. Fortunately, these were the only MSS bands required to calculate NDVI, using the following formula:

$$NDVI_{MSS}=(band\ 4-band\ 2)/(band\ 4+band\ 2) \quad (2)$$

Fieldwork

For the purpose of relating image NDVI values to actual woody cover, several key areas in Mwanza District were visited in November 1996: Thambani Forest Reserve, the nearby border area, and the three large refugee camps (Chifunga, Luwani and Ndelema camps). Percentage woody canopy cover was measured at eight sites using the plotless Bitterlich technique (Mueller-Dombois & Ellenberg, 1974; Friedel & Chewings, 1988). Sites were situated at least 100 m within visually consistent vegetation covering several acres and thus represented by a sizeable number of Landsat MSS pixels. Sites selected showed no evidence of canopy cover change over the previous few years, allowing the assumption that percentage woody canopy cover had not noticeably changed since acquisition of the May 1992 MSS image. Sampling points were geolocated using a global positioning system (GPS) to an accuracy of <100 m (Nel & Jackson, 1995). Differential corrections could not be performed given the absence of concurrent base station data, but such accuracy was considered unnecessary given the care with which sampling points were selected well within visually homogeneous areas.

Spatial analysis

The four MSS NDVI images were spatially analysed in a geographic information system (GIS) constructed in GRID, the raster module of ARC/INFO Version 7.0 software (ESRI, Redlands, California, USA). Field validation site locations established by GPS were added to the GIS. Relevant land use features—administrative boundaries, roads, and villages—were digitized into vector coverages (Calcomp 9100 digitizing table) from 1:50,000 topographic maps and a 1:250,000 Blantyre regional map (1991) obtained from the Department of Surveys in Blantyre.

In a study of vegetation decline in Botswana, due in large part to fuelwood collection, Ringrose et al. (1996) found that most degradation occurred within 2–3 km (walking distance) of settlements. Hence we chose a distance of 2.5 km, along either side of the major highway (M6) passing through the study area, as an appropriate buffer zone. NDVI values were extracted near this highway and then compared between the Mozambique and Malawi sections. This was an interesting comparison because the local Mozambican population had fled, while in Malawi the M6 highway was well used. Using a similar rationale, a buffer zone of 10.0 km was created on either side of the international border, to compare NDVI values on unprotected border lands (Thambani Forest Reserve was masked out).

Every effort was made to use MSS images acquired during the same season to minimize the influence of phenology on NDVI, which can mask the more subtle changes in vegetation cover which were of primary interest. Yet phenological differences still existed between the three late-autumn images because they spanned a five-week seasonal window. Therefore, a control site 5 km in diameter was established in the remotest available area, an area of *miombo* woodland in Mozambique untraversed by any roads and at least 10 km from any villages or the border (see Fig. 2). It was assumed that minimal land cover change had occurred at this control site between 1981 and 1992. The assumption of relatively stable vegetation cover at this site was corroborated by a cropland use intensity map produced by the US Geological Survey (1992) that indicated minimal agricultural activity. Differences in NDVI at the control site could then be attributed almost entirely to phenological differences. The 13 March 1987 image was excluded from further analysis because it was acquired during the summer, when the green herbaceous understory pushes NDVI to peak values, and because this image contained cloud cover in the vicinity of the control site. NDVI values were standardized between the three late autumn images by forcing the mean NDVI at the control site in the 1981 and 1987 images to match the mean NDVI at the control site in the 1992 image. Two NDVI adjustment constants (K) were calculated at the control site (CS) according to the following equations:

$$K_{92-81}=CSNDVI_{92}-CSNDVI_{81} \quad (3)$$

$$K_{92-87}=CSNDVI_{92}-CSNDVI_{87} \quad (4)$$

Thus, $K_{92\text{-}81}$ and $K_{92\text{-}87}$, calculated as 0.088 and 0.118, respectively, were added to the 1981 and 1987 NDVI images, respectively. By then differencing the standardized images and examining the output, the change in NDVI due to apparent cover change could be quantified, as well as mapped, with the assumption that the phenology throughout the *miombo* woodlands portion of our study area was uniform.

Local variability in the NDVI difference images has been found to be higher than in original NDVI images (Townshend & Justice, 1995). This also proved true in the present study, giving the maps a very busy appearance. Therefore, for the sole purpose of mapping, a mean filter (3×3 pixels) was applied to the 80-m difference images to produce output images of 240-m resolution. These were sliced into five contiguous classes representing degrees of NDVI change and then mapped.

Validation

This study utilized MSS images acquired in late autumn, when the herbaceous understory has senesced but the woody overstory is still green and thus the major determinant of NDVI. To test the strength of this relationship, buffer zones of 250-m radius were formed around each of eight field sites where percentage woody canopy cover was measured. Mean NDVI within each buffer zone was calculated from the 1992 image, and these values compared to the 1996 woody cover field data.

As an additional validation tool, 1986 (1:40 000) and 1995 (1:25 000) black-and-white aerial photos were obtained for the Chifunga, Luwani and Ndelema camp sites, to compare canopy cover before and after the refugee occupation. Photos covering a portion of Thambani Forest Reserve in the years 1976 (1:25 000), 1986 (1:40 000) and 1995 (1:25 000) were also obtained, to measure deforestation stemming from the construction of an access road in 1985. The photos were scanned, with the resolution of the scanner adjusted to account for the differential photo scales, producing output images with a consistent resolution of approximately 4 m; this was the lowest common integer value possible given the smaller scale of the 1986 photos and the maximum optical resolution of the scanner (300 dpi). However, we believed 4-m resolution sufficient, given that 10 m is the principal scale of tonal variation in medium-scale aerial photos of woodland savanna vegetation (Hudak & Wessman, 1998). An automatic brightness and contrast optimization feature of the scanning software was employed to initially standardize these variables as much as possible. The multitemporal images were then coregistered, using the 1995 images as the base. In each case, a histogram matching utility was employed to force the brightness and contrast of an earlier image to match these variables in a coregistered 1995 image.

Photo interpreters typically use an visual judgement technique to estimate canopy closure of forest canopies, especially those of low density, from aerial photos with scales smaller than 1:15 000 (Avery, 1977: 245–247). However, this technique rounds the resulting estimate to the nearest 10%; here a more precise estimate of percentage woody cover was needed. Therefore, a slight variation of the dot grid technique was employed (Avery, 1977: 245–247). Each image was overlaid with a 240×240 m grid. The number of grid intersections falling on a tree or woody clump was counted, summed, and then divided by the total number of available intersection points to derive an estimate of percentage woody cover. While this technique is recommended for estimating canopy closure from aerial photos with scales larger than 1:15 000 (Avery, 1977: 245–247), this recommendation was targeted towards foresters who work with closed canopies, where larger scale is required to resolve individual trees. The grid overlay technique worked well for the present purposes because savanna woodland canopies are open, with wider spacings between tree crowns.

Results

Fig. 4a illustrates the relationship between rainfall and NDVI over a nearly 11-year period. Note that while summer rainfall is the principal driver of green-up,

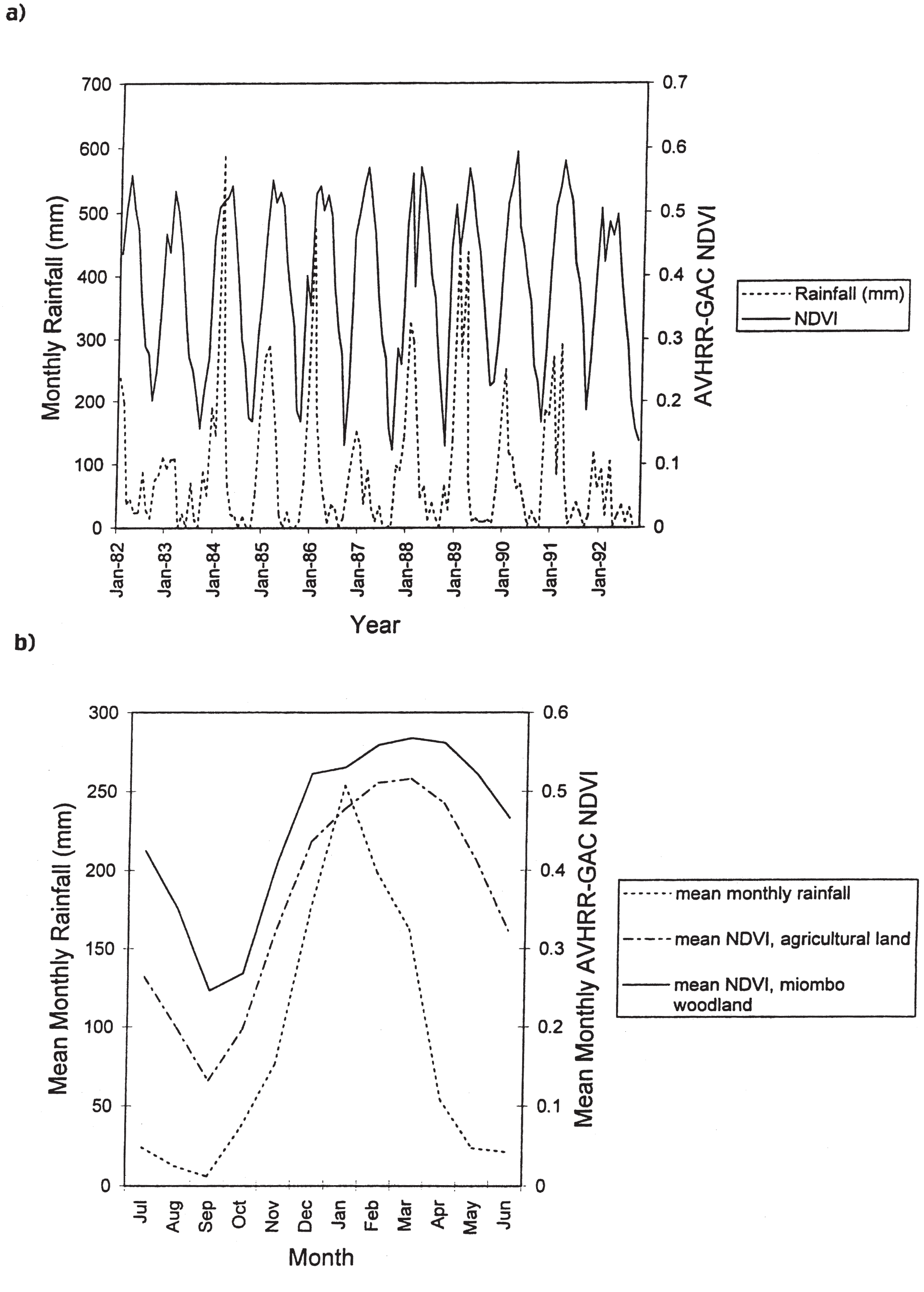


Fig. 4. (a) Monthly AVHRR-NDVI and monthly rainfall records, January 1980–October 1992; (b) Mean monthly rainfall recorded at Thambani rainfall station, January 1980–September 1996, and mean monthly AVHRR-NDVI of predominantly *miombo* woodland and predominantly agricultural land, January 1982–October 1992. *Source:* Rainfall records from Mwanza District Forestry Office.

NDVI is much more consistent interannually than rainfall (Fig. 4b). Although NDVI values are consistently higher in predominantly *miombo* woodlands than in predominantly agricultural areas, both cover types have the same greening response to rainfall.

The change trajectories shown in Fig. 5a compare actual NDVI values from the four MSS images, while those in Fig. 5b show adjusted NDVI values after standardization. It should be noted that while the 13 March 1987 image is removed from Fig. 5b (for reasons mentioned earlier), it was informative to include it in Fig. 5a to demonstrate the relative contribution of the herbaceous component to peak summer NDVI.

To test for significance between the mean NDVI values plotted in Fig. 5b, z statistics were calculated. This is a useful test for a significant difference between the means of two large populations, which is the case here given that each region of interest consists of thousands of pixels. Mean NDVI values in Fig. 5b were found to significantly differ in all cases (error bars were too small to plot).

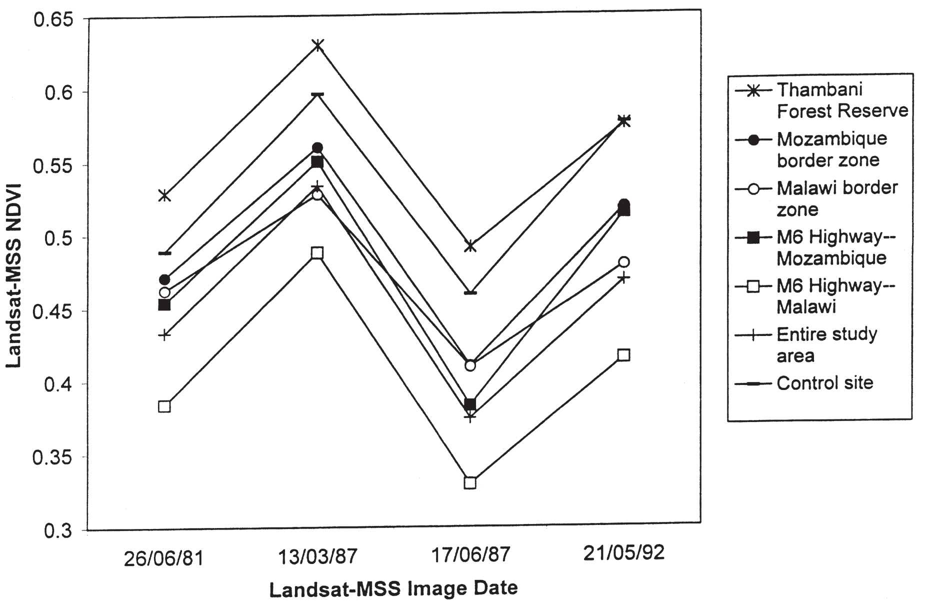
The 1987–81 NDVI difference image showed a general decline in NDVI across the entire study area, while the 1992–87 and 1992–81 NDVI difference images showed nearly identical patterns in NDVI change. Therefore, for brevity, only this latter map covering the full time span is included (Fig. 6).

Fig. 7 shows a significant correlation between mean 21 May 1992 Landsat MSS NDVI values and field measurements of percentage woody cover, suggesting that NDVI on this date was an adequate indicator of percentage woody cover. A simple linear regression model ($\% \text{ cover} = 3.3624 \times (\text{NDVI} - 1.0659)$) was therefore used to predict percentage woody cover and its degree of change between 1981 and 1992 (Table 2). Aerial photos were used to estimate percentage woody cover change from 1986 to 1995 at the three large refugee camp sites, portrayed in Fig. 8, and from 1976 to 1995 in the northwestern portion of Thambani Forest Reserve, portrayed in Fig. 9. The results of these aerial photo validations are shown in Table 3.

Discussion

As has been shown, the annual NDVI pattern is more consistent in comparison to rainfall (see Fig. 4a). The greater variability in the rainfall record may partially stem from local patchiness in rainfall distribution, which would affect a single rainfall station but average out at the much larger scale of AVHRR pixels. However, saturation in the NDVI response to increasing rainfall is probably the greater contributing factor (Huete, Liu, Batchily & van Leeuwen, 1997). The absence of a time lag between the onset of spring rains and the NDVI response is a consequence of the pre-rains flush characteristic of many tree species in *miombo* woodlands (Fuller, 1994). In summary, NDVI appears to be more closely related to season than to rainfall. This is a subtle yet important point, because the strategy adopted here for standardizing NDVI values between the MSS images can work if NDVI varies in a consistent manner from year to year.

Anderson, Hanson and Haas (1993) found that, if green biomass is quantified in a)



b)

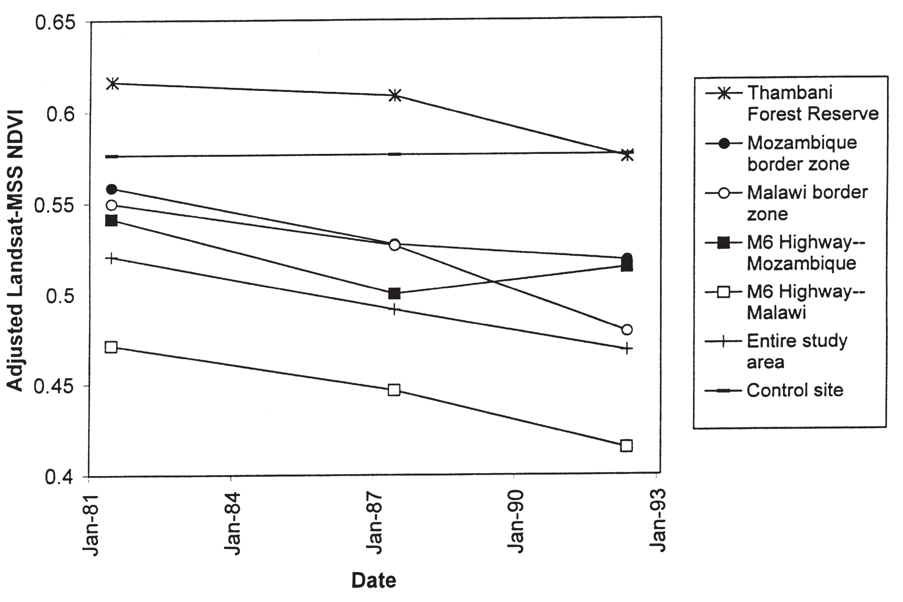


Fig. 5. Change trajectories for several regions of interest illustrating (a) the effect of seasonal phenology on NDVI values (from all four MSS images), and (b) adjusted NDVI values (from just the three autumn images) after standardizing for phenological variation.

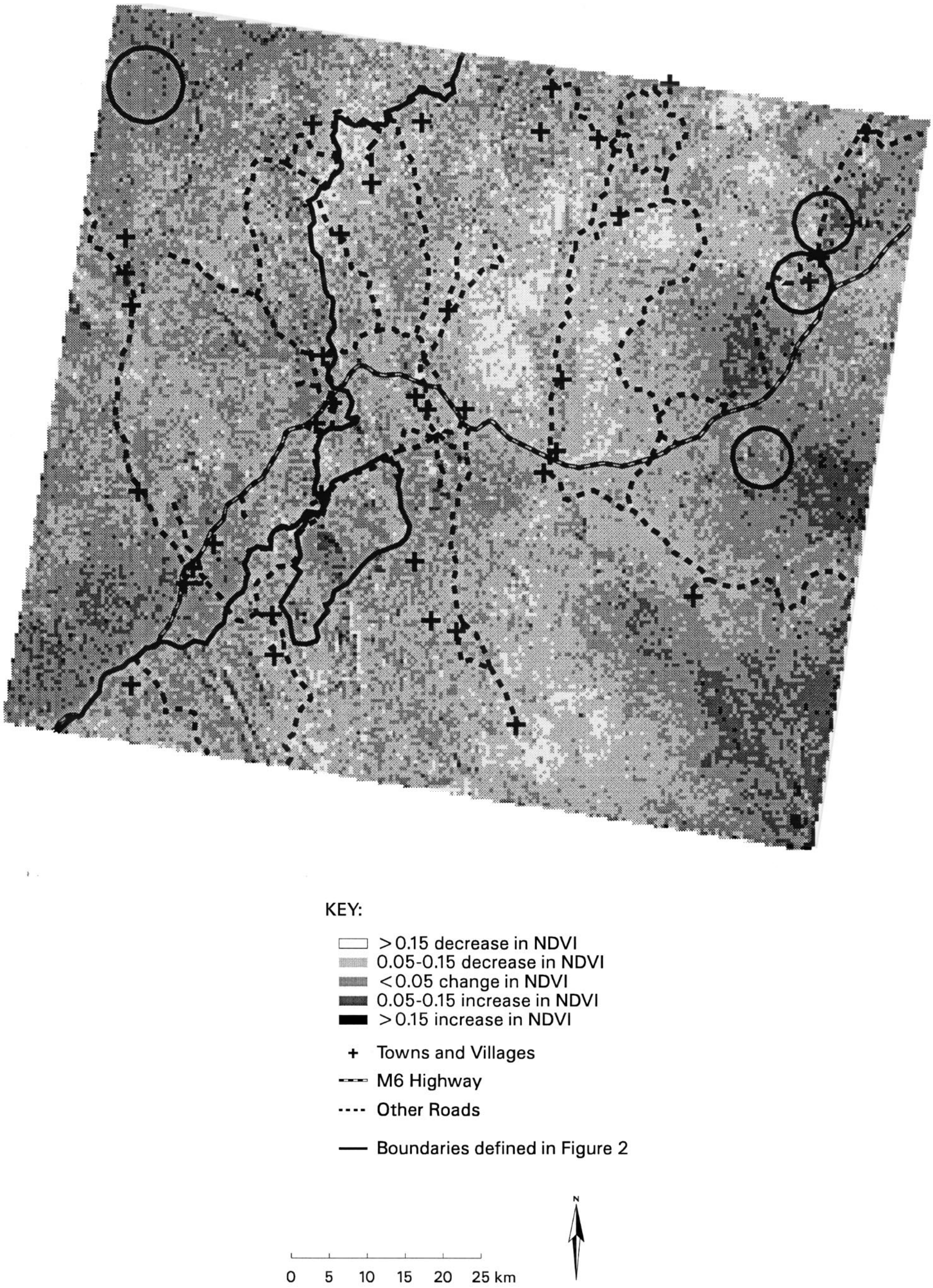


Fig. 6. Map of changes in standardized NDVI, 1981–92. Important land use features have been overlaid to aid interpretation.

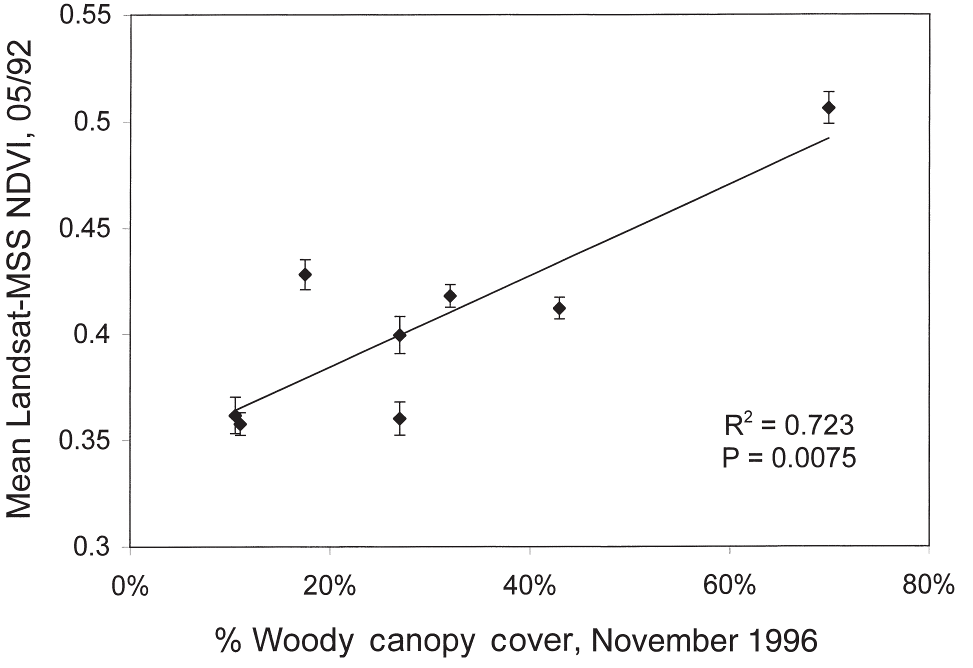


Fig. 7. Correlation between 21 May 1992 Landsat MSS NDVI values, averaged within a 196 350 m^2 area (~70 pixels) at eight sites, and point measurements of percentage woody cover made in the field at the same eight sites in November 1996.

Table 2
Change in percentage woody cover and annual deforestation rate, 1981–1992, based on a regression between eight field sites and 21 May 1992 Landsat-MSS NDVI values

Period	Mean change in standardized NDVI	% woody cover change	Annual change in % woody cover
Malawi			
1981–7	−0.0304	−10.2	−1.7
1987–92	−0.0293	−9.9	−2.0
1981–92	−0.0597	−20.1	−1.8
Mozambique			
1981–7	−0.0287	−9.6	−1.6
1987–92	−0.0098	−3.3	−0.7
1981–92	−0.0385	−13.0	−1.2
Entire study area			
1981–7	−0.0294	−9.9	−1.6
1987–92	−0.0229	−7.7	−1.5
1981–92	−0.0524	−17.6	−1.6

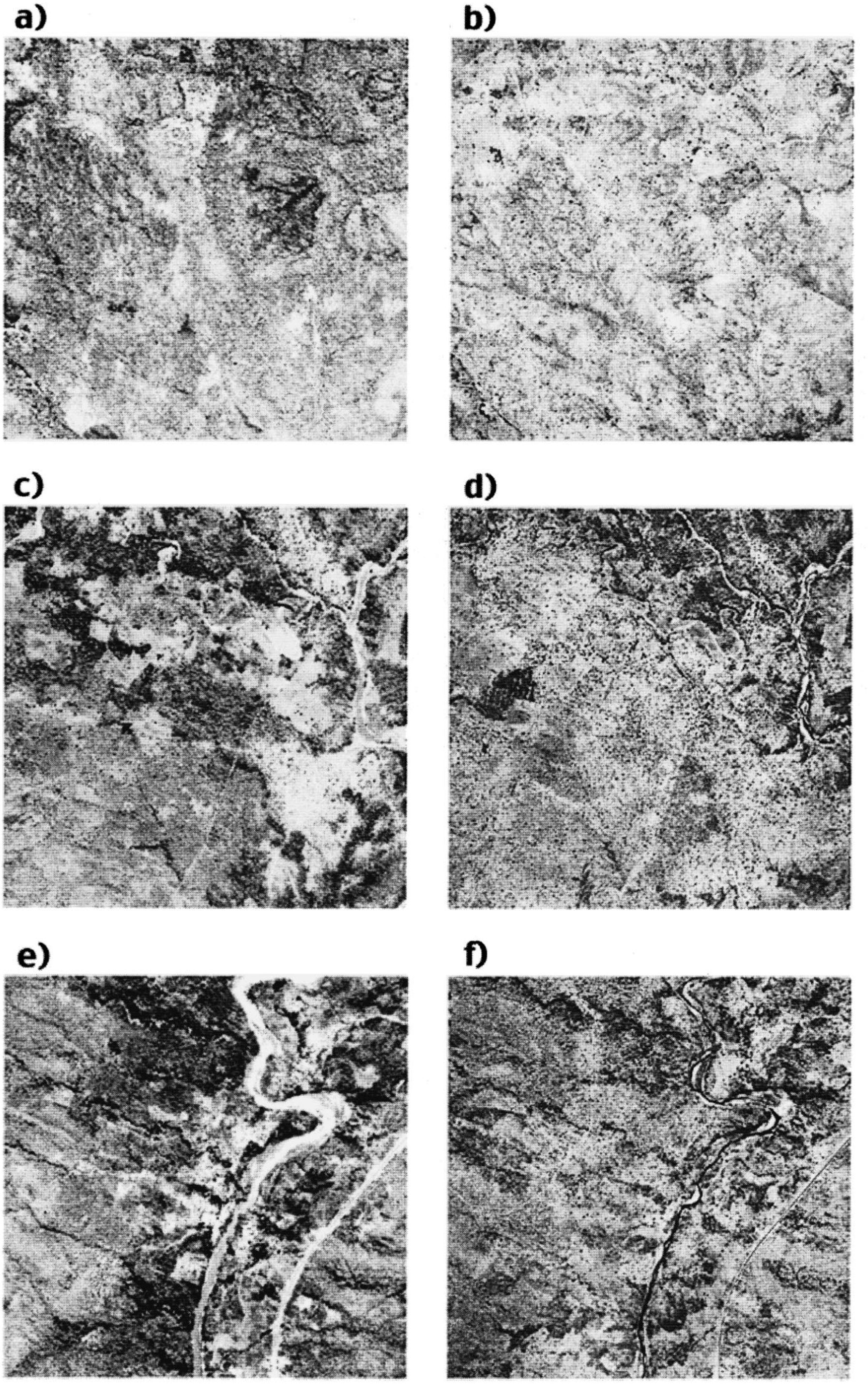


Fig. 8. Images scanned from 1986 and 1995 aerial photos, centred over the three main refugee camps: Chifunga in (a) 1986 and (b) 1995; Luwani in (c) 1986 and (d) 1995, and Ndelema in (e) 1986 and (f) 1995 (for locations see Figs. 2 and 6).

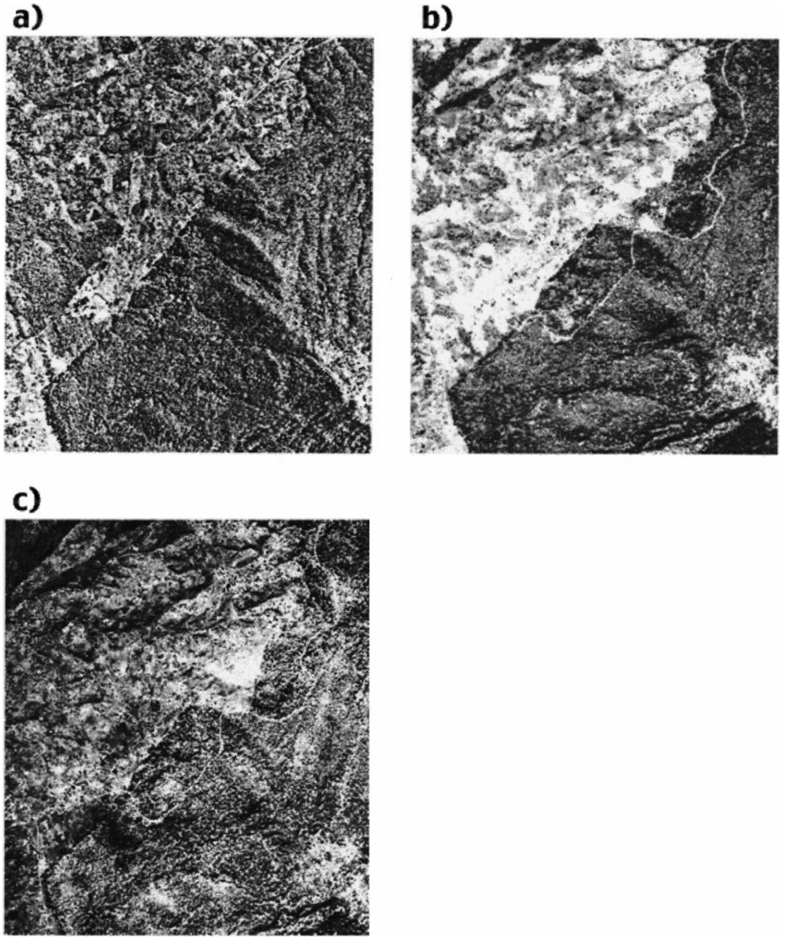


Fig. 9. Images scanned from (a) 1976, (b) 1986 and (c) 1995 aerial photos, centred over the northwestern portion of Thambani Forest Reserve on the international border (see Figs. 2 and 6).

Table 3
Comparison of changes in percentage woody cover estimated at four sites using Landsat MSS imagery and aerial photos

Validation site	MSS image	Aerial photo
Chifunga Refugee Camp	−14.3 (1987–92)	−13.1 (1986–95)
Luwani Refugee Camp	−2.1 (1987–92)	−8.0 (1986–95)
Ndelema Refugee Camp	−6.1 (1987–92)	−8.3 (1986–95)
NW Thambani Forest Reserve	−14.4 (1987–92)	−16.7 (1986–95)
NW Thambani Forest Reserve	−4.3 (1981–7)	−5.1 (1976–86)

the field concurrently with satellite data acquisition, then it is possible to predict green biomass levels in semi-arid rangelands using univariate regression models. Since the correlation between 21 May 1992 MSS NDVI values and November 1996 measures of percentage woody cover proved significant (see Fig. 7), a univariate regression model to predict percentage woody canopy cover was similarly used here. It must be cautioned, however, that the Bitterlich technique was employed to estimate percentage woody cover only once at each field site. Hence, the uncertainty in these measurements is unknown.

According to a 1993 land cover map produced by the World Bank Malawi Energy Project, land cover types in Mwanza District consist of 31% forest cover, 17% intensive agriculture (estates) and 52% extensive agriculture on customary lands. Agricultural areas and village communities do contain trees, but these are almost entirely fruit trees that are used for fuelwood only under the most desperate circumstances. Thus, the percentage woody cover loss estimates indicated in Table 2 are likely to be predominantly a consequence of deforestation of indigenous woodlands. Furthermore, the areas of NDVI loss reflect the distribution of *miombo* woodlands, while the areas of NDVI gain along the eastern margin of the study area lie in predominantly agricultural areas below the lower elevation limit of the *miombo* woodlands (see Fig. 6).

It must be cautioned that NDVI varies between vegetation communities (Justice, Holben & Gwynne, 1986). In addition, it is influenced by other landscape components besides green vegetation, such as soil and plant litter (Huete, 1988; van Leeuwen & Huete, 1996; Wessman, Bateson & Benning, 1997; Asner, 1998). Extensive field calibration of NDVI is required to overcome variability in its relationship to canopy structural parameters (Wessman & Asner, 1998). For these reasons, the paucity of historical field data and the unquantified uncertainties associated with the validation data made us reluctant to key the map in Fig. 6 in terms of percentage woody cover. Similarly, the deforestation estimates reported in Tables 2 and 3 should be interpreted with caution.

The alarming annual deforestation rates of 3.5% (Office of the President and Cabinet, 1988) and 2.3% (Bunderson & Hayes, 1995) mentioned earlier may be slightly exaggerated in comparison to the annual deforestation rate estimated here of 1.8%. Alternatively, the present estimate may be conservative or may indicate a declining deforestation rate (see Table 2). Lele and Stone (1989) estimated that about 120 000 ha of woodland were cleared annually in Malawi, while 10 years later the estimate was 50 000 ha (*Malawi News*, 1999); thus the rate of deforestation may indeed be declining. Nonetheless, we have found evidence for substantial, sustained deforestation across much of the study area. Moreover, our evidence indicates greater deforestation in Malawi than in Mozambique (see Fig. 5b and Table 2), as would be expected given Malawi's denser population. The lower thresholds for the two NDVI-loss classes in Fig. 6, which correspond to NDVI reductions of 0.05 and 0.15, translate into alarming percentage woody cover losses of 17% and 50%, respectively.

Conclusion

The research reported here found a significant decline in standardized NDVI values from 1981 to 1987 and from 1987 to 1992, indicating that deforestation was already widespread in Mwanza District even prior to the 1988 influx of Mozambican refugees. The NDVI was a good indicator of percentage woody canopy cover in this application because the imagery used was acquired in late autumn, when only the woody component remains green. The use of a control site to remove phenological variation from multitemporal NDVI values before differencing them produced reasonable results in this study, but should be tested in others. Landsat MSS data have sufficiently high spatial resolution to map spatial patterns in woody cover and sufficiently broad temporal coverage to quantify slow degradation of savanna woodlands.

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References

Agnew, S., & Stubbs, M. (1972). *Malawi in maps.* New York: Africana Publishing.

Allen, J. C., & Barnes, D. F. (1985). The causes of deforestation in developing countries. *Annals of the Association of American Geographers, 75,* 163–184.

Anderson, G. L., Hanson, J. D., & Haas, R. H. (1993). Evaluating Landsat Thematic Mapper derived vegetation indices for estimating above-ground biomass on semiarid rangelands. *Remote Sensing of Environment, 45,* 165–175.

Asner, G. P. (1998). Biophysical and biochemical sources of variability in canopy reflectance. *Remote Sensing of Environment, 64,* 234–253.

Avery, T. E. (1977). *Interpretation of aerial photographs* (3rd ed.). Minneapolis: Burgess Publishing.

Bunderson, W. T., & Hayes, I. M. (1995). Agricultural and environmental sustainability in Malawi. Paper presented at the Conference on Sustainable Agriculture for Africa, Abidjan, Cote d'Ivoire. In.

Friedel, M. H., & Chewings, V. H. (1988). Comparison of crown cover estimates for woody vegetation in arid rangelands. *Journal of Ecology, 13,* 463–468.

Fuller, D.O. (1994). *Foliar phenology of vegetation in south-central Africa and its relevance to climatic change*. Unpublished PhD thesis, University of Maryland.

Gore, W.T. (1992). *Visit report: energy from biomass in Malawi*. Pretoria: Division of Forest Science and Technology, CSIR (FOR-I 310).

House, W. J., & Zimalirana, G. (1992). Rapid population growth and poverty generation in Malawi. *The Journal of Modern African Studies, 30,* 141–161.

Hudak, A. T., & Wessman, C. A. (1998). Textural analysis of historical aerial photography to characterize woody plant encroachment in South African savanna. *Remote Sensing of Environment*, *66*, 317–330.

Huete, A. R. (1988). A soil-adjusted vegetation index (SAVI). *Remote Sensing of Environment*, *25*, 295–309.

Huete, A. R., Liu, H. Q., Batchily, K., & van Leeuwen, W. (1997). A comparison of vegetation indices over a global set of TM images for EOS-MODIS. *Remote Sensing of Environment*, *59*, 440–451.

Justice, C. O., & Hiernaux, P. H. Y. (1986). Monitoring the grasslands of the Sahel using NOAA AVHRR data: Niger 1983. *International Journal of Remote Sensing*, *7*, 1475–1497.

Justice, C. O., Holben, B. N., & Gwynne, M. D. (1986). Monitoring East African vegetation using AVHRR data. *International Journal of Remote Sensing*, *7*, 1453–1474.

Justice, C. O., Townshend, J. G. R., Holben, B. N., & Tucker, C. J. (1985). Analysis of the phenology of global vegetation using meteorological satellite data. *International Journal of Remote Sensing*, *6*, 1271–1318.

Kalipeni, E. (1992). Population growth and environmental degradation in Malawi. *Africa Insight*, *22*, 273–282.

King, D.J. (1987). *Mozambique: a country profile*. Washington, DC: Office of US Foreign Disaster Assistance, US AID.

Lele, U., & Stone, S.W. (1989). *Population pressure, the environment and agricultural intensification: variations on the Boserup hypothesis*. Washington, DC: World Bank (MADIA Discussion Paper 4).

Malawi News (1999). Winter Edition of quarterly newsletter published by Friends of Malawi, Brooklyn, New York in association with South Africa Contact, Copenhagen, Denmark.

McCloy, K. R., & Hall, K. A. (1991). Mapping the density of woody vegetative cover using Landsat MSS digital data. *International Journal of Remote Sensing*, *12*, 1877–1885.

Millington, A., Townshend, J., Kennedy, P., Saull, R., Prince, S., & Madams, R. (1989). *Biomass assessment: woody biomass in the SADCC region.* London: Earthscan.

Moyo, S., O'Keefe, P., & Sill, M. (1993). Malawi. In *The Southern African environment: profiles of the SADCC countries* (pp. 92–125). London: Earthscan.

Mueller-Dombois, D., & Ellenberg, V. (1974). The count-plot method and plotless sampling techniques. In *Aims and methods of vegetation ecology* (pp. 96–108). New York: Wiley.

Munslow, B., Katerere, Y., Ferf, A., & O'Keefe, P. (1988). *The fuelwood trap: a study of the SADCC region.* London: Earthscan.

Myneni, R. B., Keeling, C. D., Tucker, C. J., Asrar, G., & Nemani, R. R. (1997). Increased plant growth in the northern high latitudes from 1981 to 1991. *Nature*, *386*, 698–702.

National Statistical Office (1988). *Malawi Population Census 1987*. Zomba, Malawi: Government Printer.

Nel, E.M., & Jackson, M.E. (1995) An independent evaluation of the accuracy of handheld GPS receivers. *Earth Observation Magazine*, March, 36-38.

Office of the President and Cabinet (1988). *Statement of development policies 1987–1996*. Lilongwe, Malawi: Department of Economic Planning and Development.

Prince, S. D. (1991). Satellite remote sensing of primary production: comparison of results for Sahelian grasslands 1981–1998. *International Journal of Remote Sensing*, *12*, 1301–1311.

Prince, S. D., & Astle, W. L. (1986). Satellite remote sensing of rangelands in Botswana I. Landsat MSS and herbaceous vegetation. *International Journal of Remote Sensing*, *7*, 1533–1553.

Ringrose, S., & Matheson, W. (1987). Spectral assessment of indicators of range degradation in the Botswana hardveld environment. *Remote Sensing of Environment*, *23*, 379–396.

Ringrose, S., & Matheson, W. (1992). Visual analysis of Landsat MSS imagery to determine the aerial extent of woody vegetation cover and indications of change over time in the west-central Sahel. *Global Ecology and Biogeography Letters*, *1*, 176–181.

Ringrose, S., Matheson, W., Tempest, F., & Boyle, T. (1990). The development and causes of range degradation features in south-east Botswana using multi-temporal Landsat MSS imagery. *Photogrammetric Engineering and Remote Sensing*, *56*, 1253–1262.

Ringrose, S., Vanderpost, C., & Matheson, W. (1996). The use of integrated remotely sensed and GIS data to determine causes of vegetation cover change in southern Botswana. *Applied Geography*, *16*, 225–242.

Townshend, J. R. G., & Justice, C. O. (1986). Analysis of the dynamics of African vegetation using the normalized difference vegetation index. *International Journal of Remote Sensing*, *7*, 1435–1445.

Townshend, J. R. G., & Justice, C. O. (1995). Spatial variability of images and the monitoring of changes in the Normalized Difference Vegetation Index. *International Journal of Remote Sensing*, *16*, 2187–2195.

Tucker, C. J., Fung, I. Y., Keeling, C. D., & Gammon, R. H. (1986). Relationship between atmospheric CO_2 variations and a satellite-derived vegetation index. *Nature*, *319*, 195–199.

Tucker, C. J., Townshend, J. G. R., & Goff, T. E. (1985). African land cover classification using satellite data. *Science*, *227*, 369–375.

US Geological Survey (1992). Cropland use intensity map available at the USGS African Data Dissemination Service site: http://edcsnw4.cr.usgs.gov/adds/adds.html#adds_data_anchor

van Leeuwen, W. J. D., & Huete, A. R. (1996). Effects of standing litter on the biophysical interpretation of plant canopies with spectral indices. *Remote Sensing of Environment*, *55*, 123–138.

Wessman, C. A., & Asner, G. P. (1998). Ecosystems and problems of measurement at large spatial scales. In M. Pace, & P. Groffman, *Successes, limitations, and frontiers in ecosystem science* (pp. 346–371). Berlin: Springer–Verlag.

Wessman, C. A., Bateson, C. A., & Benning, T. L. (1997). Detecting fire and grazing patterns in tallgrass prairie using spectral mixture analysis. *Ecological Applications*, *7*, 493–511.