Supplementary Information

Deforestation since independence: a quantitative assessment of four decades of land cover change in Malawi
Rachel A Bone, Kate E Parks, Malcolm D Hudson, Mathews Tsirinzeni and Simon Willcock
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Supplementary Appendix S1: Post-processing of spatial data

(1) Landcover

Although a recent complete land cover map of Malawi was obtained from GlobCover (European Space Agency 2009), there was no complete historical land cover map available for the immediate post-colonial period. To form a land cover map, two maps of natural vegetation (dated 1972) and agriculture (1972) were combined by superimposing one on to the other (Agnew and Stubbs 1972). If any given pixel contained a single land cover, that land cover was allocated to that cell. However, for areas where both agriculture and natural vegetation were present a 50:50 ratio of agriculture to natural vegetation was assumed, giving rise to mosaic land covers consisting of a mixture of cropland and forest, woodland, grassland, scrubland or other natural vegetation (Figure S1). This assumption was required for 54,300km^2 (47 % of total land area).

Following Willcock et al. (2016), to make the historical and recent land cover maps comparable, all pixels of all maps were harmonised into six uniform land cover classes: forest (open and closed evergreen, semi-deciduous, and deciduous forest/woodland); mosaic cropland and vegetation (mosaic of forest, shrubland, grassland and cropland); cropland (rain fed, irrigated or post flooding); swamp (grassland or woody vegetation on regularly flooded or waterlogged soil); urban areas (artificial surfaces and associated areas); and water bodies (Figure S1; Table S1).

(2) Socioeconomic variables

(I) Cattle density

The historical map (1968) of cattle consisted of a layer of points, whereby each point represented 250 cattle (Agnew and Stubbs 1972). The number of cattle within each district were totalled and an average density per square kilometre was calculated. The recent cattle distribution layer was a density map showed the number of cattle per square kilometre (FAO 2009). For both historical and recent maps, the number of cattle was average across each district.

(II) Child-woman ratio

The child-woman ratio was defined as the number of children under the age of 5 for every 1000 women aged 15-49. The historic map (1966) was available in the form of a point data map (Agnew and Stubbs 1972) where the size of the point represented the number of females aged 15-49 and the labelling of the point represented the child-woman ratio. Subsequently, the number of females aged 15-49 was totalled and, using the mid-point in the ranges of ratios, the number of children under 5 was calculated for each district.

The total numbers of males and females from the 2008 Population and Housing Census was obtained for each district (NSO 2008). However, as gender figures for each district were not divided in to age groups, the sex ratio had to be calculated first in order to estimate the number of females aged 15-49 from all people aged 15-49. The child-woman ratio for both past and present for each district was then calculated using Equation 1.

$$\text{Child} - \text{Woman Ratio} = \frac{\text{Total children} < 5}{\text{Total females aged 15 to 49}} \times 1000 \qquad (1)$$

Figure S1: The harmonisation of the original land cover classes to form new, comparable land cover classes in a) historical land cover maps (dated 1972; Agnew and Stubbs (1972)) and b) modern land cover maps (dated 2009; European Space Agency (2009))

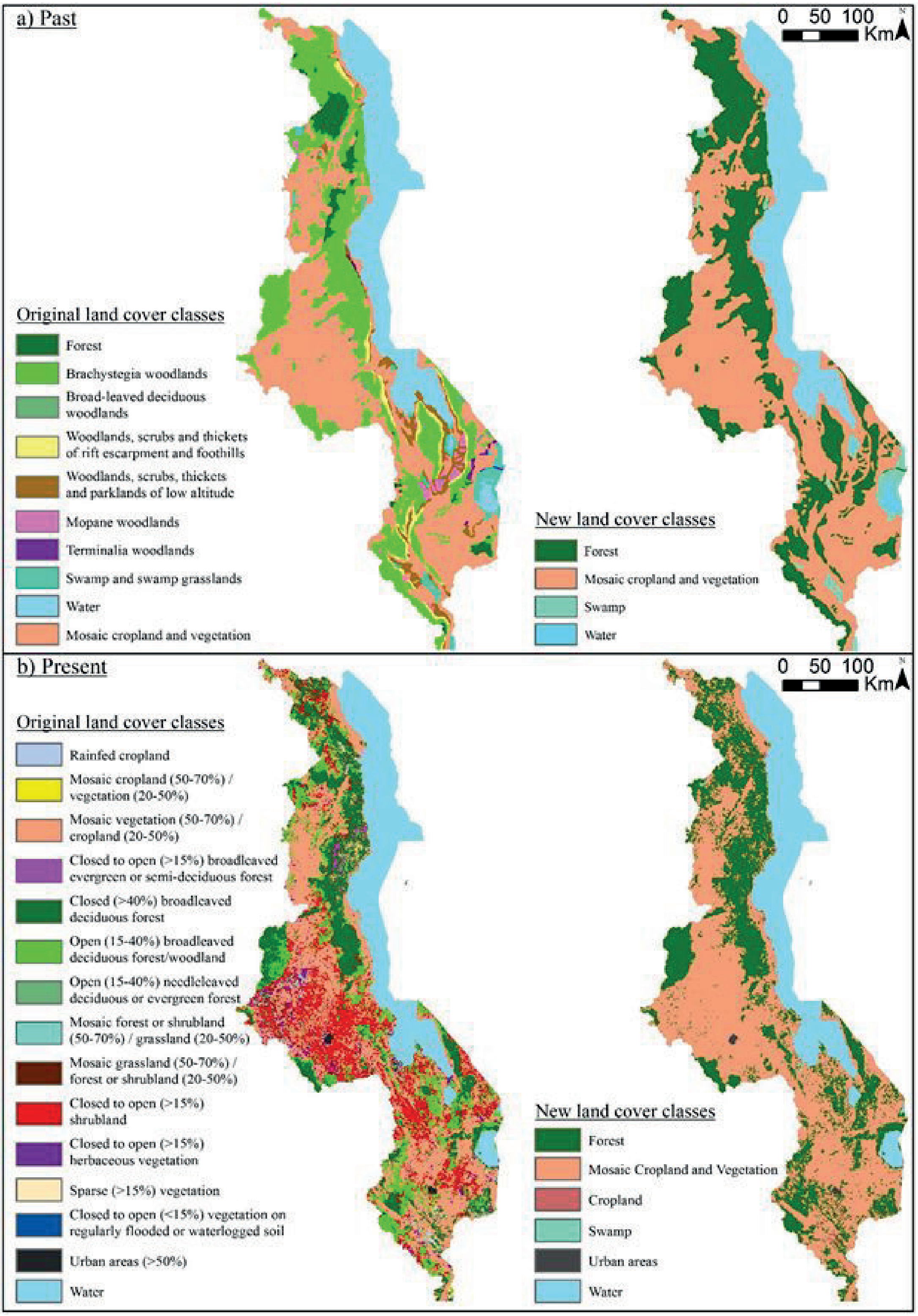


Table S1: The harmonisation of land cover categories to make compatible **groups**

New Description	Past	Present
Forest	-Montane forests, scrubs and grasslands -Moist semi-deciduous forest -Brachystegia woodland -Brachystegia-Evergreen closed	-Closed to open (>15%) mixed broadleaved and needleleaved forest (>5m) -Closed to open (>15%) broadleaved evergreen or semi-deciduous forest (>5m)
Mosaic cropland and vegetation	-Mosaic cropland and vegetation -Woodlands, scrubs and thickets of the rift escarpment and its foothills	-Mosaic cropland (50-70%) / vegetation (20-50%) -Mosaic vegetation (50-70%) / cropland (20-50%) -Mosaic forest or scrubland (50-70%) / grassland (20-50%)
Cropland	-	-Rainfed croplands
Swamp	-Swamp and swamp grasslands	-Closed to open (>15%) grassland or woody vegetation on regularly flooded or waterlogged soil -Closed to open (>15%) broadleaved forest regularly flooded
Sparse vegetation	-	-Sparse (<15%) vegetation
Urban areas	-	-Artificial surfaces and associated areas (urban areas >50%)
Water	-Water	-Water bodies

(III) Dependency rate

The dependency rate was defined as the number of children aged 0-14 and adults over 65 for every 1000 people aged 15-64. The historical map (1966) was in the form of a point data map in which the size of the point represented the number of people aged 15-64 and the labelling of the point represented the ratio of persons 0-14 and >65 per 1000 persons aged 15-64 (Agnew and Stubbs 1972). From this, both the total number of persons aged 15-64 in each district and, using the mid-point in the range of ratios, the number of persons 0-14 and >65 were calculated. The dependency rate for each district in the past was calculated using Equation 2 and using 2008 Population and Housing Census data the same calculation was also performed (NSO 2008).

$$\text{Dependency rate} = \frac{\text{Total persons aged 10 to14 and} > 65}{\text{Total persons aged 15 to 64}} \times 1000 \qquad (2)$$

(IV) Distance to roads and railway

The historical (1969) map showed the route of main roads within Malawi (Agnew and Stubbs 1972) and therefore, to maintain consistency, only the main roads were extracted from the more detailed recent roads map (OSM 2013). The average Euclidean distance to roads within each district was then calculated for both the past and present. The preparation of the historical railway dataset (Agnew and Stubbs 1972) and the present railway dataset (OSM 2013) was identical to that previously outlined for the roads data, but all railways were included.

(V) Male school attendance

The historical (1966) map was in the form of a point map in which the size of the point represented the number of males aged 10-14 and the labelling of the point represented the percentage of males attending school (Agnew and Stubbs 1972). Using this, the total number of males attending school was calculated so that the overall percentage attending school in each district could be deduced (Equation 3).

$$\text{males attending school} = \frac{\text{male school attendance}}{100} \times \text{total males aged 10 to 14} \qquad (3)$$

The percentage for male school attendance from recent data was calculated based on the overall number of male children attending school due to the 2008 Population and Housing Census not recording school attendance specifically for the 10-14 age range (NSO 2008).

(VI) Number of hospital beds

The historical map (1969) showed the location of hospitals in Malawi and the number of beds at each hospital (Agnew and Stubbs 1972), whilst the recent map showed the location of all health services and attributes about each one; including the number of hospital beds available (MASDAP 2013). Thus, to infer changes in the provision of health care across Malawi instead, hospital beds were totalled for each district in the past and present maps.

(VII) Population density

The historical map of population density was depicted as persons per square mile (Agnew and Stubbs 1972). The midpoint of the ranges on the map legend was taken to be the estimated value and then the density was averaged across each district. The averages were converted to persons per square kilometre in order to be comparable with the recent population densities for each district using 2008 Population and Housing Census data (NSO 2008).

(VIII) Protected areas

All protected areas, regardless of size or type was totalled in both the past map (Agnew and Stubbs 1972) and present map (MASDAP 2013) for each district.

(IX) Sex ratio

The sex ratio was defined as the number of males to every 1000 females. The size of the point in the historical (1966) map represented the number of people aged 15-64 and the labelling of the point represented the number of males per 1000 females in this age group (Agnew and Stubbs 1972). Using this data, the number of males and females for each point was calculated using Equation 4 and then Equation 5.

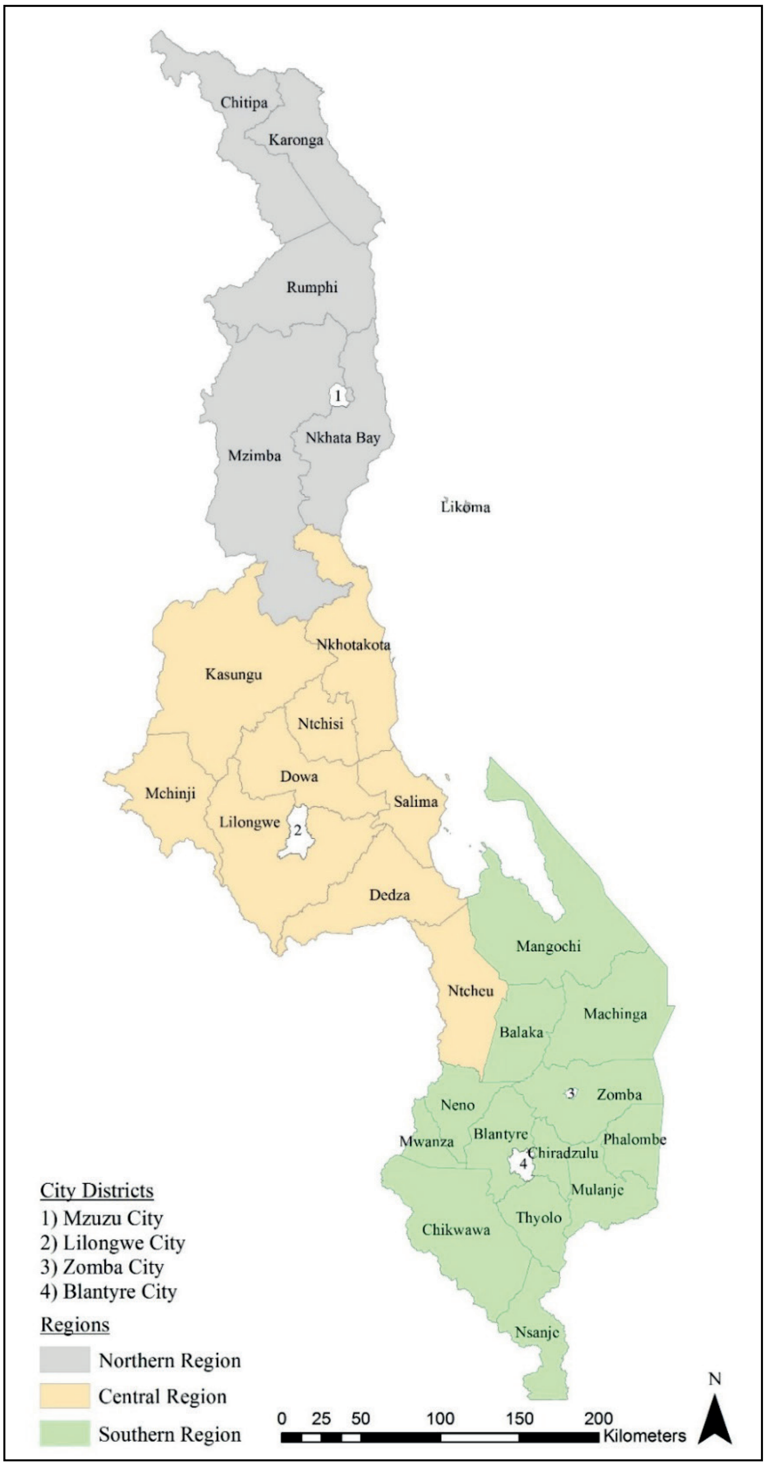
$$\text{Number males} = \frac{\text{Total people aged 15 to 64}}{\text{sex ratio} + 1000} \times \text{sex ratio} \tag{4}$$

$$\text{Number females} = (\text{total people 15 to 64}) - \text{Number males} \tag{5}$$

The recent data was obtained from the 2008 Population and Housing Census (NSO 2008). Equation 6 was used to determine the sex ratio from the past and present data in each district.

$$\text{Sex Ratio} = \frac{\text{Total number males}}{\text{Total number females}} \times 1000 \tag{6}$$

Supplementary Appendix S2: The regions and districts of Malawi



*Likoma, a district comprised of islands situated in Lake Malawi, was excluded from our analysis as there was no historical land cover data and therefore the change in forest land cover could not be calculated.

Supplementary Appendix S3: Correlates of forest area change

One of the most influential correlates of deforestation was sex ratio ($p < 0.001$) where the positive correlation suggested that as the ratio of men to women increased, deforestation increased. Men tend to be the dominant gender involved in the collection of commercial wood (Abbot and Homewood 1999); an often destructive process involving the removal of entire trees for activities such as illegal charcoal production (Fisher 2004). Men are more likely to have more substantial tools for wood collection – which would increase the likelihood of deforestation; 42% had axes compared with 13% of women (Abbot and Homewood 1999). Of the individuals collecting fuelwood in Malawi, 84% are thought to be women (Bandyopadhyay et al. 2011). Women tend to collect dead wood and small branches which are easy to gather, lighter to carry and contribute more to forest degradation than deforestation (Gbadegesin 1996).

Population density was another correlate within the deforestation model ($p < 0.01$). The positive relationship suggests that the greater the increase in population density, the greater deforestation, which is consistent with a priori expectations, as when the density of a population increases, the demand for agricultural land increases. This relationship is firmly established within the forest transition theory globally (Rudel et al. 2005). In Malawi, the influx of 800,000 refugees from Mozambique in the 1980s led to the clearing of large areas of land for cultivation in the border districts; a line clearly visible from aerial photos at the time (Potts 2006). Since independence, there has been a gradual migration of people to the northern and central districts in search of cultivatable land (Potts 2006). It is these areas that have also experienced the greatest amount of deforestation since independence.

Male school attendance ($p < 0.001$) and the number of hospital beds ($p < 0.01$) were two other positively correlated significant variables included within the deforestation model. The greater the increase in the percentage of males attending school or the number of hospital beds, the more forest lost. Both healthcare and education are key developmental indicators (World Bank 2013). Since independence in 1964, the government has sought to balance development across the country (Kalipeni 1997). During the colonial period, the development of the central and northern regions of Malawi was often ignored as the majority of the population and commercial activities occupied the southern region (Kalipeni 1997, Potts 2006). Initially, the capital was moved to Lilongwe to be more centrally located (Potts 1985) and improvements and extensions were made to road and rail links (Kalipeni 1997). By 1987 there had been the establishment of 10 “growth centres” to act as vehicles to spread development throughout the country, which included, among an extensive list, the building of schools and health centres in each place (Kalipeni 1997). The increasing population and subsequent deforestation occurring at the same time as increasing development, particularly in the northern and central regions, is perhaps why the positive relationship between deforestation and male school attendance or the number of hospital in this model exists.

Dependency rate was also shown to positively correlate with deforestation ($p < 0.05$). This suggests that as the ratio between dependents and working age adults moved towards dependents, deforestation increased. The greater the number of dependents in a household, the further the income of working members has to stretch. On average, 30% of a household income in Malawi is derived from the forest (Fisher 2004), with poor households having the highest level of reliance on forest income (Kamanga et al. 2009). The more the forests are used, the more likely forests could become degraded and/or deforested.

The least influential correlate of deforestation identified in this study was that of protected areas ($p < 0.05$), which suggest that the greater the increase in protected areas, the more deforestation. Although this may initially seem counter-intuitive, this relationship may be explained as a result of leakage whereby people who originally utilised this resource have to relocate their activity elsewhere. This condenses activity in remaining areas of accessible forest increasing the likelihood of deforestation (Ewers and Rodrigues 2008). Alternatively, protected areas may have been created in areas of high deforestation in order to halt the rate of land cover change (Willcock et al. 2016). Furthermore, although an area might be deemed protected it does not mean the forest escapes all degradation and deforestation. This is a problem in some protected areas in Malawi. For example, the area around five villages situated in Lake Malawi National Park is still being deforested as the villages continue to increase in population yet have no alternate source of forest resources (Abbot and Homewood 1999). More recently, 58% of people living near to Kasungu National Park identified the boundaries of the park as their primary source of fuelwood (Walker and Peters 2007) and deforestation has also been found within a reserve adjacent to one of the villages studied by Fisher (2004). Throughout East Africa, the effectiveness of protected areas has been shown to be highly variable across protected area categories; for example 45.8% of National Parks in the region show decreasing forest area over time compared to over 60.0% of Forest Reserves, with human pressure and livelihoods identified as key challenges (Pfeifer et al. 2012).

Generally, it is harder to separate the correlates of forest establishment, as it is the effect of three separate processes: afforestation, reforestation and forest regeneration. Broadly, the correlates of forest establishment were identified as the inverse of the relationships observed with deforestation. For example, more forest establishment was found in areas that showed a reduction in population density ($p < 0.05$), perhaps as a result of land abandonment allowing for recovery of the natural forest. Similarly, it was found that as the ratio of men to women moved towards men, there was less forest establishment ($p < 0.05$). If men are more involved with commercial activities such as farming, then the land is likely to be more in demand for agriculture, rather than reforestation. However, Mwangi et al. (2011) found the inverse relationship to be true - possibly because men are more likely to be involved with deforestation (as found in this study), it is these areas of greater deforestation that are targeted for forest establishment. The authors went on to argue that, as women spend more time in the forests, they are more likely to notice degradation and subsequently make an effort to reduce pressure on particular areas to avoid or mitigate against hardship (Mwangi et al. 2011). In Nigeria, areas with higher proportions of women have been observed to be more likely to take part in more environmentally friendly practices such as the planting of trees at farm boundaries and the use of the taungya system whereby crops are grown amongst young trees at the start of forest establishment (Gbadegesin 1996). In Malawi there have been forestry programs targeted at women and children such as the "learning by education" programme whereby women and children were encouraged to plant seedlings to sell to the forestry department (Feder 1997).

Some correlations, for example distance to railways ($p < 0.01$), were unique to forest establishment. The distance to railways was the most influential correlate of forest establishment and it was found that as the change in distance to railways decreased, the greater the forest establishment. The railway line provides the potential for trade, both within Malawi and internationally to neighbouring countries of Mozambique, Zambia and beyond. In the literature elsewhere in Africa, the opposite relationship is more commonly cited; that the introduction of railways increases deforestation as a result of the trade in timber products (Laurance et al. 2006, Das 2011). However, railways also bring in timber supplies, reducing the pressure for deforestation and perhaps allowing for forest establishment. Alternatively, the railway transport provides employment opportunities for men other than deforestation related activities, perhaps with increased labour invested in plantation establishment near these transport links. In future research, a more reliable investigation into the spatial link between railways and forest change, could be to use the distance to railway stations. Although a railway line may pass through districts with greater forest establishment, it is of little significance if stations are too far away. It is likely that the distance to railways correlation is driven by city districts (in which railway stations are likely to be located) as this correlation was only identified in the model where city districts were included (Table 3). Within the major cities other sources of fuel are available (Bandyopadhyay et al. 2011, Zulu 2010), enabling forested areas to either naturally regenerate or be re-established by city authorities.

Supplementary Information References

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