Deforestation Since Independence: A quantitative assessment of four decades of land cover change in Malawi

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Abstract

Land cover has changed rapidly across the tropics over the past century; however detailed historical information describing the extent and possible drivers of such change is widely lacking. Here, we constructed a history of land cover change at the district level in Malawi over a 37 year period from 1972 to 2009, the immediate post-colonial phase. Overall, there was a loss of 12,760km^2 (36%) of original forested area but also 11,161km^2 of new forest establishment resulting in a relatively modest overall net loss of 1,599km^2 (5%). We correlated changes in deforestation and forest establishment with changes in socioeconomic variables derived from spatially explicit data from the same time period. Deforestation was positively correlated with (in order of influence) changes in male school attendance, sex ratio, population density, hospital bed numbers, protected areas, and dependency rate, but negatively correlated with changes in cattle density; with forest establishment broadly showing the inverse relationships with the same variables. Although direct drivers of deforestation are well known for Malawi and much of Africa, the significance of socioeconomic variables within this study can help understand the underlying social pressures behind such drivers. In particular, development, population pressure, and demographic factors are important predictors of deforestation rate within our study area.

Introduction

Humans have been deforesting and over-exploiting forests for millennia, but it is only relatively recently that the rate of deforestation (defined here as the conversion of forest to non-forest land covers) has been so widespread. Of particular concern is the rapid deforestation of tropical forests, one of the world's most biologically diverse ecosystems (Lepers et al. 2005). Sub-Saharan Africa, which is home to the second largest expanse of tropical forest after the Amazon, has been rapidly deforested in recent years (Baccini et al.

2012). For example, a recent estimate of deforestation in sub-Saharan Africa shows a yearly average deforestation rate of 0.7% accounting for a loss of around 3 million hectares every year (Brink and Eva 2009).

The proximate drivers of tropical deforestation are the human activities which most directly result in deforestation. Proximate drivers are well documented and similar across much of sub-Saharan Africa, including: agricultural expansion; wood extraction; and expansion of infrastructure (Geist and Lambin 2002). However, an increased demand for agricultural land or wood extraction may be a response to numerous socio-economic pressures – for example, the degree to which forest resources are utilised has been found to be influenced by education, housing type, occupation and socio-economic status (Feder 1997). These underlying relationships of deforestation are less frequently documented but may vary considerably between regions (Lambin and Geist 2003, Fisher and Shively 2005, Kamanga et al. 2009).

The aim of this study was to quantify changes in forest area across Malawi between 1972 and 2009; and to subsequently investigate potential relationships between changes in land cover and socio-economic variables at a district level across the entire country over this period.

Study Area

This study focussed on Malawi, a landlocked country in south-eastern Africa which gained independence from Britain in 1964 (Figure 1). Malawi is one of the ten most densely populated countries in Africa, with a population that has tripled in size since independence to over 15 million resulting in a population density of 158 per km^2 (FAO 2013). The combination of a high population density and over 50% of the population being described as below the poverty line (World Bank 2013) undoubtedly puts pressure on the available natural resources in Malawi. Previous estimates suggest substantial deforestation in Malawi, from 45% of land area in 1972 to 25.3% in 1990 (a loss of 18,572 km^2 (Satellitbild 1993)), followed by an additional loss of 6,690 km^2 by 2008 (MARGE 2009). However, these estimates have not been peer-reviewed and were produced using differing methodologies which may not be fully compatible (MARGE 2009, Satellitbild 1993). Therefore, these estimates could be substantially improved upon (FRA 2010).

In the 19th century, the arrival of British settlers to Malawi ('Nyasaland' at the time) introduced agricultural systems and cash cropping; particularly for tobacco (Feder 1997). Agriculture remains the dominant economic activity, involving 84% of the workforce (Malawi Government 2010) and 59% of the total land area (FAO 2013), and is commonly cited as a significant cause of deforestation in Malawi (Kamanga et al. 2009, Davies et al. 2010, Palamuleni et al. 2011). Brink and Eva (2009) estimated an expansion of agriculture across sub-Saharan Africa of 57% between 1975 and 2000, at the expense of forested land.

The reliance upon fuelwood or charcoal for domestic fuel in Malawi is another commonly cited direct cause of deforestation (Davies et al. 2010). This is not dissimilar across much of sub-Saharan Africa, where 90% of the energy demand is met by burning biomass (Bailis et al. 2005). In rural areas of Malawi, 97% of the population is thought to rely on fuelwood as an energy source (Bandyopadhyay et al. 2011). Prolonged and intense fuelwood demand may result in land cover change through successive waves of forest degradation (Abbot and Homewood 1999, Asner et al. 2009).

Finally, the commercial use of forests is documented as influencing deforestation rates (Feder 1997). Malawian timber is cheaper in international trade than many other sub-Saharan countries, which promotes rapid deforestation (Malawi Government 2010) and the impact of activities such as tobacco curing involves burning a huge amounts of biomass (Fisher 2004).

[INSERT FIGURE 1]

Methods

We geo-referenced and digitised historical maps describing land cover and potential socioeconomic drivers in the immediate post-colonial period using ArcGIS 10.1. Due to historical data deficiency, this limited our study to a single historical land cover map and ten socioeconomic drivers: cattle density, child-woman ratio, dependency rate, distance to railways, distance to roads, hospital beds, male school attendance, population density, protected areas, and sex ratio (Table 1). The maps were georeferenced to a modern international border for Malawi and transformed using the adjust transformation with root mean square errors approaching zero. Once corresponding recent data and maps were sourced, post-processing on land cover maps and the data for the ten socioeconomic variables was performed following Willcock et al. (2016) before statistical analysis, ensuring internal consistency and like-for-like comparisons (e.g. imperial units used in older maps were converted to metric units). Thus, any differences in land cover detected are unlikely to result from changes in the definition of forest (Willcock et al. 2016, Putz and Redford 2010); see Appendix A for further details. The spatial data on forest and mosaic land (defined as a mixture of cropland, forest, woodland, grassland, scrubland and other natural vegetation) cover was aggregated at the district level, the highest resolution at which most data is available (Hietel et al. 2007). The change of each variable over time was then calculated by subtracting the historical value from the modern value.

Prior to statistical modelling, Likoma, a district comprised of islands situated in Lake Malawi, was excluded as there was no historical land cover data and therefore the change in forest land cover could not be calculated. In addition, for districts with no past forest area, a value of $1 km^2$ was substituted to enable a calculation of percentage change. Furthermore, where both the past and recent forest area values were zero a percentage change of zero was given.

[INSERT TABLE 1]

Statistical analysis

Two separate statistical relationships were investigated, the correlation of socioeconomic variables with both deforestation and forest establishment respectively. Although the drivers of deforestation and afforestation could be the same variables but with inverse relationships, it is possible separate drivers could be involved in one and not the other. Additional models, where all of the city districts (Blantyre City, Lilongwe City, Mzuzu City and Zomba City) were excluded, were also created to allow for the investigation of potentially differing relationships between socio-economic variables and land cover change in rural and urban districts.

All statistical relationships were performed in R x64 3.0.1 (R Development Core Team 2010) using multiple linear regressions, transforming the scaled data using cubed root functions to ensure normality. The most appropriate model was chosen by forward and reverse stepwise selection using the Akaike Information Criterion (AIC) (Bozdogan 1987).

Results

[INSERT FIGURE 2]

(1) Changes in forest area

Between 1972 and 2009, the area of forest cleared totalled 12,760km^2, a reduction of 36% of original forested area (Figure 2). However, due to the simultaneous establishment of

11,161km^2 of forest in other areas, the net loss of forest was 1,599km^2; a reduction of only 5% of the total forest area from the 1972 baseline.

The overall loss of forest area varied spatially, with northern and central regions showing an overall reduction (-1,124km^2 and -1,666km^2 respectively) but the southern region having an overall gain in forest area (+1,192km^2; Table 2; Appendix B). The greatest decline in forest area was in the districts of Nkhotakota (-595km^2; -19%), Karonga (-579km^2; -28%), and Chitipa (-565km^2; -20%). By contrast, the districts of Balaka (-48%; -437km^2), Ntcheu (-45%; -378.27km^2), and Karonga (-28%; -579km^2) experienced the greatest forest loss per unit area.

In 56% of districts there was an overall gain in forested area (Table 2; Appendix B). The districts with the largest overall gain were Manchinga (+402km^2; +36%), Mulanje (+385km^2; +98%), and Mzimba (+344km^2; +11%). The three districts with the largest percentage gain in forested area were Zomba City (+550%, +18km^2), Lilongwe City (+405%, +4km^2), and Mzuzu City (+300%, +44km^2). The small areas of forest in these city districts in 1972 meant even relatively small changes resulted in large percentage changes.

[INSERT TABLE 2]

(2) Changes in mosaic land cover

Throughout the period studied, mosaic land cover had a net gain of 2,804km^2 (+5%). However, in terms of original mosaic land in 1960, there was a loss of 20% (-10,703km^2), of which 72% became forest. This was offset by the gain in 13,508km^2 of newly classified mosaic land cover, which resulted in the overall net gain across Malawi from 1972 to 2009 (Table 2).

The largest overall gain was seen in the central region (+1,583km^2) and then followed by the northern region (+1,330km^2). However, the southern region experienced a relatively small net loss of -109km^2. The districts of Chitipa (+54%, +622km^2), Rumphi (+85%, +608km^2), Nkhotakota (+57%, +565km^2), and Karonga (+44%, +523km^2) experienced the largest net gains in mosaic land cover and were also the districts with the largest percentage gains. These districts were also those where deforestation were greatest. In every district that had an overall loss in forest, there was an overall gain in mosaic land cover.

Even though there was a net gain across the whole country, only half of the 32 districts experienced a gain in mosaic land cover. The districts of Mulanje (-27%, -422km^2), Thyolo (-22%, -343km^2) and Mzimba (-3%, -239km^2) were those with the greatest loss in mosaic land cover. Similarly to the districts with large percentage changes for forest establishment, the city districts were those with the greatest percentage changes for a loss in mosaic land cover. These were Blantyre City (-54%, -113km^2), Zomba City (-48%, -18km^2), Mzuzu City (-39%, -47km^2) and Lilongwe City (-29%, -113km^2).

[INSERT TABLE 3]

(3) Correlates of deforestation

The deforestation model, ($n = 14$, F-value = 19.18, $p < 0.01$) had an adjusted R-squared value of 0.91, indicating that most variance in deforestation between 1972 and 2009 could be explained by the socioeconomic variables included in this study (Table 3). In order of influence, the variables included within the model were the changes in: male school attendance; sex ratio; population density; hospital beds; dependency rate; protected areas; and cattle density (Table 3). Changes in population density ($p < 0.01$), hospital beds ($p < 0.01$), sex ratio ($p < 0.001$), and male school attendance ($p < 0.001$) were positively correlated with deforestation. Cattle density, although not significant within the model ($p > 0.200$), was the only variable to be negatively correlated with deforestation.

(4) Correlates of forest establishment

The best fit model for forest establishment included both city and rural districts ($n = 17$, F-value = 6.665, $p < 0.01$) and had an adjusted R-squared value of 0.71. The variables included in the model, in order of influence, were changes in male school attendance, sex ratio, population density, dependency rate, distance to railways, child woman ratio and number of hospital beds (Table 3). The changes in hospital beds ($p > 0.100$), dependency rate ($p > 0.100$) and male school attendance ($p > 0.200$) were positively correlated with forest establishment whereas all other variables (changes in sex ratio [$p < 0.05$], population density [$p < 0.05$], distance to railways [$p < 0.01$], and child woman ratio [$p >0.100$]) were negatively correlated.

On removal of the city districts from the analysis, the model was largely unchanged, including identical variables, except for the addition of changes in distance to roads and cattle density (Table 3). Of the variables included within both forest establishment models, the relationships were in the same direction except for population density which now showed a positive relationship and changes in male school attendance which showed a negative relationship. Unlike the model including the city districts, none of the variables were identified as significant ($p > 0.05$) and the adjusted R-squared value was much lower at 0.52. The removal of city districts from the deforestation model was not necessary as none of the city districts showed any deforestation.

Discussion

(1) Change in forest area

Our results show that Malawi has experienced a deforestation rate of around 1% ($345km^2$) per annum between 1971 and 2008, most (98%) was replaced by mosaic land cover. This is at the lower end of the 1-2.8% estimate from the Malawi State of Environment and Outlook report (Malawi Government 2010), in accordance with previous estimates of 1.8% by Hudak and Wessman (2000) and 1.4% by Hansen et al. (2013). Lower deforestation rates are likely due to an underrepresentation of forest within the historical land cover; a finer resolution in the recent map enabled smaller patches of forest ($<300m^2$) to be identified. Due to the lack of data from intervening years in this study, any changes in the rate of deforestation throughout the time period are unable to be inferred. Some authors have noted however that the rate of deforestation in Malawi may be declining (Hudak and Wessman 2000, Davies et al. 2010).

Despite the high rate of deforestation, the rate of forest establishment is also rapid; an observation shared by Hyde and Seve (1993). In this study, the overall net loss of forest was only 5% between 1972 and 2009 due to the $12,760km^2$ original forest loss being offset by an $11,161km^2$ of forest establishment. However, as discussed in Willcock et al. (2016), it is impossible to distinguish afforestation, forest regeneration, and reforestation. Just under half of the districts experienced overall deforestation (14/32 districts), which showed deforestation is not the dominant trend across the districts of Malawi. Similarly, in Angola, not all districts experienced the levels of deforestation that national figures would suggest (Cabral et al. 2011). In Tanzania, both continual forest establishment and continual deforestation were found at the village level depending on how traditional the village practices were (Strömquist and Backéus 2009).

Effort put into forest establishment have been successful in Malawi; particularly in the southern region which experienced a net gain in forest. The Malawi State of Environment and Outlook report (Malawi Government 2010) outlined a number of reforestation initiatives, including piloting a programme of payment in return for tree planting and the 'Community-based Forest Management' policy in 2003 where village committees were encouraged to promote forest conservation, management and tree planting within the village's forested areas. The planned introduction in 1964 of 40km^2 of forest annually until 1977 as part of the Vipya pulpwood project (Chapman and White 1970); the presence of several hundred tree nurseries to encourage farmers to use the seedlings (Walker 2004); and public awareness schemes such as a national tree planting day (Walker 2004) are other examples throughout the period studied. Hyde and Seve (1993) quantified forest establishment suggesting government plantations added 30km^2 year^{-1} by 1985 and private smallholders added 11km^2 year^{-1} by 1990. However, although there has been much forest establishment, it is unlikely the new forested areas would have the same levels of biodiversity as remaining original forests (Mwase et al. 2007).

(2) Correlates of forest area change

Whilst we are able to report the land cover change trends that have occurred in Malawi between 1972 and 2009 with some certainty, the statistical correlations of the forest area change with socioeconomic variables is unable to support strong cause and effect conclusions. Below, we briefly consider some of the possible cause-effect relationships identified from our results (see Appendix C for more details).

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.

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) which cannot be disaggregated without further study (Willcock et al. 2016). 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. However, some correlations, for example distance to railways ($p < 0.01$), were unique to forest establishment (see Appendix C for more details).

Conclusion

In Malawi, there has been significant deforestation (12,760km^2; 36%) over a 37 year period from 1972 to 2009. However, much of this was balanced by significant forest establishment over the same time period (11,161km^2), resulting in a net loss of 5% of forested area. Broadly, deforestation and forest establishment show similar but inverse relationships with socioeconomic variables. Specifically, development, population pressure, and demographic factors are important predictors of forest area change within our study area.

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Table and Figure captions

Figure 1. Map of Africa, highlighting the location of Malawi.

Figure 2. The change in forest area in Malawi between 1972 (Agnew and Stubbs 1972) and 2009 (European Space Agency 2009).

Table 1. A summary of the data used within the study.

Table 2. Changes in forest and mosaic land cover between 1972 and 2009 in each district of Malawi; city districts are show in bold.

Table 3. A summary of the regression models relating changes in forest cover to socioeconomic variables.

Table 1. A summary of the data used within the study.

Data	**Description (see Appendix A for further details)**	**Broader Indicator**	**Historical data**		**Modern da**
			Year of estimate	**Source**	**Year of estimate**
Cattle density	An average density of cattle per km^2	Agricultural intensity	1968	Agnew and Stubbs (1972)	2005
Child-woman ratio	The ratio of children under 5 to females aged 15-49	Demography	1966		2008
Dependency rate	The ratio of those aged 10-14 and >65 to people aged 15-64	Demography			
Distance to railways	The average Euclidean distance to railways (km)	Infrastructure	1969		2013
Distance to roads	The average Euclidean distance to roads (km)	Infrastructure			
Hospital beds	The number of hospital beds per district	Development (health)			
International Malawi boundary	The international border of Malawi	International Malawi boundary	-	-	
Land cover	The land cover harmonised into six uniform land cover classes: forest; mosaic cropland and vegetation; cropland; swamp; urban areas; and water bodies	Land cover	1972	Agnew and Stubbs (1972)	2009

Male school attendance	The percentage school attendance for males aged 10-14	Development (education)	1966		2008
Population density	The density of people per km^2	Population pressure			
Protected areas	The area of land under legal protection (km)	Protected areas			2013
Sex ratio	The ratio of the number of males to every 1000 females	Demography			2008

Table 2. Changes in forest area between 1972 and 2009 in each district of Malawi; city districts are show in bold.

Region	**District**	**Forest change (km^2)**	**Percentage forest change (%)**	**Mosaic land cover change (km^2)**	**Percentage mosaic land cover change (%)**
Northern Region	Chitipa	-565	-20	622	55
	Karonga	-579	-28	523	44
	Likoma	No data	No data	No data	No data
	Mzimba	344	11	-239	-3
	Mzuzu City	**44**	**300**	**-47**	**-39**
	Nkhata Bay	184	6	-147	-19
	Rumphi	-554	-15	608	85
Central Region	Dedza	-181	-15	154	6
	Dowa	-6	-4	6	0
	Kasungu	-462	-14	487	11
	Lilongwe	-133	-14	136	3
	Lilongwe City	**4**	**405**	**-113**	**-29**

	Mchinji	-62	-16	92	3
	Nkhotakota	-595	-19	565	57
	Ntcheu	-378	-45	396	17
	Ntchisi	31	9	-31	-2
	Salima	116	30	-108	-7
Southern Region	Balaka	-437	-48	489	43
	Blantyre	23	7	-23	-2
	Blantyre City	**24**	**97**	**-113**	**-54**
	Chikwawa	-53	-3	217	9
	Chiradzulu	-4	-7	4	1
	Manchinga	402	36	303	18
	Mangochi	104	4	-57	-2
	Mulanje	385	98	-422	-27
	Mwanza	92	30	-87	-20
	Neno	-75	-10	82	10

	Nsanje	204	39	-41	-4
	Phalombe	28	16	-7	-1
	Thyolo	300	245	-343	-22
	Zomba	181	57	-92	-5
	Zomba City	**18**	**550**	**-18**	**-48**

472 **Table 3.** A summary of the regression models relating changes in forest cover to socioeconomic variables.

Broader Indicator	**Explanatory variables**	**Deforestation**		**Forest establishment (including city districts)**		**Forest establishment (excluding city districts)**	
		Coefficient estimate	**p-value**	**Coefficient estimate**	**p-value**	**Coefficient estimate**	**p-value**
Agricultural intensity	Cattle density	-0.114	0.291	-	-	4.194	0.148
Demography	Child-woman ratio	-	-	-1.481	0.228	-1.065	0.298
	Dependency rate	0.384	0.023*	2.065	0.136	2.028	0.232
	Sex ratio	1.974	0.000***	-3.388	0.014*	-1.986	0.095
Development (education)	Male school attendance	4.227	0.000***	3.501	0.200	-9.417	0.301
Development (health)	Hospital beds	0.527	0.001**	0.878	0.131	0.669	0.281

Infrastructure	Distance to railways	-	-	-1.815	0.009**	-0.802	0.350
	Distance to roads	-	-	-	-	1.020	0.343
Population pressure	Population density	1.112	0.008**	-2.577	0.047*	1.550	0.245
Protected areas	Protected areas	0.337	0.013*	-	-	-	-

Signifiance codes: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

Deforestation Since Independence: A quantitative assessment of four decades of land cover change in Malawi

Supplementary Information

Appendix A – 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 A1). 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 A1; Table A1).

(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.

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

Figure A1. 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)).

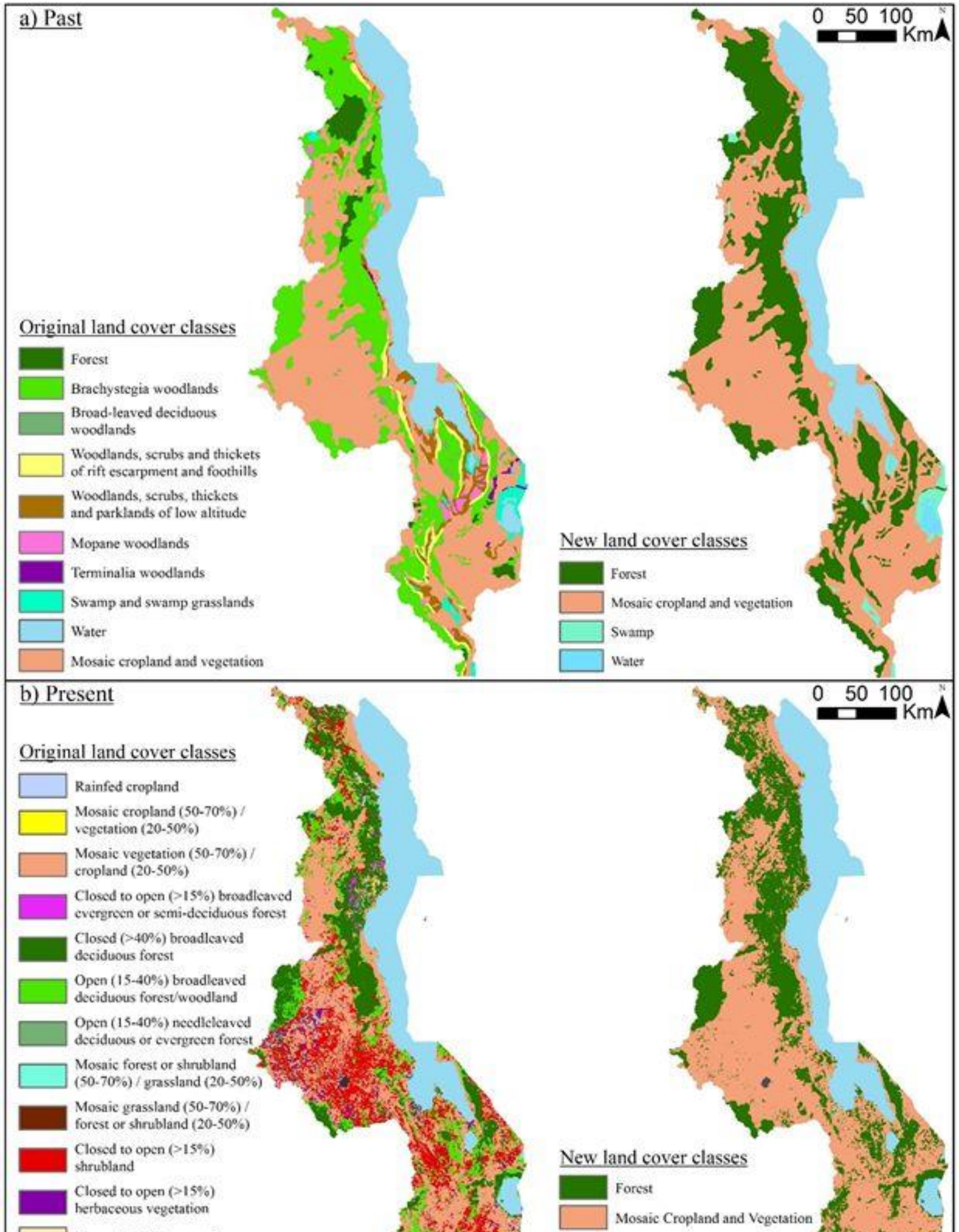

a) Past
0 50 100
Km
N
Original land cover classes
Forest
Brachystegia woodlands
Broad-leaved deciduous woodlands
Woodlands, scrubs and thickets of rift escarpment and foothills
Woodlands, scrubs, thickets and parklands of low altitude
Mopane woodlands
Terminalia woodlands
Swamp and swamp grasslands
Water
Mosaic cropland and vegetation
New land cover classes
Forest
Mosaic cropland and vegetation
Swamp
Water
b) Present
0 50 100
Km
N
Original land cover classes
Rainfed cropland
Mosaic cropland (50-70%) / vegetation (20-50%)
Mosaic vegetation (50-70%) / cropland (20-50%)
Closed to open (>15%) broadleaved evergreen or semi-deciduous forest
Closed (>40%) broadleaved deciduous forest
Open (15-40%) broadleaved deciduous forest/woodland
Open (15-40%) needleleaved deciduous or evergreen forest
Mosaic forest or shrubland (50-70%) / grassland (20-50%)
Mosaic grassland (50-70%) / forest or shrubland (20-50%)
Closed to open (>15%) shrubland
Closed to open (>15%) herbaceous vegetation
New land cover classes
Forest
Mosaic Cropland and Vegetation

Table A1. The harmonisation of land cover categories to

Present
-Closed to open (>15%) mixed broadleaved and needleleaved forest (>5m) -Closed to open (>15%) broadleaved evergreen or semi-deciduous forest (>5m)
-Mosaic cropland (50-70%) / vegetation (20-50%) -Mosaic vegetation (50-70%) / cropland (20-50%) -Mosaic forest or scrubland (50-70%) / grassland (20-50%)
-Rainfed croplands
-Closed to open (>15%) grassland or woody vegetation on regularly flooded or waterlogged soil -Closed to open (>15%) broadleaved forest regularly flooded
-Sparse (<15%) vegetation
-Artificial surfaces and associated areas (urban areas >50%)
-Water bodies

New Description	Past
Forest	-Montane forests, scrubs and grasslands -Moist semi-deciduous forest -Brachystegia woodland -Brachystegia-Evergreen closed
Mosaic cropland and vegetation	-Mosaic cropland and vegetation -Woodlands, scrubs and thickets of the rift escarpment and its foothills
Cropland	-
Swamp	-Swamp and swamp grasslands
Sparse vegetation	-
Urban areas	-
Water	-Water

(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.

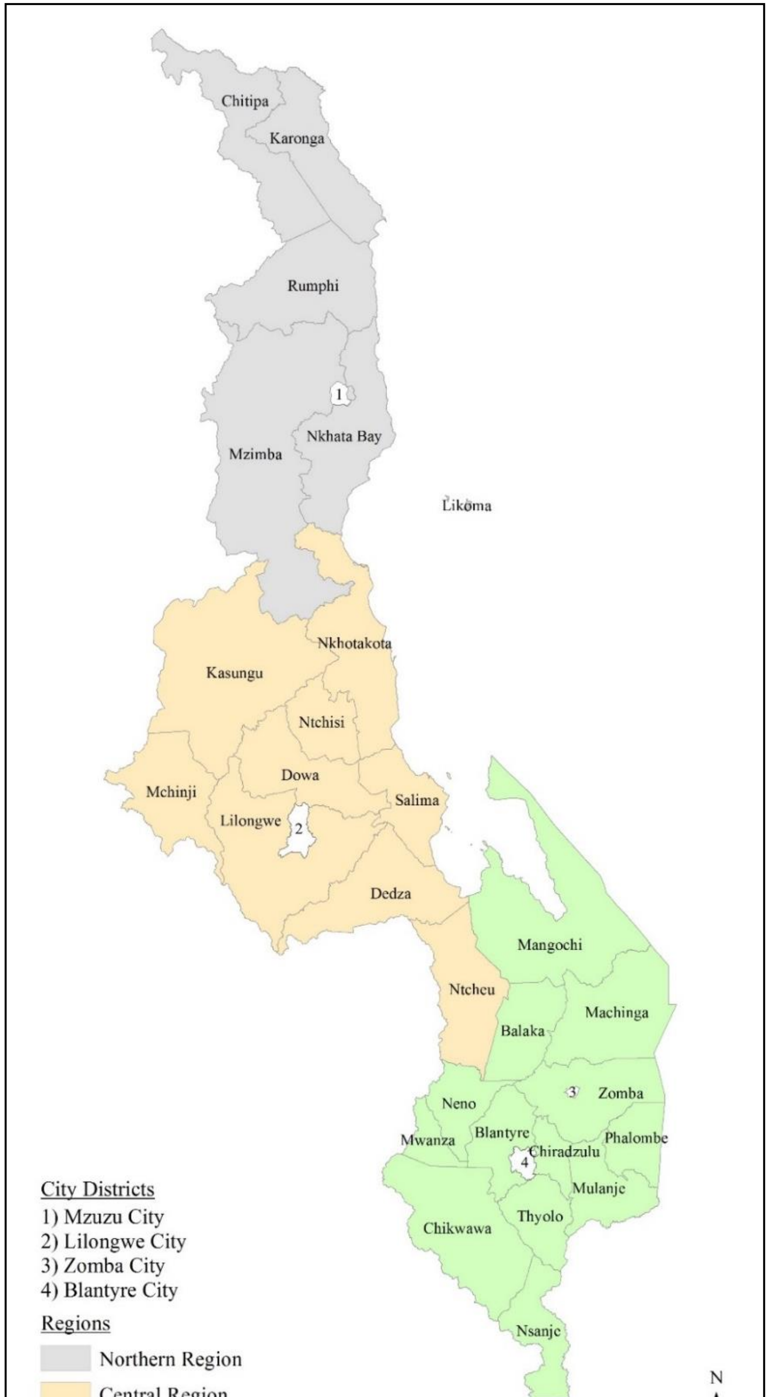
$$\text{Number males} = \frac{\text{Total people aged 15 to 64}}{\text{sex ratio} + 1000} \times \text{sex ratio} \tag{4}$$

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

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.

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

Appendix B – The regions and districts of Malawi.


Chitipa
Karonga
Rumphi
Nkhata Bay
Mzimba
Likoma
Nkhotakota
Kasungu
Ntchisi
Dowa
Mchinji
Salima
Lilongwe
Dedza
Mangochi
Ntcheu
Machinga
Balaka
Zomba
Neno
Blantyre
Phalombe
Mwanza
Chiradzulu
Mulanje
Thyolo
Chikwawa
Nsanje
City Districts
1) Mzuzu City
2) Lilongwe City
3) Zomba City
4) Blantyre City
Regions
Northern Region
Central Region
N

*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.

Appendix C – 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.

Appendix D – Supplementary Information References

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