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# LAND COVER CHANGE AND WOODLAND DEGRADATION IN A CHARCOAL PRODUCING SEMI-ARID AREA IN KENYA

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## ABSTRACT

Woodlands in Kenya are undergoing land cover change and degradation leading to loss of livelihoods. Uncontrolled charcoal production, although a livelihood source for communities living in woodland areas of Kenya, leads to woodland degradation. We used Landsat imagery, field plot data and household interviews to describe land cover change and the role of charcoal production in woodland degradation. An unsupervised classification was used to determine land cover change from woodland to open/farmland, and five 16-km transects were used to investigate the extent of charcoal production in the target woodlands. Semi-structured interviews were conducted on 117 households to understand their perceptions on woodland cover change and the role of charcoal production. The overall accuracy of our classification was 86%. Woodland areas decreased by 24% between 1986 and 2014. The trend of woodland area change compared well between remote sensing and interview data. The density of kilns, a proxy for charcoal-led woodland degradation, varied across the sample plots. Despite charcoal providing a livelihood for 66% of the households, the community felt that their environment, wealth and social relations have been affected by land cover changes caused by charcoal production. Based on these results, we recommend that appropriate measures aimed at improving the productivity of agriculture, adapting to climate change and reducing dependence on charcoal for sustenance should be encouraged to mitigate woodland cover loss and degradation. Copyright © 2016 John Wiley & Sons, Ltd.

KEY WORDS: charcoal; woodlands; Landsat imagery; community perceptions; land use

## INTRODUCTION

Tropical savannahs and woodlands are a major component of the world's vegetation, covering one sixth of the land surface and over half of the African continent. They account for about 30% of the primary production of all terrestrial vegetation, playing a crucial role in the energy, water and carbon balance (Ribeiro *et al*., 2013). Savannahs and woodlands provide a range of goods and services to humans in general and to local rural communities in particular (Pote *et al*., 2006; Kalema *et al*., 2015). Woodlands are therefore a key source of livelihood for over 50 million people in Africa (Campbell & Costanza, 2000). Ecological services provided by woodlands include soil quality maintenance through erosion and leaching protection (Ni *et al*., 2015; Zhang *et al*., 2015) thus avoiding erosion-induced soil quality deterioration that is a major impediment to global food and economic security (Erkossa *et al*., 2015).

Woodlands and forests are key in regulation of water flow regimes and maintenance of morphology of water bodies (Keesstra, 2007; Keesstra *et al*., 2009), microclimate regulation (Belsky *et al*., 1989), carbon sequestration (Kalema *et al*., 2015) and economic benefits in the form of food and energy (Malimbwi *et al*., 2010). Despite their importance, tropical savannahs and woodlands are given less attention than tropical rainforest and other ecosystems in the land cover and land use change literature (Grainger, 1999).

Tropical savannahs and woodlands are among the most degraded and threatened ecosystems (MacFarlane *et al*., 2015). Degradation represents the temporary or permanent reduction in density, structure, species composition or productivity of vegetation cover (Malimbwi *et al*., 2010). It occurs when woodlands are not managed sustainably or controlled through appropriate environmental regulatory policies and frameworks (Bodart *et al*., 2013; Lemenih *et al*., 2014). Woodland degradation can have different drivers: overuse of resources, climatic conditions such as increased drought frequency, urbanization and agricultural expansion (Rocheleau *et al*., 1995; Le Polain de Waroux & Lambin, 2012).

In Africa, woodland degradation results from grazing, human-initiated fires for land clearing for agriculture and vegetation removal for fuelwood, charcoal and building material (Malimbwi & Zahabu, 2008; Ouedraogo *et al*., 2010). These activities can affect the structure and productivity of woodland areas, for example, by altering the soil properties (Yimer & Abdelkadir, 2010; Bruun *et al*., 2015; Mohawesh *et al*., 2015) and the hydrological regimes (Montenegro & Ragab, 2010; Yu *et al*., 2015). The way in which charcoal production links to deforestation and degradation has been debated (Chidumayo & Gumbo, 2013; Coomes & Miltner, 2016). Charcoal can lead to the transformation of woodland to bush and bush to scrub, over very

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large areas (Arnold & Persson, 2003). Charcoal making can occur when the land is being cleared for agriculture and thus may not be the main driver of degradation (Zulu & Richardson, 2013). In some cases however, charcoal production can be linked directly to woodland degradation (Chidumayo & Gumbo, 2013). Despite the unknown extent, woodland degradation because of charcoal production has been reported in Kenya (Kirubi *et al*., 2000; KFS, 2013).

The ongoing debate on the role and extent of fuelwood-driven degradation in woodlands (Butz, 2013) indicates that woodland degradation in arid and semi-arid areas is not sufficiently investigated. This is partly because woodlands are more difficult to monitor with traditional forestry tools and remote sensing as compared with other forest types. Woodland degradation is also more subtle than clear-cutting a forest making it difficult to detect its occurrence and extent. Moreover, woodlands are viewed as less commercially important (Grainger, 1999).

To obtain a comprehensive understanding of woodland degradation requires a combination of change detection by remote sensing, physical field observations and sociological data. The objective of this paper is to enhance the understanding of woodland degradation and to assess the role of charcoal making in woodland degradation for a study area in Kitui, Kenya using such a portfolio of methods. The novelty of this paper lies in linking woodland degradation and perceived change to livelihoods. We explicitly include perceptions by local inhabitants as this can provide information for planning (Vila Subirós *et al*., 2015) and gain support for restorative work (Davies *et al*., 2010) and better management of land cover change. We have chosen the woodlands of Kitui, Kenya as these have been undergoing rapid socio-economic, climatic and environmental change (Zaal & Oostendorp, 2002; Lasage *et al*., 2008).

Within this context, the specific aims of this study are to (1) investigate the spatial patterns and trends of local woodland degradation and cover change; (2) link woodland degradation with the perception of local people on the land cover/use change and the effect on their well-being; and (3) explore the role of charcoal in woodland degradation.

## MATERIALS AND METHODS

The study area is located in Kitui County in Kenya about 150 km east of Nairobi (38°–23′, 38°–37′E and 1°–46′, 1°–58′S) and covers an area of 442 km$^2$ (Figure 1). The altitude is about 550 m above sea level. The average yearly rainfall for Kitui is around 1,000 mm with large local differences. The rainfall pattern is bimodal consisting of ‘long rains’ between March and May, while the ‘short rains’ season occurs between October and December (Lasage *et al*., 2008). The vegetation of the study area is described as Somalia–Masai Acacia–Commiphora deciduos bushland and thicket within the Somalia–Masai ecoregion (Brink & Eva, 2011) dominated by *Commiphora* spp., *Acacia* spp. and *Adansonia digitata* L.

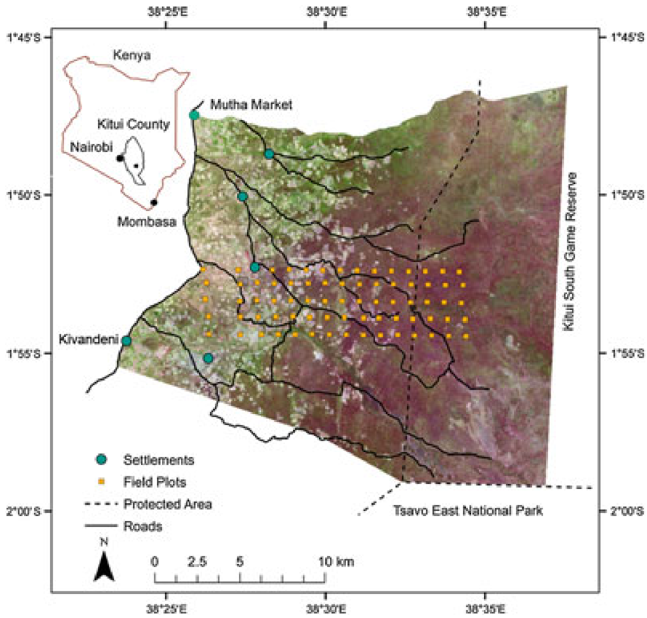


Figure 1. The location of study area within Kitui County, Kenya (Landsat image path 167 row 61). The image is in true colour, based on Landsat bands 4, 3 and 2.

The study area borders Tsavo East National Park to the south-east and Kitui South Game Reserve to the east. Mutha market is the largest settlement in the area. The land in the study area is privately owned through family lineages although formal titling has not been done. Shifting cultivation is practised within the family land holdings, which are generally a few kilometres apart. The population of the area is 10,154 people in 1,865 households (KNBS, 2010) with an average density of 27 persons km$^{-2}$ (KCDP, 2013). We selected the study site as it is located deep inside in the charcoal producing area of Kitui County. Furthermore, it is located at the intersection of two major roads connecting it to the Nairobi and Mombasa highway, where the charcoal is mostly transported to. Charcoal making was introduced in the study area in 1998 by evictees from Chyulu Hills in the neighbouring Makueni County about 120 km south-west of the study area, which was gazetted as a national park in 1995 (Muriuki *et al*., 2011).

Different methods were combined in order to analyse woodland degradation: land cover change detection based on the interpretation of satellite imagery, field-based charcoal site identification and interviews with local landowners. Figure 2 summarizes the data sources and processes followed to analyse the Kitui woodlands.

### *Landsat image analysis*

We chose Landsat satellite images because they enabled us to work on a local scale of 30-m resolution and cover the desired time. Images for the years 1986 (26 August), 1999 (25 October), 2005 (22 August) and 2010 (1 June) were used (USGS, 2015). For 2014, we used a cloud-free mosaic from Hansen *et al*., (Hansen *et al*., 2013). The satellite images were chosen based on time of the year, their clarity

 

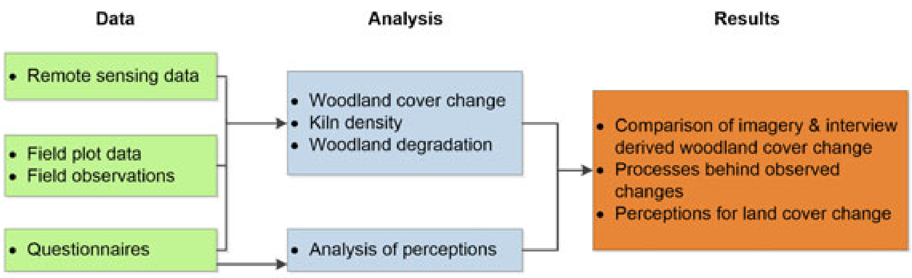


Figure 2. An overview of the research process.

and major socio-economic changes in the area (e.g. 1998 Chyulu Hills eviction). Images for the dry months were chosen to minimize the chances of error in classification because of seasonal differences in vegetation. The satellite images were pre-processed using ENVI 5.1 and ERDAS Imagine 9.1 software. We masked clouds—cloud cover however never exceeded 5% of the study area and was limited to the south-east section.

The unsupervised Iterative Self-Organizing Data Analysis algorithm was used to cluster image areas with common reflectance. We performed the classification in ERDAS with the convergence value at 0.95 and 20 maximum iterations, resulting in 20 clusters. These were later reclassified to three predetermined classes based on the knowledge of the area and visual examination of colour composites of raw satellite images (Stringer & Harris, 2014). The three classes were woodland, transitional woodlands and farmlands/open areas (Figure 3). It was not possible to map and analyse changes in the area occupied by settlements. This was because of the spatial resolution of Landsat images and the characteristics of mostly informal, small settlements, with a low share of sealed surfaces. The accuracy assessment was performed using a stratified random sample of 200 units, which were visually interpreted from the satellite images. We calculated the overall, user's and producer's accuracy for each classified image for the three land cover classes (Congalton, 1991; Foody *et al*., 2002).

A post-classification change detection was applied to analyse woodland degradation through space and time. The images from the different time periods were compared to create a change image map (Macleod & Congalton, 1998). This method has the advantage that various images are classified separately hence reducing the challenges associated with radiometric calibration (Singh, 1989; Lillesand *et al*., 2004).

*Charcoal and woodland degradation*

To further assess the impact of charcoal on woodland degradation, five parallel transects were aligned in a west–east direction. The transects, which were 16 km in length and 1 km apart, started from the Kivandeni-Mutha Market main road going towards the Kitui South Game Reserve boundary. They represent a gradient of accessibility as we assumed that accessibility might affect the degree of charcoal extraction (Figure 1). Rectangular plots (50 by 20 m) of 0.1 ha were sampled every kilometre along the transects, giving a total of 75 plots. The 50 by 20 m plot size has been widely used for assessments of shrub lands, tropical savannahs and woodlands (Luoga *et al*., 2002; Kalema *et al*., 2015). For every sampling plot, the global positioning system (GPS)

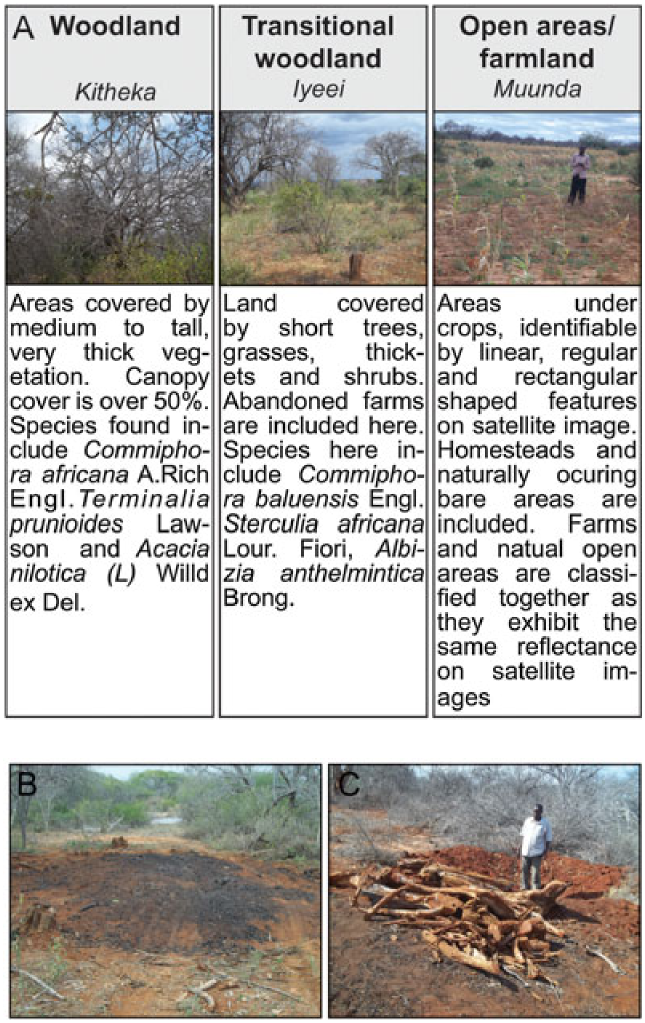


Figure 3. (a) A typical representation of the land cover classes used: woodland, transitional woodland and open areas/farmland, (b) charcoal kiln and extraction road and (c) tree stumps dug out for charcoal production.

 

coordinates were captured and the number of charcoal kilns was counted. A kiln is an insulated chamber for wood carbonization made by covering a wood pile with herbaceous material and soil (Chidumayo & Gumbo, 2013, refer to Figure 3b). Furthermore, the number of tree stumps and species used for charcoal making within the plot was counted and identified with the assistance of local guides (Figure 3c). This plot level data was used as a proxy for the contribution of charcoal towards woodland degradation. The plot data was analysed using both inferential and descriptive statistics, including Pearson's correlation coefficient. We also compared the reported kiln density with the land cover at the plot. As charcoal making involves felling of preferred tree species, a single kiln usually has a 'catchment' distance of several metres depending on the density of the tree species. To account for this, we extracted the land cover at the sampling plot locations within a 50-m buffer from the centre of the plot.

### *Comparison of woodland loss between remote sensing and community trends*

In order to compare community knowledge and perceptions with remote sensing results, a total of 117 households were interviewed using a semi-structured questionnaire. The interviews were conducted between May and July 2015 by the lead author and four assistants whose mother tongue is the local language (*Kamba*). The assistants were trained on using GPS equipment and questionnaire administration. The questionnaire was also pre-tested to ensure appropriate wording and meaning of the questions. Systematic sampling of households was applied using eight transects evenly spread across the study area. The households interviewed were systematically picked at a distance of 1 km from each other along the transect. If no household was present after 1 km, the nearest household was picked. This method was adopted as there was no reliable settlement data or maps of the area available.

We targeted household heads (both male and female) who have lived in the area for at least 20 years to receive an accurate account of the past land use activities in the study area. The respondents were asked to explain the land cover changes within their holdings for the last 20 years, by indicating the estimated size of woodland and farmland within the land holding for 5-year time intervals. They were also requested to give their views on the impact of charcoal making on the land cover. Finally, the interviewees were asked to rate the effect of land cover change on their immediate environment, wealth and social relations on a Likert scale ranging from 1 (no change) to 6 (extreme change), as well as their motivation for the values given. In-depth semi-structured interviews have successfully been used to study stakeholder perceptions in land use and management (Teshome *et al.*, 2014; Vila Subirós *et al.*, 2015). Finally, personal observations of land cover/use types and sources of livehoods were recorded to supplement the satellite, plot and community-based information.

## RESULTS

### *Landsat image analysis and accuracy assessment*

The results of the Landsat image analysis show the conversion from woodland and transitional woodland to open areas (Figure 4). The conversions from woodlands to transitional woodlands cannot always be related to human activity. For example, in several areas, we observed swaps between woodlands and transitional woodlands that were a consequence of seasonality and different levels of dryness in the area. The woodland area has been gradually declining in the study area from 1986 to 2014, from a total of 31,084 ha in 1986 to 23,930 ha in 2014 (Table I). The biggest change to the woodland land cover occurred between 2005 and 2014. Transitional woodland also increased but at a more moderate pace, from 9,966 to 11,572 ha. Although some changes to this class can be associated to land cover change, often these changes are as a result of seasonality of woodlands. This is also shown by the fluctuation of the area covered by transitional woodland and the low classification accuracy of this land cover class. Overall, the results show an increase in farmland and transitional woodland areas at the expense of woodlands. There are few noticeable changes within the Kitui South Game Reserve.

The user's and producer's accuracy for woodland range from 84 to 98% (refer to Table II). The transition class has the lowest user's accuracy of 69 and 75% for the year 2010 and 2014 respectively. This is because of the difficulty to map this particular land cover class.

### *Charcoal and woodland degradation*

Evidence of charcoal making was recorded in 38 of the 75 sample plots. The number of kilns ranged from 1 to 6 (10–60 kilns $ha^{-1}$) per plot, and kilns had an average area of 25 $m^2$. The number of trees harvested per plot ranged from

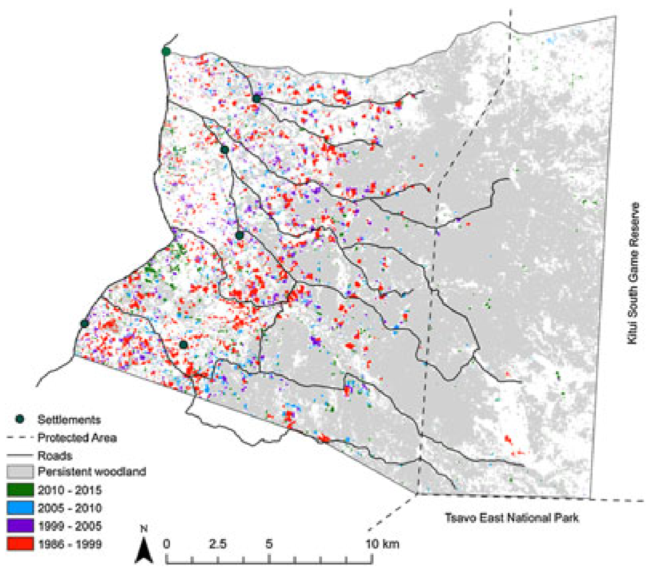


Figure 4. Woodland change from original and transitional woodlands into open areas in Kitui County, Kenya, for the period 1986–2014.

Table I. Observed land cover changes from 1986 to 2014 in Kitui, Kenya

| LUC type | 1986 | | 1999 | | 2005 | | 2010 | | 2014 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | ha | % | ha | % | ha | % | ha | % | ha | % |
| Woodland | 31,084 | 70.3 | 30,714 | 69.5 | 29,180 | 66.0 | 27,266 | 61.7 | 23,930 | 54.1 |
| Transitional woodland | 9,966 | 22.5 | 9,018 | 20.4 | 10,540 | 23.8 | 9,363 | 21.2 | 11,572 | 26.2 |
| Farmland | 3,168 | 7.2 | 4,487 | 10.1 | 4,496 | 10.2 | 7,583 | 17.2 | 8,697 | 19.7 |

1 to 16 (10–160 stems $ha^{-1}$) with diameters ranging from 9.2 to 79 cm (recorded 30 cm off the ground). Almost complete clear fell of trees is carried out on plots with high density of preferred species, and little or no extraction is observed on plots with low preferred tree species density. The species harvested for charcoal making include *Strychnos spinosa* Lam., *Acacia nilotica* L. Willd., *Cassia abbrevieta* Oliv. and *Acacia tortilis* Forsk. Harvesting is normally done by felling the tree at approximately half a metre off the ground using an axe. In some instances, charcoal makers dig up the stumps of the preferred charcoal species (Figure 3c). The harvesting intensity, the alignment of extraction roads and cutting of shrubs to use on kiln construction all contribute to woodland degradation. Thirty-one plots (81.5%) with charcoal kilns were found in the area where woodland or transitional woodlands were the dominant land cover (>51%). Only five plots were found in the area classified as farms/open areas thus indicating the importance of transitional woodlands and woodland land cover types as a source of charcoal (Figure 5).

The land cover type and the number of kilns on each plot were examined in relation to the distance of each plot from the main road. We found a weak relationship between the number of kilns and the distance from the main road ($r = -0.178$, $p = 0.284$) and a positive relationship between woodland cover and the distance from the main road ($r = 0.672$, $p < 0.001$).

### *Household characteristics and woodland cover loss*

Out of the 117 respondents, 57 were female and 60 were male. Their average age was 45 years, and 84% have only had basic education. Eighty-eight % of the respondents ranked agriculture as their main source of livelihood, while 7 and 6% respectively ranked livestock and charcoal making as their main source of livelihood. The average farm holding was 20 ha, while the average household size was seven people.

The respondents reported a downward trend of the woodland cover over time. Between 1995 and 2015, the woodland cover was lost at rates of 4.8, 5.6, 10.8 and 17.2% for every 5 years respectively. The highest rates of woodland cover loss were reported for the years 2005–2015 when the woodland area dropped from 2,093 to 1,545 ha. Most of this area was converted to farmland/open areas (Table S1).

### *Woodland area loss: comparison between remote sensing and community interviews*

We made a comparison of the woodland loss rates calculated from the interviews and the remote sensing analysis (Figure 6). For both analysis, we set the initial state of the woodland to 100% and computed the percentage change based on each data type. The calculated rates of woodland reduction as derived from the interviews are consistently higher than those from the satellite imagery. In spite of this difference, the trends are highly correlated ($r = -0.96$, $p = 0.03$).

The interviews indicate that 74% of the households have made charcoal for commercial purposes at one point in time, and the number currently involved in charcoal production is 66% of the sampled households. The average production per household is 22 bags per month (Figure 7). The average weight of a charcoal bag is 35 kg (KFS, 2013) and is currently sold at Ksh 450 (€4.5).

### *Community perceptions on the consequences of charcoal making*

The perceptions on how charcoal making has contributed to observed woodland degradation and landscape changes within the last two decades vary (Figure 8a). Thirty-eight % of the respondents believe that charcoal making has led to a reduction in rainfall through the massive felling of trees. Other reported associations with charcoal making are woodland area reduction (19%), increased soil erosion (12%) and increase in dust and wind speed (8%).

Table II. Accuracy assessments for the study area for the year 1986–2014

| | 1986 | | 1999 | | 2005 | | 2010 | | 2014 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | User's accuracy | Producer's accuracy | User's accuracy | Producer's accuracy | User's accuracy | Producer's accuracy | User's accuracy | Producer's accuracy | User's accuracy | Producer's accuracy |
| Woodland | 84 | 88 | 97 | 91 | 98 | 98 | 93 | 90 | 94 | 91 |
| Transition | 89 | 82 | 75 | 89 | 93 | 93 | 69 | 84 | 75 | 84 |
| Farms | 75 | 90 | 78 | 78 | 93 | 87 | 100 | 80 | 93 | 93 |
| Overall accuracy | 86 | | 89.5 | | 96 | | 87.5 | | 89 | |

 

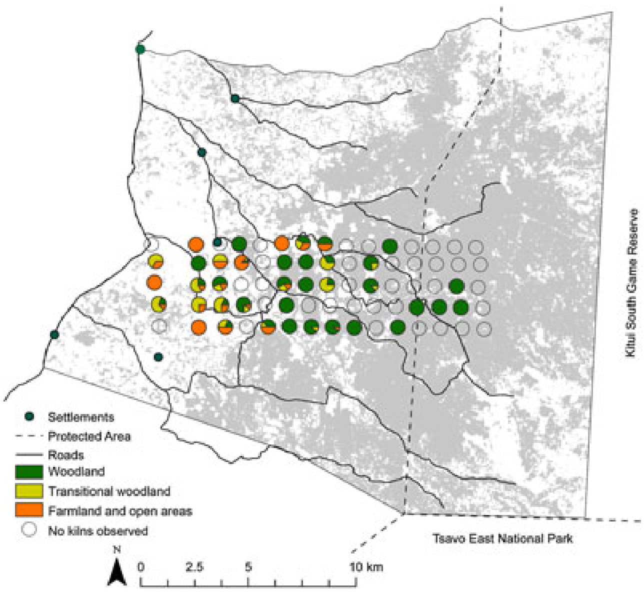


Figure 5. Location of sample plots where charcoal kilns where found and their corresponding land cover types.

The perceived consequences of charcoal making and woodland degradation on community well-being are reported on a Likert scale ranging from no change (1) to extreme change (6) in Figure 8b. Less than 25% of the respondents believe that woodland degradation has had no impact on their immediate environment, wealth and social relations between 2010 and 2015, while at least 70% of the respondents ranked the effect as moderate to extreme change for the last 10 years. The reported aspects of environmental change mentioned overlap with the reported consequences of charcoal production, including increase in temperature, dust whirls and migration of bees. As a 45-year-old man from Kendoo village explained: "*Bees have migrated. I have six bee hives out of which only one is occupied. The smoke from the kilns has driven the bees away*".

Reduction in harvest volume of maize and green grams (mungbeans) and the number of livestock are key reasons why respondents think that their wealth has gone down considerably. A 60-year-old man reported that: "*I had 30 herd of cattle but now I have none. I used to harvest a lot of honey but now the bees are nowhere. I used to harvest 15 bags of maize but now I harvest 1 bag*". Perceived reduction in rainfall amounts and predictability has severely affected agricultural activities, and as a consequence, communal activities such as voluntary farmer self-help groups (*mwethya*) have since stopped. Exchange of agriculture-based gifts such as food items and livestock has also reduced. Overall, individuals have focused their time on daily survival efforts through non-farm activities such as charcoal making, small businesses and local employment. This shift in social relations is best captured through the sentiments

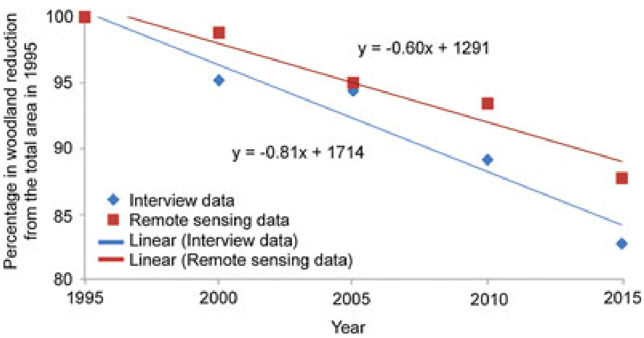


Figure 6. Comparison of woodland cover loss trends calculated from community interviews and satellite imagery.

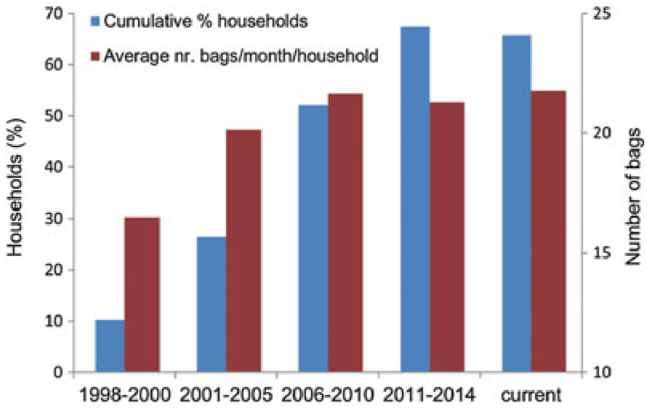


Figure 7. Households involved in charcoal making and average production per month.

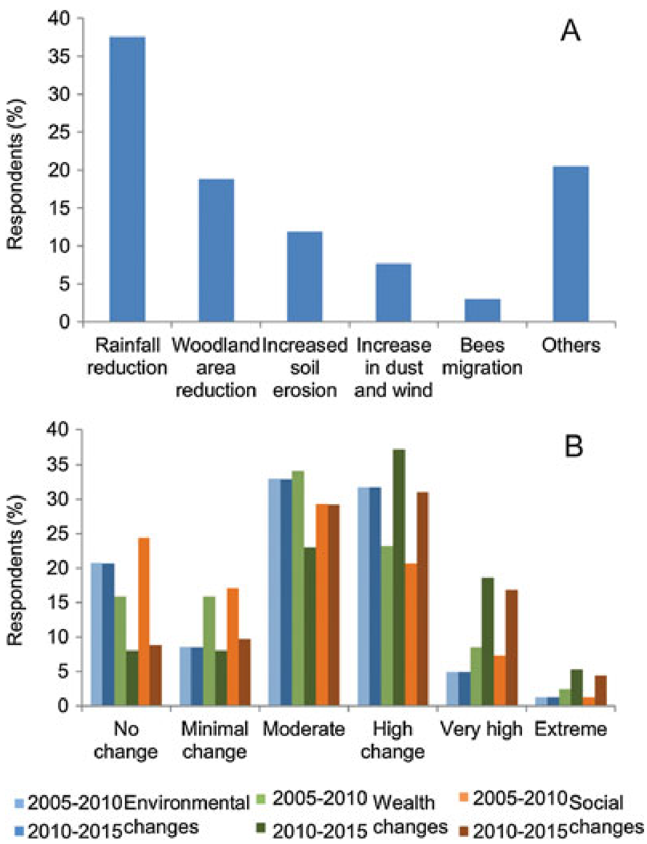


Figure 8. Community perceptions on (a) the effects of charcoal making on the landscape and (b) on the environmental conditions, wealth and social changes.

 

of a 60-year-old man from Ithango village: "*we no longer share gifts, the mwethya no longer function and we no longer visit each other. We wake up early in the morning to search for food and return home late to sleep*".

## DISCUSSION

### *Land cover change from satellite imagery*

Although the use of satellite imagery to derive information on woodland degradation has its drawbacks, an 86% overall accuracy of our land cover classification indicates a sufficient level of accuracy to show real changes (Treitz & Rogan, 2004). Our accuracies are comparable to other studies in the region, for example, in Ugandan woodlands (Mwavu & Witkowski, 2008). Nevertheless, post-classification maps are subject to uncertainty, where the errors of individual maps propagate when different maps are compared to analyse land cover change (Olofsson *et al*., 2013). This can impact the validity of the observed locations and spatial pattern of woodland cover change. Additional confidence in the results is gained as the spatial pattern of woodland change follows a logical pattern near or adjacent to roads and settlements and is not randomly scattered across the landscape. Moreover, the change trends correspond well with the field measurements and interview results that each have their own, different uncertainties. By comparing different ways of measuring woodland change and degradation through a triangulation of evidence, we overcame the limitations of each individual approach.

The decrease of woodland area and an increase in farmlands in the study area are indicative for the rapidly changing land use regime in the area attributable to an increase in farmlands and shifting cultivation. This increase is partly because of population increase that rose from 3 persons $km^{-2}$ in 1989 (CBS, 1994) to 11 persons $km^{-2}$ in 1999 (KNBS, 2010) and drought adaptation mechanisms of the local population. Households have responded to the decreased rainfall amounts by clearing increasingly bigger farmlands hoping to compensate for lowered output per unit area. Our field observations point to shifting cultivation as one of the causes of woodland loss. Farmers use a particular portion of the farm holding for a period of time and clear a new woodland area for farming once the previous one is exhausted. The effects of shifting cultivation on reducing woodland cover have been reported in other African woodlands (Luoga *et al*., 2005; Kalema *et al*., 2015).

Conversion of woodlands to farmlands/open areas can have adverse effects on soils. Conversion of woodland to other land use has been noted to reduce soil organic carbon by 22–30% and total nitrogen by 19% for a study in Ethiopia (Yimer & Abdelkadir, 2010). An adequate amount of soil organic matter is considered essential for sustainable agriculture, and its reduction decreases crop productivity (Yimer *et al*., 2007). Loss of vegetation cover can lead to the formation of soil sealing that increases the risk of runoff and soil erosion. Mohammad & Mohammad (2010) reported high soil loss in cultivated fields as compared with land under woody vegetation, an observation they attributed to the breakdown of soil aggregate stability, loss of vegetative cover and exposure of the soil particles to direct impact of rain drops.

### *Charcoal as a driver of land degradation*

Whereas population growth and the demand for cropland were the main drivers until 1999, charcoal burning became a significant driver of woodland degradation afterwards as evidenced by the large proportion of households who engage in charcoal production, the large number of kilns counted in woodland cover area and evidence of trees harvested for charcoal making. This is supported both by our field observations and interviews. It is not possible to attribute the drivers of woodland degradation directly from remote sensing data. The spatial pattern and distribution of woodland degradation derived from the remote sensing images after 1999 suggests charcoal burning among the major factors of degradation. Patches of woodland degradation after 1999 are smaller as compared with the ones between 1986 and 1999. The larger patches are likely the result of land clearing for agriculture, while the smaller ones are more characteristic for charcoal production. Nevertheless, it is difficult to point out one single driver, as often areas that had been cleared for charcoal production are afterwards used for cropland.

The degree of degradation is highly place-specific and depends on the density of preferred charcoal making species. Almost all the charcoal kilns were observed in woodland cover areas suggesting that charcoal making is an activity not directly associated with land clearing for agriculture. The role of charcoal making in land degradation has also been reported elsewhere (Luoga *et al*., 2002; Luoga *et al*., 2005; Chidumayo & Gumbo, 2013). As charcoal makers construct the kilns near the tree cutting site, kilns further contribute to degradation as they remain bare for a long time (Dons *et al*., 2015). Removal of vegetation cover and subsequent burning around charcoal kilns can result in soil fertility reduction. This can occur in numerous ways: soil erosion with nutrient loss on bare grounds, reduction of soil organic matter through volatilization and loss of soil microbial biomass because of increased decay and loss of heat-sensitive microbes (Certini, 2005; Zhang *et al*., 2015).

The effect of woodland degradation is further compounded by the presence of uncontrolled extraction roads that involves clearing of vegetation all the way to the kiln site. Furthermore, selective harvesting of preferred charcoal species may completely wipe away some species, changing the structure of the woodland and its ability for self regeneration (Butz, 2013). Many woodland and dryland species regenerate through coppicing (Sawadogo *et al*., 2002; McLaren & McDonald, 2003), and therefore, digging up their stumps severely compromises this ability (Malimbwi & Zahabu, 2008).

It is difficult to relate woodland degradation to charcoal even with using relatively high-resolution Landsat images, as charcoal making is a phenomenon occurring at subpixel size scale. To overcome this challenge, very high-resolution satellite imagery such as Quickbird and Ikonos are being used to analyse charcoal-related degradation (Oduori *et al*., 2011; Dons *et al*., 2015).

Extended droughts and low farm productivity are cited as some of the factors enhancing charcoal making in the savannah areas and Kitui County in particular (PISCES, 2010). With no other source of livelihood, poverty-striken residents turn to charcoal making for subsistence and commercial purposes, as shown by other examples in Africa (Malimbwi & Zahabu, 2008; Kalema *et al*., 2015). People are attracted to charcoal production as it requires neither formal education nor large capital investment while at the same time charcoal is a cash product with a large market ready to absorb the entire production (Malimbwi & Zahabu, 2008).

The weak relationship between kilns and distance from the main road contrasts sharply with what is normally expected in wood resource extraction (Albers & Robinson, 2013). Studies in South Africa (Pote *et al*., 2006) have shown that the amount of harvesting decreases with distance from settlements as the most favoured species are removed first from accessible areas. The pattern in our study can be attributed to the nature of land ownership in the study area, local vegetation variations and the commercial aspect of charcoal making. Land is individually owned, and thus, owners can exert some degree of control on how trees can be used. The commercial nature of charcoal extraction, fuelled by demand for charcoal in cities such as Nairobi and Mombasa, has encouraged middlemen to venture deep into the woodlands, leading to charcoal production all over the woodlands. Charcoal can be sourced from long distances as long as the price increases result in marginal gain (Ahrends *et al*., 2010)

### *Comparison of woodland loss between remote sensing and community interviews*

The high degree of similarity of woodland cover trends between remote sensing and from interviews indicates that the community is well aware of their surroundings and the land use changes. Combining interviews and remote sensing provides more reliable and comprehensive data on land use and land cover as various aspects of land use and cover change, their causes and effects can be clarified and verified. Also, several other studies have successfully compared satellite-derived land cover changes with interview data from multiple stakeholders ranging from farmers, communities, businesses and institutions. In these studies, the interviews focussed on identifying the drivers of change (Malek *et al*., 2014; Ariti *et al*., 2015), the impact of changes (Garedew *et al*., 2009) or the stakeholder perception of (Yiran *et al*., 2012; Ariti *et al*., 2015). The argument is that whereas remote sensing can provide quantitative data on the magnitude of land cover change, it is the stakeholders who can inform on the driving forces of change and how the changes affect their lives. However, interviews are time-consuming and may be subjective, and for periods further back in time, it is more difficult to gather reliable results (Garedew *et al*., 2009). As stakeholders base their decisions on their perception of the drivers and impacts of land use and land cover change (Ariti *et al*., 2015), there is the need to link the observed changes with the driving forces to inform effective and sustainable land use planning (Yiran *et al*., 2012). Our study provides an example of the analysis of woodland degradation at a local level using a portfolio of methods complementing each other and thus enabling a comprehensive understanding of woodland degradation and the role of charcoal production in specific.

In order to reduce woodland degradation, incentives for landowners to maintain woodland areas should be combined by disseminating technical information and alternative management options, such as beekeeping. This will reduce woodland degradation and dependence on charcoal for sustenance. Extending forestry services to tree planting for charcoal and wood production could reduce the pressure on existing woodlands, as examples of local non-governmental organizations (NGO) such as Katulu have already shown. Moreover, encouraging the use of alternative charcoal production technologies, such as the casamance charcoal kiln and briquetting, can increase the efficiency of charcoal production by reducing the number of trees necessary to produce a given volume of charcoal hence slowing down land cover change (Mekuria *et al*., 2012). Finally, pressures on woodland can be reduced by increasing agricultural productivity, for instance through the introduction of drought-tolerant crops, manure for fertilization, seasonal forecasts and promotion of soil and water conservation techniques (Recha *et al*., 2014).

## CONCLUSIONS

Landsat imagery analysis, field transects and household interviews provide an in-depth understanding on woodland cover change and degradation. Our study has shown that woodlands are being converted to farmlands and are degraded mainly through charcoal making as result of a host of physical and socio-economic factors. The community is well aware of the woodland degradation and land cover change and relate degradation of the land cover to their perceived worsening livelihoods. To reduce woodland cover loss, our results indicate that there is a need for appropriate policy and technological measures to reduce woodland cover change and degradation. Such measures should target improving the productivity of agriculture to reduce shifting cultivation practice, adaptation to climate change and reducing dependence on charcoal for sustenance in order to address the combined drivers of woodland degradation and loss.

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## SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article at the publisher's web-site:

**Table S1.** Woodland cover loss for the years 1995–2015 as determined from community interviews