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Planting of *Acacia decurrens* and Dynamics of Land Cover Change in Fagita Lekoma District in the Northwestern Highlands of Ethiopia

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Understanding the magnitude and drivers of land cover change is key to designing effective natural resource management interventions and restoring degraded landscapes. We analyzed land cover change from 1995 to 2015 in Fagita Lekoma District in northwestern Ethiopia using Landsat images and found that forest cover increased by 1.2% per year, while areas covered by cropland decreased by 1% per year. The increase in forest cover is mainly attributable to increased planting of Acacia decurrens. *The expansion of* A. decurrens *plantations could be attributed to its potential to provide short-term economic benefits. This indicates that economic activities that generate short-term benefits may strongly influence the selection of land uses in the study area. Planting of* A. decurrens *generates job opportunities for the landless and enables farmers to diversify their livelihoods. It rarely restricts other agricultural practices, as farmers are able to grow cereals between the trees in the first 2 years following the establishment of an* A. decurrens *plantation. This enhances the efficient utilization of farmlands and diversifies agricultural products. Providing training to farmers on silvicultural practices and presenting alternative tree species are crucial to enhance their benefits and sustain charcoal production in such mountainous regions. Studies are required to understand how the observed land cover change affects land productivity, landscape, and biodiversity.*

Keywords: Acacia decurrens*; ecology; land cover change; Landsat; silviculture; Ethiopia.*

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Introduction

The economy of Ethiopia largely depends on agriculture and natural resources (Dejene 2003). Increases in human demands for food, livestock feed, energy, and other resources have led to increased land use conversion, particularly the conversion of forest and grazing lands into agricultural lands (Zeleke and Hurni 2001; Hurni et al 2005; Amsalu et al 2007). Similar to other parts of Ethiopia, the dominant land use conversion in the highlands of northwestern Ethiopia, our study area, is the conversion of forests to agricultural lands, which is attributed to widely practiced cereal-based crop production (Abegaz 2005). This has led to a reduction in forest cover (Zeleke and Hurni 2001; Bewket 2002; Wondie et al 2011), increases in runoff and soil erosion (Mekuria et al 2009), loss of biodiversity (Mekuria et al 2015), and decreases in ecosystem services (Mekuria et al 2011). The dominant form of land use conversion has also increased heterogeneity and modified landscape configuration and ecology (Barasa et al 2011; Ruishan and Suocheng 2013).

While land use and land cover change studies by Zeleke and Hurni (2001), Hurni et al (2005), and Amsalu et al (2007) have shown that forest cover has decreased due to increased deforestation and conversion to agricultural lands, Bewket (2002) and Wondie et al (2011) have shown an increase in forest cover at the expense of agricultural lands. These results seem to contradict one another, as they all use a similar definition of forest and cropland, but they are based on site-specific differences. Degradation of natural resources, including increasing soil acidity in the highlands of Ethiopia, is a dominant phenomenon that compromises the livelihoods of local communities (Bewket and Teferi 2009; Endalew et al 2014; Hurni et al 2015).

In response to the degradation of natural resources and associated negative impacts on the environment and livelihoods, the government of Ethiopia launched a country-wide campaign in sustainable watershed management in 2010. Such government initiatives require proper design and effective natural resource management interventions. Understanding the evolution, dynamics, and magnitude of land cover change is key to designing such interventions and thereby enhancing agricultural productivity and ensuring food security. Also, analysis of land cover dynamics is useful in developing a methodological framework for analyzing the economic costs of land cover changes (Hein et al 2008), soil dynamics (Bruun et al 2015), and the benefits of sustainable land management (Girmay et al 2008; Hein et al 2008).

The conversion of forests into other land uses is common in mountain regions of Ethiopia. In contrast, planting of *Acacia decurrens*—a fast-growing tree species that is adaptable to acidic soil conditions (Endalew et al 2014)—on degraded mountain land has been expanding in Fagita Lekoma District in the northwestern highlands of Ethiopia. This practice has substantial short-term economic benefits, including enhanced access to fuelwood and construction materials.

However, the magnitude of such changes in the study area and the implications for the reduction of cropland are not well understood and have not been quantified. Understanding land conversion in a study area is important to deliver decision-support ideas and identify the incentives and requirements to expand planting activities. This would enable practitioners to effectively implement development interventions and reduce the degradation of forest and other natural resources in the highlands of Ethiopia, while improving smallholders' livelihoods.

This study was conducted in Fagita Lekoma District to assess the evolution and magnitude of land cover changes caused by human activity during a period of 20 years (1995–2015) using remote sensing data. It also aimed to provide insight into the landscape dynamics linked to tree-based farming. Fagita Lekoma, which has experienced considerable expansion of *A. decurrens* plantations, provides an opportunity to understand the requirements and incentives to enhance local communities' participation in the restoration of degraded mountains through tree planting. The study adds knowledge on the successful implementation of restoration measures on degraded mountain land by providing evidence of site-specific drivers of land cover change. This knowledge can support the design of forest restoration and development programs that are effective and attractive to local communities. Based on our observations, the rapid expansion of forest cover in cropland and marginalized lands in the study area is attributed to the planting of *A. decurrens*. We also hypothesized that this expansion is mainly driven by the effectiveness of *A. decurrens* in improving livelihood diversification and by the species' adaptability to acidic soil conditions.

Material and methods

Study area

Fagita Lekoma District, the study area, is located at approximately 36°40′–37°06′ E longitude and 10°56′–11°12′ N latitude. It is northwest of Addis Ababa, the capital of Ethiopia, in Amhara National Regional State (Figure 1). The district encompasses about 67,750 ha, and the population is estimated (based on the 2007 census) at 149,000. The district is in the northwestern highlands of Ethiopia, which are characterized by a rugged mass of mountains. Elevation ranges from 1888 to 2915 m above sea level. Most of the mountain land in the study area is degraded and devoid of vegetation.

The average annual rainfall is 1700 mm, based on data from the closest meteorological stations for 1983–2012, with peak rainfall occurring from June to August and the dry season from January to April. The major crops are cereals and pulses. The main land cover types (LCTs) are cropland, forestland, grassland, and settlements. The soil, predominantly Acrisols and Nitosols, has been severely eroded (Nigussie et al 2017b). The predominant exotic tree species grown in the area are *A. decurrens* and *Eucalyptus* species, which are used for fuel and other wood-related products.

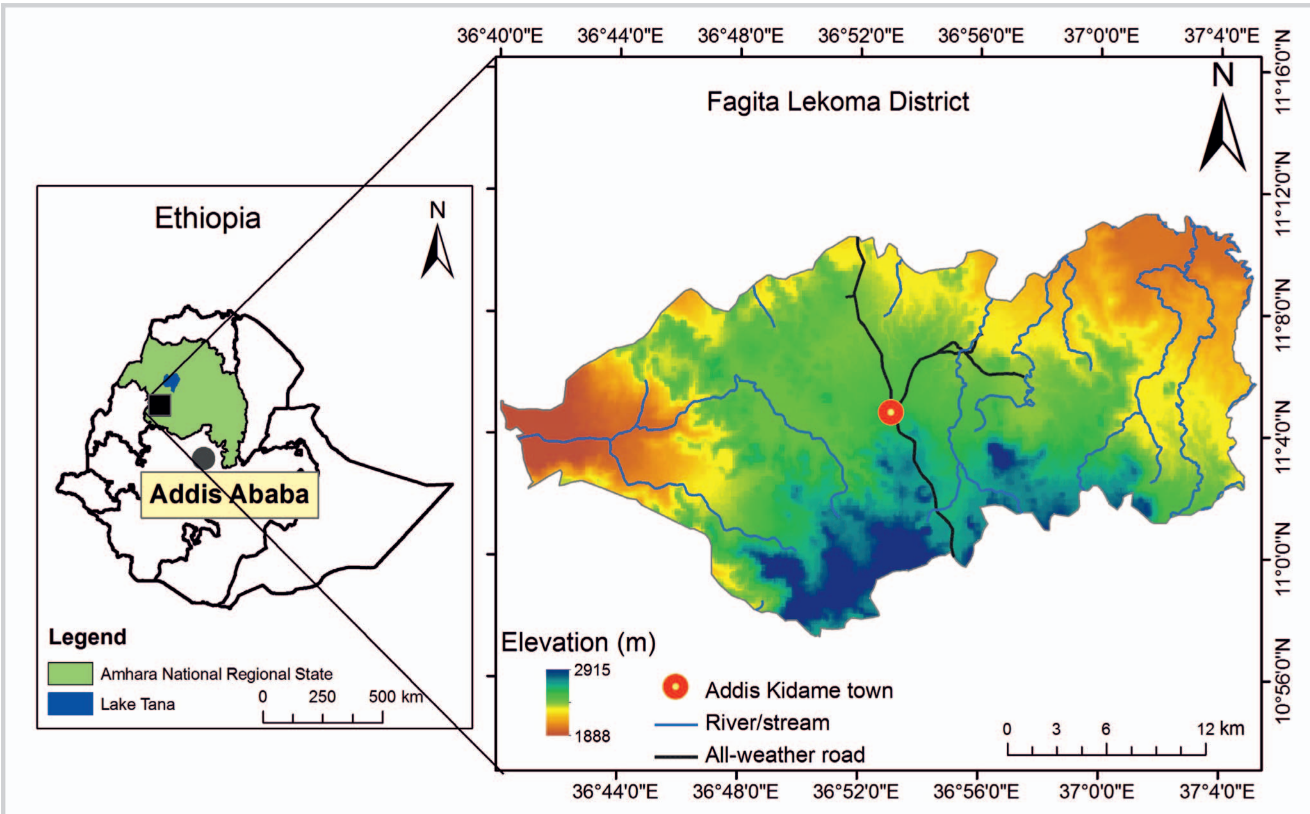
Subsistence agriculture is the predominant economic activity in the study area, as in other parts of the Amhara region and the country (Tesfaye et al 2014). The average household farmland holding is 0.25 ha. The smallholder farmers in the study area predominantly practice cereal-based production, tree-based farming, livestock raising, or a combination of these practices (Abegaz 2005). Nigussie et al (2017a) indicated that the most important motivations for tree-based farming in the study area include income, soil fertility management, and soil and water conservation. Over 95% of the annual agricultural output is produced on fragmented microholdings (Tesfaye et al 2014). Average production varies depending on the crop. For example, the average production of teff, a popular grain, is estimated at 800 kg per hectare, while that of potato is about 6500 kg per hectare.

Limited off-farm activities—mainly charcoal production, nursery management, and production of bamboo furniture—are also available in the study area. The district is divided into *kebele* or municipalities, which are further subdivided into villages.

Data sources and preparation

Temporal and spatial changes were analyzed using images from the Landsat Thematic Mapper and Landsat Operational Land Imager, acquired from the website of the US Geological Survey (https://earthexplorer.usgs.gov) at no cost. Four datasets were used representing dates ranging from 1995 to 2015 (Table 1). These datasets were chosen based on the availability of the data and because

FIGURE 1 Location of the study area. (Map by Menale Wondie)



they were cloud free. Preparation of the data from these multispectral images—such as layer stacking, enhancement, and haze reduction—was done using ERDAS (Earth Resources Data Analysis System) Imagine software. Geometric correction was not considered necessary due to the near-nadir viewing characteristics of Landsat.

To generate elevation and slope information, a digital elevation model with a 30 m spatial resolution was obtained from the US Geological Survey website. Global Positioning System (GPS) point data were obtained during a field survey conducted in September and October 2015. We used these GPS data to familiarize ourselves with the study area and to facilitate the selection of 143 training sites for land cover classification (hereafter referred to as areas of interest or AOIs). The number of AOIs for cropland, forestland, grassland, and settlements were 50, 51, 31 and 11, respectively. The AOIs were selected randomly after identifying the availability of representative LCTs in an image. Different parts of the study area were visited to facilitate the collection of training samples for each LCT.

We also conducted key informant interviews to strengthen and triangulate the information obtained from Landsat image analysis and to better understand the historical land cover changes in the study area. Nine key informants were interviewed—6 farmers, 1 forest expert, 1 land administration expert, and 1 soil and water conservation expert. Farmers were members of village-level administrative bodies, elders, or model farmers (ie farmers who perform well and are early adopters of farm technologies). The key informants were selected in

TABLE 1 Data sources and dates of acquisition.

Source	Path/row	Year/day	Spatial resolution
Landsat 5/Thematic Mapper	170/052	1995/044	30 m
Landsat 5/Thematic Mapper	170/052	2000/042	30 m
Landsat 5/Thematic Mapper	170/052	2010/357	30 m
Landsat 8/Operational Land Imager	170/052	2015/035	30 m

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TABLE 2 Land cover classification scheme.

Classification	Description
Cropland	Cultivated land used for annual production of cereals, pulses, or oil crops.
Forestland	Plantation forest, shrubland, or natural forest.
Grassland	Land allocated for grazing or hay production.
Settlement	Settled areas large enough to be recognized in 30 m resolution Landsat image (excludes scattered rural settlements).

consultation with local administrative bodies and the district agricultural office and were chosen due to their active involvement in natural resources management initiatives, including community mobilization, construction of soil and water conservation structures, and afforestation and reforestation programs.

Classification methods

We defined cropland as the land used for annual crop production, such as the production of cereals, pulses, and oil crops. Forestland was defined as the land covered by plantation forest, shrubland, or natural forest. On satellite images, cropland appears as smooth surface, has sharp edges, and is easy to delineate, while the surface of forestland is rough and textured. Altogether, 4 LCTs were defined for use as a reference during image analysis (Table 2). To develop this classification scheme, data from the 2015 Landsat satellite images were analyzed and compared with data obtained during a field survey.

For the Landsat data, a supervised classification method was used with a maximum likelihood algorithm. This algorithm was chosen because it accounts for the variance and covariance, and assumes that the data are normally distributed. The enclosed polygons, referred to as AOIs, were used to train for classification. AOIs were defined as a signature for the respective LCT to enable supervised classification. Relatively homogenous AOIs were selected visually to minimize mixture of signatures and misclassification. Each AOI was assigned based on the description developed for the classification scheme. The size and number of AOIs depended on the availability of the respective land cover signature. AOIs were distributed throughout the study area to represent the signature of each LCT. Additional homogeneous training areas were chosen when misclassification had to be assumed. Multiple attempts were made with modified training areas by looking at the separability values obtained from the AOIs for each LCT.

The accuracy of the automated classifications derived from the Landsat image was evaluated by comparing them to geographically referenced GPS point data obtained during the field survey (van Oort 2007) and developing an error matrix (Table 3). The comparison was done by overlaying the GPS reading of a certain LCT on the corresponding classified data. Then, the accuracy of each of the land cover classifications was computed by dividing the number of correctly classified GPS readings by the total number of GPS readings collected from the field.

Analysis of changes in land cover

Land cover changes were detected by comparing 1995 image values with the corresponding values from 2015. The ERDAS IMAGINE Spatial modeler was used to detect land cover change between the datasets for these 2 years. The ERDAS IMAGINE Spatial modeler is a toolbox in ERDAS Imagine software. It has an interface where the required functions and modeling can be developed for change analysis—in other words, where scripts for change analysis can be developed. The following conditional formula was used to develop scripts for change analysis and detect the change:

$$\begin{aligned}&\text{Difference of 1995 to 2015}\\&\quad= \text{CONDITIONAL}\{(<test1>)<arg1>,\\&\qquad\qquad(<test2>)<arg2>,..\}\end{aligned}$$

where <test> is the if condition, and <arg> is the argument or the output due to the developed script or analysis.

In this study, the 4 LCTs were cropland (labeled as 1), forestland (2), grassland (3), and settlement (4). Using the previously described script or formula, change analysis was carried out, for example as

Land cover change = If (if (cropland in 1995 remains cropland in 2015, it gets the value 1), if (cropland 1995 changed into forestland in 2015 = 2), if (cropland in 1995 changed into grassland in 2015 = 3), if (cropland in 1995 changed into settlement in 2015 = 4), …, if (settlement in 1995 changed into cropland in 2015 = 13), if (settlement in 1995 changed into forestland in 2015 = 14), if (settlement in 1995 changed into grassland in 2015 = 15), if (settlement in 1995 changed into settlement in 2015= 16))

The result of this operation gave a change map for every pixel. There were 16 change classes (including "no change") corresponding to the change from each of the 4 LCTs in 1995 to each in 2015. A conversion matrix was compiled to quantify land cover change in terms of number of pixels for each LCT. The number of pixels was then changed into hectares or percentages for presentation (Tables 4, 5).

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TABLE 3 Error matrix showing the accuracy of the land cover type classification.[a)]

Class types determined from reference source (field survey data)					Totals	User's accuracy[b)]
Plots	Cropland	Forestland	Grassland	Settlement		
Class types determined from classified map (ie Landsat-based data)						
Cropland	17	0	3	2	22	77%
Forestland	0	22	0	0	22	100%
Grassland	2	0	15	0	17	88%
Settlement	1	0	0	5	6	83%
Totals	20	22	18	7	67	
Producer's accuracy[c)]	85%	100%	83%	71%		Total 88%

[a)] *Note:* accuracy assessment: Total accuracy: $Accuracy_{total} = \frac{17+22+15+5}{67} \times 100 = 88\%$. Diagonals represent sites classified correctly according to reference data. Off-diagonals were misclassified.

[b)] User's accuracy tells us how many of the pixels on the map are actually what they say they are for a given class. It is calculated as:

$$\frac{\text{Number correctly identified in a given map class}}{\text{Number claimed to be in that map class}}$$

For example, $Accuracy_{user-cropland} = \frac{17}{22} \times 100 = 77\%$

[c)] Producer's accuracy tells us how many of the pixels on the map are labelled correctly for a given class in reference plots. It is calculated as:

$$\frac{\text{Number correctly identified in reference plots of a given class}}{\text{Number actually in that reference class}}$$

For example, $Accuracy_{producer-cropland} = \frac{17}{20} \times 100 = 85\%$

The LCT change rates were analyzed using the method of Peng et al (2008):

$$K1 = \left(\frac{(A_t - A_0)}{A_0}\right) \times \left(\frac{100\%}{T}\right) \qquad (1)$$

where K1 is the LCT change rate; A_t and A_0 are the area of the target LCT at the start and end of the study period, respectively, and T is the study period in years.

Limitations of the classification

A precise definition of LCTs was difficult. There were mixtures of spectral values from the pixels selected for training. Such mixtures could be explained in 2 ways:

1. Seedlings and young trees (1 to 1.5 years old) were not detected as forest at the spatial resolution of the acquired Landsat image due to their smaller size, which could result in underestimation of forest area (Wulder et al 2004). Seedlings or young trees might be classified as cropland or grassland, depending on the undergrowth or LCT surrounding them, which could result in an overestimation of those categories. This was confirmed using GPS point data obtained during the field survey. Also, individual trees scattered in farm plots used for agroforestry with a smaller crown size than the pixel size of the Landsat data were not recognized and therefore not classified as forest. This resulted in the assignment of those pixels to the dominant LCT (eg cropland or grassland) surrounding them.

TABLE 4 Land cover change, 1995–2015.

Land cover	1995		2000		2010		2015	
	ha	%	ha	%	ha	%	ha	%
Cropland	44,390	65.5	49,581	73.2	38,581	57.0	35,443	52.3
Forestland	13,935	20.6	12,369	18.3	11,397	16.8	17,330	25.6
Grassland	9,357	13.8	5,528	8.2	17,284	25.5	14,411	21.3
Settlement	56	0.1	259	0.4	476	0.7	554	0.8
Total	67,737	100.0	67,737	100.0	67,737	100.0	67,737	100.0

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TABLE 5 Annual rate of land cover change, calculated using equation 1.

Period	Rate of change (percent per year)			
	Cropland	Forestland	Grassland	Settlement
1995–2000	2.3	−2.2	−8.2	72.5
2000–2010	−2.2	−0.8	21.3	8.4
2010–2015	−0.8	5.2	−1.7	1.6
1995–2015	−1.0	1.2	2.7	44.5

2. AOIs representing settlements were selected from urban surfaces by looking at the pattern and texture of clustered villages. However, houses in rural areas are scattered, and the roofs are not large enough to be recognized at the resolution of the Landsat data, so they were probably assigned to other LCTs. Consequently, the land allocated for settlement might be underestimated.

Results and discussion

Accuracy of the classification process

The overall accuracy and Kappa values were 88 and 83%, respectively. The classification of forest displayed a 100% producer's accuracy, indicating that no pixel was incorrectly excluded from this LCT (Table 3). The classification of settlement displayed the lowest producer's accuracy (71%).

Land cover change over time

Cropland was the dominant LCT during the entire study period (1995–2015); the second dominant LCT was forestland. The overall farming system in the study area changed during this period, and there were considerable changes in LCTs (Figure 2, Table 4).

The area covered by cropland increased in the first 5 years (1995–2000) and decreased thereafter (Table 4). In the study period as a whole, it decreased by 8946 ha. This could be attributed to the increase in forest cover and

FIGURE 2 Land cover in the study site in 1995, 2000, 2010, and 2015.

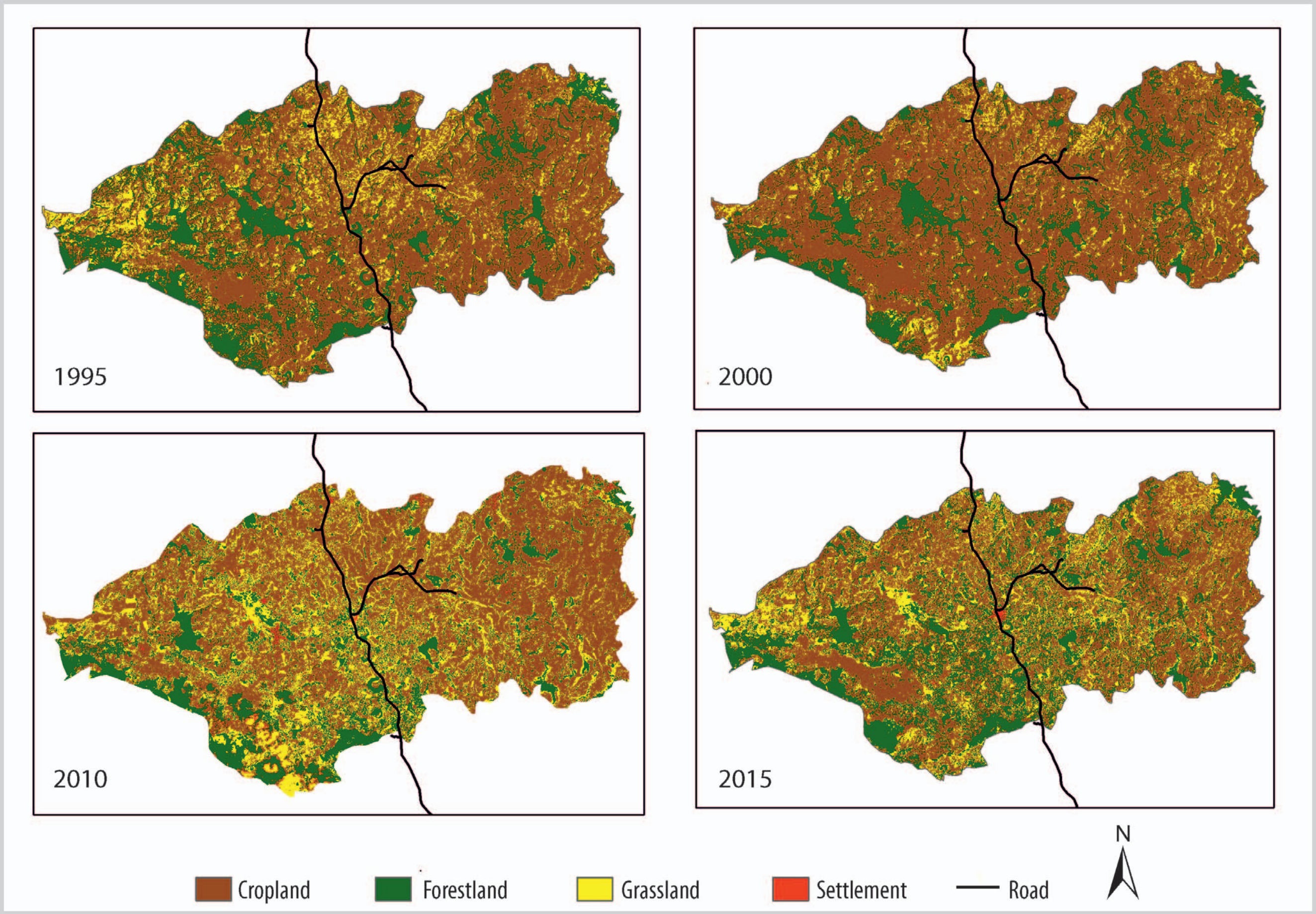
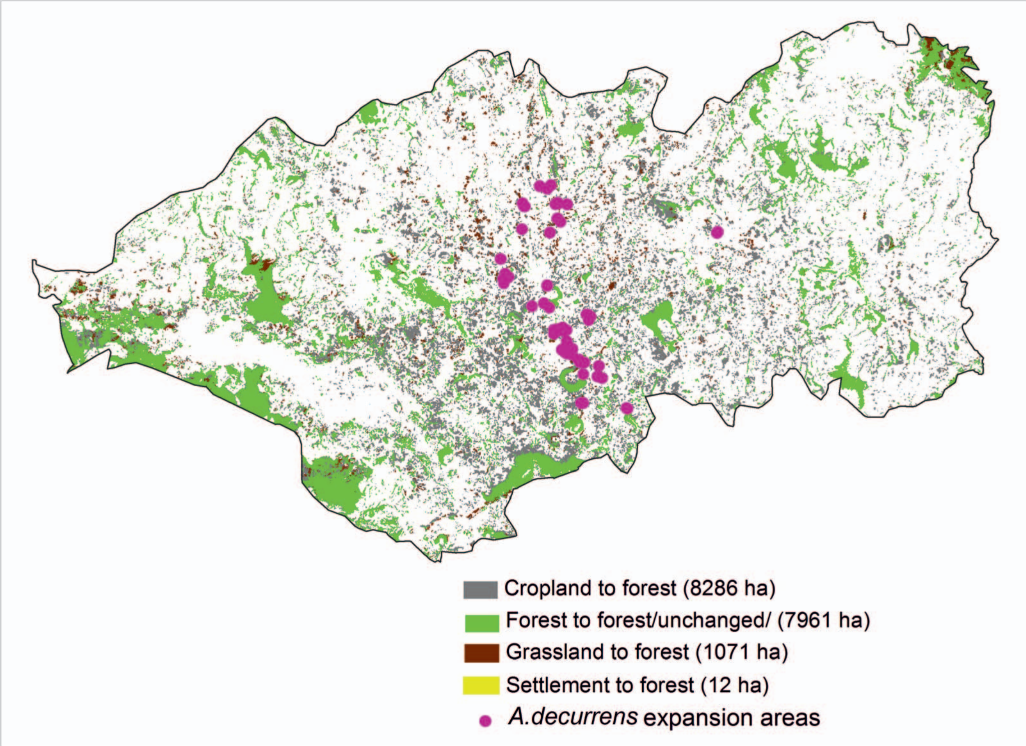


FIGURE 3 Land cover change to forest, 1995–2015.



other land uses. Settlement areas increased from 0.1% in 1995 to 0.8% in 2015, especially along the highway (Table 4). This remarkable increase is an indication of population growth and is one of the drivers of land cover change. Expansion of small villages along the highway has led to increased construction of infrastructure, which competes with the surrounding land that was previously used for farming and grazing.

During the entire study period (1995–2015), cropland displayed a 1% decline per year, while forestland increased by 1.2 % per year, grassland increased by 2.7% per year, and settlement areas by 44.5 % per year (Table 5). Forests (mainly through planting of *A. decurrens*) and grasslands showed the most significant changes over the 20-year period (Figure 3). This pattern suggests that, at the present rate of change, the study area is likely to be mostly covered by forest and grassland in 15 to 20 years.

According to key informants, in 1995, the forest in the study area was predominantly natural forest, and the contribution of tree plantations to total forest cover was negligible until 2010. Forest cover decreased from 1995 to 2010. This could be attributed to population growth and the associated increases in demand for agricultural land, fuelwood, and construction materials, as well as limited tree planting during this period. For example, within 5 years (1995–2000), cropland increased by 5191 ha (2.3% per year). However, from 2010 onward, forest cover increased (Table 4). This could partly be explained by the recent expansion of *A. decurrens* in the area, which farmers are planting around homesteads, farmland, and communal land due to its economic importance (Figure 4).

A. decurrens is an important source of fuel and of money from the sale of charcoal (Figure 5). According to development experts and key informants, the area planted to *A. decurrens* continues to increase for these reasons. Its expansion is considerable along the roads, which could be related to market access for forest products.

Benefits and disadvantages of *A. decurrens*

A. decurrens is preferred by the smallholder farmers in the study area because of its fast growth (farmers harvest it 4 or 5 years after planting) and wide adaptability. The trees are planted either after clearcut or on farm plots that were used for other purposes. During the first 2 years after planting, farmers usually grow cereals together with *A. decurrens* (Figure 4B). This is a new farming system in the study area that was introduced to efficiently use the space between seedlings and maximize the benefits per unit area. It also minimizes the decline in agricultural productivity due to planting of *A. decurrens*. These activities indicate the possibility of maximizing benefits by integrating fast-growing trees with annual crops.

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FIGURE 4 *Acacia decurrens* in the study area, planted (A) around homesteads; (B) on agricultural land; and (C) on communal land. (Photos by Dessalegn Tadesse)

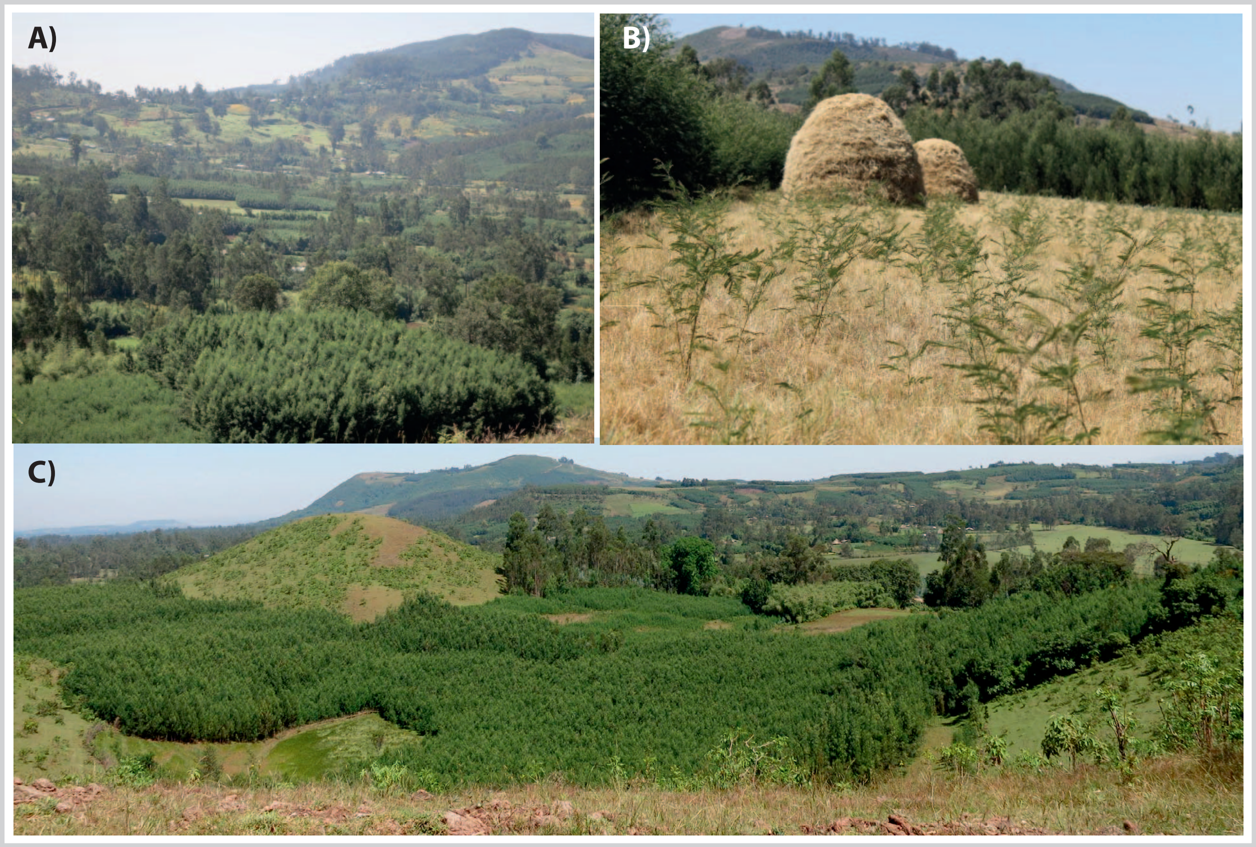

FIGURE 5 Charcoal production from *Acacia decurrens*. (Photo by Dessalegn Tadesse)

Key informant interviews demonstrated that expansion of *A. decurrens* plantations in degraded landscapes creates additional jobs for landless youth and provides an opportunity to diversify livelihoods. For example, it creates job opportunities at various stages such as planting, managing, and harvesting, as well as during charcoal production and marketing of products. However, it could also lead to a reduction in crop production, as it has led to a decrease in cropland, as discussed previously. Other studies (eg Cao et al 2010) have also demonstrated that expansion of such monoculture plantations is not necessarily entirely beneficial. Indeed, such plantations might have long-term negative impacts due to the occurrence of diseases and pests as well as due to reduction in water availability.

Our results are consistent with those of Bewket (2002), who demonstrated that forest cover has increased around homesteads in the highlands of Ethiopia, which is related to growing trees to meet household energy demands, as the surrounding forests are degraded. Wondie et al (2011) demonstrated increases in forest cover in Semen Mountain National Park, though this increase was not due to planting. Studies by Tekle and Hedlund (2000) and Zeleke and Hurni (2001) found a general decrease in

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natural forest and an increase in plantation forests in the highlands of Ethiopia. This indicates that site-specific evidence is needed to understand the drivers of deforestation and restoration of degraded landscapes in the highlands of Ethiopia.

Drivers of change

The probability of conversion from one LCT to another is dependent on demographic changes, as well as the economic and financial returns of the chosen farm enterprise—that is, the market demand, land availability, policy decisions, and social or cultural values. Most rural people in the Ethiopian highlands allocate more land for crop production than for other LCTs to feed their families. The increase in forestland in the study area between 1995 and 2015 is, thus, in contrast to the trend in most rural areas in Ethiopia. The changes in our study area are driven by soil fertility and market demand for charcoal. Farmers are major contributors to the decline or increase of an LCT. Because trees require more space than annual crops, farmers who have more land can diversify their livelihoods by planting trees to supplement their income and reduce the risk of failure. The soil of the Awi Zone, which includes Fagita Lekoma District, is highly acidic (Endalew et al 2014). Soil acidity causes difficulties for annual crop production because of nutrient fixation. This compels farmers to either grow crops that tolerate acidity, or plant trees that can restore soil fertility and/or generate additional income for the household.

Conclusions and recommendations

The landscape of the study area has been modified by human activities, mainly the expansion of *A. decurrens* plantations and settlement areas. Farmers in the study area have been replacing other LCTs, mainly cropland, with *A. decurrens*, and thus increasing the forest cover. The expansion of *A. decurrens* is mainly attributable to its adaptability, fast growth, and potential short-term economic benefits from the sale of charcoal and fuelwood. This indicates that introducing economically important tree species could support efforts to restore degraded landscapes. The expansion of *A. decurrens* has benefited smallholder farmers; hence, we suggest that this activity be expanded, especially in degraded landscapes. Further investigation of the multiple uses of the tree would help maximize its benefits. Although our study showed that the expansion of *A. decurrens* plantations is effective at increasing forest cover and smallholder incomes, it also reduces the amount of land that can be allocated for crop production. In addition, monocropping of *A. decurrens* requires careful consideration of the risks of disease and pest infestation. In addition, the social consequences of such a decision should also be considered.

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