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Quantifying longitudinal land use change from land degradation to rehabilitation in the headwaters of Tekeze-Atbara Basin, Ethiopia

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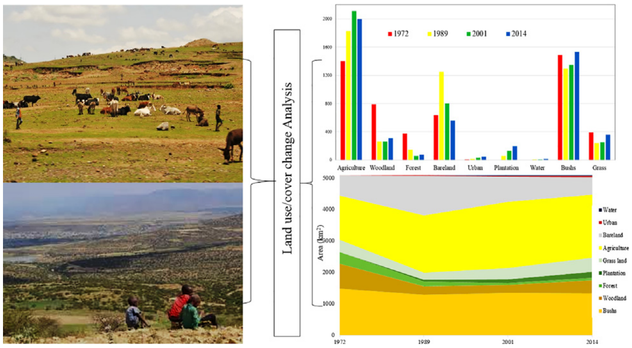
HIGHLIGHTS

- Accurate information on land use/cover dynamics is essential for improved understanding of land and water management.
- Landscape transformations were studied based on satellite and in-situ information.
- 72% of the landscape has changed its category during the past 4 decades.
- Although both net and swap changes occurred, the latter is more dominant.
- Increasing of vegetation cover resulted from intensive watershed management programs

GRAPHICAL ABSTRACT



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ABSTRACT

The spatiotemporal variability of the Land Use/Cover (LULC) is a strong influence on the land management and hydrological processes of a river basin. In particular in semi-arid regions like the Tekeze-Atbara (T-A) basin, accurate information about LULC change is a prerequisite for improved land and water management. The human-induced landscape transformations in the T-A basin, one of the main tributaries of the Nile River, were investigated for the last four decades (1972–2014). Separate LULC maps for the years 1972, 1989, 2001, and 2014 were developed based on satellite images, Geographic Information System (GIS) and ground information. Change detection analysis based on the transitional probability matrix was applied to identify systematic transitions among the LULC categories.

The results show that >72% of the landscape has changed its category during the past 43 years. LULC in the basin experienced significant shifts from one category to other categories by 61%, 47%, and 45%, in 1972–1989, 1989–2001, and 2001–2014, respectively. Although both net and swap (simultaneous gain and loss of a given LULC during a certain period) change occurred, the latter is more dominant. Natural vegetation cover, including forests, reduced drastically with the rapid expansion of crops, grazing areas and bare lands during the first two decades. However, vegetation started to recover since the 1990s, when some of the agricultural and bare lands have turned into vegetated areas. Forest land showed a continuous decreasing pattern, however, it has increased by 28% in the last period (2001–2014). In contrast, plantation trees have increased by 254% in the last three decades. The increase of vegetation cover is a result of intensive watershed management programs during the last two

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decades. The driving forces of changes were also discussed and rapid population growth and changing government policies were found to be the most important.

1. Introduction

Understanding land and water management in a basin require detailed information on Land Use/Cover (LULC) management practices (Cheema and Bastiaanssen, 2010; Kiptala et al., 2013; Sanyal et al., 2014; Woldesenbet et al., 2017). LULC change in combination with unsustainable land management directly impacts biodiversity, ecosystem services, crop productivity, hydrology (Ariti et al., 2015; King et al., 2005; Kiptala et al., 2013; Teferi et al., 2013), and may even influence local climate if it occurs at relatively larger scales (Wang et al., 2015). For example, changes in LULC of a catchment modify the availability of water resources of a basin in complex ways (Liu et al., 2005), and in particular the partitioning of rainfall to overland flow, interflow, and deep percolation (Taniguchi, 2012). The impact of LULC on the environmental processes is not universal, and depends on the local context in a particular region (Haregeweyn et al., 2014; Lu et al., 2015; Chen et al., 2016). For example, vegetation cover reduces direct runoff volume, as well as the flow peaks, whilst enhancing the infiltration rate and hence the base flow of the stream (Yair and Kossovsky, 2002). In contrast, other studies reported reduced direct runoff and lower base flow because of the increased vegetation cover, e.g. Ott and Uhlenbrook (2004), Sanyal et al. (2014). This emphasizes the need to study both natural and anthropogenic processes, and how these may influence the environmental processes of a given basin.

The literature shows that anthropogenic factors are the main drivers of changes in land management practices and variability in water availability in Ethiopia (Bewket and Sterk, 2005). The drastic increase of population (more than doubled from 1984 to 2012) and economic development of Ethiopia escalates the pressure on natural resources (CSA, 2008). The need to provide food, water and shelter for people and livestock coupled with poor land management has significantly contributed to land degradation in the highlands (Hurni et al., 2005). A substantial increase of agricultural and grazing lands during the last few decades was at the expense of forest and shrub lands (Ariti et al., 2015; Teferi et al., 2013; Haregeweyn et al., 2014). Such changes in land surface reduced land productivity and increased water scarcity in most parts of Ethiopia (Wondie et al., 2011; Teferi et al., 2013). For example, Gebremicael et al. (2013) demonstrated that change in LULC in the Upper Blue Nile basin increased surface runoff by 75% and decreased the dry season flow by 25% during 1973–2005. However, in recent decades, the country has made significant efforts to rehabilitate degraded lands through integrated watershed management (IWSM) programs (Nyssen et al., 2010; Teferi et al., 2013). The IWSM increased vegetation cover and decreased land degradation (Alemayehu et al., 2009; Belay et al., 2014).

Local studies in the Geba catchment of the Tekeze-Atbara (T-A) basin revealed that no specific pattern of LULC change is observed. Belay et al. (2014) reported increased vegetation cover whilst Alemayehu et al. (2009) and Bizuneh (2013) showed opposite results. However, most of those studies were conducted in a very small watershed (145–275 km^2) which cannot represent the entire catchment. A limitation reported by these studies is that only net change was considered (not swap change), which could underestimate the amount of the LULC change. Pontius et al. (2004) and Teferi et al. (2013) showed that swap change (simultaneous gains and losses among LULC categories) is more important in recognizing the total change than the net change.

Therefore, the main objective of this study was to accurately assess the spatiotemporal dynamics of LULC and the associated land management changes in Geba catchment, being the source region of the T-A basin. This basin is known for its severe land degradation and simultaneously for best experiences in environmental rehabilitation programs (Nyssen et al., 2010). Therefore, studying the patterns of LULC changes in such a contrasting environment has the potential to improve our understanding of land and water management of the basin.

2. Study area description

The Geba catchment (5085 km^2) is located in northern Ethiopia which extends from 38°38′ to 39°48′E and 13°14′ to 14°16′N (Fig. 1). It forms the headwaters of the T-A River basin, one of the major tributaries of the Nile River. The topography is characterized by highlands and hills in the north and north-eastern and plateaus in the central part of the catchment. The central plateaus are dissected by several rivers that flow towards the southwestern part of the basin and joins the main Tekeze River at Chemey. The altitude varies from 3300 m above seas level (m·a.s.l.) at Mugulat Mountains near Adigrat town to 930 m·a.s.l. at the basin outlet. The Geba catchment is characterized by a semi-arid climate in which the majority of the rainfall occurs from June to September after a long dry season. >70% of the total rainfall is falling in July and August only with high storm intensities (Gebremicael et al., 2017). Rainfall over the catchment is highly variable mainly associated with the seasonal migration of the intertropical convergence zone (ITCZ) and the complex topography (Nyssen et al., 2005). The mean annual precipitation ranges from below 440 mm/year in the Eastern part to 800 mm/year in the Northern and the Western part of the basin.

Land use in the basin is dominated by rainfed agriculture (40%) followed by shrubs (27%), bare land (20%), grassland (9%), forest (1%) and residential areas (3%). Common rainfed agriculture in the basin includes Teff, wheat, barley, maize, sorghum and pulses. However, irrigated agriculture at the household level has also increased significantly in the recent years (Alemayehu et al., 2009; Nyssen et al., 2010). Bare land and shrubs are mainly dominant in the semi-arid eastern lowlands of the basin whilst most of the cultivable lands and very small forest coverage occur in the highlands but dry areas of the basin. Agricultural and bare lands have been expanded at the expense of all other land uses in the basin.

The majority of the geological formations are Enticho Sandstone, Edag Arbai Tillites, Adigrat Sandstone, Antalo Super sequence and Metamorphic (basement) rocks (Virgo and Munro, 1977; Gebreyohannes et al., 2013). The dominant soil types of the catchment are clay loam (40%), sandy clay loam (30%), clay (19%), loam (10%) and sandy loam (1%) (Zenebe et al., 2013; Abraha, 2014). The occurrence of soil textures across the whole catchment is deeply weathered soil in the upper most plateaus, rocky and shallow soils in the vertical scarps, coarse and stony soils in the steep slopes, finer texture soils in the undulating pediments and most deep alluvial soils are found in the alluvial terraces and lower parts of the alluvial deposits (Abraha, 2014; Gebreyohannes et al., 2013). Most of the soils in the basin are limited in depth due to contagious hard rocks and cemented layers and hence not suitable for agricultural production despite farmers having cultivated them for a long time because of shortage of arable land in the basin (Virgo and Munro, 1977).

This catchment is known for its severe land degradation resulted from the high population and socio-economic developments. However, the recent IWSM programs have led to significant improvements of natural resources. Various forms of intervention programs including; physical Soil and Water Conservation (SWC), biological SWC, water harvesting programs and conservation agriculture have been implemented in the basin (Belay et al., 2014; Nyssen et al., 2010; Alemayehu et al., 2009; Munro et al., 2008). A brief summary of these

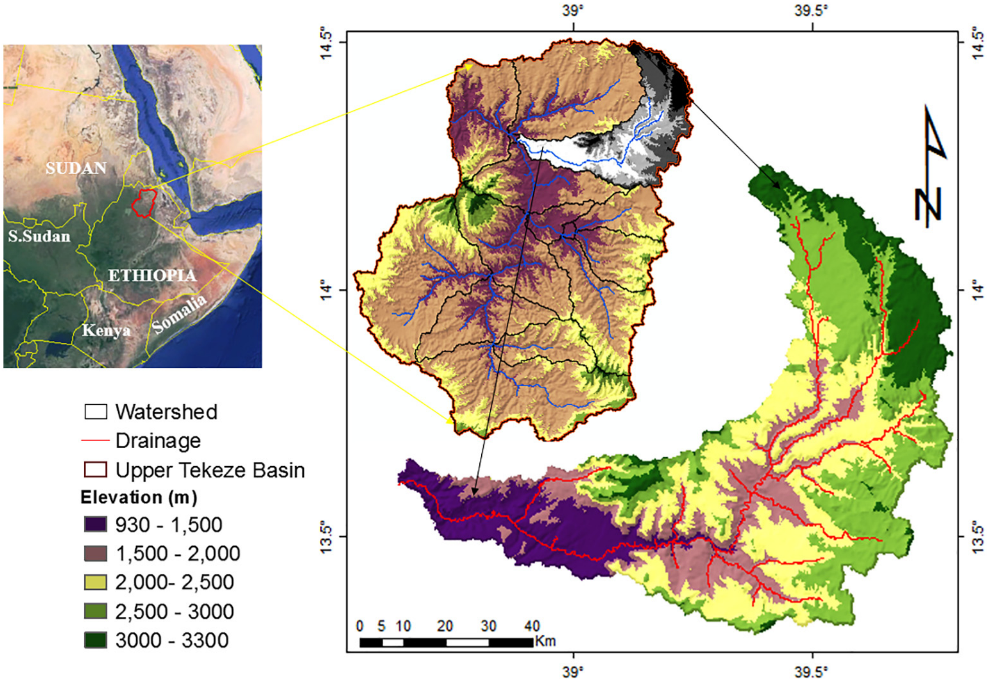

Fig. 1. Location map of the Geba catchment with its elevation (m·a.s.l) in the upper Tekeze river basin.

intervention programs is given in the supplementary material (Table S1). These programs have been implemented by mobilizing the community for free-labour days and food for work through different programs including; Managing Environmental Resources to Enable Transition to more sustainable livelihoods (MERET), Productive Safety Net Program (PSNP), and the National Sustainable Land Management Project (SLMP), (Haregeweyn et al., 2015; Munro et al., 2008).

3. Data and methods

3.1. Data acquisitions

Satellite images for the years 1972, 1989, 2001, and 2014 were acquired to analyse the spatiotemporal patterns of the LULC in the Geba catchment of the T-A basin. Landsat images for the selected years were obtained from the US Geological Survey (USGS) Centre for Earth Resources Observation and Science (EROS) found in http://glovis.usgs.gov/. A brief descriptions of the collected satellite images including, satellite and sensors used, resolution, acquisition date, swath/row of each images for each period is summarized in Table 1. The years for analysis were selected based on key signs of LULC change, e.g. land degradation, land policy changes, the IWSM interventions, and finally, the availability of satellite image. Images from the same period (October–December), i.e. immediately after the rainy season, were selected in order to minimize the seasonal effect on the classification results (Wondie et al., 2011). Ancillary data, including field data (ground truth points (GTP), interviews and observations), topographic maps, aerial photographs, and secondary literature were collected to derive reference data and topographic variables.

The GTP used for the classifications and accuracy assessment were collected during a field survey from 12/12/2015 to 29/06/2016, as well as from the ancillary data. The GTPs for the 2014 image were collected using Geographic Positioning System (GPS) whilst for 2001, 1989 and 1972, these were derived from available aerial photographs (1994, 1986 and 1965), and existing local and national LULC maps (HTSL, 1979; Belay et al., 2014). In-depth interviews were conducted with 120 local elderly farmers to collect LULC information on 2001, 1989 and 1972. A digital elevation model (DEM) from Shuttle Radar Topographic Mission (SRTM) with 30 m resolution and topographic maps of scale 1:50,000 from the Ethiopian Mapping Agency (EMA) were also collected for geo-referencing and deriving topographic variables.

To determine the impact of socio-economic development and IWSM interventions on LULC change, population data and historical information of IWSM were collected from the Central Statistical Agency of Ethiopia (CSA), the Bureau of Agriculture and Rural Development (BoRD) of the region and from a field survey through interviews of local elders.

3.2. Image pre-processing

Image pre-processing (geometric and atmospheric corrections and topographic and temporal normalizations) was done for all LULC maps. This was vital to establish a direct association between the acquired data and physical occurrences of the study area (Hassan et al., 2016). All satellite images and digitized ancillary paper maps were

Table 1
Specifications of satellite images used for this study.

Satellite	Sensor	Path/row	Resolution (m)	Acquisition date
Landsat 1–3	MSS Multispectral	181/50/51	60	02-11-1972
Landsat 4–5	TM Multispectral	168/51 169/50/51	30	21-11-1989
Landsat 7	ETM^{+} Multispectral	168/51 169/50/51	30	16-11-2001
Landsat 8	Operational Land Imager (OLI)	168/51 169/50/51	30	04-12-2014 11-12-2014

georeferenced to a common coordinate system using the topographic map at 1:50,000 scale and Universal Transverse Mercator (UTM) map projection (Zone 37) and WGS 84 datum in ArcGIS 10.1 and Erdas Imagine 2014. Even if the collected satellite data were georeferenced from the sources, it was necessary to geo-rectify them against the base map using 60 control points in order to avoid some misalignments in the study area.

The study area is characterized by rugged topography and topographic and atmospheric corrections of the images were needed to retrieve the actual surface reflectance. The reflectance in rugged terrains is strongly influenced by solar illumination and viewing geometry. Moreover, the terrain illumination correction is important in the time series imagery analysis as its effect may vary with different dates (Kopačková et al., 2012). Such effects were minimized using Topographic and Atmospheric Correction for Airborne Imagery (ATCOR-4) package (Richter and Schlapfer, 2012). This method is a well-established process for atmospheric and topographic corrections using DEM (Kopačková et al., 2012). High accuracy of atmospheric compensation and topographic correction is achieved by employing the correlated k algorithm in the ATCOR-4 software. Finally, normalization of pixel brightness value variations among the images taken in the different period was done by applying image regression (Jensen, 1996).

3.3. Image classifications, accuracy assessments and post classifications

A hierarchical LULC classification was derived based on descriptions of US Geological Survey LULC approach (Anderson et al., 1976.), author's prior experiences to the study area and local studies (Alemayehu et al., 2009; Belay et al., 2014). Descriptions of identified major LULC classes are given in Table 2.

First, unsupervised classification was performed to identify clusters by their spectral similarities. An Iterative Self-Organizing Data Analysis technique (ISODATA) clustering algorithm which is the most common for clustering of pixels was selected to identify the spectral classes (Congcong et al., 2014). This algorithm is the most commonly used technique for cluster grouping of pixels during unsupervised classifications. It compared each candidate pixel to the cluster mean by lowest spectral distance method and a pixel with closer distance to the candidate pixel is assigned to the cluster. Final classifications were done using ISODATA algorithm based on a 96% convergence threshold.

The LULC maps were further refined with expert judgment and field observations using supervised classifications. Information on 3326 GTPs was collected from different sources for each map. Out of this, 1186 points were used for classifications whilst the remaining 2140 points were used for accuracy assessment. These GTPs were sampled by a stratified random design which is the most common technique to attain high overall accuracy (Congalton, 2001). The sample size of GTPs required for each LULC was assigned based on the dominant classes and inherent variability within the group. Training sites corresponding to each classification type were taken among the collected samples. Signatures for each LULC type were developed and their separability was evaluated based on Euclidean distance. Accordingly, it was found that bare land was difficult to distinguish from urban areas and, to avoid the confusion, urban areas were masked out from the image and classified independently. In addition, there was some confusion between bare and arable lands and plantation and forest classes in the preliminary classification, but these uncertainties were minimized by adding more training samples for each class. Finally, the Maximum Likelihood Algorithm which has superior performance compared to other approaches was used for classification (Al-Ahmadi and Hames, 2009).

Table 2
Descriptions of identified LULC of the study area.

LULC class	Description	Code
Grassland	A land dominated by natural grass, small herbs and grazing lands	GRAS
Agriculture	Areas covered with annual and perennial crops covering >70% of the land.	AGRI
Bushes and shrubs	Areas covered by low woody of <3 m in height, multiple stems, vertical growing of bushes and shrubs with canopy cover between 5 and 50%.	BUSH
Wooded bushes	An intermediate b/n forest and bushes with >3 m in height and less dense	WOOD
Settlements	Built up areas including towns, cities and small villages	URBA
Water body	Any types of surface water	WATE
Bare land	Little or no vegetation cover, exposed rocks and degraded land	BARE
Forest land	High and dense natural forest in churches and reserved areas	FORE
Plantation forest	Forests planted by man	PLAN

To determine the degree of acceptability of the classification processes, accuracy assessment is an important task in remote sensing image analysis (Congalton, 2001). In this study, a holistic accuracy assessment approach using GTPs, validation of land use type with local datasets and visual inspection was adopted. First, visual inspections were performed considering the first author's knowledge of the study area. This evaluation method is a necessary first step in checking the quality of classified maps (Foody, 2002).

Next, the final LULC maps were evaluated using independent GTPs. The accuracy of classified maps was evaluated by computing an error matrix which compares the classification outputs with the GTPs. Quantitative accuracy assessment based on an error matrix is an effective way of evaluating the quality derived maps (Foody, 2002). By comparing the maps and collected 2140 GTPs, characteristic coefficients (User's and Producer's accuracy, overall accuracy and Kappa coefficients) were obtained from the confusion matrix. The User's and Producer's accuracy were used to estimate the accuracy of each LULC types whilst the overall accuracy was applied to estimate the overall mean of user and producer accuracy. The Kappa coefficient expresses the agreement between two datasets corrected for the expected agreement (Van Vliet et al., 2011). Further validations of these LULC maps were done using local datasets and field observations. Information from local LULC change pattern studies (Alemayehu et al., 2009; Belay et al., 2014) were used to cross-check the results. Moreover, field visits to 80 randomly selected sites were done to verify whether the classified LULC types were the same at ground level. The maps were further verified from the pre-determined sites through observations and consulting of 42 local elders.

The post-classification change detections between two independent LULC maps were performed in ArcGIS 10.1 (Jensen, 2005). The developed LULC maps of 1972, 1989, 2001 and 2014 were overlaid two at a time and converted areas from one particular class to any other classes were computed. Transition matrices were computed to analyse the LULC change between two independent maps. To analyse the rate of change, location and nature of the changes, the gains, losses, net change (Ng), total change (Tg), persistence, gain to persistence ratio (Gp) and loss to persistence ratio (Lp) and swap change (Sw) were computed. Detailed descriptions of such calculations can be found in Yuan et al. (2016). These indicators can give robust information on the resistance and vulnerability of a given LULC type (Braimoh, 2006). Patterns of degradation and recovering were carefully examined and compared among the study periods.

To understand the possible drivers of changes, information on socio-economic and environmental factors, including population growth, drought and famine events, government policy changes and environmental rehabilitation programs were analysed using qualitative and descriptive statistics. The relationships between these potential driving forces and land degradation or rehabilitation programs were examined by describing the state of change in these factors and the reactions of the LULC type over time. To find out the contribution of watershed management interventions, analysis of LULC changes before and after IWSM was done in representative small watersheds. The selected watersheds were taken from different locations where intensive IWSM has been implemented since the early 1990s.

4. Results and discussion

4.1. Classification and change detection

The results of the LULC classification for the years 1972, 1989, 2001 and 2014 are shown in Fig. 2. The accuracy of the developed maps was evaluated using statistical indices described in Section 3.3. The overall accuracy and Kappa coefficient of the 2014 map were 84.3% and 81.1%, respectively. Similarly, overall accuracy (and Kappa coefficient) of 86.5% (84.3%), 86.2% (82.6%) and 84.3% (80.4%) were obtained for the maps of 2001, 1989 and 1972, respectively. Confusion matrices for all LULC maps are presented as supplementary material (Table S1). The User's and Producer's accuracies of all maps exhibited a relatively good accuracy of >80% for the majority classes. A lower individual accuracy was obtained for plantation (72%) and agriculture (76.4%) which may be associated with the confusion of reflectance with forest and bare land, respectively. Kappa coefficient >80% represents a strong agreement between classified classes and the reference data (Ariti et al., 2015; Kiptala et al., 2013). Obtained statistical indices demonstrated that the produced maps are sufficiently accurate for further LULC change detections.

The produced maps and estimated area of each LULC category are presented in Figs. 2 and 3a, respectively. The results showed that bushland, agriculture, woodland and bare land were the dominant LULC types at the beginning of the study period. However, as indicated in Fig. 3b, wood, forest, grass and bush lands significantly declined whilst bare land and agriculture increased during the 1972–1989 period. This indicated that there was a substantial reduction of vegetation cover in this period to obtain more crop and grazing lands. Furthermore, in 1989, plantation and water body emerged as new land cover classes.

During the period 1989–2001, the largest decreasing rate was observed in forest cover (−63%) which reduced from 145 km^2 in 1989 to 55 km^2 in 2001 and bare land (−36%) reduced from 1250 km^2 to 800 km^2 with a slight decrease (from 262 to 257 km^2) in woodland whereas the other categories showed a relative growth. The observed decrease in bare land and slight increase in bushland during this period reflects the government policy of the region towards recovering the environment after the devastating drought of 1984/1985. Despite the efforts made to rehabilitate the environment, deforestation of natural forests in highland areas of the basin continued at a significant rate during this period (Figs. 2 and 3a). Although the water body is hard to appraise from Figs. 2 and 3, it has significantly increased from <0.25 km^2 in 1989 to 7 km^2 in 2001. The reason is most likely due to the attention given to small and medium scale water harvesting programs in the 1990s (Haregeweyn et al., 2006). Similarly, urban settlements also significantly increased (from 12 to 31 km^2) during this period, which may be associated with population growth and industrial development around towns.

During the period 2001–2014, all LULC categories except agriculture and bare land showed a relative increase ranging from 4% to >90% (Fig. 3b). A slight decrease (−5%) in agriculture during this period is due to the intensification of urban areas and homestead plantations at the expense of cultivable land. Although at a slower rate compared to the previous period (1989–2001), bare land continued to decrease (from 800 to 561 km^2) during this period. One possible reason is the impact of environmental rehabilitation programs which have been

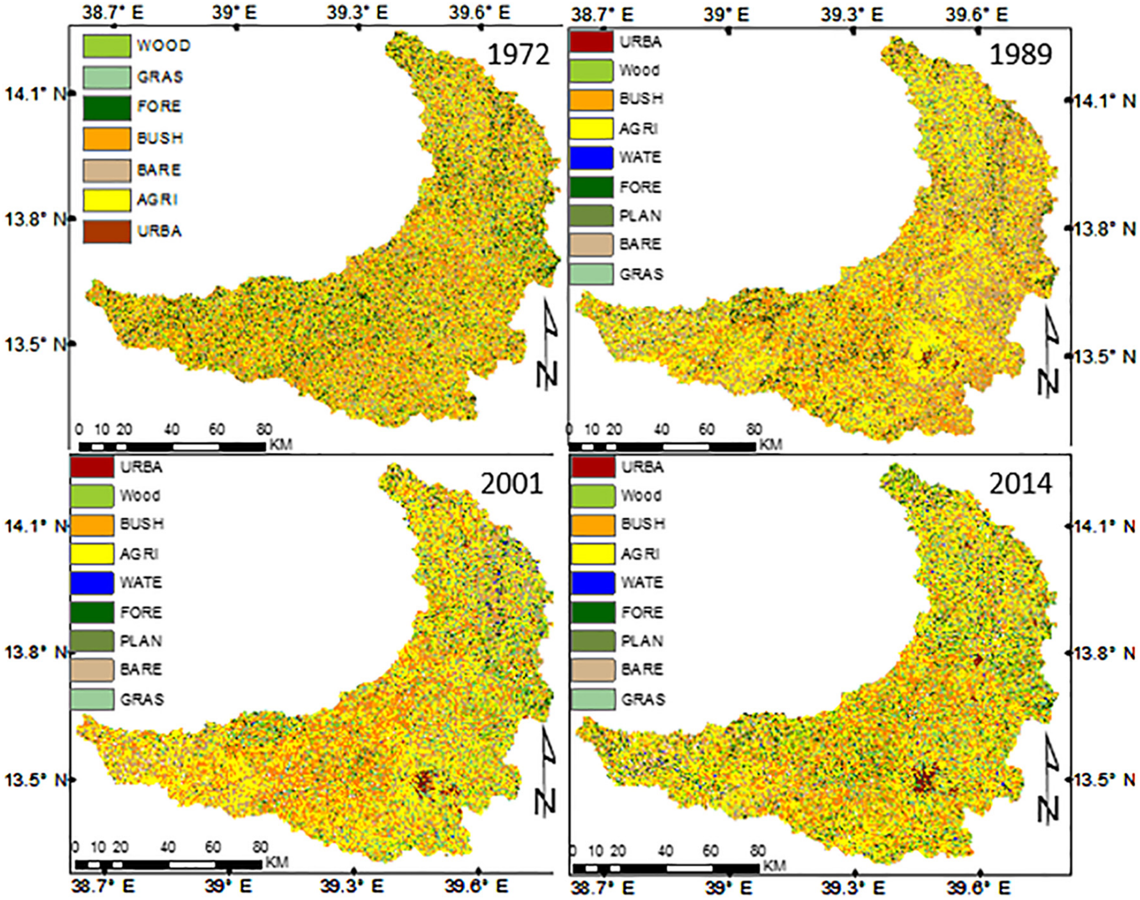

Fig. 2. Land use and land cover maps of the Geba catchment in 1972, 1989, 2001 and 2014. The nature of LULC class across the whole basin is very mixed and some of the classes may not visible in grey scale and readers are recommended to read the details from colour maps.

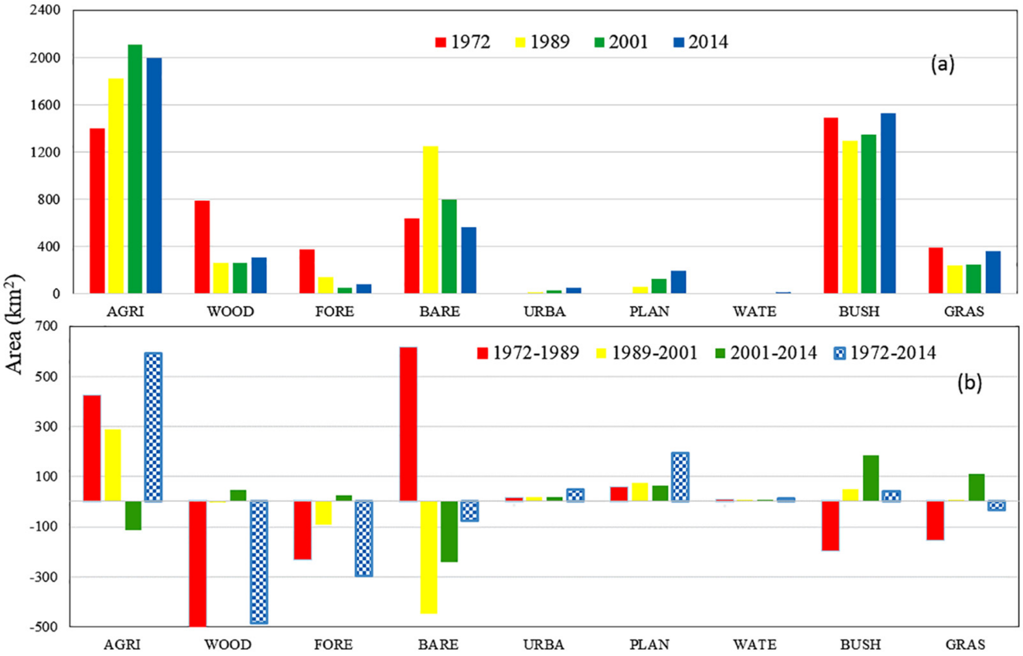

Fig. 3. Area coverage for each LULC (a) Absolute area of each LULC for the four periods, (b) Change in areas between each time step (note that the last bar of each LULC type is the total change for the entire study period, 1972–2014).

intensively implemented in the last two decades (Nyssen et al., 2010; Belay et al., 2014). The positive change (14%) in bush land during 2001–2014 was more pronounced compared to the period 1989–2001 which was only 4%. Significant increases of wood (18%) and forest lands (28%) during this period indicates the emergence of new bush and shrub lands whilst existing ones were transformed into wood and forest land. Urban and the water body areas that have started to increase in the preceding period continued the increasing trend from 31 to 48 km^2 (57%) and from 6.4 to 12 km^2 (92%), respectively.

Overall LULC in the catchment has considerably changed in the last 43 years. Plantation, urban and water body showed a continuous increasing trend in all periods but the remaining LULC categories exhibited different change patterns in different periods.

Fig. 4 explicitly shows how the area of each LULC has fluctuated for the entire study period. Agricultural land increased in the 1972–1989 (30%) and 1989–2001 (16%) but started to decline in 2001–2014 by −5%. In contrast, bush and grasslands decreased by 13% and 39%, respectively in 1972–1989 then slightly increased in the 1989–2001 and 2001–2014 periods. Over the whole period (1972–2014), agriculture, urban areas, bush and shrubs, plantations and surface water showed a relative increment whilst the remaining LULC types exhibited a decreasing trend (Figs. 3b and 4). The largest and smallest percentage of positive changes were observed in urban area (4874%) and bushes (2.8%), which increased from 1 to 48 km^2 and from negligible to 12 km^2 respectively whilst forest and Grass land showed the largest (−79%) and smallest (−8.4%) decreasing percentage for the entire period. A remarkable result is that forest land showed a continuous decreasing trend until 2001, but then increased from 56 km^2 in 2001 to 78 km^2 in 2014.

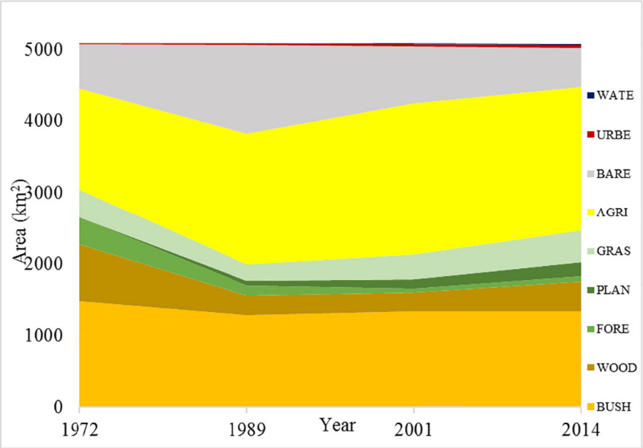

Fig. 4. Evolution of LULC change in the Geba catchment, 1972–2014.

The transition matrix, which indicates the sources and direction of change (supplementary material, Table S6), shows that the Geba catchment experienced significant shifts from one LULC category to other categories by 61%, 47%, 45% and 72%, in 1972–1989, 1989–2001, and 2001–2014, respectively. Both swap (i.e. simultaneous gain and loss of a given category during a certain period) and net changes occurred in all periods. However, the changes attributed to swap were higher than the net changes in all stages. For example, total changes in bushland (56%), agriculture (53%), and bare land (28%) for the entire 1972–2014 period were attributed to swap changes by 40%, 49% and 26%, respectively. This implies that only 16%, 4% and 2% of the total changes for these classes were net changes. In summary, higher swapping than net changes was observed in most categories during all periods (Table S6). The dominance of swap change indicates that there were coinciding gains and losses among the LULC categories in all periods. Analysis of LULC patterns based on the net change underestimates the total changes as it fails to account the swap changes (Pontius et al., 2004). For example, the total change (72.2%) of the landscape for the whole study period (1972–2014) would have been underestimated if only the net change (17.7%) would be considered. Higher swap changes were observed in agriculture, bushland, and bare land during the whole study period which suggests these LULC classes were the most dynamic categories that have reshuffled among each other.

A key finding of this study is that there were periodic fluctuations on the rate of transitions among LULC categories throughout the study period. All LULC categories exhibited a shift from one category to a different category. More proportion of changes were experienced during all periods except in the 2001–2014 that have shown more persistence in the majority of the LULC categories.

Agricultural land was the category that has systematically gained most from all other LULC classes. The rapid expansion of agricultural lands for the period 1972–1989 was mainly at the expense of natural vegetation. However, there was also a substantial exchange of areas between bare land and agricultural lands in all periods (Table S6). The growing pressure from human and livestock population might have significantly contributed to the rapid expansion of agricultural lands in the first three periods. However, the rate of clearing vegetation for agriculture slowed down and vegetation cover has started to recover from the early 1990s. Some of the agricultural, bare and grasslands have turned into plantations and bushes. The plantations were established through government and international aid programs following the increased demand in construction and fuel woods (Tekle and Hedlund, 2000; Zeleke and Hurni, 2001). However, plantations of Eucalyptus trees on agricultural lands has slowed down after 2001.

The most prominent transitions from agriculture in the 2001–2014 period were to bush and shrubs, bare land, urban areas and plantations (Table S6). The slight decrease of agricultural areas and an increase of vegetation cover during the 2001–2014 period are the result of environmental rehabilitation programs. This finding is in agreement with local studies (e.g. Alemayehu et al., 2009; Belay et al., 2014) who reported that vegetation cover in the basin has significantly improved. The broken trends in most LULC categories (Fig. 4) during the period under study demonstrate that LULC change in the basin was dynamic.

4.2. Possible drivers of the land use/cover changes

Natural environmental, demographic, socio-economic and infrastructure developments are the most important factors influencing the LULC dynamics (Tsegaye et al., 2010; Biazin and Sterk, 2013). The response of LULC transitions to population growth and government policy changes are discussed in this section.

The pressure of population growth on LULC has been considered the most important driving factor in Ethiopia (Haregeweyn et al., 2014). According to the 1994 (CSA, 1994) and 2007 censuses (CSA, 2008) and projections, the total population within the Geba catchment nearly tripled from 335,500 in 1972 to 934,290 in 2014, and population density increased from 65 to 185 persons per square kilometre. The rapid increase in population led to the expansion of farmlands, settlements and uncontrolled utilization of natural vegetation for firewood. The increase in population was paralleled by decreasing vegetation cover. Correlation analysis between each LULC and population in each period shows that population is positively correlated with the expansion of agricultural areas ($r = 0.76$), but negatively correlated with bushes ($r = -0.48$), forest ($r = -0.63$) and wood ($r = -0.64$) lands. The weaker negative correlation between population growth and bushland may reflect the impact of the recent IWSM programs.

Government's strategy and policy on land tenure and economic development might have also significantly contributed to the observed LULC changes. For example, an agricultural-led industrialization and economic development policy has been adopted since 1991 by the current government (Zenebe et al., 2013). The observed prompt expansion of agricultural and settlement areas after the early 1990s could be attributed to this policy and strategy changes. The policy on environmental rehabilitation, and the associated implementation programs, has most plausibly been the key driver behind the observed increasing trend of vegetation cover since 1989 (Nyssen et al., 2010). Similar studies elsewhere in the world (e.g. Liu et al., 2008; Wang et al., 2010; Biazin and Sterk, 2013) also underline that government policy can play an important role in the modification of landscapes in a basin. Given the significance of the reversing of land degradation trends in the Geba catchment, the following section briefly elaborates on the impact of the environmental rehabilitation policy.

4.3. Effects of watershed management interventions on the LULC patterns

Implementation of IWSM interventions in the last two decades has significantly contributed to the recovery of vegetation cover. To establish the contribution of these interventions, LULC change before and after IWSM were analysed in three small watersheds (Abreha Atsbiha, Negash and Birki). Results from these watersheds confirm that vegetation cover has continuously increased from 1989 to 2014 (Table 3 and supplementary materials, Figs. S1–S3). Plantation, forest, wood and grasslands in the Abreha Atsbiha watershed has increased by 140%, 75%, 420%, and 41%, respectively (Table 3, Fig. S1). Most of the bare, bushes and shrub lands were transformed into these LULC classes. Agricultural areas slightly decreased for the same period to allow homestead plantations. Similarly, woods and plantations significantly increased after IWSM in the Negash watershed (Table 3, Fig. S2). Bare land areas in this watershed significantly declined and converted into vegetation cover. Similar patterns were observed in the Birki watershed (Table 3, Fig. S4). In summary, biological SWC interventions, particularly exclosures and plantations on steep slopes, have significantly enhanced vegetation cover which is also supported by Descheemaeker et al. (2006) and Alemayehu et al. (2009).

The results from these watersheds are evidence that the observed recent increment in vegetation cover at the watershed level may be attributed to IWSM. However, the rate of increase over the entire Geba catchment appeared to be small compared to the treated watersheds. This suggests that significant improvements in vegetation cover in areas with intensive SWC interventions are counter-balanced by continued land degradation in areas without such interventions. In conclusion, the collective evidence from this and previous studies confirms that the observed increase in vegetation cover at the basin scale resulted from the recent IWSM programs.

The observed reversal in LULC dynamics in the catchment will certainly have implications for the hydrological processes both at local and basin scales. Continuously changing LULC is likely to have influenced the partitioning of rainfall into different hydrological components. Gebremicael et al. (2017) showed that variations in streamflow in the absence of significant change in rainfall patterns in the T-A headwaters could be attributed to changes in land management practices.

It is also important to highlight some of the limitations of this study as they are essential to know the negative effects on the result. Uncertainties and inconsistencies from collection devices (sensors), discrepancies in LULC class definitions and uneven distribution of reference data are some of the limitations that may have affected the result of this study.

5. Conclusion and recommendations

Detailed information on the spatiotemporal patterns of LULC are essential for understanding land and water management in a basin. Analysis of multi-temporal LULC change and possible associated drivers were done in the source region of the T-A river basin. The general

Table 3
The rate of LULC change after IWSM interventions in three watersheds, between 1989–2001, 2001–2014 and 1989–2014 (km^2).

Watersheds	Period	LULC category						
		FORE	PLAN	WOOD	GRAS	BARE	BUSH	AGRI
Abreha Atsbiha	1989/2001	0.1	0.4	0.5	1.4	−1	−0.4	−0.9
	2001/2014	0.4	1.2	1.3	−1	−1	−1.8	−0.5
	1989/2014	0.8	1.6	1.4	0.9	−1.4	−2.2	−1.4
Negash	1989/2001	−0.1	0.7	0.7	1.1	−2.2	−0.6	0.5
	2001/2014	0.1	0.4	−0.7	−0.4	−0.7	0.4	0.7
	1989/2014	−0.5	1.5	2	1.6	−4.7	0.1	0
Birki	1989/2001	0	0	3.2	2.3	−2.3	−3.1	−0.1
	2001/2014	−0.4	0.4	0.1	−0.7	0.7	−0.7	0.4
	1989/2014	0.1	0.5	2.6	1.9	−3	−2.7	0.6

trend observed in the present study is a decrease in vegetation cover and an increase in agricultural and settlement areas. The majority of LULC categories has changed substantially in the last 43 years (1972–2014). Three LULC categories (tree plantation, urban and water body) exhibited an increasing trend over the entire period, whereas the other categories exhibited trends that reversed. Agricultural land continued to grow until 2001 and started to decrease slightly in the 2001–2014 period. A decreasing tendency of agricultural land during the last period is attributed to the rapid expansion of urban areas and homestead plantations. A substantial deforestation of natural vegetation cover occurred in the 1972–1989 period and the proportion of degraded and agricultural lands significantly increased during the same period. However, vegetation cover has started to recover since the 1990s, when some of the agricultural, bare, and grasslands have turned into vegetation cover.

More than 72% of the total landscape of the study area exhibited a shift from one category to other categories during the entire study period. The largest changes occurred during 1972–1989. Whereas both swap and net changes occurred in all periods, the changes attributed to swap were much larger than the net changes. The most important driving forces for the observed changes were found to be rapid population growth and changing government policies. The recent government policy on environmental rehabilitation and its associated implementation programs have significantly contributed to the recovery of vegetation cover in the region. Strengthening such interventions with high-level participation of local farmers is essential for the sustainability of biophysical resources. Apart from the well-being of the ecosystem and environmental stabilization, much effort is needed to convert the improved vegetation cover into sources of income for the local communities to secure the gains made so far and to prevent further deterioration.

The result of this study can have significant implications on the future land and water management of the basin. Improved understanding of LULC change dynamics will allow more reliable information for improved land water resources management in the basin. The observed LULC change patterns are essential for establishing relationships between hydrological processes and catchment characteristics, which may reveal the effects of the wide-spread implementation of IWSM programs on the upstream-downstream hydrological linkages at larger spatial scales.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2017.10.034.

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