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Historical landscape photographs for calibration of Landsat land use/cover in the northern Ethiopian highlands

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Abstract

The combined effects of erosive rains, steep slopes and human land use have caused severe land degradation in the Ethiopian highlands for several thousand years, but since the 1970s however, land rehabilitation programs have been established to reverse deterioration. In order to characterize and quantify the transformations in the north Ethiopian highlands, a study was carried out over 8884 km² of the Tigray highlands of northern Ethiopia. Using Landsat Multi Spectral Scanner and later Thematic Mapper imagery (1972, 1984/86 and 2000), historical terrestrial photographs (1974-75) and fieldwork (2008), we prepared land use and cover maps. For assessing the use of the historical terrestrial photographs, Landsat images from 1972 were classified using two different methods, namely conventional change detection (image differencing) and ground truthing (using the historical photographs of 1974-75). Results show that the use of terrestrial photographs is promising, as the classification accuracy based on this method (Kappa coefficient 0.54) is better than the classification accuracy of the method based on image differencing (Kappa coefficient 0.46). Major land use and cover changes indicate (1) a gradual but significant decline in bare ground (32% in 1972 to 8% in 2000), (2) a significant increase of bushland (25% to 43%) and total forest area (including eucalypt plantations, 2.6% to 6.3%) and (3) creation of numerous lakes and ponds. The dominant

change trajectory (27% of the study area) indicates a gradual or recent vegetation increase. These changes can be linked to the population growth and the introduction of land rehabilitation initiatives, complemented by growing awareness of land holders.

Keywords: Remote sensing, land use and land cover change, satellite imagery, Tigray, terrestrial photographs

1. Introduction

Since the origin of settled agriculture about ten thousand years ago, human land use has interfered with the natural process of land cover change (Houghton, 1994, Ojima *et al.*, 1994). During the last three centuries the global human population has increased dramatically, and peoples activities have become an important factor in global change processes (Petit & Lambin, 2002). Tropical mountain regions are often very densely populated, and are thus more vulnerable to changes of the environment (Nyssen *et al.*, 2009b). During the last few decades however, efforts have been made towards land rehabilitation, and these initiatives have proven that land recovery is possible and is economically viable (Boyd & Turton, 2000).

Land use can be defined as “the human employment of the land” and land cover as “the physical and biotic character of the land surface” (Meyer & Turner, 1992). Since land use is often linked to the land-cover type, these concepts are frequently used interchangeably in land use and cover (LUC) studies (Green *et al.*, 1994). Land use and cover change processes are caused by interactions between physical, biological and social forces and can lead to enhanced productivity and long-term sustainability, but also to conversion of potentially productive land into degraded land, loss of species and emission of (greenhouse) gasses into the atmosphere (Houghton, 1994, Ojima *et al.*, 1994, B. L. Turner *et al.*, 1994). Sustainable management of natural resources therefore requires knowledge and quantification of LUC change processes.

Temporal series of remotely sensed data and analysis of change trajectories are useful to measure LUC change and have been widely applied (e.g. Mertens & Lambin, 2000, Petit *et al.*, 2001, Serneels *et al.*, 2001, Petit & Lambin, 2002, Muñoz-Villers & Lopez-Blanco, 2008). Most LUC change studies use aerial photographs, satellite imagery or a combination of both. Especially if satellite imagery is used, ancillary data is needed for establishing training areas and performing accuracy assessment. For recent periods, ancillary data can be easily collected through field observations. However, for satellite imagery up to four decades old, these data are often not readily available. As an alternative, aerial photographs (e.g. Mertens & Lambin, 2000, Petit *et al.*, 2001), vegetation maps (Muñoz-Villers & Lopez-Blanco, 2008) or interview methods (e.g. Atwell *et al.*, 2009) have been used. However, old aerial photographs often require ground truthing themselves (Rembold *et al.*, 2000) and are therefore not an optimal data source. The limited scope and often questionable reliability are major drawbacks of interview methods (Tra & Egashira, 2004, Aynekulu *et al.*, 2006). Historical terrestrial photographs could be a promising alternative ancillary data source. Although there are studies using historical terrestrial photographs to study LUC change (Hoffman & Rohde, 2007, Munro *et al.*, 2008), sometimes also comparing interpreted historical terrestrial photographs to observations on Landsat imagery (McClaran et al., 2010), there is no record of any studies using such photographs as training sites to classify land use and land cover types observed in old satellite images.

Land use and cover change studies in the north Ethiopian highlands have thus far only been performed at a local scale (e.g. Crummey, 1998, Kebrom Tekle & Hedlund, 2000, Zeleke & Hurni, 2001, Munro *et al.*, 2008). The aim of this study is to assess LUC change (1972 – 2000) in north Ethiopia at a regional scale, using a unique dataset consisting of historical terrestrial photographs, field observations, satellite-based remote sensing and geographic information systems (GIS).

2. Study area

2.1 Geographical context

The study area (Fig. 1) is located in the highlands of Tigray, the northernmost Ethiopian regional state, between 12°30’ to 14°10’ N, and 39°00’ to 39°45’ E and comprises an area of 8884 km² at an altitude from 1500 to 3939 m a.s.l.

The geological structure of Tigray results from the evolution of the East African Rift System. Precambrian metasediments and metavolcanics are unconformably overlain by subhorizontal Paleozoic and Mesozoic sedimentary rocks. In turn these are unconformably overlain by Tertiary lavas and basalts (Bussert, 2010). After the Miocene and Plio-Pleistocene tectonic uplift, erosion processes formed the benched landscape that is characteristic throughout the study area (Nyssen *et al.*, 2007a). Quaternary alluvium, colluvium and tufa have been mainly deposited in river valleys, depressions and topographic concavities (Nyssen *et al.*, 2004a).

Soil development in the north Ethiopian highlands depends strongly on topography and parent material (Virgo & Munro, 1978). On basaltic parent materials a typical red-black soil catena has developed (Van de Wauw *et al.*, 2008) with deep, black Vertisols in colluvial lowlands and on the basalt plateaux and Luvisols and Cambisols on steeper sections. On limestone parent material, Phaeozems, dark organic soils, can be found in remnant forests (Descheemaeker *et al.*, 2006). Intensive land use in other limestone areas led to soil erosion, high sediment deposition rates and the development of Leptosols and Regosols on slopes, while Cambisols occur in less steep areas (Van de Wauw *et al.*, 2008).

The study area (Fig. 1) corresponds to a wider region in which a high density of historical terrestrial photographs is available from the mid-1970s. The eastern boundary is the Rift Valley escarpment, at 1500 m a.s.l. The northwestern and western boundary of the study area relate to the commencement of the outcrop of Precambrian and lower Palaeozoic lithologies. The geological map of Ethiopia (Merla *et al.*, 1979) and the hydrogeological map of Mekele (EIGS, 1978) were used to delineate these formations.

*** Fig. 1 approximately here ***

2.2 Climate

Rainfall in the north Ethiopian highlands is linked to the position of the Inter Tropical Convergence Zone (Nyssen *et al.*, 2005). The current climate is tropical semi-arid (Virgo & Munro, 1978) with 400 – 900 mm of annual precipitation, which varies with slope aspect and altitude. Although temperature varies with altitude the average air temperature for the region is 18°C. There are three seasons: a dry season in the winter (October-April), a rainy season in the summer with maximum precipitation in July and August and an unreliable small rainy season from March to May which is most marked in the southern part of the study area. Analyses of time series of annual rainfall in northern Ethiopia, as reported by Nyssen et al. (2004a), have shown that there is no significant long term change in the annual precipitation regime.

2.3 Vegetation

The original climax vegetation in the north Ethiopian highlands consisted of three types of vegetation (Wilson, 1977, Bard *et al.*, 2000, Aerts *et al.*, 2006). Dry evergreen montane forest dominated by *Juniperus procera* and *Olea europea* ssp. *africana* was present at altitudes above 2200 m a.s.l. In moister areas between 1400 and 2200 m a.s.l. was a mixed *Podocarpus gracilior* and *Juniperus procera* forest. Deciduous wooded grassland was present at altitudes below 2200 m a.s.l. with tree species consisting mainly of *Acacia*, *Ficus*, *Euphorbia*, *Olea* and *Terminalia*.

It has been claimed that deforestation in Ethiopia is a recent process with 40% of the country still covered with forests in 1900 (Allen-Rowlandson, 1988, Taddesse, 1995, Bewket, 2002 and many others). However, no evidence is available to support this hypothesis. The current viewpoint about deforestation is that it commenced between 3000 and 2000 BP due to growing human land cultivation (Bard *et al.*, 2000, Nyssen *et al.*, 2004a). Today, most of the vegetation is semi-natural and consists of cropland and semiarid degraded savanna, as well as non-indigenous species like *Eucalyptus* spp. and *Opuntia ficus-indica*. Small remnants of the forest climax vegetation are found near churches and in isolated areas (Wilson, 1977, Descheemaeker *et al.*, 2006). Land cover can generally be categorized into bare ground, grassland, cropland, bushland, (church) forest, *Eucalyptus* plantation and village. The crops that are grown in the study area mainly include annual food crops, e.g. *Eragrostis teff* L. (tef), *Hordeum vulgare* L. (barley), *Triticum sativum* L. (wheat), *Eleusine coracana* L. (millet), *Sorghum bicolor* L. (sorghum), *Zea mays* L. (maize) and *Vicia faba* L. (beans).

2.4 Socio-economic environment

Ethiopia has a long human settlement history, with land cultivation starting at 7000 - 5000 BP (Hurni, 1990). Historically, the earliest and most powerful kingdom within the contemporary boundaries of Ethiopia was situated in the highlands north and west of Addis Ababa (Crummey, 2000). Christianity was introduced in the early fourth century. By the fifteenth century, the state increasingly dominated the church, mainly by granting land (*gult* rights) to monasteries and churches. The *gult* system implied that farmers owed one fifth of their harvest to the clerical *gult* holders and one tenth to the king. By the early 1970s, centuries long feudalism had led to a great inequality in land holding. In 1974 a communist military government, the Derg, took over and eliminated all private land titles; they also controlled the agricultural market. Droughts, famine and growing opposition led to the downfall of the Derg in 1991. After the new constitution (1995), all land remained state property and is now managed by the rural communities, who allocate land to their members as equitably as possible, and manage the remainder as common grounds (Crummey, 2000).

Ethiopia is ranked 12th least developed country in the world according to the Human Development Index (UNDP, 2010). The average life expectancy is 54.7 years (UNDP, 2010). The economy is based on subsistence agriculture, more than 85% of the population live in rural areas and rely on land resources for their livelihood (Diao & Pratt, 2007). The agricultural system in the highlands is described as the 'grain-plough complex', with barley, wheat and tef as the main crops (Westphal, 1975). The upland farming system entailing livestock keeping (Ruthenberg, 1980) prevails in the Tigray highlands. Agriculture practices are traditional, tillage being performed with an ox-drawn ard plough, locally called *maresha.* Crop production almost exclusively is based on the summer rainy season. Poverty and food shortages are severe in Tigray, and although absolute food production has increased, food production per capita has stagnated due to the fast population growth. Many households rely on food aid (Nyssen *et al.*, 2004a).

2.5 Land degradation

The mountainous terrain combined with the climatic conditions make the Ethiopian highlands vulnerable to land degradation. Land use conflicts have caused further land degradation, such as deforestation, conversion of bushland to cultivated areas, overgrazing, shorter crop rotation cycles, soil erosion and desertification (e.g. Hurni, 1990, Epema *et al.*, 2000, Feoli *et al.*, 2002, Mekuria *et al.*, 2007).

As a response, soil and water conservation (SWC) measures were intensively promoted in Tigray from 1975 onwards (Munro *et al.*, 2008). This resulted in the establishment of stone or soil bunds along slopes, check dams in gullies, reforestation, exclosures (areas closed for grazing and agriculture) and reservoirs (Gebremichael *et al.*, 2005, Descheemaeker *et al.*, 2006, Haregeweyn *et al.*, 2006). Many of the sloping cropland areas in the study area contain contour stone or soil bunds which reduce soil erosion rates. Reforestation mainly included plantation of *Eucalyptus*, that grows rapidly and supplies timber wood, and exotic Australian *Acacia* species, mainly planted on shallow soils and steep slopes.

3. Materials and methods

3.1 Data collection

Land use and cover was derived for 1972, 1984-86 and 2000 from

- Historical terrestrial photographs (1974-75);
- Fieldwork (2008);
- Landsat Multi Spectral Scanner - MSS (1972), Thematic Mapper - TM (1984-86) and Enhanced Thematic Mapper Plus - ETM+ (2000) imagery.

3.1.1 Historical terrestrial photographs

In 1974 and 1975, R.N. Munro, G. Edgeley and K. Virgo (and numerous others) photographed north Ethiopia as part of the Tigrai Rural Development Study (Munro *et al.*, 2008), a technical assistance and development planning project that was aimed to counteract the consequences of drought and famine. Part of this project studied the natural resources of central Tigray and recorded the Tigrayan landscape through several thousand terrestrial photographs. Twenty-two of these historical terrestrial photographs (Fig. 2) were selected and related to different sites throughout the study area (Fig. 1).

*** Fig. 2 approximately here ***

3.1.2 Collection of ground truth data

Ground truth data was collected during the rainy season of 2008 from 9 July until 3 September, followed by a shorter campaign in November 2008, in six study sites spread throughout the study area (Fig. 1). At each site, the historical terrestrial photographs were re-photographed and compared to the current landscape to determine training sites for land cover and land use classification (Fig. 2). Given the accuracy of the GPS positioning (Garmin eTrex Vista®, 7 m on average) and the pixel size of the Landsat images, training sites had to be areas of minimum 100 m x 100 m with homogenous land use/cover both in 2008 and in 1974-

75. Every land unit was visited in order to register its location (using GPS) and register its LUC properties. Parameters that influence spectral signature (e.g. tree species, tree density, canopy cover, lithology, soil texture, stoniness) were also recorded for every land unit for the current (based on fieldwork) and the 1975 (based on the historical terrestrial photographs) situation. Since the most recent Landsat images date from 2000 and fieldwork was performed in 2008, the LUC situation of 2000 was obtained through interviews with the local population and field observations. A total of 196 training sites were observed during fieldwork.

3.1.3 Satellite imagery and pre-processing

Landsat MSS (1972), TM (1984/86) and ETM+ (2000) imagery, collected in the dry season, were corrected geometrically, radiometrically, atmospherically and topographically in order to meet the requirements for change detection. The ETM+ images were georeferenced using image-to-map rectification. The location of 321 ground control points, mostly at river junctions, was derived from the Ethiopian 1:50,000 scale topographic map series.

The effects of atmospheric absorption and scattering (Du *et al.*, 2002) were removed using the COSine Theta (COST) method (Chavez, 1996). Due to the mountainous nature of the study area, the imagery contained shadowing effects; hence topographical correction was performed using the method of Riaño et al. (2003), using ground reflectance. Topographical slope and aspect data were derived from a missing value corrected 3-arc second Shuttle Radar Topography Mission DEM, information about the azimuth and zenith angles from image metadata. Finally, all preprocessed Landsat images were mosaicked into single images for the periods 1972, 1984-86 and 2000. More details on the procedures followed are presented as Online Supporting Information, section A.

http://onlinelibrary.wiley.com/doi/10.1002/ldr.2142/suppinfo

3.2 Land use and cover change analysis

The Landsat ETM+ (2000) image was spectrally classified using the supervised classification method. Training areas were selected based on the ground truth information of the 196 land units that had been collected during fieldwork. The spectral separability of the LUC classes was assessed using the Transformed Divergence (TD) statistical measure (Swain, 1973, Bourne & Graves, 2001) and the maximum likelihood classifier, that generates very accurate classification results (Dewidar, 2004), was applied to classify the six non-thermal bands of the

Landsat ETM+ image. Based on the TD values and visual inspection of the classification result, LUC classes were joined or added until a satisfactory result was achieved.

No ground truth or other reference data were available for the period in which the Landsat 5 TM images were recorded (1984-86 was in a period of civil war in the study area and its access was extremely difficult). Therefore, the TM images were classified using the image differencing method, which is based on the subtraction of two spatially registered images from different time periods to define change and no-change areas (Rogerson, 2002).

In order to test the performance of the Landsat MSS classification based on the historical terrestrial photographs, these images were also classified using image differencing. Because Landsat 1 MSS and Landsat 7 ETM+ have different spectral resolutions, it is not justified to difference their image bands. Therefore, the image differencing was performed using the Normalized Difference Vegetation Index (NDVI), an objective index of vegetation that is calculated using the red and near-infrared image bands (Lillesand *et al.*, 2008). Based on the image difference result, change and no-change areas were identified. In both cases, classifications were performed by selecting training pixels in the no-change areas.

Last but not least, as an alternative to conventional change detection (e.g. image differencing) methods, the Landsat 1 MSS images were classified using information from ground truthed historical terrestrial photographs, a method that has not been applied before. During fieldwork, the location and LUC properties of land units were registered for the current situation (2008) and for 1974-75 (based on the historical photographs). This 'ground truth' was thus used to define training pixels for the classification of the MSS imagery. Originally, the LUC classes were the same as the ones used for the classification of the ETM+ images. Based on the TD values, some LUC classes were merged or left out. This iterative process was executed until a satisfactory classification result was produced. More details on the LUC change analysis are presented as Online Supporting Information (section B).

http://onlinelibrary.wiley.com/doi/10.1002/ldr.2142/suppinfo

3.3 Accuracy assessment

The accuracy of the Landsat 7 ETM+ and Landsat 1 MSS classifications was assessed using repeated historical ground-based photographs (1974-75 and 2007-08) from the Tigray Repeat Photography Database (Nyssen *et al.*, 2009a) that had not been used during the classification process. The classification result was tested against reality by comparing selected spots in the photographs with the classified images. Unfortunately no reference data were available to assess the accuracy of the Landsat 5 TM classification (1984-86).

The 1972 LUC maps were validated based on 24 historical terrestrial photographs (1974-75), and the 2000 LUC map was validated using the equivalent repeat photographs (2007-08). Accuracy assessment was performed in ArcGIS 9.2® and resulted in a confusion or error matrix (Foody, 2002). From this matrix, the omission error (error of exclusion, linked to producer accuracy), commission error (error of inclusion, linked to user accuracy) and overall accuracy were calculated. Fleiss' Kappa (K) values (Stehman, 1997) were also calculated. This statistic is a measure of classification accuracy that ranges from -1 (complete discordance between datasets) to 1 (no misclassified pixels).

3.4 Analysis of land use and cover change (1972 - 1984-86 - 2000)

LUC change was quantified using post-classification comparison, despite the disadvantage that the accuracy of the change map strongly depends on the accuracies of the compared maps (Singh, 1989). This analysis was performed in ArcGIS 9.2®. Firstly, each time period was analyzed separately by calculating the proportion of each LUC class and comparing the LUC proportions of all observation years afterwards. Secondly, to quantify the extent and nature of LUC change, a change matrix and change maps (from-to change) were prepared for both pairs of observation years (i.e. 1972-1984/86 and 1984/86-2000). The change matrix gives the proportions of the study area by type of LUC in the first time period that changed to a different class in the second. Thirdly, all time periods were combined into LUC change maps, with (1) a map that visualizes the LUC change trajectories that have occurred over the observed period and (2) a map that visualizes the stability (number of changes) of each image pixel.

4. Results

4.1 Image classification

4.1.1 2000 LUC map

During fieldwork different types of settlement were observed, namely traditional villages, mixed villages and modern villages (depending on the proportion of houses with a traditional thatched or soil roof and metal sheet roof). In order to determine the spectral separability of these classes, a preliminary classification of settlements was performed. TD values pointed out that traditional and mixed villages were the most difficult to distinguish, so these classes were merged.

Initially, all training pixels were assigned to one of the 11 LUC classes (Table 1). However, the first classification result was unsatisfactory because field knowledge and comparison with topographical maps indicated that the LUC classes ‘modern village’ and ‘traditional village’ were over-represented. As closer examination pointed out that these wrongly classified areas were mainly roads and wetland areas, LUC classes ‘road’ and ‘wetlands’ were added to the previously defined LUC classes. In view of the difficulty to spectrally distinguish ‘shrubland’ from ‘dense bushland’, ‘open forest’ and ‘traditional village’ (TD lower than 1000), these classes were merged into one class, i.e. ‘bushland’. The excessive area of modern villages was reduced, but fragments remained present. According to the geological map (EIGS, 1978), these were mostly areas with Precambrian or Palaeozoic-aged lithologies that contain many high-reflecting minerals such as mica and quartz. Also, classification problems in the east of the study area were attributed to the different rainfall pattern (rain in the winter in the Rift Valley and its western escarpment). Lack of ground truth on such areas clearly caused classification problems. Therefore, a new LUC class ‘other’ was defined, with training pixels in areas on distinct different lithology or with a different rainfall pattern. Eventually, 11 LUC classes were defined (Table 1). The average TD value was 1889, four pairs of LUC classes were spectrally difficult to separate, i.e. cropland and bare ground (TD 870), cropland and bushland (TD 1124), *Eucalyptus* plantation and bushland (TD 1231) and bare ground and bushland (TD 1310). The 2000 LUC map (Fig. 3) was achieved with equal prior probabilities for each LUC class and after applying a 3x3 kernel majority filter.

*** Table 1 approximately here ***
*** Figure 3 approximately here ***

4.1.2 1972 LUC map (based on historical terrestrial photographs)

Based on contemporary ground truthing (derived from the historical terrestrial photographs during fieldwork), training areas were selected on the Landsat MSS image. Since there was no ground truthed information for eucalypt plantations, which only existed in a few localities in

1975, this class was left out. Roads could not be identified on the MSS images, most likely due to the combined effect of low MSS resolution (60 m x 60 m) and the fact that the road network mainly consisted of narrow earth roads in 1972. The class *other* was defined using exactly the same training areas as for the ETM+ images, but was expanded with training areas of cloudy pixels present in the southern part of the study area. TD values indicated low separability (TD < 1500) for many LUC class pairs. Given the limited number of training areas, very little could be done to address this problem. Because separability problems were most severe for the LUC class 'traditional village', this class was combined with the class it spectrally resembled the most, i.e. 'cropland'. TD values were still low for six pairs of LUC classes, mainly bare ground-cropland, bushland-cropland and bushland-bare ground (Fig. 4).

*** Figure 4 approximately here ***

4.1.3 1984-86 and 1972 LUC map (based on image differencing)

Six normalized difference images were created by subtracting each TM image band (1-5 and 7) from the according ETM+ image band. Based on these difference images, a mean difference image was constructed. The change and no-change areas were determined based on the mean and standard deviation of this image. Several threshold values (ranging from 1 to 3 standard deviations with an increment of 0.5) were tested and evaluated visually. A threshold value of 1.5 standard deviation around the mean was considered optimal. Based on the Landsat 7 ETM+ classification result, training pixels were selected in the no-change areas and the observed LUC class was applied. After repetitive evaluation of the TD values and adjustment of the training pixels, an average TD of 1820 was obtained. Image classification was performed using the maximum likelihood classifier and a mode (3x3 kernel) filter was applied (Fig. 5).

Image differencing was performed also, and was based on the NDVI of the Landsat ETM+ and MSS images. A threshold value of 1.5 standard deviations around the mean was used to distinguish change from no-change areas. Training pixels were selected in the no-change areas based on the Landsat 7 ETM+ classification result and after optimizing TD values to an average TD of 1790, a maximum likelihood classification was performed (Fig. 5). Band 1 contains considerable noise (striping) that influences the classification results by causing stripes of alternating LUC classes in some areas. This was taken into account with the interpretation of the 1972 LUC map.

*** Figure 5 approximately here ***

4.2 Accuracy assessment

A confusion matrix was produced for the 1972 LUC maps and the 2000 LUC map. Firstly, all LUC classes were included in the confusion matrix. Later, classes with less than four sample locations were left out (wetland and water). Sample points that were classified as 'other' were not taken into account. A total of 107, 101 and 97 land units were eventually used to assess the accuracy of respectively the ETM+, MSS (ground truth) and MSS (image differencing) classification results. The required minimum of fifty samples per LUC category (Congalton & Green, 1999) was not achieved, with even less than ten ground data points for grassland, forest and road.

The Kappa coefficient (0.75) indicates that there is a substantial level of agreement between the classification result and reality for the 2000 classification (Table S2). The user accuracy percentage is lowest for forest (25%), which was often misclassified as bushland. The bare ground class (user accuracy of 58%) also was difficult to differentiate and is mixed up with cropland, modern village, bushland and road.

There is a better agreement between the classification result and reality for the Landsat 1 MSS classification based on ground-based photographs (overall accuracy of 64%, Table S3) compared to the classification based on image differencing (overall accuracy of 59%, Table S4). Major differences in user accuracy are bare ground (86% versus 53%) and forest (14% versus 0%). The classification based on image differencing only has a higher user accuracy for bushland (79% versus 68%). The producer accuracy varies most for grassland (75% versus 56%) and bare ground (47% versus 63%).

4.3 Analysis of land use and cover change from 1972 until 2000

The LUC maps for three time periods (1972, 1984-86 and 2000) were used to quantify the LUC change in the study area. For the 1972 period the classification based on the historical ground-based photographs was used since it had the highest Kappa coefficient and overall accuracy.

4.3.1 LUC proportions in 1972, 1984-86 and 2000

In 1972 the study area was dominated by cropland (36%), bare ground (32%) and bushland (25%) (Fig. 6). In 1984-86 cropland (42%) and bushland (32%) were the major LUC classes. By 2000 bushland further increased to 43% while bare ground only occupied 8% of the total area and cropland diminished again (35%). The overall trend of LUC change in the study area between 1972 and 2000 is a significant decrease in bare ground (especially from 1972 to 1984-86) and an increase in bushland, *Eucalyptus* spp. plantations and modern villages.

*** Figure 6 approximately here ***

4.3.2 Change maps and matrices

The spatial pattern and nature of LUC change in the study area was analyzed by producing a change matrix and map for two periods (1972 – 1984-86 and 1984-86 – 2000). Before analysis, the number of classes was reduced by merging 'water' with 'wetland' for all classifications and 'road' with 'modern village' for the 2000 and 1984-86 classifications. The 1972 classification result was resampled to match the spatial resolution of the other classifications (30x30 m) using nearest neighbor resampling. All areas classified as 'other' in one or more LUC maps were left out from the analysis (4.93%).

4.3.2.1 LUC change between 1972 and 1984-86

In order to achieve an interpretable change map, the initial 49 from-to change categories (change matrix, Table 2) were reduced to six major LUC change classes, which were then visualized in a change map (Fig. 7a). Between 1972 and 1984-86, 62% of the study area has undergone LUC change (Table 2, bottom). The most significant change is the decrease of bare ground as more than two thirds of the 1972 bare ground area was converted to cropland or bushland by 1984-86. During these twelve years *Eucalyptus* plantations increased, mainly comprising former bushland and bare ground, and the grassland area more than doubled. Forestation and other increase in vegetation mainly took place in the southeastern part of the study area (Fig. 7a). The major degradation area is situated in the northeastern part of the study area. The increase of cultivated land is spread throughout the study area, but concentrations are present in the central (Mekelle) and western (Hagere Selam) part of the study area.

*** Table 2 approximately here ***
*** Figure 7 approximately here ***

4.3.2.2 LUC change between 1984-86 and 2000

From 1984-86 to 2000 LUC has changed in almost half of the study area (49.7% or 4412 km²). The change matrix (Table 3) indicates that the change area mainly consists of conversion from cropland to bushland (13% of the total area), bushland to cropland (ca. 6%) and bare ground to bushland (ca. 5%). The forest area decreased by 1.5% of the study area and was mainly changed into bushland and *Eucalyptus* plantation (mainly in the eastern and southwestern part of the study area). This LUC change is mainly found in the southeastern part of the study area (Fig. 7b). Change to cultivated land is limited, and mainly occurs in the southeastern part of the study area (Adi Shuho, Maychew and near Ashenge). Vegetation increase dominates the northern part of the study area, while deforestation occurred mainly in the southeastern part of the study area.

*** Table 3 approximately here ***

4.3.3 LUC change trajectory map

In order to analyze LUC change over the three periods in time, a LUC trajectory map was generated. Because representing all 418 occurring LUC change trajectories would not generate an interpretable map, specific LUC trajectories were defined by taking into account major LUC changes that occurred in each time interval. These trajectories (Table 4) encompass the difference between early (between 1972 and 1984-86) and recent (between 1984-86 and 2000) vegetation increase or decrease. Cropland areas are vegetated for only three months a year and are comparable to bare ground in the dry season (and therefore difficult to distinguish). It is concluded that a change from bushland to cropland (for example) is considered to be (woody) vegetation decrease. A change trajectory regions map (Fig. 8) was generated by generalizing the trajectory map applying the Idrisi mode filter (7x7 kernel) fifteen times. In 19% of the study area LUC did not change in the period 1972 – 1984-86 – 2000. The dominating change trend (27% of the study area) is a gradual or recent increase in vegetation. Main regions of recent vegetation increase are situated in the May Mekdan area and in eastern parts of the study area (Rift Valley escarpment). The area south of Adi Shuho has undergone a gradual increase in vegetation. Vegetation decrease occurred only in 7% of the study area, and is mainly situated near Hagere Selam and in the central part of the study area.

*** Table 4 approximately here ***
*** Figure 8 approximately here ***

5. Discussion

5.1 Methodology

In contrast to former LUC research in northern Ethiopia that focused on local-level changes, this study assessed LUC change on a regional level (over 8884 km²) in a study area that is considered to be representative of the north Ethiopian highlands. Furthermore, our research put particular emphasis on developing a methodology using historical photographs as ground truth for 1973 Landsat imagery.
The classification based on historical ground-based photographs yielded a κ coefficient of 0.54 and an overall accuracy of 64%, which still differs greatly from the required accuracy of 85% (Thomlinson *et al.*, 1999). Although all satellite imagery had been captured during the dry season, the specific recording date varies from November to January-February. Since the rainy season lasts until September, there is significantly more vegetation in November (which is part of the harvest season), compared to February. Although this does not have consequences for individual image classification, it does influence the process of image differencing since the phenological stage of the vegetation differs.

Ground truth data were collected in the summer of 2008 to perform a classification of the Landsat 7 ETM+ (2000) images. Since landscapes are dynamic and significant changes may occur in a time span of eight years, efforts were made to retrieve the 2000 LUC properties but this was not always possible. Furthermore, the accuracy of the 2000 classification result was

assessed using field photographs that date from 2006-08. Such time difference could lead to misinterpretation in rapidly changing environments. Further classification improvements can be made by collecting ground truth data in all geological sub-areas and agroclimatic zones (especially the eastern part) of the study area, as these have proved to cause misclassification.
Class separability is problematic for cropland and bare ground in all classifications. Although these classes have different land use, their land cover (especially in the dry season) and thus spectral signature is very similar. In the MSS classification based on information from ground truthing the historical photographs, there is also low separability for cropland-bushland and bushland-bare ground. Both the season in which the images are recorded (early dry season) and the possible misinterpretation of historical ground-based photographs (especially for distant areas on the photographs) probably contributed to this confusion.
Although the image differencing technique can perform well when images from the same sensor are used (e.g. Landsat 7 ETM+ and Landsat 5 TM), images from sensors with different spectral resolutions like Landsat 7 ETM+ and Landsat 1 MSS are more difficult to compare. This problem was solved by differencing the NDVI of both images instead of the original image bands, which is not an ideal solution. The second problem with image differencing is the difficulty in determining the change/no-change threshold value, which is a subjective process. The shortcomings of this method are expressed by the accuracy of this classification, the κ coefficient is 0.46. Comparatively, the classification based on historical ground-based photographs yielded a κ coefficient of 0.54, which is an improvement.

All in all, the use of ground-based historical photographs is considered to be very promising, and generates significantly better results compared to the more classic method of image differencing. Improving ground truth recording by (1) increasing the number of historical photographs used and (2) doing the fieldwork in the same season as the historical photographs were taken could further enhance this classification result.

5.2 LUC change and explaining factors

5.2.1 LUC change trend

From 1972 to 2000, LUC has undergone major changes in the north Ethiopian highlands. Bare soil area has declined from 32% to 8% of the study area. It has been replaced mainly by bushland (25% to 43%) and the total forest area (including *Eucalyptus* spp. plantations), which more than doubled (2.6% to 6.3%). These findings are in line with observations made in specific (smaller) areas of the northern Ethiopian highlands (Wøien, 1995, Crummey, 1998, Bewket, 2002, Nyssen *et al.*, 2009c). It contrasts however with decreasing forest cover and woody vegetation areas observed by Epema et al. (2000) who studied an area nearby ours over a period of 11 years only (1987-1998), neither with those by Kebrom Tekle & Hedlund (2000), Zeleke & Hurni (2001) and Tegene (2002) who all concern study areas more to the SW; those studies also cover the decades between 1957 and 1986-2000, a period that includes a most probable decline in vegetation cover in its first half and a partial recovery in the second half, in contrast to our study that concerns only the decades after 1972, a period with regenerating vegetation.

5.2.2 Causes of LUC change

Although a thorough explanation of LUC change is not the objective of this study, some explanatory factors can be elucidated. Ethiopia has recently known two major shifts in land tenure system (Crummey, 2000). Prior to 1974, and for more than 900 years, feudalism (the *gult* system) had led to increasing inequalities in land holdings. In 1974 the Marxist government declared all land state property, thus reducing land holders inequality, and controlled the grain market. In 1991 the post-Derg government legislated on ownership rights, and freed the agricultural market. However, all land remained state property with tenured user rights on cropland. Increasingly, common land management focuses on land rehabilitation and sustainability. The population of Tigray has increased from 3.1 million in 1994 to 4.3 million in 2007 (CSA, 2008), which has led to increasing cultivation of land, more livestock and greater exploitation of wood for fuel and timber. The upland farming system faces increasing competition between livestock and crops. This has led farmers to allow grazing on croplands between harvest and sowing (Grepperud, 1996). Eventually, increased land cultivation, compaction and removal of crop residues and deforestation cleared the land and made it more vulnerable to land degradation. Ethiopia has been subject to recurring droughts and famine in 1972, 1980 and 1984. From 1975 onwards, but mainly since the 1990s, soil and water conservation measures have been undertaken (Nyssen *et al.*, 2004b, Descheemaeker *et al.*, 2006, Vancampenhout *et al.*, 2006), aimed at environmental rehabilitation and income generation. At the onset some farmers feared negative consequences (e.g. rodents shelter, loss of cultivated land) and therefore destroyed the physical structures. The establishment of exclosures also caused more pressure on the remaining grazing land. SWC efforts however continued and their positive results (as reported by Nyssen *et al.*, 2007b) have increased farmers' interest and awareness.

The progressive changes in Tigray in land tenure policy, population growth and SWC have been major factors in LUC change. In 1972 the main LUC class was bare soil (32%), but afterwards vegetation cover has rapidly increased in most of the study area. The increase of bushland and forest is considered mainly due to SWC initiatives, which stimulated also agroforestry intitiatives and established exclosures. Of course, the awareness of farmers is also crucial to preserve and expand such areas. SWC too, caused the recent creation of numerous earth dams and ponds, and these have offered increased water availability and irrigation possibilities. These results demonstrate that growing population pressure does not necessarily lead to irreversible land degradation. Similar conclusions were drawn by Tiffen *et al.* (1994) and Boyd and Slaymaker (2000). Tiffen et al. (1994) introduced the 'more people, less erosion' hypothesis based on a case study in the Machakos district (Kenya), where an increase in human population also resulted in more sustainable land use practices. Boyd and Slaymaker (2000) further discussed the 'more people, less erosion' hypothesis based on six cases in Africa, and conclude that there are other examples of degradation reversal.
Further study is needed to fully understand the dynamics of LUC change in the northern Ethiopian highlands and to determine its causes and driving factors.

6. Conclusions

The objective of this study was to detect LUC change in the north Ethiopian highlands at a distinctive regional scale, using a unique dataset consisting of historical terrestrial photographs, field observations, satellite-based remote sensing and geographic information systems (GIS).

Overall, the use of ground-based photographs, fieldwork, satellite-based remote sensing and GIS has proven to be very useful in the study of LUC change in the northern Ethiopian highlands. Although the satellite imagery has shortcomings (e.g. noise, acquisition date) and the combination of Landsat 1 MSS, Landsat 5 TM and Landsat 7 ETM+ images presents specific difficulties (mainly due to their different spectral resolution), satisfying classification results were achieved.

Two classification methods were compared to classify Landsat 1 MSS imagery. The first is based on historical ground-based photographs and the second on image differencing with recent Landsat imagery. Historical ground-based photographs are a useful ground truth resource for the classification of old satellite images. This method allows one to generate an independent classification of Landsat 1 MSS imagery. It does however require a sufficient number of ground-based photographs, preferably spread throughout the study area, and field observations to determine the location of training areas. Although the aspect of retrieving the exact location and angle of the historical photographs was not part of this study, it requires both time and field knowledge and thus has to be taken into account.

The study area showed significant LUC change over the last three decades. Major changes have been a decrease in bare soil and a considerable increase in bushland and forest. In 1972, the study area consisted mainly of bare ground and cropland. There was only a limited area covered by forest. By 2000, bushland dominates and bare soil has been reduced to a fourth of its former area. Numerous lakes and ponds were created in the central part of the study area. Although the forest area decreased slightly, the total area of *Eucalyptus* spp. plantations almost doubled over the last fifteen years. These results demonstrate that growing population pressure does not necessarily lead to irreversible land degradation. This change can be attributed to the SWC initiatives and the growing awareness of local communities.

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Tables:

Table 1
Definition of LUC classes

Nr	Class	Land cover (LC) and land use (LU)
1	Cropland	LU Cultivated land, not irrigated[1]; LC (at the moment of image recording) bare with some weeds
2	Grassland	LC 0% trees, 0% shrubs, > 90% herbs and grasses; LU grazing area, sometimes set aside for a few months to allow regeneration
3	Bare ground	LC 0% trees, < 10% shrubs (< 3m), < 10% herbs and grasses; LU no visible use or used as rangeland
4	Bushland - consists of:	
	4.1 Shrubland	LC 0% trees, 10 – 50% shrubs (< 3m), 10 – 80% herbs and grasses; LU rangeland and fuel wood source or exclosure
	4.2 Dense bushland	LC 0% trees, > 50% shrubs (< 3m), 10 – 80% herbs and grasses; LU rangeland and fuel wood source or exclosure
	4.3 Open forest	LC tree canopy cover 10 – 50%; LU rangeland and fuel wood source or exclosure
	4.4 Traditional village	LC mix of houses, roads, paths, stone walls, gardens and trees (mainly *Eucalyptus*), where more than 50% of the houses has a thatched or traditional soil roof
5	Forest	LC tree canopy cover > 50%; LU mainly church forest, exclosure
6	*Eucalyptus* plantation	LC plantation of *Eucalyptus* trees, canopy cover > 50%; LU wood source, exclosure
7	Modern village	LC mix of houses, roads, paths, stone walls, gardens and trees (mainly *Eucalyptus*), where more than 50% of the houses has a metal sheet roof
8	Water	LC Lakes and ponds
9	Wetland	LC Rivers, shallow ponds, riparian vegetation
10	Road	LC Asphalt and gravel roads
11	Other	Areas not covered during fieldwork (with different lithology or rainfall pattern)

[1]Irrigated croplands were not included in this classification because no ground truth was recorded in such areas, given their limited area and complexity (the phenological stage of vegetation in such areas can vary greatly)

Table 2

LUC change matrix between 1972 and 1984/86 (total surface area in %)

1972 \ 1984-86	Crop land	Grass land	Bare ground	Bush land	Forest	*Eucalyptus* plantation	Modern village	Water	*1972 total*
Cropland	**19.2**	1.4	4.4	8.5	0.2	0.2	0.2	0.02	*34.1*
Grassland	0.8	**0.6**	0.2	0.4	0.0	0.0	0.0	0.00	*2.1*
Bare ground	12.1	1.4	**3.1**	12.5	1.2	0.7	0.2	0.03	*31.2*
Bushland	8.7	1.1	2.9	**9.3**	1.2	1.1	0.2	0.04	*24.4*
Forest	0.3	0.0	0.2	0.8	**0.9**	0.4	0.0	0.00	*2.6*
Modern village	0.0	0.1	0.1	0.1	0.0	0.0	**0.0**	0.00	*0.3*
Water	0.1	0.0	0.0	0.0	0.0	0.0	0.0	**0.14**	*0.3*
1984-86 total	*41.2*	*4.6*	*10.8*	*31.7*	*3.5*	*2.4*	*0.7*	*0.24*	

Legend of major LUC change categories for the period between 1972 and 1984-86.

	Description	*Proportion of study area (%)*
	Deforestation	1.3
	Forestation	5.5
	Degradation	7.5
	Vegetation increase	21.4
	Conversion to water	0.1
	Bare ground/bushland to crop/grassland	23.3
	Other change	3.7
Bold	No change	33.3
	Areas classified as other	4.9

Table 3
LUC change matrix between 1984-86 and 2000 (total surface area in %). Major LUC change categories are indicated by colors, as defined in Table 2

1984-86 \ 2000	Crop land	Grass land	Bare ground	Bush land	Forest	*Eucalyptus* plantation	Modern village	Water	*1984/86 total*
Cropland	**22.1**	1.0	2.9	13.3	0.1	0.7	0.9	0.24	*41.2*
Grassland	1.1	**0.8**	0.5	1.8	0.0	0.1	0.3	0.04	*4.6*
Bare ground	3.0	0.3	**1.9**	5.3	0.1	0.2	0.1	0.01	*10.8*
Bushland	6.3	0.6	1.8	**19.5**	0.6	2.0	0.8	0.13	*31.7*
Forest	0.1	0.0	0.1	1.8	**1.0**	0.6	0.0	0.00	*3.5*
Eucalyptus plantation	0.2	0.1	0.1	0.8	0.2	**0.1**	0.1	0.85	*2.4*
Modern village	0.2	0.0	0.1	0.2	0.0	0.2	**0.1**	0.01	*0.7*
Water	0.0	0.0	0.0	0.0	0.0	0.1	0.2	**0.00**	*0.2*
2000 total	*33.0*	*2.8*	*7.2*	*42.7*	*1.9*	*3.9*	*2.4*	*1.3*	

Table 4
Classification of LUC change trajectories over the period 1972 – 1984-86 to 2000

Change trajectory name	**Trajectory definition*** **1972**	**→**	**1984/86**	**→**	**2000**	**Percentage of total study area**
No-change	X	→	X	→	X	19%
Early vegetation decrease	Bu/F	→	Ba/C	→	Ba/C	5%
Recent vegetation decrease	Bu/F	→	Bu/F/E	→	Ba/C	2%
Gradual vegetation increase	Ba/C	→	Bu	→	Bu/F/E	14%
Recent vegetation increase	Ba/C	→	Ba/C	→	Bu/F/E	13%
Other change trajectories						42%

* X (any LUC class), Ba (Bare ground), Bu (Bushland), C (Cropland), F (Forest), E (*Eucalyptus* plantation)

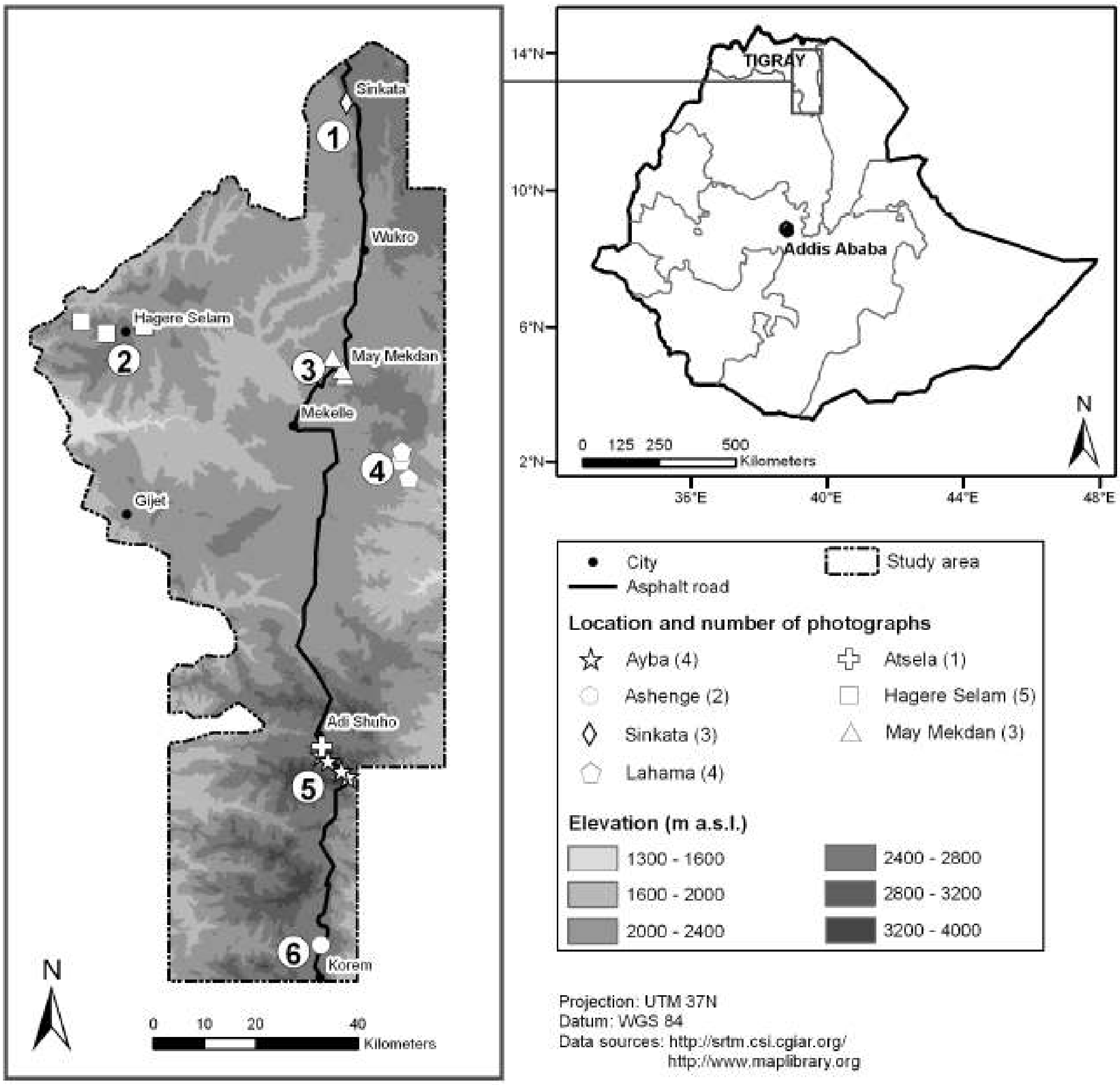
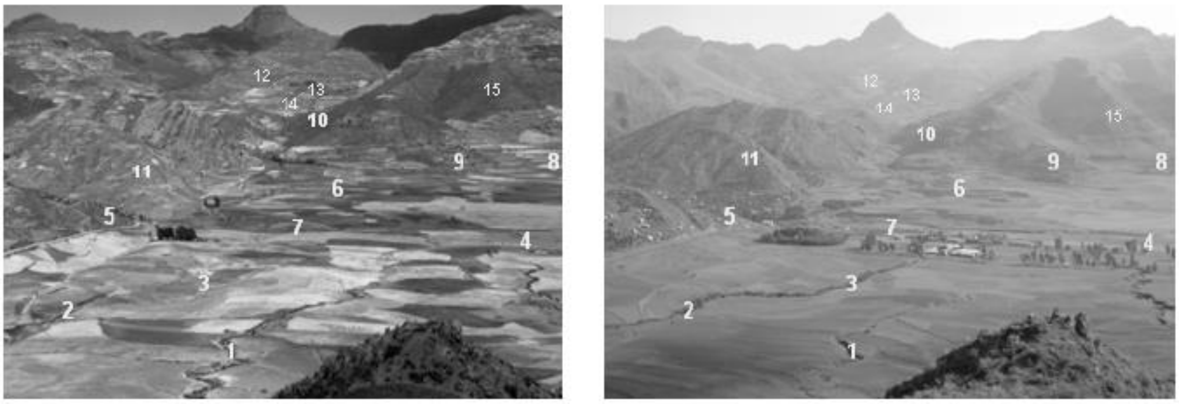
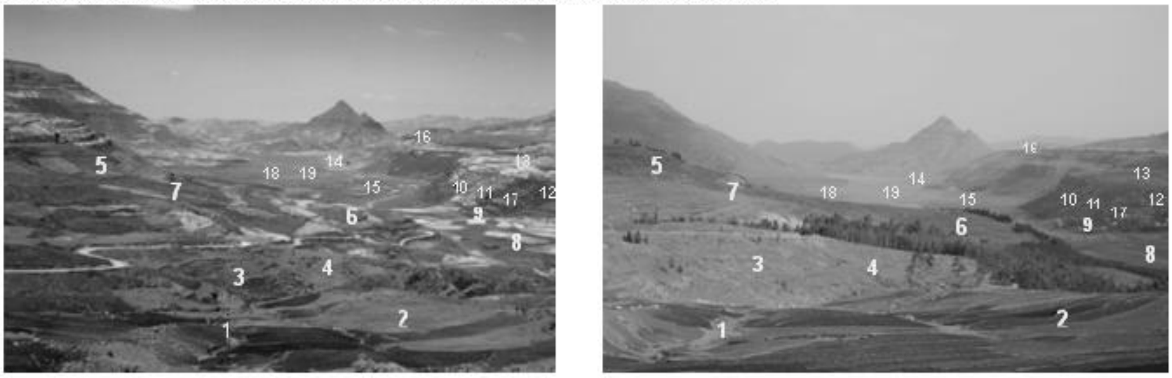


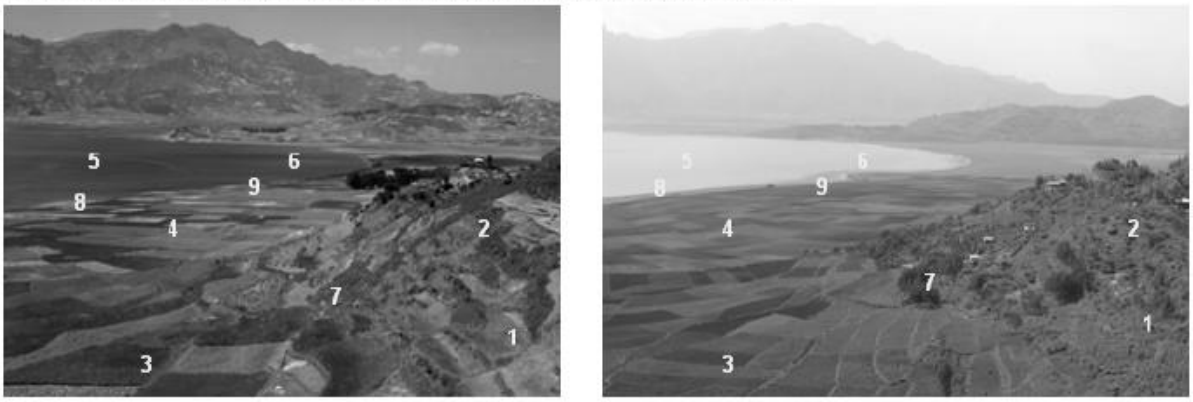
Fig. 1. Location of the study area and areas of ground truthing (1: Sinkata, 2: Hagere Selam, 3: May Mekdan, 4: Lahama, 5: Ayba and Atsela, 6: Lake Ashenge, Bahri Hatsera).



(a) Atsela in October 1975 (left, N. Munro) and August 2008 (right, S. de Mûelenaere)



(b) Ayba valley in October 1975 (left, N. Munro) and July 2008 (right, S. de Mûelenaere)



(c) Ashenge in October 1975 (left, N. Munro) and July 2008 (right, S. de Mûelenaere)

Fig. 2. Example of interpreted terrestrial photographs in (a) Atsela, (b) Ayba and (c) Ashenge. The numbers indicate the land units that were used as training sites for land cover and land use classification.

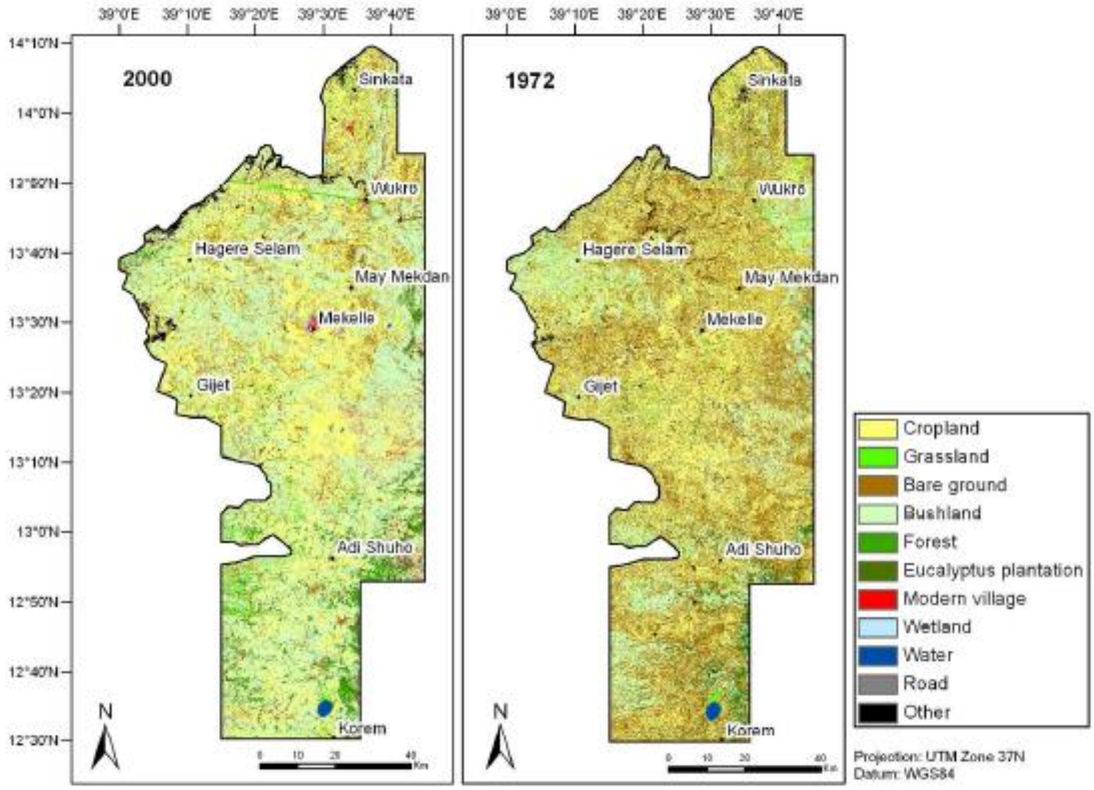


Fig. 3. Land use/cover classification of Landsat ETM+ imagery (2000) using ground truthing in the field (left), and Landsat MSS imagery (1972) using information from ground truthed historical terrestrial photographs (right).

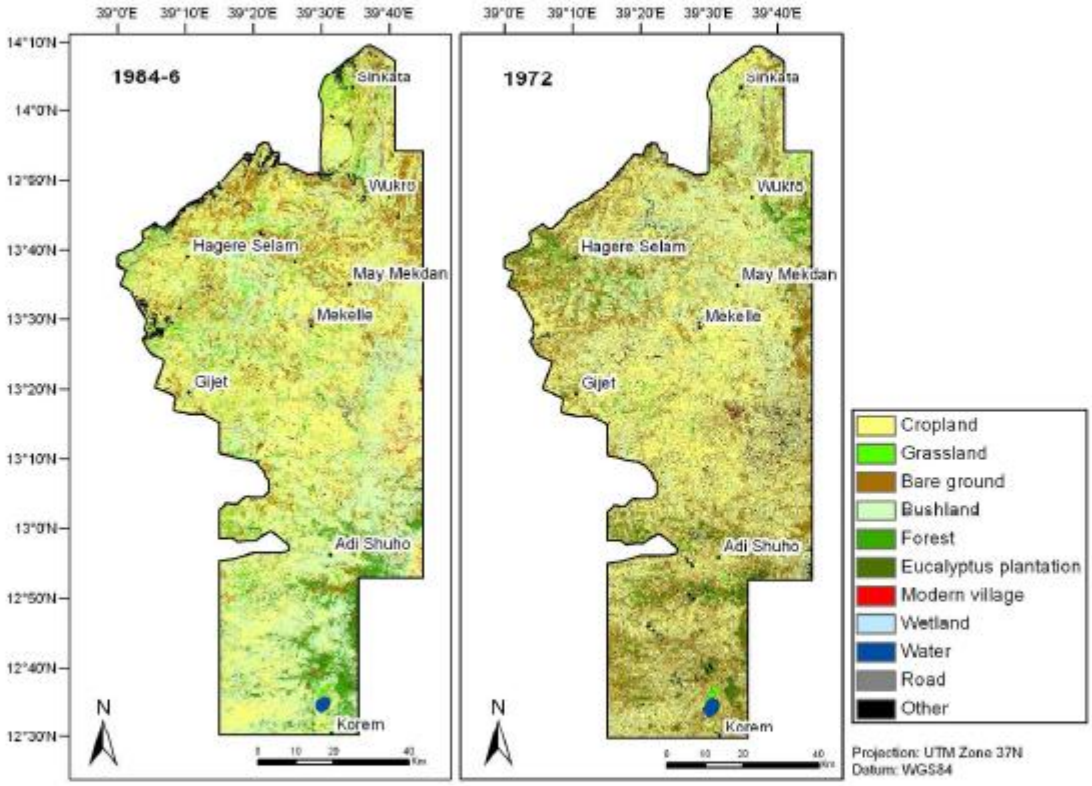


Fig. 4. Land use/cover classification of Landsat TM imagery (1984-86) (left), and of Landsat MSS imagery (1972) (right), both based on image differencing.

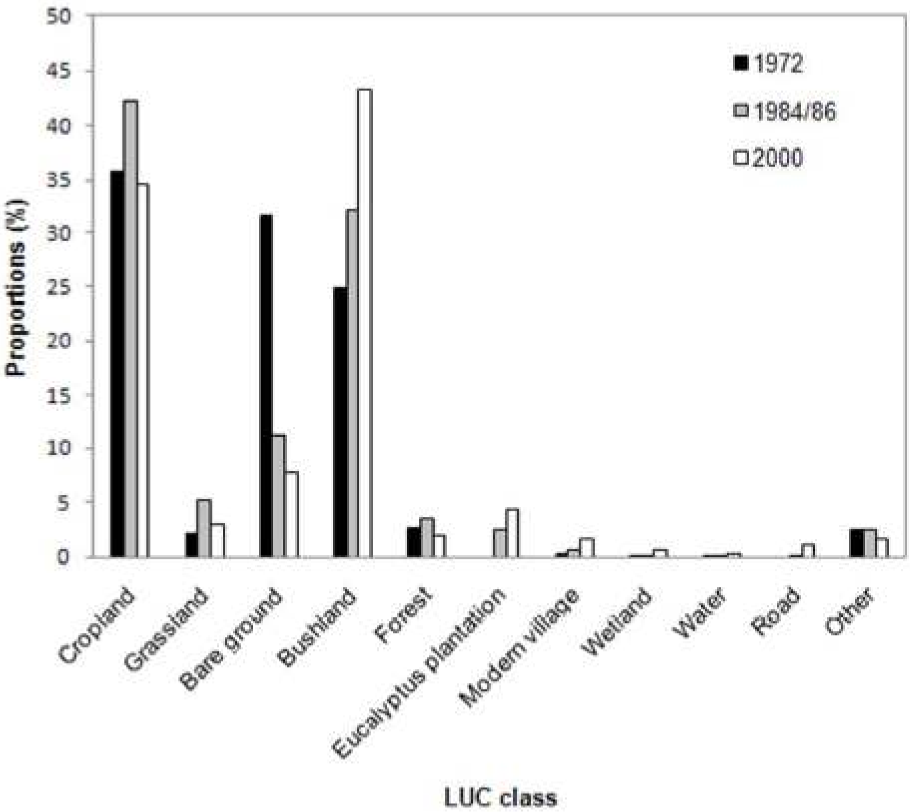


Fig. 5. LUC class proportions in 1972, 1984-86 and 2000.

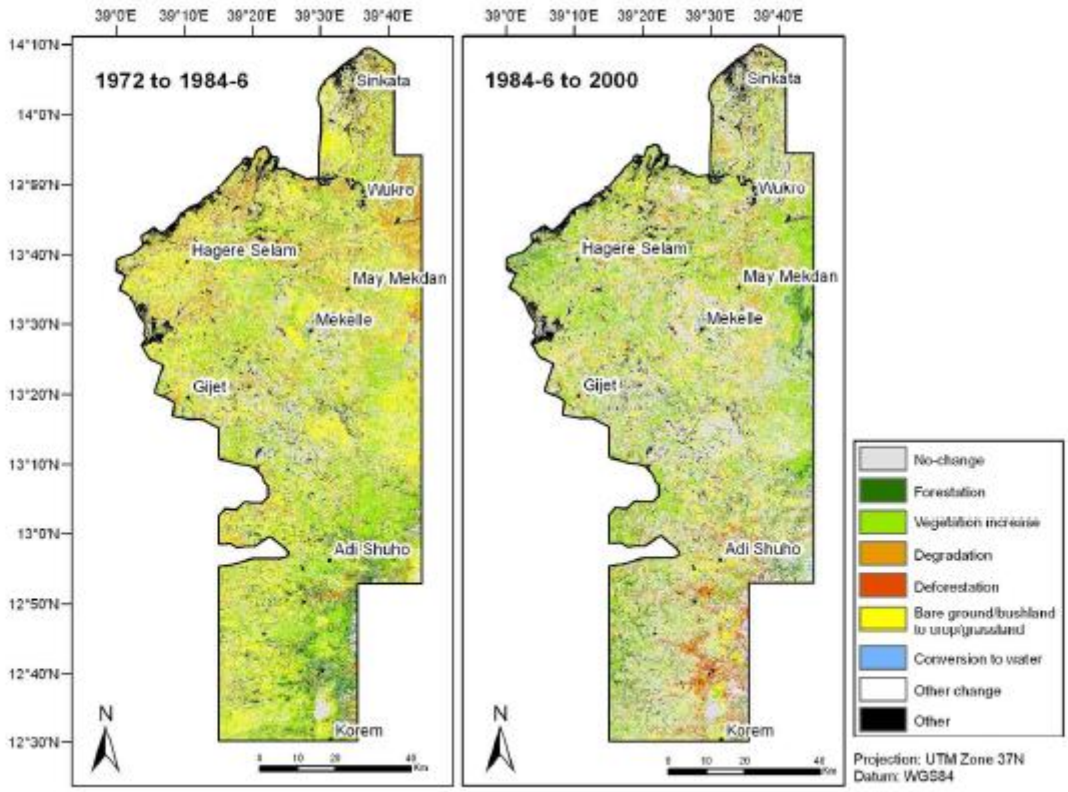


Fig. 6. LUC change between 1972 and 1984-86 (left), and between 1984-86 and 2000 (right). LUC changes, limited to eight major LUC change classes, are indicated by different colors. Areas classified as 'other' LUC in the classification results (Fig. 3 and 4) were left out of the change analysis and are represented in black color.

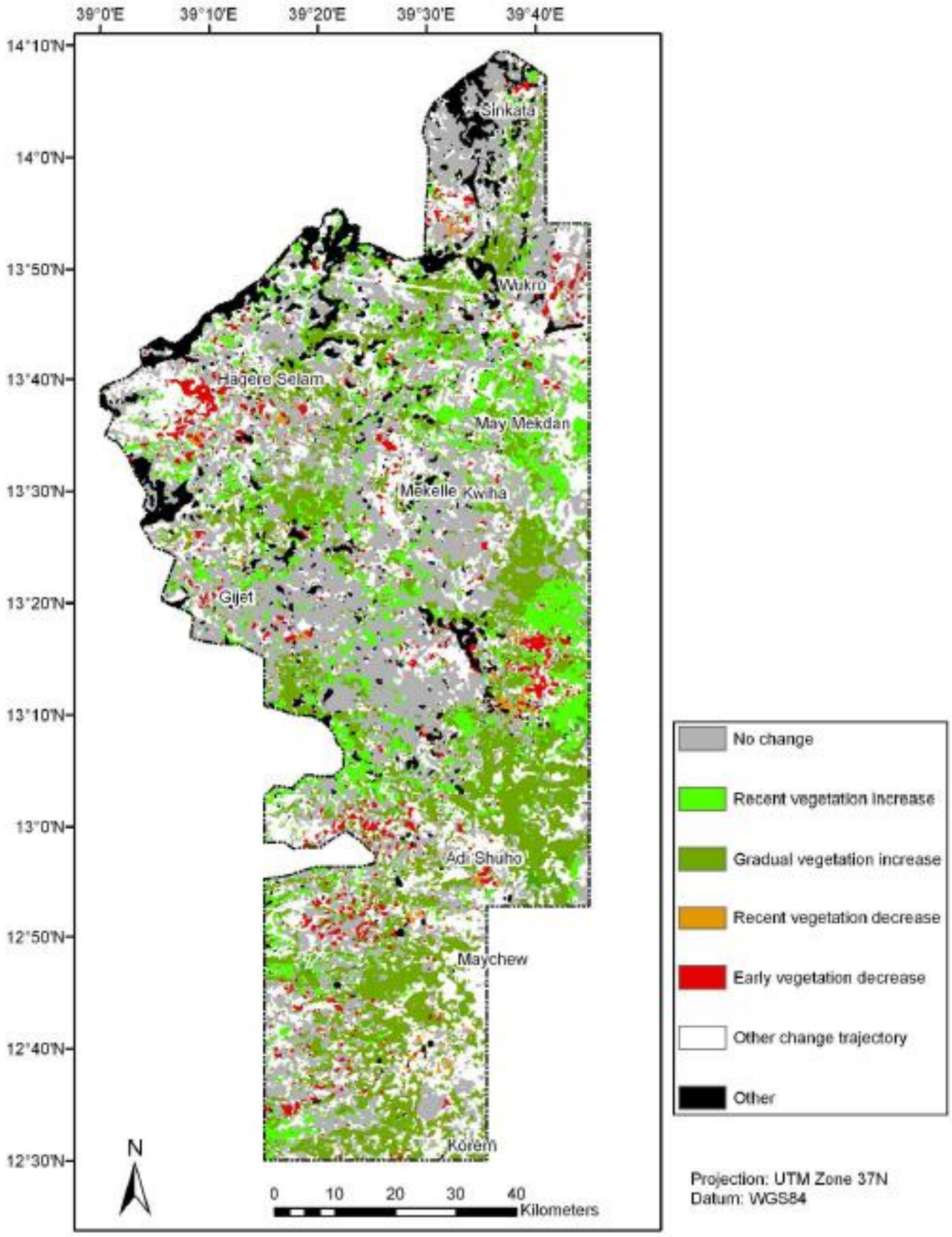


Fig. 7. Overview of LUC change in the study period (1972 – 1984-86 – 2000). The six major LUC change trajectories are indicated by different colors. Areas classified as 'other' LUC in the classification results (Fig. 3 and 4) were left out of the change analysis.