Meire, E., Frankl, A., De Wulf, A., Mitiku Haile, Deckers, J., Nyssen, J., 2013. Land use and cover dynamics in Africa since the 19th century - warped terrestrial photographs of North Ethiopia. *Regional Environmental Change*. 13 (3): 717-737.

Land use and cover dynamics in Africa since the 19th century – warped terrestrial photographs of North Ethiopia

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1 Introduction

It is commonly suggested that Ethiopia was far more forested 2-3 generations ago than it is at present, claiming that 40% of the country was covered by forests only 100 years ago (e.g., Tadesse, 1995). However, based on historical documents and observations from archival terrestrial photographs, such claims have been questioned and even contradicted (e.g., Pankhurst, 1995; Wøien, 1995; Mc Cann, 1997; Crummey, 1998; Nyssen et al., 2004; Nyssen et al., 2009). Quantitative assessments of land use and cover (LUC) so far relied on aerial photographs and satellite images, allowing the preparation of LUC maps from the 1950s onwards (e.g., de Mûelenaere et al., 2012; Wøien, 1995). Historical terrestrial photographs, which are available since 1868 in Ethiopia, were never used in a quantitative way for LUC studies.

Preparing LUC maps from terrestrial photographs can rather easily be done by the use of metric or calibrated cameras (e.g., Welch et al., 2002). From conventional ground-based photography, which use non-metric or uncalibrated cameras, LUC maps can not readily be prepared. Photographing landscapes from the on-the-ground perspective results in large distortions of the scenery as displayed on photographs. Most studies which are based on conventional terrestrial photographs therefore limit themselves to qualitative assessments of LUC, and do not add real geographical positions to their interpretations (e.g., Butler, 1994; Kull, 2005; Byers, 2007). A semi-quantitative approach was proposed by Dervieux (2004), by visually transferring LUC entities to topographic maps. Strict quantitative assessments of LUC from terrestrial photographs were also proposed, but are usually difficult to apply. For example, Corripio (2004) presented a technique that georeferences oblique photographs to a high-resolution Digital Elevation Model (DEM), by defining a mapping function between photograph pixels and DEM cells. Web-based 3D-reconstructions of LUC from photographs have also been elaborated (e.g., Vergauwen and Van Gool, 2006; Frahm et al., 2010).

The presented study introduces a methodology to produce LUC maps from interpretations on terrestrial photographs, by warping topographic units observed on the photographs to the horizontal plane of the map. The methodology is illustrated for Northern Ethiopia. Results will allow to assess (and to a certain extent, to explain) the major land use and cover changes that occurred in the Northern Ethiopian Highlands since the late 19th century. To a further extent, this study will contribute to the understanding of LUC changes in African Highlands starting from the late 19th century.

2 Materials and Methods

2.1 Study area

2.1.1 General setting

The study was conducted in the Northern Ethiopian Highlands (Tigray Regional State), in an area located between 12°30' - 14°10' N and 39°15' - 39°45' E (**Fig. 1**). Five study sites were selected along a 200 km north-south transect, based on the variability in environmental characteristics in terms of elevation, relief, geology,

soils and land use (history). From north to south the study areas are: Sinkata (2200 m a.s.l.; 0.1 km²), Adi Shuho (2600 m a.s.l.; 4.9 km²), Ayba (2750 m a.s.l.; 2.6 km²), Bolago (3500 m a.s.l.; 4.0 km²) and Ashenge (2450 m a.s.l.; 0.3 km²).

*** Insert Fig. 1 approximately here ***

The Highlands border the Rift Valley on the west and are mainly composed of Mesozoic limestone and sandstone covered by Tertiary volcanics (Hofmann et al., 1997; Arndt and Menzies, 2005). The uplift of these lithological units over the past 25 million years (Cohen et al., 1993) and their differential resistance to erosion gave the Highlands their typical relief of stepped, flat topped mountains (*ambas*), dissected by canyon-like valleys. Elevations range between 1500 and 4000 m a.s.l.

Located in the sub-Saharan semi-arid belt, the Northern Ethiopian Highlands are one of the world's most drought-prone zones. The istic rainfall regime is driven by the position of the Inter Tropical Convergence Zone (Robinson and Henderson-Sellers, 1999). Its passage over the Highlands from March until May announces the beginning of the monsoon type rainy season (called the *belg* season), intensifying from June until September (called the *kiremt* season). Precipitation occurs as intense rainstorms with large rain-drop sizes (Nyssen et al., 2005). Annual precipitation increases from north to south, ranging between 500 and 900 mm y⁻¹. The inter-annual variability, however, differs considerably. Mean annual temperatures range from 13° C (Bolago) to 21° C (Ashenge) (as derived from the FAO® New_LocClim V1.11 database).

2.1.2 Land use

The land use types that prevail in Northern Ethiopia comprise of: (i) cropland, (ii) villages, (iii) exclosures and (iv) pastures and rangelands (Fig. 2**Error! Reference source not found.**). Small-scale rain-fed agriculture dominates the farming system (Virgo and Munro, 1978). Individual land holdings seldom cover an area larger than 1 ha (Atakilte et al., 2006). Croplands are preferably situated on flat areas, but also appear on (steep) hillslopes. There, soil and water conservation (SWC) measures like stone bunds or trenches are usually applied to constrain soil erosion. Villages mainly include clustered farms, community or commercial buildings, footpaths and Eucalypt trees. Exclosures are demarcated areas for woody vegetation recovery in which grazing and wood harvesting are restricted or prohibited (Badege, 2001). They are implemented on community land, most frequently on very steep and degraded slopes which suffer from severe erosion (Descheemaeker et al., 2006). Exclosures can eventually give rise to secondary forests, but contrast from the remnants of natural forests, which are usually church forests (Aerts, 2007). Pastures and rangelands constitute the areas primarily used for livestock grazing. Rangelands include all kinds of terrestrial ecosystems in which grazing is allowed (Szaro and Johnston, 1996), but in this study concern all grazing lands apart from grasslands (e.g., shrubland). Grasslands are areas with moist soil conditions that are used for livestock feeding.

Land use is typically related to the geomorphic setting. Croplands and grasslands are mostly situated in valley bottoms or on intermediate flats. Forests and rangelands usually cover mountain slopes, while villages generally occur on mountain slopes or breaks of slopes where shallow soils prevail (Fig. 2).

*** Insert Fig. 2 approximately here ***

2.1.3 Land cover

Main crops grown in the Northern Ethiopian Highlands are tef (*Eragrostis tef*), barley (*Hordeum vulgare* L.), wheat (*Triticum* sp.), sorghum (*Sorghum bicolor*), and maize (*Zea mays*), complemented by leguminous crops such as field peas (*Pisum sativum*), chickpeas (*Cicer arietinum*) and horse bean (*Vicia faba*). Around homesteads, *Gesho* (*Rhamnus prinoides*) is cultivated as an ingredient of a local beer called *sowa*. Major herb species are *Argemone mexicana*, *Aloe* spp., *Phytolacca dodecandra* and *Kniphofia foliosa*. Grass species have not been inventoried. *Opuntia ficus-indica*, *Carduus nyassanus* and *Rumex nervosus* constitute the largest part of the natural shrub cover, *Sansevieria trifasciata* is especially found in villages. Tree cover is dominated by *Eucalyptus globulus*, *Eucalyptus camaldulensis*, *Juniperus procera*, species of *Acacia*, *Olea europaea* ssp. *africana*, and *Euphorbia candelabrum*. *Eucalyptus* is by far the most encountered tree genus in the study areas and probably all over Northern Ethiopia. It occurs under the form of (i) large patches: plantations/exclosures and church forests, (ii) linear shapes: planted along gullies with the aim of limiting their lateral expansion; on land use boundaries near villages and (iii) small clusters: on farmlands and in villages. Species were determined following November et al. (2002) and Addis et al. (2005).

2.2 Repeat photography

Among the numerous existing historical terrestrial photographs of Northern Ethiopia (Munro et al., 2008; Nyssen et al., 2009; Frankl et al., 2011), a subset was selected that covers early periods for which remote sensing techniques are no option.

In total, ten photographs were selected from 1868, 1936, 1942, 1944 or 1961 (**Error! Reference source not found.**). Five 1868 photographs were taken during the British military expedition of 1867-1868 to former Abyssinia. The objective was to release a number of Europeans who had been imprisoned by Emperor Theodore (Sharf et al., 2003). During that campaign, sepia photographs were taken by the 10th Company of Royal Engineers, and represent the oldest landscape photographs of Ethiopia. They were made with a Dallmeyer's triplet achromatic camera (Gordenker and Cohen, 2006). The back-and-white 1936 photograph was taken during the Italian occupation by an anonymous photographer. It was obtained from Ritler and Scheidegger (1999). Two black-and-white photographs from 1942 and 1944 were taken by David Buxton while travelling in Ethiopia (Buxton, 1949). The 1961 color photographs considered in this study were taken by Alfred T. Grove while investigating Quaternary landforms in Eastern Africa (Adams et al., 1999).

*** Insert Table 1 approximately here ***

The landscapes photographed have been revisited in the rainy season of 2008. Since the old photographs were not taken with the aim of being repeated, the camera locations were not permanently marked in the landscape. The repositioning was based on relocations carried out in 2007, by lining up landscape features in the fore- and background in a triangulation system (Nyssen et al., 2009; Frankl et al., 2011). Particular problems concerned atmospheric conditions and the lack of a clear, unobstructed view over the subject. For example, trees were an obstacle in Adi Shuho and Bolago. Repeat photographs were then taken by standing on top of large

boulders or by ascending upon a near mountain slope at the back of the original viewpoint. The recent photographs were made using a digital Olympus© FE-210/X-775 camera. Several repeat photographs of the same historical photograph were taken successively; the one that closely matched the old one was selected for further research. As the repeat photographs had a larger angle of view, they were cropped to be precise repeat photographs. This created a uniform sampling area, which is a requisite for quantitative photo-analysis (Manier and Laven, 2002).

2.3 LUC classification

By investigation the LUC on the historical and repeat photographs and by making observations in the field, the following LUC classes could be distinguished: cropland, forest, Eucalypt plantation, bushland, grassland, village, bare ground and bedrock (**Error! Reference source not found.**). These classes and their definition are in accordance with de Mûelenaere et al. 2011, which investigates LUC changes from Landsat imagery in Northern Ethiopia.

*** Insert Table 2 approximately here ***

2.4 GPS measurements

Global Positioning System (GPS) measurements were done with a differential Trimble® GPS (Geo XH 2005 series) providing 0.30 m to 1 m planimetric accuracy and 1 to 3 m altimetric accuracy after postprocessing. GPS measurements were required for two purposes: (i) for the creation of orthophotographs and, (ii) to warp LUC units that were demarcated on the photographs to the horizontal plane of the map.

2.5 Preparation of orthophotographs

Orthophotographs served as a base for the production of LUC maps. These were produced by digital image processing of the scanned aerial photographs (scale ~ 1:50 000 (EMA, 1965a,b; EMA, 1986a,b,c; EMA, 1994a,b,c,d) scanning at 1200 dpi) with Supersoft® Inc VirtuoZo 2.2 . The geometric rectification was based on a digital elevation model (DEM) devised for the same area. The DEMs were produced through digital photogrammetric restitution and included inner and exterior orientations. The relative orientation was based on > 300 tie points per stereo pair, and the exterior orientation was based on ground control points (GCPs).

Typical GCPs were mountain tops, large trees, road crossings, remarkable points on cliffs, edges of rocks, large boulders and small churches. Recording the elevation of some features required reading the z-coordinate on a nearby rising slope or was calculated on the basis of trigonometry (Tovey, 1982). The GCPs were located at different elevations and as much as possible homogeneously distributed over the area covered by the aerial photographs. This was not always the case since some areas were inaccessible. For example, in Ayba a few extreme mountain peaks were too steep to climb. In Sinkata, a minefield was avoided.

Several orthophotographs were created for each area, by using an increasing number of GCPs. The orthophotograph with the greatest positional accuracy was selected, based on (i) the lowest Root Mean Square

Error (RMSE) in x and y and, (ii) the positional accuracy as compared to 1:50 000 topographic maps from the Ethiopian Mapping Authority.

2.6 Warping land use and cover interpretations to the horizontal plane of the map

The interpretation of LUC on the historical and repeat photographs was done primarily from the camera location, by looking over the photographed landscape. LUC was defined for the previous and current situation per land unit. A land unit corresponds to an area delimited on the photographs, which is homogeneous in LUC (according to **Error! Reference source not found.**) for a certain period. Every land unit was numbered and the historical and the current LUC types were specified. LUC units that were demarcated on the photographs were characterized in detail in accordance to Section 2.3. This involved observing and documenting the present-day LUC in the field. The smallest land unit that could be mapped, has an area of about 1×10^{-6} km² and was observed in Sinkata.

The interpretation of LUC for the historical period was not always straightforward. For example, on sepia or black-and-white photographs, a dark zone on a far-away mountainslope could equally be shadow from a cloud or a forest patch (Kull, 2005). Hence, such distant backgrounds were excluded from the analysis. Care was also required when assessing LUC on historical photographs that were not from the same season as the field visit. Especially differences in vegetation status between dry and rainy season needed to be accounted for.

Warping LUC interpretations to the horizontal plane of the map required to eliminate deformations in the photograph that are apparent when mountainous landscapes are photographed from the on-the-ground perspective. This was done by considering topographic units visible on the photographs separately. Each of these units, having a distinct slope gradient and orientation, has a specific angle of incidence (Aguiló and Iglesias, 1995). The incident angle introduces an optical effect that brings on a perspective distortion which influences the mapping resolution. Areas on the foreground and steep slopes oriented towards the observer's spot have larger incident angles than (nearly) flat areas in the background (**Fig. 3**).

*** Insert Fig. 3 approximately here ***

Topographic entities were warped separately to the horizontal plane of the map. Therefore, numerous GPS measurements delimiting the topographic units were made in the field. As these recordings relate to the terrestrial photograph, they were called Photograph Control Points (PCPs). Additionally, recordings derived from the orthophotographs were used. With this methodology, topographic units that were not visible from the observer's point were excluded (Fig. 3).

2.7 Delineation of the mapping boundaries

The delineation of the mapping boundaries was done by transferring the area covered by the terrestrial photographs visually to the orthophotographs. In addition, two techniques were applied to minimize errors. Firstly, an ESRI® View Shed analysis with the photograph recording point as center was performed. This excludes all areas that cannot be viewed from the photograph location. Secondly, a method was developed to delineate left and right photograph boundaries when visually indefinable. Therefore, the horizontal field of view

(β) was calculated for the uncropped repeat photographs (equation (1); Covington, 2007). β is the field of view of a photograph measured along the horizontal axis (Greene, 2001). Together with the vertical field of view, β determines the angle of view (Simmons, 1987). From β , the horizontal angle (α) between the midpoint of the uncropped image and the left or right boundary of the cropped or precise repeat photograph could be determined. Therefore, we assumed that (i) the image sensor of the camera was held nearly horizontally and, (ii) the midpoint of the historical landscape photograph, or another point on the photograph with perpendicular bisector could be located on the orthophotograph.

$$\beta = 2 \arctan (l/2f) \quad (1)$$

where:

f = focal length, and

l = length of the digital image format

A three dimensional representation of β shows how to quantify α using goniometry (**Fig. 4**). The elaborated technique could also provide additional points to delineate the lower or upper boundary of a photograph. For example, the intersection of the footpath on the foreground of photograph KO-1961-GR-531 and its lower boundary can be located by calculating δ (**Fig. 4**).

*** Insert Fig. 4 approximately here ***

2.7 From interpreted terrestrial photograph to LUC map

Fig. 5 shows the step-by-step method of creating LUC maps from terrestrial photographs, illustrated by the case of Bolago. The Geographic Information System package used for this was ArcGIS 9.2.

STEP 1: Defining topographic units and characterizing land units

Topographic units (TU) were defined on the photographs and LUC was interpreted per land unit. Targeted photo control points were indicated on the photographs.

STEP 2: Recording Photo Control Points in the field (PCPs) and selecting additional tie-points from orthophotographs

For each topographic unit, PCPs were measured in the field. In addition to PCPs, stable landscape features that could be recognized on the orthophotographs were also pointed on the terrestrial photographs.

STEP 3: Warping the topographic units to the horizontal plane of the map and delineation of the mapping area

Warping the rasterized topographic units was done by a spline transformation method, which gave the best results. At least ten tie-points were required per topographic unit to optimize the warping. Next to PCPs, tie-points consisted of features visible on both the terrestrial photograph and the orthophotograph. The delineation of the mapping boundaries was done by a viewshed analysis and by calculating the horizontal field of view of the historical photographs (see Section **Error! Reference source not found.**).

STEP 4: Quality check

The quality check of the warping result involved:

- plotting view lines from the recording point toward the mapped area ('locations that are in vertical alignment on the ground photographs should be located on a single view line on the plane of the map');
- the creation of a virtual photograph of every warping product in ESRI® ArcScene 9.2 - the warping procedure is optimal when this virtual image provides the same view as the ground photographs;
- analyzing LUC as related to contour lines derived from the DEM. This allows investigate on the accuracy at which the topographic unit boundaries have been warped.

STEP 5: Preparation of LUC maps

Finally, a LUC map was prepared according to mapping standards.

*** Insert Fig. 5 approximately here ***

3 Results

LUC changes within the three study areas of Bolago, Ayba and Sinkata are presented here. The complete set of maps is provided by Meire (2009). LUC change patterns are represented using LUC transition matrices (note that, due to rounding, the totals presented in the last row and column of the transition matrices may slightly differ from the arithmetic sum of the values in the cells). LUC changes have been classified into two major classes: 'increase of woody vegetation cover' and 'decrease of woody vegetation cover' (**Error! Reference source not found.**).

*** Insert Table 3 approximately here ***

3.1 Land use and cover changes in Bolago (1868-2008)

The 1868 map of Bolago combines results from three terrestrial photographs, which were taken in panorama. The grassed plain in the lower center of the map corresponds to the overlapping part. Presumably, a fourth photograph taken towards the west completed the panorama.

Over the period 1868-2008, LUC has changed considerably in Bolago (**Table 4, Fig. 6 a and b**). The 1868 situation shows a rather homogeneous landscape of extensive shrubland that includes some scattered *Juniperus procera* trees (3.4 km²). In the southern part, some large patches of juniper forest occur. A smaller patch is found as church forest, around the Tsibet Yohannes church. Central in the area there is some grassland.

*** Insert Table 4 approximately here ***

*** Insert Fig. 6 approximately here ***

The 2008 map of Bolago is more heterogeneous when compared to the previous situation. The number of LUC classes has doubled and the number of LUC patches strongly increased. Bushland was reduced from 3.4 km² to 0.2 km², or by 80%. Instead, the area covered by cropland (0.6 km²), forest (0.8 km²), *Eucalyptus* plantation (0.5 km²) and village (0.6 km²) increased. The small church forest of 1868 has expanded to 0.4 km², which is a sixteenfold increase.

The analysis of land use and cover change in the Bolago valley showed that important conversions took place over the past 140 years. Forests have expanded and became denser, which is often the result of the creation of exclosures since the mid-1980s, especially at the expense of bushland. In forests, Eucalypt trees were often introduced (**Fig. 7**). The cropland in the valley bottom of 1868 has been displaced to steeper slopes by 2008. This all occurred together with the establishment or expansion of villages in the mapped area, which cover 16% of the area at present.

*** Insert Fig. 7 approximately here ***

3.2 Land use and cover changes in Ayba (1942-2008)

Land use and cover changes between 1942 and 2008 in Ayba are summarized in **Table 5** and shown on **Fig. 5**. The most apparent are the villages on the 2008 maps. In total, 28% of the study area has been subjected to village development. These villages developed mainly at the expense of cropland (0.3 km²). Villages are however not composed of built-up area only. They include patches of cropland, shrubland or *Eucalyptus* and *Acacia* trees (**Fig. 8**). The apparent loss in cultivated land (-11%) is thus rather attributable to the classification system (the merging of detailed LUC classes into composite LUC classes) than to actual loss of cropland.

*** Insert Table 5 approximately here ***

About 12% of the former bushland (0.2 km²) has been replaced by *Juniperus* forest and *Eucalyptus* plantations. In the southwestern part of the study area, the 1942 situation shows a forest with apparently no settlements nearby. This suggests that it is a remnant of primary forest. Whether the Adi Weynago Yohannes church was already present in 1942 remains unclear, as it could have had a thatched roof at that time and thus remains unobserved (Fig. 9). More to the east, an open *Eucalyptus* plantation was established on the highest and steepest part of the study area, at the expense of bushland.

*** Insert Fig. 8 approximately here ***

*** Insert Fig. 9 approximately here ***

3.3 Land use and cover changes in Sinkata (1868-2008)

Land use and cover changes between 1868 and 2008 in Sinkata are summarized in **Table 6** and shown on **Fig. 10**. The studied area of Sinkata is the smallest one, as it merely covers an area of 0.046 km². It is composed of two small maps, based on two 1868 photographs that were taken about 3 km apart.

The northern study site (**Fig. 10 a and b**) was relatively forested in 1868, with centrally a forest of primarily *Acacia* and *Olea*. By 2008, this has been replaced by dense *Eucalyptus* plantations covering 0.024 km². Under the cliff, the large bedrock patch of 1868 improved to degraded shrubland in 2008. The area of cropland, which is represented on the foreground of the photographs, has remained unchanged. It takes up a minor part of the study site (0.001 km² or 12 %).

The southern study area (**Fig. 10 c and d**) included a traditional village in 1868. This village has been abandoned and a dense bushland is now at place, including *Opuntia ficus-indica*. Probably, the 1868 village used to be a military camp, as it occurred around a fortification (**Fig. 11**) of which the foundations are still visible today. The degraded shrubland that takes up the largest part of the southern area (0.003 km²) has been enriched with some *Eucalyptus* and *Olea*.

*** Insert Table 6 approximately here ***

Vegetation cover has increased considerably near Sinkata during the studied period (1868-2008). The dominating LUC in the considered areas has changed from a relatively open forest (34%) to dense *Eucalyptus* plantation (52%).

*** Insert Fig. 10 approximately here ***

*** Insert Fig. 11 approximately here ***

3.4 Land use and cover changes in North-Ethiopia (1868-2008)

In addition to the three already discussed areas, **Error! Reference source not found.** summarizes findings on LUC for the combined historical time span 1868-1942 and the 2008 situation, incorporating the sites Ashenge and Adi Shuho (for details see Meire, 2009). Information is also given on the total area of LUC patches with presence of *Eucalyptus*, trees in general and houses, both in historical and in recent times. In order to contrast between the late 19th-early 20th century and the present, the 1961 photographs are not discussed in this section.

*** Insert Table 7 approximately here ***

Bushland covered the majority of the area in 1868-1942 (4.65 km² or 70%), followed by croplands (1.41 km² or 21 %), forests (0.36 km² or 5 %), grassland (0.21 km² or 3 %), bedrock and villages (both <0.01 km² or <1 %). *Eucalyptus* trees did not occur in the 1868-1942 landscape. Other trees did however cover 2.91 km² (25%) of the total area and only a small fraction of the total area did include housing (<0.01 km²).

In 2008, the situation changed considerably. Villages are now the first LUC class of the area (2.02 km² or 30%), followed by grassland (1.37 km² or 21%), forests (1.28 km² or 19%), cropland (1.01 km² or 15%) and *Eucalyptus* plantations (0.98 km² or 15%). Clearly, woody vegetation cover has increased considerably over the period 1868-2008. Forests became larger and Eucalypt plantations were introduced. In total, 94% of the total

area included trees, of which 62% were Eucalypt. Clearly, villages increased in size and number. These changes merely occurred at the expense of bushland.

4 Discussion

4.1 Land use and cover trends in North-Ethiopia (1868-2008)

The important increase in built-up area over the period 1868-2008 from less than 1% to 32% can be explained by a strong increase in population density. An extrapolation by Nyssen et al. (2009), based on data presented by Maddison (2006) and McEvedy and Jones (1978), indicated that the population of Ethiopia in its current boundaries has increased 8- to 10-fold between 1868 and 2008.

Surprisingly, the woody vegetation cover increased over the same period from, especially after 1961. The surface covered by forest increased from 5% in 1868-1942 to 19% in 2008. The situation of 1868-1942 shows an environment where trees are scarce. With the increase in population density and in built-up area, the demand of construction wood and fuelwood strongly increased. According to Woldeamlak (2002), this motivated the local communities to protect vegetated areas and to start reforestation programs. Indeed, since the 1980s, environmental recovery programs were established in order to reverse the decline in woody vegetation (Nyssen et al., 2004), resulting in, for example, the creation of exclosures. This also proved to decrease gully erosion rates (Frankl et al., 2011, 2012). For building purposes, *Eucalyptus* trees were introduced as an alternative to endemic species especially since the 1970s (Jagger and Pender, 2003; Nyssen et al., 2009). At present, they occur everywhere in the landscape, planted as individual trees or small clusters by individual farmers or introduced as plantations on a community basis. Eucalypt trees were also introduced to forests (**Error! Reference source not found.**).

The observed relative small increase in cultivated areas might be explained by the fact that the remaining areas were rather unsuitable for cultivation or that, especially since the 1980s, they were under the protection of local and regional administrations (Descheemaeker et al., 2006). Other studies (e.g. Nyssen et al., 2008; de Mûelenaere et al., 2012) reported an increase of the cropped area in Northern Ethiopia till 1980 and a decrease afterwards.

Significant improvement of the biomass production in the Tigray Highlands between 1975 and the years 2000 has also been indicated by previous research (e.g., Munro et al., 2008; Nyssen et al., 2009; de Mûelenaere et al., 2012). Similar findings are noticed in studies that were carried out in Amhara Region, which is situated south of Tigray. Over the time span 1957-1986, Wøien (1995) reported a remarkable increase in forests and in Eucalypt woodlots at the Mafud escarpment. Crummey (1998) compared terrestrial photographs of the 1930s to the situation in the 1990s, and concluded that tree cover strongly increased in Welo. Such tendencies of woody vegetation recovery were also noted by Woldeamlak (2002) in the Chemoga watershed (period 1957-1998), and by Girmay (2003) in the Tehuledere district (period 1936-1994).

As regarding to the people's perception of the state of the 19th century environment, the information collected by interview has to be considered with much care. For instance, in Bolago the inhabitants told us that "at the time of our grandparents everything was forest here". When we showed the 1868 photographs depicting a much poorer woody vegetation cover than the actual landscape, they simply did not believe it. Local people are mostly not used to be confronted with photographs displaying their village.

4.2 Quantifying land use and land cover from repeat photography

Using historical terrestrial photographs for LUC change assessments is not new (for examples see the Introduction Section). However, using 1868 photographs in a quantitative way is rather innovative. Furthermore, few work on LUC changes cover the period before 1950s, especially when considering Africa.

Much care is required when extrapolating results of repeat photography studies at a regional scale. Terrestrial photographs usually cover only small areas and are therefore not necessarily representative for the broader region. More reliable results can be obtained when a large dataset of photographs is at hand. Furthermore, the lack of uniform time scales of historical photographs make time-generalizations difficult. However, when using a random set of photographs in representative environments and when tendencies are straightforward, even a limited set of photographs can give valuable insights on historical LUC.

The accuracy of the warping results was strongly related to the incident angle at which topographic units were displayed. Warping flat areas located in the photograph background usually resulted in large positional errors, which needed to be resolved during the quality check. The warping of moderate to steep slopes oriented towards the recording proved less problematic. Warping results also showed to be more accurate when the number of tie-points was large for a topographic unit. Units for which the number of tie-points were too limited had to be analysed visually, based on contour lines and land boundaries observed on the orthophotograph. The method was rather time-consuming.

5 Conclusions

The proposed methodology allowed to produced land use and cover (LUC) maps on the basis of old terrestrial photographs. LUC tendencies could therefore be studied over a period of 140 years, which is rather unique for Africa. Results indicate that woody vegetation cover, and in particular tree cover, has increased in Northern Ethiopia over the period 1868-2008. This essentially occurred after 1961. Forests (especially composed of *Juniperus procera*) enlarged and *Eucalyptus* trees widely introduced. These developments particularly occurred at the expense of bushland. The increase in woody vegetation has been accompanied by an increasing population density, as evidenced by the increase in both size and number of villages. Our study is in line with other studies, and confirms that land management strategies improved in the Northern Ethiopian Highlands, which resulted in improved livelihoods.

Acknowledgements

This study has been realized thanks to the support of the programme for Travel Grants of the Flemish Interuniversity Council (VLIR)-University Development Cooperation (UOS) and the Belgian Research Foundation – Flanders (FWO) research credit 31500409. The authors wish to acknowledge Stephanie de Mûelenaere, Gebrekidan Mesfin, Yohannes, Gebreyohannes Tsigae and numerous farmers for the great assistance with fieldwork. Thankfulness also goes Tsega Kiros Zebreabruk for household support. Couderé Geomatic Engineering is acknowledged for lending out GPS equipment. Thanks to Rudi Goossens for providing conceptual insights in geometrical warping. R. Neil Munro fostered contacts that allowed to obtain the historical

photographs by Buxton and Grove. Scientific and technical staff at the Institute for Land and Water Management, Mekelle University and at the Department of Geography, Ghent University, supported the research in various ways.

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Online Resource 2 From interpreted terrestrial photograph to LUC map – Bolago

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Online Resource 5 From interpreted terrestrial photograph to LUC map – Sinkata

Overview of tables

Table 1:

Study area	Photocouple*	Author	Year
Ashenge	1	KO-1936-AN-I19	Unknown
		KO-1936-AN-I19-R1-2009-NY	J. Nyssen
	2	KO-1961-GR-531	A. T. Grove
		KO-1961-GR-531-R3-2008-ME	E. Meire
	3	KO-1961-GR-528	A. T. Grove
		KO-1961-GR-528-R3-2008-ME	E. Meire
Bolago	4	MA-1868-RE-25	British Royal Engineers
		MA-1868-RE-25-R2-2008-ME	E. Meire
	5	MA-1868-RE-26/27	British Royal Engineers
		MA-1868-RE-26/27-R2-2008-ME	E. Meire
Ayba	6	MA-1942-DB-2	D. Buxton
		MA-1942-DB-2-R1-2008-ME	E. Meire
Adi Shuho	7	MA-1944-DB-26/27	D. Buxton
		MA-1944-DB-26/27-R1-2008-ME	E. Meire
	8	MA-1961-GR-526	A. T. Grove
		MA-1961-GR-526-R2-2008-ME	E. Meire
Sinkata	9	SE-1868-RE-19	British Royal Engineers
		SE-1868-RE-19-R3-2008-ME	E. Meire
	10	SE-1868-RE-20	British Royal Engineers
		SE-1868-RE-20-R3-2008-ME	E. Meire

* Photographs earlier than 1961 are black-and-white or sepia photographs

Table 2:

LUC class or detailed LUC class	Description
I CROPLAND	CULTIVATED LAND WITH RAINFED OR IRRIGATED, ANNUAL OR RARELY PERENNIAL CROPS
I.A Cropland	Without soil or stone bunds, always located on flat areas (e.g. plains)
I.B With soil/stone bunds	With soil and/or stone bunds, preferably located on areas with gentle slopes (e.g. foot slopes, plateaus, valley floors), herbs and grasses appear on the bunds
I.B.1 and scattered trees	With scattered <i>Juniperus procera</i> , seldom more than 2 trees per land unit
I.B.2 and clustered <i>Eucalyptus</i>	With groups of <i>Eucalyptus</i> (e.g. afforestation in gullies) that cover only a small area of the land units (< 5%)
I.B.3 and mixed shrubland	Including patches of shrubs that cover <50 % of total land unit area
I.B.4 and mixed shrubland and grassland	Including patches of grassland and shrubs, height < 30 cm, that cover <50 % of total land unit area
II FOREST	TREE-PLANT PATCH, TOTAL CANOPY COVER >20 %, SHRUBS, HERBS AND GRASSES CAN COVER THE LOWEST FOREST LAYER, GENERALLY FOUND ON STEEP SLOPES THAT ARE OFTEN PROVIDED WITH STONE BUNDS
II.D Dense mixed forest	Total canopy cover >50 %, <i>Juniperus procera</i> and <i>Eucalyptus</i> mostly are the dominant tree species, or dominant tree species has not been identified
II.E Open mixed forest	Total canopy cover 20-50 %, <i>Juniperus procera</i> and <i>Eucalyptus</i> mostly are the dominant tree species, or dominant tree species has not been identified
II.F Dense <i>Juniperus</i> forest	Total canopy cover >50 %, <i>Juniperus procera</i> is dominant tree species
II.F.1 with mixed housing	Including patches of traditional/modern/mixed housing that cover <20 % of total land unit area
II.G Open <i>Juniperus</i> forest	Total canopy cover 20-50 %, <i>Juniperus procera</i> is dominant tree species
II.G.1 with high stoniness	Stoniness >40 %
III <i>EUCALYPTUS</i> PLANTATION	<i>EUCALYPTUS</i> PLANT IS MAIN LAND COVER, TOTAL CANOPY COVER >20 %, SHRUBS, HERBS AND GRASSES CAN COVER THE LOWEST FOREST LAYER, FOUND ON STEEP SLOPES THAT ARE OFTEN PROVIDED WITH STONE BUNDS
III.H Dense <i>Eucalyptus</i> plantation	Total canopy cover >50 %, <i>Eucalyptus</i> is dominant tree species, usually found around churches ('church forest') and steep slopes
III.H.1 with high stoniness	Stoniness >40 %
III.I Open <i>Eucalyptus</i> plantation	Total canopy cover 20-50 %, <i>Eucalyptus</i> is dominant tree species, usually found on the highest and steepest slopes
IV BUSHLAND	SHRUBS CONSTITUTE THE PREVAILING LAND COVER, OFTEN RELATED TO RANGELAND, FOUND ON STEEP SLOPES, RANGELAND OR ENCLOSURE
IV.I Shrubland	10-50 % of total land unit area is covered with shrubs, <50 % herbs and grasses, no woody vegetation
IV.I.1 with scattered trees	Including scattered trees (e.g. <i>Acacia spp.</i> , <i>Juniperus procera</i>)
IV.I.2 with clustered <i>Eucalyptus</i>	Including patches of <i>Eucalyptus</i> plantation, total canopy cover <20 %
IV.I.3 with scattered trees and clustered <i>Eucalyptus</i>	Including scattered trees (e.g. <i>Acacia spp.</i> , <i>Juniperus procera</i>) and patches of <i>Eucalyptus</i> plantation, total canopy cover <20 %
IV.I.4 with mixed cropland	Including patches of cropland that cover <50 % of total land unit area
IV.I.5 with traditional housing	Including traditional houses
IV.I.6 with mixed housing and scattered trees	Including mixed housing and scattered trees (e.g. <i>Acacia spp.</i> , <i>Juniperus procera</i>), canopy cover <20 %
IV.I.7 with high stoniness	Stoniness >40 %
IV.I.8 with high stoniness and scattered trees	Including scattered trees (e.g. <i>Acacia spp.</i> , <i>Juniperus procera</i>), canopy cover <20 %, stoniness >40 %
IV.J Degraded shrubland	10-30 % of total land unit area is covered with shrubs, <50 % herbs and grasses, exposing bedrock up to 60 % of total land unit area, no woody vegetation

IV.J.1 with clustered trees	Including clustered <i>Olea europaea ssp. Africana</i> or <i>Eucalyptus</i> , canopy cover <20 %
IV.K Dense bushland	>50 % of total land unit area is covered with shrubs, <50 % herbs and grasses, no woody vegetation
IV.K.1 with scattered trees	Including scattered trees (e.g. <i>Acacia spp.</i> , <i>Juniperus procera</i>), canopy cover <20 %
V GRASSLAND	GRASSES AND HERBS CONSTITUTE THE PREVAILING LAND COVER, USUALLY RELATED WITH GRAZING LAND, MAINLY FOUND ON FLAT AREAS
V.L Grassland	>90 % of total land unit area is covered with grasses and herbs, no woody vegetation
V.L.1 with scattered trees	Including scattered trees (e.g. <i>Juniperus procera</i>), intermediate between grassland and open forest
V.M Degraded grassland with scattered shrubs	<50 % of total land unit area is covered with grasses and herbs, exposing bedrock up to 30 % of total land unit area
VI VILLAGE	RURAL SETTLEMENT, INCLUDING COMMUNITY BUILDINGS AND HOUSES, PREFERABLY LOCATED ON GENTLE TILL SLEEP SLOPES
VI.N Modern village	Frequency of houses with a metal roof >50 %
VI.N.1 with mixed cropland and shrubland	Including patches of cropland and shrubland, total canopy cover < 50 %
VI.N.2 with mixed cropland and clustered <i>Eucalyptus</i>	Including patches of cropland and <i>Eucalyptus</i> clustered in patches or as living fences, total canopy cover <50 %
VI.N.3 with mixed cropland, scattered trees and clustered <i>Eucalyptus</i>	Including patches of cropland, scattered trees (e.g. <i>Acacia spp.</i> , <i>Juniperus procera</i>) and <i>Eucalyptus</i> clustered in patches and/or as living fences, canopy cover <50 %
VI.N.4 with mixed cropland, shrubland and clustered <i>Eucalyptus</i>	Including patches of cropland, shrubland and <i>Eucalyptus</i> clustered in patches and/or as living fences, canopy cover <50 %
VI.N.5 with mixed cropland, shrubland, scattered trees and clustered <i>Eucalyptus</i>	Including patches of cropland, shrubland, scattered trees (e.g. <i>Acacia spp.</i> , <i>Juniperus procera</i>) and <i>Eucalyptus</i> clustered in patches and/or as living fences, canopy cover <50 %
VI.N.6 with mixed shrubland, scattered trees and clustered <i>Eucalyptus</i>	Including patches of shrubland, scattered trees (e.g. <i>Acacia spp.</i> , <i>Juniperus procera</i>) and <i>Eucalyptus</i> clustered in patches and/or as living fences, canopy cover <50 %
VI.N.7 with mixed grassland and clustered <i>Eucalyptus</i>	Including patches of grassland and <i>Eucalyptus</i> clustered in patches and/or as living fences, canopy cover <50 %
VI.N.8 with mixed grassland, scattered trees and clustered <i>Eucalyptus</i>	Including patches of grassland, scattered trees (e.g. <i>Acacia spp.</i> , <i>Juniperus procera</i>) and <i>Eucalyptus</i> clustered in patches and/or as living fences, canopy cover <50 %
VI.O Traditional village	Frequency of houses with straw roof >50 %
VIO.1 with clustered trees	Including clustered <i>Olea europaea ssp. Africana</i> or <i>Eucalyptus</i> , canopy cover <50 %
VI.O.2 with mixed shrubland and scattered trees	Including patches of shrubland and scattered trees (e.g. <i>Juniperus procera</i> , <i>Acacia spp.</i>)
VI.O.3 with mixed shrubland and clustered <i>Eucalyptus</i>	Including patches of shrubland and <i>Eucalyptus</i> clustered in patches or as living fences, canopy cover <50 %
VI.P Mixed village	Frequency distribution of houses with a metal and a straw roof is 50 %-50 %
VI.P.1 with scattered trees and clustered <i>Eucalyptus</i>	Including scattered trees (e.g. <i>Juniperus procera</i> , <i>Acacia spp.</i>) and <i>Eucalyptus</i> clustered in patches or as living fences, canopy cover <50 %
VI.P.2 with mixed cropland, shrubland and clustered <i>Eucalyptus</i>	Including patches of cropland, shrubland and clustered <i>Eucalyptus</i> , canopy cover <50 %
VI.P.3 with mixed cropland, shrubland, scattered trees and clustered <i>Eucalyptus</i>	Including patches of cropland, shrubland, scattered trees (e.g. <i>Juniperus procera</i> , <i>Acacia spp.</i>) and clustered <i>Eucalyptus</i> , canopy cover <50 %
V.I.P.4 with mixed shrubland, scattered trees and clustered <i>Eucalyptus</i>	Including patches of shrubland, scattered trees (e.g. <i>Juniperus procera</i> , <i>Acacia spp.</i>) and clustered <i>Eucalyptus</i> , canopy cover <50 %
VII BARE GROUND	NO WOODY VEGETATION, <5 % SHRUBS, HERBS AND/OR GRASSES, EXPOSING SOILS UP TO 99 % OF TOTAL LAND UNIT AREA, FOUND ON GENTLE TO VERY STEEP SLOPES

VIII BEDROCK	EXPOSING BEDROCK UPT TO 80 % OF TOTAL LAND UNIT AREA
VIII.Q with clustered shrubs and trees	Including groups of shrubs and trees, tcanopy cover < 20 %

Table 3:

LUC _{year 1}	LUC _{year 2}	LUCC class	LUC _{year 1}	LUC _{year 2}	LUCC class
Cropland	Forest	Increase of woody vegetation cover	Bushland	Cropland	Decrease of woody vegetation cover
Cropland	Village				
Bushland	<i>Eucalyptus</i> plantation		Bushland	Grassland	
Bushland	Forest				

Table 4:

1868 \ 2008	Cropland	Forest	<i>Eucalyptus</i>	Bushland	Grassland	Village	Total
Cropland	0.0	0.08	0.00	0.00	0.08	0.03	0.20
Forest	0.0	0.19	0.03	0.00	0.00	0.00	0.25
<i>Eucalyptus</i> plantation	0.0	0.00	0.00	0.00	0.00	0.00	0.00
Bushland	0.57	0.79	0.51	0.16	0.76	0.61	3.40
Grassland	0.0	0.00	0.00	0.00	0.21	0.00	0.21
Village	0.0	0.00	0.00	0.00	0.00	0.00	0.00
Total	0.57	1.07	0.54	0.16	1.05	0.65	4.04
Change (%) of the total area	9	20	13	-80	21	16	

Table 5:

1942 \ 2008	Croplandd	Forest	<i>Eucalyptus</i>	Bushland	Grassland	Village	Total
Cropland	0.75	0.00	0.00	0.00	0.00	0.28	1.03
Forest	0.00	0.09	0.00	0.00	0.00	0.00	0.09
<i>Eucalyptus</i> plantation	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Bushland	0.00	0.12	0.09	0.47	0.00	0.46	1.13
Grassland	0.0	0.00	0.00	0.00	0.32	0.00	0.32
Village	0.0	0.00	0.00	0.00	0.00	0.00	0.00
Total	0.75	0.20	0.09	0.47	0.32	0.73	2.56
Change (%) of the total area	-11	5	3	-26	0	28	

Table 6:

1868 \ 2008	Cropland	Forest	<i>Eucalyptus</i> plantation	Bushland	Village	Bedrock	Total
Cropland	0.0018	0.0000	0.0000	0.0000	0.0000	0	0.0018
Forest	0.0000	0.0007	0.0148	0.0000	0.0000	0	0.0155
<i>Eucalyptus</i> plantation	0.0000	0.0000	0.0000	0.0000	0.0000	0	0.000
Bushland	0.0000	0.0000	0.0090	0.0056	0.0000	0	0.0148
Village	0.0000	0.0000	0.0000	0.0001	0.0027	0	0.0028
Bedrock	0.0000	0.0000	0.0000	0.0111	0.0000	0	0.0109
Total	0.0018	0.0007	0.0238	0.0168	0.0027	0.000	0.0459
Change (%) of the total area	0	-32	52	5	<1	-24	

Table 7:

Period	1868-1940s		2008	
Total area	6.65 km ²	%	6.65 km ²	%
I Cropland	1.41	21	1.01	15
II Forest	0.36	5	1.28	19
III <i>Eucalyptus</i> plantation	0	0	0.98	15
IV Bushland	4.65	70	0	0
V Grassland	0.21	3	1.37	21
VI Village	< 0.01	< 1	2.02	30
VII Bare ground	0	0	< 0.01	< 1
VIII Bedrock	0.01	< 1	0	0
Total area with presence of <i>Eucalyptus</i>	0	0	4.11	62
Total area with presence of trees ¹	2.91	44	6.24	94
Total area with presence of houses	< 0.01	< 1	2.14	32

¹All tree species, including *Eucalyptus*