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LAND USE AND COVER DYNAMICS SINCE 1964 IN THE AFRO-ALPINE VEGETATION BELT: LIB AMBA MOUNTAIN IN NORTH ETHIOPIA

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ABSTRACT

Human induced land use and land cover (LUC) changes threaten the ecosystem services of the vulnerable tropical afro-alpine vegetation. Several LUC change studies are available for the Ethiopian highlands, but relatively little is known about LUC change in the afro-alpine zones. In this study, LUC changes between 1964 and 2012 were mapped for the afro-alpine zone of Lib Amba Mountain, part of the Abune Yosef Mountains in North Ethiopia. Historical LUC was derived from georeferenced aerial photographs of 1964 and 1982, and the present LUC (2012) from Bing Map satellite imagery. Based on these successive LUC maps a time-depth map, LUC proportions, LUC transition matrices and LUC change trajectories were calculated. Two main phases of LUC change could be distinguished linked to the neo-Boserupian perspective. (i) Between 1964 and 1982, there was a large-scale deforestation and general degradation of the vegetation above 3500 m, in a period of low population pressure; (ii) Between 1982 and 2012, an intensification of land use prevailed accompanied with a slight regeneration of the vegetation and the *Erica arborea* L. forest, under increased population pressure. Depth interviews indicated that local and governmental land management measures are very important for the protection against vegetation depletion and soil degradation. Quick recovery of the forest on Lib Amba provides confidence that degraded afro-alpine areas would benefit in a short time from complete protection, given the vicinity of remaining patches of afro-alpine vegetation. Management interventions are thus vital to restore the important ecosystem services of the afro-alpine vegetation belt.

KEY WORDS: Human impact; Land use and land cover change; Intensification; Deforestation; Forest recovery; Tropical highlands

INTRODUCTION

Land use and land cover (LUC) changes induced by human activity have an undeniable impact on natural vegetation cover (Lambin *et al.*, 2001; Turner *et al.*, 1993) and on the soil system (Brevik *et al.*, 2014; Leh *et al.*, 2013). African tropical mountainous areas, generally have a greater vulnerability to LUC changes due to the high population density and the presence of steep slopes (Lambin, 1997). The northern Ethiopian highlands suffer from severe land degradation due to the highly intensified land usage (Nyssen *et al.*, 2009d). Several studies indicate that LUC in the Ethiopian highlands have significantly changed during the second half of the 20th century (Amsalu *et al.*, 2007; Bewket, 2002; Teferi *et al.*, 2013; Tegene, 2002; Tekle & Hedlund, 2000; Zeleke & Hurni, 2001). The majority of these studies indicate deforestation in favour of cultivation land as an important cause of land degradation. However, most of these studies mainly deal with lower vegetation belts, whereas LUC changes in the afro-alpine zone are less widely studied. The growing population of Ethiopia mainly lives from self-subsistence agriculture, which causes a high pressure on the landscape's natural resources (Belay *et al.*, 2014). This caused in combination with early land cultivation several thousand years ago severe soil degradation in Ethiopia (Hurni, 1988). The effect of land cover changes on soil erosion in Ethiopia is increasingly studied (Gelaw *et al.*, 2013; Gessesse *et al.*, 2014; Mekuria & Aynekulu, 2013; Yeshaneh *et al.*, 2015). Removal of vegetation cover historically has been a cyclic process in Ethiopia, but overall there was a tendency of deforestation over the last one hundred year (Bishaw, 2001). Deforestation in favour of cropland or overgrazing has many negative effects on the soil: e.g. decreased soil depths especially on steep slopes, decreased surface roughness, decreased soil organic matter content, soil compaction. (Lemenih *et al.*, 2005). Despite this long history of deforestation and the high population increase, land rehabilitation is observed over the last two decades in the northern Ethiopian highlands (Lemenih & Kassa, 2014; Nyssen *et al.*, 2009b). However, intensified anthropogenic modifications of the vegetation cover (LUC change) and increased climatic stress (drought) on the vegetation have increased the vulnerability of the land to degradation (Frankl *et al.*, 2011, 2013b). Lanckriet *et al.* (2014) emphasize the importance of the political-ecological system and its conservatory policies for land degradation cycles. However, these drivers of dynamics of occupation and cultivation may not be applicable to the afro-alpine areas in the Ethiopian mountains, as they were occupied much more recently (Hurni & Messerli, 1981). Nevertheless, insufficient investments in soil and water conservation (SWC), removal of natural vegetation and overpopulation are determining factors of land degradation in the highlands of northern Ethiopia (Amsalu *et al.*, 2007).

High altitude forests and vegetation plays a crucial role in the vulnerable environment of the northern Ethiopian highlands. On a global scale, it is estimated that nearly half of the human population directly or indirectly depends on water yield from mountain catchments (Messerli, 2004). The ecology and richness of the highland vegetation plays a vital role for clean and steady water discharge. The Ethiopian highlands also form hot spots of biodiversity, due to high habitat diversity caused by a compression of climatic zones and differences in microclimate, exposure, soil integrity and slope steepness (Spehn & Liberman, 2006). Endemic species richness is particularly high in the north Ethiopian highlands. The endangered Ethiopian wolf (*Canis simensis*) forms a striking well known example, threatened by habitat destruction (Ashenafi *et al.*, 2005). Ecosystem stability in the highlands is a requisite for erosion control, catchment quality and biological richness (Spehn & Liberman, 2006). By storing rainfall, highland forests reduce soil erosion and form a buffer against flooding in lower areas (Aerts *et al.*, 2002; Miehe & Miehe, 1994). Hence, one of the crucial elements of land management in highland areas is the recovery of forests at critical locations. Over the last few decades, removal of vegetation has been locally slowed down or reversed (Nyssen *et al.*, 2009c). Local initiatives of land rehabilitation, afforestation and natural resource management have shown that recovery from severe degradation is possible (Boyd *et al.*, 2000; de Mûelenaere *et al.*, 2014). This re-greening transition is induced by environmental conservation and policy interventions (Belay *et al*., 2014). According to Nyssen *et al.* (2009d) there was a gradual recovery of the mountain forests in the Bela-Welleh catchment in the northern Ethiopian highlands, approximately 100 kilometres north of the study area of this research. Hence, land degradation is not necessarily irreversible despite the ongoing increase of population pressure (de Mûelenaere *et al.*, 2014).

An improved understanding of past and present LUC changes is essential to provide an accurate analysis of the changes (Srivastava *et al.*, 2012). Human interference has a decisive impact on these changes. Knowledge of patterns of LUC changes is necessary to enable a sustainable management of the environment. At present, little is known about general LUC change in the afro-alpine environment of the northern Ethiopian mountains. This study provides a detailed insight in LUC change of the afro-alpine belt for a case study in the north Ethiopian highlands since 1964. The objectives of this paper are (i) detection and analysis of LUC and their changes around the tropical mountain of Lib Amba and (ii) determining the underlying causal factors of LUC change in the study area.

MATERIALS AND METHODS

Study area

The study area of Mount Lib Amba (20 km², 12°8'N, 39°11'E, 3993 m) is part of the Abune Yosef Mountain Range in North Ethiopia (Fig. 1). The highlands of Northern Ethiopia consist of a high basaltic plateau situated west of the Main Ethiopian Rift (Coltorti *et al.*, 2007). Four rivers spring at Mount Lib Amba: Derege (in the south), Dengelsa (in the west), Shal (in the northeast) and Golina (in the southeast). The first two rivers belong to the drainage area of the Tekezze river, while Shal and Golina river drain to the Western Rift Valley in the east. The typical soils found at lower elevations in the basalt-dominated highlands are reddish Skeletic Cambisols and black Pellic Vertisols (Descheemaeker *et al.*, 2006; Van de Wauw *et al.*, 2008). Andosols form the prevalent soil type in the afro-alpine zone with a lower limit at 3400 - 3600 m a.s.l. (Hurni & Messerli, 1981; Hurni, 1989). There are two rainy seasons with high inter-annual rainfall variability in North Ethiopia. The main rain season is generated by the annual movement of the Intrertropical Convergence Zone (ITCZ) (Cheung *et al.*, 2008; Nyssen *et al.*, 2005) and is responsible for 65-95% of the annual rainfall (Segele & Lamb, 2005). The climate in the afro-alpine zone is moister, due to decreasing temperatures and evaporation with altitude (O'Hare *et al.*, 2005). Aspect, altitude and latitude are important factors controlling the variation of precipitation in the Ethiopian mountains (Nyssen *et al.*, 2004, 2005).

Small scale agriculture dominates in the valleys up to 3500 m, which is the altitudinal limit of barley (Hurni & Messerli, 1981). Farmers use a flexible farming system that takes the local environmental conditions in account. Cropping systems with shorter cropping season are generally found on the valley-side, while longer crop cycles are found in the valley-bottom (Frankl *et al.*, 2013a). The crops consist mainly of barley, lentils, peas, beans and potatoes. Since 1975, Soil and Water Conservation (SWC) measurers are implemented to limit land degradation in Ethiopia (Gebremichael *et al.*, 2005). This is also visible in the study area by the wide use of stone bunds at the edge of the farmland to reduce overland flow and soil erosion. Settlements in the study area are scattered and consist of small traditional houses. Eucalyptus plantations are common in the valleys below 3500 m, along gullies and around the villages. The population density in the study area is increased with 26% during the last decade, from 130 p/km² in 2000 to 164 p/km² in 2010 (CIESIN & CIAT, 2005).

The naturally occurring subalpine vegetation belt of Juniper forests (*Juniperus procera*) is missing along the slopes of Lib Amba. A protected *Erica* forest prevails on the north side with trees that reach up to three metres and with the upper individuals growing up to 3800 m (Jacob *et al.*, 2014). Small patches of remnant forest with high 3-4 metres *Erica* trees, but without undergrowth are found on the southern slopes of Lib Amba Mt (Fig. 2a). The afro-alpine highlands are important for biodiversity. *Hypericum revolutum* shrubs are very common up to 3650 m, especially in places with less intensive grazing. While *Helichrysum citrispinum* shrubs are more common at higher altitudes (Friis *et al.*, 2010) (Fig. 2b). A unique specie in the afro-alpine zone is giant lobelia (*Lobelia rhynchopetalum Hemsl.*), which can mostly be found at wetter depressions (Fig. 2c). At high altitudes the vegetation dominated by afro-alpine tussock grasses that are well adapted to the cold mountain environment (Friis *et al.*, 2010) (Fig. 2d).

This afro-alpine vegetation of the Ethiopian highlands is home to a wide range of endemic wildlife species, but fragmentation and destruction of the afro-alpine vegetation threatens their habitat (Kidane *et al.*, 2012). The population of the endangered Ethiopian wolf (*Canis simensis*) is estimated to be only 19 individuals in the Lib Amba and Abune Yosef community conservation area (Marino & Sillero-Zubiri, 2013), other well-known endemic species encountered in the study area are the Gelada baboon (*Theropithecus gelada*) and the Abysinian owl (*Asio abyssinicus*).

Data and pre-processing

Bing maps satellite imagery (IKONOS, GeoEye) was used to map the LUC of 2012 and historical LUC was derived from aerial photographs of 1964 and 1982. Multiple overlapping photographs were needed to cover the study area without cloud cover (3 for 1964 and 4 for 1982). The aerial photographs were geometrically rectified by co-registration with the 2012 satellite imagery as reference (table 1). Image-to-image registration enables identification of a large number of corresponding points on both layers. This method yields reasonable results when considering small areas and using a high density of control points (Hughes *et al.*, 2006; James *et al.*, 2012). For every aerial photograph, a total of 250 co-registration points were manually indicated concentrated in the study area, this is on average 2.5 points per km². The RMSE (Root Mean Square Error) of every georeferenced photograph was calculated from the comparison between coordinates of 20 unrelated control points on the aerial photograph and the Bing Maps imagery. The highest total RMSE is 5.92 m in x and 5.99 m in y for the 1982 photographs and 5.46 m in x and 4.75 m in y for the 1964 photographs (table 1).

Global Navigation Satellite System (GNSS) data points were collected in the field using a Garmin eTrex H with a planimetric accuracy between 3 and 10 m. A total amount of 45 Ground Truthing (GT) points distributed in the study area were recorded and characterized. For each GT point, 4 main parameters were described in the field: (1) different vegetation types (2) estimation of the vegetation cover per vegetation type (3) rock outcrop and (4) land management of the area. Accompanying ground photographs were made at the location of each GT point. Such GT points have proven valuable to map LUC (Lillesand *et al.*, 2008).

Land Use Cover (LUC) classification

A classification legend was developed based on GT data and on previous work in North Ethiopia by Meire *et al.* (2013) and de Mûelenaere *et al.* (2014). The legend is adjusted to the ecotopes represented in the study area, i.e. the *Moist evergreen Afromontane forest* (MAF), the *ericaceous belt* (EB) and the *afro-alpine belt* (AA) (Friis *et al.*, 2010) and is subcategorized by type of vegetation. The classification legend consists of the following 8 classes: cropland, forest, *Eucalyptus* plantation, bushland, grassland, village, rock outcrop and river bed. The classes for rock outcrop and river bed have very similar textures on the imagery, but the location makes it easy to distinguish them. The main classes are subdivided in subclasses: (i) Farmland is subdivided by occurrence of stone and soil bunds and occurrence of other vegetation or clustered *Eucalyptus*; (ii) Forest is subdivided in open and dense forest; (iii) Bushland is subdivided in plain bushland, bushland mixed with grass and bushland with scattered other vegetation; (iv) Grassland is subdivided in plain grassland and grassland mixed with other vegetation.

Based on this classification legend the LUC of the three time stages (1964, 1982 and 2012) was mapped in ArcGIS with the co-registered aerial photographs and Bing Maps imagery as base layers and the GT points as field reference. The LUC classes were identified on the base maps using interpretation techniques such as anisotropy, grey scale and texture differences. The minimal mapable unit (MMU) was derived from the largest RMSE. The largest error of the used aerial photographs was 5.98 m, which occurred in a photograph from 1982. The used MMU was therefore 10 m.

Land Use and Land Cover (LUC) change analysis

The LUC maps were used to study LUC change between 1964 and 2012 in the afro-alpine highlands of North Ethiopia. A time-depth map was constructed to distinguish the areas that have changed with those that have a permanent LUC. Because the time depth map showed a clear distinction of change between high and low elevated areas, the study area was divided into two elevation zones. The elevation boundary was taken at the 3500 m contour line, thus accounting for the agro-ecological boundary of barley and other crops (Hurni & Messerli, 1981).

Metrics of LUC and LUC change were derived for each time series and per elevation zone. The LUC proportions reveal the trends of change per LUC class and transition matrices show the nature of change. Four important LUC change types were derived from de Mûelenaere *et al.* (2014) and adapted to this research, indicated on the matrices and represented on a map. These change types are:

- (i) Deforestation: the change of forest in the first time period to any other LUC class in the second time period;
- (ii) Degradation: the change of bushland, grassland or Eucalyptus plantation to farmland, the change of farmland, bushland, grassland and Eucalyptus plantation to rock outcrop and the change of bushland to grassland;
- (iii) Forestation: the change of any other class to forest;
- (iv) Vegetation increase: the change from farmland or grassland to bushland and the change from rock outcrop to grassland, bushland or Eucalyptus.

Socio-ecological dynamics of LUC change

To understand the underlying long-term social determinants of LUC changes, in-depth interviews with key informants were conducted. The interview method is based on individual interviews with key persons and farmers, which were asked open questions. These questions concern interlinkages between the political and ecological history of the study area (Lanckriet *et al.* 2014). A total of 24 in-depth interviews were conducted in the Lib Amba study area with key informants in the field. The interviews were structured and composed of specific questions concerning the following:

- (i) Evolution in population density and settlement evolutions; e.g. *Have settlements in the valley changed? How old is the farmland?*

(ii) Crop system and livestock farming; e.g. *Which crops are grown on the farmland? Is a cycle with bare soil used? Is transhumance used?*

(iii) Vegetation dynamics; e.g. *Did the extent of the Erica forest change? Since when is the forest protected?*

Because previous research showed people can give imprecise answers, stating collective perception rather than personal experience for a variety of reasons, a semi-structural set-up of the questions was adapted to the surroundings and references were made to the landscape at the time of the interview (Nyssen *et al.*, 2006). A historical ground photograph of the southern valley in the study area from 1916 was used to make a reference to the past environment (Jacob *et al.*, 2014, figure 2).

RESULTS

Land Use Land Cover (LUC) maps for 1964, 1982 and 2012

The LUC of Lib Amba Mt. was mapped for the three successive periods (Fig. 3). These maps reveal the vegetation boundaries of the LUC classes. Farmland is dominant in the valleys below 3500 m, except for a small area with farmland up to almost 3700 m in 1964, but this farmland was abandoned by 2012. The density of stone bunds in the farmlands increased between 1964 and 2012. Settlements used to be spread and confined to the lower parts, but associated with population growth new settlements were created higher up the mountain (up to 3696 m) by 2012. The natural *Erica* forest, growing between 3274 and 3712 m in 1964, strongly decreased. While Eucalyptus forest increased in the lowlands from a single small patch at 3332 m in 1964 to several small patches up to 3445 m in 2012. Furthermore, in the highlands above 3700 m, plain bushland increased at the expense of mixed grass- and bushland and grassland. The extent of the river beds in the valleys increased considerably and was mapped on the 2012 LUC map.

Land Use and Land Cover (LUC) change

The time depth map gives an overview of the spatial and temporal distribution of the landscape between 1964 and 2012 (Fig. 4). Prominent is the unchanged character of the farmland in the valleys. However, in all valleys Eucalyptus plantations and villages increased between 1982 and 2012, indicating the intensification of land use. The development of broader river beds below 3500 m also occurred between 1982 and 2012. Overall, most changes occurred above 3500 m, but there is also a considerable area of permanent bushland. The extent of the remaining central *Erica* forest has had a very dynamic character over the last 48 years.

The proportions of every LUC class of 1964, 1982 and 2012 reveals the major trends in the study area (Fig. 5). Bushland (43% in 2012) and farmland (44% in 2012) are clearly the major classes. *Erica* forest has known a severe decline in the first 18 years (from 16% of the study area in 1964 to 4% in 1982) and kept decreasing at a slower rate after 1982. Bushland on the contrary has constantly increased between 1964 and 2012 (from 26% to 43%). The proportion of farmland is fairly stable, there was only a decrease between 1982 and 2012 at areas above 3600 m. Eucalyptus forests were non-existent in 1964 and are quickly expanding (2% in 2012). Grassland doubled between 1964 and 1982, but dropped back after 1982, probably due to reduced grazing in the higher areas since 2007. There was also an increase of the proportion of the villages.

LUC transition matrices and change maps reveal the nature of the long-term changes between 1964 and 2012 (table 2). The largest proportion of change is given by deforestation (13.7 %), primarily forest changing into bushland (11.3 %). Deforestation occurred mainly in the first phase (between 1964 and 1982) in large patches in the north, east and centre of the study area. On the contrary, the area with vegetation increase (8.8 % over the whole period) is most prominent in the second phase (11% between 1982 and 2012). Over the full period, this change occurred almost exclusively above 3500 m

(12.9 %). Vegetation increase is mainly due to the change of farmland into bushland (5.1 %) and grassland into bushland (3 %). Forestation is only limited (0.2%) and primarily occurred in the second phase in one large patch in the centre of the study area above 3500 m. Naturally, trees are not growing above the treeline at app. 3700 m, which explains a more stable vegetation of the afro-alpine vegetation above the treeline.

Degradation occurred in one elongated patch in the northeast of the study area and in some smaller patches scattered over the entire area (3.7 %, almost exclusively above 3500 m). The change of bushland into grassland (1.8 %) and bushland into farmland (0.8 %) are the main components. The rate of degradation is similar between the two periods, but slightly higher in the first phase. Prominent in the lower elevation zone is the considerable change in the category 'other change' (8.6 %). This proportion is chiefly composed of the transition of farmland into Eucalyptus plantations, village and river bed between 1982 and 2012. This represents the intensification of land use in the valleys. Overall, 70% of the study area remained unchanged, chiefly comprised of farmland in the valleys (41.9 %) and bushland on the mountain slope (22.5 %).

Eight LUC-trajectories explain 98.2 per cent of the LUC changes (table 3). The largest proportions consist of stable non-forested areas (47.2 %) mainly in the valleys and continually vegetated areas (31.5 %) mainly in the highlands. When considering the two proportions of unchanged areas (together 78.7 %), it can be concluded that only 21.3 % of the study area changed between 1964 and 2012. Of these are proportions of trajectories with a recent vegetation increase distinctly higher than proportions of trajectories with a recent vegetation decrease (table 3).

Drivers of LUC change dynamics

The 24 in depth interviews provide insight in the underlying drivers of the LUC dynamics observed in the study area. Older informants stated that the number of settlements began to increase after the land reform in 1988, when farmland was obtained from the government.

However, many of the highest settlements are only very recent and appeared in 2007, driven up due to the high population density in the lower areas. Cultivation of new farmland occurred to some extent high up in the western valley, but was reversed after some time because the yield was very low. The government stimulated the cultivation of Eucalyptus trees from 1991 onwards. After the downfall of the Derg, the new government also introduced several new varieties of crops adapted to the highland conditions (from 1997 onwards).

Transhumance is practiced on a broad scale in the Tigray highlands (Nyssen *et al.*, 2009a). This was also the case in the study area until the government in 2007 prohibited grazing in the uppermost areas. Due to this restricted access to fodder, the amount of livestock was reduced. The remaining animals are kept close to the house during the rain season and are fed straw from the land. Some informants also mention the opportunity to cut grass in the 'highlands' on which to feed their livestock and a minority declared to let their animals graze in the 'highlands' illegally. Transhumance had a major impact on the extent of the *Erica* forest. Livestock grazing exerted high pressure of the vegetation in the highlands and prevented forest regeneration. While, in addition the shepherds degraded the forest by chopping for firewood. The degradation started already in 1974, when population density started to increase. However, during the government of the Derg forest cutting was forbidden but grazing continued, further enhancing degradation. However, protection of the forest against cutting was inadequate and illegal cutting went on. Only after the downfall of the Derg (1990), the cutting of the forest really ceased. But grazing in the forest continued until complete protection in 2007. This social-ecological background suggests, settlement dynamics that confirm the observed past deforestation and degradation and recent vegetation increase and the intensification of LUC in the study area.

DISCUSSION

This research gives an extensive overview of LUC change in the afro-alpine highlands of northern Ethiopia over a period of 48 years (1964-2012). Figure 6 summarizes the main trends by plotting the LUC proportions in time for the two elevation zones separately.

Evolution of farmland and settlements: a neo-Boserupian perspective

In contrast to the constant proportion of farmland up to 1982 in the study area, a significant increase of farmland in North Ethiopia was found by several studies from 1965 until the 1980's (e.g. de Mûelenaere *et al.* 2014; Belay *et al.* 2014). This difference could be explained by the late colonisation of the highest areas (Hurni & Messerli, 1981). The second trend of a decrease in farmland between 1982 and 2012 at Lib Amba is in accordance with the regional trends reported by de Mûelenaere *et al.* (2014) and more locally by Belay *et al.* (2014). The observed decrease in the second phase can be ascribed partly to the conversion of farmland into settlements to house the growing population and partly to the abandonment of degraded lands with a low yield on steep slopes (Belay *et al.*, 2014; de Mûelenaere *et al.*, 2014). During this period, there was also an increase of the density of stone bunds. Overall, this second phase corresponds with a period of land intensification.

Abandonment of farmland seems contradictory to the increasing population density in northern Ethiopia (e.g. Bishaw 2001 and Belay *et al.* 2014). However, high population density is not necessarily related to land degradation caused by land clearing for agriculture and overgrazing, as this can mostly be ascribed to conservation policies (Haile *et al.*, 2006; Lemenih *et al.*, 2014). Nyssen *et al.* (2014) even found that the increase of woody vegetation was higher in areas with greater population densities. Our findings are thus compatible with a neo-Boserupian perspective of population-forest dynamics. Following Boserupian theory, extensive land clearing (deforestation and degradation) would prevail during human colonization under relatively low population densities (i.e. the period 1964-1982). When population pressure then rises, necessity would drive farmers to invest in better land management and agricultural intensification (i.e. the period 1982-2012).

Vegetation increase by the conversion of farmland into bushland might also have been the result of the land reform after the downfall of the Derg. This governmental programme focused on egalitarian land rights and effective implementation of soil conservation measurements, resulting in decreased land degradation and a vegetation increase (Lanckriet *et al.*, 2012).

Another considerable proportion of farmland changed into Eucalyptus plantations (almost 2%) after 1982. The evolution of Eucalyptus plantations occurred almost simultaneously to the establishment of settlements in the study area. De Mûelenaere *et al.* (2014) found a similar result of an increasing number of small Eucalyptus plantations on a regional scale in the Ethiopian highlands. This has a political background, along with the change of government in 1991, the plantation of Eucalyptus in the private sector was encouraged (Holden *et al.*, 2003).

Evolution of vegetation

A number of studies have shown a tendency of improvement of the biomass production and recovery of the natural forest cover in many parts of the Ethiopian highlands, despite the increasing population pressure. Meire *et al.* (2013) and Munro *et al.* (2008) both found an increased vegetation cover since 1975, based on repeated terrestrial photographs in Tigray. Wøien (1995) reported a remarkable regrowth of the natural forest in the Mafud escarpment in Amhara region between 1957 and 1986. Many more studies in different districts in Amhara region observed an increase of cover by trees and forest regrowth since the 1930's and 1950's (Bewket, 2002; Crummey, 1998; Girmay *et al.*, 2000). However, these studies deal mainly with lower sub-alpine zones and the findings in this study on the evolution of forest cover in afro-alpine areas are in contrast with the described re-greening trend in lower areas. Since 1964, the extent of the forest on Lib-Amba has shown an ongoing downward trend and has been reduced to only a fraction of its size. The forest very likely had already been degrading for decades before 1964 due to exploitation for fuel and construction wood, pressure by overgrazing and land clearing for agriculture (Bishaw, 2001; Hurni, 1983). Deforestation and agricultural intensification are also observed in the Bale mountains (Kidane *et al.*, 2012). In the Simen mountains the highland forest shows a similar evolution near to the villages, but isolated forest patches show an expansion of the forest (Nievergelt *et al.*, 1998). A gradual recovery of the highland forest is also observed in the Bela Wellah catchment under government intervention (Nyssen *et al.*, 2009d). This is in line with the recent reforestation trend in the protected forest in the study area and fits within the neo-Boserupian perspective.

In contrast to the forest cover, the total amount of woody vegetation (bushland, *Erica* forest and *Eucalyptus* plantations together) in the Lib Amba study area has recovered and even increased after 1982. This is mainly as a result of the major ongoing increase of bushland since 1964 that occurred partly because of the deforestation for firewood, but can also be explained by the recent decrease of pressure by livestock grazing (Fig. 7). During the Derg government, livestock grazing in the *Erica* forest went on but cutting the forest was forbidden. However, the protection of the forest was inadequate and illegal cutting could not be prevented. Local and governmental initiatives for environmental conservation and recovery are crucial for the re-greening trend (Aerts *et al.*, 2006; Meire *et al.*, 2013; Munro *et al.*, 2008; Nyssen *et al.*, 2009d). Due to the strict protection with thirty-one guards of the highland area and more specifically the *Erica* forest in the north of Lib Amba since six years, the forest was able to increase slightly. Patches of remnant forests act as refuges and species pools and are therefore proven very important for a quick and successful regeneration of the vegetation and the biodiversity (Aerts *et al.*, 2006).

The trend of vegetation increase and forest recovery are also reflected in the relatively high proportions of the 'vegetation increase' (6%) and 'early vegetation decrease and recent increase' (5%) change trajectories. This trend is likely to proceed in the following years if the protection of the forest is respected. The stimulation of private initiatives in rural areas to plant *Eucalyptus* for firewood and construction material (Pohjonen & Pukkala, 1990) also had a positive impact on the recovery of the natural forest (de Mûelenaere *et al.*, 2014; Wøien, 1995). Despite the increase of *Eucalyptus* plantations, the majority of the woody vegetation increase happened in the highest elevation zone.

CONCLUSIONS

This study gives quantitative evidences of LUC changes in the afro-alpine zones of northern Ethiopia since 1964. LUC was mapped from aerial photographs and satellite imagery to determine the proportions of change and change trajectories over a period of 48 years around mount Lib Amba (3962 m). Two main phases of LUC changes could be distinguished. Between 1964 and 1982, large scale deforestation and general degradation of vegetation occurred in the afro-alpine vegetation zones above 3500 m. In a second phase between 1982 and 2012, intensification of land use prevailed, accompanied by an increase of settlements in the valleys below 3500 m. The strong deforestation at Lib Amba is a clear representation of the strongly degraded highlands of northern Ethiopia. Change trajectories and change maps show that there has recently been a slight regeneration of the *Erica arborea* L. forest in the highest areas and a tendency to abandon farmland with low yields on the highest slopes in the valleys. However, the vegetation increase caused by these recent tendencies in the afro-alpine area around Lib Amba is still very limited compared to other regions in northern Ethiopia. The increase of settlements in the second phase was induced by the high population pressure in lower areas, which forced people to move to higher elevated areas. The natural vegetation degraded because of land clearing for farmland, woodcutting and livestock grazing. The recent increase of woody vegetation and the limited abandonment of farmland can be framed within the neo-Boserupian perspective. Local and governmental land management measures are very important as protection against vegetation depletion and soil degradation. The poor management of the protected forest during the period of the Derg government prevented the vegetation from restoring, but the recent successful exclosure since 2007 in the afro-alpine zone has already led to a small regeneration of the *Erica* forest and a large impact of land management on vegetation cover. This quick response of vegetation recovery on Lib Amba gives confidence that other degraded afro-alpine areas would benefit in a short period of time from the installation of exclosures, given the vicinity of remaining patches of afro-alpine vegetation.

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Table 1: Geometric accuracy of the imagery

	Resolution	*RMSE*[2]		*Date*	*Source*
		RMSE X	*RMSE Y*		
Bing Maps - 2012	1 m	7.9[3]		2012	Bing maps
Time series 1982 AP[1]	1: 50.000			23-01-1982	EMA[4]
ET2 S11 29 1 0389		4.28	4.62		
ET2 S11 29 1 0390		5.92	5.99		
ET2 S12 30 0435		2.91	4.95		
ET2 S12 30 0436		3.57	3.70		
Time series 1964 AP	1: 50.000			09-11-1964	EMA
R-113 11128		4.15	4.21		
R-113 11129		5.46	4.55		
R-153 14479		5.45	4.75		

[1]AP: Aerial Photograph; [2]RMSE: Root Mean Square Error; [3]ALOS/PRISM as reference (Ubukawa, 2013); [4]EMA: Ethiopian Mapping Agency

Table 2a: Land use and cover transition matrix of the entire study area 1964-2012 (surface area in per cent). The colours represent the LUC change types: (red) deforestation, (brown) degradation, (dark green) forestation and (light green) vegetation increase.

Land use 2012 / Land use 1964	farmland	forest	Eucalyptus	bushland	grassland	village	rock	river bed	total
farmland	41.90	0.02	1.33	5.08	0.79	0.92	0.08	0.50	50.63
forest	0.68	2.19	0.06	11.32	1.44	0.08	0.07	0.00	15.84
Eucalyptus	0.00	0.00	0.08	0.00	0.00	0.00	0.00	0.00	0.09
bushland	0.76	0.13	0.02	22.49	1.82	0.01	0.35	0.00	25.59
grassland	0.39	0.03	0.00	3.02	1.04	0.00	0.31	0.00	4.79
village	0.16	0.00	0.07	0.00	0.00	0.14	0.00	0.00	0.37
rock	0.01	0.00	0.00	0.73	0.00	0.00	1.96	0.00	2.69
river bed	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0.00
total	43.89	2.38	1.57	42.63	5.10	1.16	2.76	0.50	100.00

Table 2b: Relative proportions of LUC change categories (derived from the LUC transition matrices) for elevation zone 1, elevation zone 2 and for the entire study area. Prominent proportions are represented in bold.

	Relative proportions (%)		
	Zone 1 (< 3500 m)	Zone 2 (> 3500 m)	Entire study area
1964-1982			
deforestation	**10.8**	**13.4**	**12.5**
degradation	1.0	**8.3**	**5.9**
forestation	0.2	0.5	0.4
vegetation increase	0.8	5.7	4.1
other change	1.8	0.9	0.9
no change	**85.5**	71.3	76.2
1982-2012			
deforestation	3.1	3.1	3.1
degradation	1.4	**5.6**	**4.2**
forestation	0.3	2.5	1.8
vegetation increase	1.3	**15.7**	**11.0**
other change	**9.4**	1.4	4.1
no change	**84.6**	71.7	76.0
1964-2012			
deforestation	**13.5**	**13.7**	**13.7**
degradation	1.0	**5.1**	**3.7**
forestation	0.1	0.2	0.2
vegetation increase	0.6	**12.9**	**8.8**
other change	**8.6**	1.5	3.8
no change	76.2	66.6	**69.8**

Table 3: LUC change trajectories between 1964 and 2012. Trajectories with vegetation decrease are represented in red and trajectories with vegetation increase in green

Change trajectory	*Definition*					*Percentage of study area (%)*
	1964		*1982*		*2012*	
Early vegetation decrease	Fo/B	→	Fa/G/R	→	Fa/G/R	2.1
Recent vegetation decrease	Fo/B	→	Fo/B	→	Fa/G/R	3.0
Early vegetation increase, recent decrease	Fa/G/R	→	Fo/B	→	Fa/G/R	0.9
Early vegetation increase	Fa/G/R	→	Fo/B	→	Fo/B	2.4
Recent vegetation increase	Fa/G/R	→	Fa/G/R	→	Fo/B	**6.5**
Early vegetation decrease, recent increase	Fo/B	→	Fa/G/R	→	Fo/B	**4.6**
Continually vegetated areas*	Fo/B	→	Fo/B	→	Fo/B	**31.5**
Stable non-forested areas	Fa/G/V/R	→	Fa/G/V/R	→	Fa/G/V/R	**47.2**
Other trajectories	X	→	X	→	X	1.8
*Deforestation-reforestation	Fo	→	B	→	Fo	1.5

Fo, forest; B, bushland; Fa, farmland; G, grassland; R, rock outcrop; V, villages

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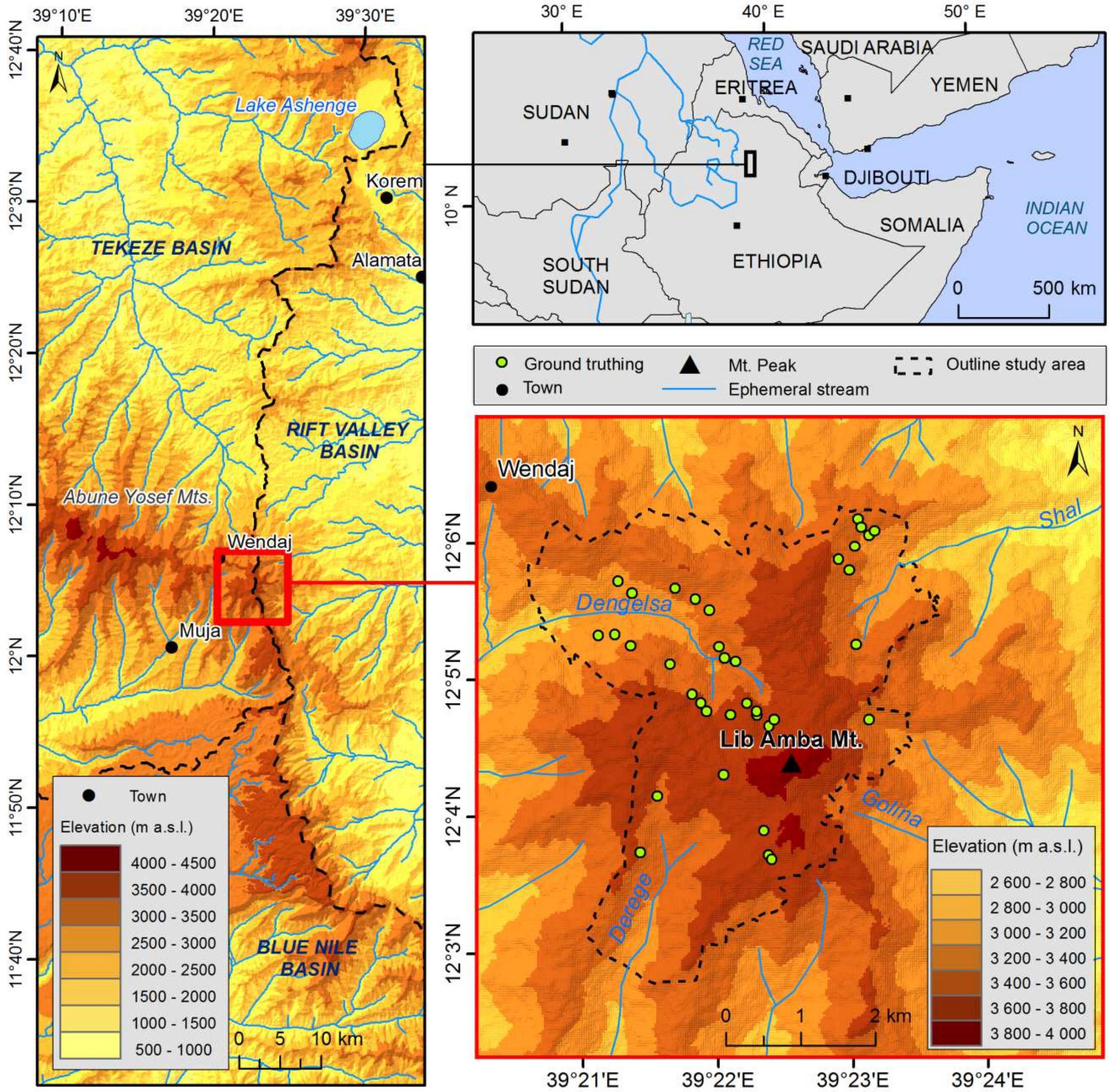

733 Figure 1: Location of the study area

734

Figure 2: Land use and vegetation types: (a) *Erica arborea* (b) *Helichrysum citrispinum* and *Hypericum revolutum* shrubs, (c) Giant lobelia (*Lobelia rhynchopetalum* Hemsl.*)*, and (d) Short and long tussock grasses (*Festuca macrophylla, Carex erythrorhiza*).

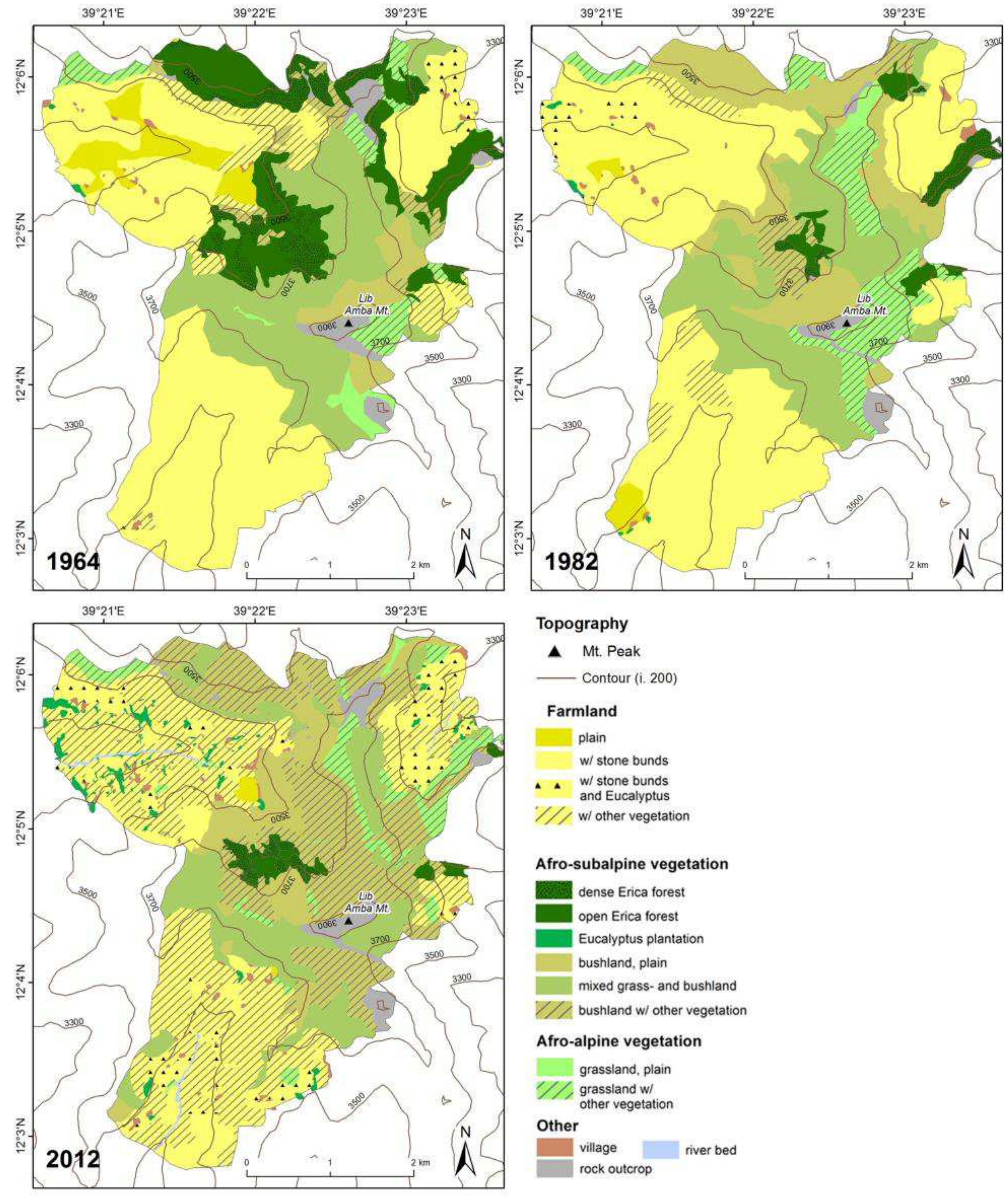

Figure 3: LUC maps for the three successive time steps (1964, 1982 and 2012)

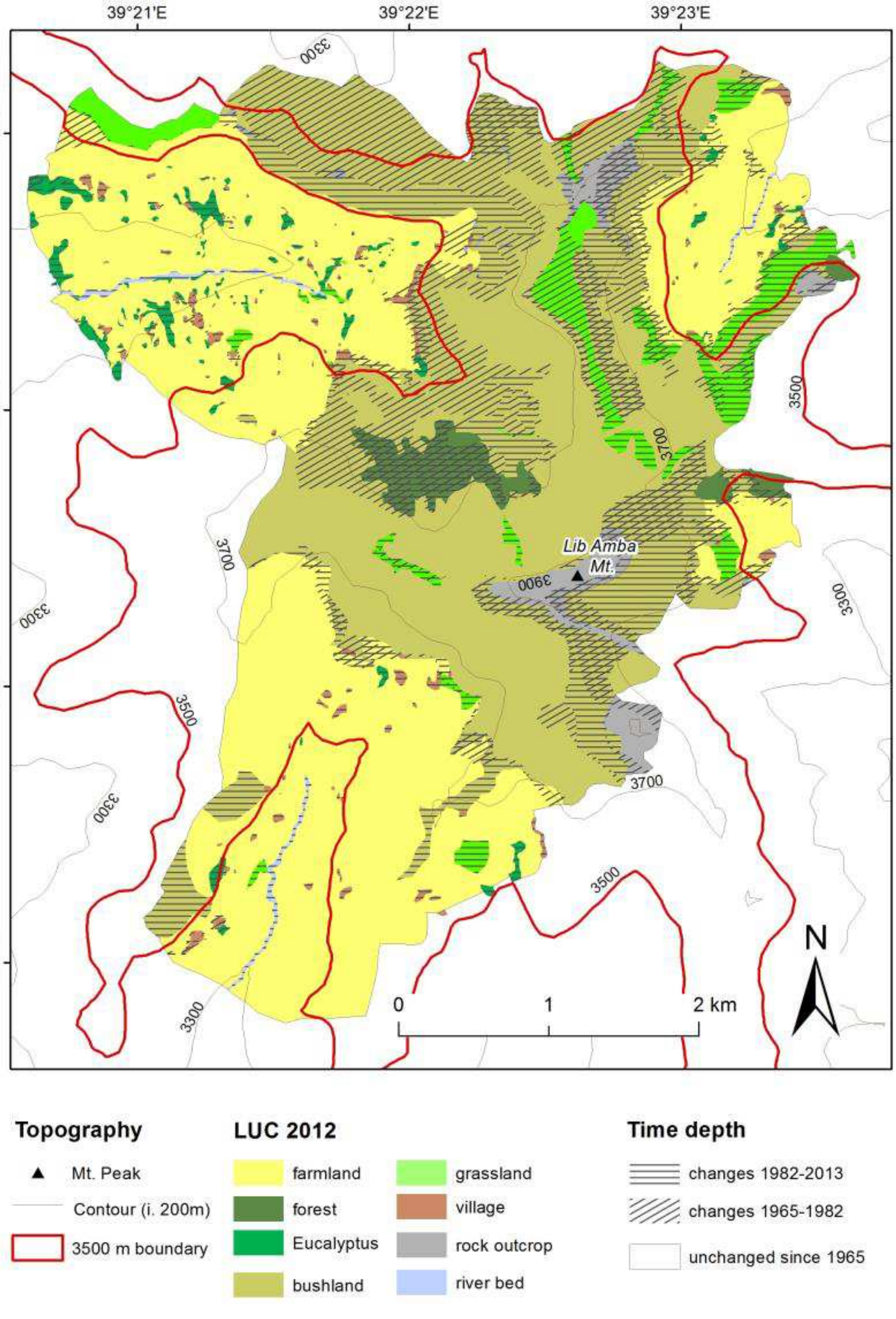

Figure 4: Time depth map of the LUC between 1964 and 2012

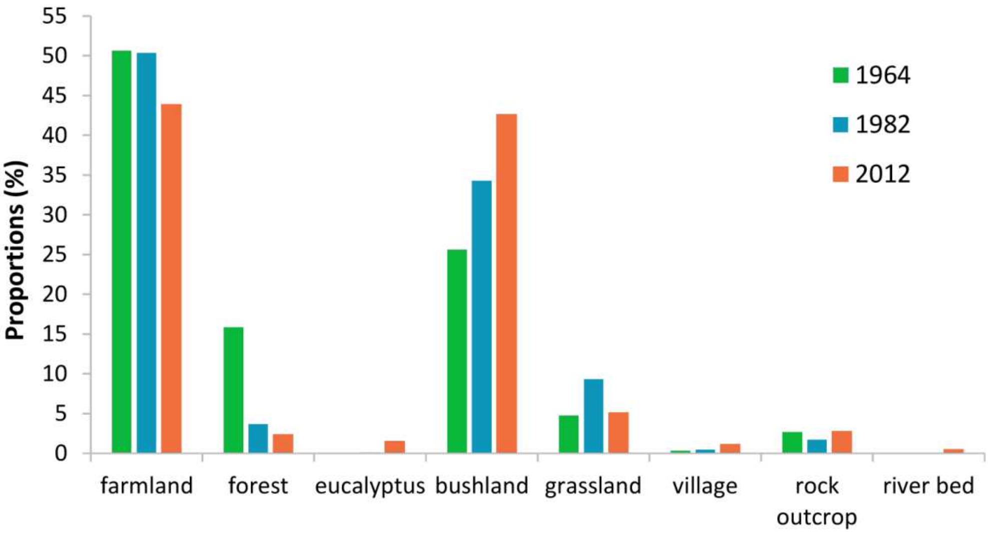

Figure 5: LUC class proportions for 1964, 1982 and 2012

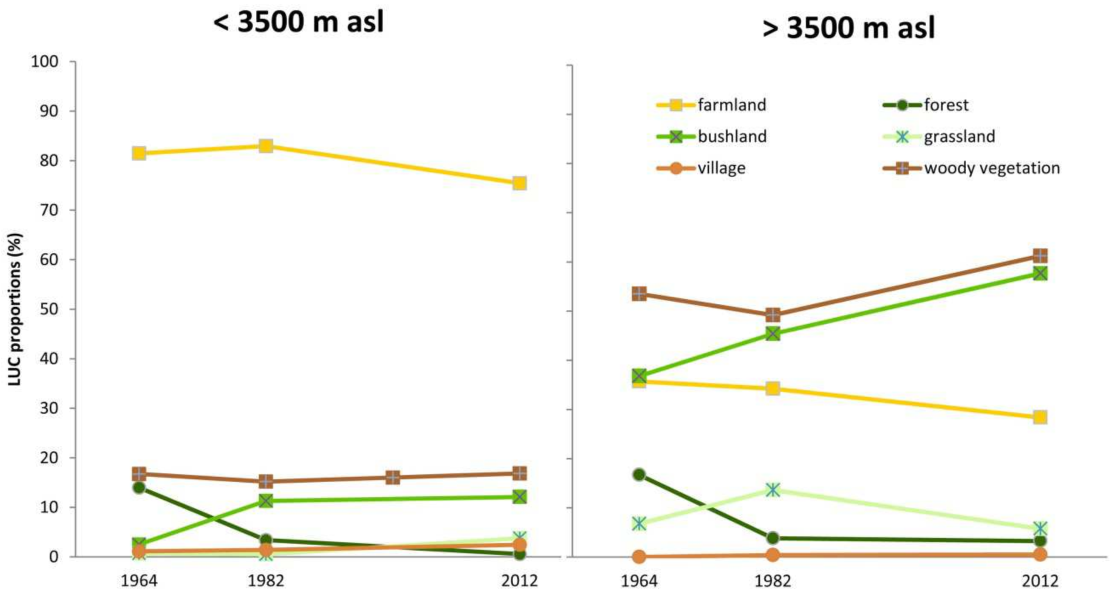

Figure 6: Overview of the most important LUC changes between 1964,1982 and 2012. Woody vegetation is the sum of the proportions of forest, bushland and Eucalyptus plantation.

Figure 7: Photograph of vegetation regeneration after livestock removal. Young growing Erica trees can be identified by their light green colour in comparison to the dark green colour of the older *Erica* trees.