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NORTH ETHIOPIAN AFRO-ALPINE TREE LINE DYNAMICS AND FOREST-COVER CHANGE SINCE THE EARLY 20TH CENTURY

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ABSTRACT

High-altitude forests are very important for local livelihood in the vulnerable environment of the densely populated tropical highlands. Humans need the ecosystem services of the forest and directly impact the forest through livestock herding, fire, and wood harvesting. Nevertheless, temperature-sensitive tree lines in the tropics are scarcely investigated in comparison with higher northern latitudes. In this study, the *Erica arborea* L. tree line is studied in a tropical mountain in the North Ethiopian highlands: Lib Amba of the Abune Yosef Mountain range (12°04′N, 39°22′E, 3993 m asl). The present tree line and forest cover was recorded by high-resolution satellite imagery from Google Maps and field data (2010–2013), while historical forest cover was studied from aerial photographs (1965–1982) and repeat photography (1917–2013). The aerial and satellite images were orthorectified and classified in forest/non-forest binary maps. The binary forest layers were used to detect forest-cover change and tree line dynamics by image differencing between the three time layers (1965–1982–2010). These maps and a terrestrial photograph indicate two periods of deforestation (1917–1965 and 1982–2013), whereas the forest cover was stable between 1965 and 1982. Deforestation was especially severe (with 63%) between 1982 and 2010, associated with a population increase from 77 to 153 inhabitants per square km. There is significant evidence that the elevation of the *E. arborea* L. tree line increased from 7 to 15 vertical meters between 1965 and 2010, in an area with decreasing anthropozoogenic pressure. Copyright © 2014 John Wiley & Sons, Ltd.

KEY WORDS: tree line shift; forest-cover change; land occupation; climate change; land management; tropical highlands

INTRODUCTION

High mountain forests are very important for the livelihoods of local communities in the tropical highlands (Bognetteau *et al*., 2007). These highlands are densely populated with more than 100 inhabitants per km^2 in areas above 2500 m asl in East Africa and Central America (Nyssen *et al*., 2009b). Local communities directly impact the forest cover for their subsistence, through livestock herding, fire, and wood harvesting (Boahene, 1998; Wesche *et al*., 2000).

These tropical high-altitude forests are important not only because of their role as a natural resource, providing wood and non-wood products but also because of their ecosystem services (Price, 2003). The high-altitude forests function as a hygric buffer benefitting the water balance of the mountain ecosystem and the agricultural areas in the surrounding lowlands (Miehe & Miehe, 1994; Aerts *et al*., 2002; Nyssen *et al*., 2004). Removal of woody vegetation leads to decreased infiltration with direct effects: decreased discharge of downstream springs and increased soil erosion (Nyssen *et al*., 2004; Descheemaeker *et al*., 2006).

The upper limit of these tropical high-altitude forests forms one of the most apparent vegetation boundaries worldwide. The tree line ecotone is formed by the transition from closed montane forests to treeless alpine vegetation, which is marked by a steep gradient of increasing stand fragmentation and stuntedness (Körner & Paulsen, 2004). The definition of the tree line is dependent upon the region of interest of the authors. Ecologists frequently use the term tree-species limit, which is the boundary formed by the upper individuals of tree species, regardless of the growth form, while forestry scientists focus on the limit of the forest. In this study, the physiognomic tree line is used to refer to this forestry limit of the continuous forest (Van Bogaert *et al*., 2011).

Tree lines are responsive to climate change (Körner & Paulsen, 2004), a change that is most prominent and rapid at high altitudes and latitudes (Holtmeier & Broll, 2005; Harsch *et al*., 2009). There are a growing number of studies about tree line dynamics in the tropics (e.g., Bader *et al*., 2007; Wesche *et al*., 2008; Sassen *et al*., 2013), but the response to climate change in the tropics and in the Southern Hemisphere is still scarcely investigated compared with tree line dynamics at higher northern latitudes (Holtmeier & Broll, 2007). At these high northern latitudes an average vertical tree line shift of 70 to 90 m occurred during the last century (Danby & Hik, 2007; Kullman & Öberg, 2009).

Improved understanding about tree line dynamics and deforestation patterns and their driving processes in tropical highlands is vital for sustainable land management strategies in these vulnerable high-altitude areas and will help us to

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understand the effects of climate change on these environments (Jacob *et al*., 2014).

In Ethiopia, deforestation started around 3000 to 2000 ^{14}C years BP with increasing land cultivation (Bard *et al*., 2000; Nyssen *et al*., 2004). By the early 20th century, large parts of North Ethiopia were already deforested. Statements about recent forest-cover changes are dependent on time span and study regions (de Mûelenaere *et al*., 2014). Based upon repeat photography, an increase of the forest cover was detected over the last 140 years (Nyssen *et al*., 2009a; Meire *et al*., 2012). On the other hand, based on satellite images and aerial photographs, Tekle & Hedlund (2000) and Zeleke & Hurni (2001) found that there has been an important deforestation period between 1957 and 1995. On a country scale, the annual deforestation rate in Ethiopia was estimated to be 1% from 1990 to 2010; this corresponds to a yearly decrease in forest cover by 1500 km^2 (FAO, 2010), despite the artificial increase of forest cover by eucalyptus plantations and forest recovery land management strategies (such as exclosures) since the mid-1980s (Gebrehiwot *et al*., 2013; de Mûelenaere *et al*., 2014).

For the tropical highlands, few in-depth studies exist that look at both forest status change and tree line dynamics (Holtmeier, 2009). The objectives of this paper are as follows: (i) to have a detailed study of forest and tree line dynamics in Lib Amba Mountain of the North Ethiopian highlands since the early 20th century, (ii) to verify whether there is an effect of climate change on the tree line, and (iii) to provide an integrated methodology that suits many tropical environments using a combination of remote sensing data sources.

MATERIALS AND METHODS

Study area

The study area consists of Lib Amba Mountain and surrounding mountains (39 km^2, 12°8′N, 39°11′E, 3993 m) of the Abune Yosef Mountain range, part of the North Ethiopian highlands (Figure 1).

The Ethiopian highlands result from the evolution of the East African Rift System. Subhorizontal Paleozoic and Mesozoic sedimentary rocks overlain by Tertiary volcanism were rapidly uplifted in the Miocene and Plio-Pleistocene (Bussert, 2010). The high-altitude soils are rich in organic matter and relatively acidic; the dominant soil types are well-developed Andosols (Wesche *et al*., 2000). The study area is situated on the western shoulder of the Rift Valley, on the water divide between the hydrological basin of the East African Rift in the east and the Tekeze basin in the west (Figure 1). It lies within the semiarid to subhumid mountain climate zone of the North Ethiopian highlands (Nyssen *et al*., 2005) and rises above the present tree line (at approximately 3700 m). The climate is characterized by unreliable seasonal rainfall, with annual rainfall ranging between 800 and 2200 mm y^{-1} (Saavedra, 2009). Most of the rainfall occurs during the summer rain season and is highly erosive (Nyssen *et al*., 2005).

The afro-alpine high-altitude forest is dominated by species of the *Ericaceae* family (Wesche *et al*., 2000). Hedberg (1951) introduced the term "the ericaceous belt," which forms the upper tree line ecotone in tropical mountains in Africa (Wesche *et al*., 2000). Hurni & Stähli (1982) identified four vegetation limits in the Simen Mountains: the Acacia limit at ca 2730 m, the *Hagenia*, *Juniperus*, and *Olea* montane forest limit at ca 3200 m, the *Erica arborea* L. tree line limit at ca 3715 m, and the upper grass-steppe vegetation limit at ca 4225 m. These successive vegetation belts are also found in Lib Amba Mountain, but at different vegetation growth limits, related to local biophysical constraints. The growth limit of the high-altitude forest of Lib Amba is also formed by the species *E. arborea* L.

Data and preprocessing

The oldest available data source providing information about the spread of high-altitude forests in our study area (Figure 1) is a historical terrestrial photograph of Aboy Gerey Mountain from 1917 made by Conte Fillipo M. Visconti © Italian Military Geographical Institute, Firenze.

Besides this terrestrial photograph, historical black-and-white aerial photographs of 1965 and 1982 (scale approximately 1:50,000, scanned at 1200 dpi) from the Ethiopian Mapping Agency were used. The aerial photograph of 1982 was orthorectified by digital image processing with ERDAS Imagine® (Intergraph, Madison, USA). As input for the georectification process, Global Navigation Satellite System –measured ground control points were used. In Table I, the accuracy of the image orientation process is shown in terms of root-mean-square error ($RMSE_{xyz}$; 3·59, 4·80, and 5·73), absolute mean error (AME_z; 2·51), and linear error at 90% probability ($LE90_z$; 3·46).

Photogrammetric restitution was unsuccessful for the aerial photograph of 1965 because fast population growth and low-technology building caused important landscape changes since 1965. Therefore, the geometric rectification was performed by co-registration with the orthophotograph of 1982. Image-to-image registration enables identification of a large number of corresponding points on both layers, in this case, 6.5 points per km^2. 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).

Similarly, the most recent situation given by high-resolution Google Maps, DigitalGlobe, satellite imagery (2010) was image-to-image co-registered with the 1982 orthophotograph as reference.

The accuracy of the co-registrations is tested by ten control points derived from the 1982 orthophotograph. The positional accuracy in x and y is given by the $RMSE_{x,y}$ computed from the difference with the 1982 reference coordinates. The $RMSE_{x,y}$ for 1965 is 3·6 and 4·8, and for 2010, it is 3·5 and 4·2; in both cases, this is not significantly different from that of the 1982 orthophotograph (Table I).

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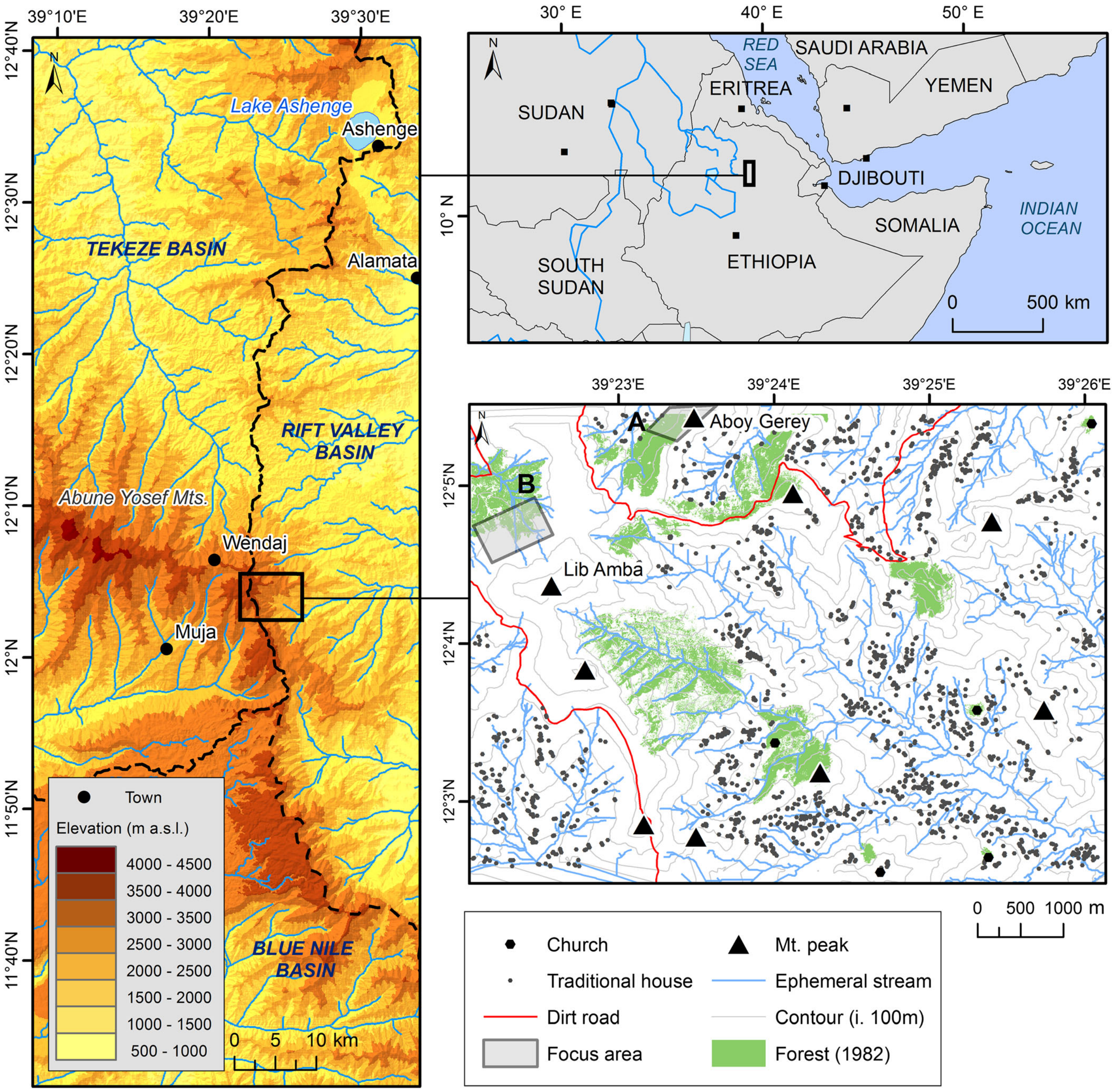

Figure 1. Abune Yosef Mountains and selected study area. In-depth focus areas: (A) repeat photograph of Aboy Gerey Mountain (B) tree line dynamics at Lib Amba Mountain. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

Forest-cover mapping

Repeat photography

Repeat photography is a very valuable tool for the study of the historical forest cover and tree line elevation before 1950 because historical photographs contain information that is not documented by systematic aerial photographic surveying (starting from ca 1950) and satellite images (from ca 1960s; Roush *et al*., 2007). Many authors have used repeat photography for the study of landscape changes; inventories are made by Meire *et al*. (2012), Roush *et al*. (2007), and Frankl *et al*. (2012). In this study, the approach of Meire *et al*. (2012) is used to warp the topographic forest unit from the terrestrial photograph on the orthophotograph.

Forest classification

Satellite images contain spectral information, which usually allows to accurately map forest-cover changes. Historical black-and-white aerial photographs provide important historical information, but they do not contain multispectral information, which makes them difficult to use for land-cover classifications. Therefore, an adjusted methodology was developed to study forest cover and tree line dynamics from black-and-white aerial photographs.

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Table I. Geometric accuracy of the image orientations: photogrammetric restitution of 1982 aerial photograph (AP-1982) and image-to-image registration of 1965 aerial photograph (AP-1965) and 2010 Google imagery (Google Maps 2010)

	Photogrammetric restitution						
		Ground control point residuals (m)					
	No. of GCP	RMSE X[a]	RMSE Y	RMSE Z	MAE Z[b]	LE90[c]	Software
AP-1982	14	3·585	4·799	5·7283	2·5047	3·4629	LPS[d]
	Image-to-image registration (with the 1982 orthophotograph as reference)						
	No. of GCP	RMSE X	RMSE Y				Software
AP-1965	150	3·559	4·818				ArcGIS
Google Maps—2010	25	3·449	4·214				ArcGIS

[a]Root-mean-square error.
[b]Mean absolute error, the mean of the absolute value of the prediction error.
[c]Linear error 90%, error range that would include 90% of the pixels within the DSM.
[d]Leica Photogrammetry Suite.

In a first step, the non-forested area was masked on the aerial photographs. This allowed in-depth analysis of the dynamics within the forested areas and reduced the redundant non-forest information. Second, texture information was computed for the masked aerial photographs (Erener & Düzgün, 2009). For the 1965 and 1982 aerial photographs, eight texture bands were calculated in ENVI® (Exelis, McLean, USA) based on the co-occurrence matrix of Haralick *et al*. (1973; i.e., homogeneity, contrast, dissimilarity, mean, standard deviation, entropy, angular second moment, and correlation). These texture statistics measure spatial frequency between the occurrences of two neighboring pixels. To reduce redundancy within the texture bands, a principle component analysis was applied to the raw texture images (Erener & Düzgün, 2009). The first five components explained 95% of the variation and were therefore stacked with the original aerial photograph as the basis for the forest classification process (Figure S1, Supporting Information).

In the third step, a supervised maximum likelihood classification with three classes (forest, bush and grassland, cropland, and rocks) was executed in ENVI (Figure S1). This method computes the statistical probability that a pixel belongs to one of the training classes based on the mean vector and covariance statistics and that the pixel is assigned to the class with the highest probability (Lillesand *et al*., 2008). Additionally, the classification was filtered with a 3 × 3-pixel majority filter, to smooth the image and remove isolated classified pixels (Lillesand *et al*., 2008).

Finally, the classified images are reclassified by merging the non-forested classes into a single class. The results of this reclassification process are binary maps with the classes: forest and non-forest. These binary maps allow studying forest dynamics by postclassification comparison (Bharti *et al*., 2012).

The classification of the Google Maps image was also executed with a maximum likelihood function in three classes. Similarly, the image was smoothed and reclassified in a binary forest/non-forest map.

Tree line mapping

Tree line dynamics were studied in detail in a subset of the study area, in which the upper forest is well protected and reaches the highest elevation (Figure 1A). In this area and at this elevation, the tree line is potentially limited by climate change.

The physiognomic tree line boundary corresponds with the 30% tree-cover isoline (Rees *et al*., 2002; Van Bogaert *et al*., 2011). To detect this 30% isoline, a moving window of 3 × 3 m (small enough to capture sufficient detail) was used to map the percentage of tree cover in the study area. From this tree-cover map, the 30% tree-cover isoline was extracted. Subsequently, the irregularity of the tree line curve is smoothed in ArcGIS with the simplify line function (10-m tolerance). This smoothed curve is referred to as the envelope tree line because of the similarity with the geometrical envelope principal.

Application of this technique for the three layers allows detecting tree line change in the study area. Quantification of the changes is made possible by segmenting the envelope tree line in 10-m segments. The elevation of these segments is statistically compared with a two-sample *t* significance test, and the difference is computed with a two-sample *t* confidence interval statistic (Moore *et al*., 2009). A slope effect can be expected because steep slopes are less accessible for anthropozoogenic influences in contrast to gentle slopes. Evidence of such a relationship between deforestation and slope angle is given by the research of Trejo and Dirzo (2000). Therefore, the same statistical tests are repeated for the segments divided into three categories: slopes of <12°, between 15° and 45°, and >45° (Trejo & Dirzo, 2000).

RESULTS

Classification accuracy

Accuracy assessment of the forest classification maps was performed by using a random point sample design with a minimum of 50 samples for each class (Congalton & Green,

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2009). The randomly generated points were overlain with the forest maps in ArcGIS and compared with the ground truth as visible on the original aerial photographs. The subtracted point values were used to assess the accuracy of the classification using a confusion (error) matrix (Congalton & Green, 2009). The overall accuracy of the 1965, 1982, and 2010 classifications is respectively 90, 85, and 84%; all are very close or above the 85% threshold value (Congalton & Green, 2009). The kappa value of the three classifications is high, respectively, 0·79, 0·70, and 0·67. The classifications are thus reliable and in substantial agreement with the ground truth (Landis & Koch, 1977; Table II). The lower accuracy of the 2010 binary map is caused by the lower amount of trees per hectare in the 2010 forests, which are more difficult to classify. Overall, classification errors are partly caused by overclassification of shaded slopes in comparison with non-shaded slopes. However, the exposition is similar for both aerial photographs; both are made during the dry season with the sun in the south (25/01/1965; 20/02/1982).

Forest-cover dynamics

The early 20th century

Although we have only one historical terrestrial photograph for the study area, this photograph has been proven important because it allows a unique comparison of the land cover over a period of almost 100 years (Figure 2). The repeat photograph of 2013 shows that there has been an important land occupation of the mountain slope since 1917, which is accompanied by an agricultural expansion upward the mountain. Indicators of these changes are new settlements on the previously inhabited mountain slopes and cultivation terraces that reshaped the mountain flanks (Figure 2). The human occupation of the mountain slope has clearly affected the forest. At some places, the forest is replaced by cropland, and overall, there has been a severe decrease of the density of the remaining forest (Figure 2). Measurement of the canopy cover, with a GRS densitometer, indicated that the canopy cover has reduced to only 15% cover in 2013.

Moreover, the warped terrestrial photograph on the horizontal plane made it possible to study forest-cover changes in detail between 1917 and 2010 for the slope of Aboy Gerey Mountain (Figure 3). Forest-cover change maps indicate that there are two periods of deforestation. The first deforestation period took place between 1917 and 1965, and the second more severe deforestation period occurred between 1982 and 2010. While between 1965 and 1982, afforestation and deforestation were in balance, and the forest cover remained unchanged.

Between 1965 and 2010

Forest-cover changes are shown by postclassification comparison of the three forest-cover maps (1965, 1982, and 2010; Figure 4). On the change maps, a stable forest cover is observed in the first period between 1965 and 1982. During this period, half of the forested area remained unchanged (52%), while 24% was deforested and also 24% was afforested (Figure S2). Deforestation mainly occurs at the edges of the forests, whereas there is an increase of the forest cover within the forest patches (Figure S2). In the second period between 1982 and 2010, the deforestation rate is much higher; overall, 54% of the forest cover is removed. During this period, 63% of the previously forested area is deforested, 28% remained forested, and only 9% is afforested (Figure S2). The forest expanded only in small patches, whereas outside these patches, the forest disappeared almost completely (Figure S2).

Tree line change

Mapping the envelope tree lines (1965–1928 and 2010) shows that there is an upward trend of the tree line along the mountain slope in the west of the study area, while the tree line is comparatively stable at the steeper ridges in the east (Figure 5). Comparison of the average tree line

Table II. Accuracy assessment of the 1965–1982–2010 forest classifications based on confusion-matrix-derived measurers and kappa values

		Classification			Omission	Overall	Kappa
		Forest	Non-forest	Total	errors	accuracy	
1965 (AP)							
Ground truth	Forest	113	5	118	0·96	0·90	0·79
	Non-forest	14	63	77	0·82		
	Total	127	68	195			
Commission errors		0·89	0·93				
1982 (AP)							
Ground truth	Forest	99	1	100	0·99	0·85	0·70
	Non-forest	28	67	95	0·71		
	Total	127	68	195			
Commission errors		0·78	0·99				
2010 (SI)							
Ground truth	Forest	69	18	87	0·79	0·84	0·67
	Non-forest	13	95	108	0·88		
	Total	82	113	195			
Commission errors		0·84	0·84				

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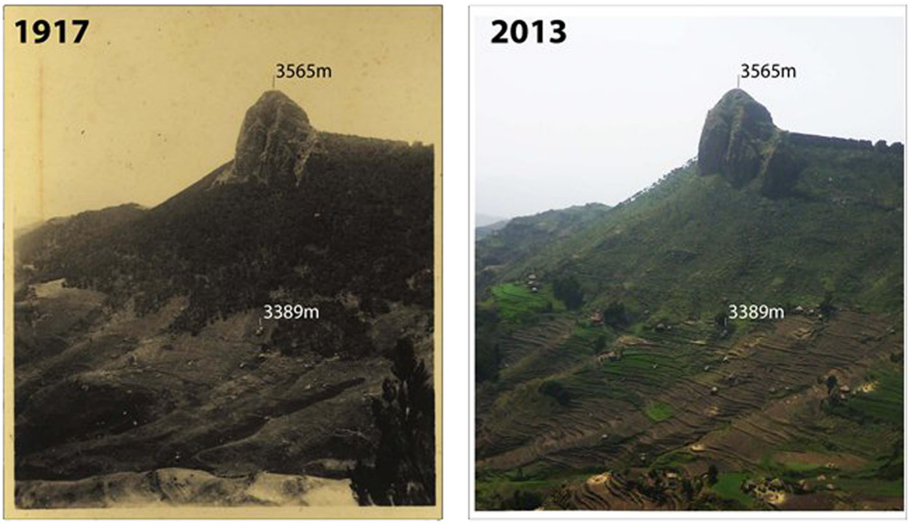

Figure 2. Repeat photograph of Aboy Gerey Mountain (3565 m asl); (left) historical terrestrial photograph of Conte Fillipo M. Visconti on an Italian trade mission from Leggu (Woldia) to Tembien © Italian Military Geographical Institute, Firenze; (right) repetition in 2013. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

elevation with a *t*-test between 1965 and 1982 indicates that there is no significant increase of the tree line. Between 1982 and 2010, there is a significant increase of the tree line between 6 and 13 vertical meters (Table III). Over the full period of 1965–2010, the tree line significantly increased between 7 and 15 vertical meters (Table III).

To control whether there is an effect of the slope gradient, the *t*-test calculations were also performed for the three slope categories. There is a significant increase of the tree line elevation in the three slope categories, but this tree line shift is much higher for the gentle slopes in the western part of the study area (Table III).

Explaining the spatial pattern of forest-cover change

Elevation and or slope gradient could be expected to partly explain the spatial pattern of forest-cover change because wood harvesting is more likely to occur at lower elevations and gentle slopes, which are more accessible and more interesting for agriculture. However, a chi-square test with Cramer's *V* coefficient for large sample sizes, between the forest-cover change maps (1965–1982 and 1982–2010) and, respectively, the digital terrain model and the derived slope gradient, shows very low associations with forest-cover change. For the period 1965–1982, the Cramer's *V* coefficient is respectively 0·14 and 0·07, and for the period 1982–2010, this is 0·14 for both elevation and slope gradient.

Another potential explanation of forest-cover change for the study area is increasing anthropozoogenic pressure. The changing anthropogenic pressure was studied by digitizing the settlements from the successive data layers (1965–1982–2010). From this, the population density was derived by multiplication of the settlements with the average household members (i.e., 3·6 ± 1·7; Stock (2011). The population pressure is more than doubled between 1965 and 2010 from 68 to 153 inhabitants per km^2. This increase occurred mainly between 1982 and 2010 (from 77 to 153 inhabitants per km^2; (Figure S3). There is a clear relation between deforestation and growing anthropogenic pressure.

DISCUSSION

Long-term land-cover changes are widely studied with Landsat images (Ouedraogo *et al.*, 2010), but their 30-m

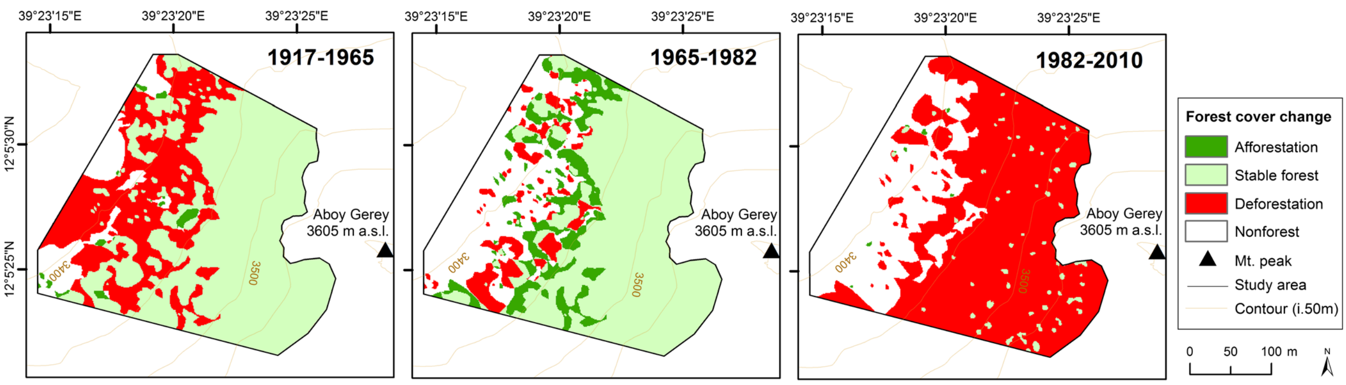

Figure 3. Forest-cover changes on the western slope of Aboy Gerey Mountain in the period 1917–2010. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

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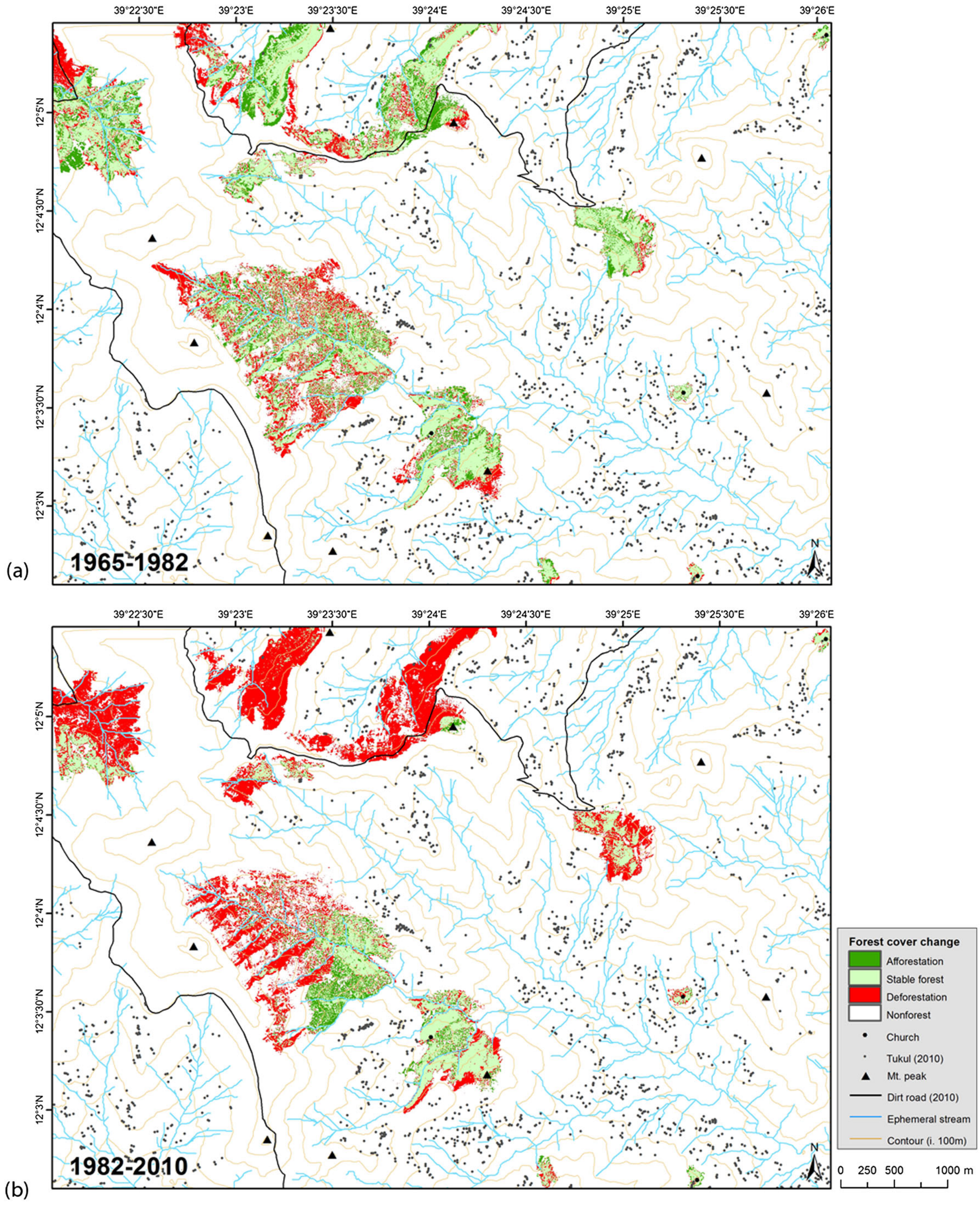

Figure 4. Forest-cover change between (a) 1965–1982 and (b) 1982–2010. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

resolution does not allow detecting small-scale changes. The proposed methodology for the detection of forest-cover change and tree line dynamics allows detailed analysis of long-term forest and tree line changes, from aerial photographs and recent satellite images. However, shading can cause overclassification of forest in comparison with non-shaded areas on the black-and-white aerial photographs. The use of aerial photographs to map forest cover also introduces a small overclassification error because trees and closed *Erica* scrubs cannot be distinguished from each other.

Application of the methodology is constrained by the forest mask that is used in the first step of the classification process to remove the non-forested area. This forest mask needs to be delimited by hand, which reduces the size of the potential mapping area. The method is thus not an alternative for region-wide land-cover mapping, such as that preformed by Brink & Eva (2009) for Africa. However, the method is suitable for detailed forest cover and tree line dynamics studies.

In this specific study, the available information for the period before 1965 is limited because there is only one historical terrestrial photograph of the study area. Nevertheless,

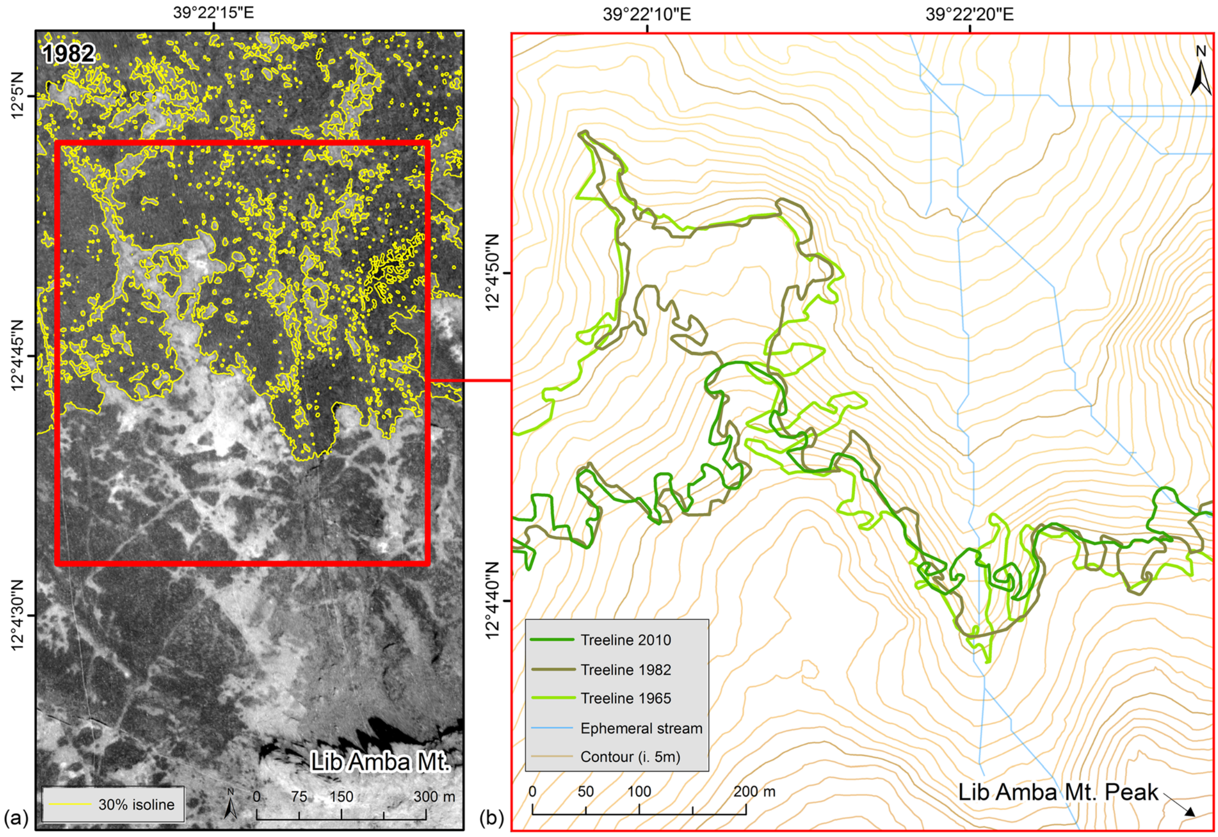

Figure 5. Tree line detection (a) 30% isoline and (b) detailed map of the derived tree lines within the red subset: 1965, 1982, and 2010. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

warping this terrestrial photograph on the horizontal plane enabled mapping forest-cover changes from the early 20th century. A large amount of historical terrestrial photographs is needed to improve understanding about forest-cover change and tree line dynamics before 1950 in the tropical highlands of Africa. Such historical landscape photographs are available in major archives, and a growing number can be traced on the Internet (Nyssen *et al.*, 2010). Environmental studies in Africa are increasingly using these historical photographs (e.g., Osmaston, 1998; Kull, 2005; Western, 2010).

Repetition of the old terrestrial photograph and post-classification comparison of the historical aerial photographs

Table III. A *t*-test comparison of tree line elevations between 1965–1982 and 2010 in order to identify potential tree line changes and slope effects

Tree line segments (10 m)		Tree line segments (*N*)	Q1[a]	Median	Q3[a]
1965		276	3651	3680	3703
1982		286	3656	3684	3700
2010		201	3681	3692	3700
Tree line change		*p*-value		95% CI [b]	
1965–1982		>0·05			
1982–2010		<0·05		6–13 m	
1965–2010		<0·05		7–15 m	
Slope categories		Tree line segments (N)	Q1	Median	Q3
All years	<12°	74	3647	3659	3702
	12 < 45°	602	3662	3687	3701
	>45°	87	3682	3692	3699
Tree line change (slope effect)		*p*-value		95% CI	
1965–2010	<12°	<0·05		9–25 m	
	12 < 45°	<0·05		4–14 m	
	>45°	<0·05		4–19 m	

[a]First quartile (Q1) and third quartile (Q3).
[b]Confidence interval.

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and recent satellite imagery indicate that the forest cover severely decreased during the 20th century. This is in agreement with the deforestation trend reported by the global forest resource assessment by the FAO (2010). Forest clearance is indicated to be much more pronounced in the 20th century (Gebrehiwot *et al*., 2013). The second deforestation phase in Lib Amba Mountain, after 1982, was also the most severe for the study area. This recent deforestation trend impedes important ecosystem services of the high-altitude forests in this vulnerable highland region.

An important driver of this deforestation is increased human pressure. Between 1965 and 1982, the population growth was small and afforestation and deforestation were in balance, whereas population pressure strongly increased between 1982 and 2010 (from 77 to 153 inhabitants per km^2). This corresponds with a period of severe deforestation in the study area. At present, population density is very high in the study area with 153 inhabitants per km^2. This is higher than the average population density of 135 inhabitants per km^2 for the Ethiopian highlands (Nyssen *et al*., 2009b). In Ethiopia, 85% of the population and 75% of the livestock live in the highlands (above 1500 m), which account for only 43% of the Ethiopian territory (Woldemariam, 1988; Amsalu & de Graaff, 2006).

Because of this growing anthropogenic pressure, the forest cover severely reduced between 1982 and 2010. At present, the forest remains only in a few patches. This indicates that land management decisions have an important impact. However, also the drought and famine of 1983–1985 could be responsible for this severe change in the forest cover because forests provide resources in times of emergency (Babulo *et al*., 2008).

This research has also indicated that the tree line elevation significantly increased by 7–15 vertical meters (95% CI) between 1965 and 2010. However, a positional error of ±5 horizontal meters must be taken into account, which corresponds for the average slope of 25° with 2.11 vertical meters. The observed tree line shift is thus clearly less than in that the Subarctic (70–90 m in the last century; Kullman & Öberg, 2009) or in the Swiss Alps (average rise of 37·9 m between 1985 and 1997; Gehrig-Fasel *et al*., 2007). This difference in tree line rise is potentially caused by the high land pressure in the study area, while it is much lower in the more northern regions.

The high land pressure in the study area is illustrated by the forest-cover change history, which raises the question whether tree line change is the result of climate change or land management changes. The land management hypothesis would be in agreement with the study of Jacob *et al*. (2014) about tree line dynamics in the tropical highlands of Africa. This study indicates that tree lines have not risen to higher altitudes in the tropical African highlands because of high anthropozoogenic pressure, which caused stabilization and even recession of the tree lines below their natural climatic limit. Strong disturbance of the tree line by human interference is also found for the Andes Mountains by Young & León (2007). Even though the study is focused on a relatively small-scale study area, the detailed research findings are valuable in supporting the general trends found in these large-scale studies of the tropical highlands.

The focus area for the study of tree line dynamics is chosen in a protected area, which in the case of long-term protection would mean that the observed tree line shift must be climate change driven. However, the forest has only been protected for 10 years, and the highest tree line shift occurred on the gentle slopes in the western part of the study area in which the tree line was suppressed to a lower elevation. It is thus likely that tree line shift is mainly caused by changing land management rules. The strong impact of the growing population might therefore outweigh the potential effects of increasing temperatures on the tree line in the study area.

CONCLUSIONS

This study revealed that there were two periods of deforestation on the slopes of Lib Amba Mountain between 1917 and 2010, a first phase of deforestation in the period 1917–1965 and a second more severe deforestation phase that started 30 years ago. Between 1982 and 2010, 63% of the remaining forest cover was removed. In the same period, the population pressure increased from 77 to 153 inhabitants per km^2. The currently forested areas are limited to delineated patches, most probably associated with protective measures. This study indicates that there has been a significant but small increase of the elevation of the tree line between 1965 and 2010, which lies between 7 and 15 vertical meters. This increase of the tree line elevation is higher on the gentle slopes. Because of the high anthropozoogenic pressure in the study area, the potential effect of climate change on the tree line remains unclear. There is a need for additional research about the potential effects of this deforestation trend. Destabilization of the key ecosystem services of the high-altitude forest can have a major impact on the livelihood of the local communities in this vulnerable mountain environment.

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